Sensitivity of thermal dileptons to the dissipative properties of a hydrodynamical evolution

Fonds de recherche sur la nature et les technologies Québec

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BEST COLLABORATION

Outline

Introduction

Part I: Modelling of the QCD Medium

- Initial condition for baryon number
- Viscous hydrodynamics

Part II: Thermal Sources of Dileptons

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

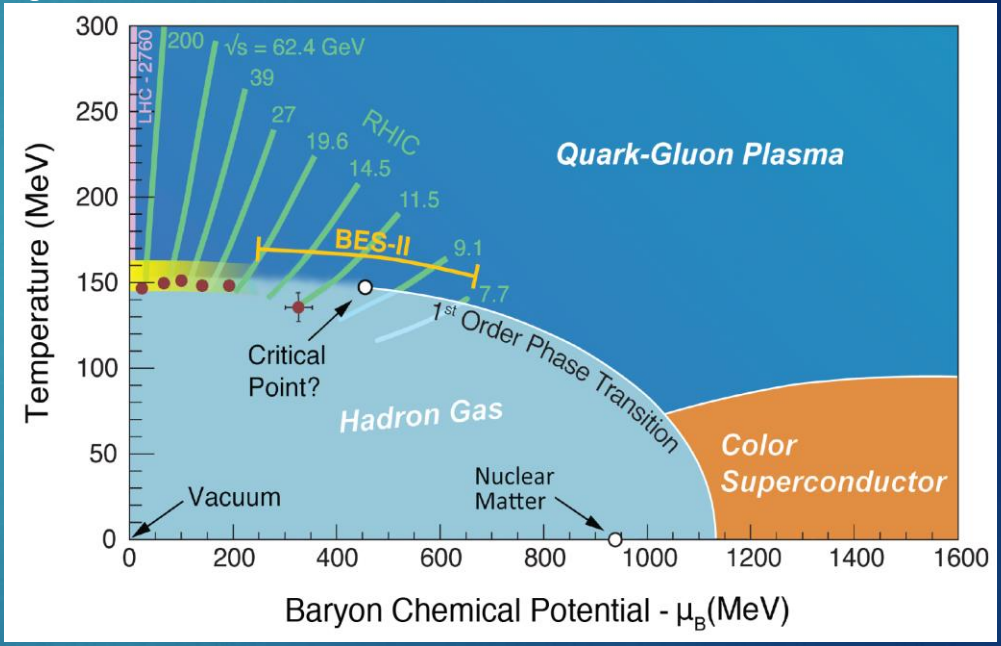
Part III: Dileptons & Dissipative Evolution

- Effects of net baryon density and diffusion on dilepton yield and v_n

Conclusion and outlook

RHIC Beam Energy Scan and the phase diagram of QCD

- The BES program at RHIC: explore properties of QCD in different regions of the phase diagram
  - Does QCD have a first order phase transition? If so, where?
  - What are its experimental signatures, i.e. observables?
  - What can we learn about poorly explored transport coefficients of QCD, e.g. κ, σ, relevant in the BES context?



- Dissipative hydrodynamics was quite successful at describing various observables at top RHIC and LHC energies.
- How are the hydro equations modified within the context of the BES and how do these affect dilepton radiation?

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

- Israel-Stewart dissipative hydrodynamics at lower beam energies:

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

$$\partial_\mu \mathrm{J}^\mu_\mathrm{B} = 0$$
$$J^\mu_B = \rho_B u^\mu + V^\mu$$
$$\tau_V \Delta^\mu_\alpha u^\sigma \partial_\sigma V^\alpha + V^\mu = \kappa \nabla^\mu\left(\frac{\mu_B}{T}\right) - \tau_V V^\mu \theta - \lambda_{VV}\sigma^{\mu\nu}V_\nu$$
$$\tau_V = \frac{0.2}{T}; \quad \kappa = 0.2\frac{\rho_B}{\mu_B}; \quad \lambda_{VV} = \frac{3}{5}\tau_V$$

PRD 77, 066014 (2008)

- $P(\varepsilon, \mu_B)$: 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:

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

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

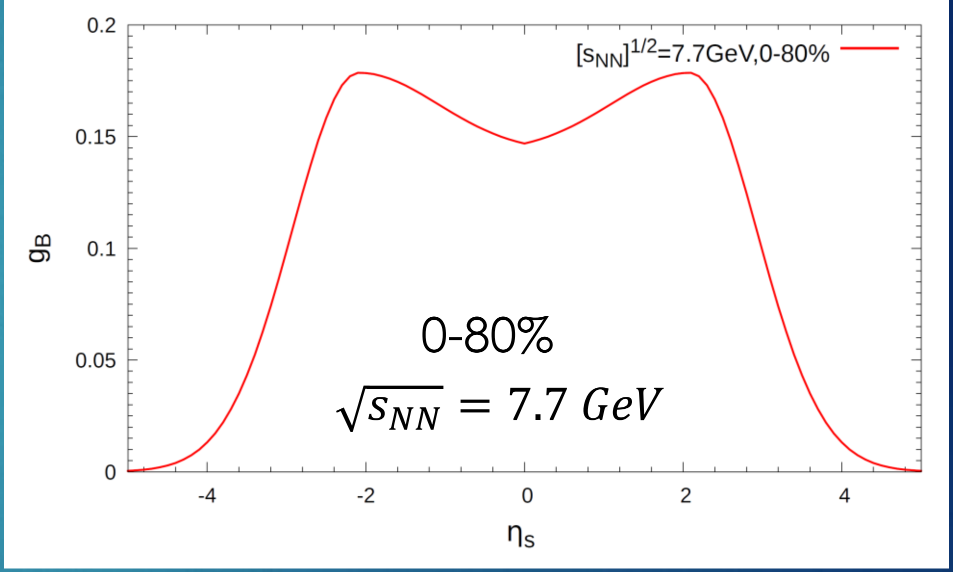
- Goals :
  - To investigate the influence of net baryon density ρ_B (or μ_B) and
  - Baryon diffusion V^{μ} on dilepton production, where the transport coefficient κ is governing the size of V^{μ}.

Initial Conditions

- Longitudinal direction: the spatial rapidity profile baryon density is

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

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



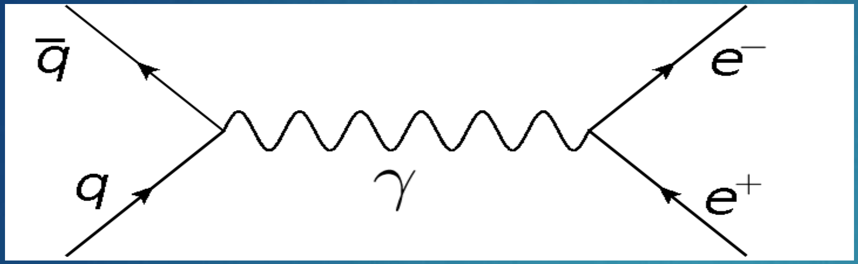
- Parameters of $g_B(\eta_s)$ tuned to the measured charged hadron $dN^{ch}/d\eta$ spectrum e.g. $\sqrt{s_{NN}} = 7.7\ GeV$

- In the transverse direction: averaged MC-Glauber initial conditions with aligned event plane angles, such that the correct $\langle v_2 \rangle$ is reproduced after averaging the MC-Glauber events.

Part II: Dilepton Rates

Dilepton rates from the QGP

- An important source of dileptons in the QGP



- The rate in kinetic theory (Born Approx)

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

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

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

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

Thermal Dilepton Rates from HM

- The dilepton production rate is :

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

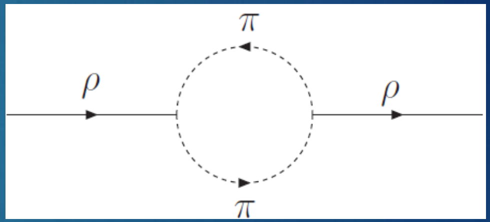
- Here

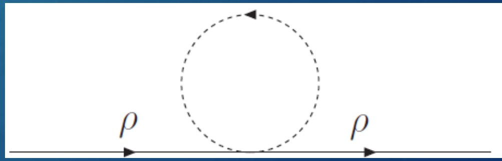
$$-Im\, D_V^R = \frac{-Im\,\Pi_V}{\left(M^2 - m_V^2 - Re\Pi_V\right)^2 + (Im\,\Pi)^2}\ ; where\ \Pi_V \equiv \Pi_V^R$$

- Model based on forward scattering amplitude [Eletsky, et al., PRC, 64, 035202 (2001)]

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

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





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

$$\Pi_{Va} = -4\pi\int\frac{d^3k}{(2\pi)^3} n_a(x_{cm})\frac{\sqrt{s}}{k_{c.m.}^0} f_{Va}^{c.m.}(s)$$

$$x_{cm} = k_{c.m.}^0/T - b_i\mu_B/T$$

Vector meson self-energies

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

- The forward scattering amplitude
  - Low energies:

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

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

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

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:

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

- Other approaches exist: e.g. effective Lagrangian method by R. Rapp [PRC 63, 054907 (2001)]

Viscous corrections to rate

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

$$T_0^{\mu\nu} + \pi^{\mu\nu} = \int \frac{d^3k}{(2\pi)^3 k^0} k^\mu k^\nu \left[n_a(x) + \delta n_a^{(shear)}(x)\right]; x = \frac{k \cdot u}{T} - b_i \frac{\mu_B}{T}$$

$$\delta n_a^{(shear)}(x) = C_a^{(shear)} n_a(x)[1 \pm n_a(x)] \frac{k^\mu k^\nu \pi_{\mu\nu}}{2T^2(\varepsilon + P)}; \; with\; C_a^{(shear)} = 1 \; \forall \; a$$

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

Viscous corrections to rate

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

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

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

$$with\ C_a^{(diff)} = 1\ \forall\ a$$

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

Viscous corrections to rate

- HM dilepton rate $$\frac{d^4R}{d^4q} = \frac{\alpha^2}{\pi^3}\frac{L(M)}{M^2}\left\{-\frac{1}{3}\left[Im\, D_V^R\right]_\mu^\mu\right\} n_{BE}(q\cdot u)$$
- Self-energy

$$\Pi_{Va}^{Total} = \Pi_{Va}^{Ideal} + \delta\Pi_{Va}$$

$$\delta\Pi_{Va} = -4\pi\int\frac{d^3k}{(2\pi)^3}\delta n_a\left(k_{c.m.}^0/T - b_i\mu_B/T\right)\frac{\sqrt{s}}{k_{c.m.}^0} f_{Va}^{c.m.}(s)$$

- For the QGP

$$\frac{d^4R^{Total}}{d^4q} = \frac{d^4R^{Ideal}}{d^4q} + \frac{d^4\delta R}{d^4q}$$

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

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

Interpolating between QGP and HM

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

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

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

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

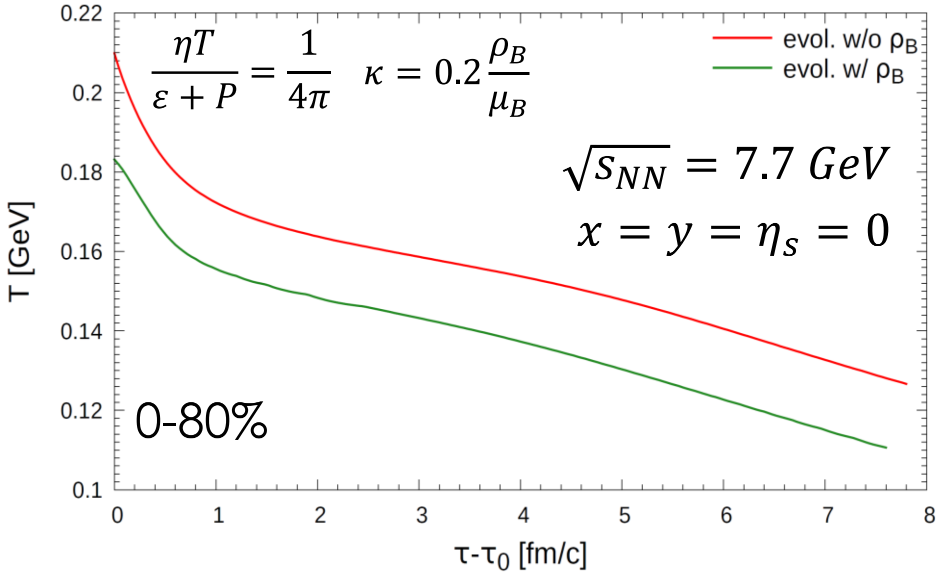
- Flow coefficients

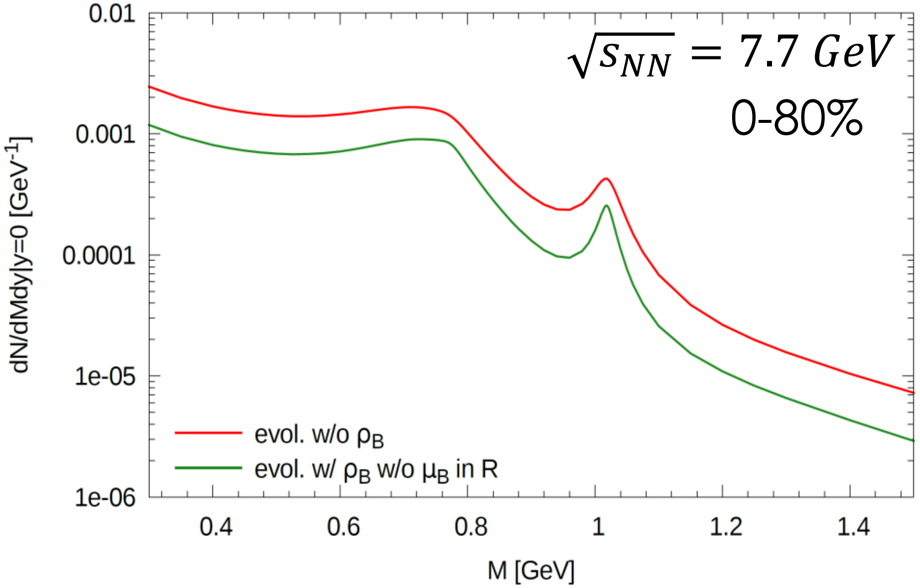
$$\frac{dN}{dMp_Tdp_Td\phi dy} = \frac{1}{2\pi}\frac{dN}{dMp_Tdp_Tdy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi - n\Psi_n)\right]$$

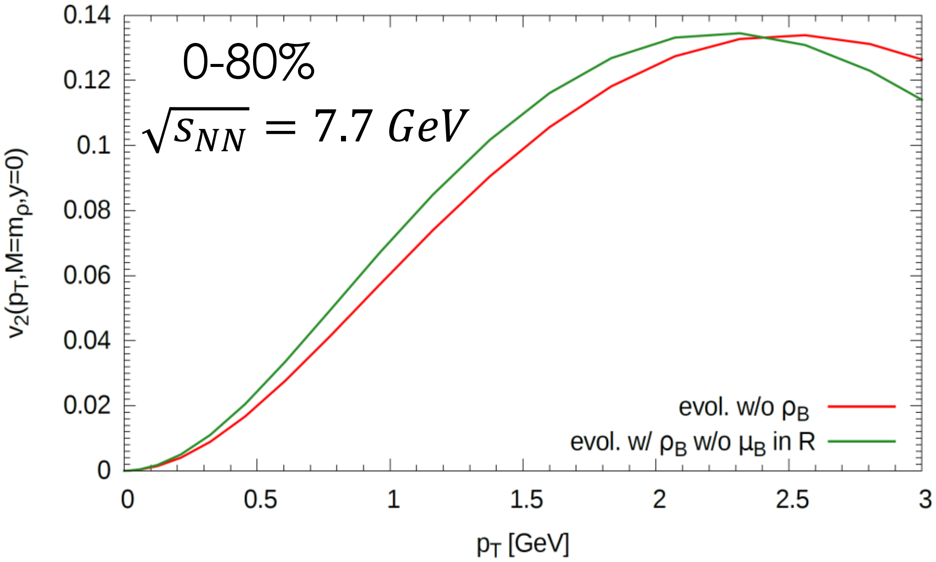
- **Important note:** v_n's are obtained via a yield weighted average of the HM and QGP sources.

Part III: Dileptons & Dissipation

Dilepton yield and elliptic flow

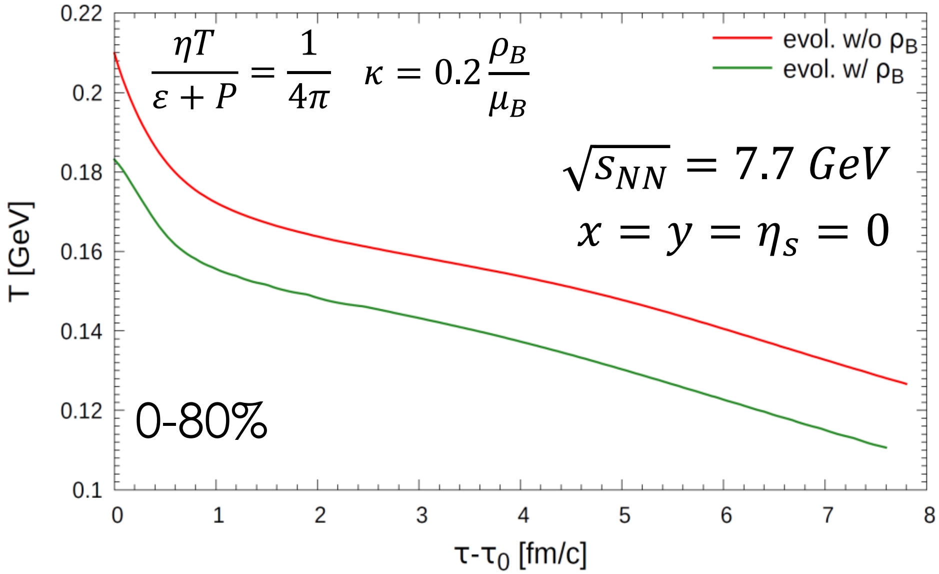


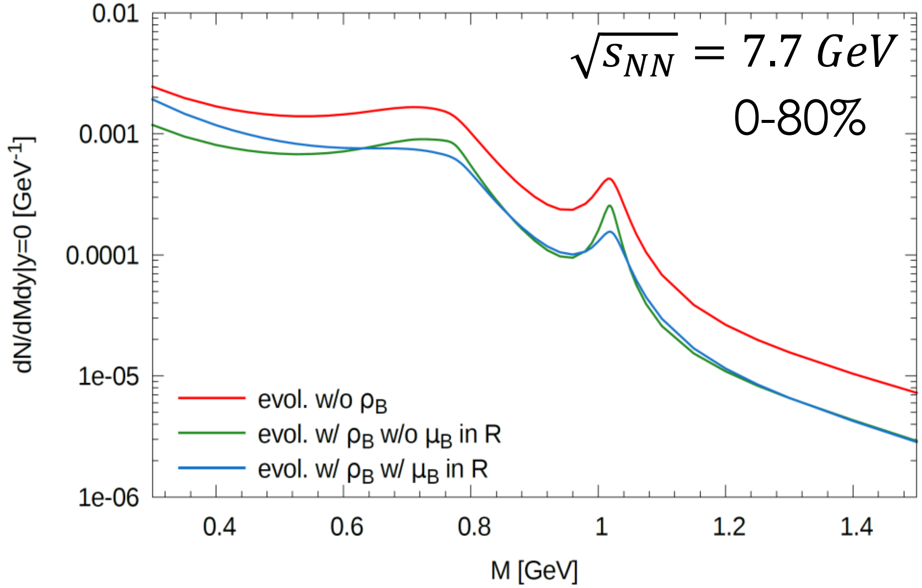


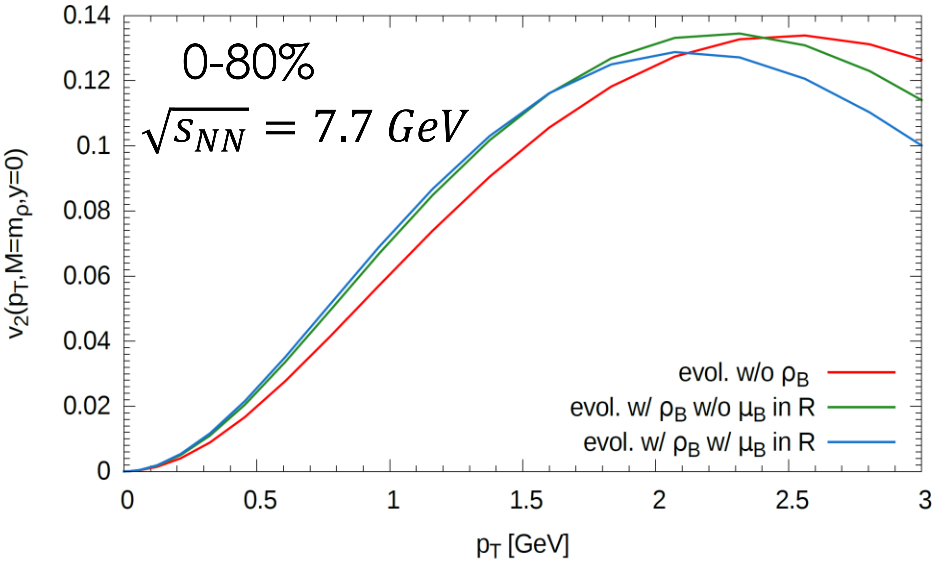


- Going from a medium w/o ρ_B to w/ ρ_B incurs a large change in dof. & ∴T ⇒ large effect on dilepton yield & v_2.

Dilepton yield and elliptic flow

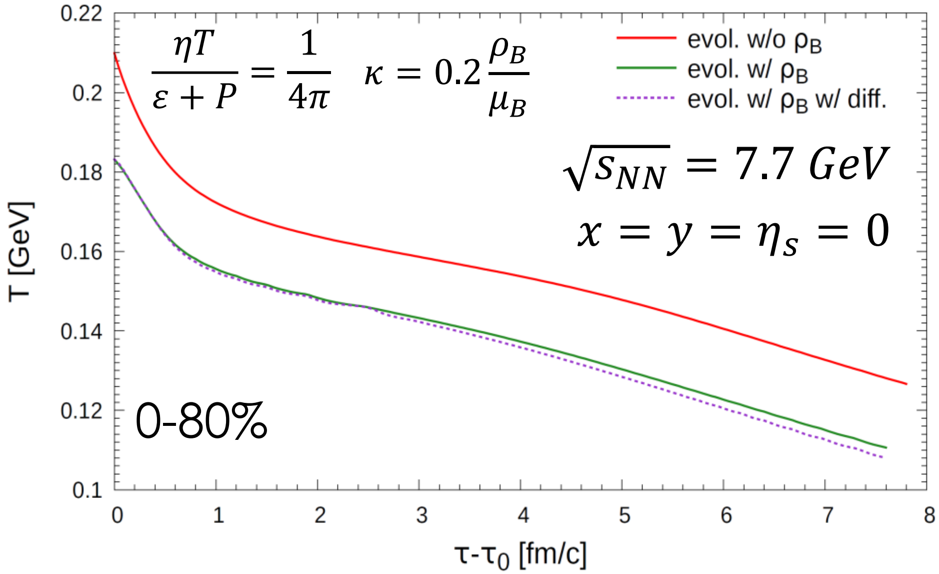


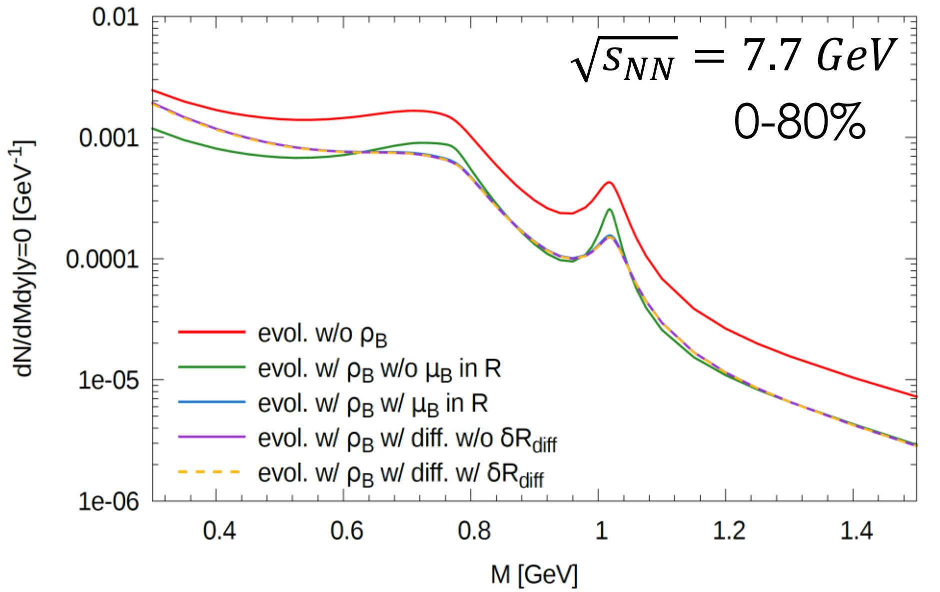


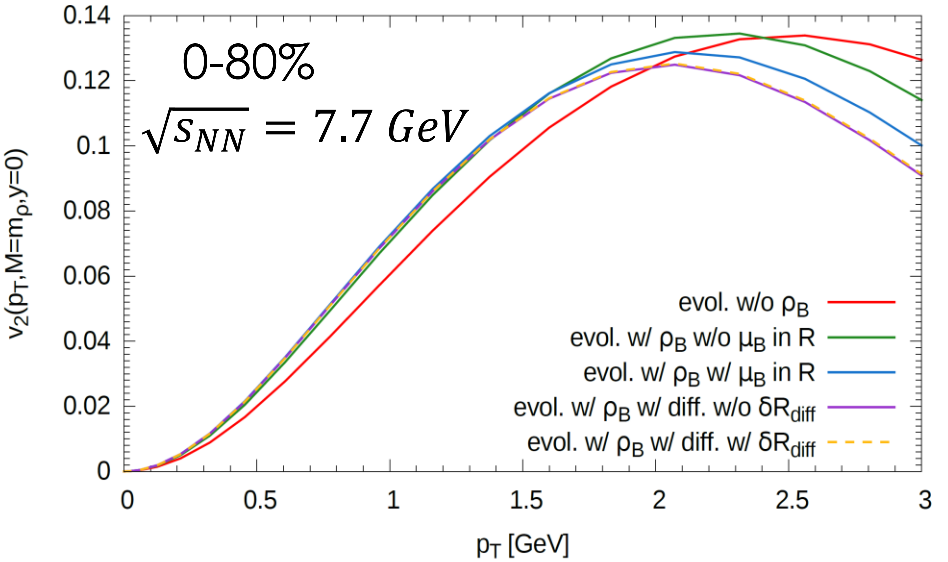


- Going from a medium w/o ρ_B to w/ ρ_B incurs a large change in dof. & ∴T ⇒ large effect on dilepton yield & v_2.
- Incl. μ_B in the dilepton rates ⇒ clear width broadening of vector mesons.

Dilepton yield and elliptic flow







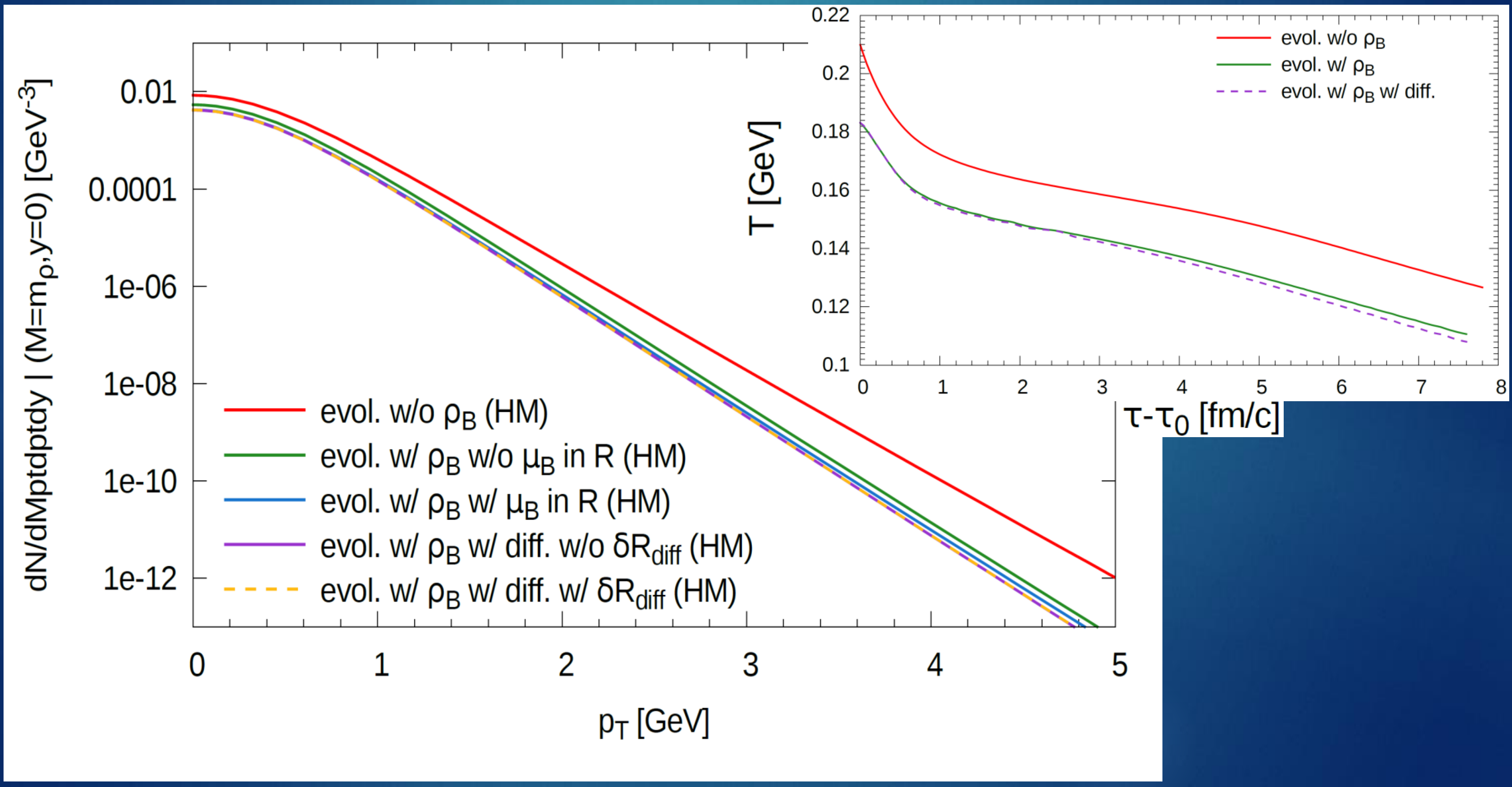
- Going from a medium w/o ρ_B to w/ ρ_B incurs a large change in dof. & ∴T ⇒ large effect on dilepton yield & v_2.
- Incl. μ_B in the dilepton rates ⇒ clear width broadening of vector mesons.
- The thermal $v_2(p_T)$ at fixed M is sizeable and sensitive to imprints left by baryon diffusion on the evolution.

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

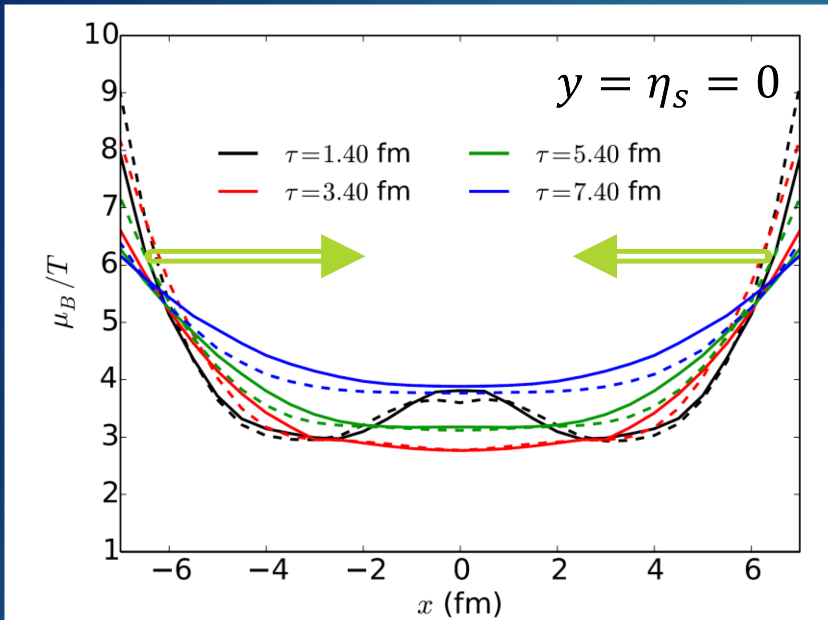
- Recall v_2^{total} is a yield weighted avg of HM's and QGP's v_2.
- v_2^{total} is reduced at high p_T because more weight is put on the QGP contribution of v_2, i.e. QGP yield remains the same while the HM yield is reduced.

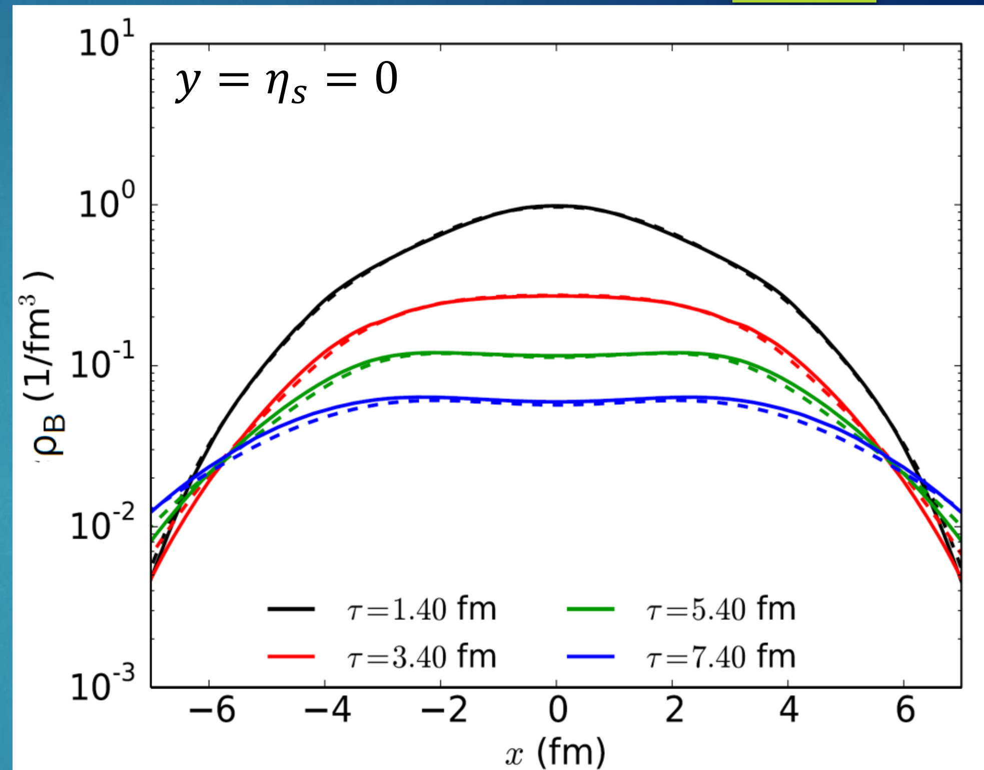
Why is total v_2 decreased with $\mu_B \& V^\mu$?

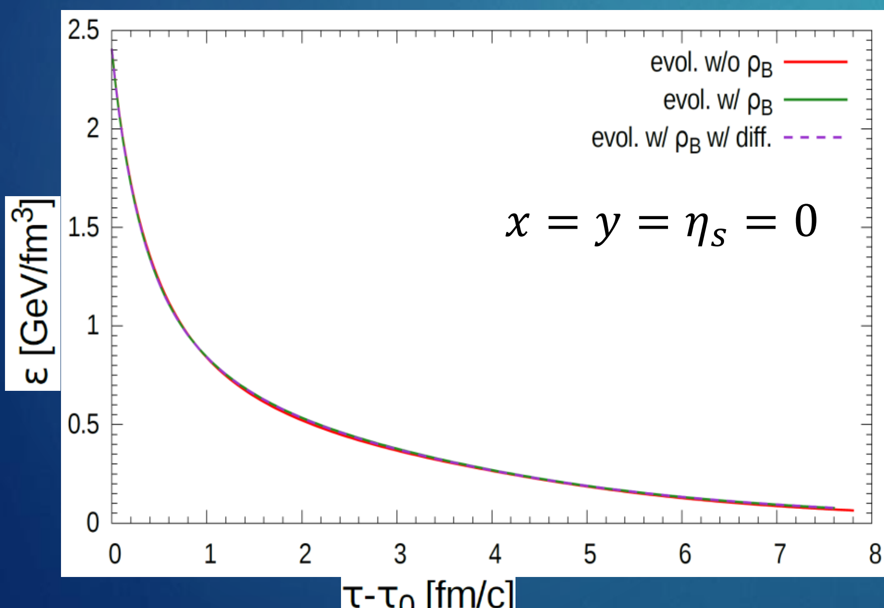
- Dilepton HM yield decreases via width broadening of vector mesons, and also because V^μ further lowers the temperature of the medium in the hadronic sector.



How does V^μ change $\frac{\mu_B}{T}$, ε and 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 $\nabla^\mu \rho_B$.

Conclusions

- A first (preliminary) dilepton calculation using 3+1D 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.

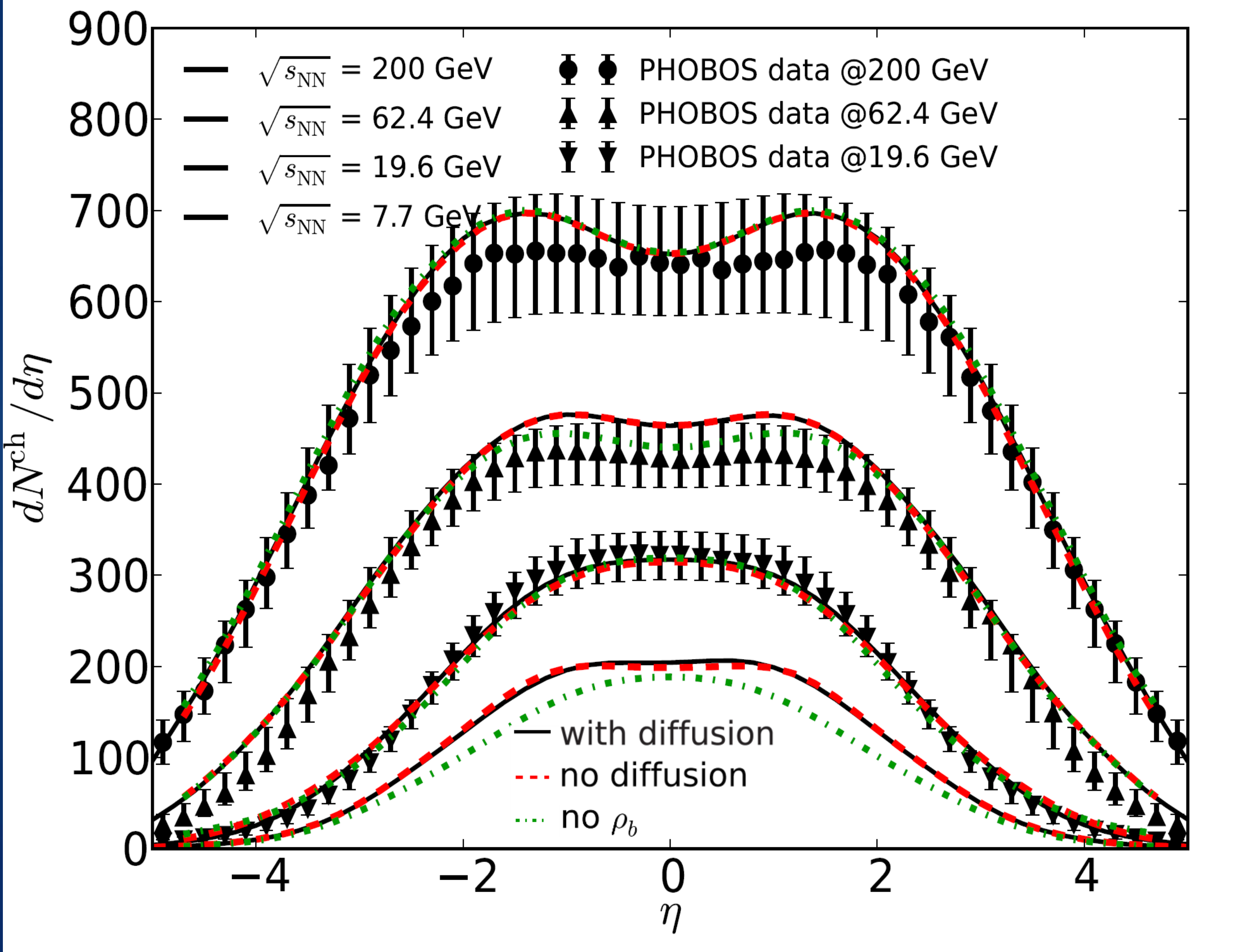
Outlook

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

Backup Slides

Effect of μ_B and V^μ on $\frac{dN^{ch}}{d\eta}$ vs $\sqrt{s_{NN}}$

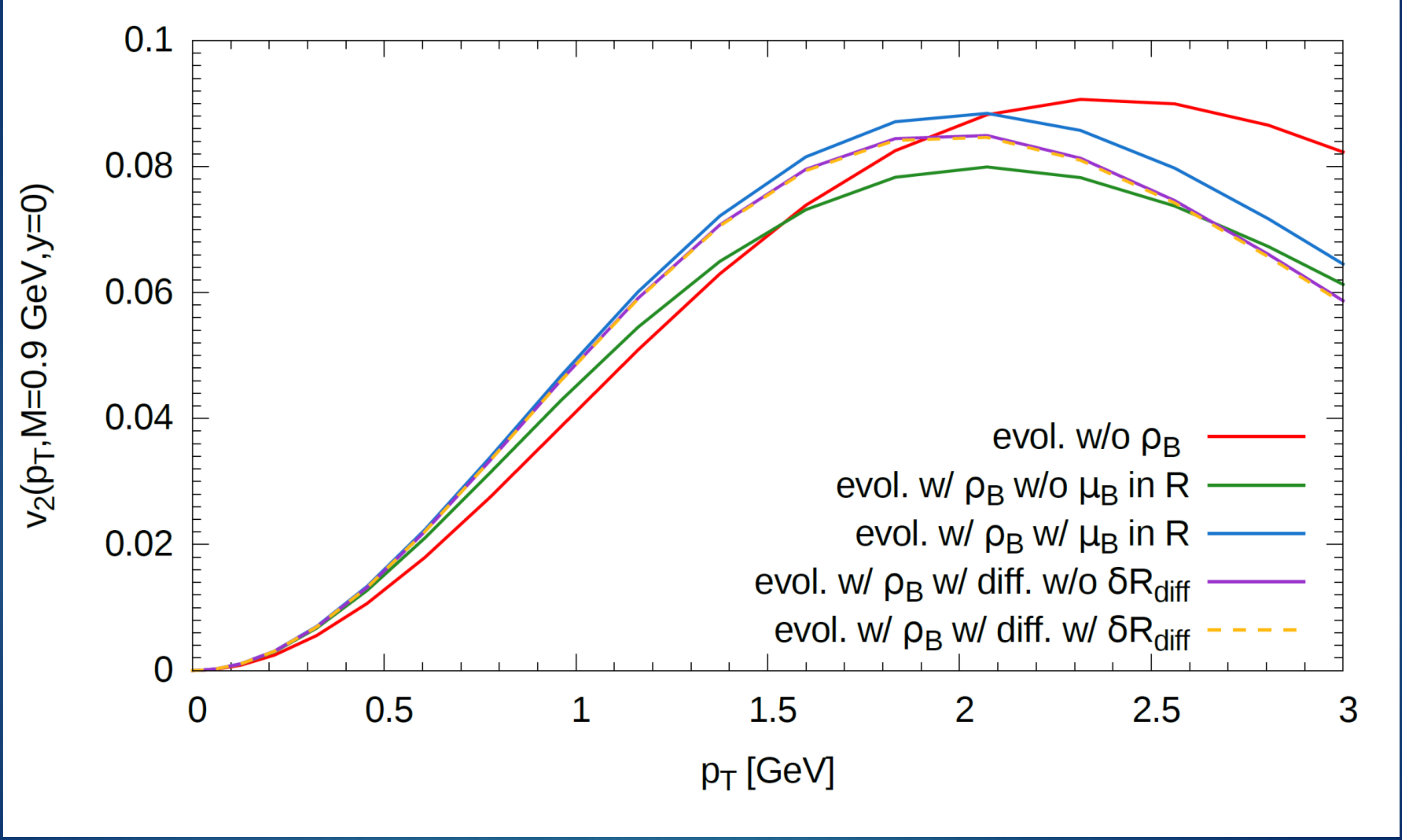
Plots by Chun Shen; Same initial ε and freezing out at a **constant** $\varepsilon_{FO} = 0.1 \frac{GeV}{fm^3}$



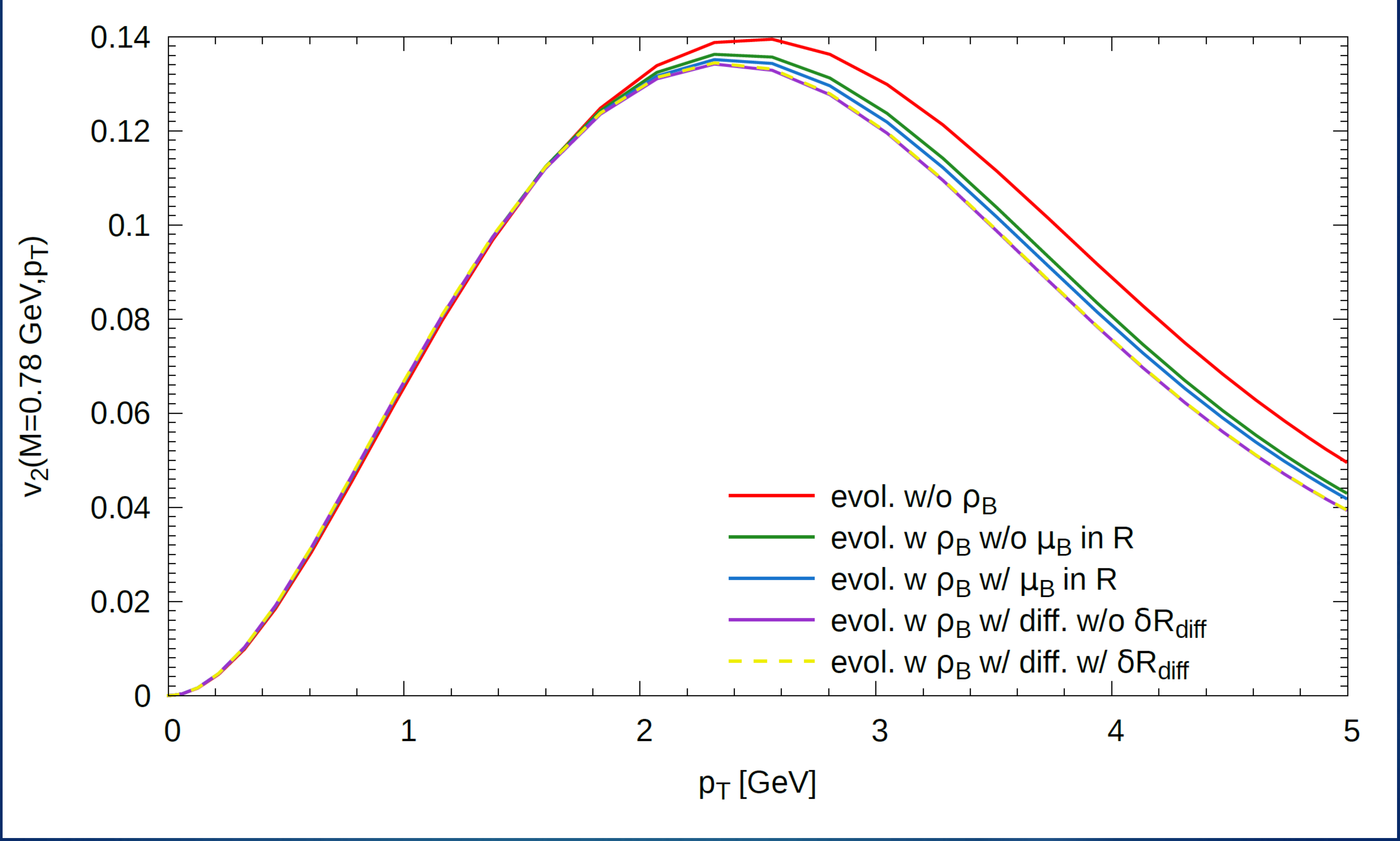
@ $\sqrt{s_{NN}} = 7.7\ GeV$ $\frac{dN^{ch}}{d\eta}$ w/ V^μ is at most 15% larger than w/o V^μ.

$\sqrt{s_{NN}}$ scaling from PRC **85**, 054902 (2012)

$v_2(p_T)$ for M=0.9 GeV

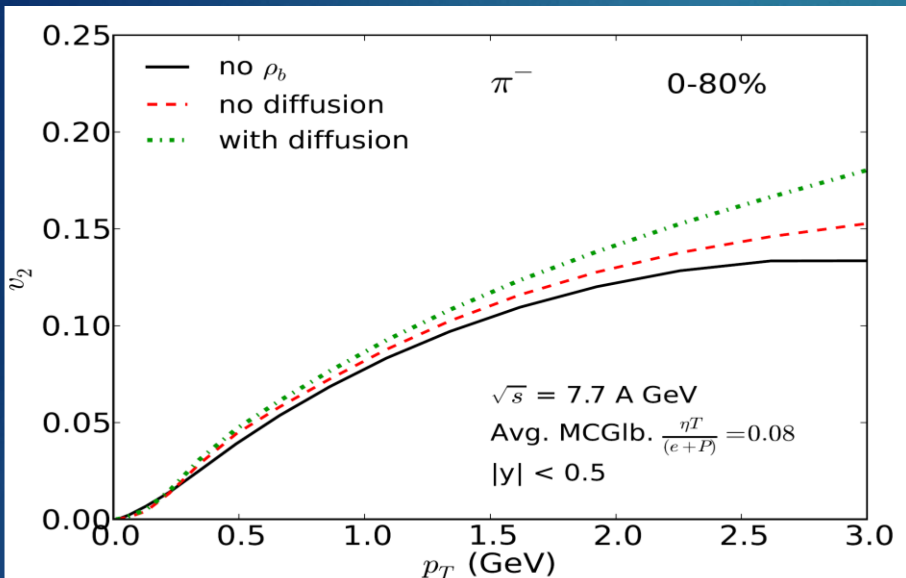


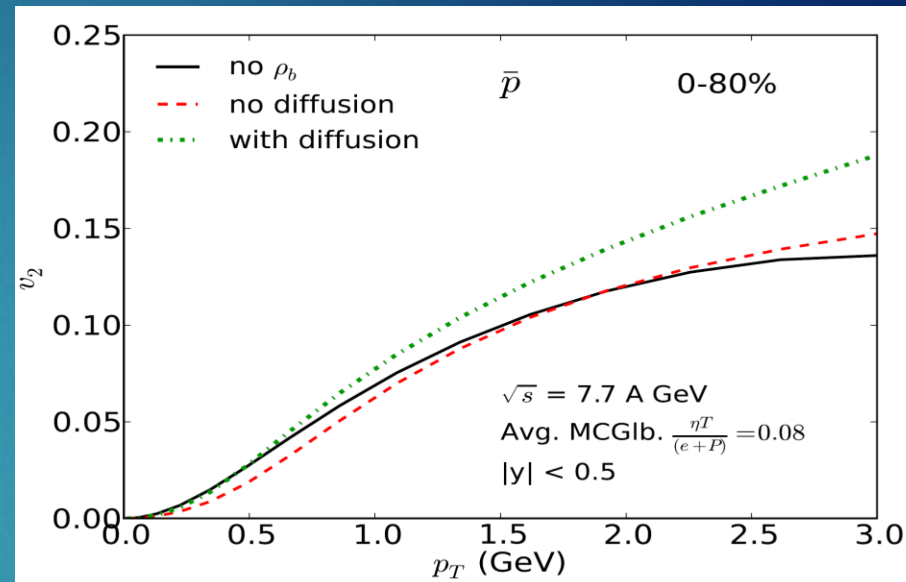
Variation of v_2 at $\sqrt{s_{NN}}$ =19.6 GeV



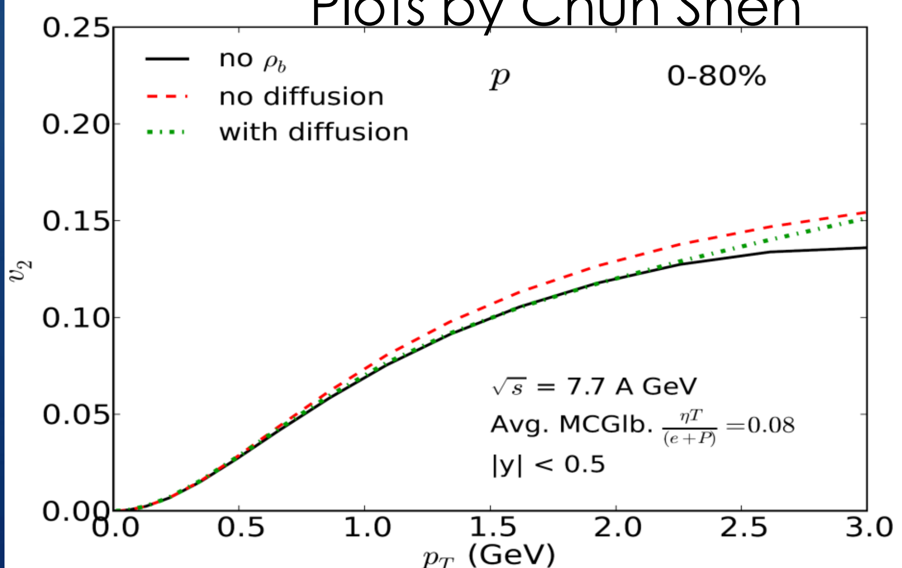
Motivation to study BES

- Sensitivity of hadronic observables to μ_B and V^{μ}





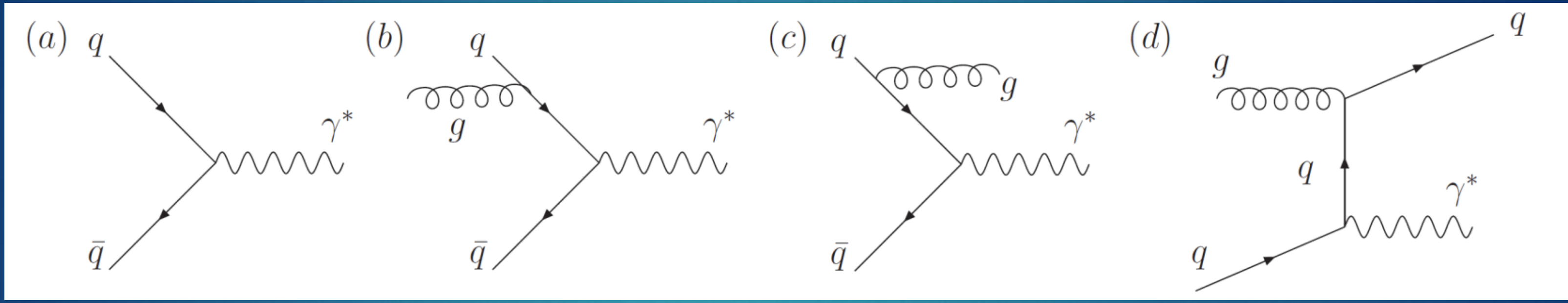
Plots by Chun Shen



- Question: what about dileptons?

NLO QGP dilepton results

- Some diagrams contributing at NLO



- Effects on dilepton yield and elliptic flow