Hadronic Freeze-outs

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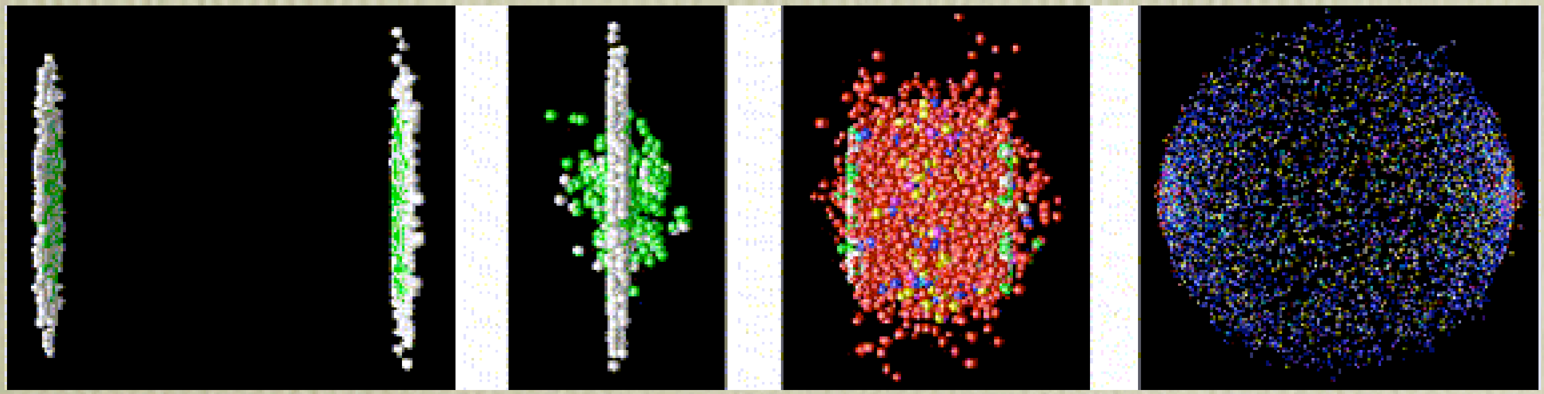
Stages of a nuclear collision

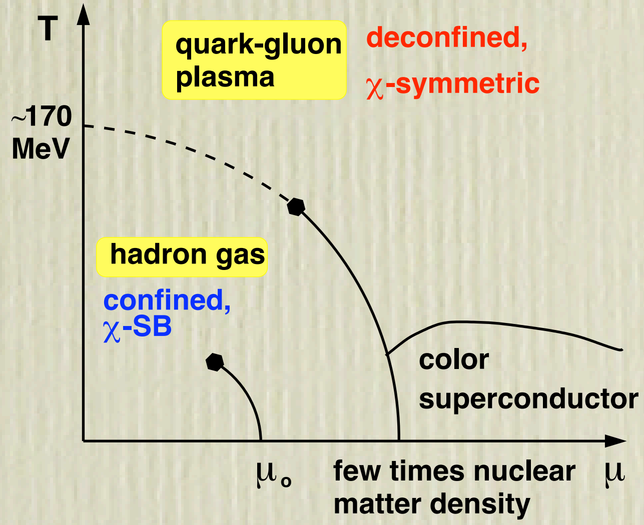
- deconfined quarks and gluons. (RHIC collisions are believed to provide conditions for QGP, early universe)

- chemical freeze-out: end of inelastic collisions. quark flavor composition is fixed. “system is cooked”

- kinetic freeze-out: after this, particles no longer interact. “system is served (as spectra)”

latQCD: QGP -> HG at Tc ~ 170 MeV

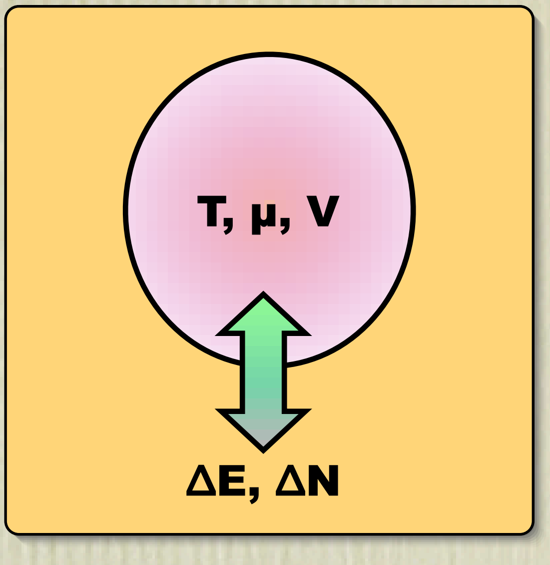




Karsch, Nucl. Phys. A698, 199c (2002)
Karsch, hep-lat/0401031

Chemical freeze-out

GC



- chemical equilibrium = particle compositions are fixed
- based on the grand canonical (GC) ensemble: large system, number of particles can fluctuate until freeze-out, conservation laws make use of chemical potential.
- as opposed to canonical ensemble, where system is small (low energy HIC, e+e-, peripheral HIC), N is fixed, and conservation laws must be obeyed within each event.

$$Z = \sum \exp(-\frac{E - \mu N}{T})$$

$$\mu = T \ln \frac{N}{Z}$$

Braun-Munzinger et al, nucl-th/0311005
Braun-Munzinger et al, nucl-th/0304013
Cleymans et al, J. Phys. G25, 281 (1999)

Statistical model

- to describe the particle yield, the model uses the chemical freeze-out temperature (T_{ch}), the chemical potentials (μ), and the strangeness saturation factor (γ_s)

$$\gamma_s = \frac{s \text{ density}}{\text{equilibrium density}}$$

- The number density of particle *i* can be described by

$$\rho_i = \gamma_s^{\langle s+\bar{s}\rangle_i} \frac{g_i}{2\pi^2} T_{ch}^3 \left(\frac{m_i}{T_{ch}}\right)^2 K_2\left(\frac{m_i}{T_{ch}}\right) \lambda_q{}^{Q_i} \lambda_s{}^{s_i}$$

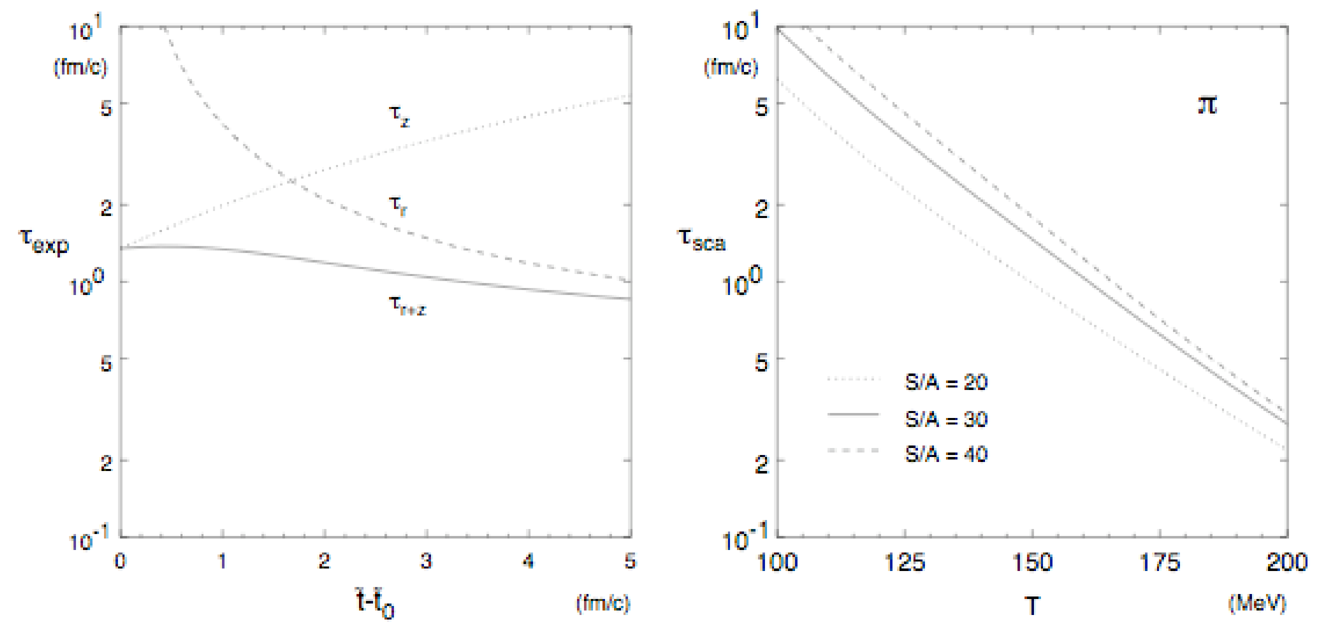
$$\lambda_q \equiv e^{\mu_q/T_{ch}} \qquad Q_i = \langle u+d-\bar{u}-\bar{d}\rangle_i$$

$$\lambda_s \equiv e^{\mu_s/T_{ch}} \qquad s_i = \langle s-\bar{s}\rangle_i$$

Rafelski, Phys. Lett. B262, 333 (1991)
Sollfrank, J. Phys. G23, 1903 (1997)
Sollfrank et al, Phys. Rev. C59, 1637 (1999)

Kinetic freeze-out

- density & temperature of the particle system are low enough that particles no longer scatter
- mean free path (λ) ≈ system size (R)
- scattering rate (<β>/λ) ≈ expansion rate ($\partial_\mu u^\mu$)
- time between collisions ≈ Hubble time (1/H)

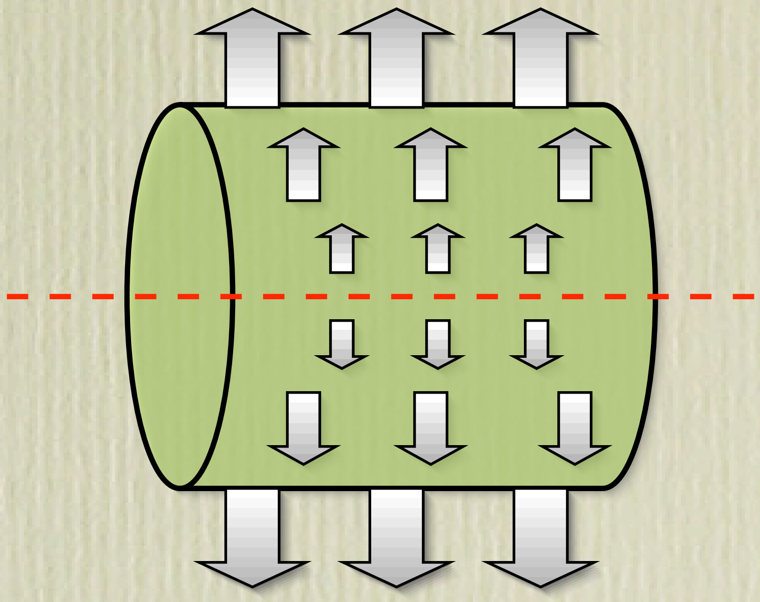


- momentum distribution "frozen"
- spectra shape gives:
  - temperature at freeze-out (inverse slope in high-m_T region)
  - collective expansion velocity (flattening in low-m_T region)

Schnedermann and Heinz, PRC50, 1675 (1994)
Kolb, nucl-th/0304036

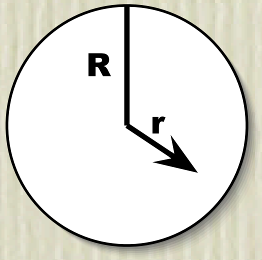
Blast-wave model

- source is boosted by scattering of produced particles
- any partonic flow would also result in final spectra
- kinetic freeze-out temperature (T_{kin}), collective flow velocity (β), and flow profile parameter (n) are used to describe transverse mass spectra



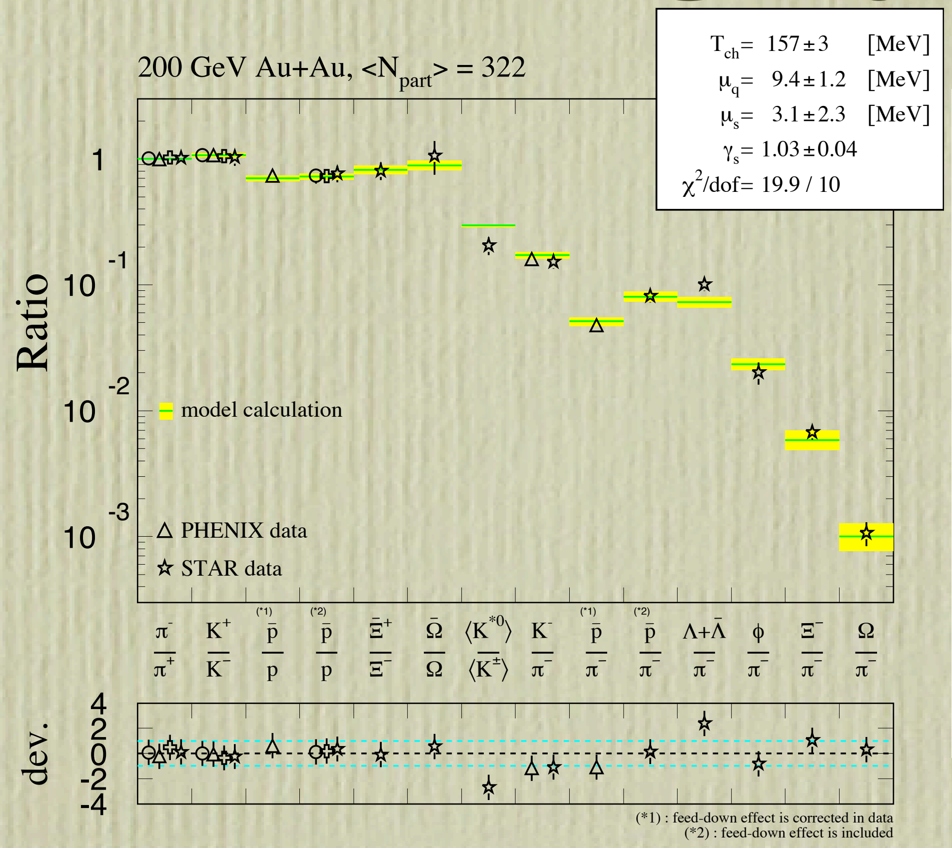
$$\frac{dN}{m_T\,dm_T} \propto \int_0^R r\,dr\,m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

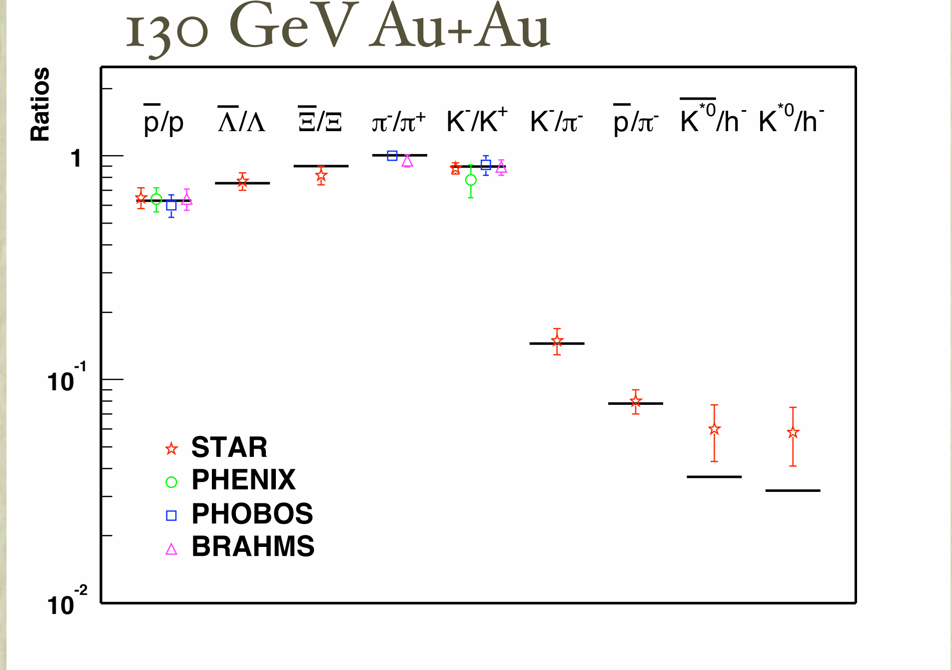
$$\rho(r) = \tanh^{-1}\beta_r \qquad \beta_r = \beta_s\left(\frac{r}{R}\right)^n$$

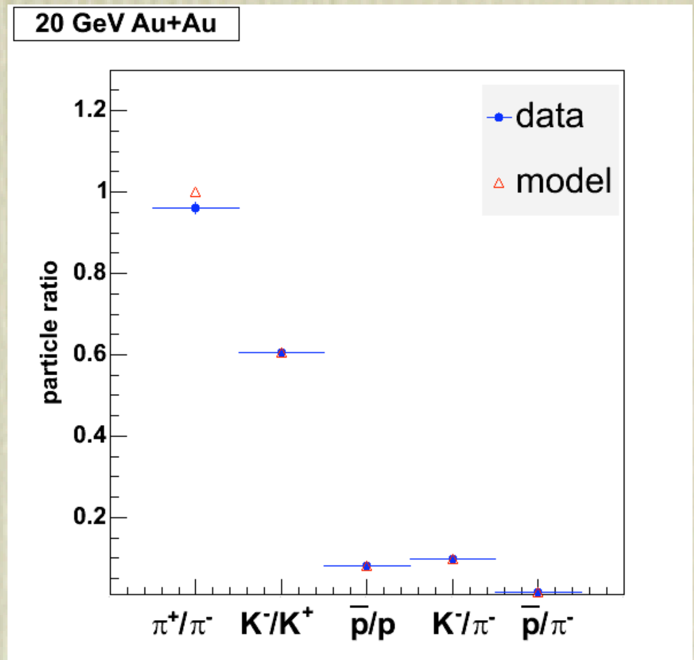


Schnedermann et al, PRC48, 2462 (1993)

Chem. FO Results



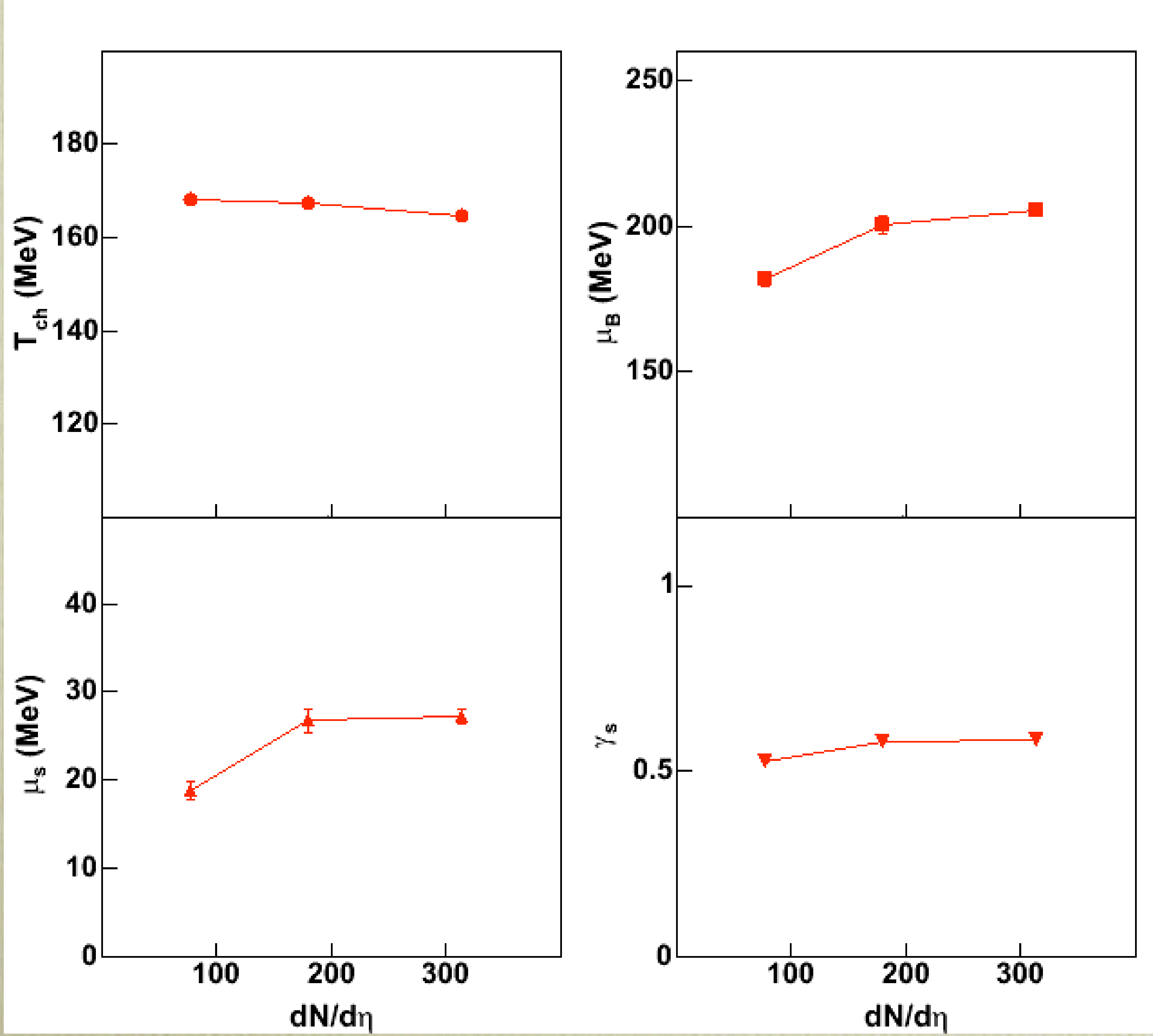




	200 GeV	130 GeV	20 GeV [***]
Tch (MeV)	157+/-3 [*] 160+/-5 [**]	169+/-6 [*] 174+/-7 [****]	165+/-1
μB (MeV)	28.2+/-3.6 [*] 24+/-4 [**]	39.6+/-4.2 [*] 46+/-5 [****]	205.5+/-0.6
μs (MeV)	3.1+/-2.3 [*] 1.4+/-1.6 [**]	2.0+/-1.5 [*]	27.2+/-0.9
γs	1.03+/-0.04 [*] 0.99+/-0.07 [**]	0.97+/-0.06 [*]	0.58+/-0.01

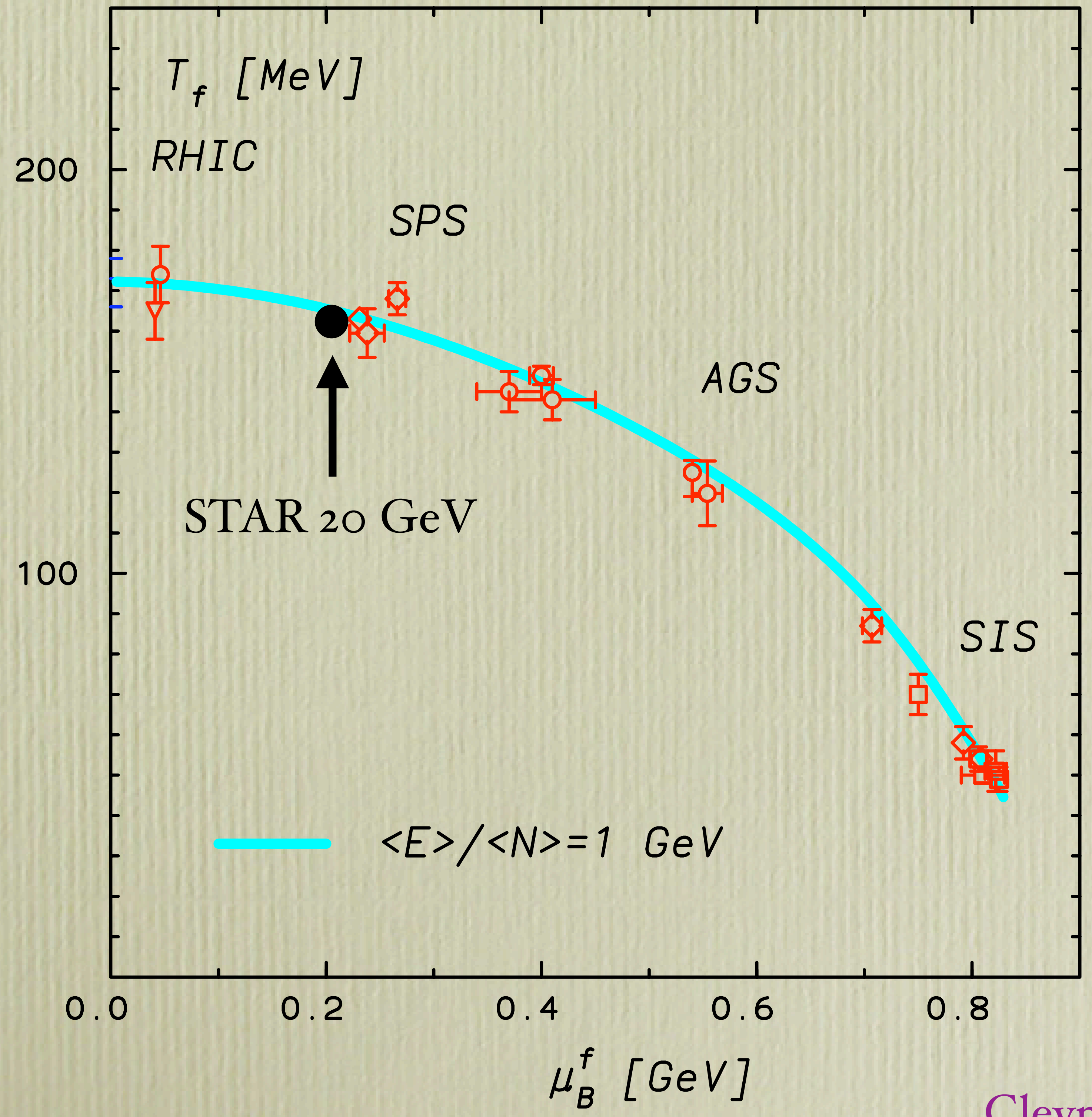
(for most central collisions)
* : nucl-th/0405068
** : nucl-ex/0403014
***: only include stat. err.
****: PLB518, 41 (2001)

Chem. FO results



- 20 GeV results as functions of centrality

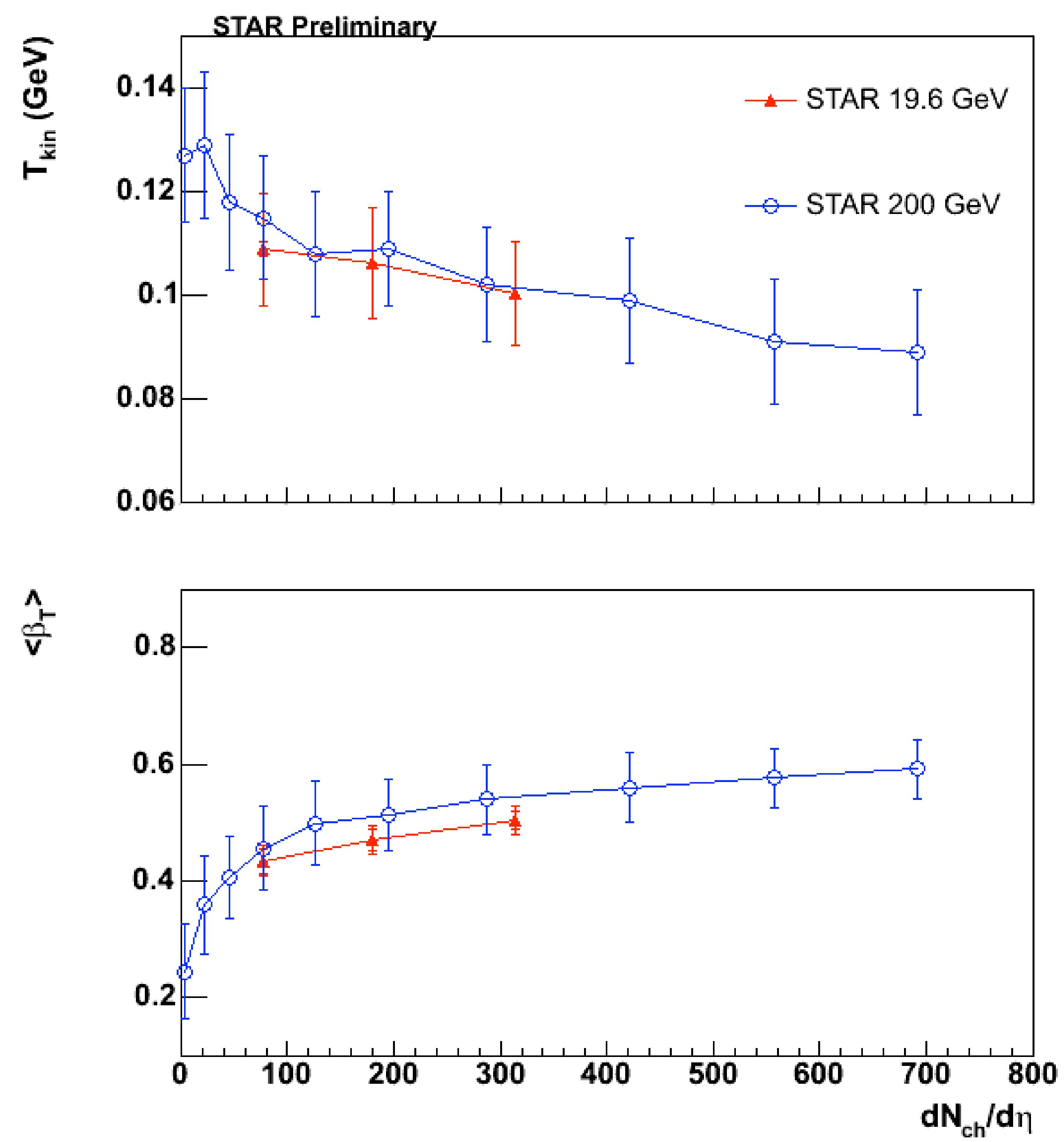
Chem. FO results



- chemical freeze-out curve, from heavy ion experiments

Karsch, hep-lat/0401031
Cleymans and Redlich, PRL81, 5284 (1998)

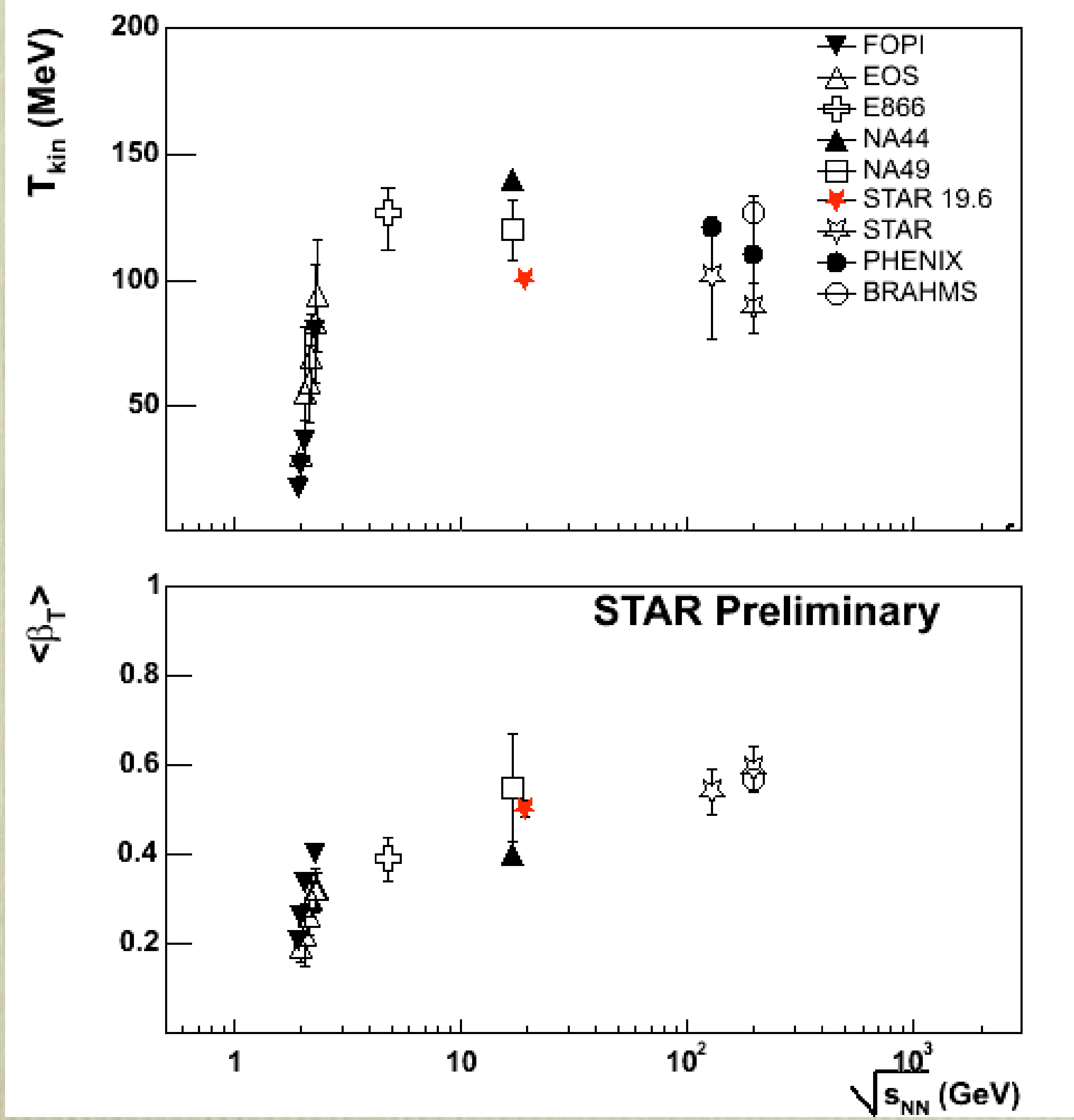
Kin. FO results



- blast wave parameters vs centrality
- opposite trends observed
- can't tell apart 20 and 200 GeV

STAR, PRL92, 112301 (2004)

Kin. FO results



- kinetic freeze-out temperature seems to saturate around SPS energy
- flow velocity increases with energy

	200 GeV	20 GeV [***]
Tkin (MeV)	89+/-10 [**]	100+/-1
β	0.59+/-0.05 [**]	0.50+/-0.02

(for most central collisions)

** : Barannikova, nucl-ex/0403014

***: only include stat. err.

Summary

- it's called freeze-out but it's not that cold. water freezes at 273 K (0.024 eV). quarks and gluons freeze at 170 MeV (2,000,000,000,000 K).
- Tch very close to predicted Tc, not much centrality-dependent.
- baryon chemical potential decreases with energy, but nonzero (= not baryon free yet).
- Tkin < Tch, varies slightly with centrality
- collective expansion is evident, larger in more central collisions
- 20 GeV system: different initial conditions (determined by centrality) led to a similar chemical freeze-out temperature, approximately 10 MeV colder than the critical temperature at the phase transition predicted by lattice QCD; then the temperature of the π, K, p, dropped about 65 MeV before they froze out kinetically.