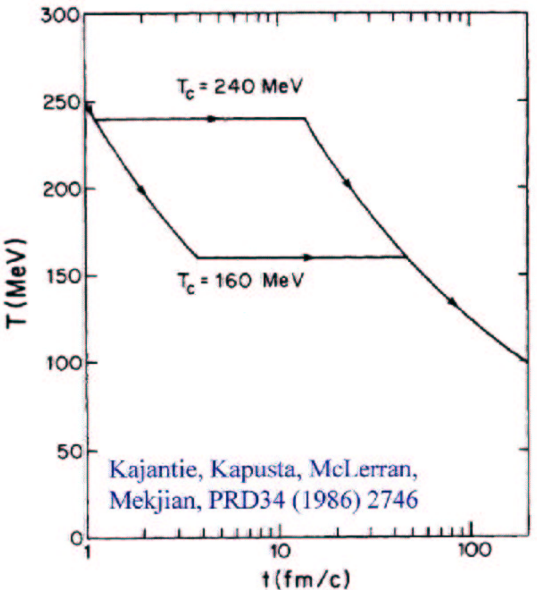
What does RHIC data tell us about Thermalization ?

Is there a consistent picture?

Thomas Ullrich, BNL, ITP, April 11, 2002



Kajantie, Kapusta, McLerran, Mekjian, PRD34 (1986) 2746

- Chemical Freeze-out
- Thermal Freeze-out
- Balance Function
- Flow: A second look
- HBT vs. Reaction plane & Flow
- A consistent picture ?

Models to Evaluate T_{ch} and μ_B

Chemical Freeze-Out Model

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

Assume: Hadron resonance ideal gas

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

Statistical Thermal Model

F. Becattini
P. Braun-Munzinger et al. PLB(1999)

Assume:

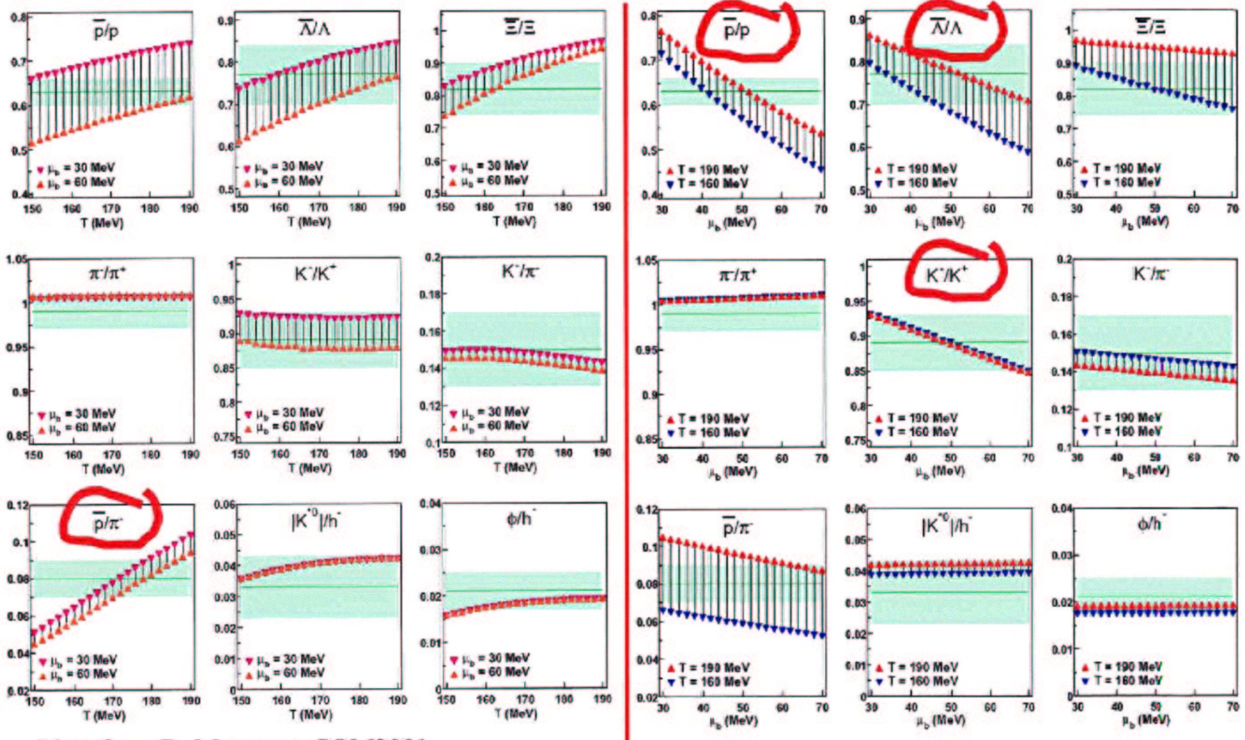
- thermally and chemically equilibrated fireball at hadro-chemical freeze-out
- law of mass action is applicable !!!

Recipe:

- grand canonical ensemble to describe partition function ⇒ density of particles of species ρ_i
- fixed by constraints: Volume V, strangeness chemical potential μ_S, isospin
- input: measured particle ratios
- output: temperature T and baryo-chemical potential μ_B

Comparable particle ratios to experimental data

Statistical Thermal Models – What drives the fit ?



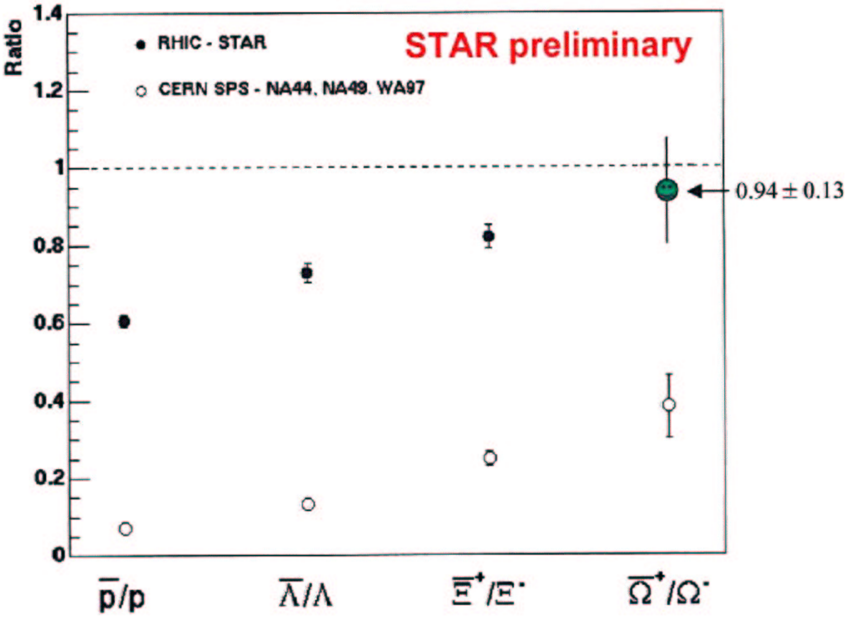
Plots from D. Magestro, SQM2001

$\bar{B}/B$ Ratios at RHIC

Ratios calculated for central events at mid-rapidity, averaged over experimental acceptance in p_t. With the assumption of equal acceptance of particle and antiparticle no corrections have to be applied

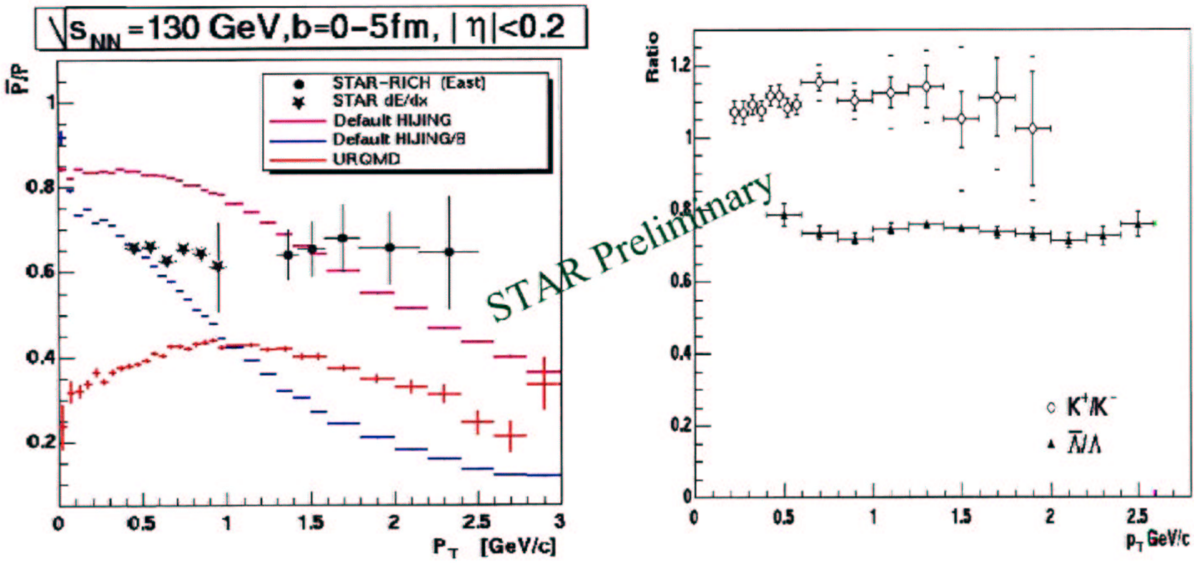
Except:

- Absorption in material
- Production of secondaries in material



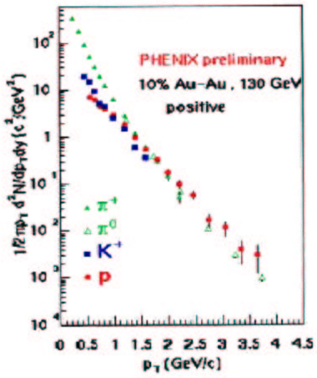
⇒ $\bar{B}/B$ ratios experimentally robust

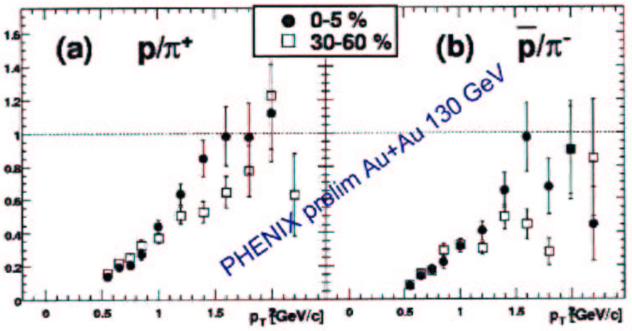
Particle/Antiparticle Ratios at RHIC - p_T-Dependence

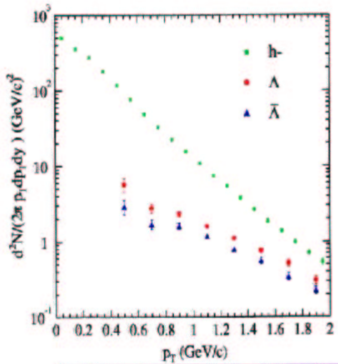


Within the errors no or very small p_T dependence

Mixed Particle Ratios at RHIC







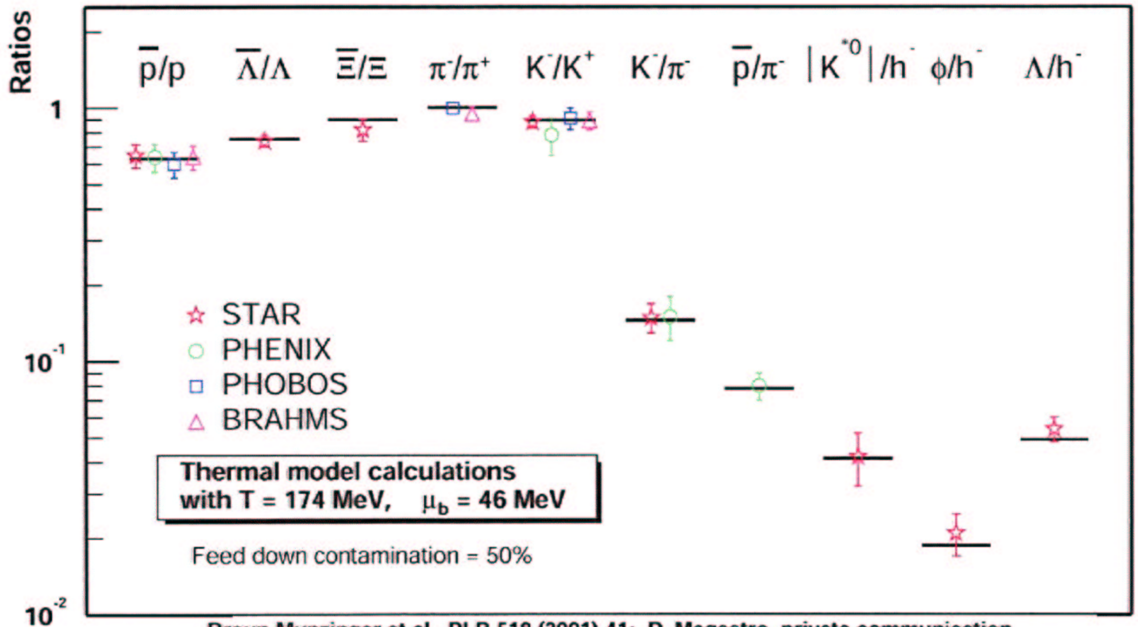
Mixed particle ratios depend strongly on the p_T

Highest yields at low end of spectrum p_T

For p_T-integrated ratios all experiments need to extrapolate to $p_T = 0$

⇒ Large systematic errors

Statistical Thermal Model: Fit Results



Braun-Munzinger et al., PLB 518 (2001) 41; D. Magestro, private communication

$T = (174 \pm 7)$ MeV $\mu_b = (46 \pm 5)$ MeV

Chemical Freeze-Out Model: Fit Results

Hadron resonance gas + decay effects

Chemical freeze-out parameters

$T_{ch} = 170 \pm 4$ MeV

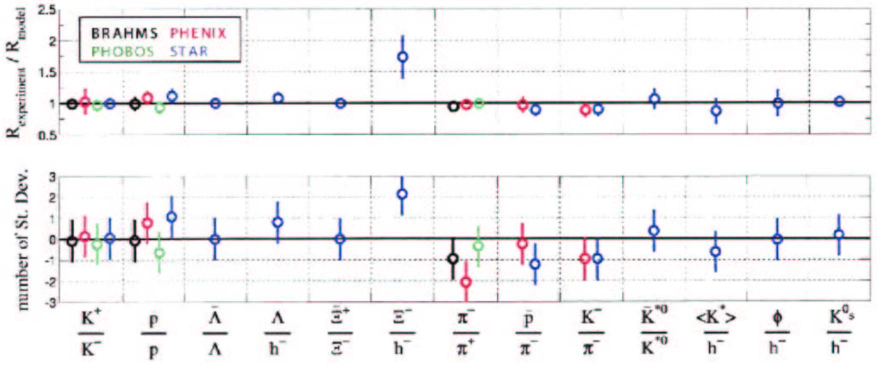
$\mu_B = 3\mu_{u(d)} = 40 \pm 4$ MeV

$\mu_s = 1.1 \pm 2.0$ MeV

$\gamma_s = 1.09 \pm 0.06$

$\chi^2/\text{dof} = 16.7/9$

($\chi^2/\text{dof} = 12.2/8$ w/o Ξ^-/h^-)

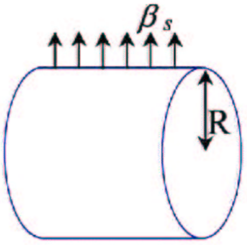


M. Kaneta, N. Xu, LBL, 2002
(Thermal Fest BNL 2001 and nucl-ex/0104021)

Thermal Freeze-Out: Hydrodynamics Type Models

Many on the market: this is just one example

Local thermal equilibrated source or boosted system:



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

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

$$\rho = \tanh^{-1}\beta_t \qquad \beta_t = \beta_s f(r)$$

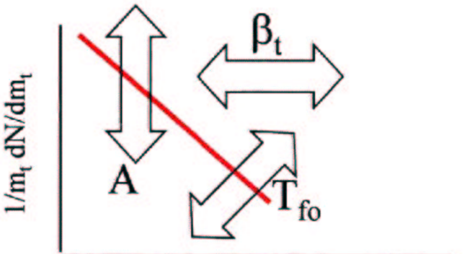
$$\frac{dn}{m_T dm_T} \propto \int_0^R r\,dr\, m_T K_1\left(\frac{m_T\cosh\rho}{T_{th}}\right) I_0\left(\frac{p_T\sinh\rho}{T_{th}}\right)$$

Ref. : E.Schnedermann et al, PRC48 (1993) 2462

flow profile selected

$(\beta_t = \beta_s (r/R_{max})^n)$

2-parameter (T_{fo}, β_s) fit to m_T distributions



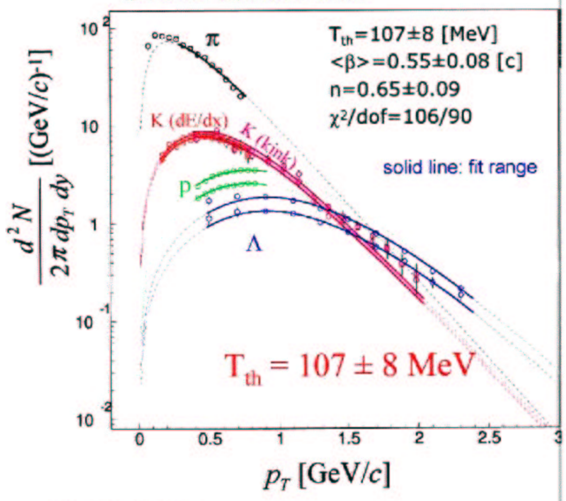
Thomas Ullrich 12 4/5/2002

BROOKHAVEN NATIONAL LABORATORY

Thermal Freeze-Out: When STAR fits it …

Thermal freeze-out models show good agreement with data from π, K, p, Λ

STAR central data



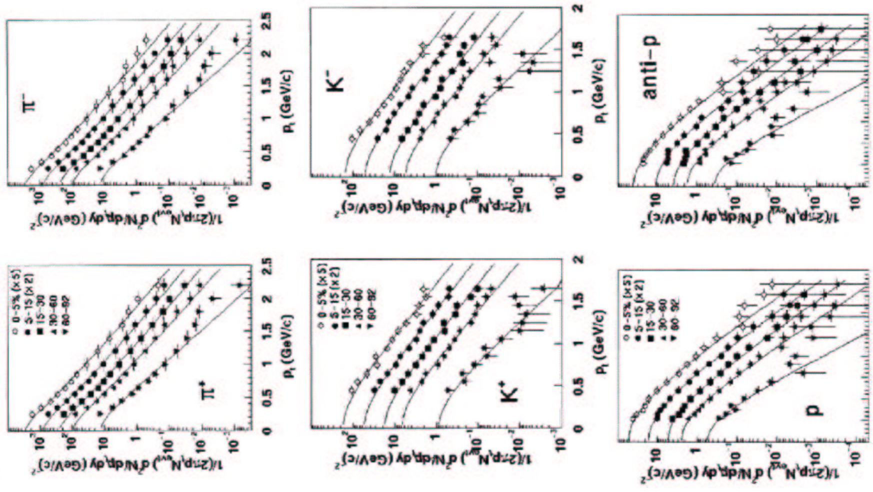
Fits by M. Kaneta

Thomas Ullrich

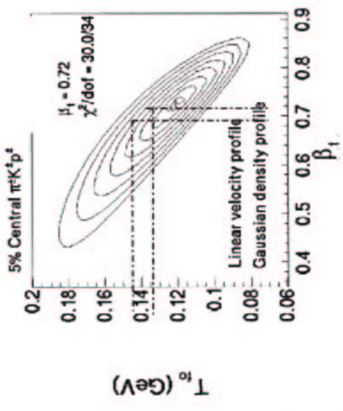
hydrodynamic analysis of spectra

when PHENIX fits it ...

Simultaneous fit to m_T-m_0 < 1 Gev/C



PHENIX Preliminary



PHENIX Preliminary

T = 122±4 MeV

$\beta_t = 0.72 \pm 0.01$

χ^2/dof = 30.0/40.0

$\langle\beta\rangle \sim 0.5$

B. Jacak

Freeze-Out Parameters from Coalescense

R. Scheibl, U. Heinz, PRC59(1999)1585; E864 nucl-ex/9909012

Model of local thermal equilibrium (with radial flow)

Yield ∝ $\exp(-(m_n \pm \mu_b)A/T)$

Note: this is μ_b at thermal (not chemical) freeze-out

here: neglect term $\exp\left[-\frac{m_\perp - m_0}{T^*}\right]$

$\hookrightarrow \sim 15\%$ correction

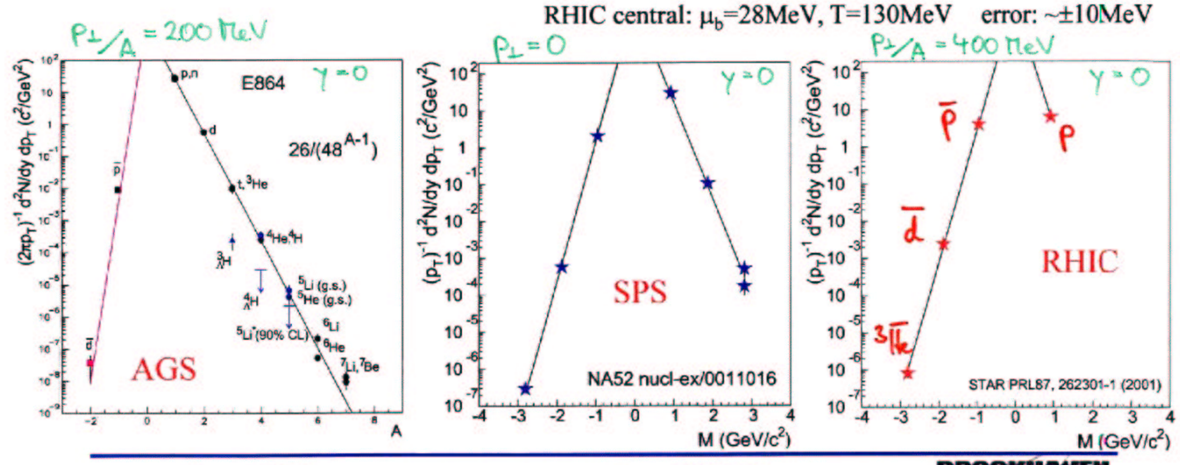
RHIC: 130 MeV ⇝ 110 MeV (μ=const)

$$\left.\frac{\mu}{T}\right|_{ch} = \frac{46}{174} = 0.26 = \frac{28}{110} = \left.\frac{\mu}{T}\right|_{fo}$$

AGS central: μ_b=500MeV, T=110MeV

SPS minbias: μ_b=170MeV, T=130MeV

RHIC central: μ_b=28MeV, T=130MeV error: ~±10MeV



The Balance Function – Motivation & Definition

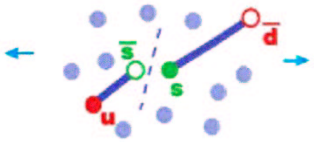
Bass, Danielewicz, Pratt, Phys. Rev. Lett. **85**, 2689 (2000)

- The balance function is a *new* observable for heavy ion collisions
- used for e^+e^- and pp jet analysis

Hadronic Scenario:

Hadronization @ 1 fm/c
Flux tube & high velocity gradient separate charges
$Y_+ - Y_- \sim 1$

QGP Scenario:



Hadronization @ 5-10 fm/c
Most $\bar{q}q$ pairs created at hadronization
> ½ of Q created at hadronization
$Y_+ - Y_- \sim (T/m)^{1/2} \sim 0.5$

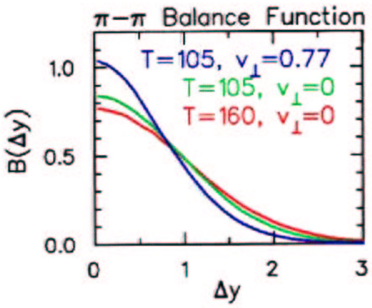
$B(\Delta y)$ identifies balancing charges statistically:

$$B(\Delta y) = \frac{1}{2}\left\{\frac{N_{+-}(\Delta y) - N_{++}(\Delta y)}{N_+} + \frac{N_{-+}(\Delta y) - N_{--}(\Delta y)}{N_-}\right\}$$

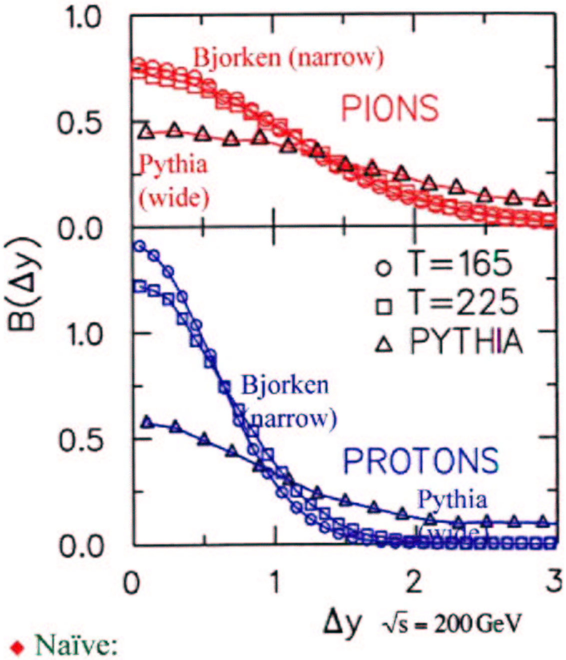
- $N_{+-}(\Delta y)$ = Histogram of $|\, y(\pi^+) - y(\pi^-) \,|$, for all possible pairs within an event.
- This histogram is summed over all events.
- Can use π, K, p, or all charged particles ($\Delta\eta$) for a balance function.

The Balance Function – Predictions

- ◆ Charge-anticharge pairs created early separate further in rapidity
- ◆ Charge-anticharge pairs created in a later stage (hadronization of QGP) will have less rapidity separation
- ◆ Simulations indicate broader balance functions for PYTHIA (pp) than a Bjorken model (QGP)
- ◆ Effects to consider
  - Diffusion $\sigma^2_{\Delta y} = 2(\sigma^2_{thermal} + \sigma^2_{diffusion})$
  - Coalescense: small effect
  - Annihilation: broadens width
  - Radial flow: narrows width



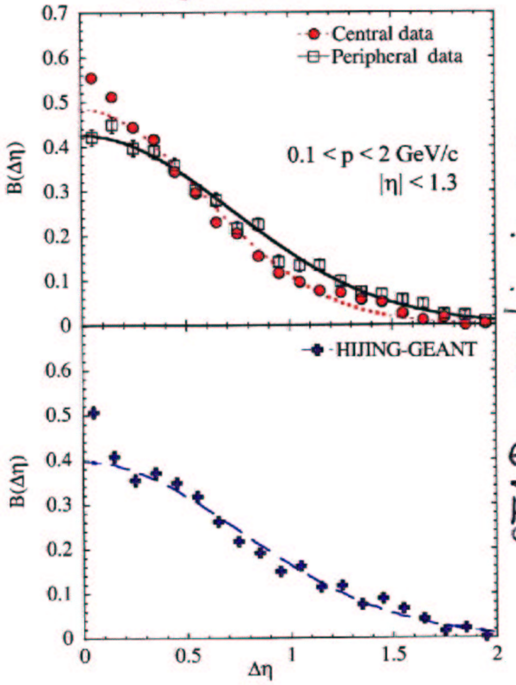
S. Pratt



- ◆ Naïve:
  - Wide ⇒ nucleon/nucleon
  - Narrow ⇒ QGP/late hadronization

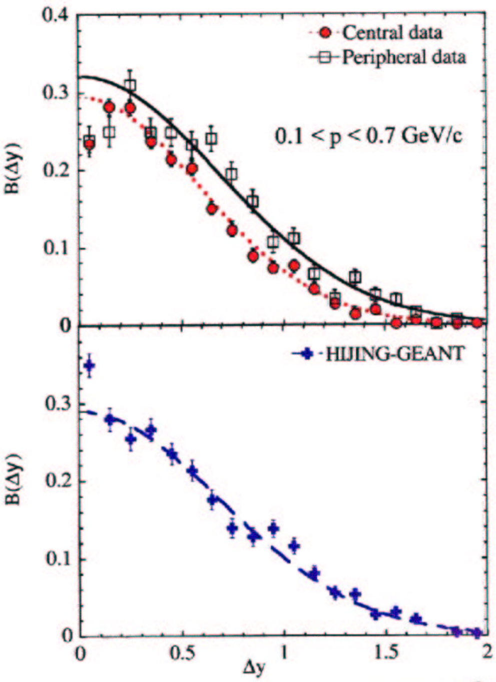
The Balance Functions – Results

Charged Particle Pairs



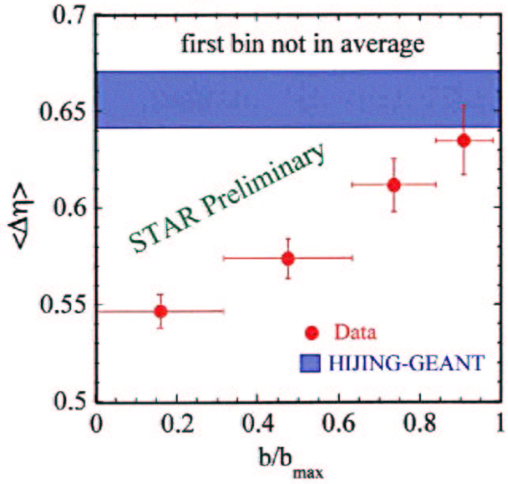
STAR preliminary

π Pairs

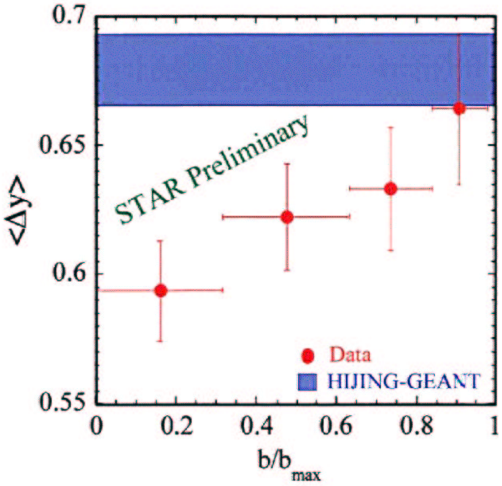


The Balance Functions - Results

Charged Particle Pairs



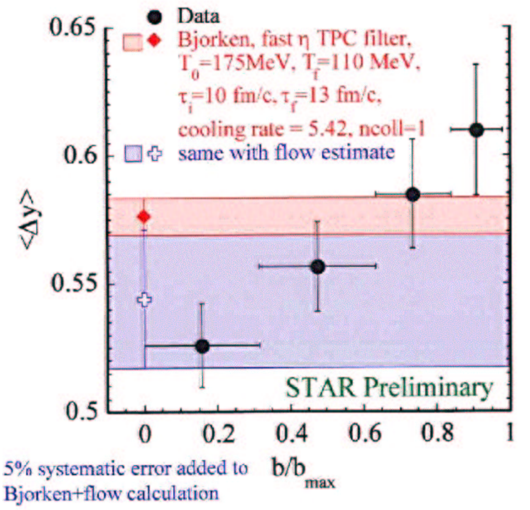
π Pairs



- $\langle\Delta\eta\rangle$ ~ width via weighted average (Gaussian fit give same results)
- First bin omitted (dip due to HBT + track splitting + track merging)
- Hijing show no dependence on centrality

The Balance Function – Interpretation

- Data resemble HIJING for peripheral events
- Balance gets narrower for central collisions consistent with idea of delayed hadronization
- What would we expect for the balance function if we indeed did get delayed hadronization?
- Use thermal Bjorken toy-model with expansion to test ideas:



5% systematic error added to Bjorken+flow calculation

- Use model from Bass, Danielewicz, Pratt, PRL **85**, 2689 (2000)
- Only pions created in pairs after expansion of a thermal system
- Assumes
  - $T_{initial}$ and a T_{fo} and T decreases linearly with time
  - Pions created at time t_i and cease to interact at t_f
- Particles rescatter
- Use full STAR detector simulation chain

Flow can narrow the predicted balance function to a value similar to STARs central bin

Narrow B(Δy) consistent with late hadronization (or change in production mechanism ?)

Elliptic Flow

Many suggested signals are subtle effects,– need to measure elliptic flow with the least possible systematic uncertainty.

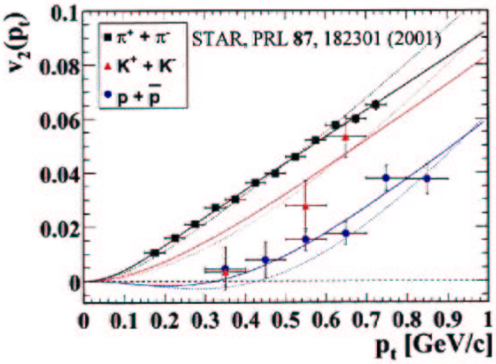
Some correlations may contribute to standard *v2* , but are unrelated to collective motion rel. to reaction plane… Examples of these NON-FLOW effects include:

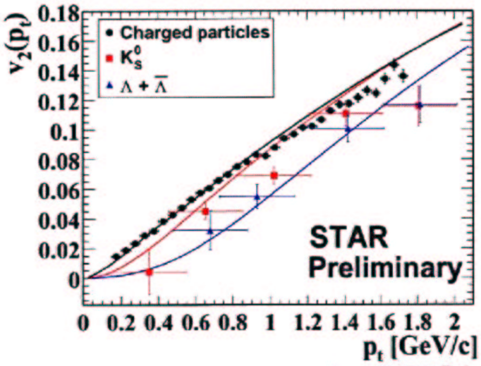
- (Mini)jets and strings
- Resonances
- FSI (especially Coulomb)
- Momentum conservation
- Quantum statistics

So far analyses treated these case-by-case e.g., partition subevents randomly, also by charge, and also on either side of a pseudorapidity gap.

$\Psi = \frac{1}{2} \operatorname{atan} \frac{\Sigma \omega_i \sin 2\phi}{\Sigma \omega_i \cos 2\phi}$

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





Four-Particle Correlations

4 particle correlation analysis: reduce or eliminate sensitivity to non-flow

The correlation between two particle is :

$$\langle u_{n,1} u^*_{n,2} \rangle = \langle e^{in\phi_1} e^{-in\phi_2} \rangle = \mathrm{v}_\mathrm{n}^2 + \delta_n$$

Correlating four particles, one gets

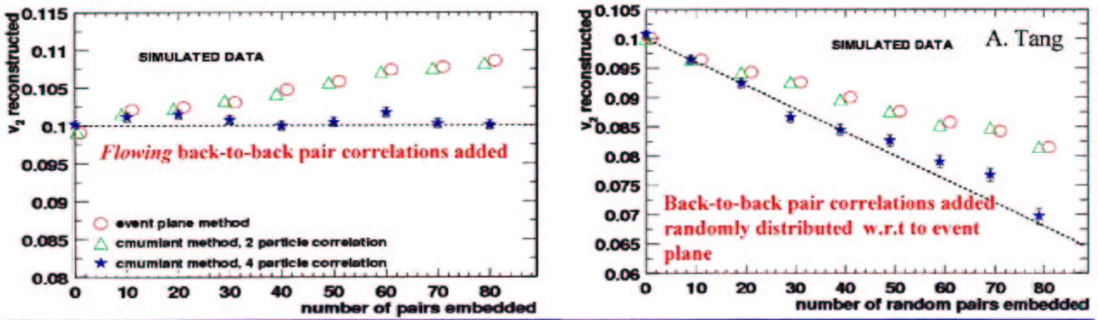
$$\langle u_{n,1} u_{n,2} u^*_{n,3} u^*_{n,4} \rangle = \mathrm{v}_\mathrm{n}^4 + 2 \cdot 2 \cdot \mathrm{v}_\mathrm{n}^2 \delta_n + 2\delta_n^2$$

⇐ Motivation only
The actual code uses cumulant generating functions
Borghini, Dinh, Ollitrault PRC 64 (2001) 054901

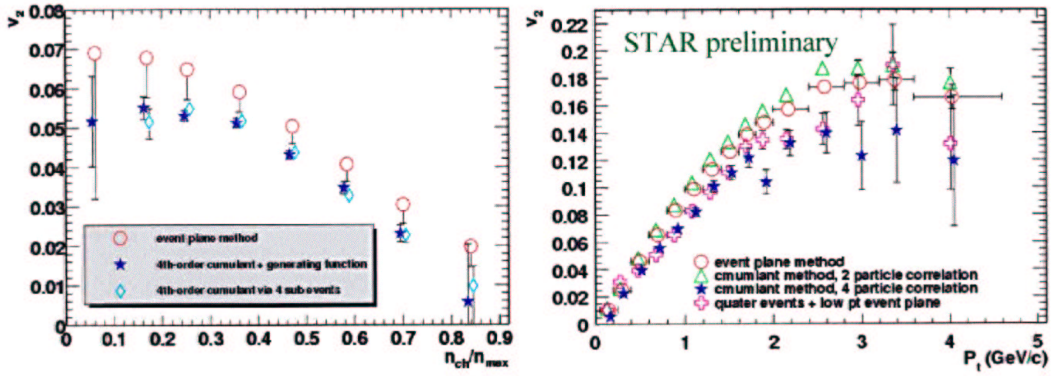
the non-flow term is thus cancelled by the cumulant defined below:

$$\langle\langle u_{n,1} u_{n,2} u^*_{n,3} u^*_{n,4} \rangle\rangle = \langle u_{n,1} u_{n,2} u^*_{n,3} u^*_{n,4} \rangle - 2\langle u_{n,1} u^*_{n,2} \rangle^2 = -\mathrm{v}_\mathrm{n}^4$$

Four-particle correlations simulations (STAR):



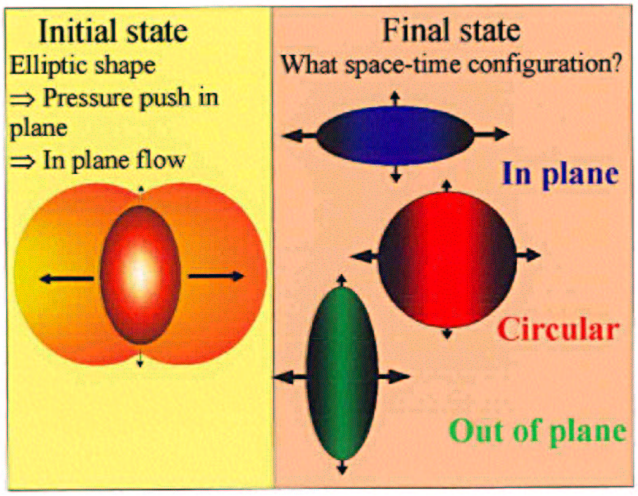
Four-Particle Correlations: Results and Comparison



Pros and Cons

- Practically zero sensitivity to non-flow
- Non-flow correction 15% at RHIC
- Confirms earlier non-flow estimates
- Needs large stats. rel. to pair analyses

Elliptic Flow: What can we learn about the system at Freeze-out?



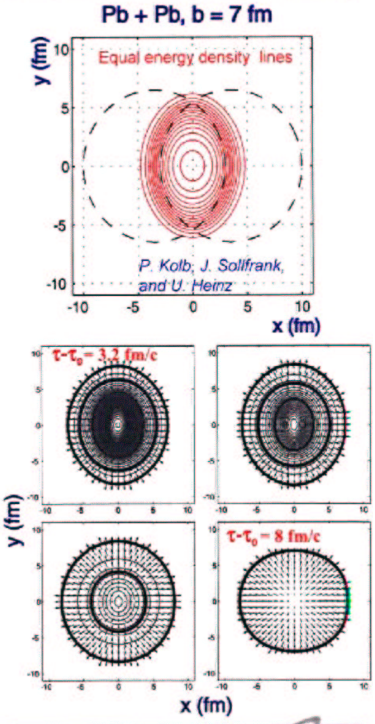
Initial state
Elliptic shape
⇒ Pressure push in plane
⇒ In plane flow

Final state
What space-time configuration?

In plane

Circular

Out of plane



Elliptic flow teaches us about the early Evolution of the system.

What's about the source shape which is related to the expansion time?

More detail: identified particle elliptic flow

$$v_2(p_T) = \frac{\int_0^{2\pi} d\phi_b \cos(2\phi_b) \mathrm{I}_2\left(\frac{p_T \sinh\rho}{T}\right) \mathrm{K}_1\left(\frac{m_T \cosh\rho}{T}\right) \boxed{(1+2s_2\cos(2\phi_b))}}{\int_0^{2\pi} d\phi_b \, \mathrm{I}_0\left(\frac{p_T \sinh\rho}{T}\right) \mathrm{K}_1\left(\frac{m_T \cosh\rho}{T}\right) \boxed{(1+2s_2\cos(2\phi_b))}}$$

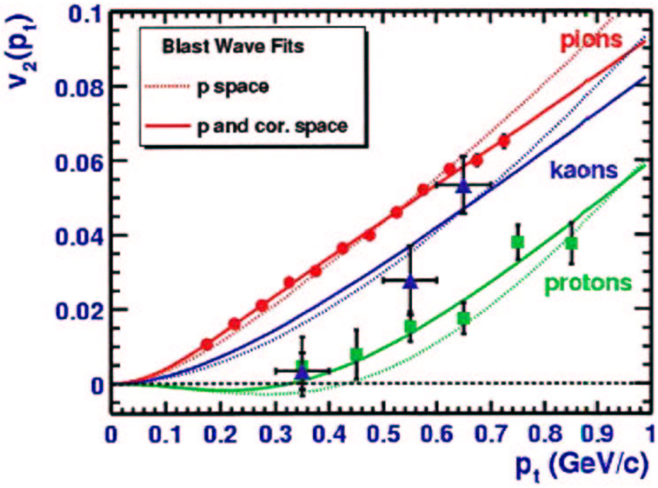
hydro-inspired
blast-wave "model"
Houvinen *et al.*

Flow boost: $\rho = \rho_0 + \rho_a \cos(2\phi_b)$

ϕ_b = boost direction, $\beta = \tanh\rho$

	dashed	solid
T (MeV)	135 ± 19	101 ± 24
ρ_0(c)	0.58 ± 0.03	0.61 ± 0.05
ρ_a (c)	0.09 ± 0.02	0.04 ± 0.01
S_2	0.0	0.04 ± 0.01

Critique: To describe a new observation just add a new parameter ?



How to interpret s_2? Spatial anisotropy?!

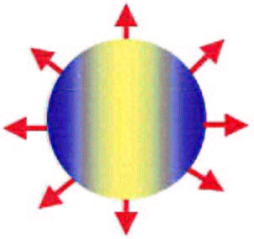
Ambiguity in Nature of the Spatial Anisotroy

$$v_2(p_T) = \frac{\int_0^{2\pi} d\phi_b \cos(2\phi_b) \mathrm{I}_2\left(\frac{p_T \sinh\rho}{T}\right) \mathrm{K}_1\left(\frac{m_T \cosh\rho}{T}\right) \left(1 + 2s_2 \cos(2\phi_b)\right)}{\int_0^{2\pi} d\phi_b \, \mathrm{I}_0\left(\frac{p_T \sinh\rho}{T}\right) \mathrm{K}_1\left(\frac{m_T \cosh\rho}{T}\right) \left(1 + 2s_2 \cos(2\phi_b)\right)}$$

ϕ_b = direction of the boost ⇒ $s_2 > 0$ means <u>more source elements</u> emitting in plane

Case 1: circular source with modulating density

$$f(\vec{x},\vec{p}) = K_1\left(\frac{m_T}{T}\cosh\rho\right) e^{\frac{p_T}{T}\sinh\rho\cos(\phi_s-\phi_p)} \left(1 + 2s_2 \frac{r}{R}\cos(2\phi_s)\right) \theta(R-r)$$



$\mathrm{RMS}_x > \mathrm{RMS}_y$

Case 2: elliptical source with uniform density

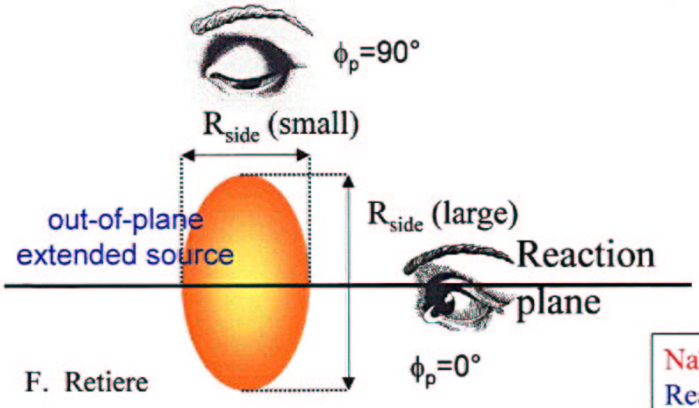
$$f(\vec{x},\vec{p}) = K_1\left(\frac{m_T}{T}\cosh\rho\right) e^{\frac{p_T}{T}\sinh\rho\cos(\phi_s-\phi_p)} \theta\left(1 - \sqrt{y^2 + \eta^2 x^2} / R_y\right)$$

$$\eta \equiv \frac{R_y}{R_x} \qquad s_2 \cong \frac{1}{2}\frac{\eta^3 - 1}{\eta^3 + 1}$$

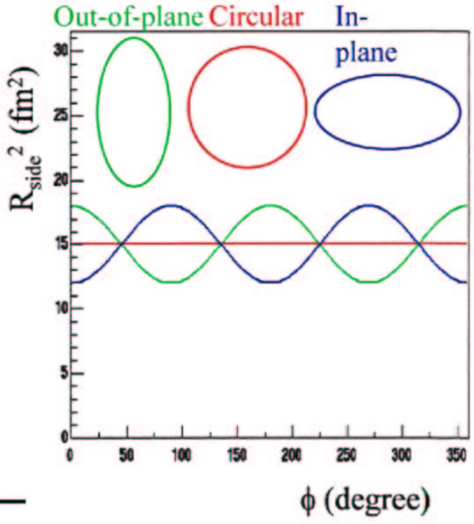
$\mathrm{RMS}_x < \mathrm{RMS}_y$

HBT with Respect to Reaction Plane - Motivation

- Elliptic geometry lead to oscillations of the radii
- For example R_{side}:



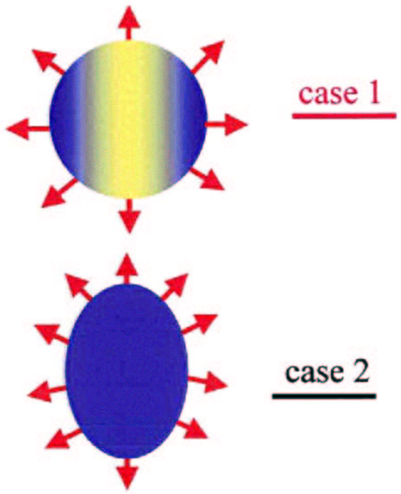
F. Retiere

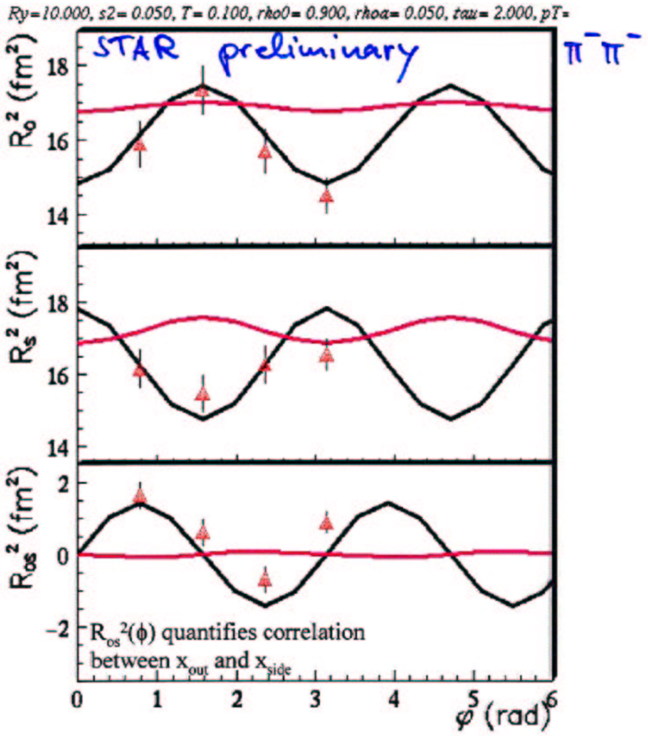


Naïve view with no flow
Reality: space-momentum correlation can “fake” anything

First Results: Out-of-plane Elliptical Shape Indicated

using (approximate) values of s_2 and ρ_a from elliptical flow



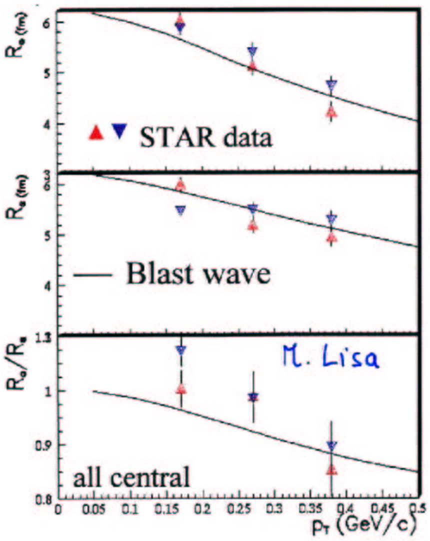


$R_{os}^2(\phi)$ quantifies correlation between x_{out} and x_{side}

•opposite R(ϕ) oscillations would lead to opposite conclusion

- Another hint for "short lived source"

Reminder: Pion HBT at RHIC – the R_{out}/R_{side} Puzzle

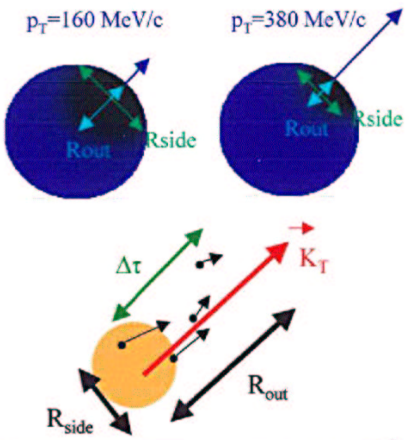


Space-momentum correlation distort the apparent source

- Effect increases with pt
  - Radii drop with pt
- R_{out} gets more squeezed than R_{side}

$$\cancel{R_O^2 = R_S^2 + (\beta\cdot\tau)^2}$$

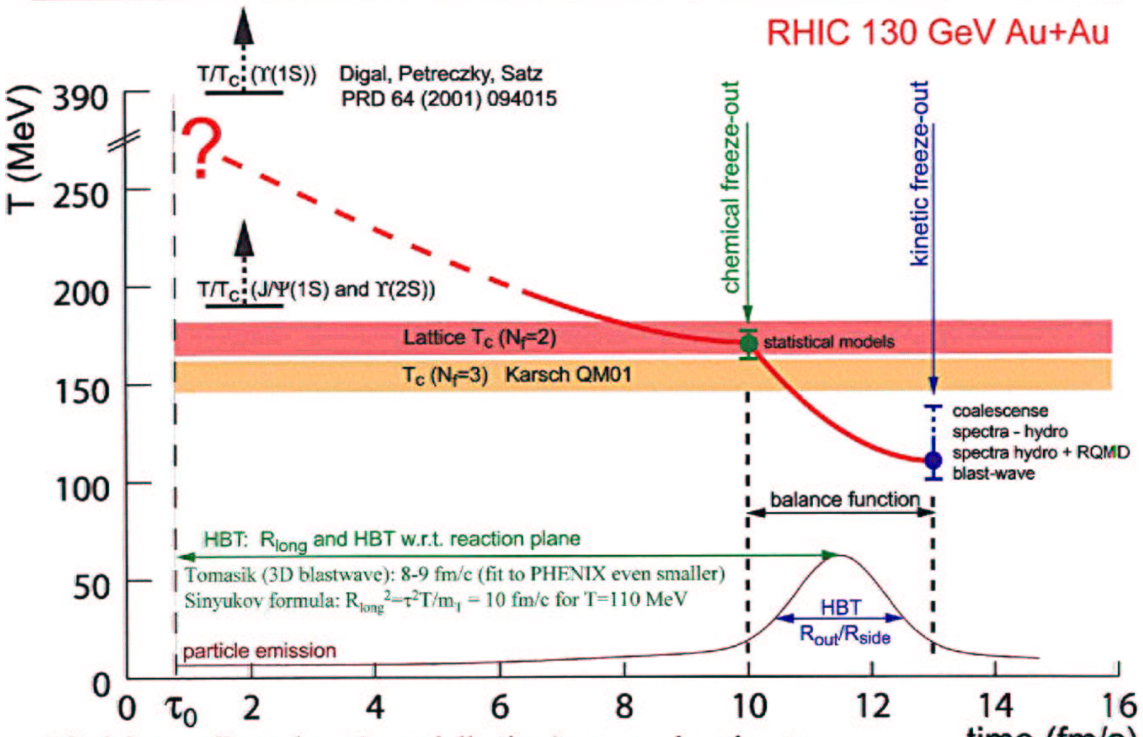
Adding emission duration enlarge R_{out} and leave R_{side} unchanged



Blast wave with "default" parameters

- p_T dependance of radii well reproduced
- Striking feature: short emission duration
  - Δτ = 1.5 fm/c

Summary



Disclaimer: all numbers (especially time) are rough estimates