(soft) physics from particle spectra

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outline:

1. heavy ion collsion
2. chemical freeze-out
3. statistical model
4. kinetic freeze-out
5. blast wave model
6. conclusions

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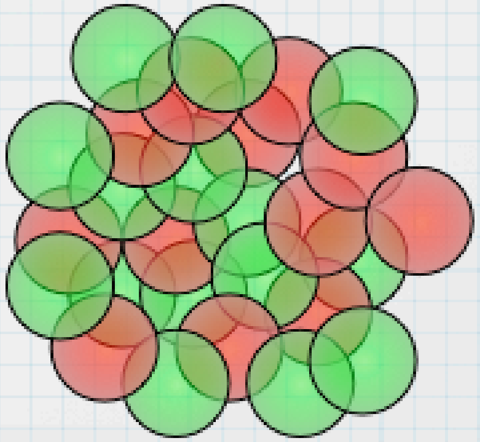
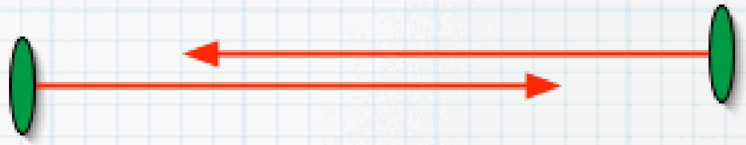
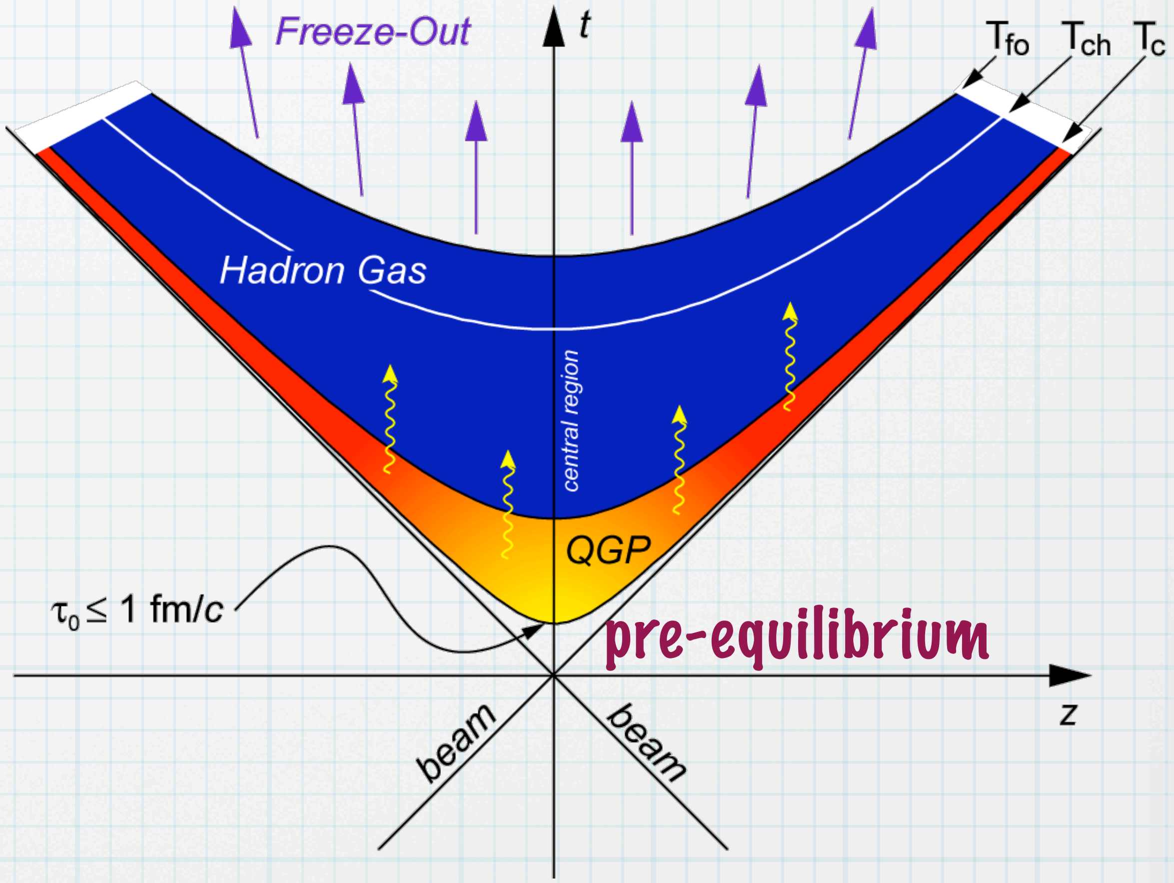
UCD Nuclear Physics Group
9 Feb 2005



heavy ion collisions

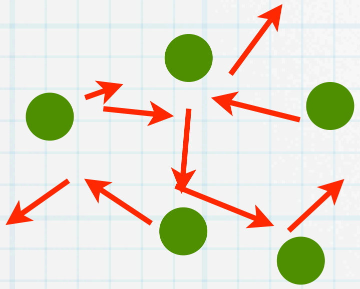
- ultimate goal of HIC = study properties of hot and dense quark-gluon plasma
- QGP = thermalized system of free quarks and gluons
- elementary collisions -> dilute
- HIC -> lots of particles -> final-state thermalization
- thermalization -> collectivity



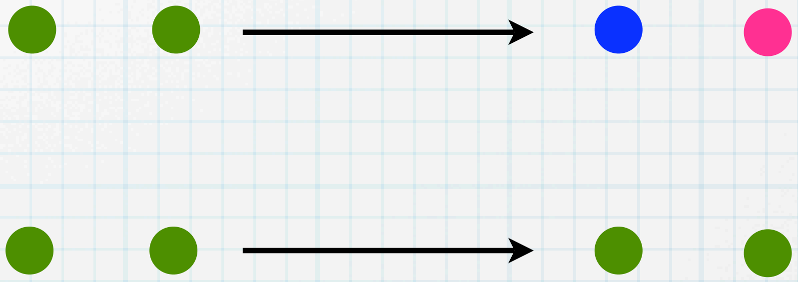


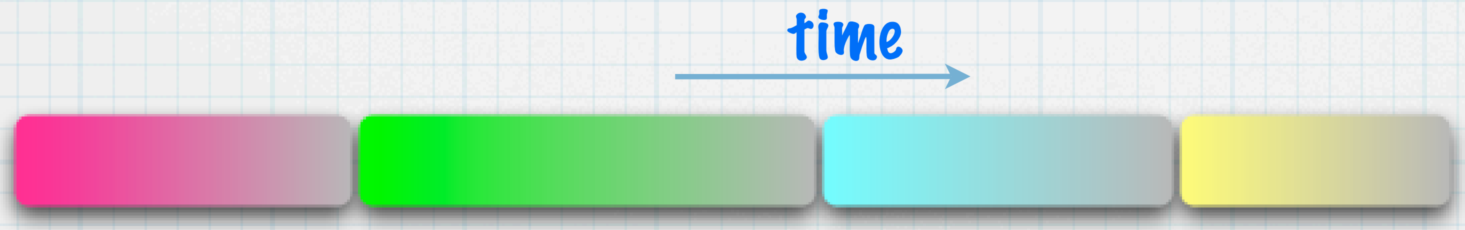
τ_0 = formation/thermalization time (Bjorken, Phys. Rev. D27, 140 (1983))

freeze-out evolution



- chemical and kinetic freeze-outs are based on similar idea: expansion rate > collision rate
- both chem. and kin. equilibria require thermalization, but at different degrees





T_{crit} -> around 175 MeV

LQCD critical temperature

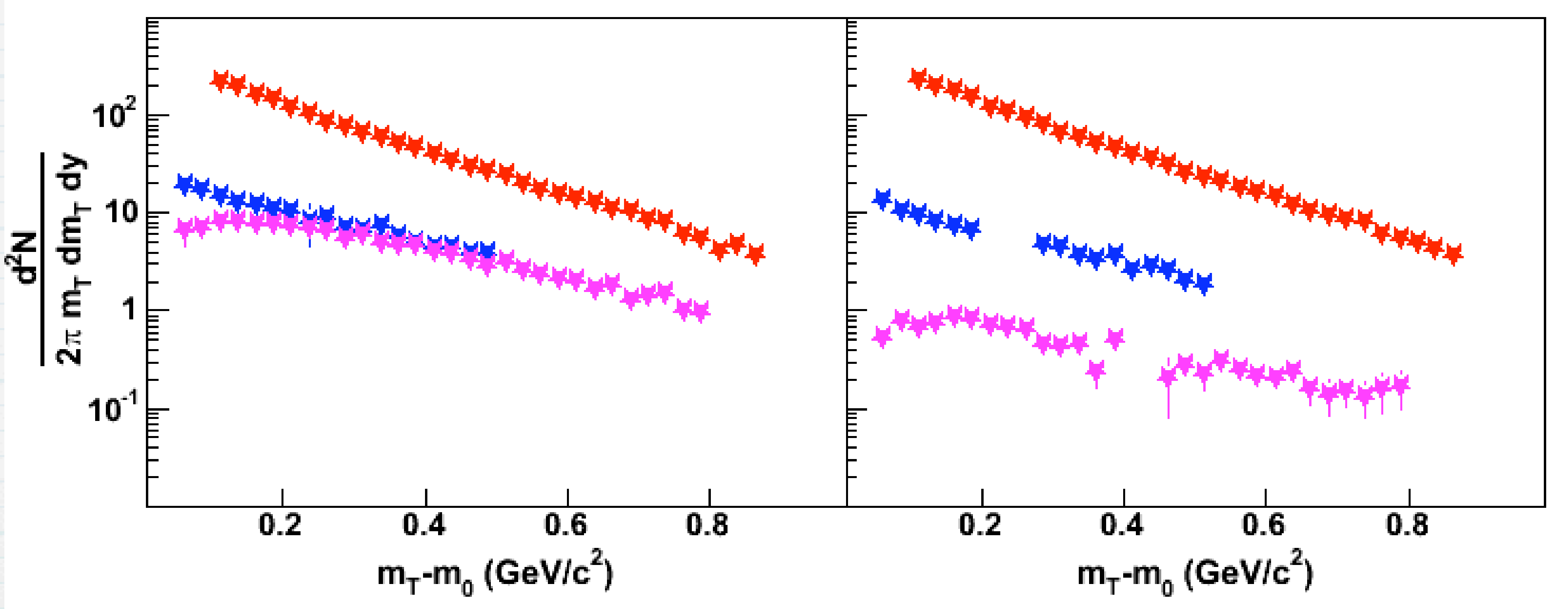
chemical freeze-out

T_{ch} -> inelastic collisions stop
-> chemical equilibrium

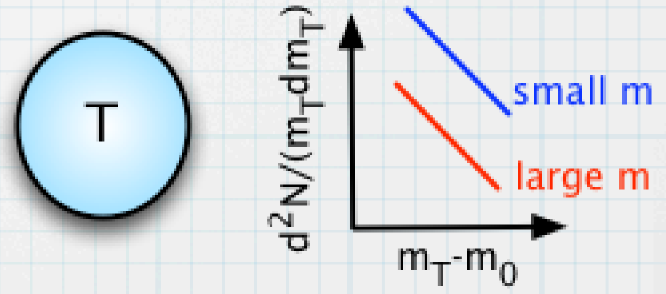
kinetic freeze-out

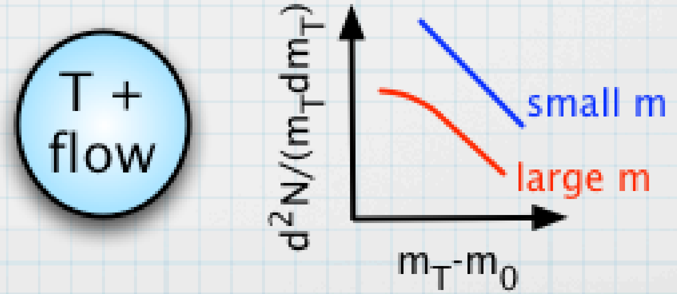
T_{kin} -> elastic collisions stop
-> kinetic equilibrium

particle spectra



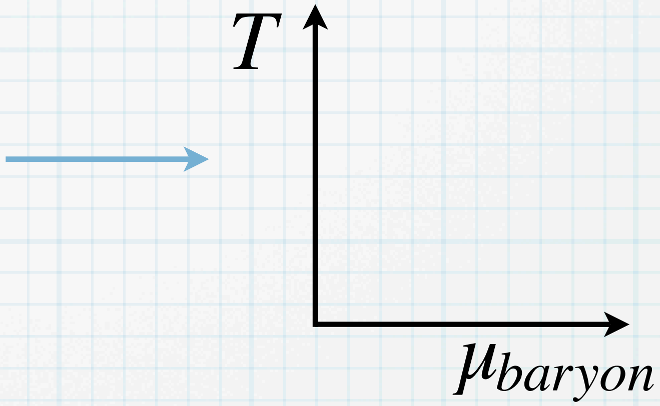
- what do they tell us?
  - momentum and energy distribution
- hadron multiplicities -> production at chemical freeze-out
- shape contributions:
  - a thermal source with temperature T -> statistical, Boltzmann-like, $e^{-E/T}$, same slopes for all particles
  - boosted -> different shapes for different masses





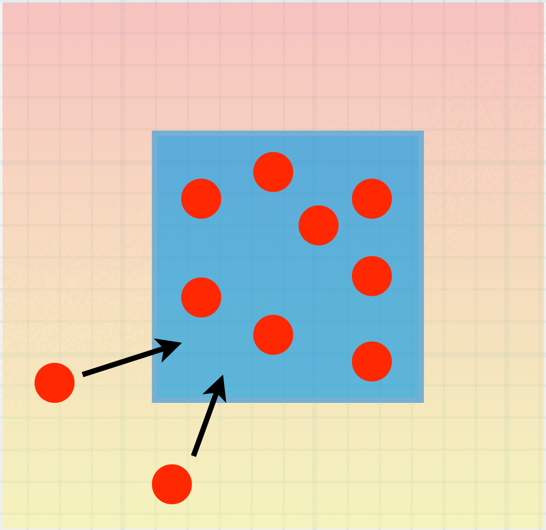
statistical model of chemical equilibrium

- a tool to tell where the system is on the phase diagram



- basic ideas:
  - thermally equilibrated (constant temp.)
  - chemically equilibrated (constant densities (n))
  - grand canonical ensemble

$$Z = \sum_i \exp\left(-\frac{E_i - \mu N_i}{T}\right)$$



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

statistical model

- model's parameters: chemical freeze-out temperature (T_{ch}), chemical potentials (μ), and strangeness saturation factor (γ_s)

- number density of particle i:

$$\rho_i = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,dp}{\exp((E_i-\mu)/T)\pm 1}$$

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

$$\lambda_q \equiv \exp(\mu_q/T_{ch})$$

$$\lambda_s \equiv \exp(\mu_s/T_{ch})$$

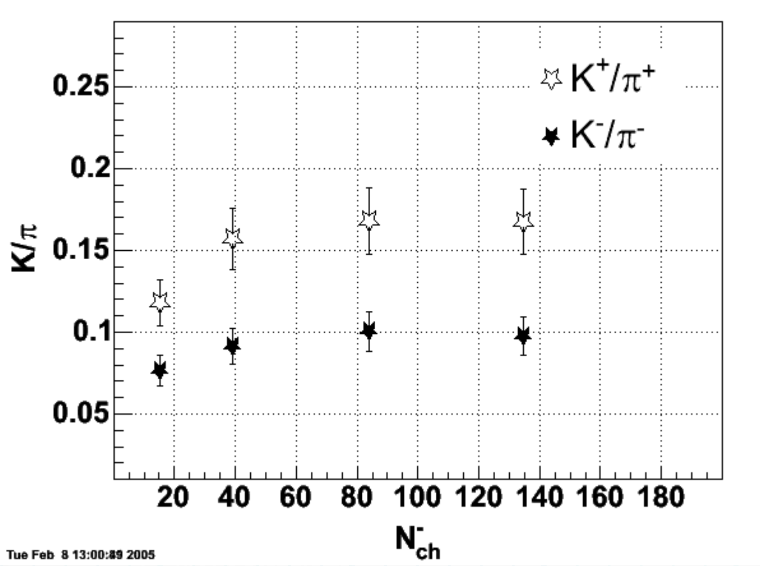
$$Q_i = \langle u+d-\bar{u}-\bar{d}\rangle_i$$

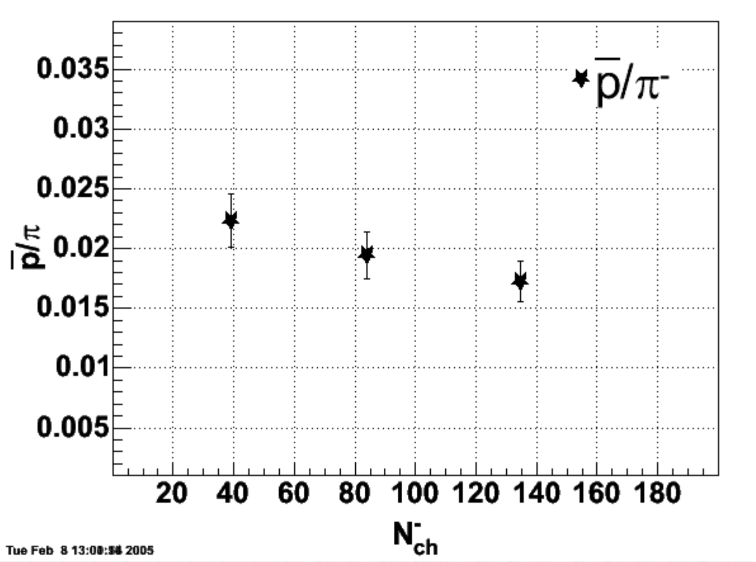
$$s_i = \langle s-\bar{s}\rangle_i$$

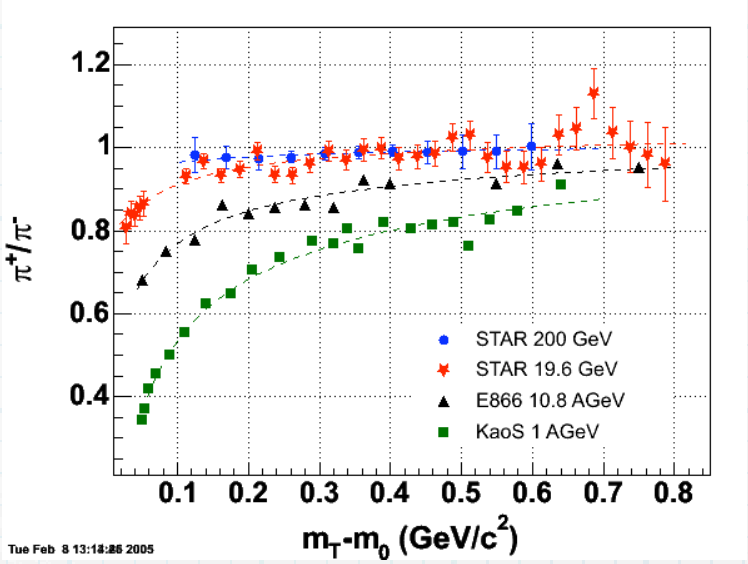
$$\gamma_s \equiv \frac{s\text{ density}}{\text{equilibrium density}}$$

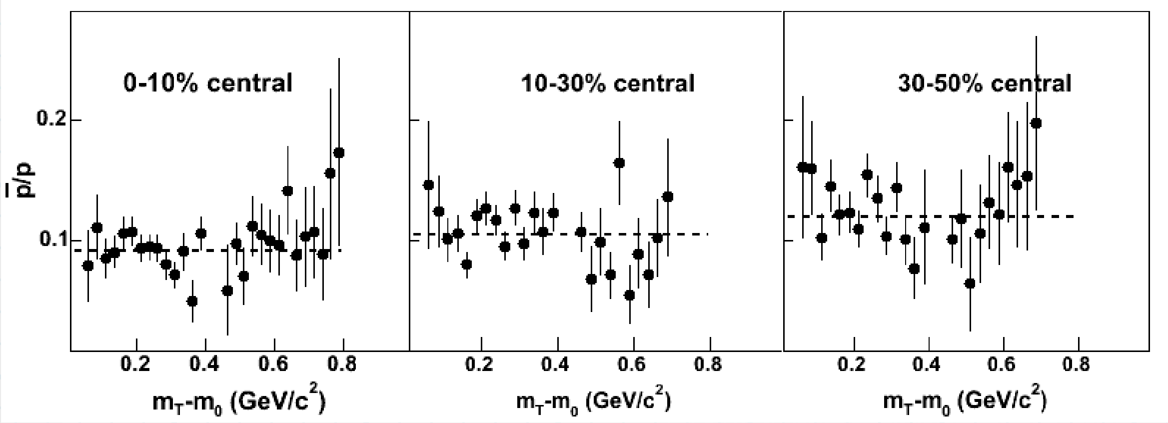
Rafelski, Phys. Lett. B262, 333 (1991)
Sollfrank, J. Phys. G23, 1903 (1997)
Sollfrank et al, Phys. Rev. C59, 1637 (1999)

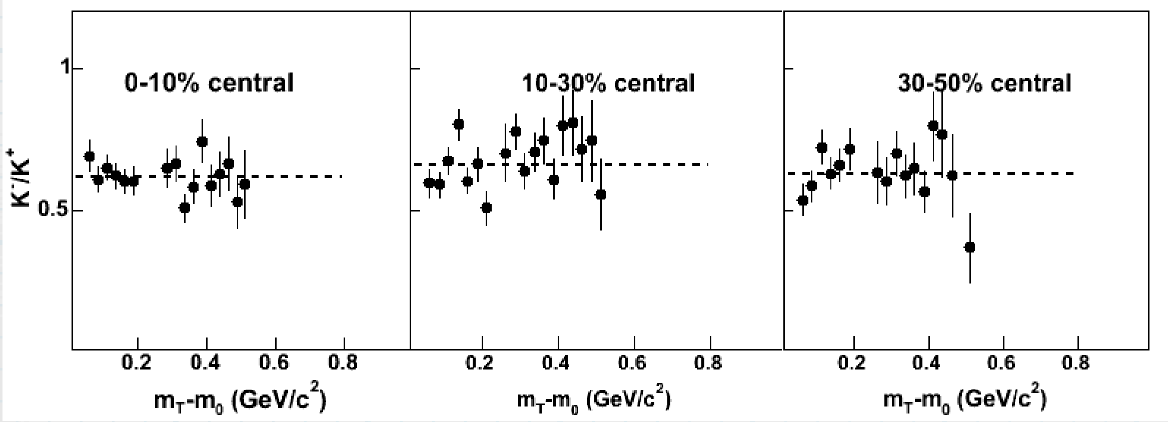
particle ratios







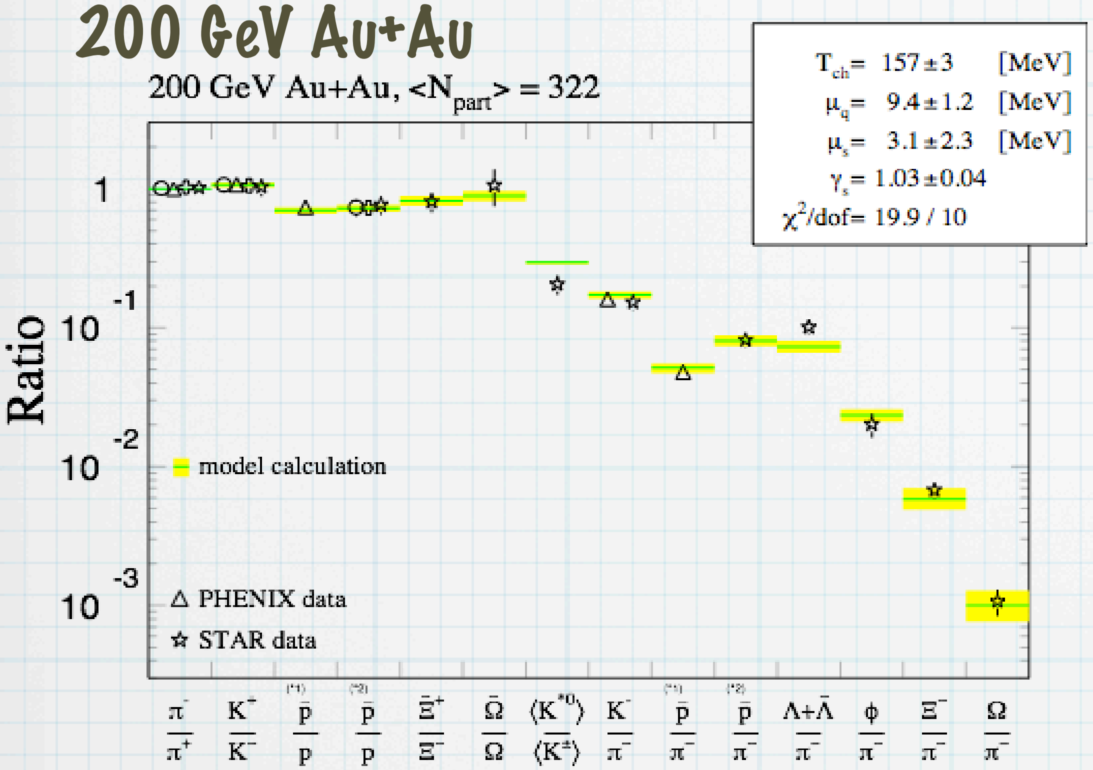




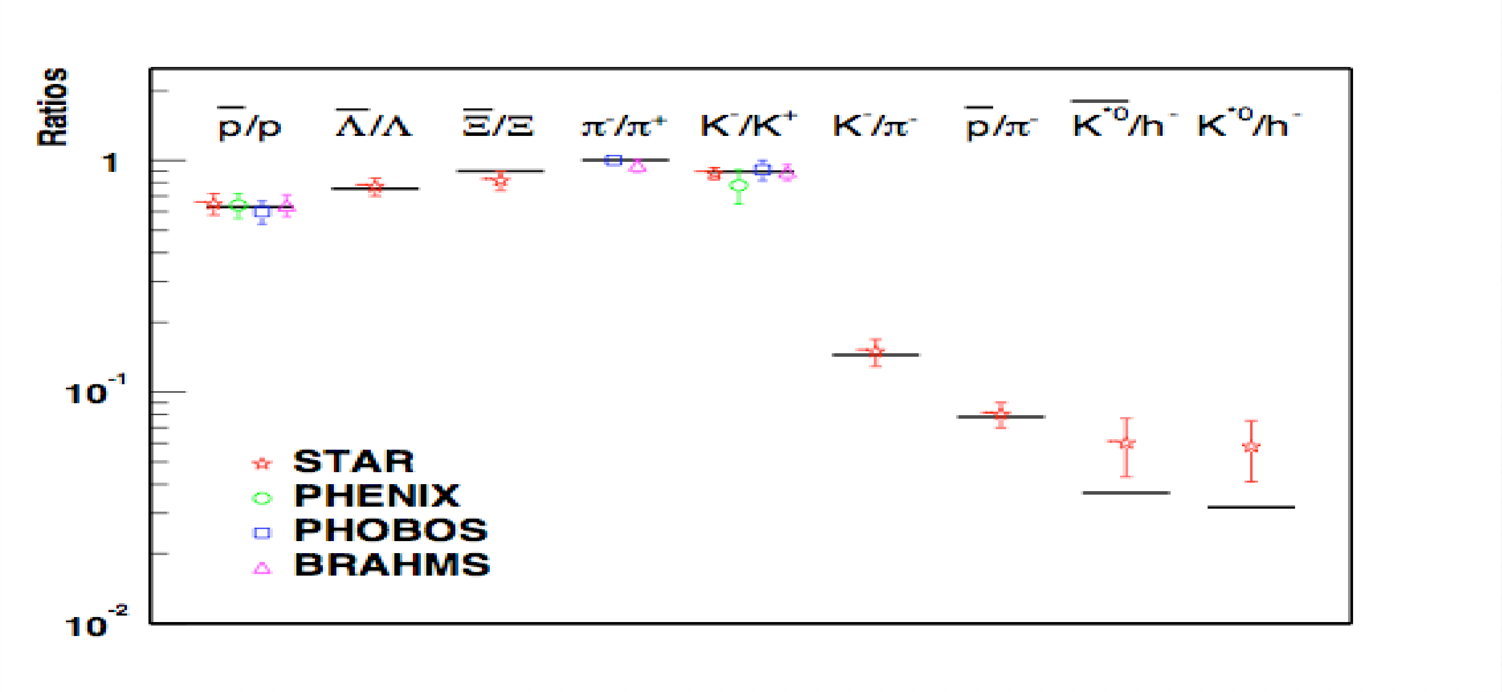
- model input is a set of particle ratios

statistical model fits

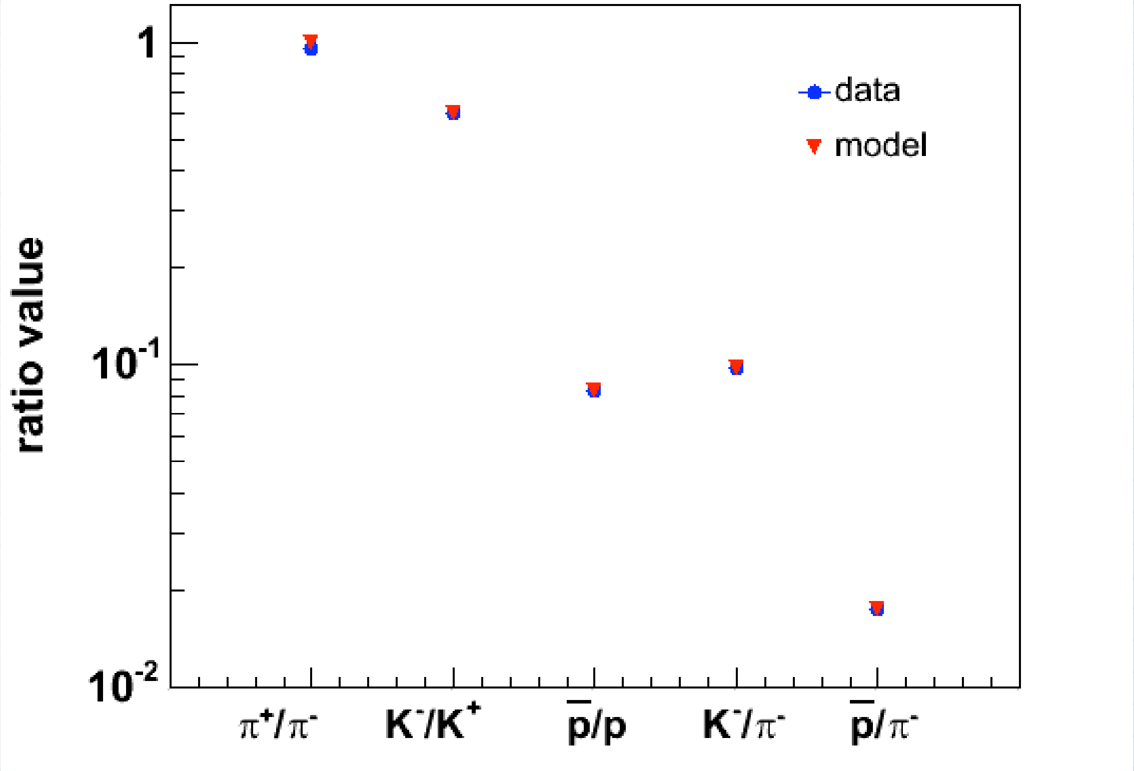
200 GeV Au+Au



130 GeV Au+Au

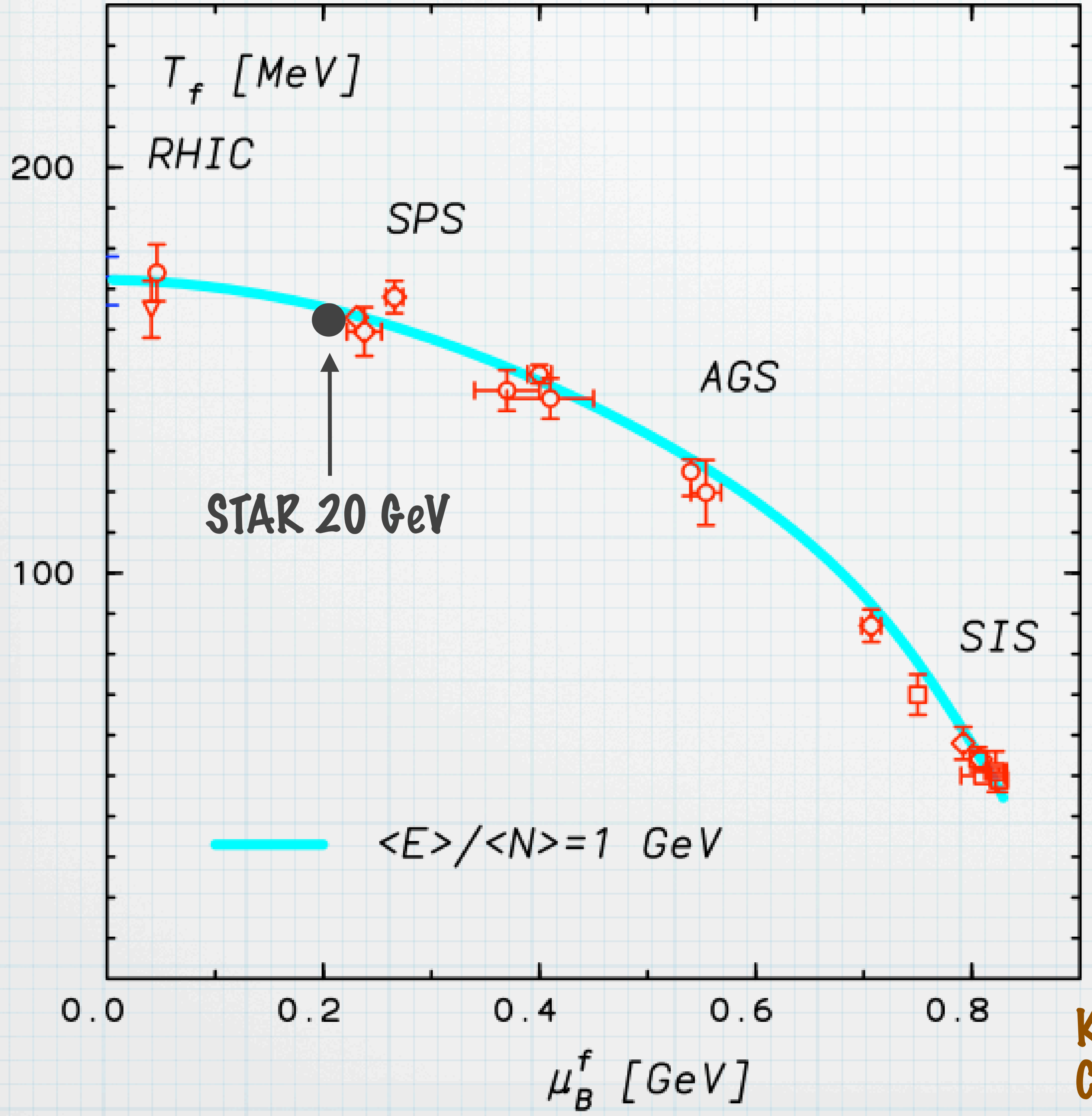


20 GeV Au+Au



Kaneta and Xu, QM04 nucl-th/0405068
Braun-Munzinger et al, PLB518, 41 (2001)

chemical freeze-out



- result is surprisingly consistent with other heavy ion experiments
- inelastic collisions stop when energy per hadron is about 1 GeV

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

spectra shape

- system of particles freezes out kinetically when density and temperature drop at a point where the particles no longer scatter

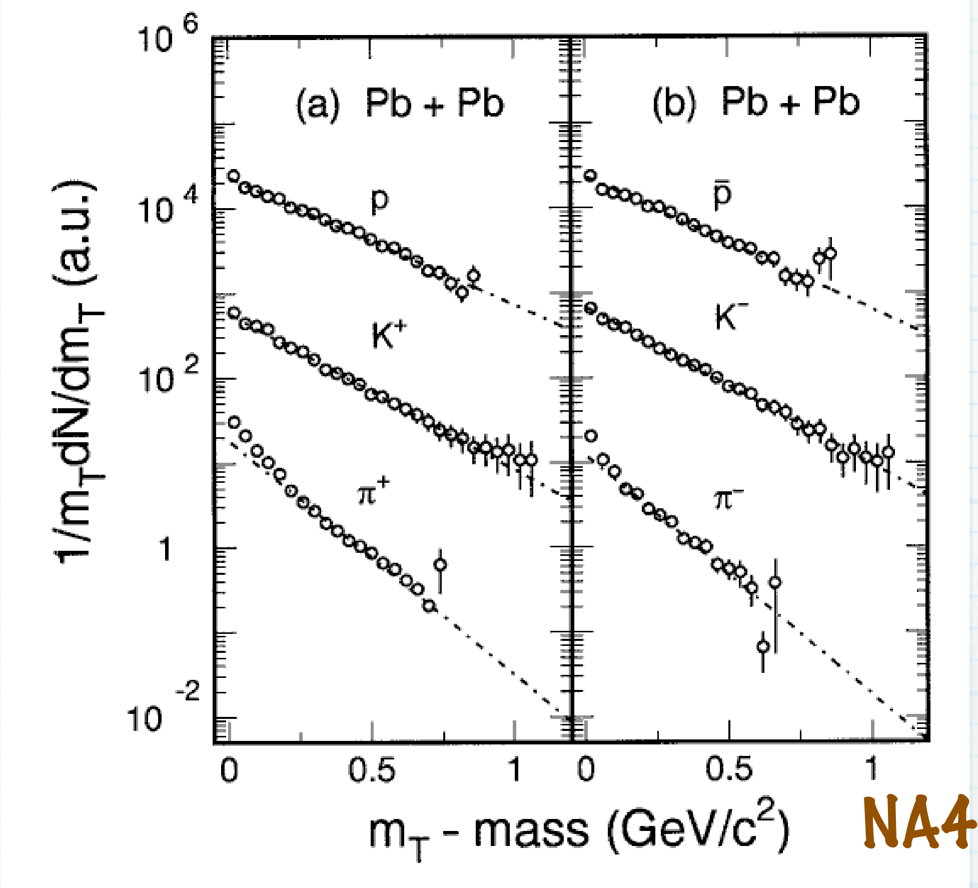
$$\text{mean free path} \approx \text{system size}$$
$$\text{time between collisions} \approx \text{Hubble time } (1/H)$$

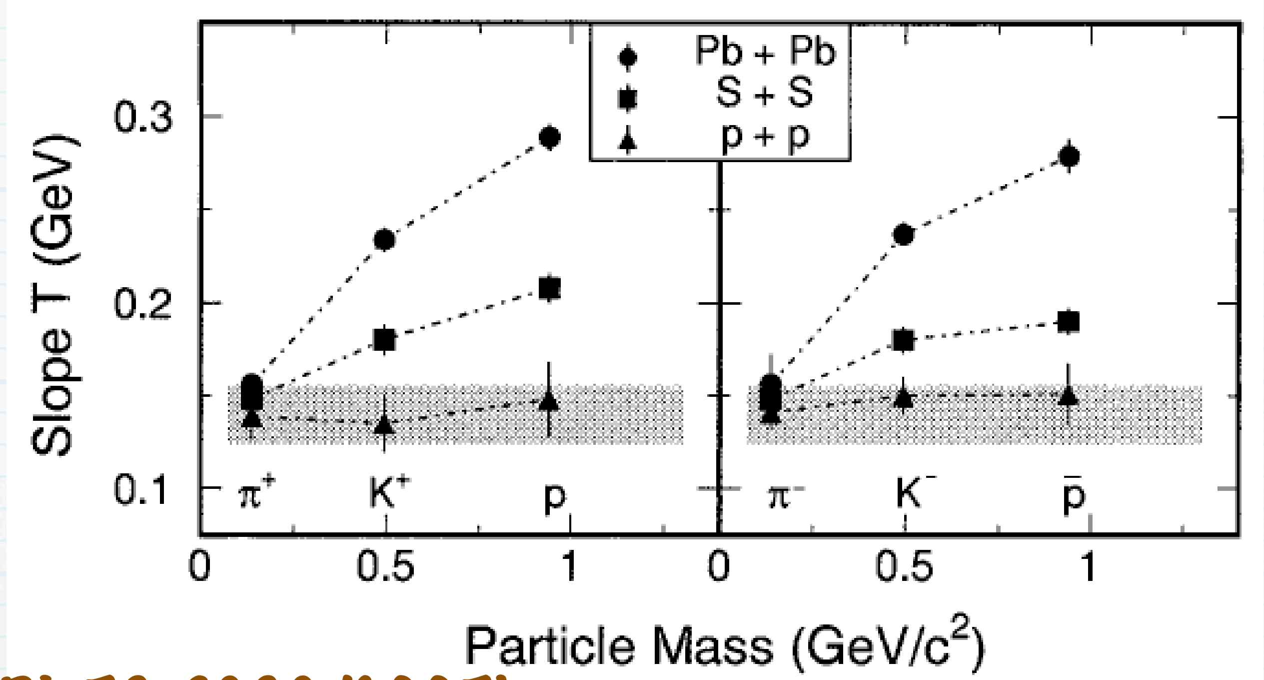
- natural observable to study transverse flow -> p_T or m_T spectra

$$m_T \equiv \sqrt{p_T^2 + m_0^2}$$

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

more on spectra shape





NA44, PRL 78, 2080 (1997)

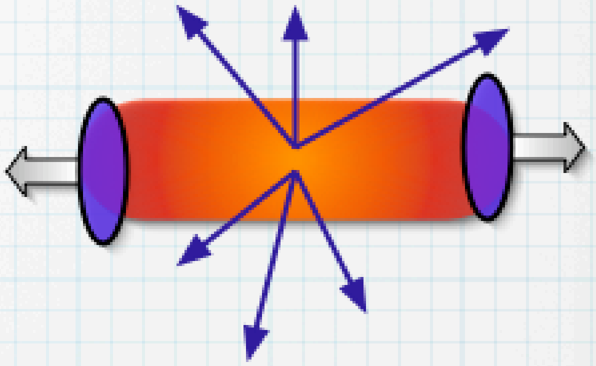
previously (SPS): obtain T for each particle, plot T vs m, then ->

$$T_{slope} = \begin{cases} T_{kin} + m\langle\beta_T\rangle^2 & \text{for } p_T \leq m \\ T_{kin}\sqrt{\frac{1+\langle\beta_T\rangle}{1-\langle\beta_T\rangle}} & \text{for } p_T \gg m \text{ (blueshift)} \end{cases}$$

problem: the value of T depends on fit range

- current: hydrodynamics-based blast wave model
- simultaneous fit to all particles

relativistic hydrodynamics



- energy momentum tensor for a fluid cell:

$$\underbrace{}_{}\overset{\text{energy density}}{} \qquad \overset{\text{velocity}}{}$$

$$T^{\mu\nu}(x) = (\overset{\text{energy density}}{e(x)} + \underset{\text{pressure}}{p(x)})\overset{\text{velocity}}{u^{\mu}(x)}u^{\nu}(x) - g^{\mu\nu}p(x)$$

$$x = (t, \vec{x})$$

- "charge" current at x:

$$j_i^{\mu}(x) = n_i(x)u^{\mu}(x)$$

"charges" = net baryon, net strangeness, net electric charge, ... etc

$T^{\mu\nu} \equiv$ flow of p^{μ} in the ν-direction

the tensor tells us about energy and momentum at every point in 4-d space-time

Kolb and Heinz nucl-th/0305084

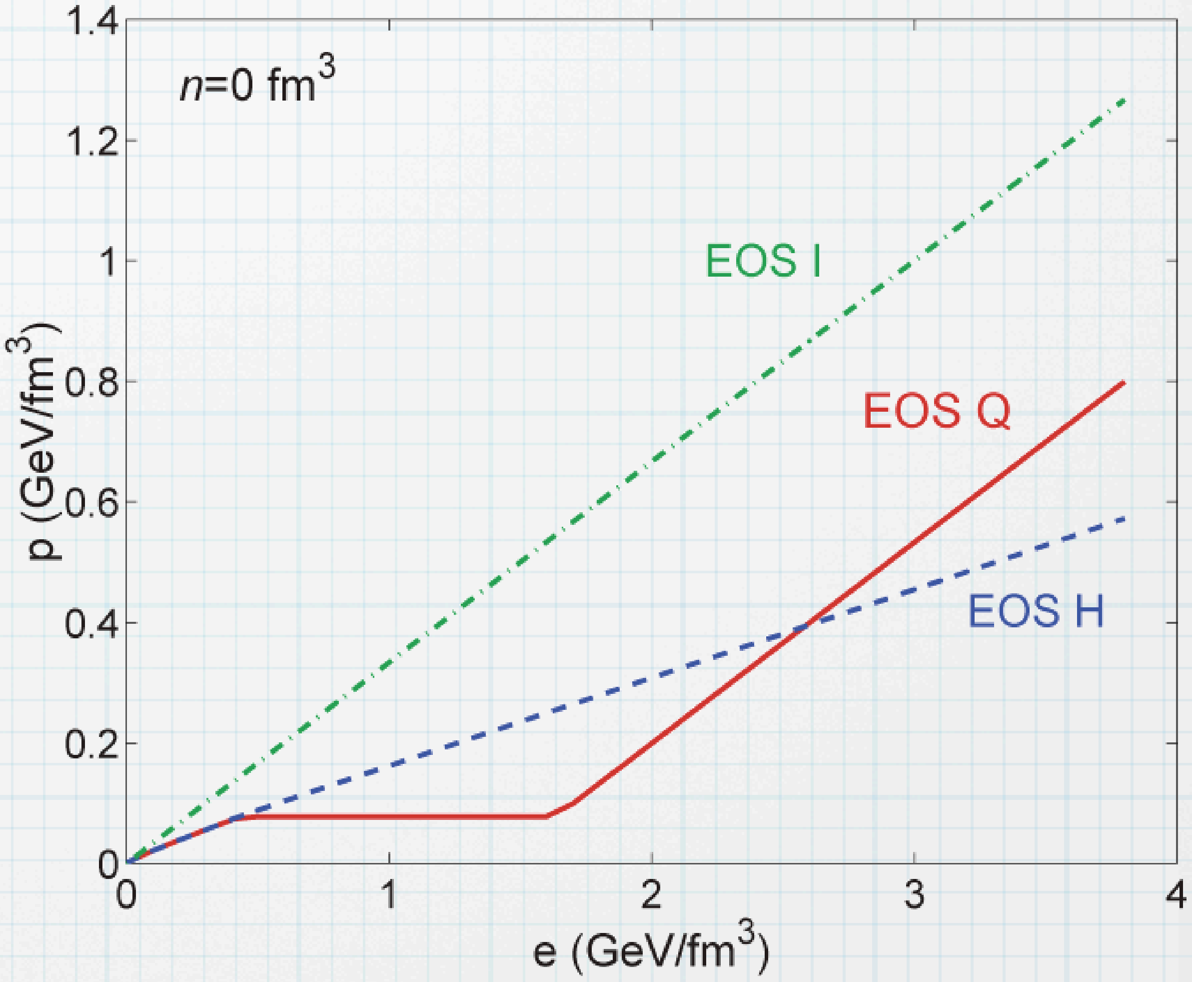
motion

- fluid motion is determined from
  - conservation of energy and momentum: $\partial_\mu T^{\mu\nu} = 0$
  - conservation of "charges": $\partial_\mu j^\mu = 0$ <- continuity equation
  - equation of state (EoS) = pressure as a function of energy, and charge densities: $p(\varepsilon, n_i)$

$$\mu = 0, 1, 2, 3 = t, x, y, z$$

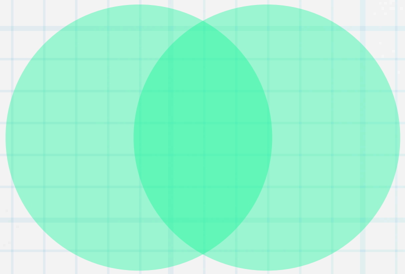
more on eqn of state

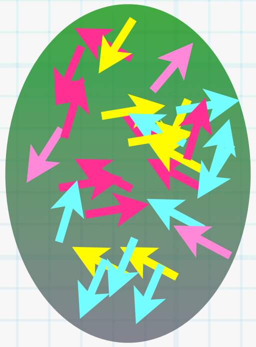
- Typical EoS used with RHIC data:
  - plasma = ideal gas of massless q, qbar, g with a bag constant. stiff. ("EoS I")
  - hadrons = gas of hadrons and resonances. soft. ("EoS H")
  - quark-hadron transition ("EoS Q")

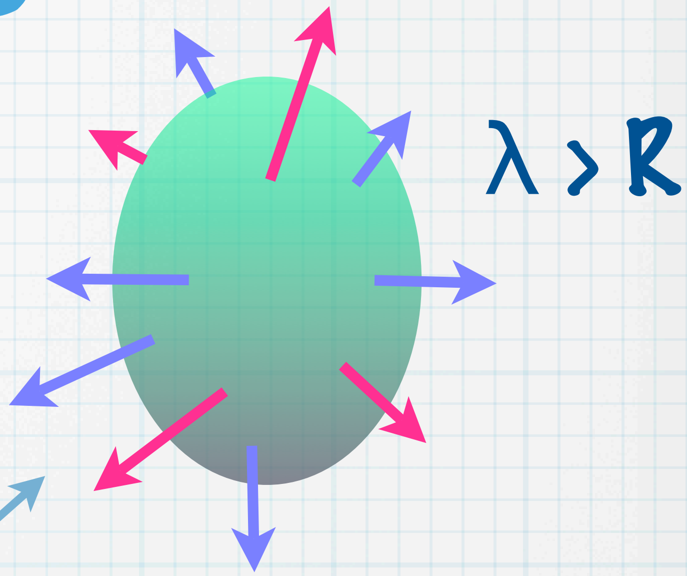


Kolb and Heinz, nucl-th/0305084

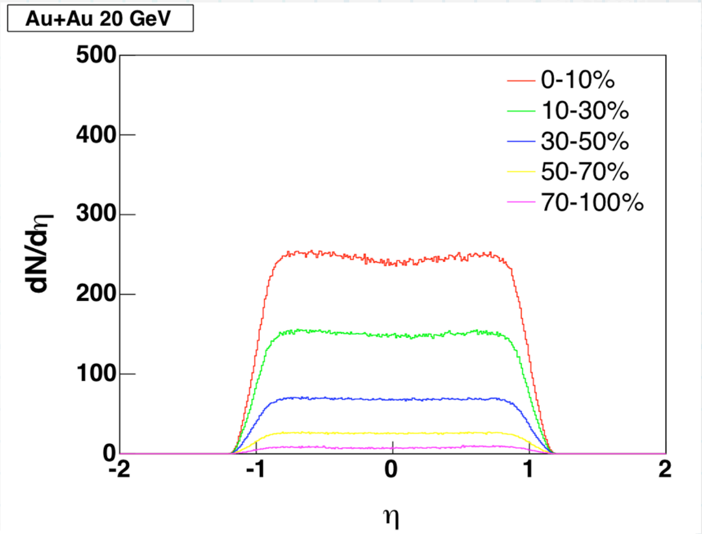
intro to blast wave

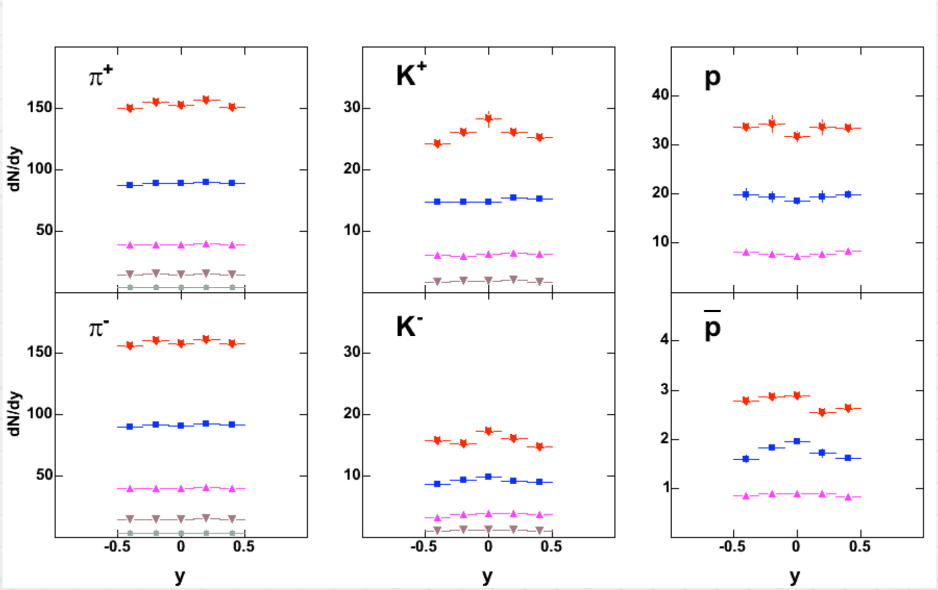






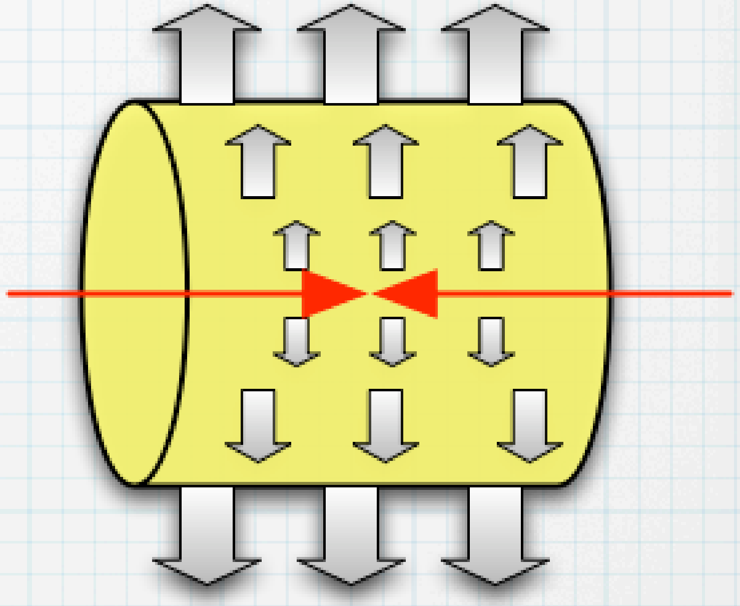
- hydro model: difficult to use, need to know initial states
- blast wave is a parametrization of hydro
- describes final freeze-out condition, but not how the system evolves
- basic ideas:
  - rescattering of produced particles -> fluid-like flow
  - assume boost invariant (true for small region at midrapidity)





blast-wave model

Schnedermann et al, PRC48, 2462 (1993)



- parameters: kinetic freeze-out temperature (T_{kin}), flow velocity (β), and flow profile parameter (n)

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

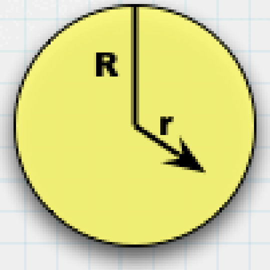
(integrated over Φ)

$$\rho(r) = \tanh^{-1}\beta_r$$

transverse rapidity

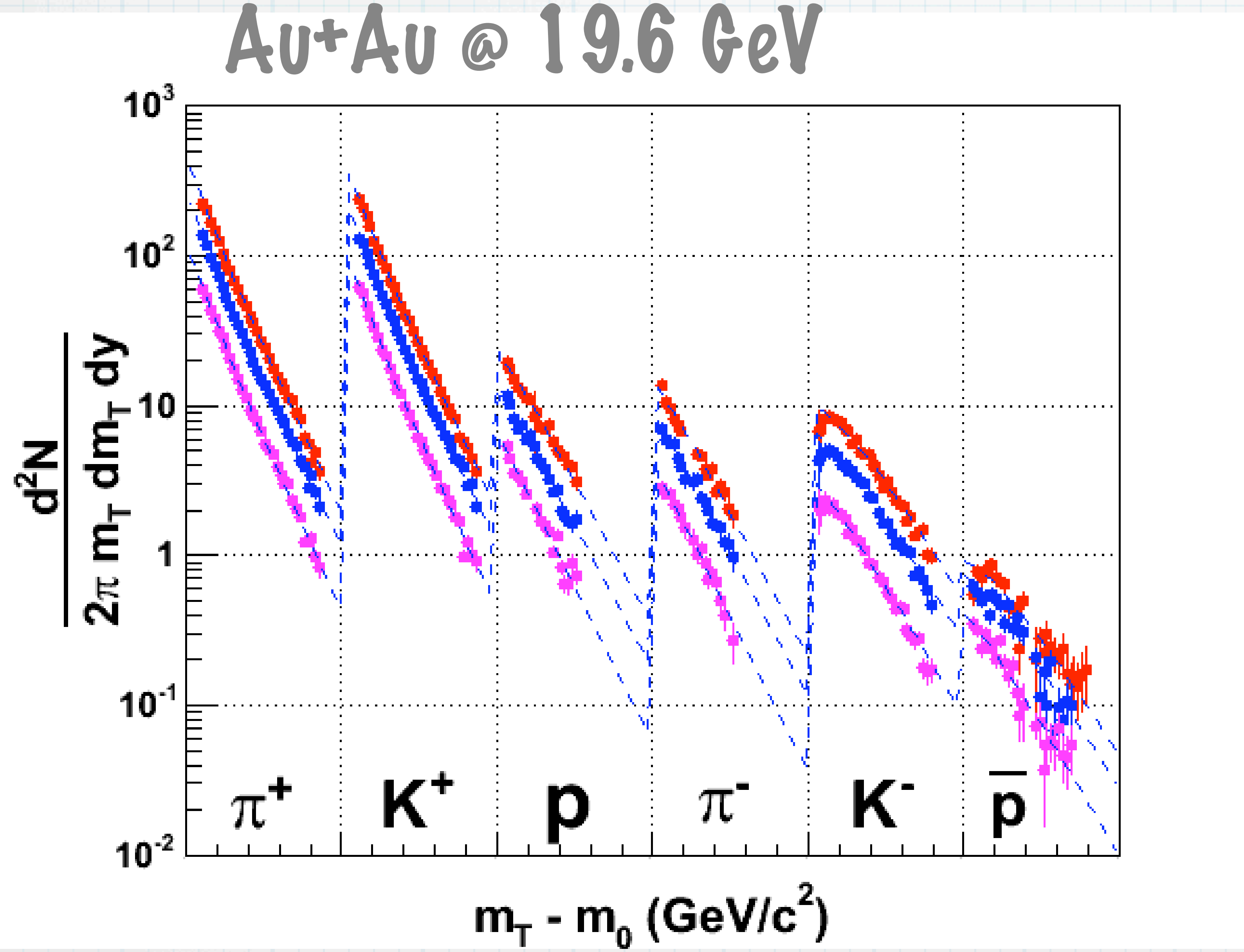
$$\beta_r = \beta_{surf}\left(\frac{r}{R}\right)^n$$

flow profile - 'Hubble-like'



(n = 2 best matches hydro, but isn't important)

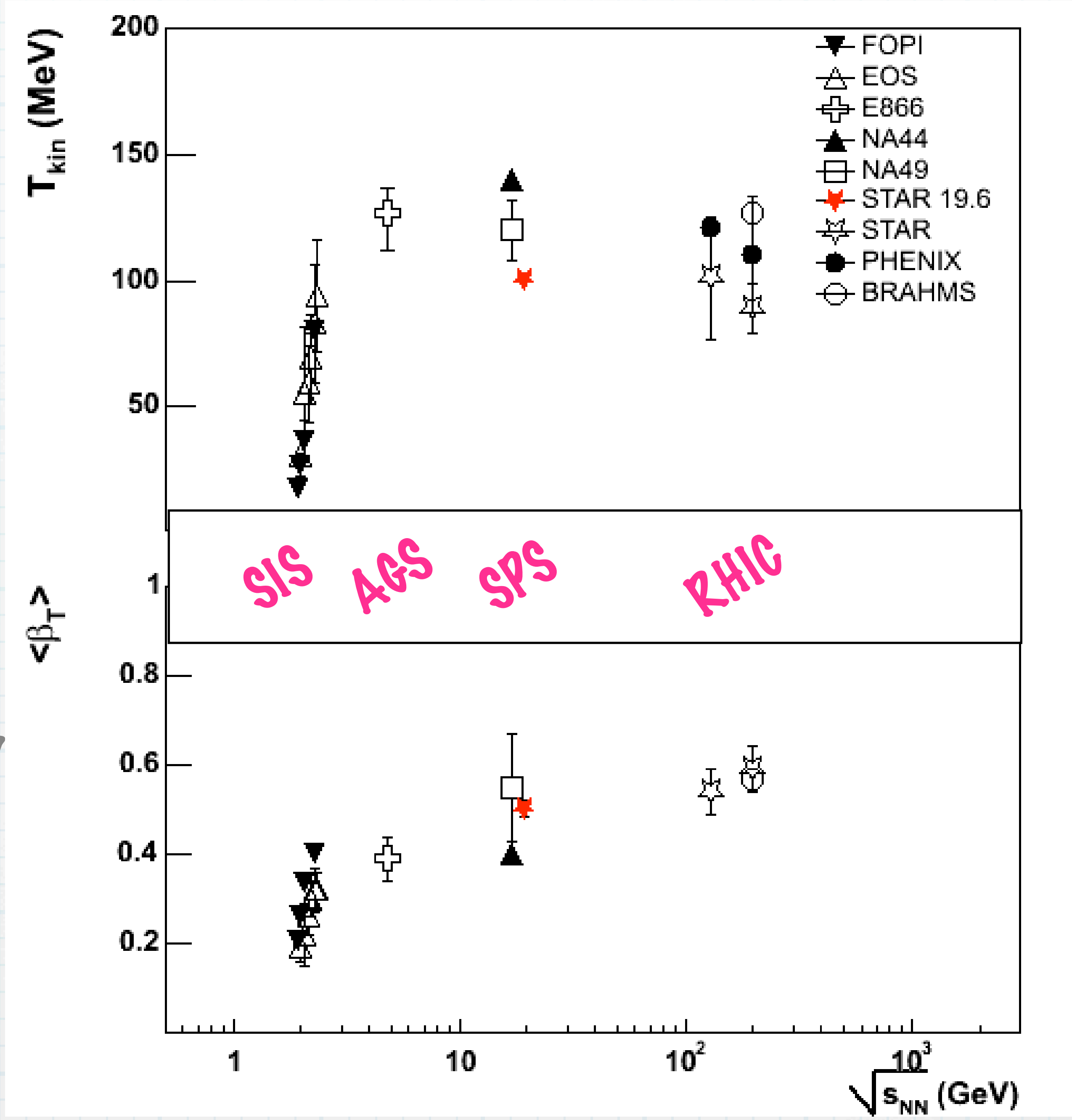
blast wave fits



- global (T, β) to fit 6 particles all at once.

kinetic freeze-out and collective flow

- saturation of temperature around SPS, or even AGS, energies
- strong collective flow
  - indicates dense system
  - increases with energy, RHIC flow about 3 times AGS flow
  - necessary condition for QGP (thermalization), but not direct evidence

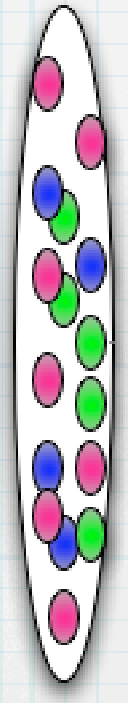


conclusions

- particle spectra provide a mean to uncover rich information about the heavy ion collisions
- chemical freeze-out: ratios consistent with statistical model
  - vanishing baryon density at increasing energy
- kinetic freeze-out: blast wave model - globally explain light particles well
  - stronger collective flow with increasing energy
  - saturated $T_{kin} < T_{ch}$
- the results support thermalization, but are not direct evidences
- to do next: understand the theories/models involved better

extras

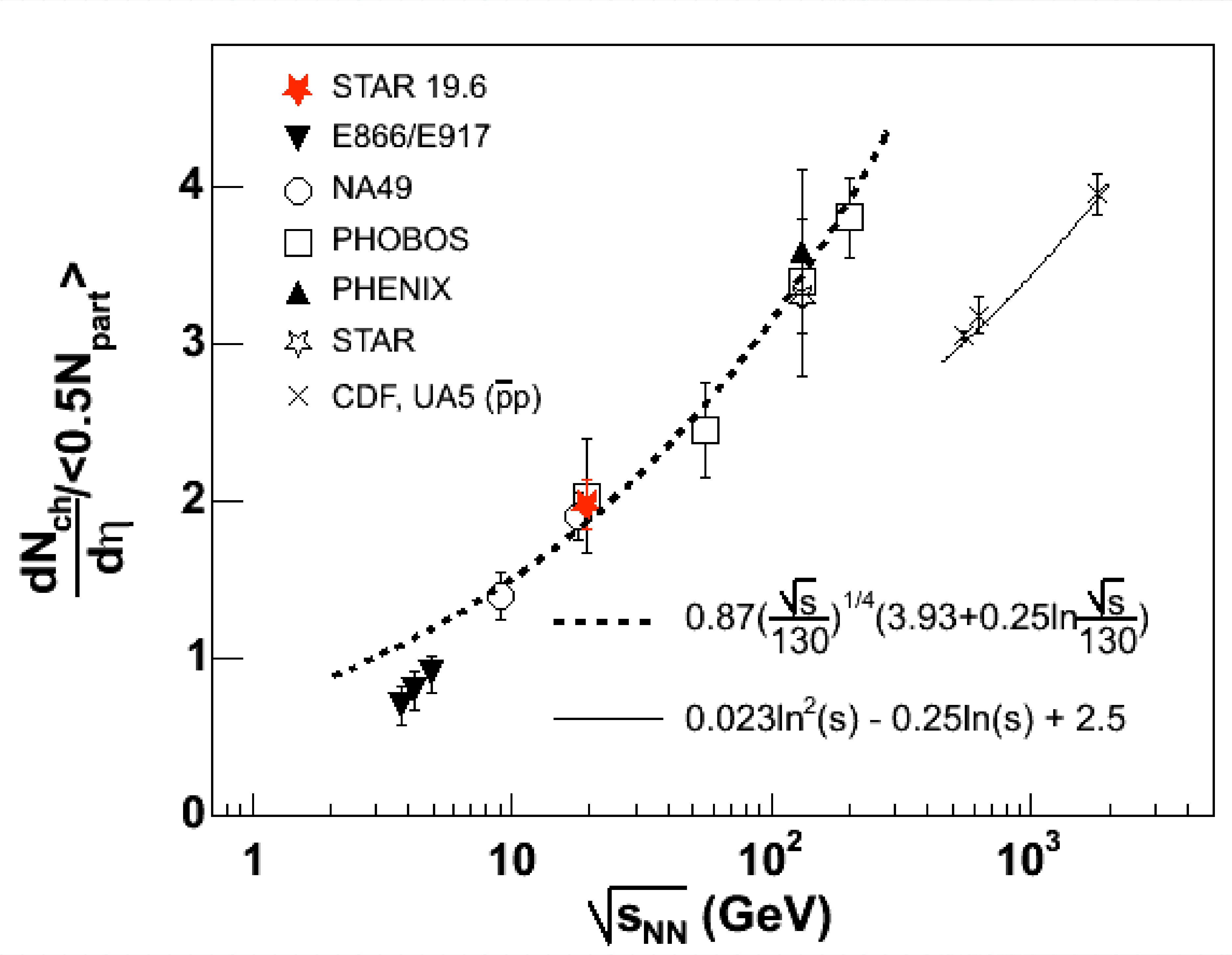
parton saturation



- **basic ideas:**
  - number of gluons is \propto 1/{\alpha_s}. at small coupling (large mom. transfer) -> lots of gluons
  - overlap leads to all kinds of interactions (scattering, annihilation, recombination)
  - this will affect final hadron multiplicity

Mueller and Qiu, Nucl. Phys. B268, 427
Kharzeev and Levin, nucl-th/0108006

pseudorapidity density



Kharzeev et al, hep-ph/0111315

more on hydrodynamics

- 4 + N eqns (4 energy-mom. conserv. + N charge conserv.)
- 5 + N fields (vec{u}, e, p + N charge densities)
- 1 eqn missing to solve eqn of motion
- equation of state (eos) = pressure as a function of energy, and charge densities