Soft-hadron Physics at RHIC

Results from the Relativistic Heavy Ion Collider (Part II)

First joint Meeting of the Nuclear Physics Divisions of APS and JPS
Maui, Hawaii, 2001 Oct. 19

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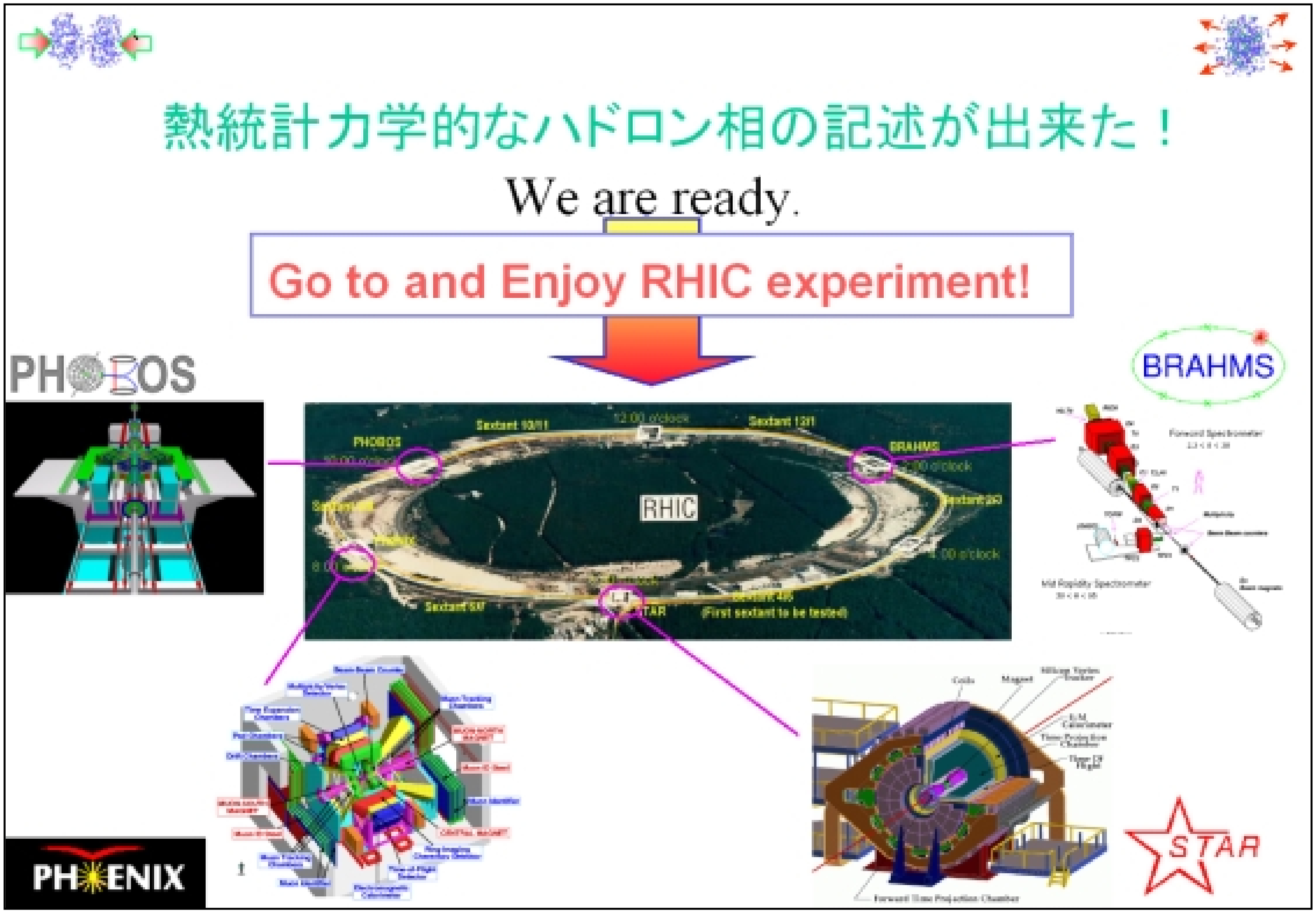
3 Years ago, in JPS meeting

- Summary of SPS results by M.K.

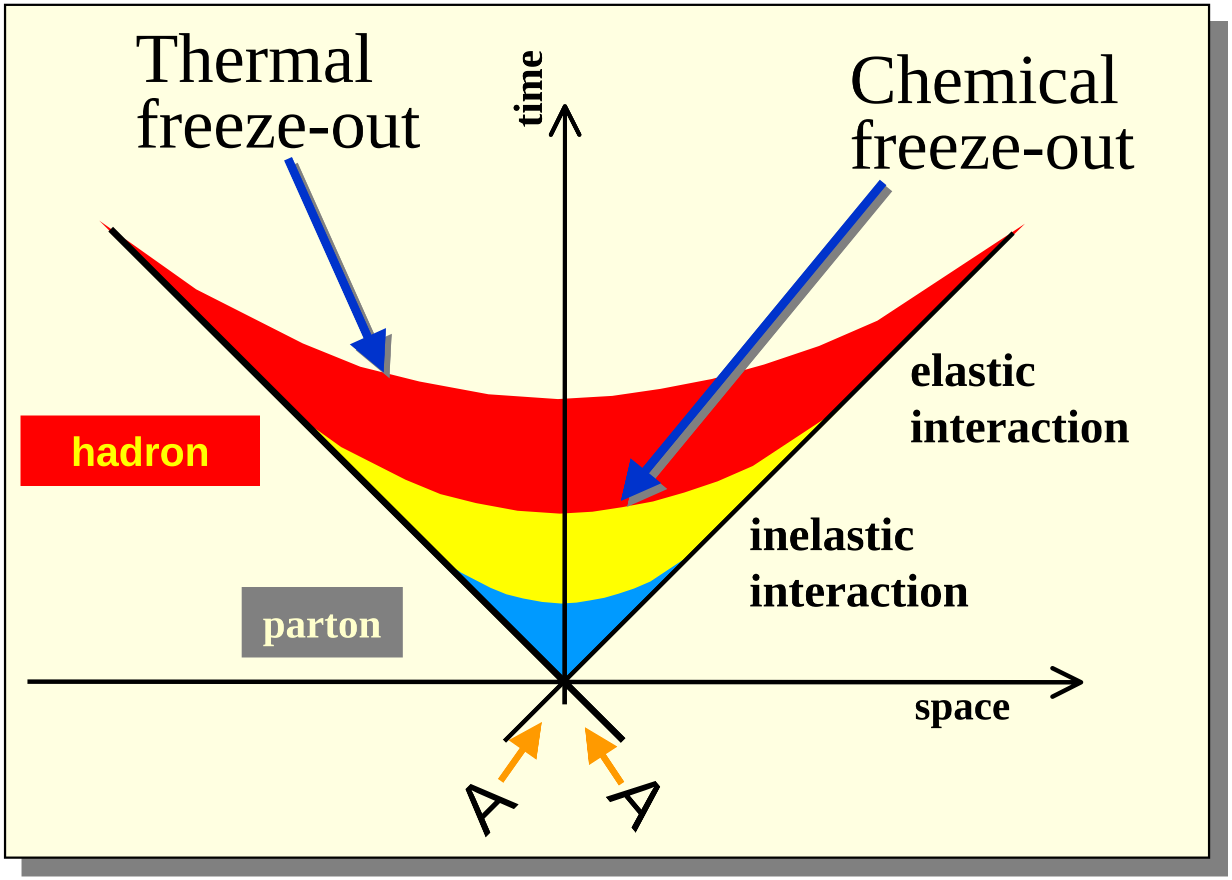


Outline

- Introduction
- Particle ratios / yield
- Identified single particle spectra
- Event anisotropy
- Particle correlation (HBT)
- Summary
- Open issues

Introduction

- Goal
  - Study bulk properties of matter under extremely high energy and particle density
  - Information of observable come from Parton / hadron level

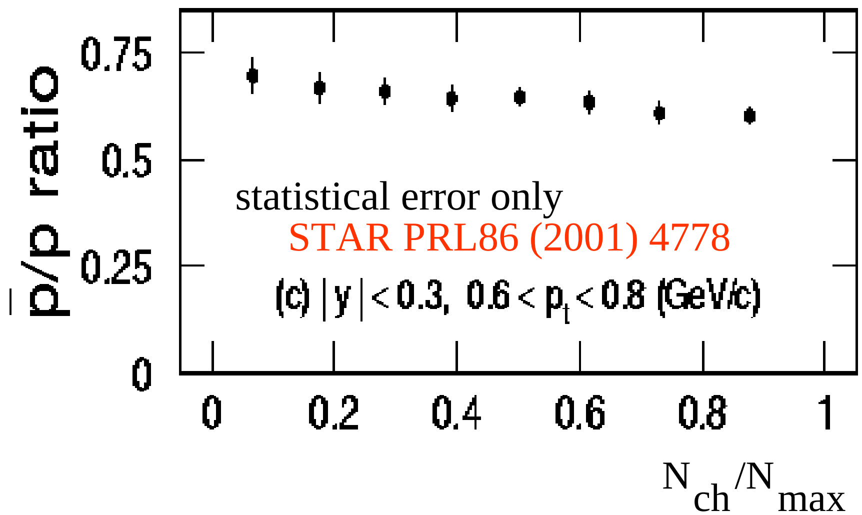


- Focus of this talk
  - Low p_T and mid-rapidity data

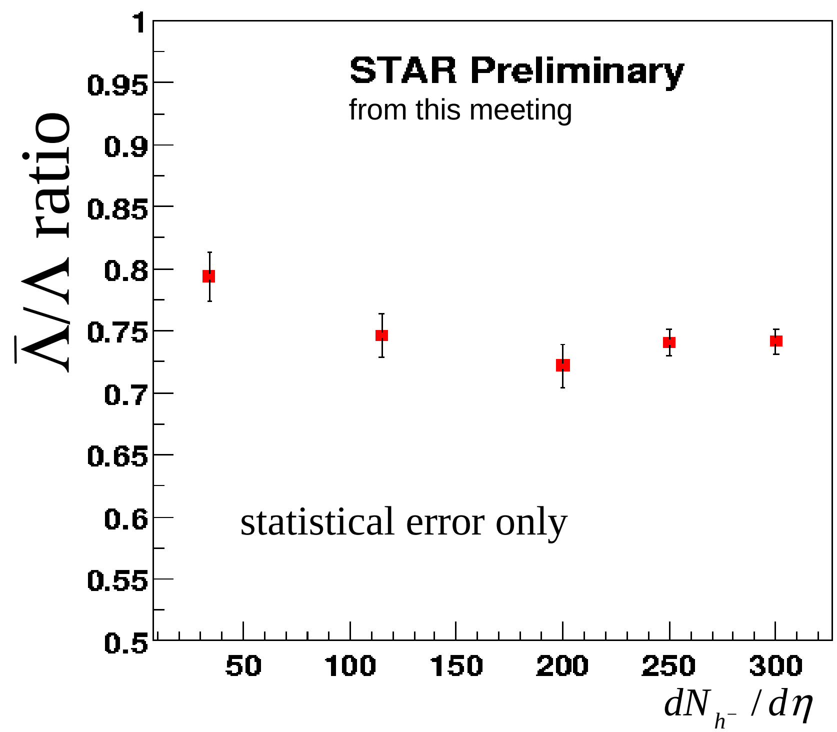
Particle ratios/yield

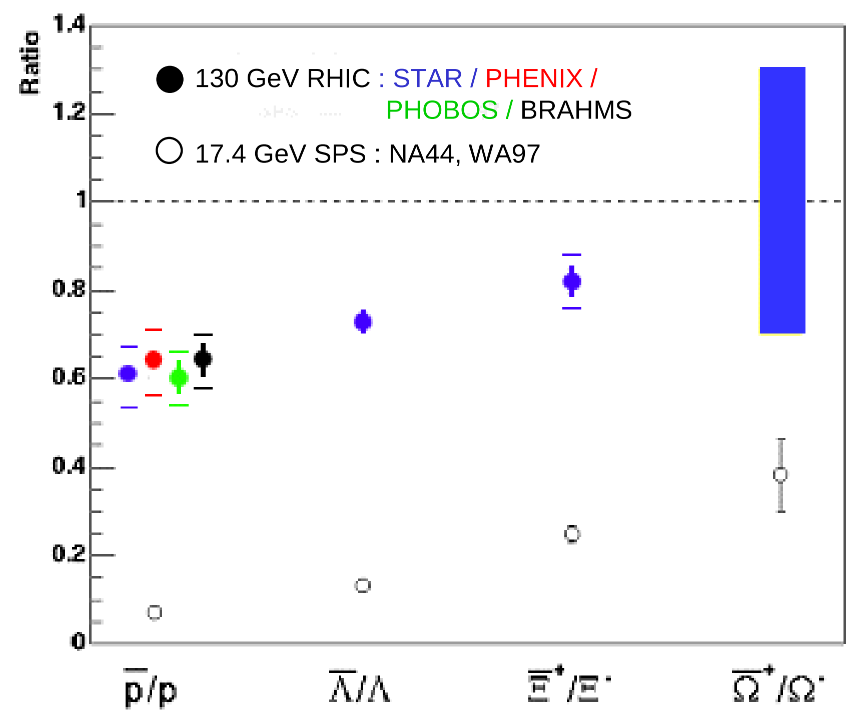
- Anti-baryon/baryon ratio and net-proton
  - Stopping or transparent?
- Particle ratios from hadrons
  - Chemical freeze-out parameters

Anti-Baryon/Baryon ratio

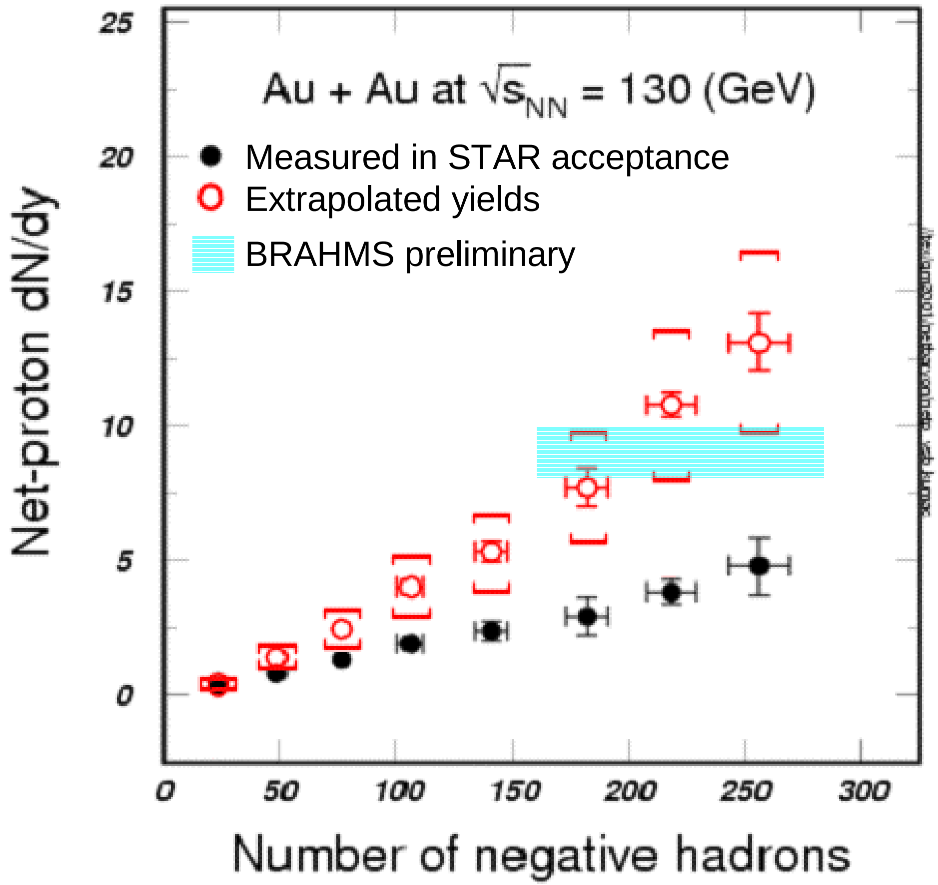


- $\bar{B}$/B <1
  - Not baryon free
- Less centrality dependence





Net-proton



- Inclusive net-proton
- Net-proton increases with centrality

STAR data : from this meeting
BRAHMS data : Quark Matter 2001

Chemical freeze-out model

Hadron resonance ideal gas

Refs. J.Rafelski PLB(1991)333
J.Sollfrank et al. PRC59(1999)1637

Particle density of each particle

$$\rho_i = \gamma_s^{|s_i|} \frac{g_i}{2\pi^2} T_{ch}^{\ 3} \left(\frac{m_i}{T_{ch}}\right)^2 K_2(m_i/T_{ch})\ \lambda_q^{\ Q_i}\ \lambda_s^{\ s_i}$$

$$\lambda_q = \exp(\mu_q/T_{ch}), \quad \lambda_s = \exp(\mu_s/T_{ch})$$

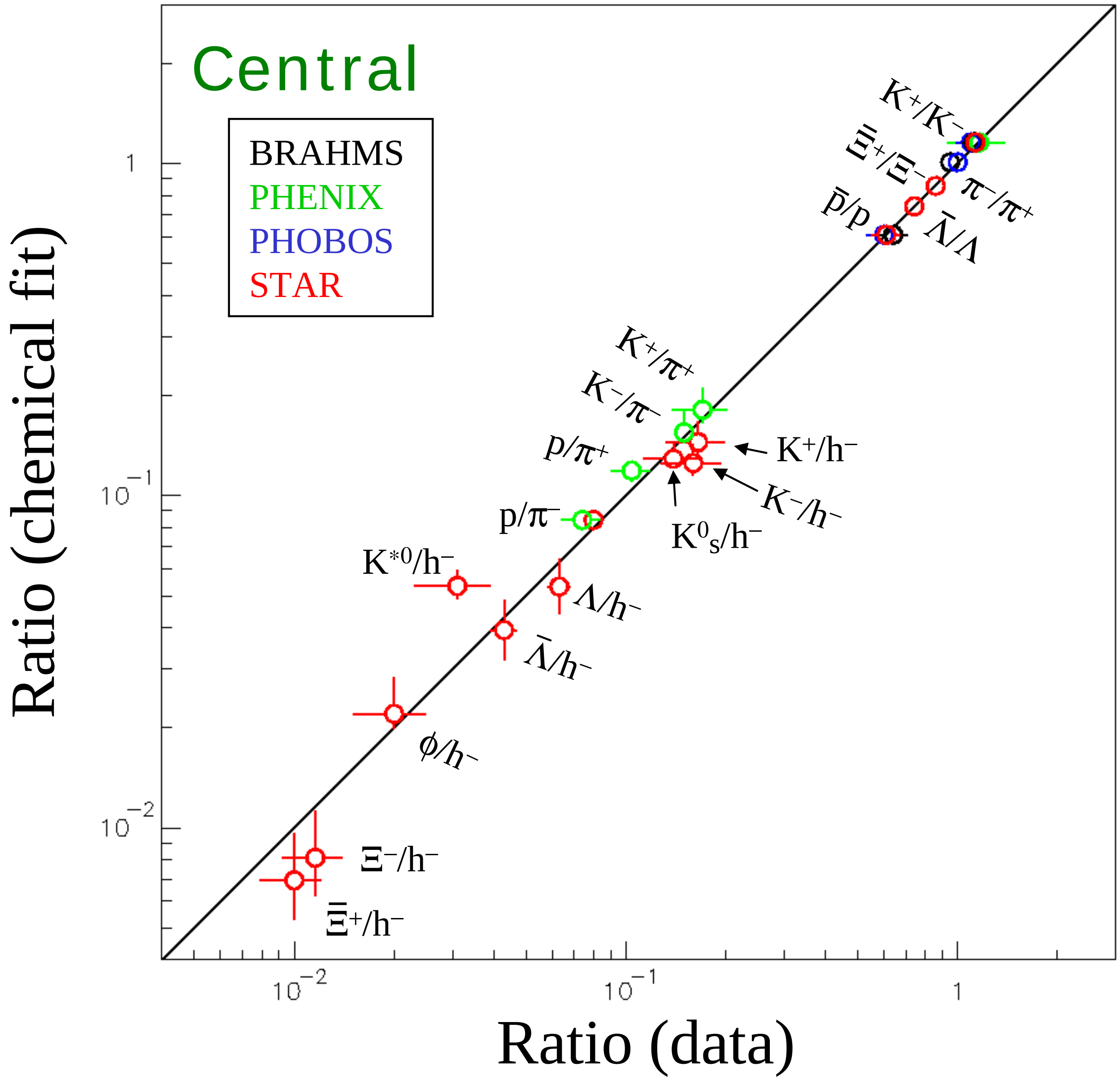
Q_i : 1 for u and d, -1 for $\bar{u}$ and $\bar{d}$
s_i : 1 for s, -1 for $\bar{s}$
g_i : spin-isospin freedom
m_i : particle mass

T_{ch} : Chemical freeze-out temperature
μ_q : light-quark chemical potential
μ_s : strangeness chemical potential
γ_s : strangeness saturation factor

All resonances and unstable particles are decayed

Comparable particle ratios to experimental data

Chemical fit result



Chemical freeze-out parameters

T_{ch} = 179±4 MeV

μ_B = 51±4 MeV

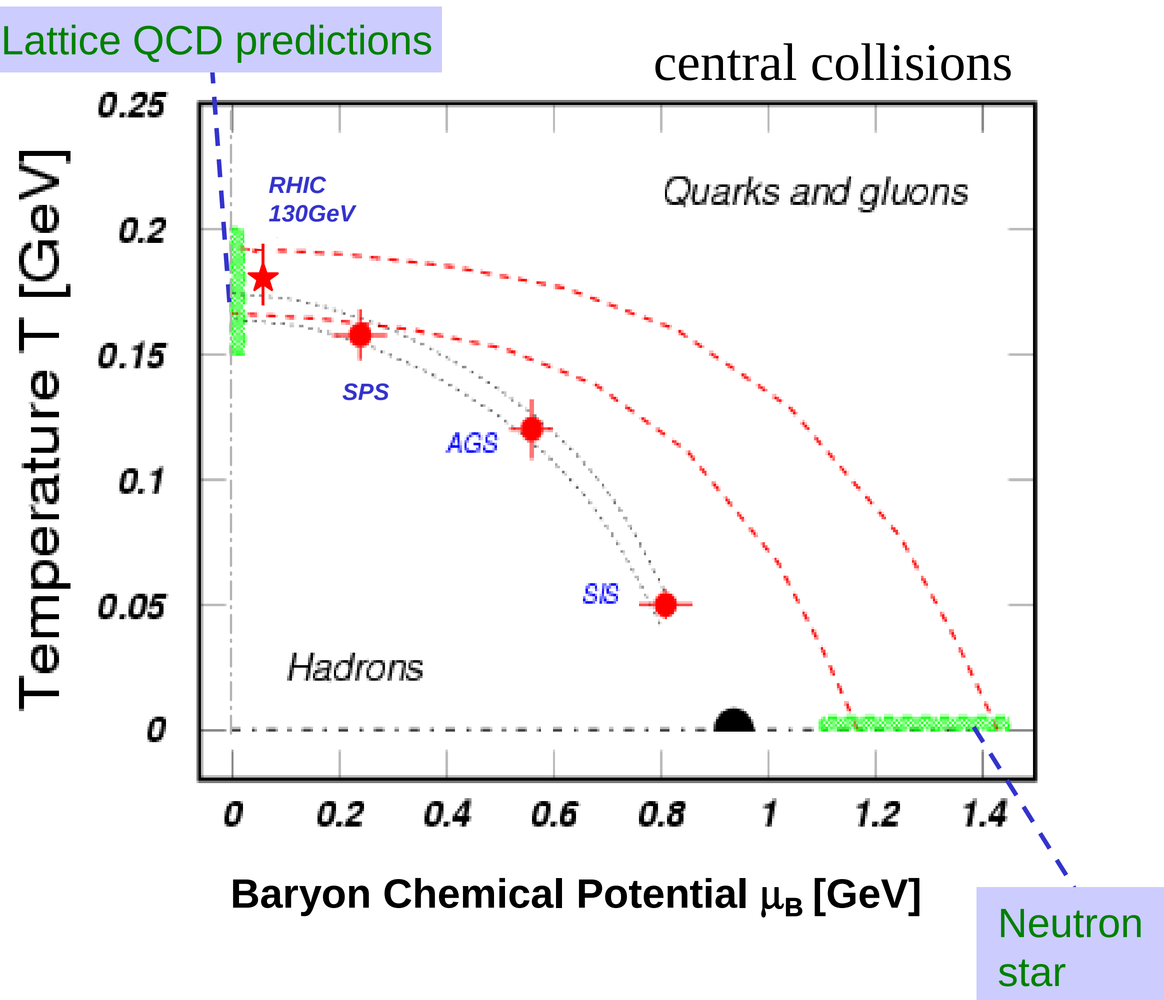
μ_s = -0.8±2.0 MeV

γ_s = 0.99 ±0.03

χ^2/dof = 1.5

Model:
M.Kaneta, Thermal Fest (BNL, Jul 2001),
N.Xu and M.Kaneta, nucl-ex/0104021

Chemical freeze-out



- - - parton-hadron phase boundary

:::::::: <E>/<N>~1GeV, J.Cleymans and K.Redlich, PRC60 (1999) 054908

- Beam energy dependence
  - Temperature increases
  - Baryon chemical potential decreases
- At RHIC
  - Being close to phase boundary
  - Fully strangeness equilibration (γ_s~1)

Identified single particle spectra

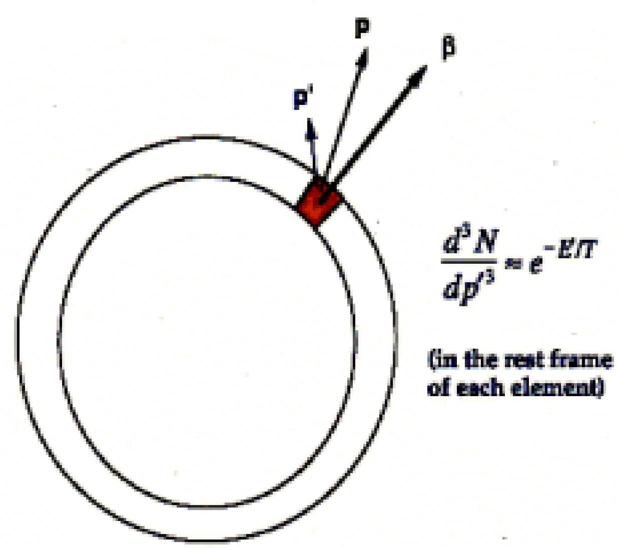
- Transverse momentum distributions
  - Boltzmann-like distribution
  - Information of thermal (kinetic) freeze-out
    - Temperature
    - Radial flow
  - The pressure gradient generates collective motion

$$E\frac{d^3n}{dp^3} \propto \int_\sigma e^{-(u^\nu p_\nu)/T_{th}} p^\lambda d\sigma_\lambda$$

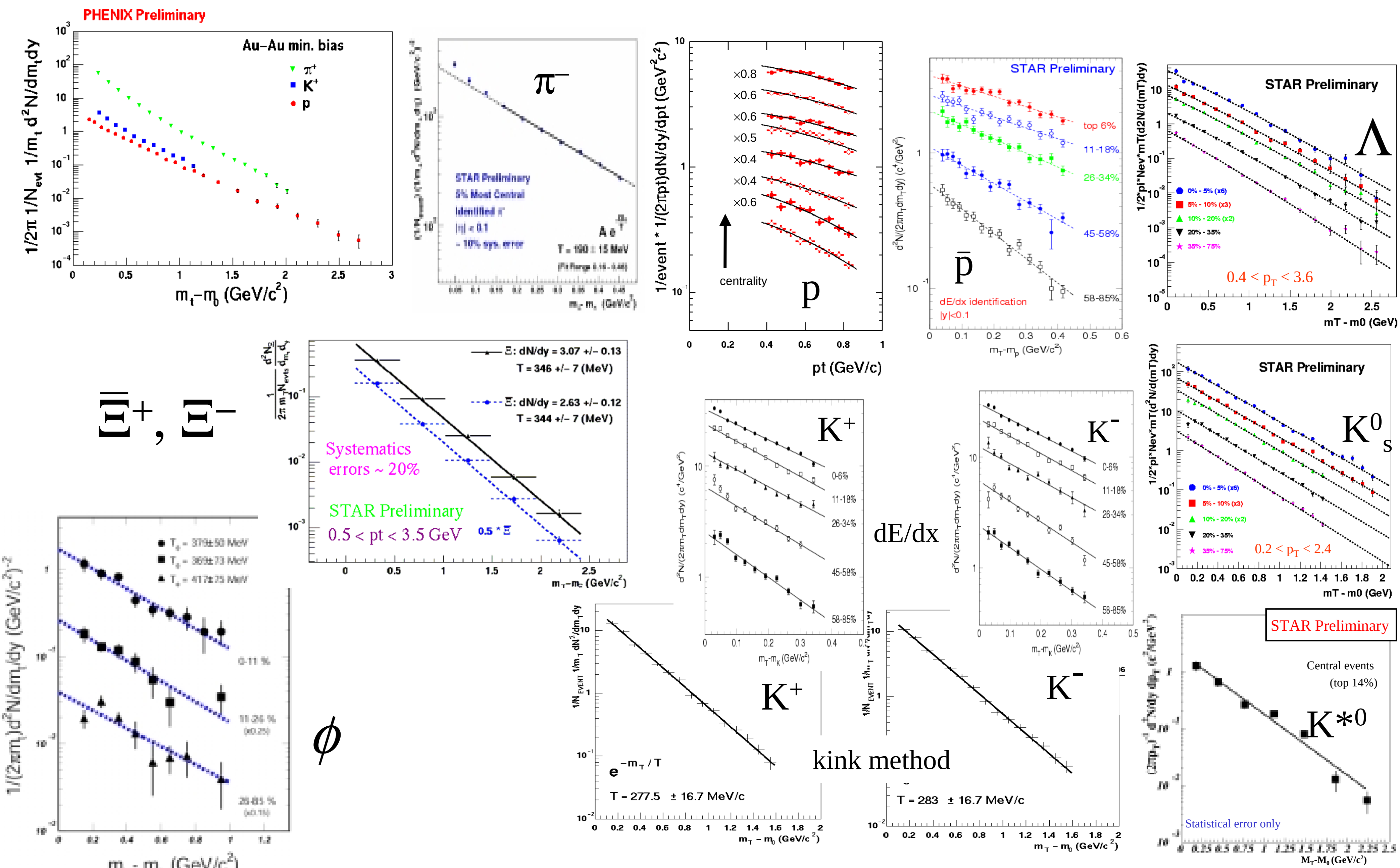
$$u^\nu(t, r, z=0) = (\cosh\rho, \vec{e}_r \sinh\rho, 0)$$

$$\rho = \tanh^{-1}\beta_r \qquad \beta_r = \beta_s\ f(x, p)$$

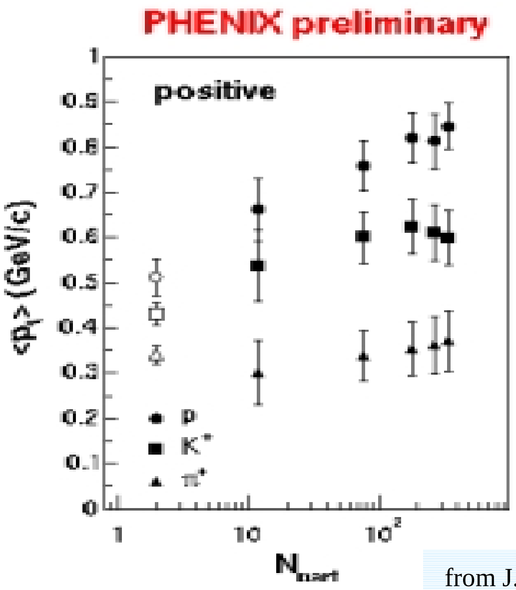
Emission from a Thermal Expanding Source

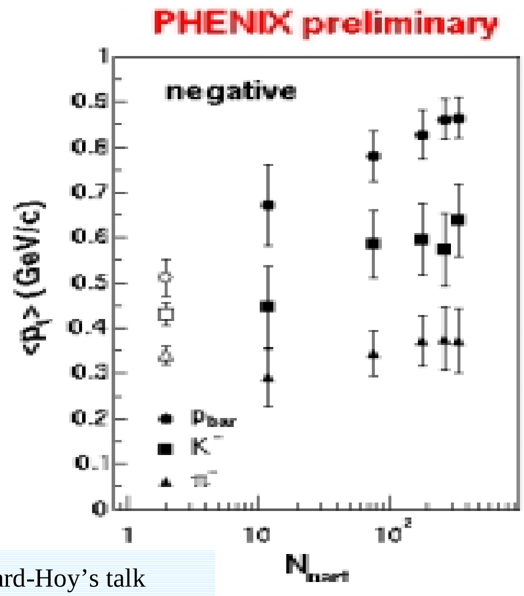


m_T distribution at RHIC



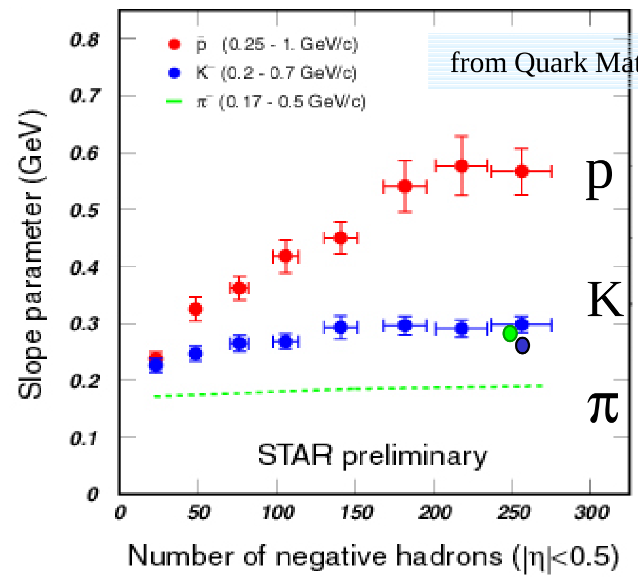
Slope parameter vs. centrality and mass





from J. Burward-Hoy's talk
in Thermal fest (BNL, Jul 2001)

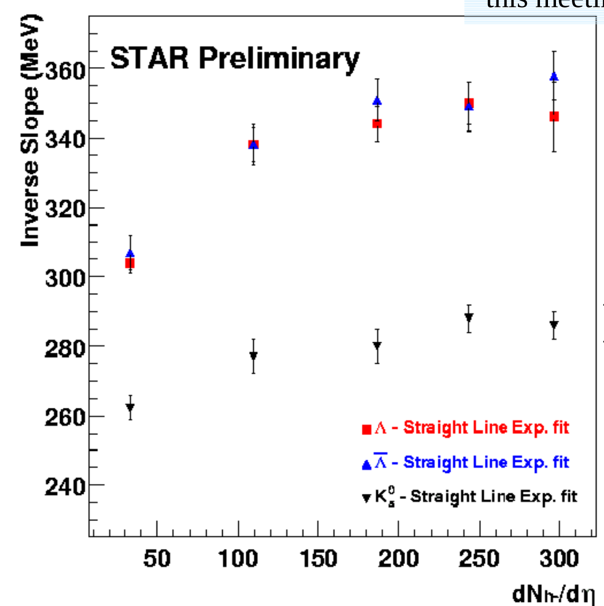
p
K
π



from Quark Matter 2001

p
K
π

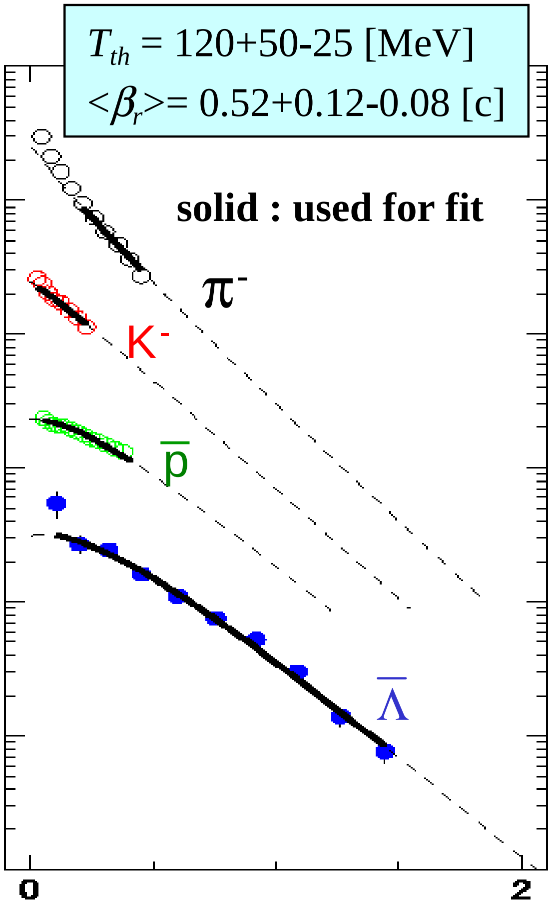
from H.Long's talk
this meeting



$\bar{\Lambda}$
Λ
K^0_s

- Inverse slope parameter
  - Increasing
    - with centrality
    - with particle mass

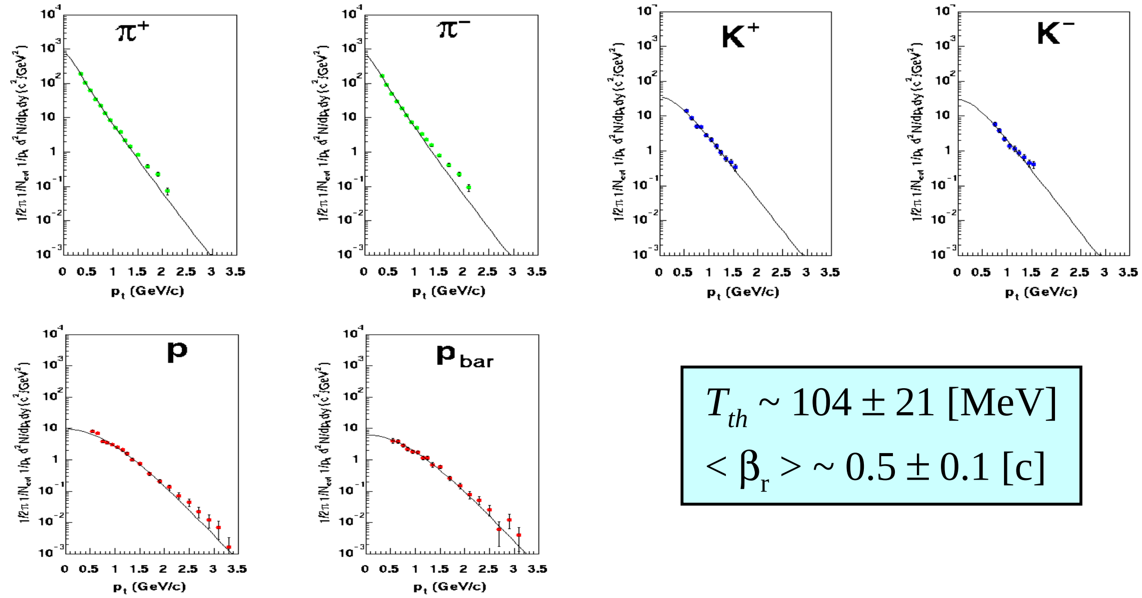
Radial flow and temperature



fit by M.Kaneta
to STAR Preliminary data

PHENIX Preliminary

from J. Burward-Hoy's talk
in Thermal fest (2001 Jul.)

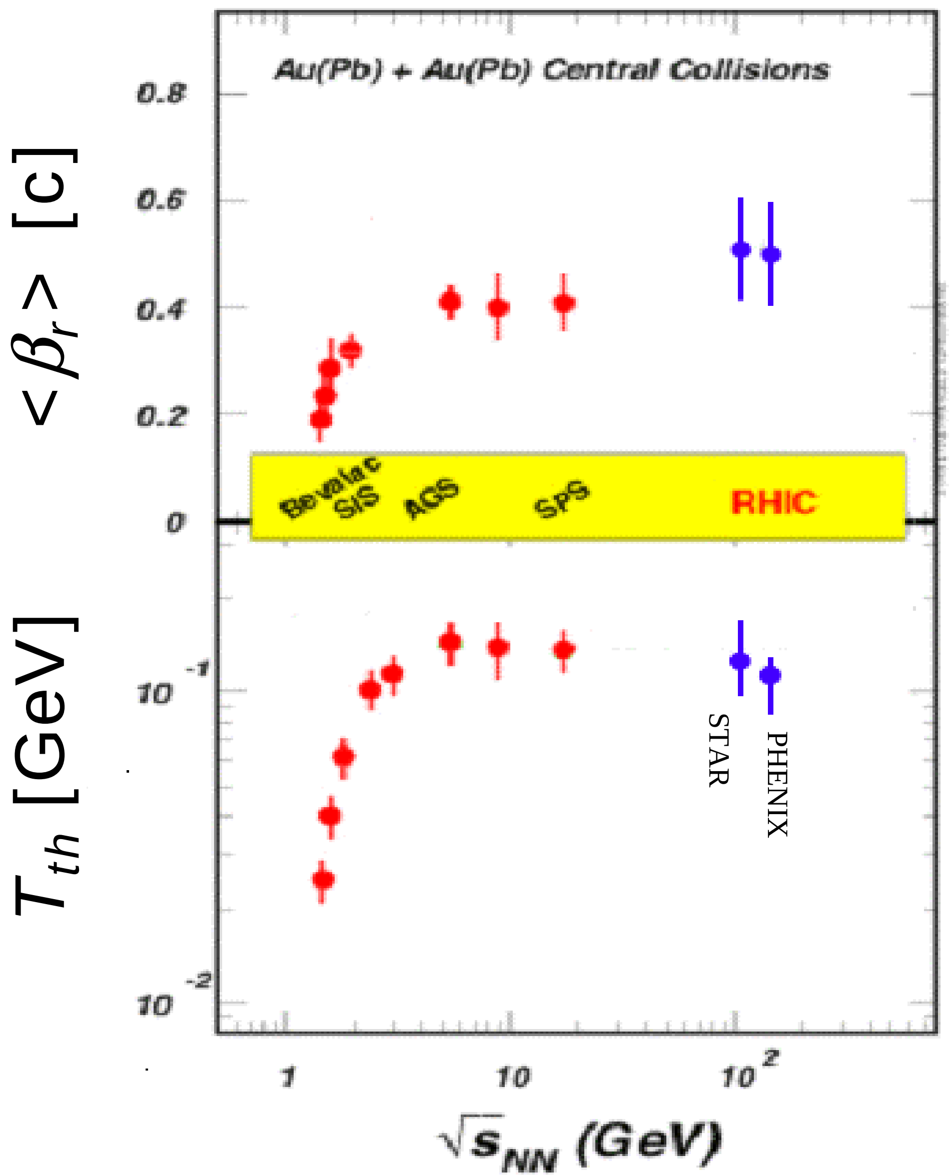


T_{th} ~ 104 ± 21 [MeV]
$<\beta_r>$ ~ 0.5 ± 0.1 [c]

- Spectra are describe by T_{th} and $<\beta_r>$
- Also, hydrodynamical model can reproduce the data

The model is from E.Schenedermann et al. PRC48 (1993) 2462
based on Blast wave model

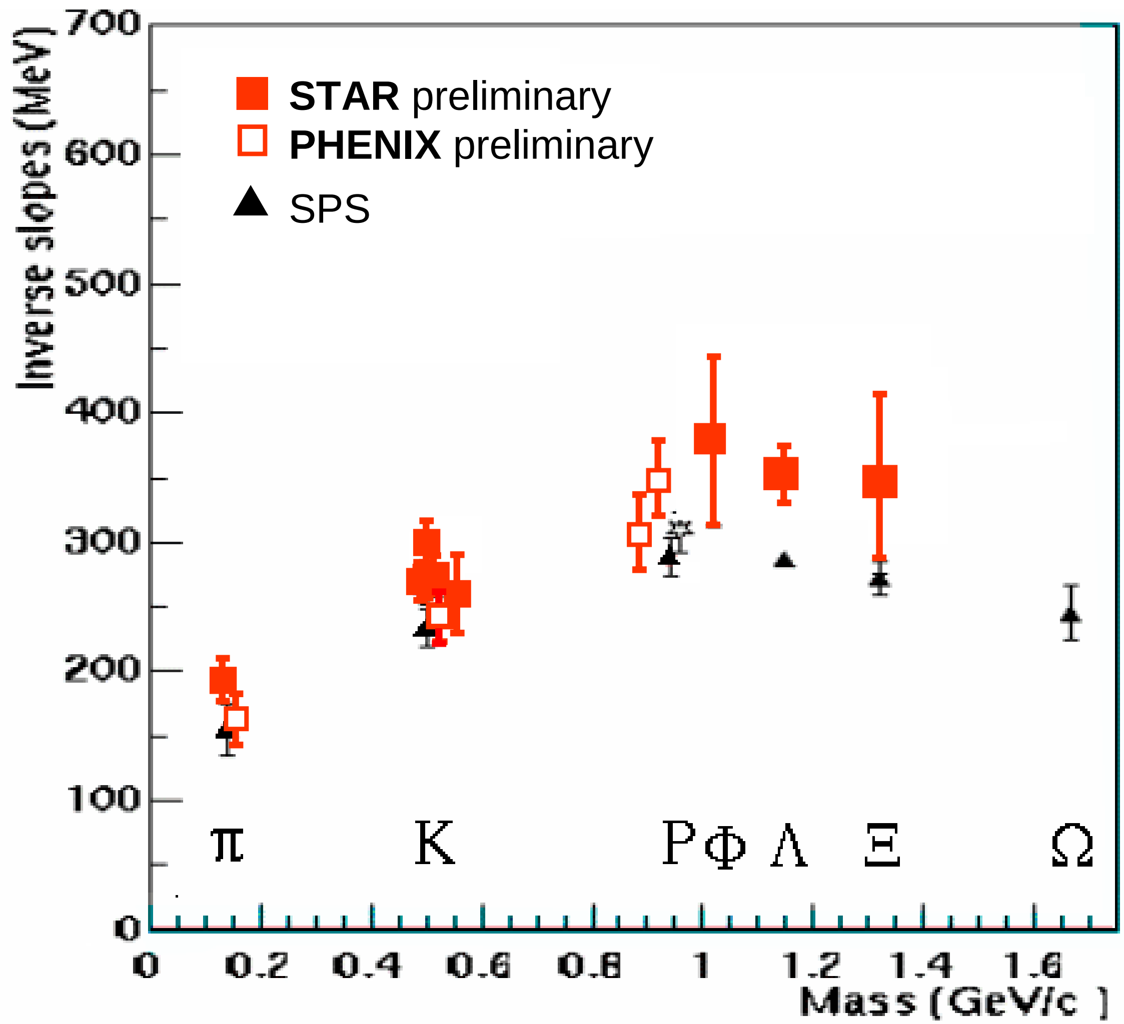
T_{th} and $<\beta_r>$ systematic



- $<\beta_r>$
  - saturates around AGS energy
  - increased at RHIC?
- T_{th}
  - saturates around AGS energy
  - behavior in (1-10 GeV) predicted by Stocker et al. in 1981 and Hagedorn
- Need 200GeV data and lower energy data

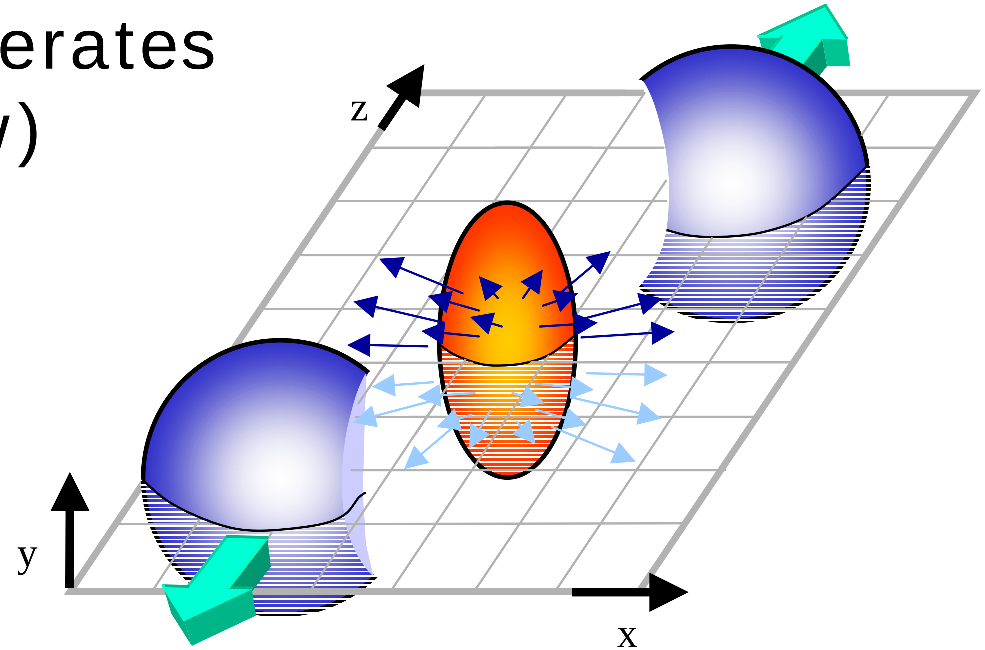
All hadrons are in equilibration?

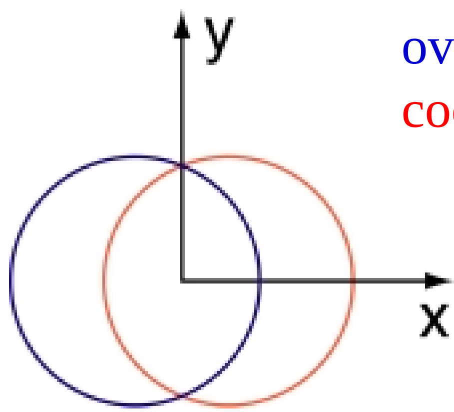
- Multi-strange baryon seems to have early freeze-out at SPS
- How about at RHIC?
  - Yes. Same trend



Event anisotropy

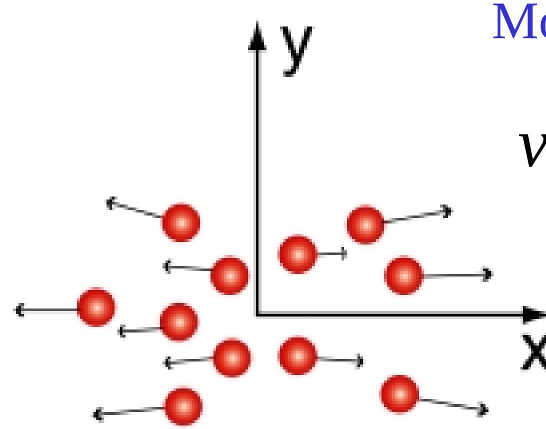
- The pressure gradient generates collective motion (aka flow)
  - Central collisions
    - radial flow
  - Peripheral collisions
    - radial flow and anisotropic flow





Almond shape overlap region in coordinate space

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

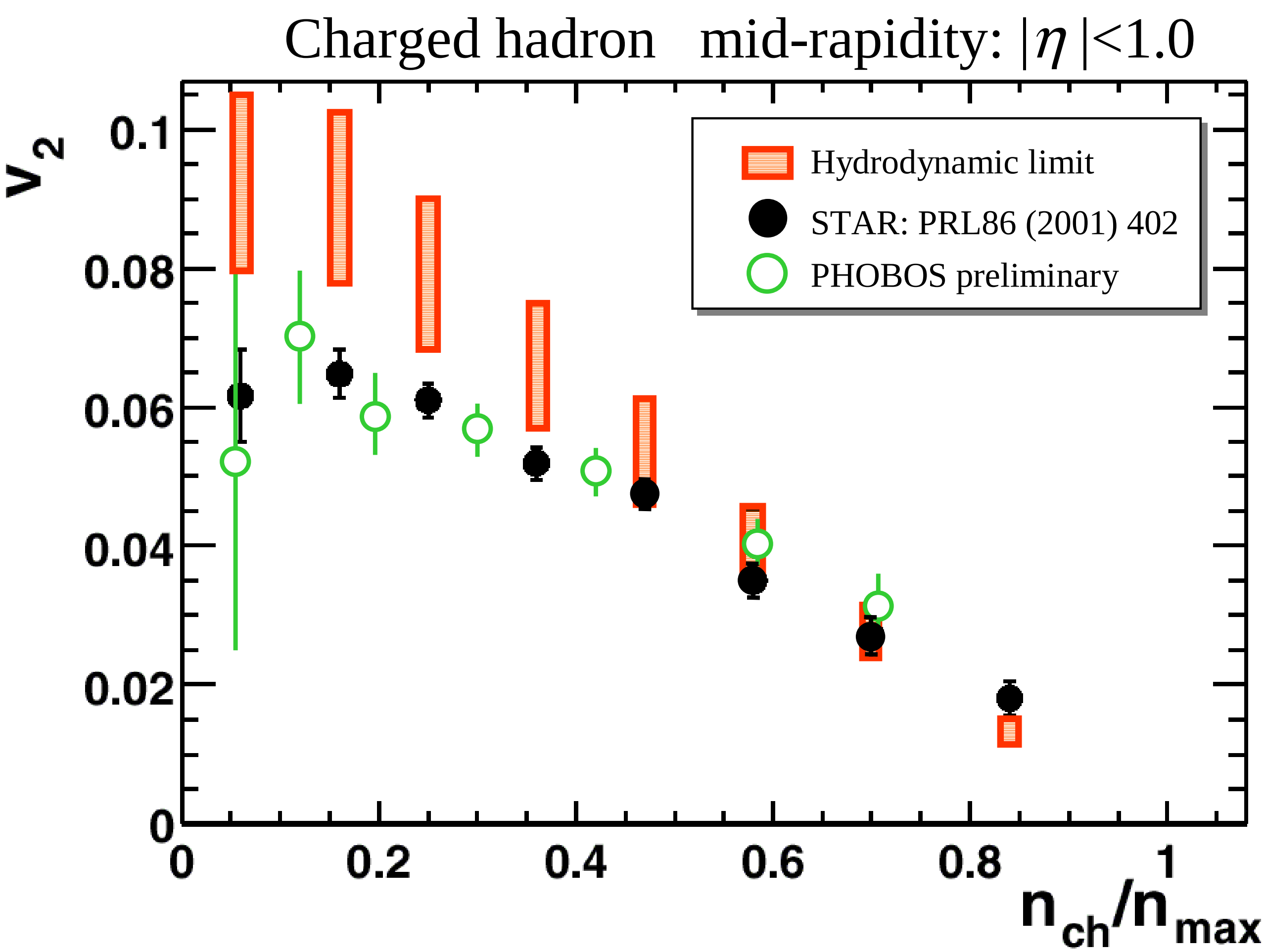


Momentum space

$$v_2 = \langle \cos 2\phi \rangle$$

$$\phi = \mathrm{atan}\frac{p_y}{p_x}$$

v_2 vs. centrality at RHIC

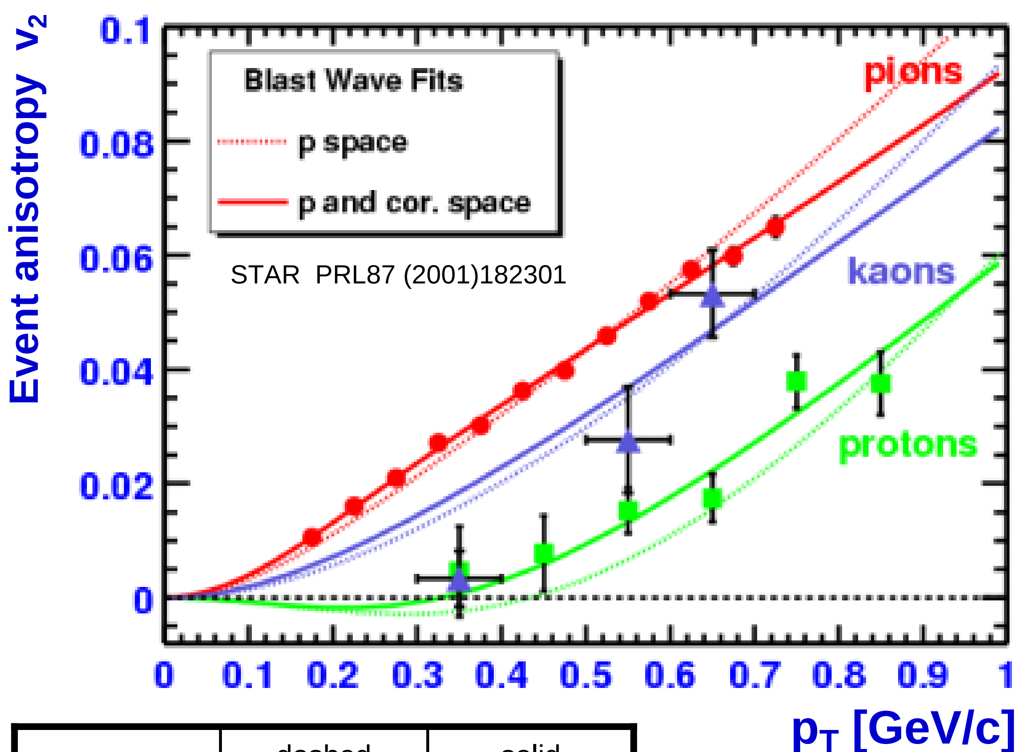


- Central region follows Hydrodynamical model at RHIC

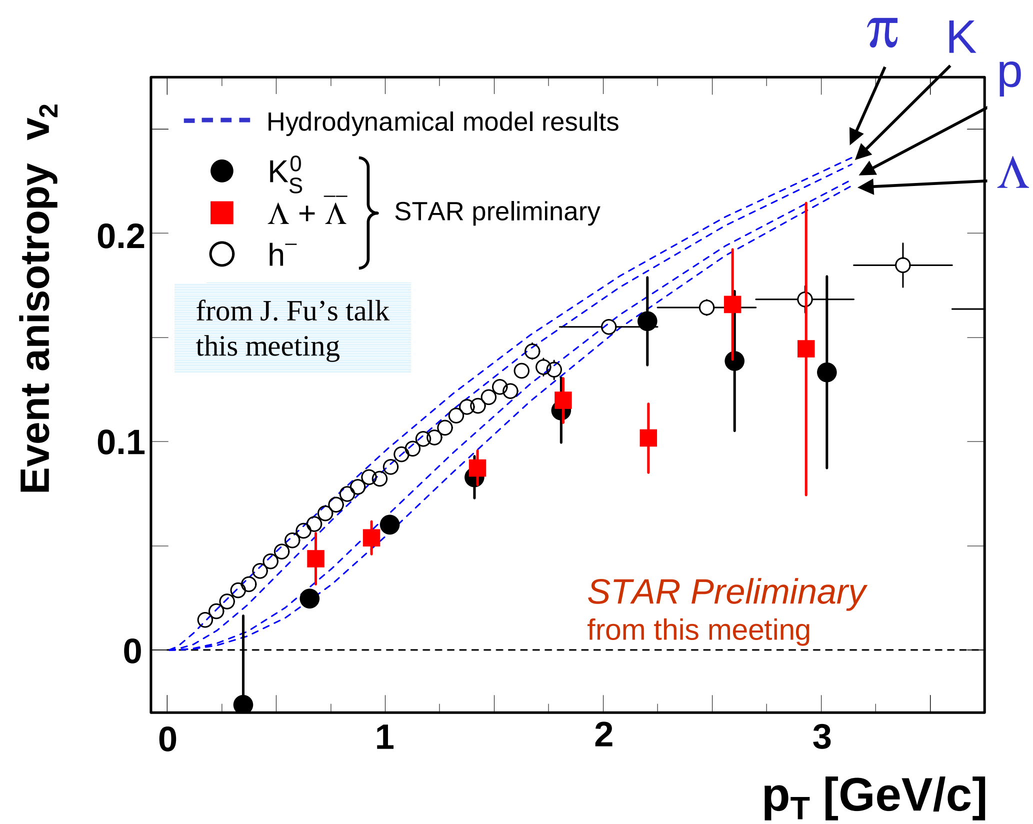
(PHOBOS : Normalized Paddle Signal)

v_2 of identified particle

- Blast wave mode and hydrodynamical model can describe data in low p_T (~2GeV/c)
- Mass dependence
  - Typical hydrodynamic behavior

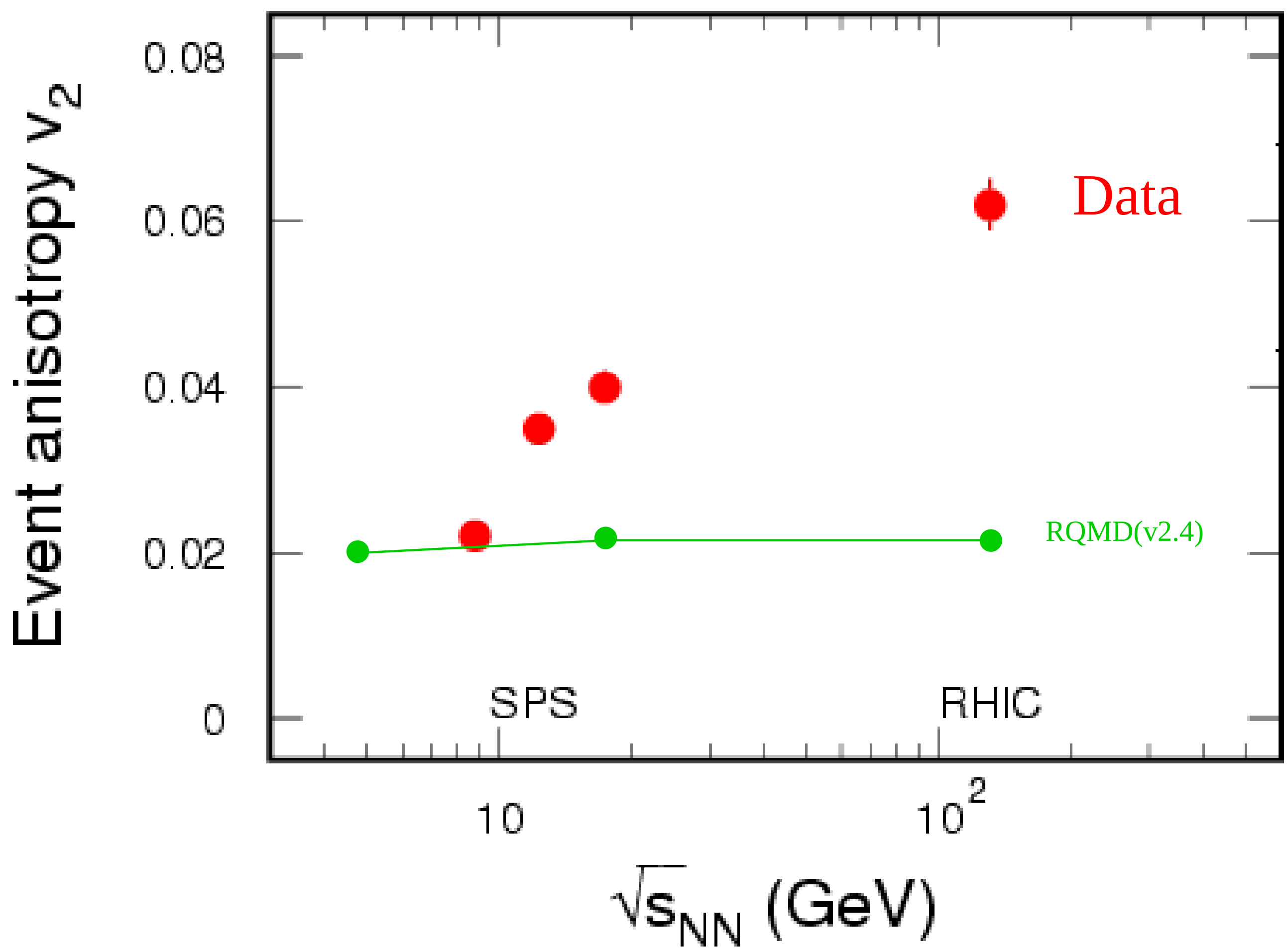


	dashed	solid
T_{th} [MeV]	135 ± 20	100 ± 24
$<b_r>$ [c]	0.52 ± 0.02	0.54 ± 0.03



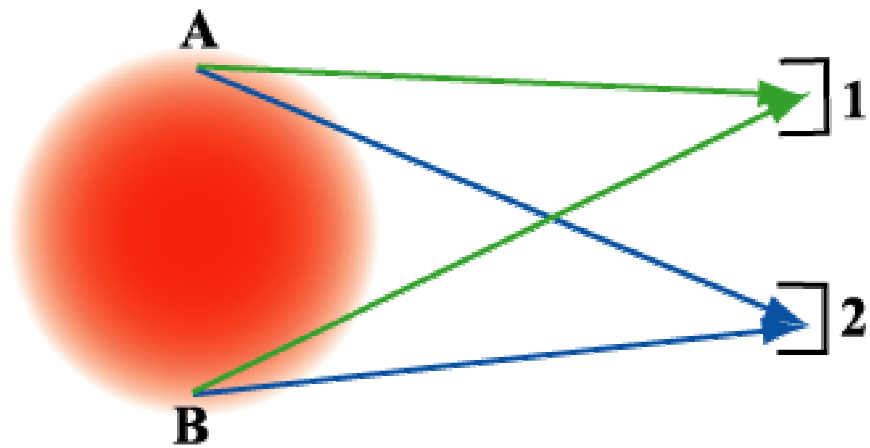
Energy dependence of v_2

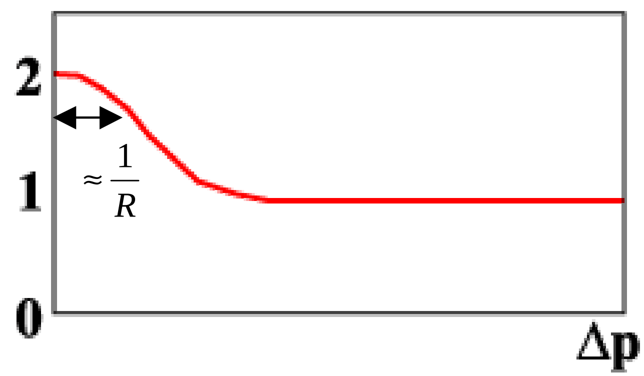
- Elliptical flow v_2 increases with collision energy



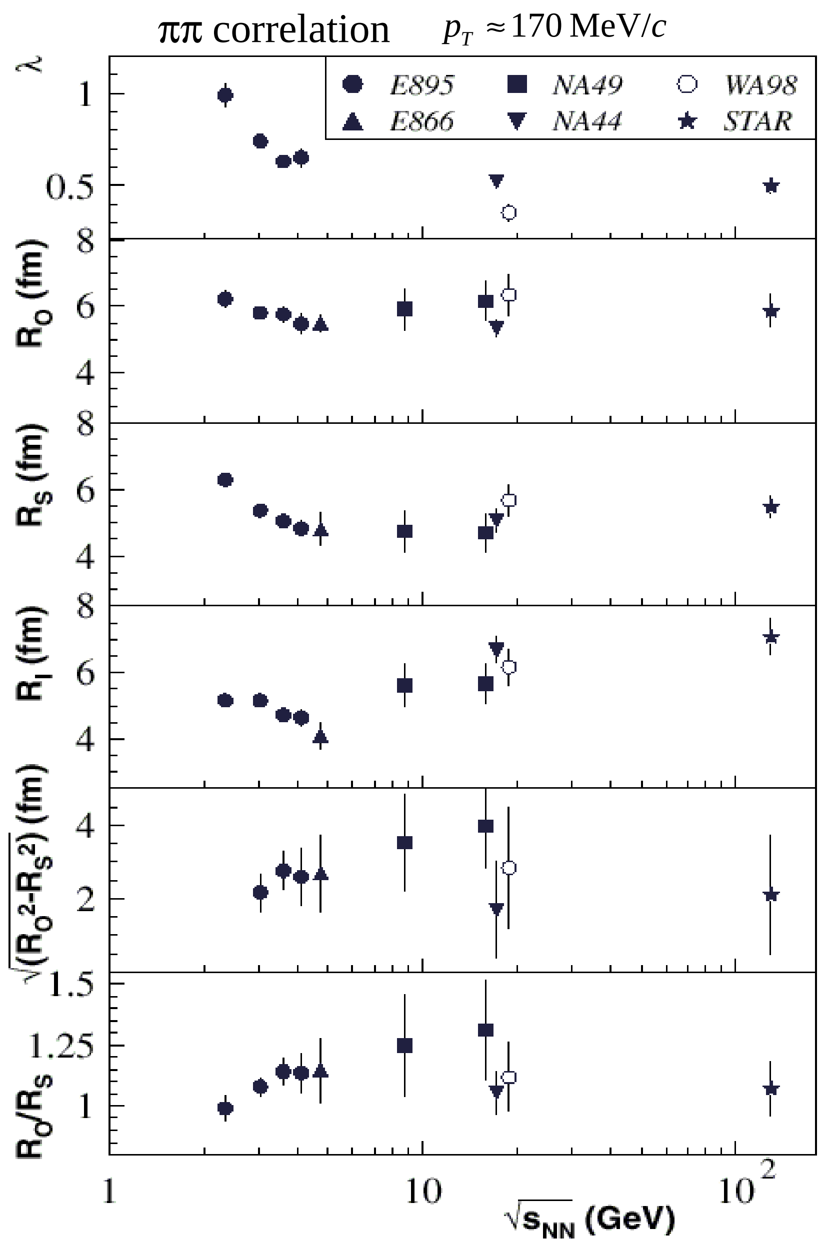
Particle correlation (HBT)

- Probe of the space time extent of heavy ion collisions
- Radius parameters
  - space-time geometry of the emitting source
  - dynamical information (e.g. collective flow)

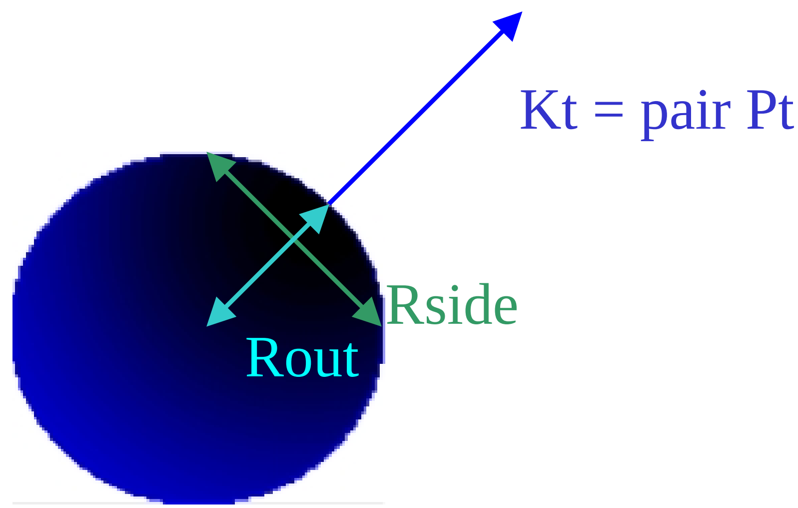




Radius parameters



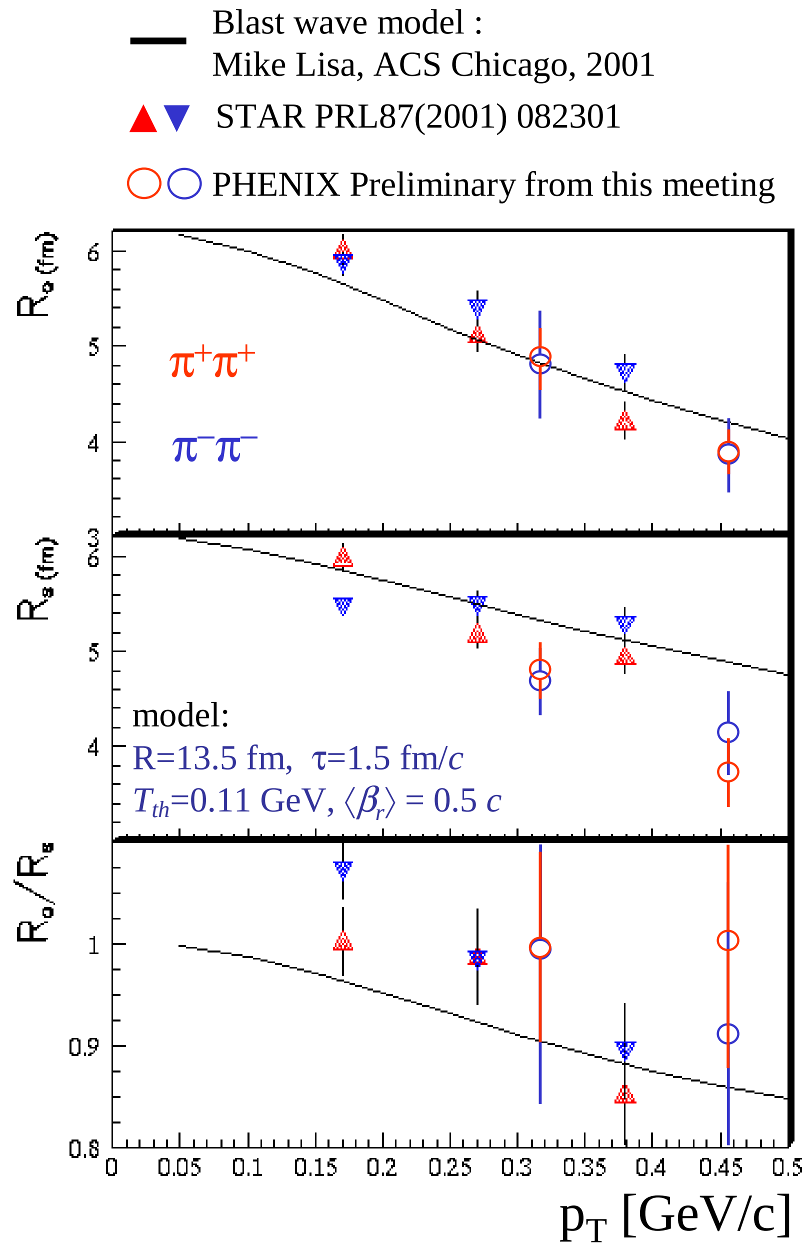
- similar radius with SPS!
- strong space-momentum correlation?

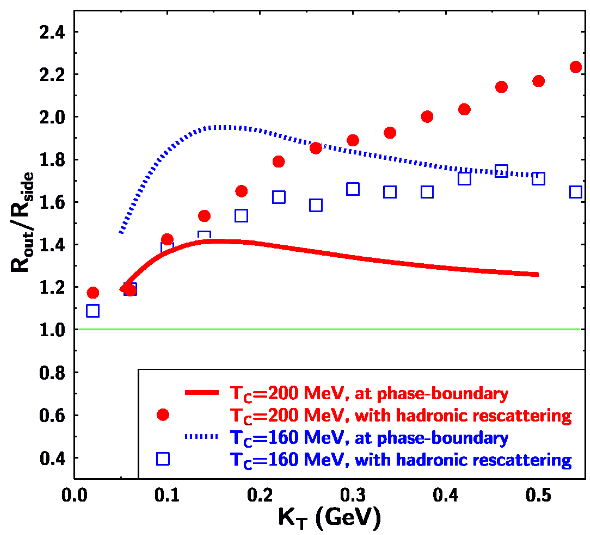


STAR data : PRL87(2001) 082301

Radii vs. p_T

- Blast wave model describes p_T dependence
  - Consistent T_{th} and $\langle\beta_r\rangle$ with them from spectra and v_2
- However
  - Hydrodynamical QGP + (uRQMD or RQMD) can not reproduce $R_o < R_s$





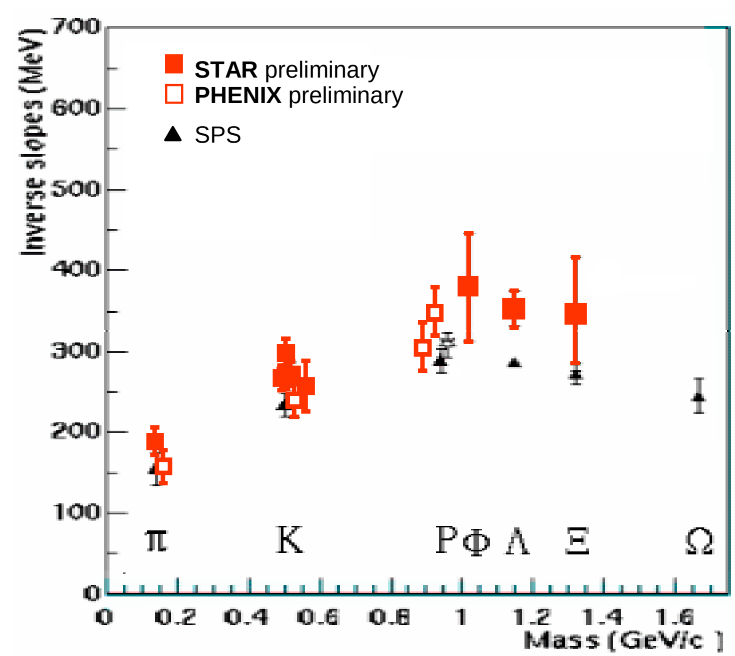
PRL86 (2001) 3981
S. Soff, S.A. Bass and A. Dumitru

Summary (I)

- Many new interesting results from RHIC year 1
- Not yet baryon free ($\bar{p}/p<1$)
- Chemical freeze-out
  - T_{ch}~180 MeV, μ_B~50 MeV, μ_s~0 MeV, γ_s~1 (central)
    - Full strangeness equilibration!
    - Close to phase boundary!
- Thermal freeze-out
  - Consistent results from spectra, HBT, and v_2
  - T_{th}~100-140MeV, $<\beta_r>$~0.5
  - Larger flow than one at SPS
  - Success of hydrodynamical approach
    - m_T spectra, v_2 ,and HBT (but only by blast wave model)

Summary (II)

- All hadrons are at same thermal freeze-out?
  - π, K, p, and Λ
    - Seem to have common T_{th} and radial flow
    - Inverse slope parameters increase with mass
  - However...
    - Cascade (Ξ) seems to freeze-out early



- Multi strange particle is one of keys for information of early stage

Open issues

- What stage is the origin of strong flow?
  - Partonic and/or hadronic level?
- We don't have a perfect microscopic model to describe data!
- Thermal/statistical model assumes ideal gas
  - The source may not be ideal gas in real world
- How to connect from hadron observable to parton level?