The effects of the order of phase transition, chemical equilibrium and freeze-out in ideal hydro

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Hydrodynamics in Heavy Ion Collisions and QCD Equation of State

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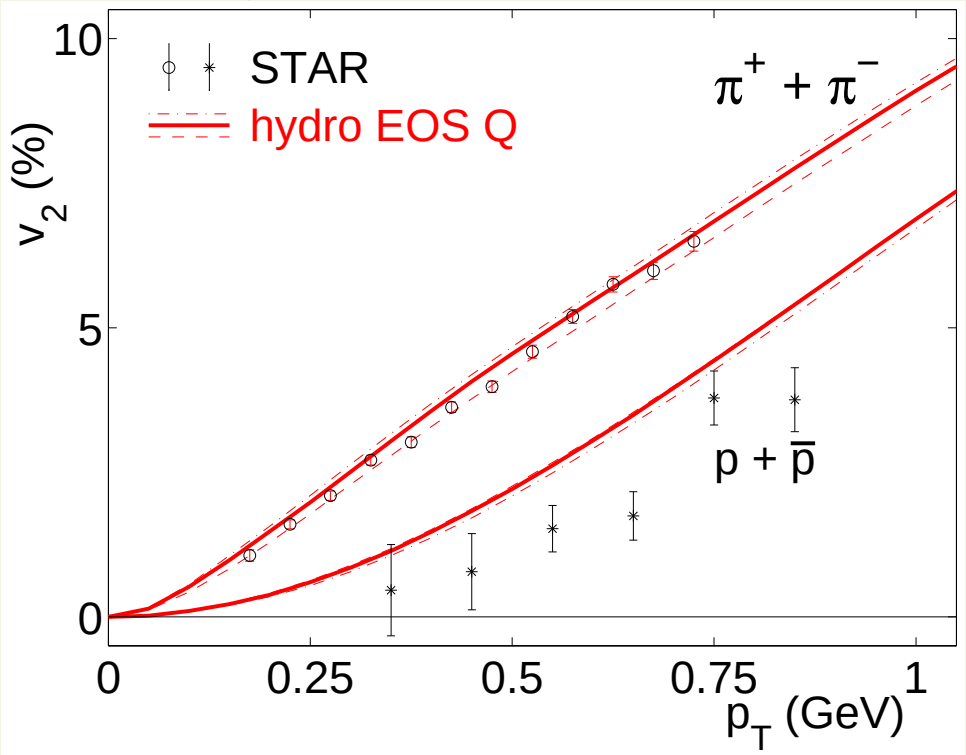
Success of ideal hydrodynamics

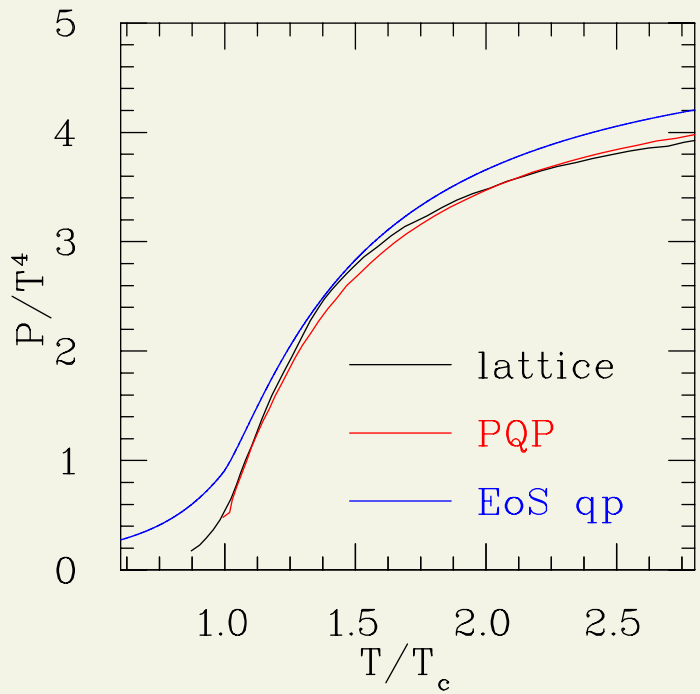
Kolb, Heinz, Huovinen et al ('01)

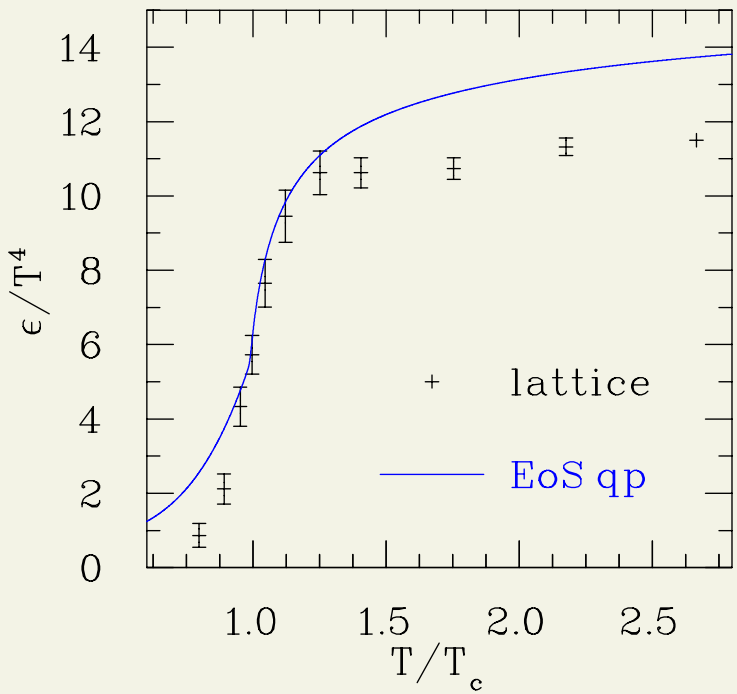
minbias Au+Au at RHIC



- **initial state from Glauber model**
- **first order phase transition at** $T_c = 165$–170 **MeV**
- **chemical equilibrium**
- **freeze-out at constant** T **or** ε

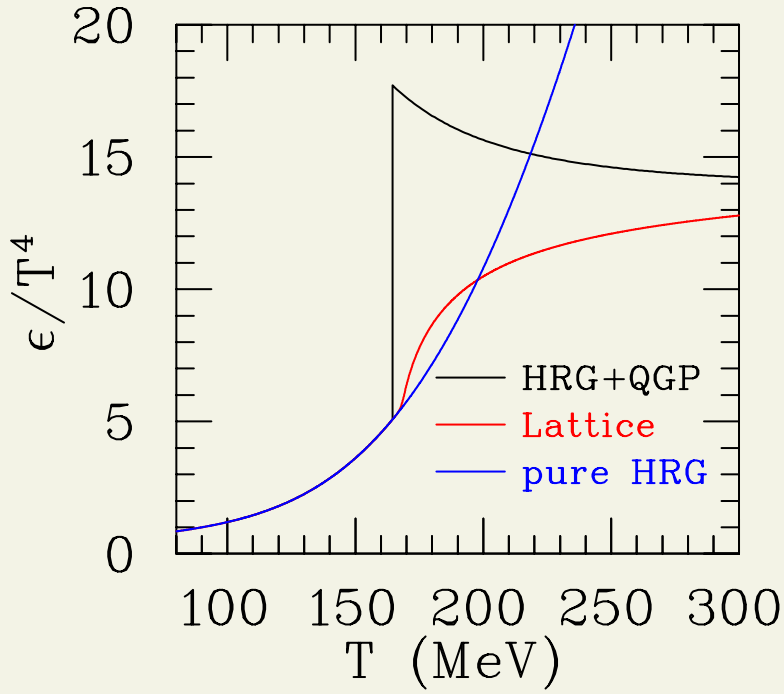
Parametrized lattice EoS

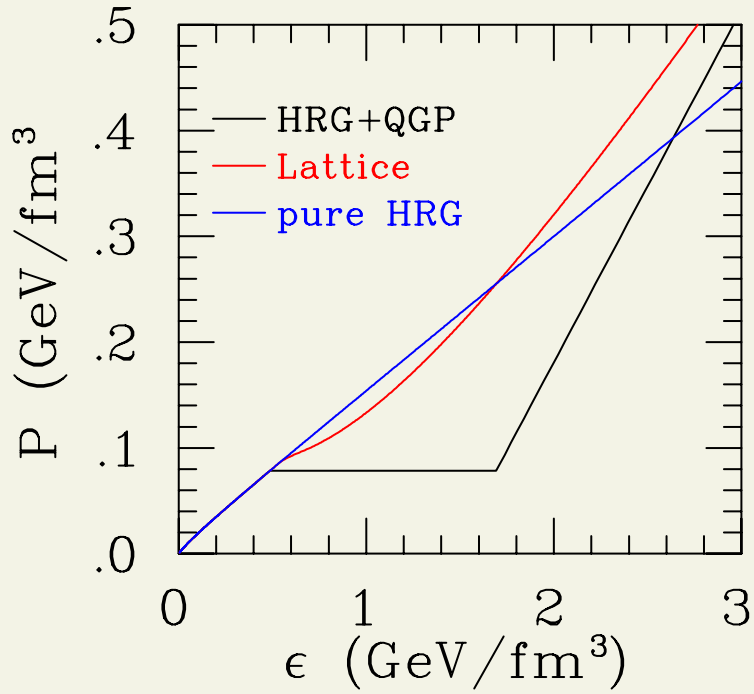




- **Extrapolation to finite quark masses?**
- **Schneider & Weise: quasiparticle model for plasma with known masses**
  - **Tune the model to fit lattice results with lattice masses**
  - **Change masses to more physical ones**

Equation of state

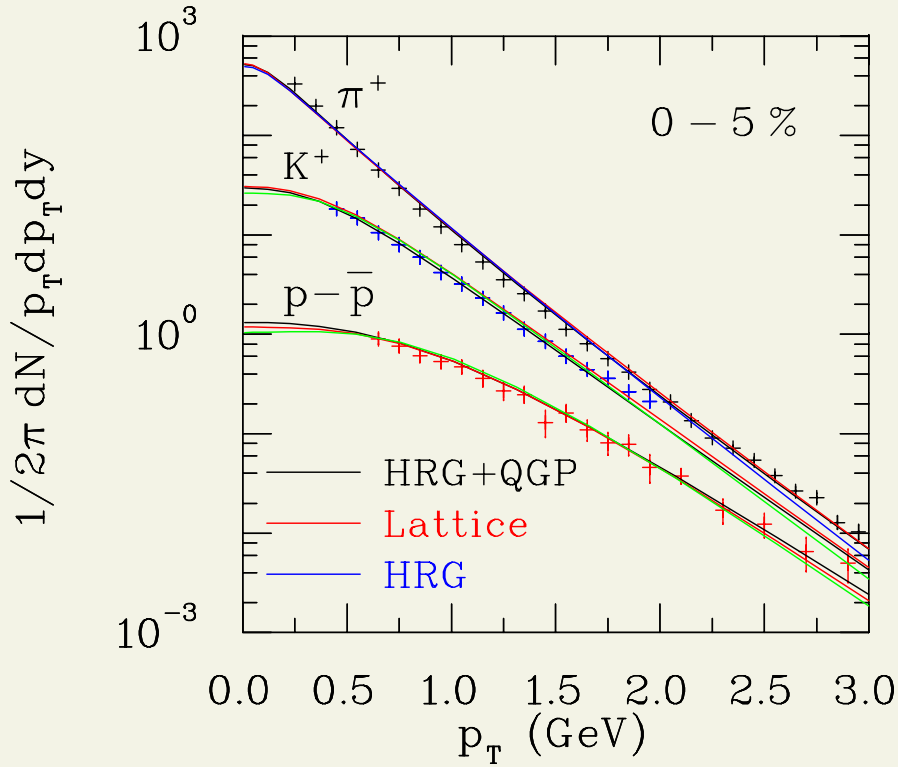


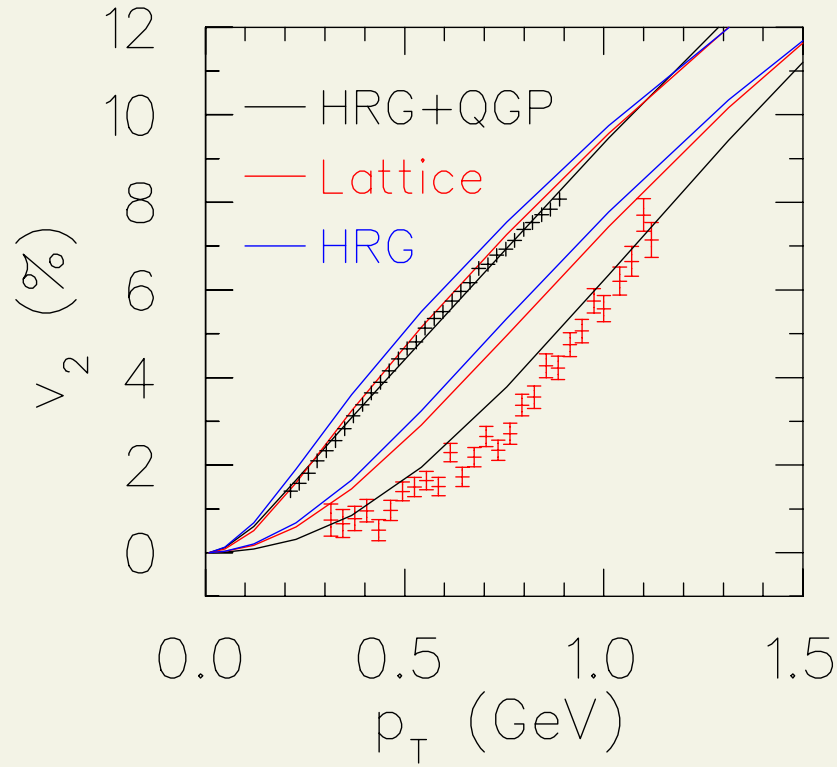


- **HRG+QGP: ideal gas of partons and hadron resonance gas, first order PT**
- **lattice: parametrized lattice EoS + hadron resonance gas, crossover**
- **pure HRG: hadron resonance gas only, no PT**

Anisotropy and p_{T}-spectra

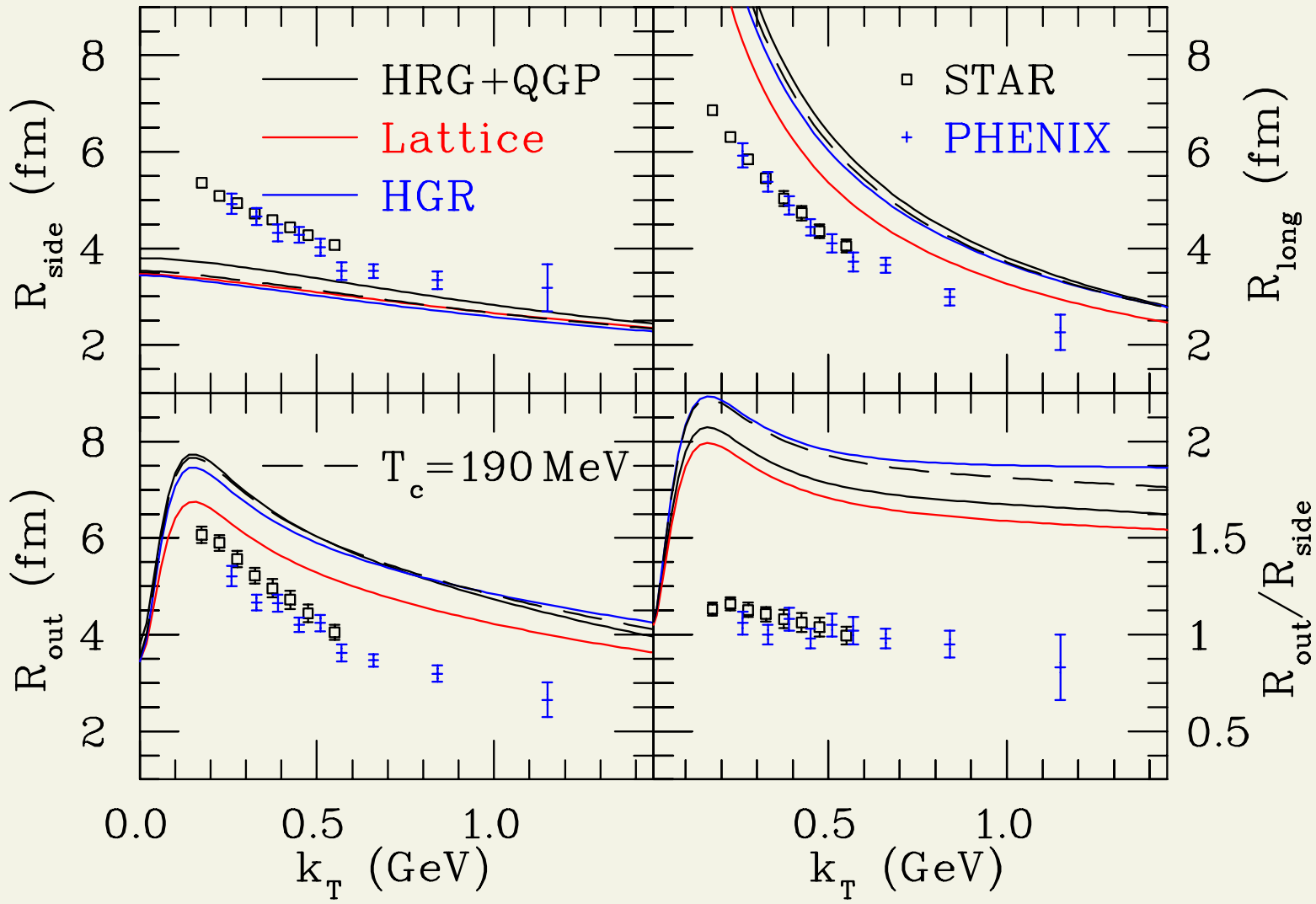
Au+Au at RHIC ($\sqrt{s_{\mathrm{NN}}} = 200$ GeV)





- **Effect on spectra negated by freeze-out temperature**
- **All EoSs lead to similar pion $v_2(p_T)$**
- **Proton $v_2(p_T)$ is sensitive to EoS:**
  - **Lattice EoS gives as bad fit than EoS without any phase transition!**
  - **An EoS with a first order phase transition is closest to the data**

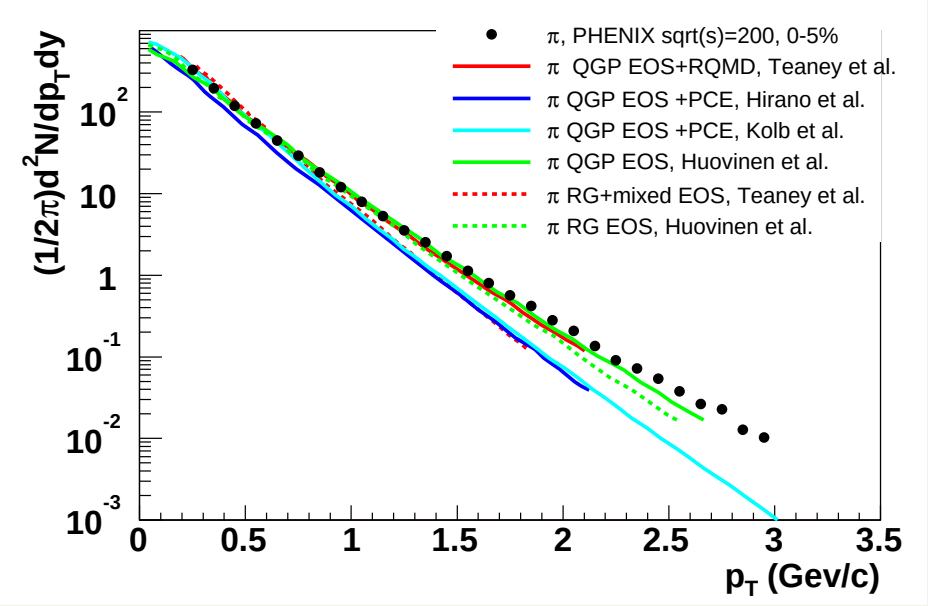
Two particle correlations



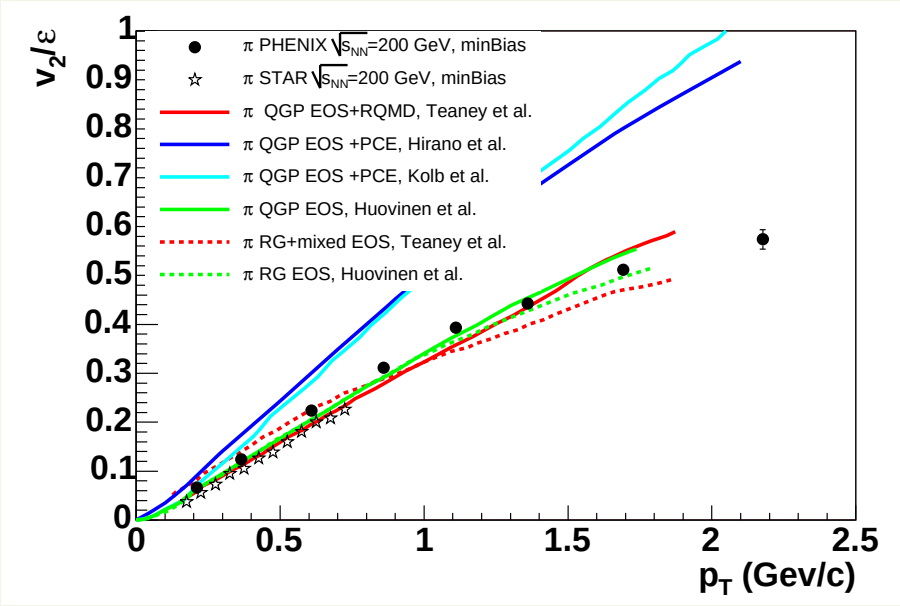
PHENIX whitepaper, NPA 757, 184 (2005)

chemical non-equilibrium in hadron gas

π p_T-spectrum:



π $v_2(p_T)$:



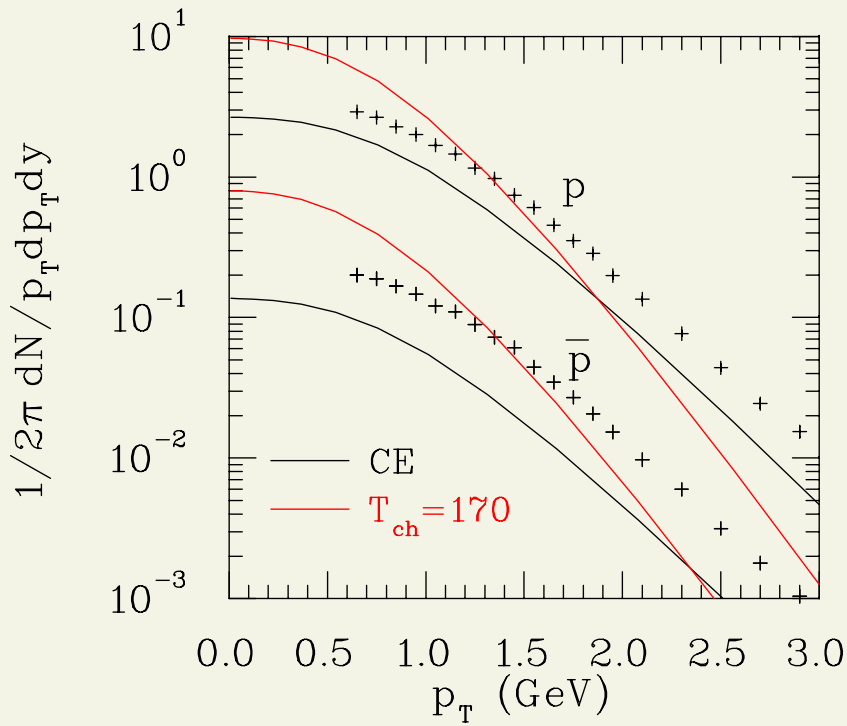
- **Blue curves: Hirano & Tsuda and Kolb & Rapp, ideal hydro, no chemical equilibrium**

$\Rightarrow$ **IT DOES NOT WORK!**

- **If ideal hydro reproduces particle yields, it does not reproduce their distributions nor elliptic flow**

Closer look at (anti)protons

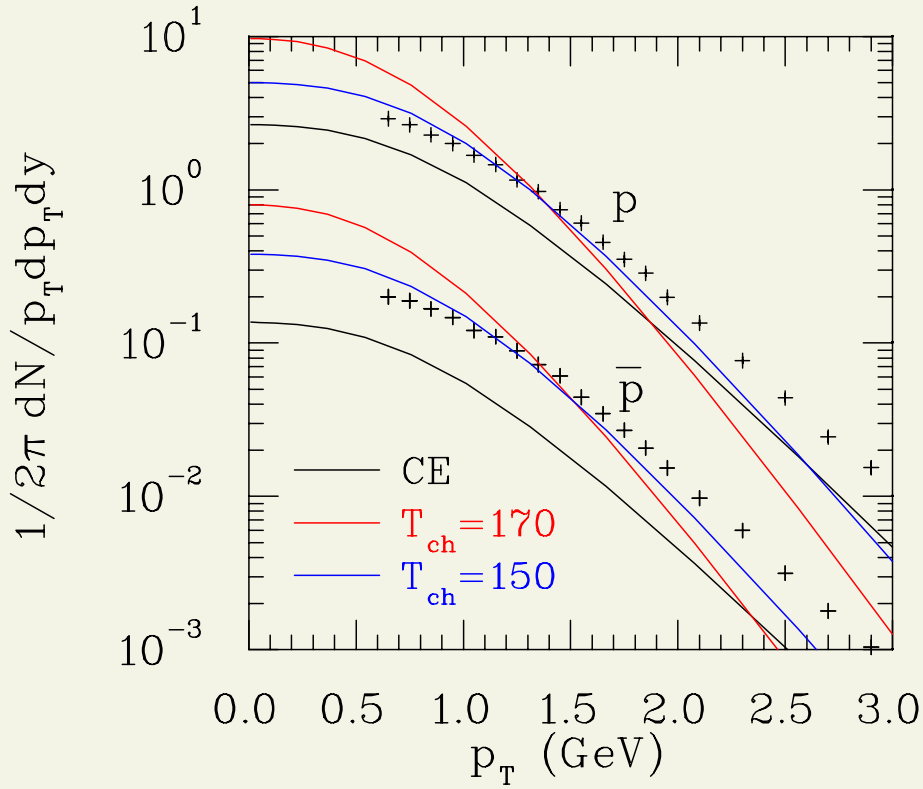
- **Too many protons and antiprotons:**



dN/dy	π^+	p	$\bar{p}$
PHENIX	286.4 ± 24.2	18.4 ± 2.6	13.5 ± 1.8
$T_{ch} = 170$	**268**	**25**	**20**

- **Thermal models slightly overestimate p/π ratio**
- **Fit of π, K, p and $\bar{p}$ ratios $\Rightarrow T \approx 150$ MeV (Cleymans et al., Phys.Rev.C71:054901,2005)**

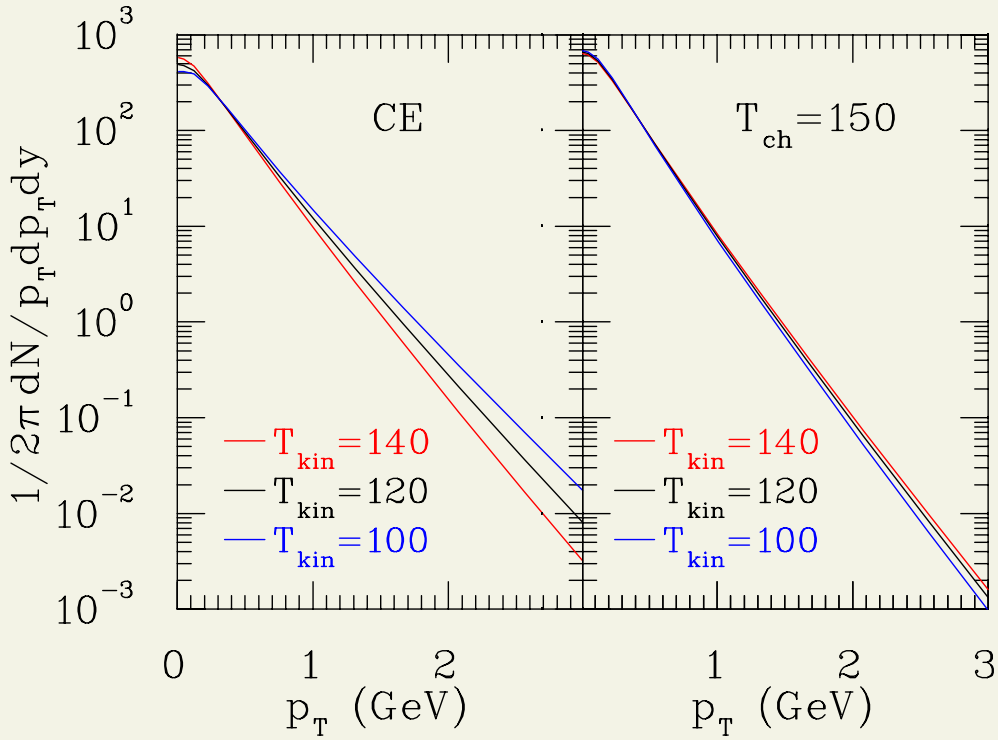
Second look at (anti)protons



- **Cooler chemical freeze-out temperature** $T_{ch} = 150$ **MeV** $\Rightarrow$ **yields OK.**

- **Slope too steep**
  - **Lower freeze-out temperature does not work**

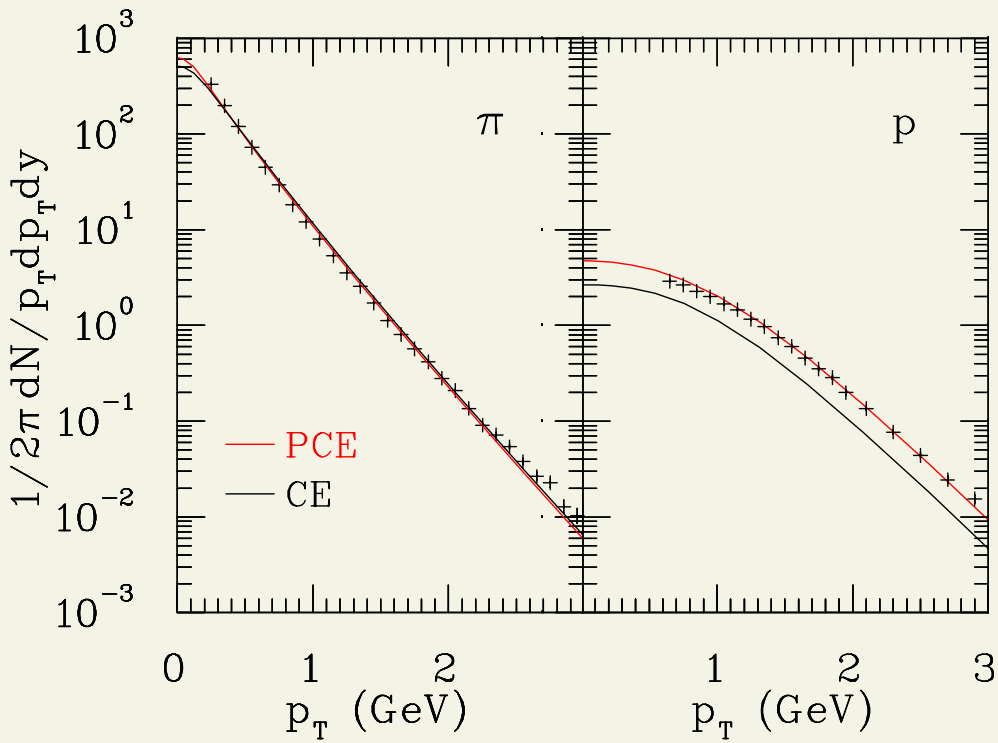
Effect of T_{kin} on pions



- **Longitudinal expansion does work ($p\,\mathrm{d}V$) $\Rightarrow$ $\frac{\mathrm{d}E_T}{\mathrm{d}y}$ decreases**
- **If particle # is conserved, $\langle p_T \rangle$ decreases**
- **In chemical equilibrium mass energy of baryon-antibaryon pairs is converted to kinetic energy $\Rightarrow$ $\langle p_T \rangle$ increases!**

Initial state

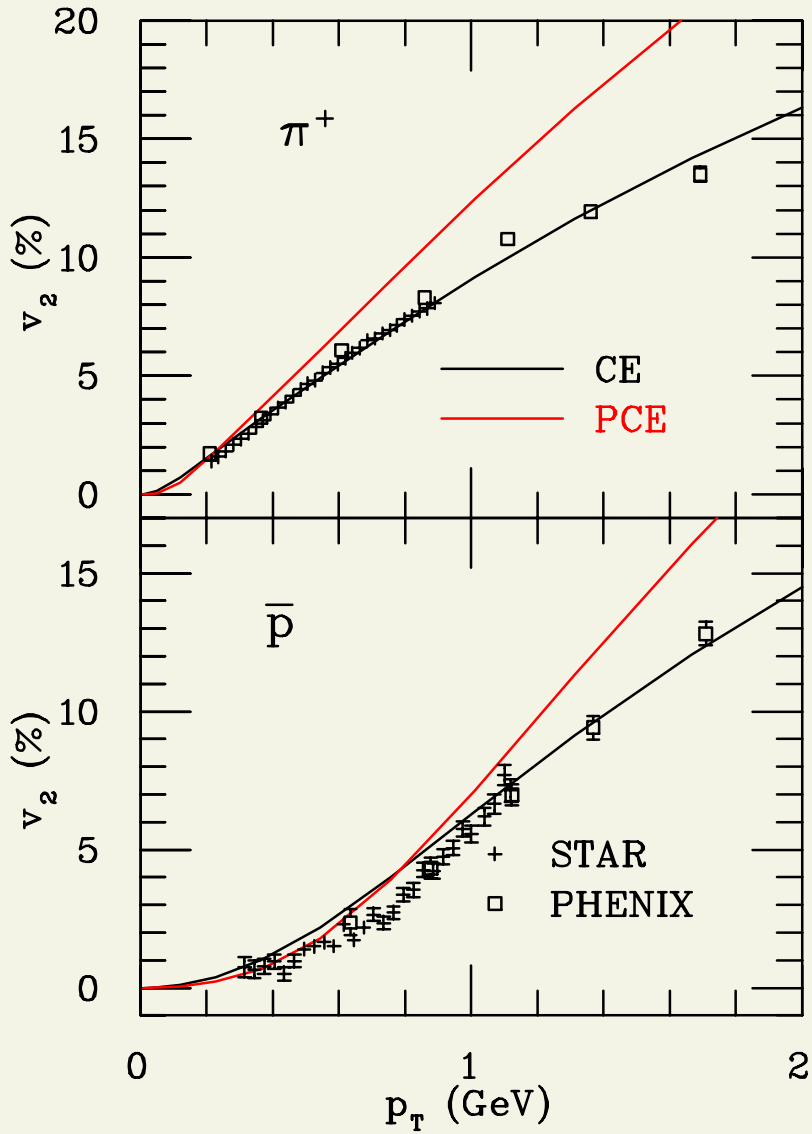
- **Need more transverse flow**
  - **Steeper initial density profile**
  - **Short initial time $\tau_0 = 0.2$ fm/c instead of $\tau_0 = 0.6$–1.0 fm/c**



- **If momentum distribution is isotropic, $\epsilon = 3P$ holds**

- **No need for exact thermalization**

Elliptic flow $v_2(p_T)$



Failed!

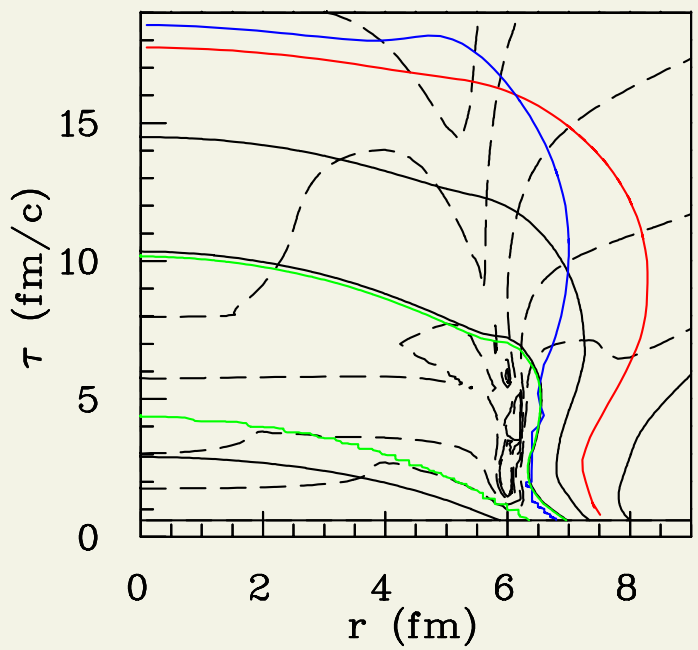
- **Dissipation required**
- **But where?**
  - **in hadronic phase?**
  - **in plasma?**
  - **or both?**

Freeze-out

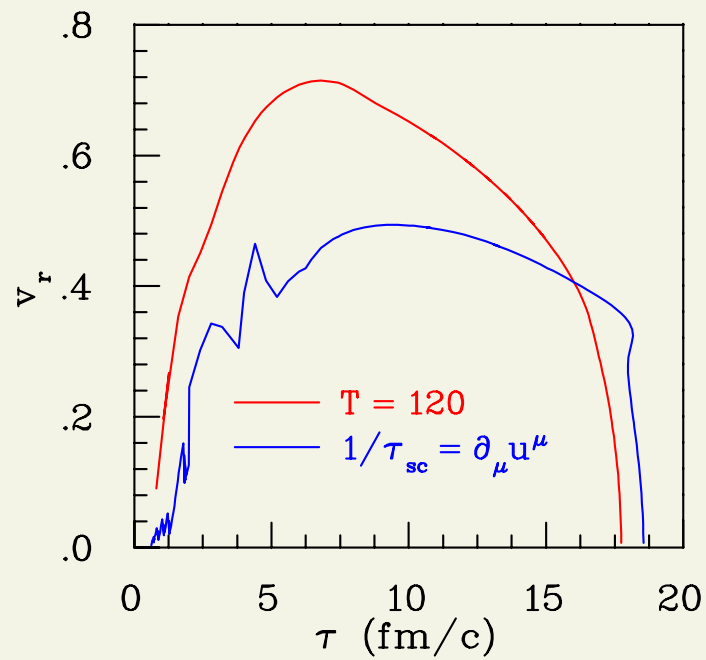
- when system no longer behaves as fluid but as free streaming particles
- momentum distributions cease to evolve $\rightarrow$ they "freeze-out"
- criterion: expansion rate larger than scattering rate:

$$\tau_{\rm scat}^{-1} \approx \partial_\mu u^\mu$$

- $\tau_{\rm scat}^{-1} \propto T^4 \rightarrow$ freeze-out at $T =$ const.
- not so good approximation:

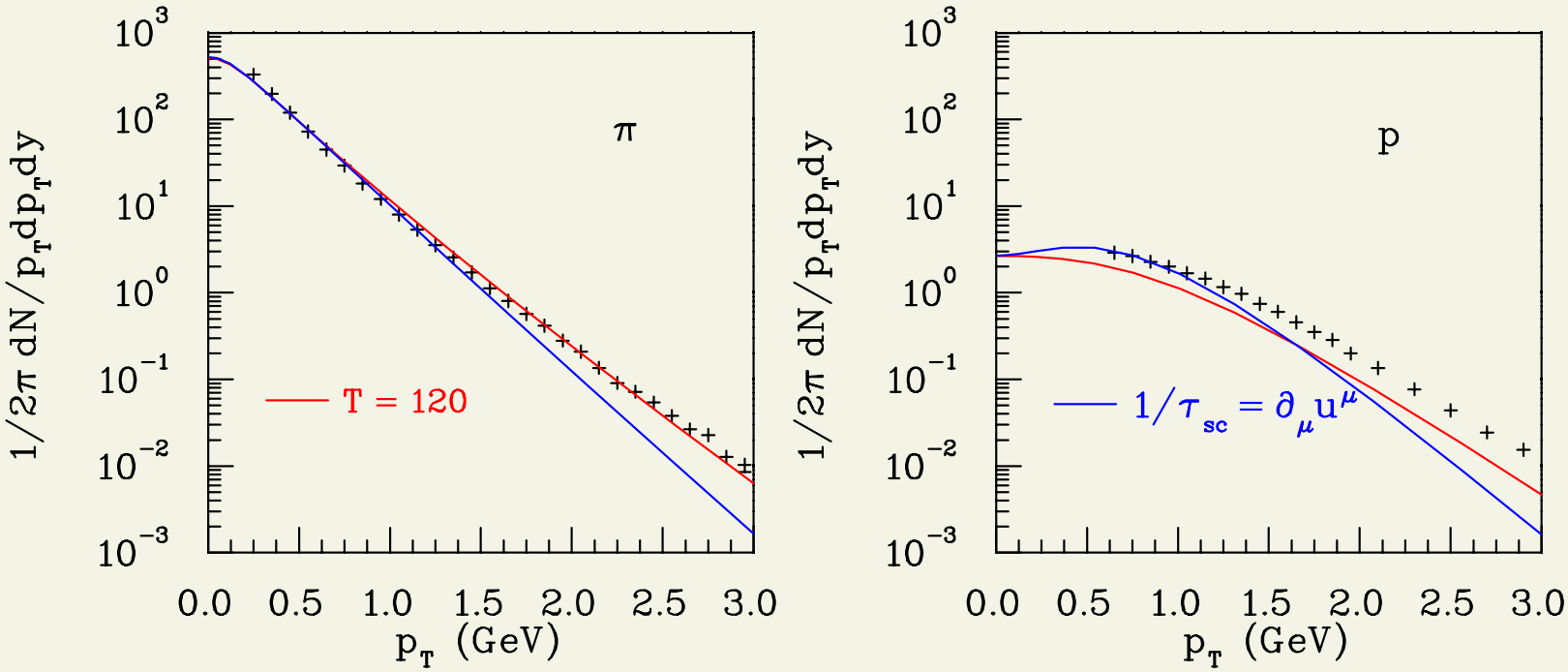


temperature and expansion rate contours



flow velocity on freeze-out surface

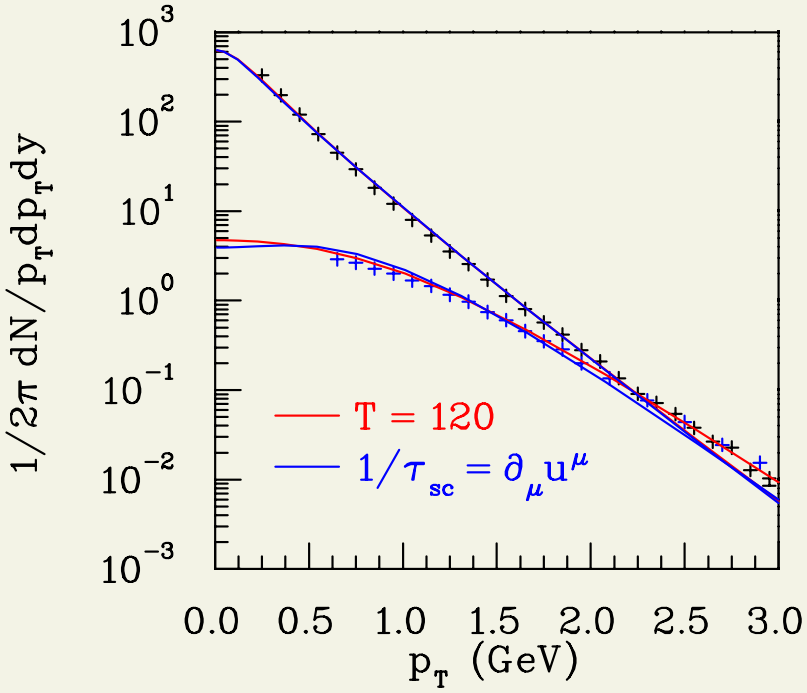
Effect on p_T spectra:

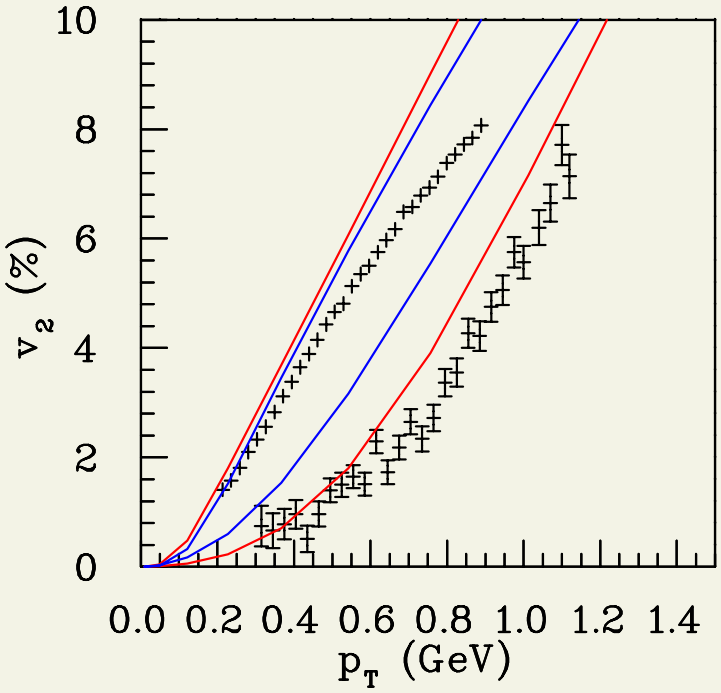


- **Need more transverse flow**

Early start?

- freeze-out has only a small effect
- system freezes out soon after phase transition anyway
- results for chemical non-equilibrium and $\tau_0 = 0.2$ fm/c:

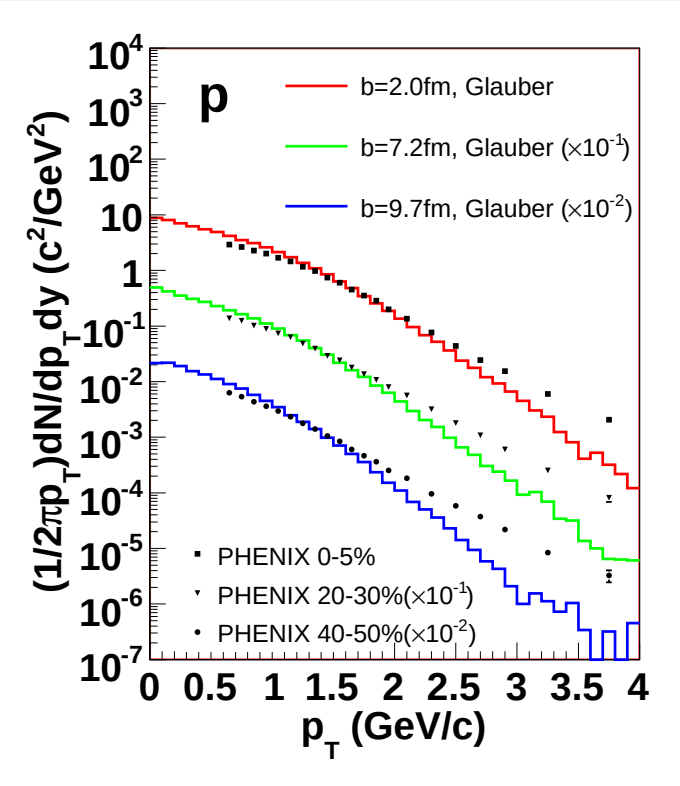




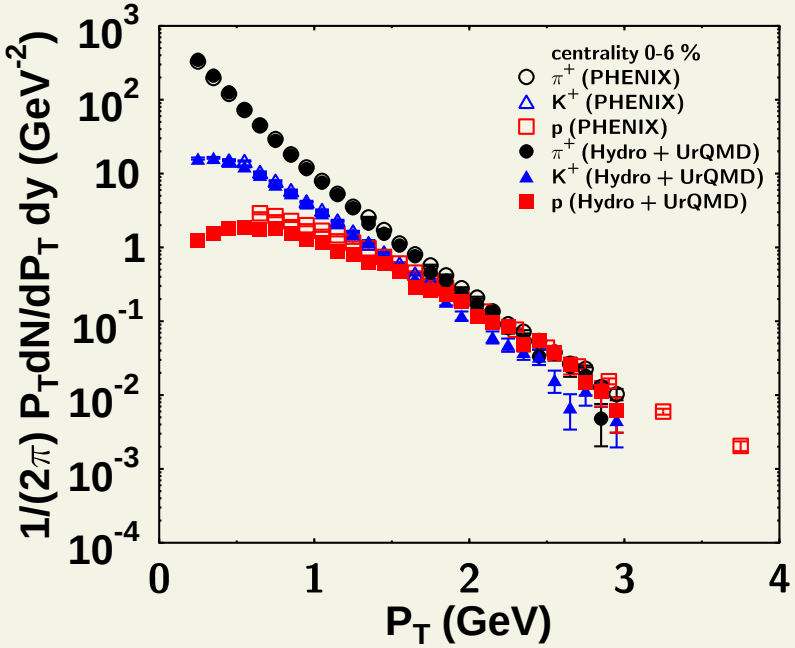
Hydro+cascade

- Cascade description describes chemistry and freeze-out
- Reproduces both spectra and v_2
- $n \to 2$ processes not included

Hirano et al., arXiv:0710.5795:



Nonaka & Bass, Phys.Rev.C75:014902,2007:



Conclusions

- p_T **spectra and pion** v_2 **insensitive to EoS**
- **proton** v_2 **sensitive to the phase transition**
  $\rightarrow$ **favours** $T_c \sim 170$ **MeV and sharp transition**

- **it is possible to fit both particle yields and** p_T **spectra in ideal hydro**
  - if EoS is hard or initial time short
- **but** v_2 **fails**

- **freeze-out based on comparison of expansion and scattering rates**
  decreases transverse flow

$\rightarrow$ **small initial time to generate enough flow**
$\rightarrow$ v_2 **fails**

dissipative corrections required to fit the data