Chemical freeze-out in hydrodynamical description

Pasi Huovinen

J. W. Goethe Universität, Frankfurt

Statistical Particle Production: Beyond the first moment

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Ideal hydrodynamics

local, macroscopic variables: energy density $e(x)$
pressure $p(x)$
flow velocity $u^\mu(x)$ $(u^\mu u_\mu = 1)$

energy-momentum and charge conservation: $\partial_\mu T^{\mu\nu}(x) = 0$
$\partial_\mu N^\mu(x) = 0$

local equilibrium: $T^{\mu\nu} = (e+p)u^\mu u^\nu - p g^{\mu\nu}$, $N^\mu = n u^\mu$

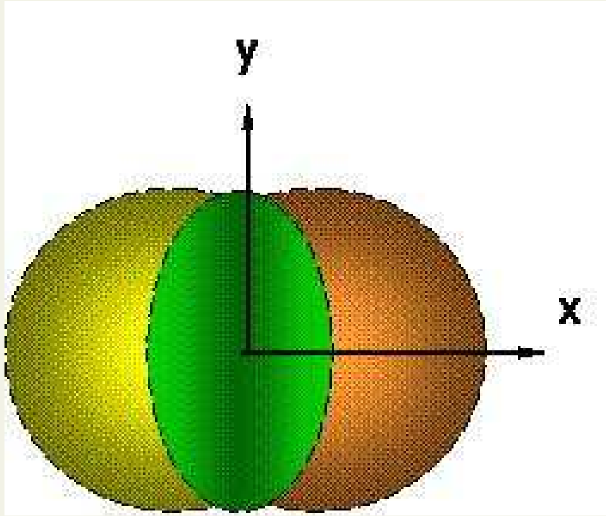
$[T^{\mu\nu}_{LR} = diag(e,p,p,p)$, $N^\mu_{LR} = (n,\vec{0})]$

matter characterized by: equation of state $p(e,n)$

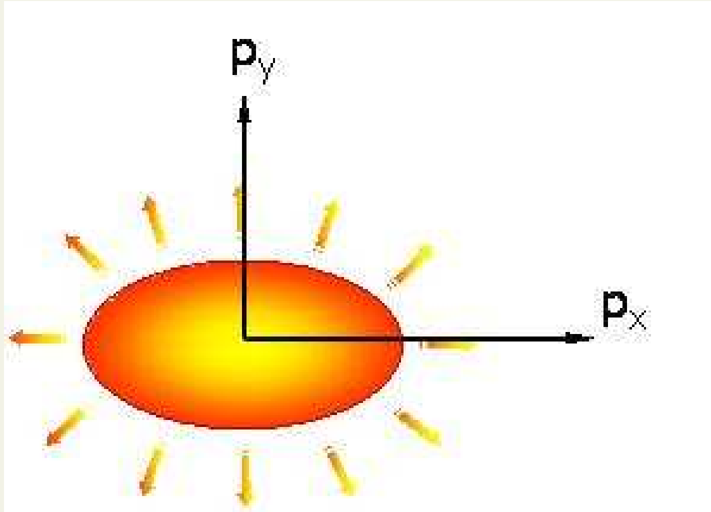
Unknowns: initial state, final state, equation of state

Elliptic flow v_2

spatial anisotropy $\longrightarrow$ final azimuthal momentum anisotropy



$\longrightarrow$



$$\varepsilon \equiv \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$$

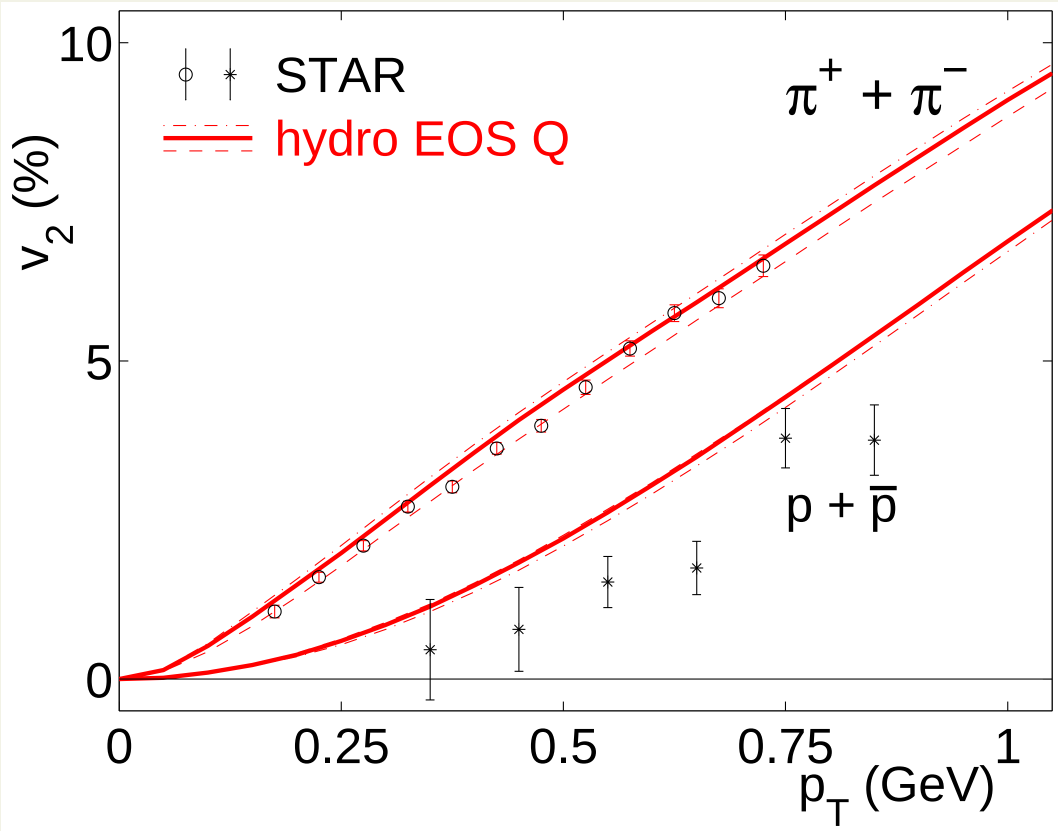
$$v_2 \equiv \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

sensitive to speed of sound $c_s^2 = \partial p / \partial e$ **and shear viscosity** η

Success of ideal hydrodynamics

Kolb, Heinz, Huovinen et al ('01)

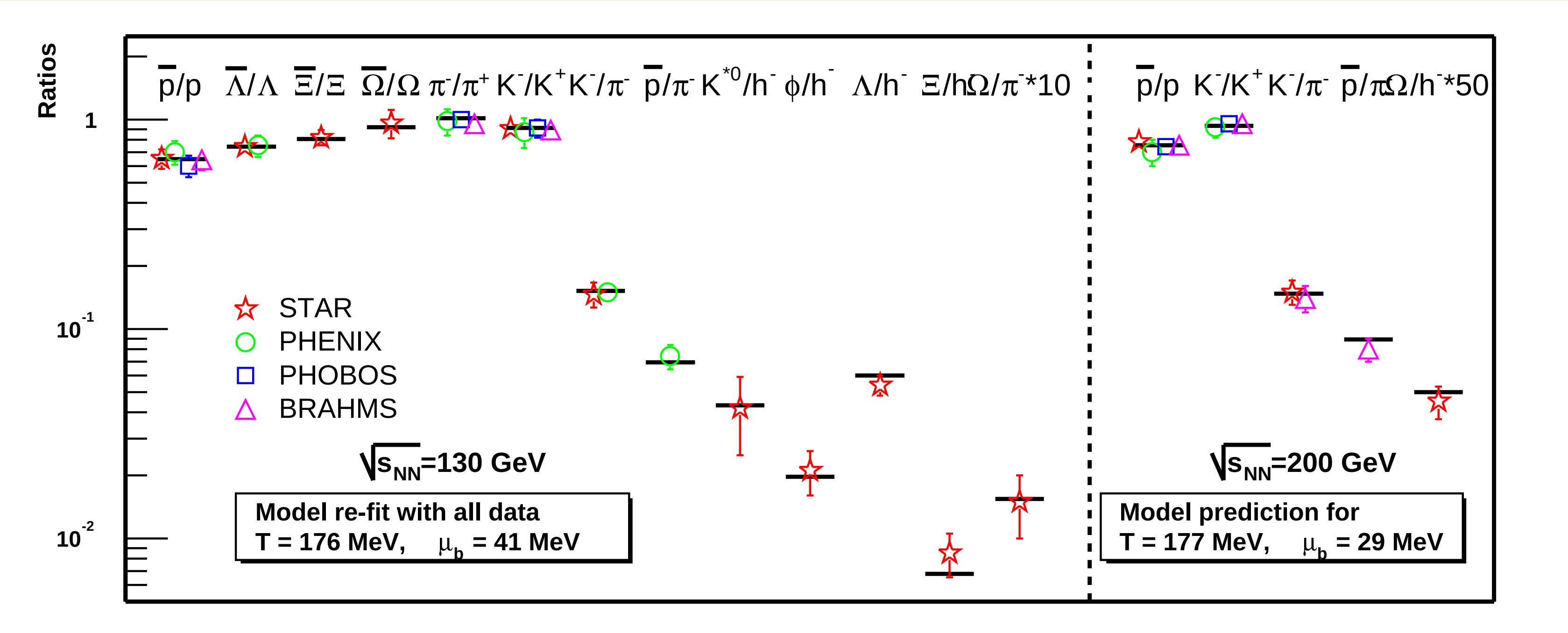
minbias Au+Au at RHIC



- **chemical equilibrium until kinetic freeze-out at $T_{\rm fo} = 128$ MeV!**

Thermal models

- Hadronic phase: ideal gas of massive hadrons and resonances
- in chemical equilibrium



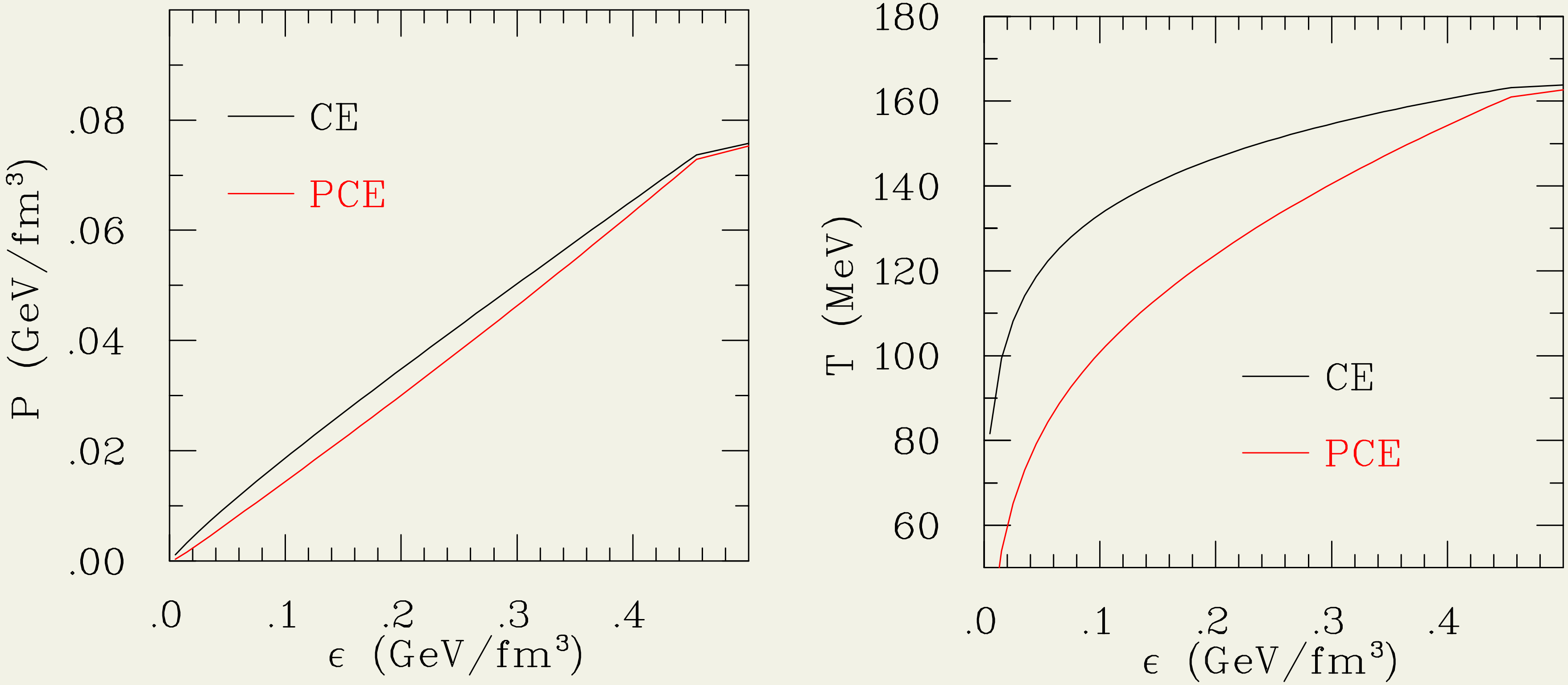
- Particle ratios (approximately) correspond to a system in $T \approx 160$–170 MeV temperature

- Evolution to $T \approx 100$–130 MeV temperature

$\Rightarrow$ In hydro particle ratios become wrong

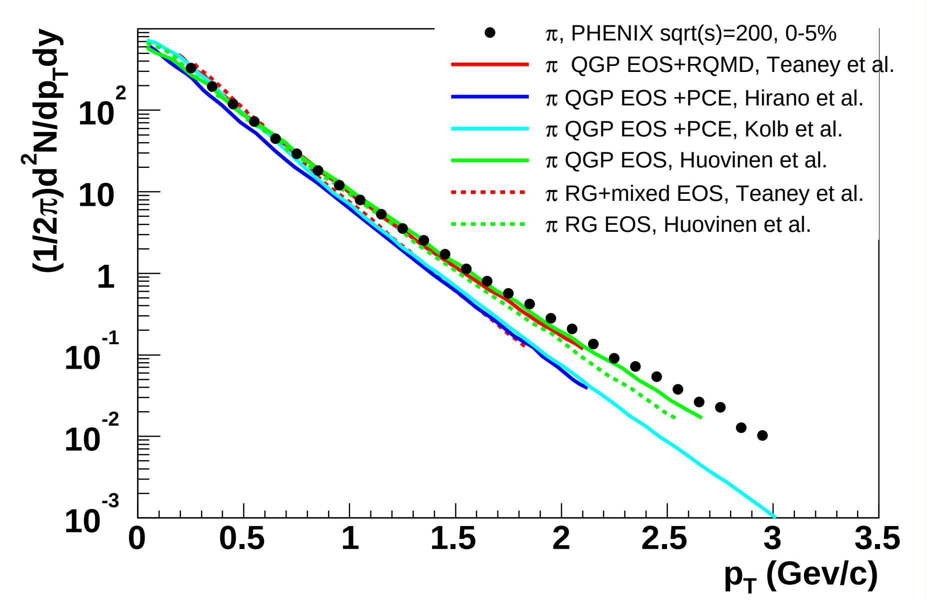
Chemical non-equilibrium

- **Treat number of pions, kaons etc. as conserved quantum numbers below T_{ch} (Bebie et al, Nucl.Phys.B378:95-130,1992)**
- $P = P(\epsilon, n_b)$ **changes very little, but** $T = T(\epsilon, n_b)$ **changes. . .**

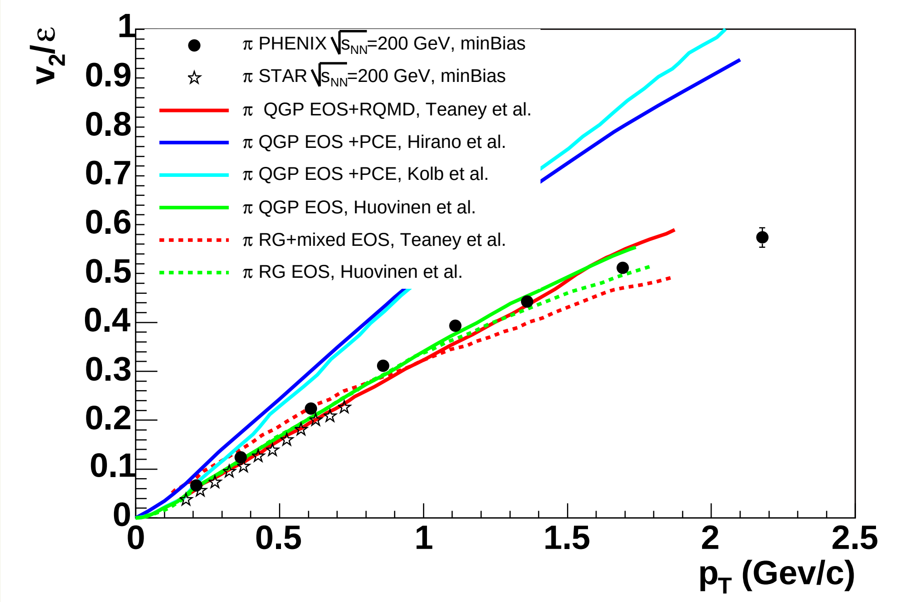


PHENIX whitepaper, NPA 757, 184 (2005)

π p_T-spectrum:



π $v_2(p_T)$:



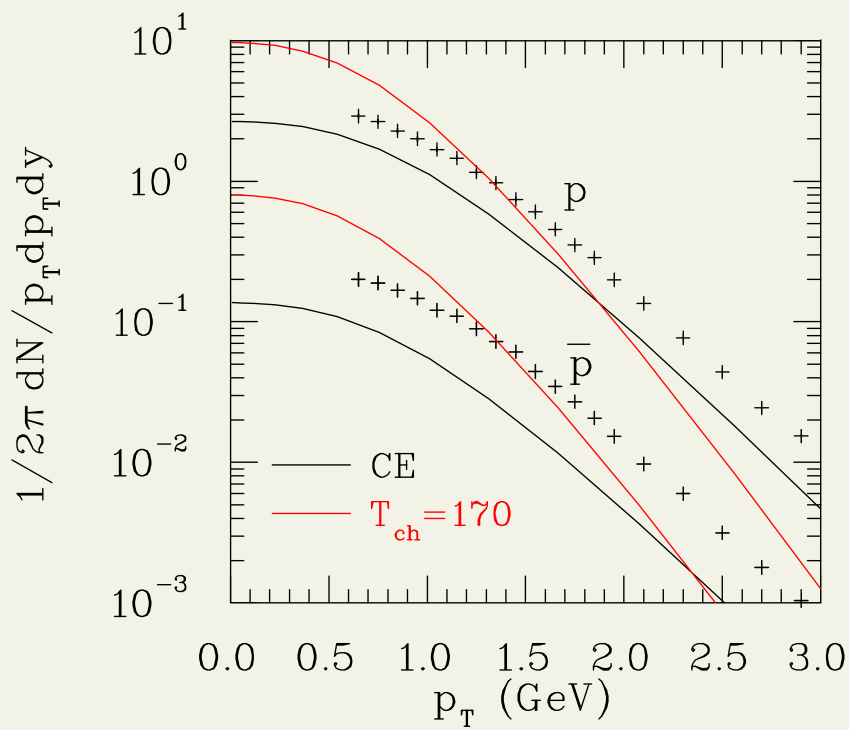
- **Blue curves**: Hirano & Tsuda and Kolb & Rapp, ideal hydro, no chemical equilibrium

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

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

Closer look at (anti)protons

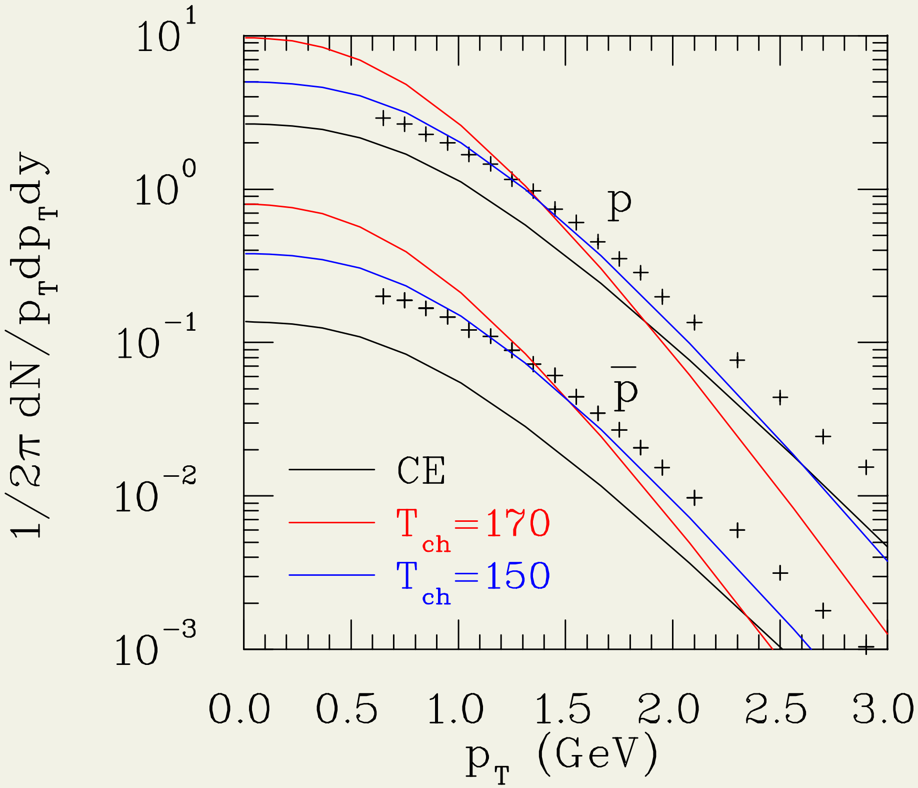
- **Too many protons and antiprotons:**



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**

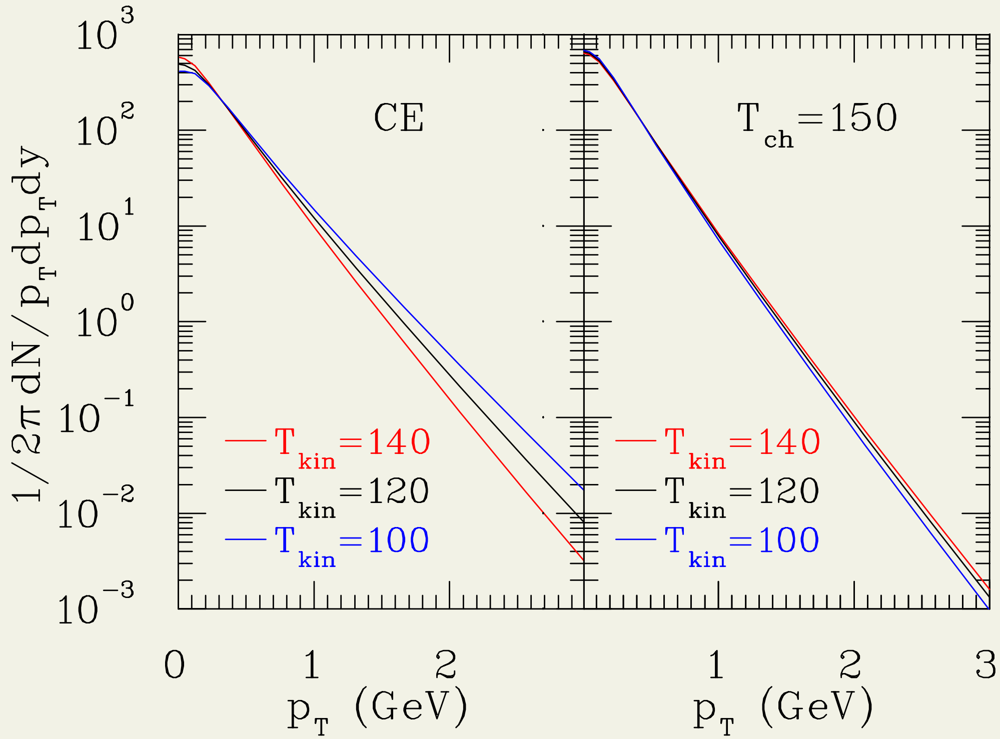
- **Thermal models slightly overestimate p/π ratio**
- **Fit of π, K, p and $\bar{p}$ ratios $\Rightarrow T \approx 150$ MeV (Cleymans et al., Phys.Rev.C71:054901,2005)**

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**

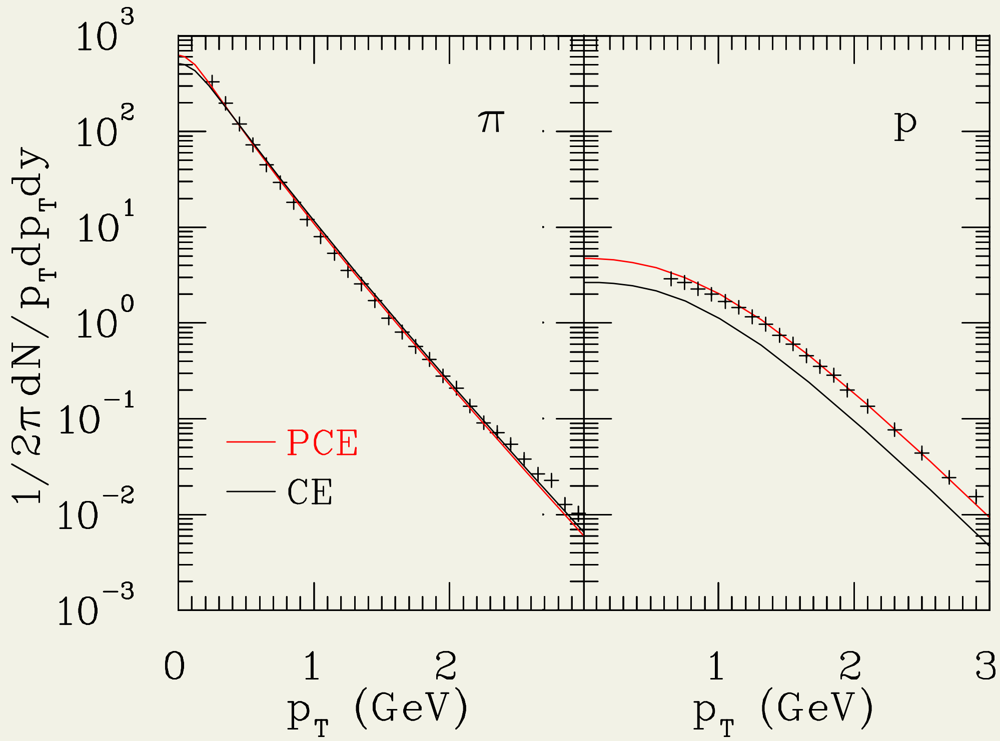
Effect of T_{kin} on pions



- **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!**

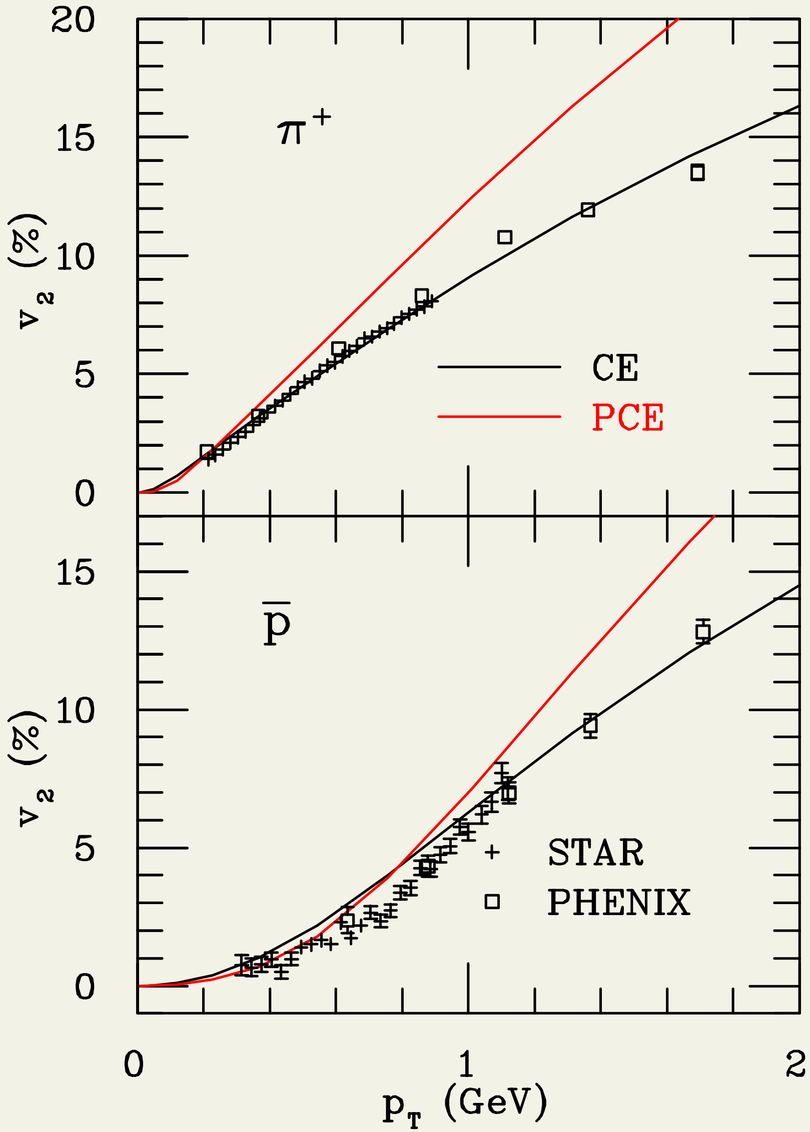
Initial state

- **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**



- **p_T-spectra can be reproduced simultaneously with yields**

Elliptic flow $v_2(p_T)$



Failed!

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

Conclusions

- pion and proton yields favour $T_{\mathrm{chem}} = 150$ MeV
- effect of hadronic chemistry to expansion nontrivial
- one can fit both spectra and yields in ideal hydrodynamics
- but not v_2!