Effects of temperature dependent η/s on the $\mathbf{p_T}$-spectra of hadrons in nuclear collisions at RHIC and the LHC

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QUARK MATTER ANNECY 2011

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arXiv:1101.2442 [nucl-th] (accepted to PRL)

FIAS Frankfurt Institute for Advanced Studies

EMMI ExtreMe Matter Institute EMMI

Israel-Stewart hydrodynamics

Model the space-time evolution of A+A collisions by relativistic fluid dynamics:

Neglect net-baryon number, bulk viscosity & heat flow and the red terms:

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

$$D\pi^{\langle\mu\nu\rangle} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle}\right) - \frac{4}{3}\pi^{\mu\nu}\left(\nabla_\lambda u^\lambda\right) + 2\pi_\lambda^{\ \langle\mu}\omega^{\nu\rangle\lambda} - 2\pi_\lambda^{\ \langle\mu}\sigma^{\nu\rangle\lambda}$$

Longitudinal expansion is treated using boost invariance: $\frac{\partial p}{\partial \eta_s} = 0$, $v_z = \frac{z}{t}$

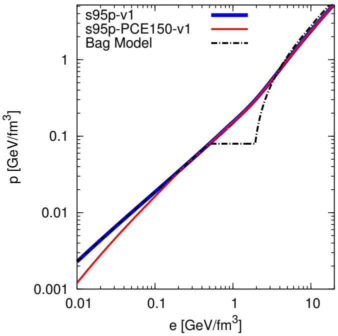
To solve this set of equations we need at $\tau = \tau_0$

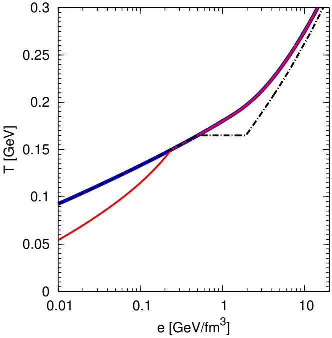
- Equation of state $p = p(e)$ and $T = T(e)$
- Initial condition $T^{\mu\nu}(\tau_0, x, y)$
- Shear viscous coefficient $\eta(T)$ and relaxation time $\tau_\pi(T) = \frac{5\eta}{\varepsilon+p}$.

Derivation of fluid dynamics: see poster (tuesday) and talk (friday) by G. Denicol

Input (EoS, Initial state, η/s)

Equation of State





- Lattice parametrization by Petreczky/Huovinen: Nucl. Phys. **A837**, 26-53 (2010), [arXiv:0912.2541 [hep-ph]] (Talk by P. Huovinen (tuesday))
- **(partial) chemical freeze-out at** $T_{\text{chem}} = 150$ **MeV (s95p-PCE150-v1)**
- for comparison bag-model EoS and lattice parametrization with chemical equilibrium (s95p-v1)
- Hadron Resonance Gas (HRG) includes all hadronic states up to $m \sim 2$ GeV

Initial profiles

- Initial energy density proportional to the density of binary nucleon-nucleon collisions (optical Glauber)
- Smooth initial conditions
(fluctuating initial conditions: talks by P. Mota and H. Holopainen (friday))
- Centrality selection according to Glauber
- Initial shear viscosity $\pi^{\mu\nu} = 0$
- $\tau_0 = 1.0$ fm (RHIC) $\tau_0 = 0.6$ fm (LHC)
- Initial velocity $v_x = v_y = 0$

$\sqrt{s_{NN}}$ [GeV]	τ_0 [fm]	ε_0 [GeV/fm^3]	$T_{\rm max}$ [MeV]
200	1.0	24.0	335
2760	0.6	187.0	506
5500	0.6	240.0	594

Freeze-out

- Standard Cooper-Frye freeze-out for particle i

$$E\frac{dN}{d^3\mathbf{p}} = \frac{g_i}{(2\pi)^3}\int d\sigma^\mu p_\mu f_i(\mathbf{p},x),$$

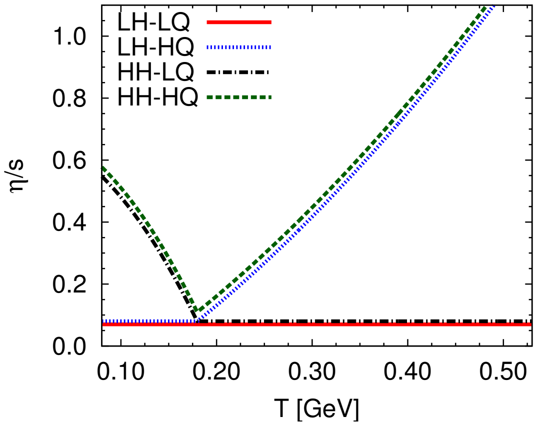
where

$$f_i(\mathbf{p},x) = f_{i,\mathrm{eq}}(T,\{\mu_i\})\left[1+\frac{\pi^{\mu\nu}p_\mu p_\nu}{2T^2(e+p)}\right]$$

- Integral over constant temperature hypersurface
- 2- and 3-body decays of unstable hadrons included
- Here $T_{\mathrm{dec}} = 100$ MeV

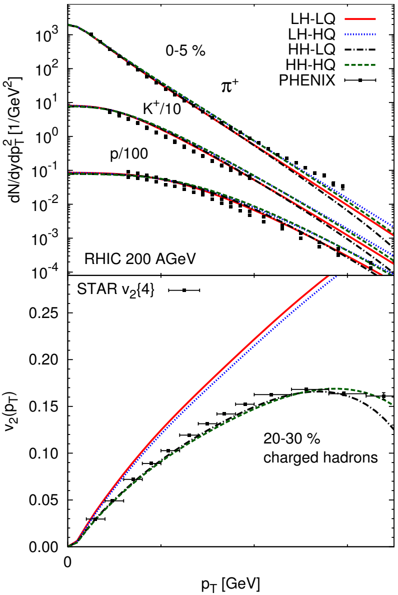
Temperature dependent η/s

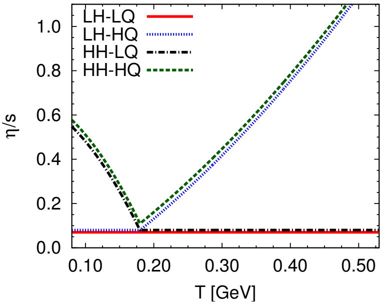
Temperature dependent η/s



- Can we separate effects of HRG viscosity from the QGP viscosity?
- Try 4 different parametrization of $\eta/s(T)$.
- We fix the minimum $\eta/s = 0.08$ at $T = 180$ MeV
- HRG: $\sim$ J. Noronha-Hostler et. al. QGP: $\sim$ lattice

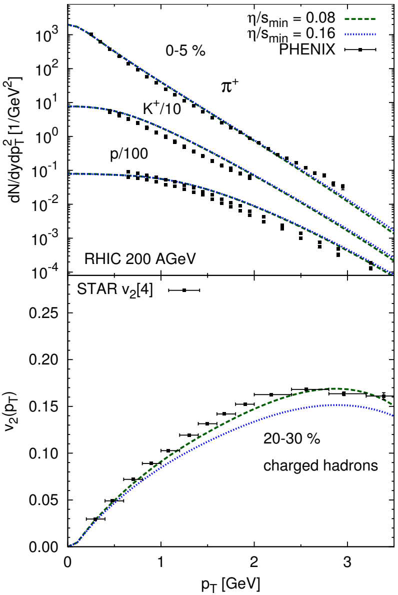
HRG vs. QGP viscosity at RHIC Au+Au $\sqrt{s_{NN}} = 200$ GeV

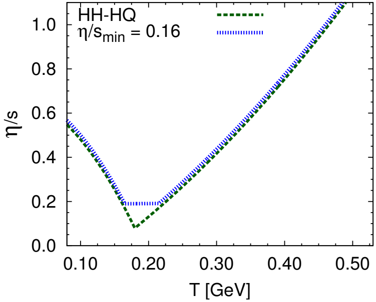




- Elliptic flow insensitive to the QGP viscosity
- Weak sensitivity of p_T-slopes on the QGP viscosity
- Behavior of $v_2(p_T)$ dominated by HRG viscosity

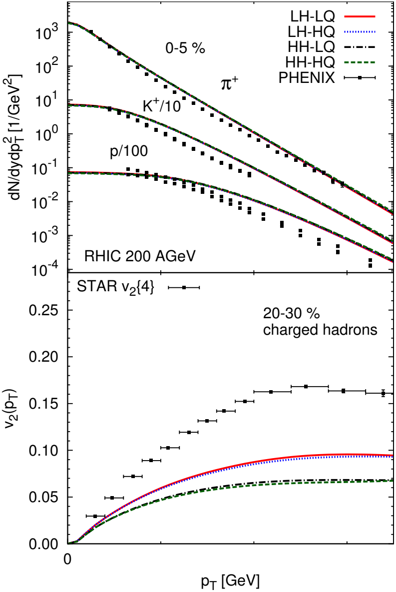
HRG vs. QGP viscosity at RHIC: Change the minimum η/s

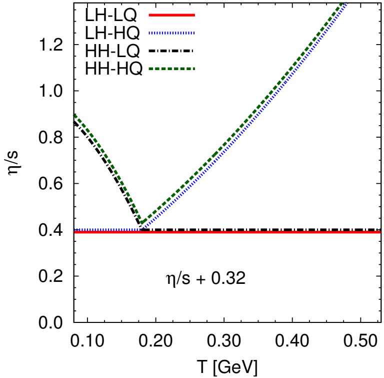




- Increase minimum η/s by a factor 2
- $v_2(p_T)$ sensitive to the minimum value

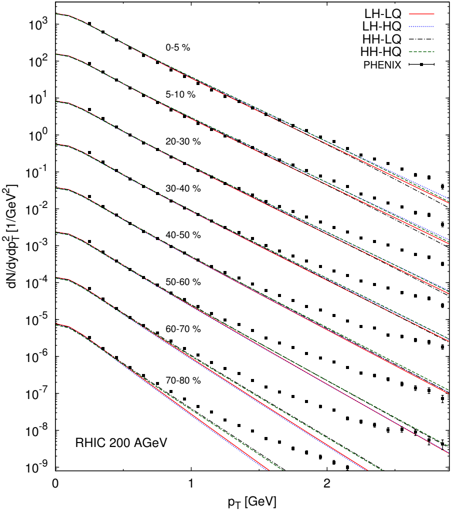
HRG vs. QGP viscosity at RHIC: Change the minimum η/s

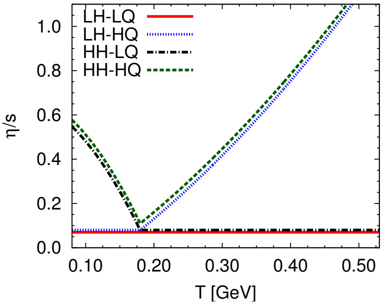




- Shift η/s up by 0.32
- Grouping remains

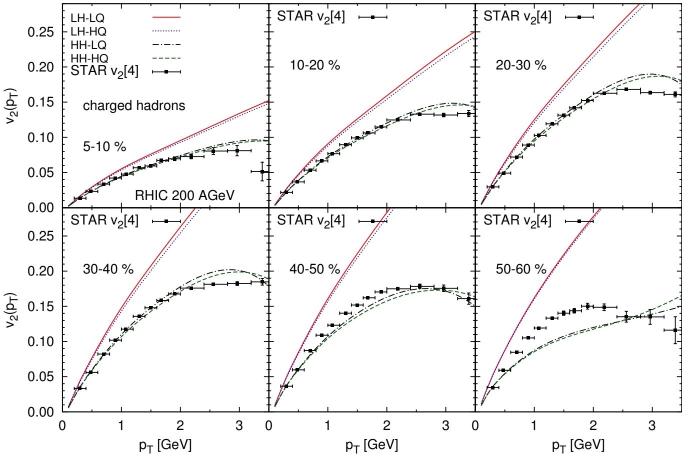
RHIC: matching the centrality classes (pions)





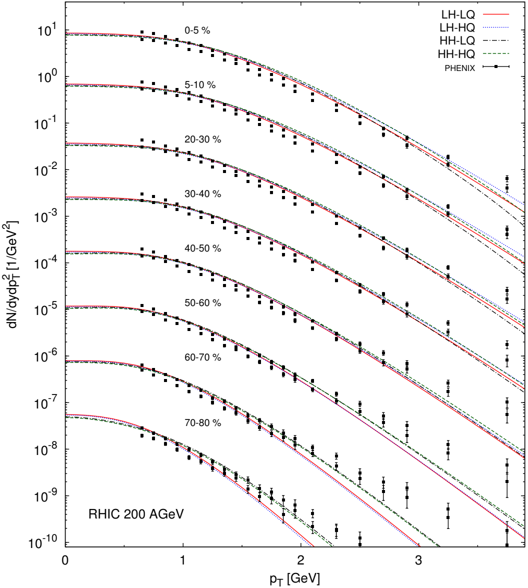
- Same eBC initialization, but scaled to give the correct normalization in each centrality class

RHIC: matching the centrality classes ($v_2(p_T)$)

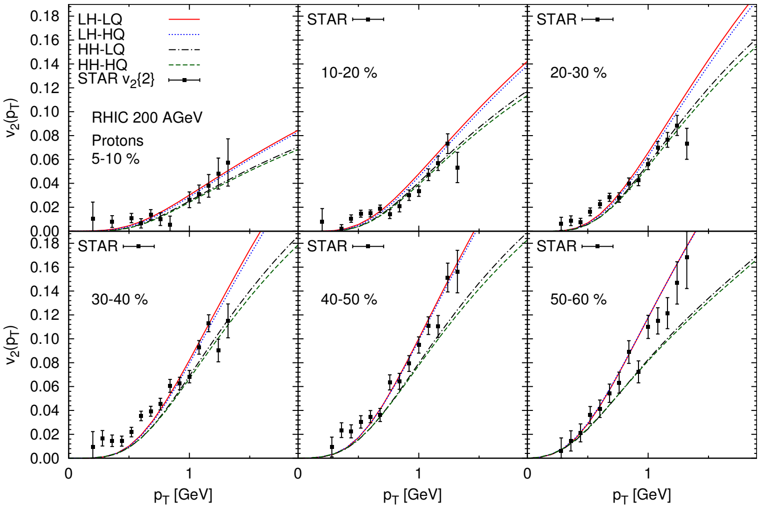


- Same grouping in each centrality class
- Impact of hadronic viscosity even stronger in more peripheral collisions

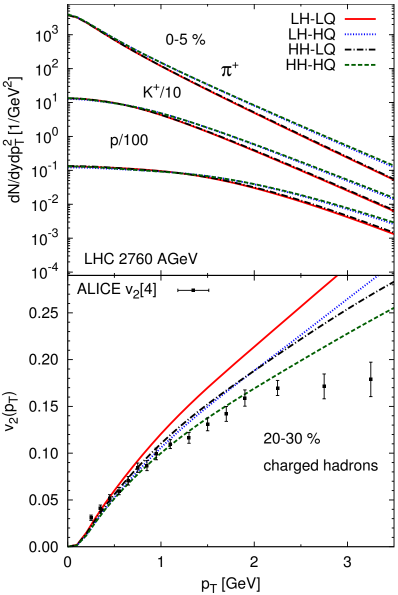
RHIC: matching the centrality classes (protons)

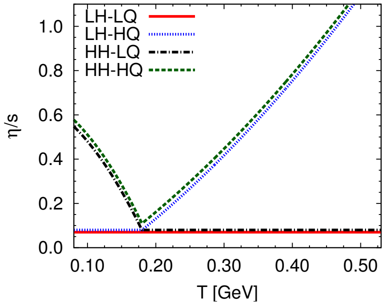


RHIC: matching the centrality classes ($v_2(p_T)$ of protons)



HRG vs. QGP viscosity at LHC Pb+Pb 2760 AGeV

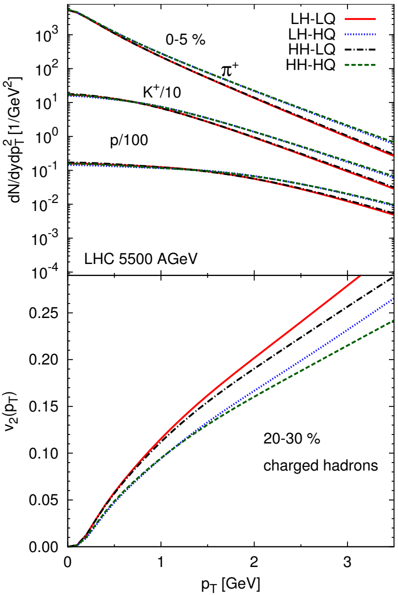


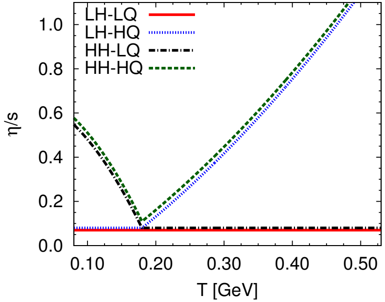


LHC $\sqrt{s} = 2760$ AGeV

- Both QGP and HRG η/s change $v_2(p_T)$
- Stronger effect of QGP η/s to p_T-slopes

HRG vs. QGP viscosity at LHC Pb+Pb 5500 AGeV





LHC $\sqrt{s} = 5500$ AGeV

- multiplicity from minijet+saturation model (prediction) Eskola *et al.*, Phys. Rev. C **72**, 044904 (2005).
- Note the difference: $v_2(p_T)$ curves group according to the **QGP viscosity!!**

Summary

RHIC Au+Au $\sqrt{s_{NN}} = 200$ GeV

- $v_2(p_T)$ is almost independent of high-temperature η/s, but very sensitive to the hadronic η/s
- Still some sensitivity to minimum value of η/s

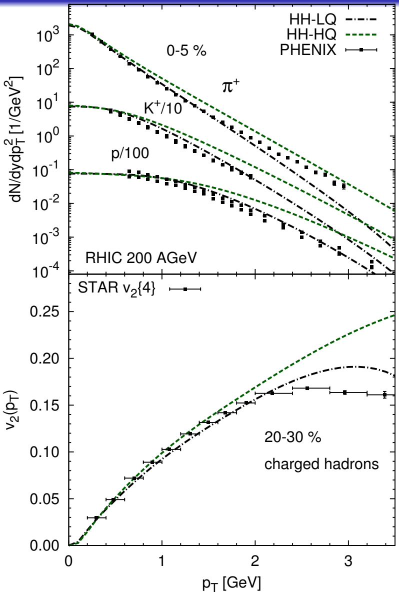
LHC Pb+Pb $\sqrt{s_{NN}} = 5.5$ TeV (prediction)

- $v_2(p_T)$ depends on the high-temperature η/s
- $v_2(p_T)$ almost independent of the hadronic viscosity

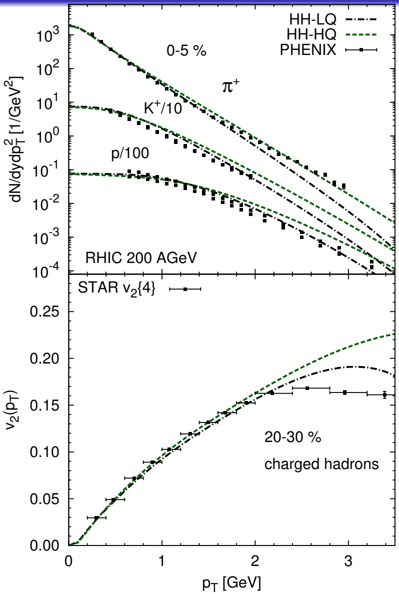
LHC Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV

- Somewhere between: $v_2(p_T)$ sensitive on the QGP and hadronic viscosity

Navier-Stokes initialization (no correction)



Navier-Stokes initialization (correction)



Numerical methods

Problems in numerical fluid dynamics

- First order solutions: numerical diffusion (but stable)
- Second order solutions: numerical dispersion (no diffusion but unstable)

SHASTA (Boris, Book, deVore, Zalesak ...)

- Calculate low-order solution with strong numerical diffusion.
- Remove numerical diffusion from the solution as much as possible without generating new structures into solution (Flux limiter).

Numerical methods: our choice

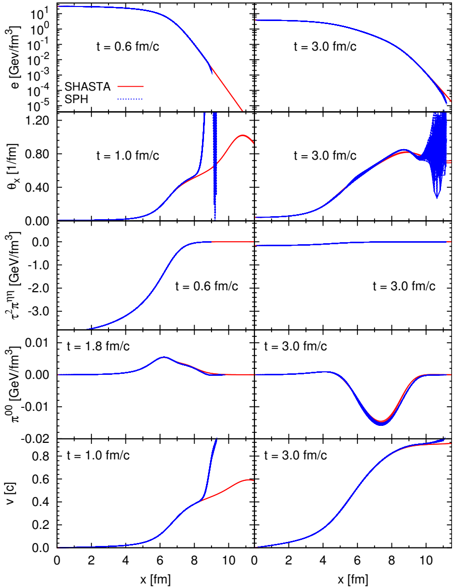
$$\partial_\mu T^{\mu\nu} = 0$$

- Normal SHASTA, with antidiffusion coefficient $A_{ad} \to 0$ at low energy density

$$D\pi^{\langle\mu\nu\rangle} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle}\right) - \frac{4}{3}\pi^{\mu\nu}\left(\nabla_\lambda u^\lambda\right)$$

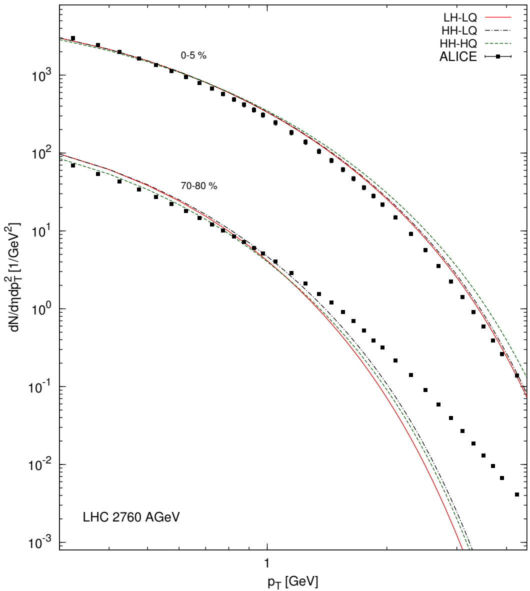
- Simple centered second-order finite differencing $\partial_x f_i = \frac{f_{i+1}-f_{i-1}}{2\Delta x}$
- Time derivatives of e.g. velocity needed on the r.h.s. : 1st order backward differencing $\partial_t f^n = \frac{f^n - f^{n-1}}{\Delta t}$

Numerical methods (TECHQM test case)

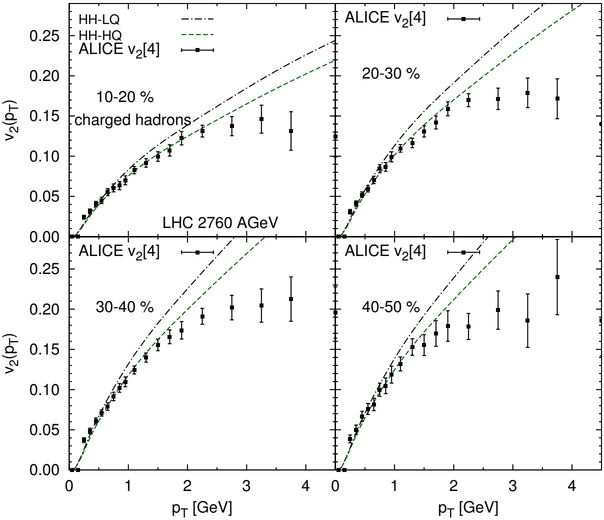


- SPH = Smoothed Particle Hydrodynamics vs SHASTA
- TECHQM test case $\eta/s = 0.08$

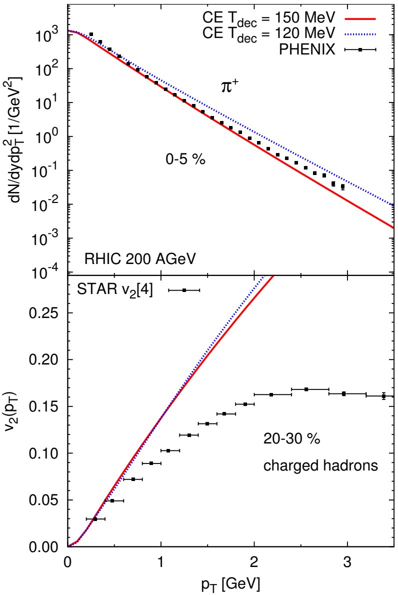
LHC: spectra (charged hadrons)



LHC: $v_2(p_T)$ (charged hadrons)



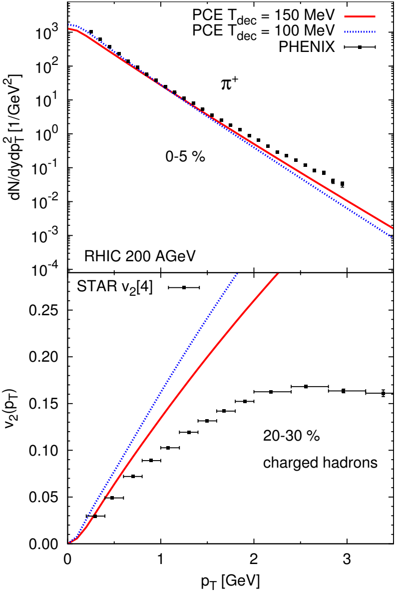
Chemical equilibrium



RHIC 200 AGeV

- Spectra get flatter with decreasing T_{dec}
- $v_2(p_T)$ almost independent of T_{dec}

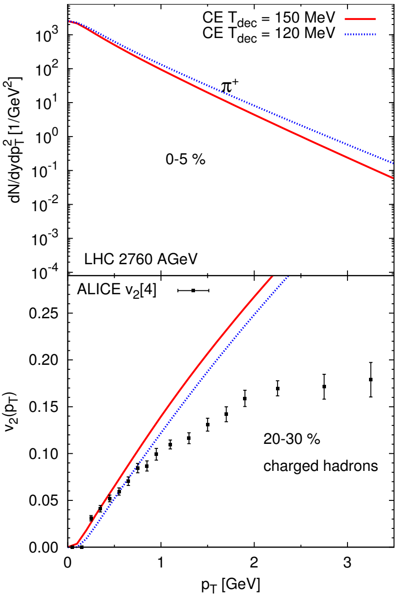
Partial chemical freeze-out



RHIC 200 AGeV

- Spectra get steeper with decreasing T_{dec}
- $v_2(p_T)$ increases with decreasing T_{dec}

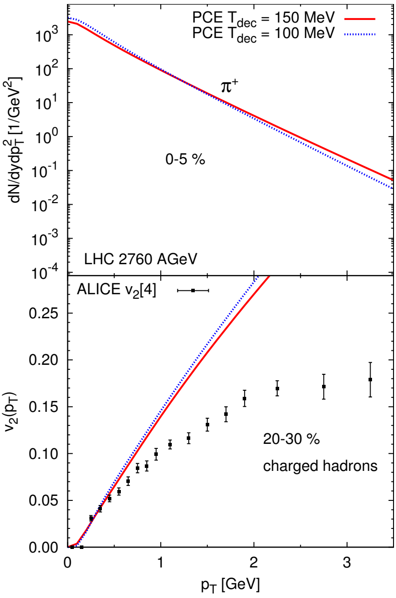
Chemical equilibrium



LHC 2760 AGeV

- Spectra get flatter with decreasing $T_{\rm dec}$
- $v_2(p_T)$ decreases

Partial chemical freeze-out



LHC 2760 AGeV

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