Bulk Dynamics in Heavy Ion Collisions

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OSU MIT BNL

Plenary Session, RHIC/AGS Users Meeting

May 12, 2004

Acknowledgements

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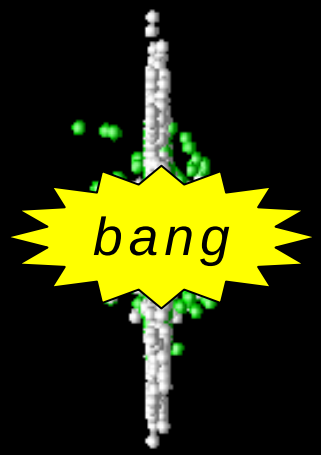
- Trento ECT*: Speaker Preparation

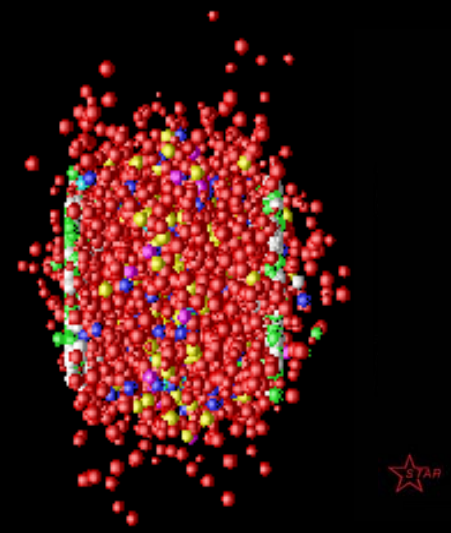
Thanks to our 11 Speakers

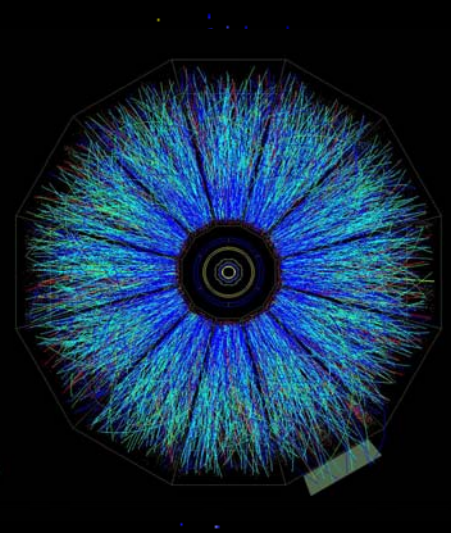
- **W. Busza** – Similarities among pp, pA, AA & e+e-
- **L. McLerran** – Bulk Dynamics: Key Issues
- **M. Lisa** – The HBT Excitation Function
- **D. Molnar** – Parton Coalescence & Flow
- **R. Snellings** – Elliptic Flow from SPS to RHIC
- **D. Teaney** – Hydrodynamics, Viscosity & Heavy Quarks
- **T. Renk** – Global Description of Heavy Ion Data
- **F. Becattini** – Statistical Models in High-Energy Collisions
- **M. Gazdzicki** – Strangeness & Deconfinement at the SPS
- **T. Trainor** – Correlations, Fluctuations, Thermalization
- **I. Klebanov** – Entropy and Viscosity from AdS/CFT

http://www.rhic.bnl.gov/~steinber/Bulk2004

What we do @ RHIC







We collide gold nuclei at the highest energies

Quarks & Gluons are released, creating a hot & dense state of matter

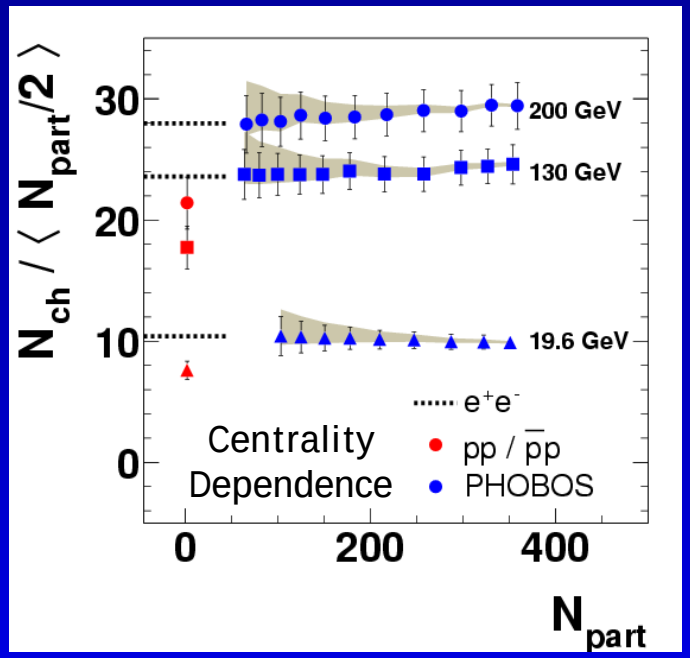
QGP "freezes out" to particles we know!

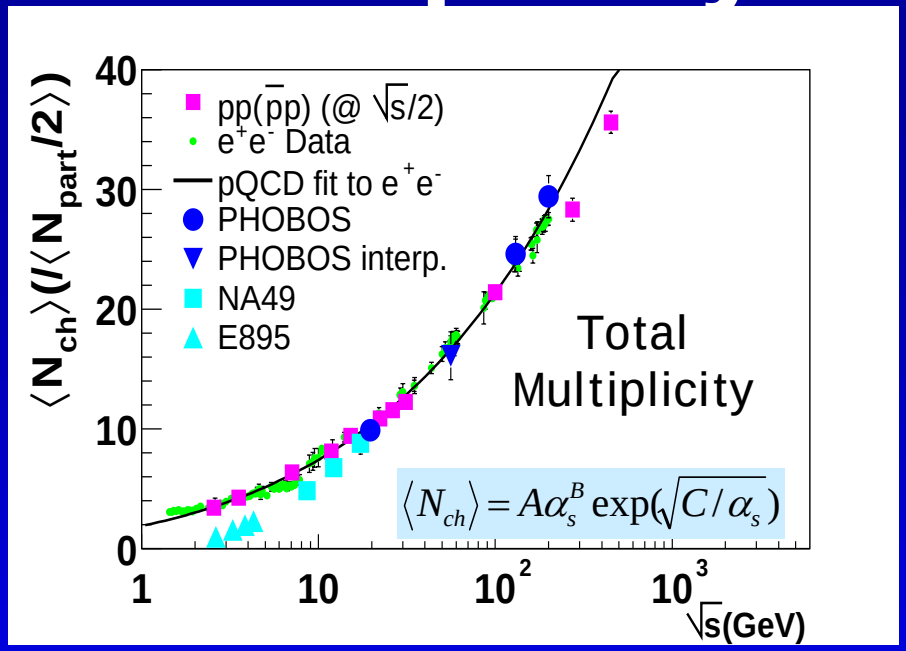
QGP

Quark-Gluon plasma

Experimental Results

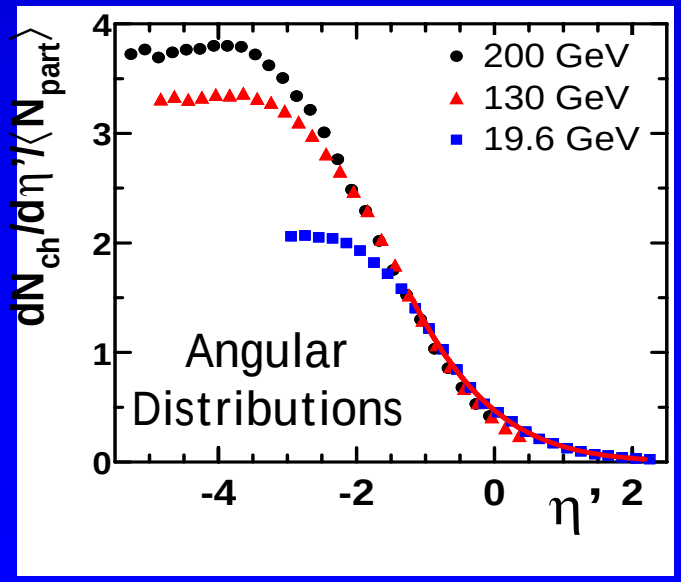
Scaling Laws for Multiplicity



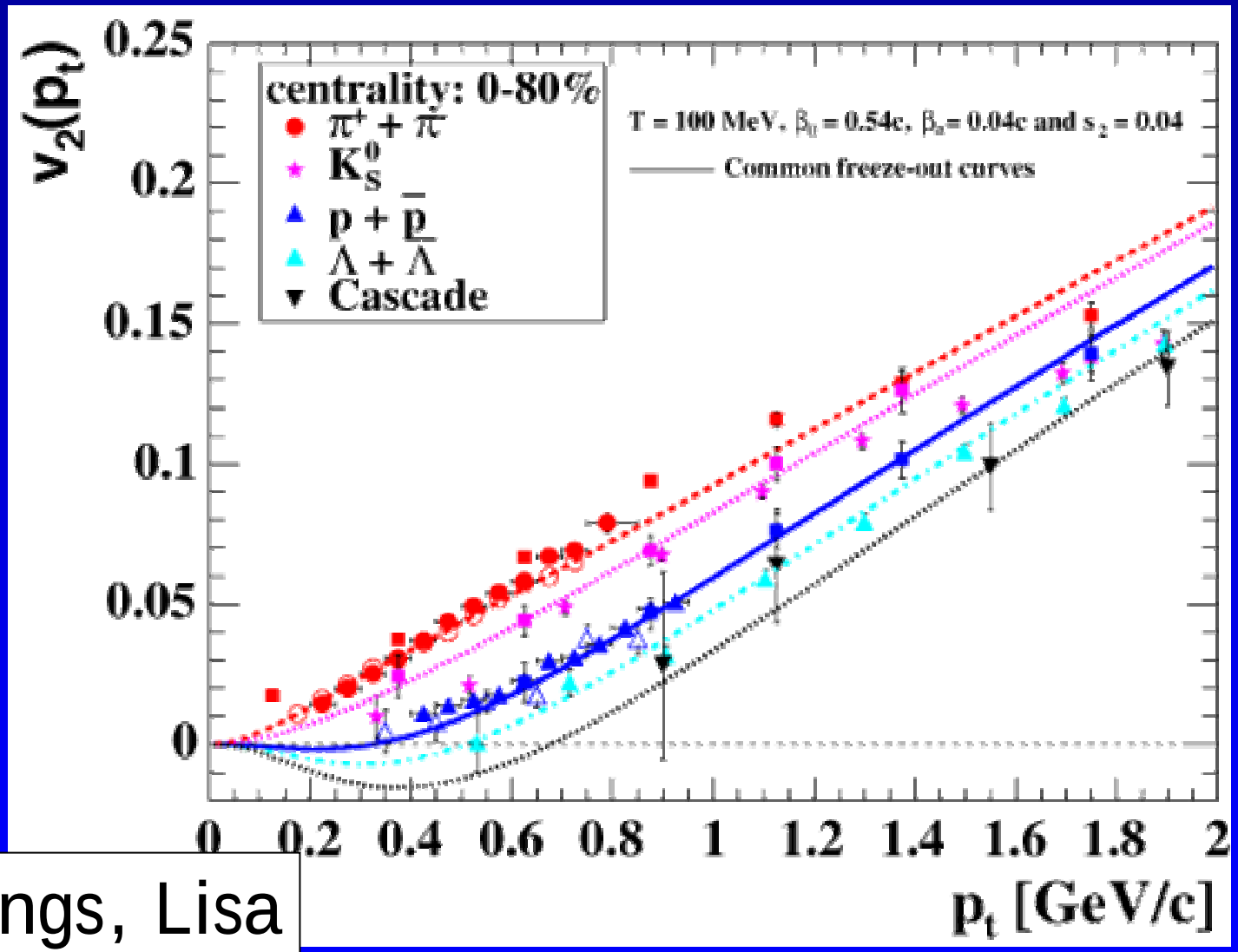


Busza

- ∇ N_{part} scaling of N_{ch}
- ∇ $N_{ch}(A+A)/(N_{part}/2) \rightarrow N_{ch}(e^+e^-)$
- ∇ "Limiting Fragmentation"



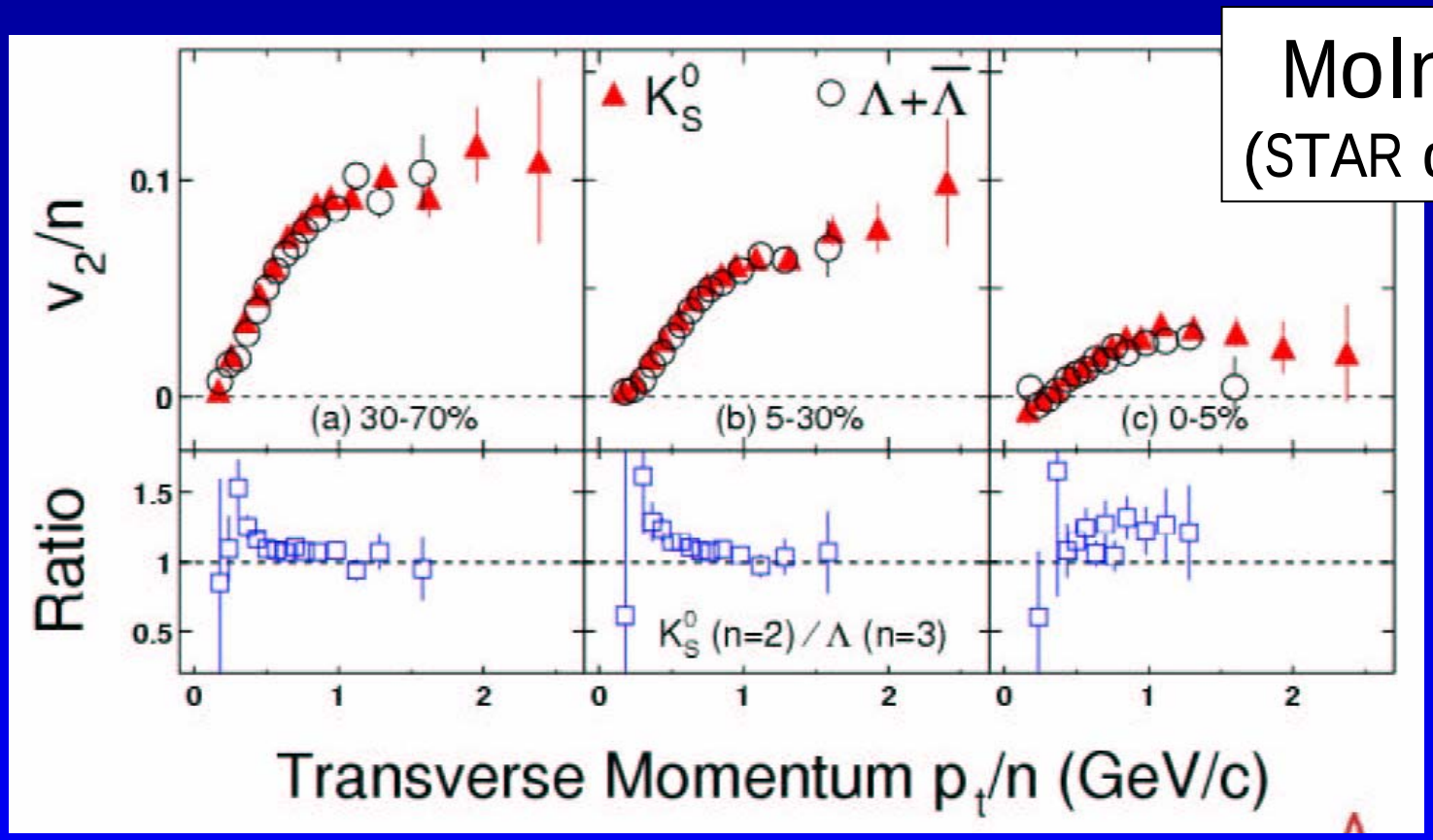
Blast-Wave Fits at Low-p_T



Snellings, Lisa

Captures low p_T dynamics at y=0

Coalescence at Moderate p_T

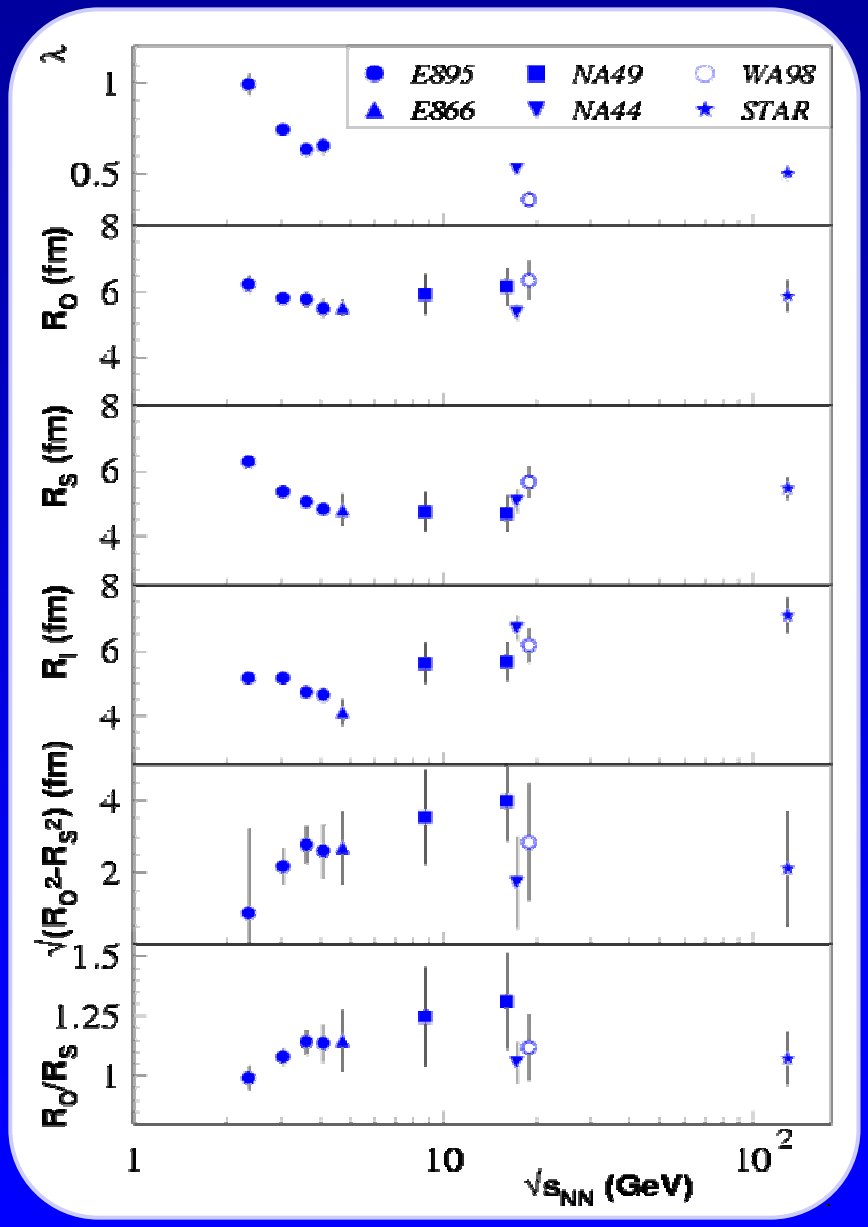


$$v_2^q(p_\perp) = v_2^\pi(2p_\perp)/2 = v_2^p(3p_\perp)/3 = v_2^\Lambda(3p_\perp) - 2v_2^p(3p_\perp)/3$$
$$v_2^s(p_\perp) = v_2^\phi(2p_\perp)/2 = v_2^\Omega(3p_\perp)/3 = v_2^K(2p_\perp) - v_2^\pi(2p_\perp)/2$$

Simplest $v_2^q = v_2^s$ **case:** $v_2^{hadron}(np_\perp)/n$ **universal fn.** ($n = 2, 3$ for meson, baryon)

Energy Dependence of HBT

Lisa



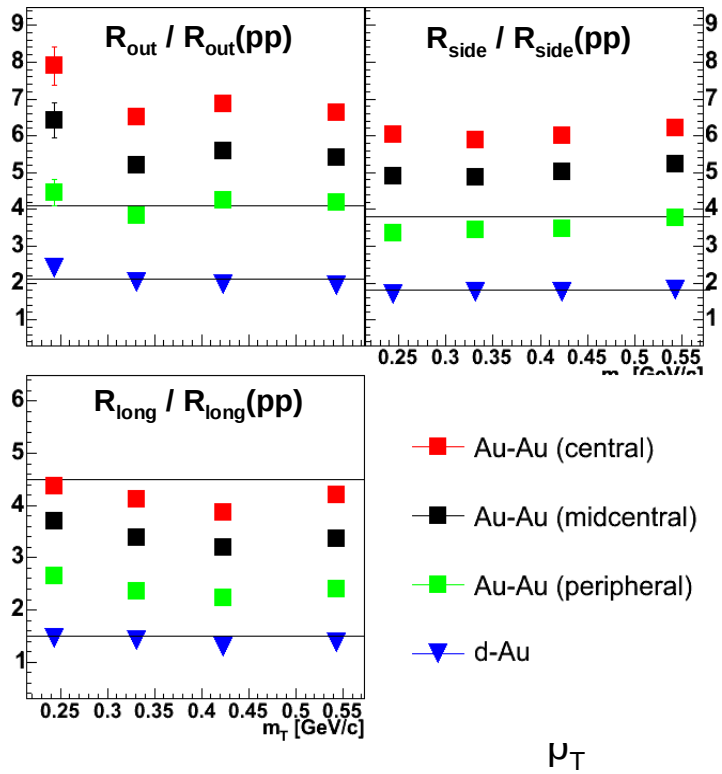
Nearly Featureless:
("Can't a dynamical Models give us 6fm?" - MAL)

m_T dependence: A+A vs. p+p

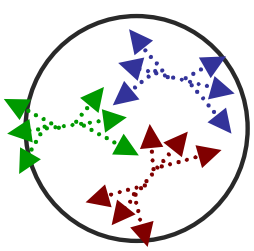
Lisa

$$\mathrm{HBT}(\sqrt{s}; p_T, y, |\vec{b}|, \phi_{\hat{b}}, m_1, m_2, A_{sys})$$

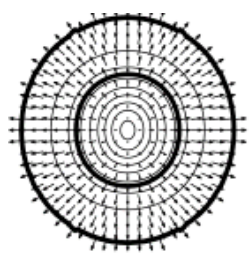
- latest "puzzle" in HBT?
- HBT radii from pp fall with p_T (as observed previously, usually attributed to string k_T kick)…
- …but as much (proportionally) as dAu and AuAu ??
  - coincidence…?
  - something deeper…?



p+p
string fragmentation



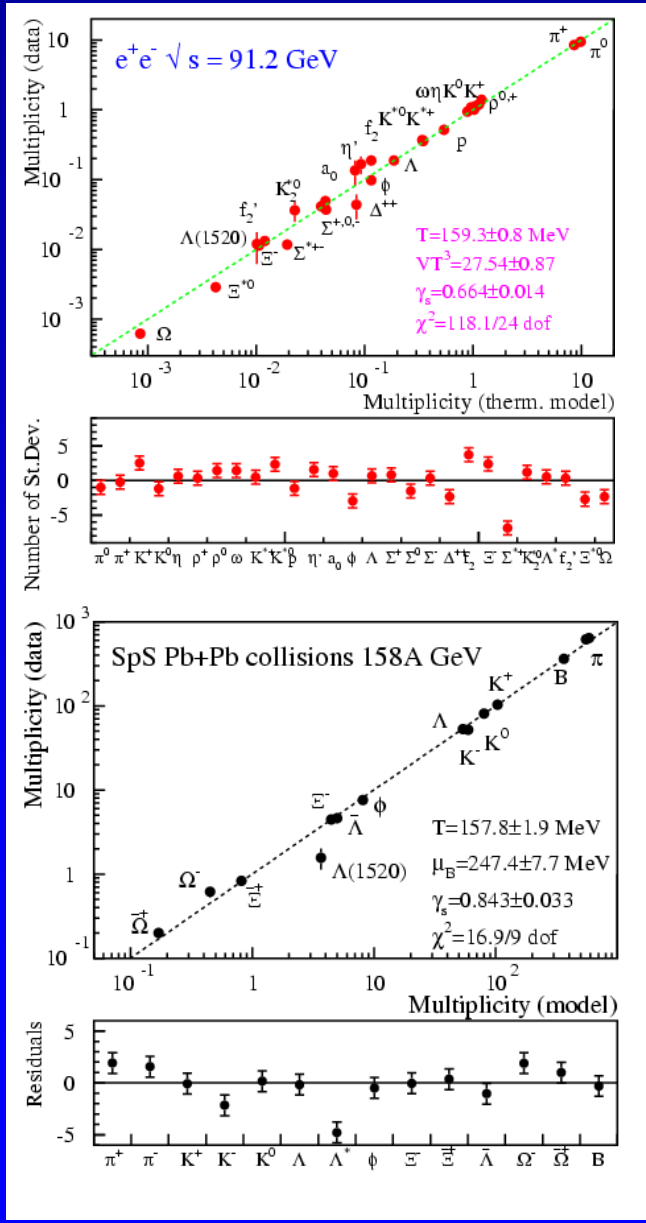
Au+Au
Collective expansion



transverse plane

STAR, QM04

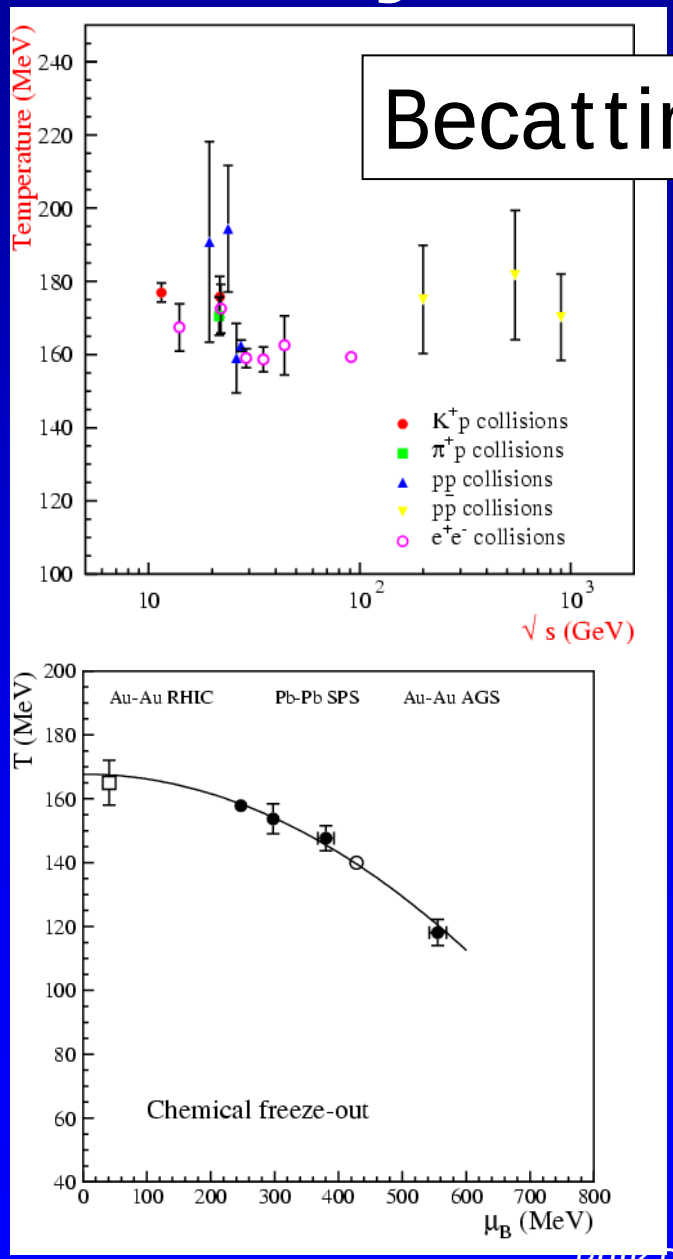
Thermal Yields Work Everywhere



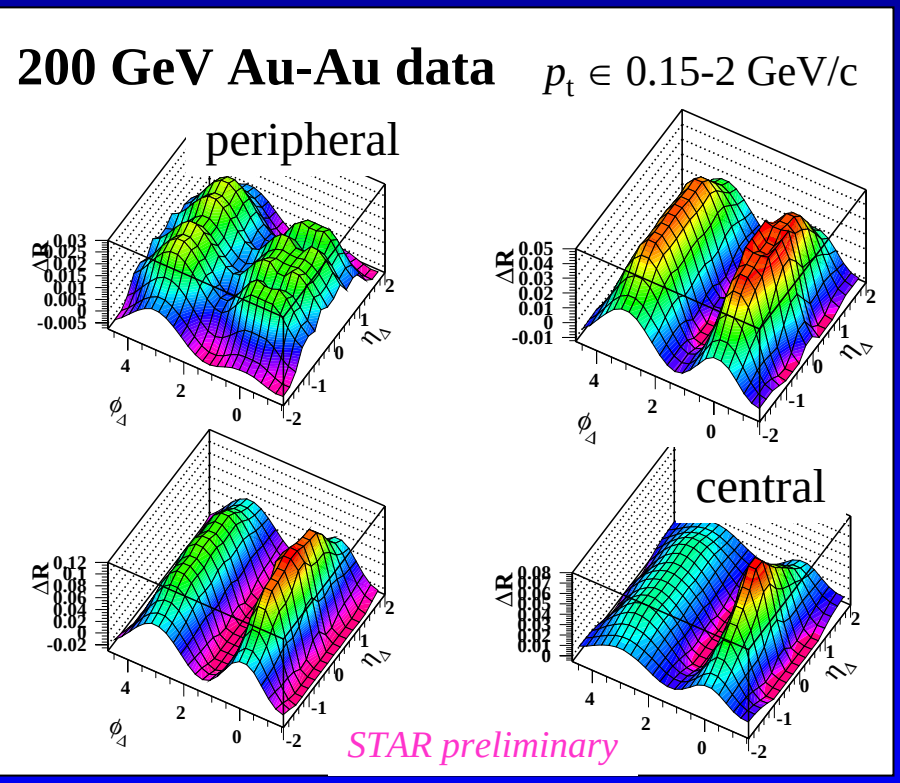
e+e-

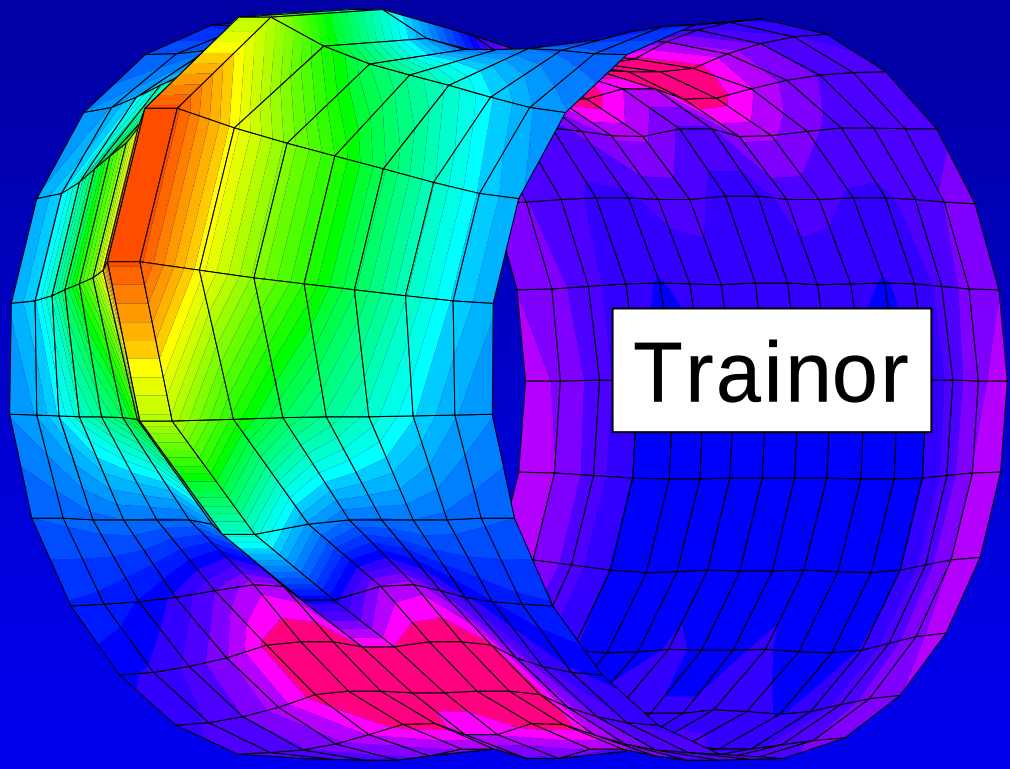
p+p

A+A



Two-Particle Correlations





p_T-p_T correlations → "Neck Formation" from minijets:
Coupling of "hard" with "soft", perhaps via energy loss

Data is Simple, but not Trivial

Busza

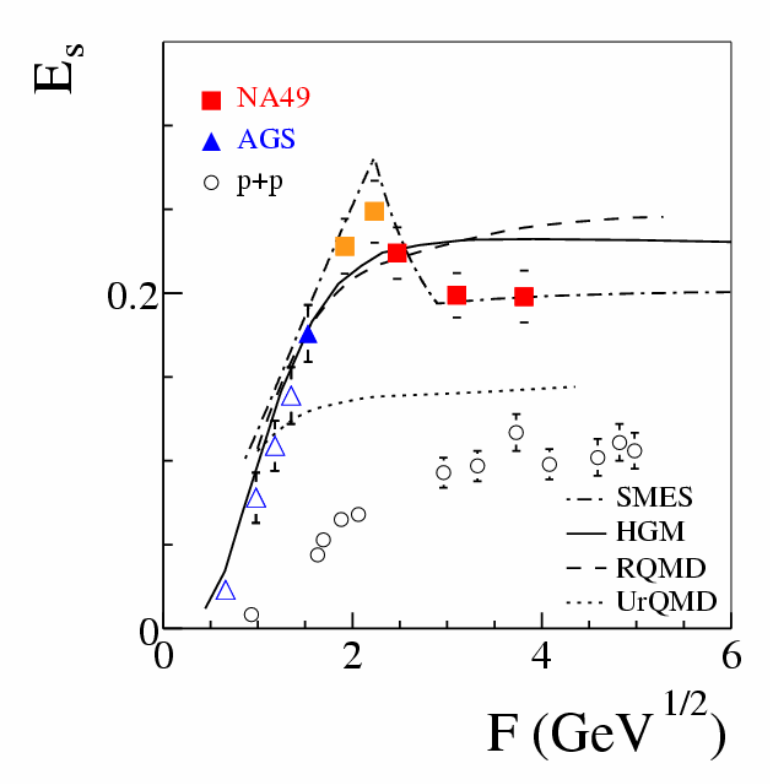
What I see in the multiparticle production data

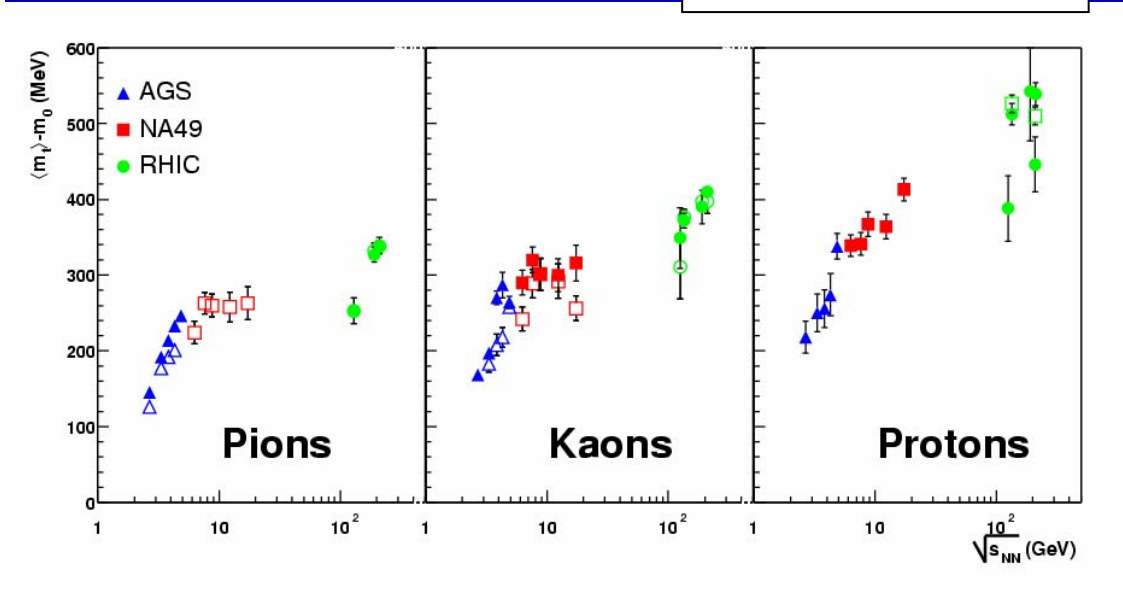
1. Same features occur in e^+e^-, pp, pA, dA and AA from 10 to 200GeV
2. For all systems, at all energies, the features can be described in terms of a few simple rules
3. Npart is a key parameter
4. Considering that we are certainly passing through very different intermediate states, the similarity of the features in e^+e^-, pp, pA, dA, and AA is intriguiging, it suggests that the number of final particles produced in any element of longitudinal phase space is determined by the early stages of the collision process
5. Expanding "fragmentation region" clearly shows something is saturating
6. Strongly interacting matter seems to be remarkably "black" to fast partons.

I am convinced that any correct theoretical description of AA collisions will automatically contain the basic features described in this talk. They will not be the consequences of detailed calculations or accidents.

Horn & Step

Gazdzicki





Clear motivation for systematic scans (energy, centrality, species)

Theoretical Issues

Transport & Coalescence

Coalescence dynamics - puzzle

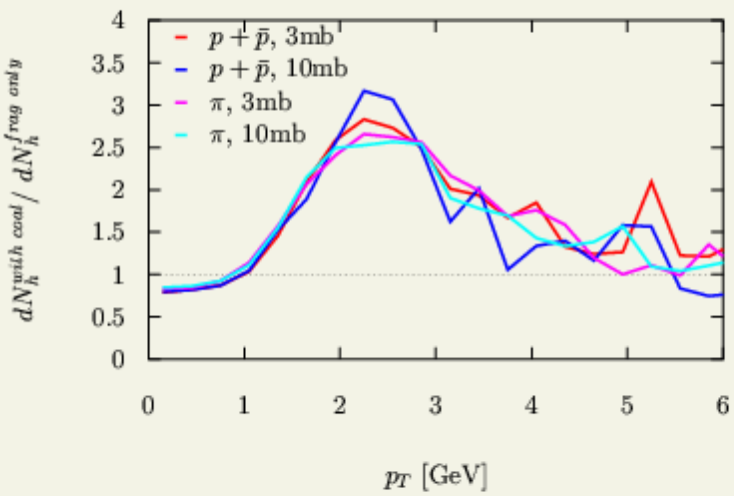
Molnar

parton transport + coalescence (e.g., MPC, AMPT, VNI/BMS)

hadronization: - partons nearby in phasespace coalesce, those without a partner fragment
- weakly-bound hadrons

Au+Au @ 200 GeV, b=8 fm - hadron enhancement

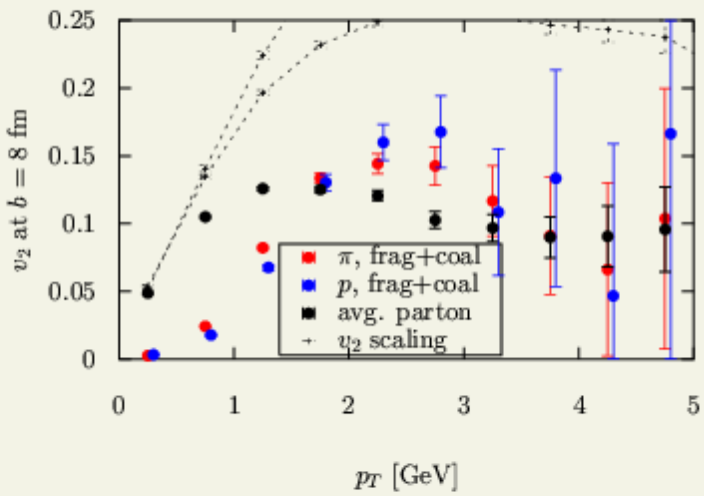
D.M. ('04):



- $2-3\times$ enhancement over fragmentation for $1.5 < p_T < 4$ GeV

but same for protons as pions $\Rightarrow$ p/π stays low
$\rightarrow$ baryons have more constituents $\Rightarrow$ are more "fragile"

elliptic flow

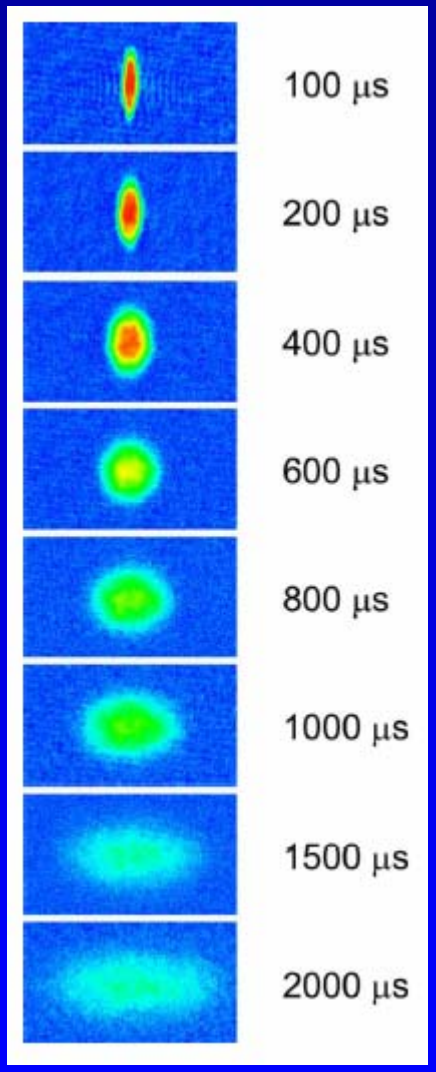


- flow amplification negated
  $\rightarrow$ 25-30% frag contribution, reduces flow
  $\rightarrow$ dynamical correlations, $f(\vec{x},\vec{p}) \neq F(\vec{x})g(\vec{p})$
  imperfect scaling
- baryon-meson splitting disappeared

D. Molnar, RHIC/AGS Users' Meeting, May 10-14, 2004 27

Hydrodynamic Evolution

Snellings, Lisa, (Shuryak)



Strongly-interacting ^{6}Li released from an asymmetric trap
O'Hara, *et al*, Science **298** 2179 (2002)

Apparently a generic feature of strongly-coupled systems:

good for cold atoms

good for hot strongly-interacting matter

Does apparent "universality" here mean that RHIC is teaching us more about strongly-interacting systems than the structure of QCD?

Is the QGP Strongly Interacting?

McLerran

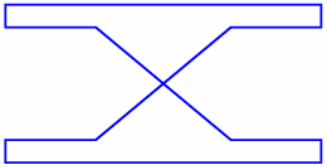
Why is Mean Free Path so Small in the QGP?

Need $\lambda_{QGP} \sim .3\ fm$!
Is this reasonable?

If weakly coupled QGP
$\lambda_{QGP} \sim 1/\alpha^2 ln(1/\alpha)T$
Requires strong coupling!
SON: SUSY theory in strong coupling OK

Large N_c :

x 1/Nc ~ 1



x $1/Nc^2$ ~ 1/Nc

$\sigma \sim 1/Nc^2$

Both Mesons & Partons

7

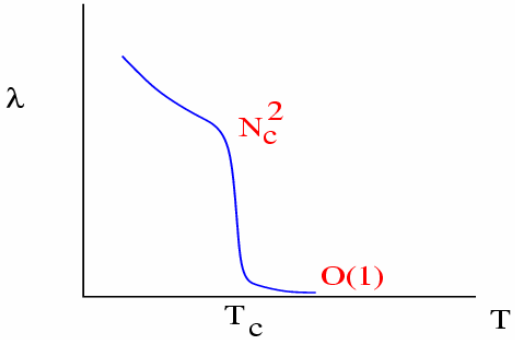
Small Mean Free Paths:

In QGP,
$\sigma \sim 1/N_c^2$
Constituent cross sections should vary by of $O(1)$ in N_c across the transition

Mean free paths
$\lambda \sim 1/(\sigma\rho)$
In QGP
$\rho \sim N_c^2$
and in meson gas
~ 1

$\lambda_{QGP} \sim 1$

$\lambda_{HG} \sim N_c^2$



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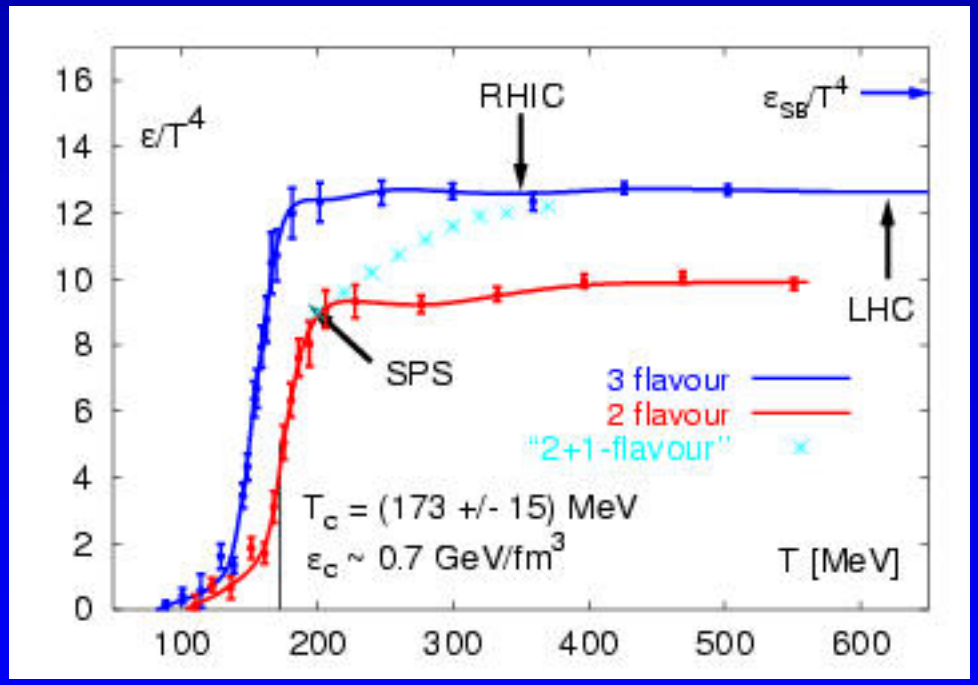
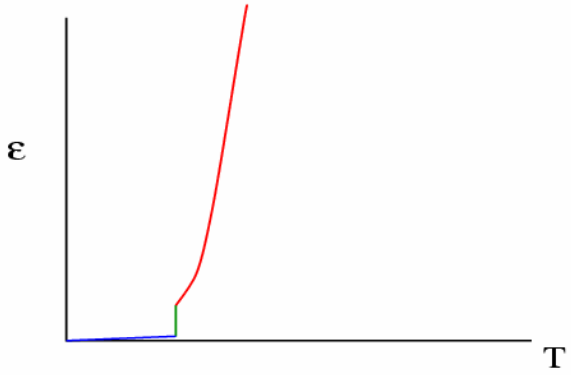
Can We Observe A Phase Transition?

McLerran



v2 and Equation of State

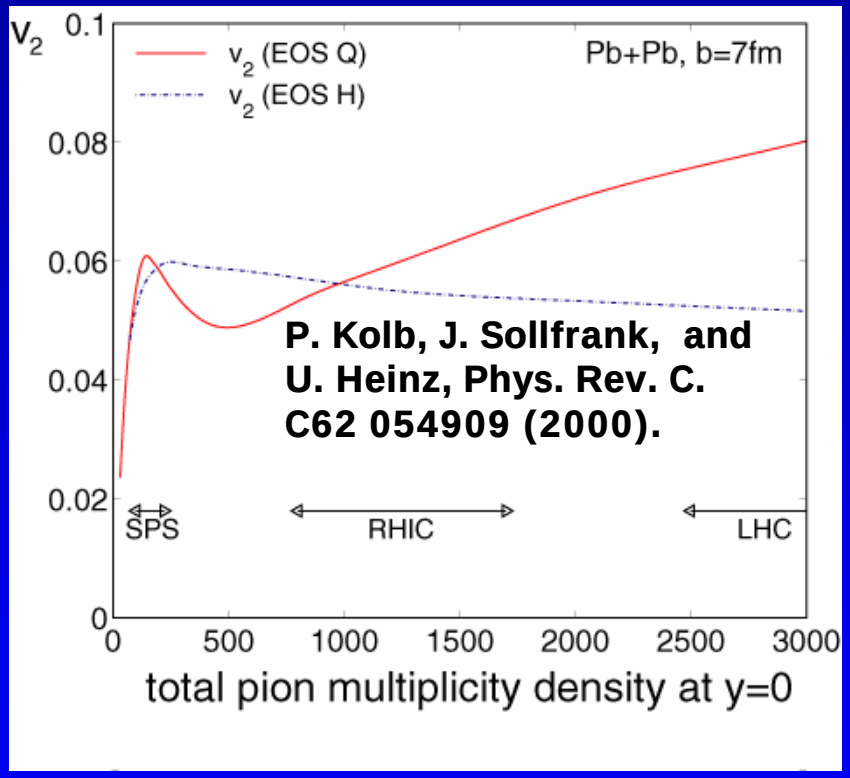
Warning:
If energy density is 20-30 Gev/Fm^3
at the earliest times when thermalization
is OK:

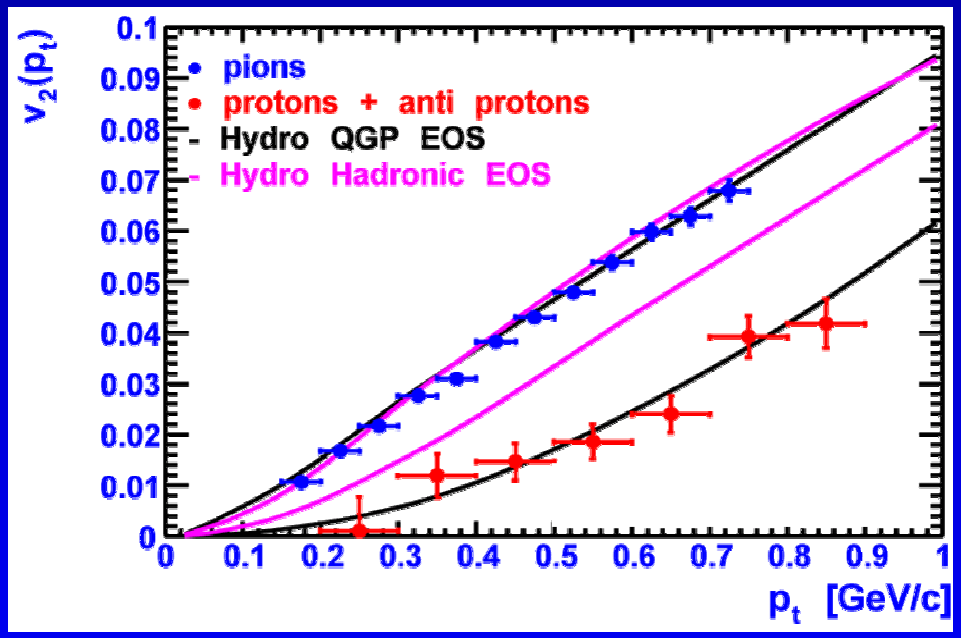


Effects of cross over swamped

Phase Transitions with v_2

Snellings

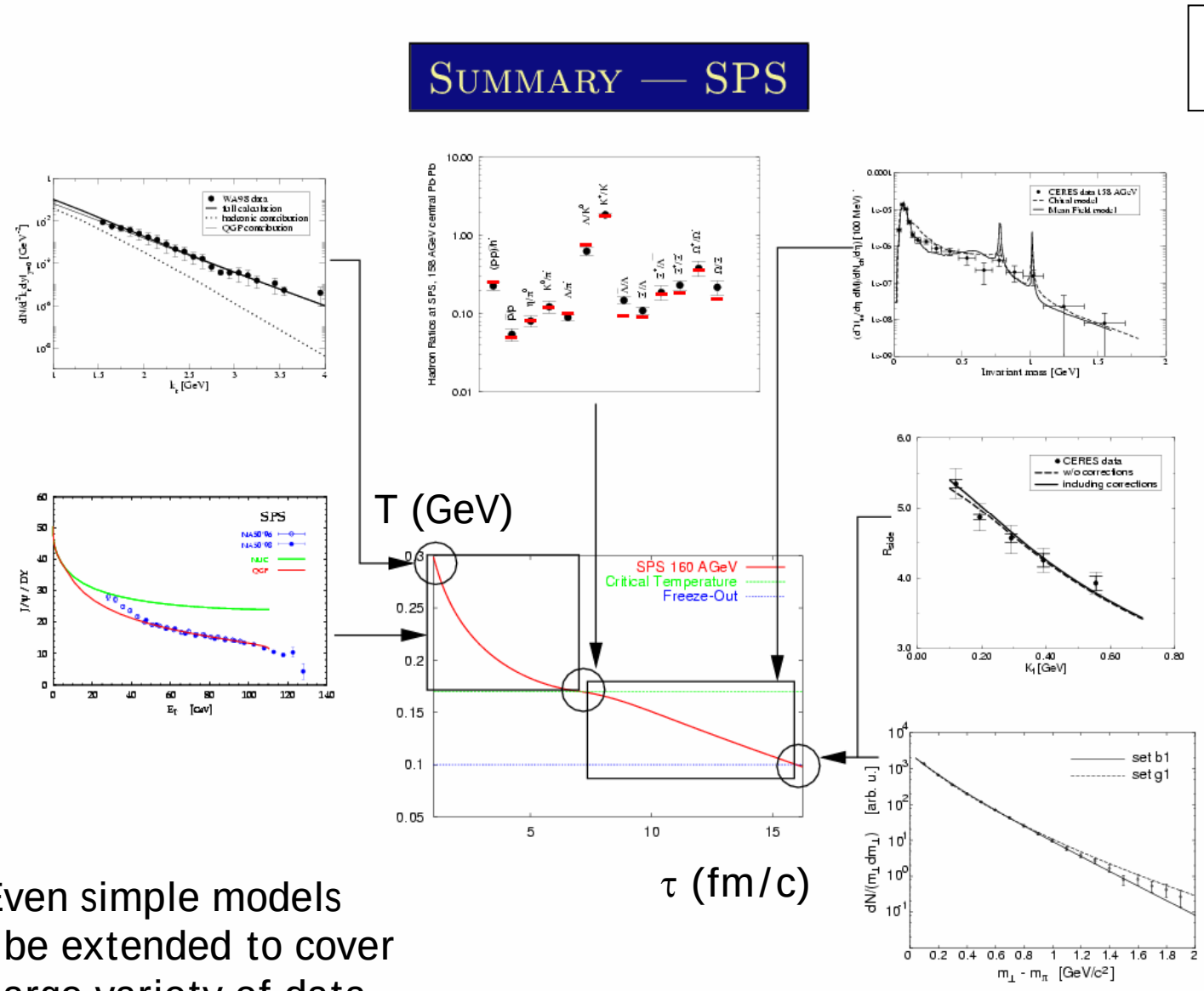




Particle Density + Hydro + EOS = Prediction for v_2

Global Fits to Heavy Ion Data

Renk



Even simple models can be extended to cover a large variety of data

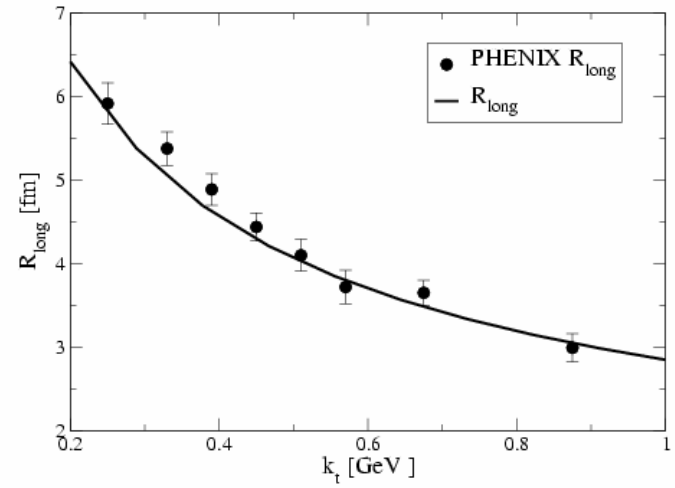
Hydro & Boost Invariance

Initial long. compression and re-expansion is required for both SPS and RHIC

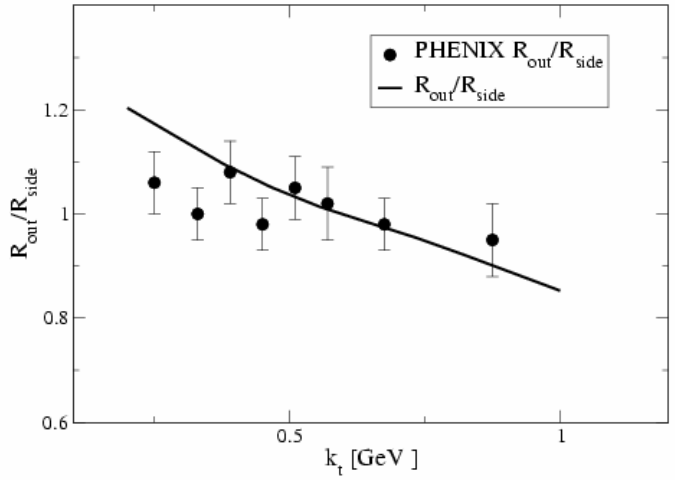
	SPS	RHIC
Transverse flow:	moderate, $v_\perp^f = 0.53c$	strong, $v_\perp^f = 0.65c$
Longitudinal dynamics:	$\eta_0 = 0.55$, $\eta_f = 1.5$	$\eta_0 = 1.8$, $\eta_f = 3.6$
Initial temperature:	$T_i = 300$ MeV (τ_0 =1 fm/c)	$T_i = 350$ MeV (τ_0 =0.6 fm/c)
Duration of QGP phase:	≈ 7 fm/c	≈ 7.5 fm/c

Expressions and estimates based on boost-invariant expansions do not work

Renk



T. Renk, hep-ph/0404140



Importance of Viscosity

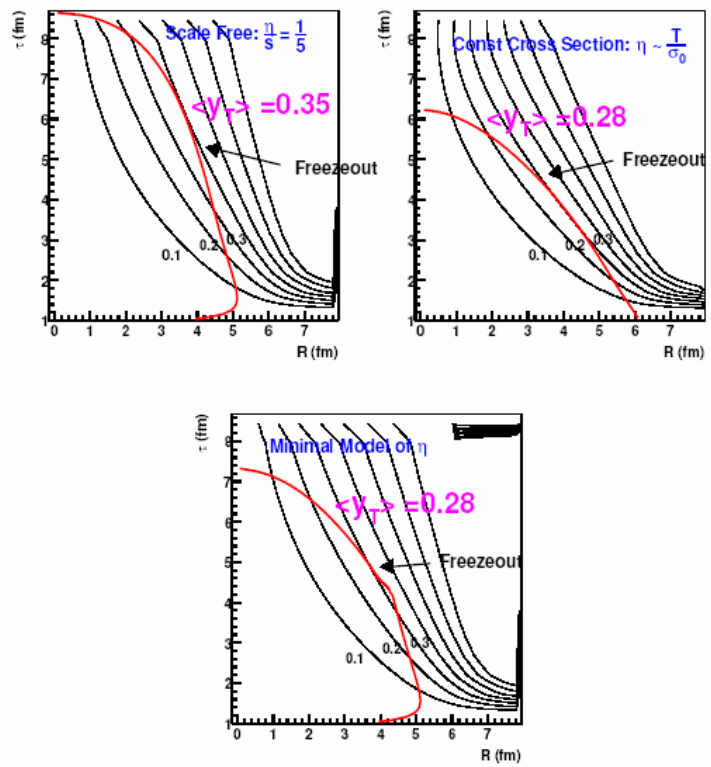
Teaney

	σ	1 D Expansion	3 D Expansion
$\eta \propto T^3$	$\frac{\alpha_s}{T^2}$	++ $\sim \frac{1}{\tau^{2/3}}$	Const.
$\eta \propto T$	σ_0	Const.	-- $\sim \frac{\tau^2}{\sigma_0}$

$$\frac{\Gamma_s}{\tau} = \frac{4}{3\tau T}\frac{\eta}{s} \ll 1$$

Viscous effects do not substantially modify radial flow from ideal hydro. Elliptic flow?...

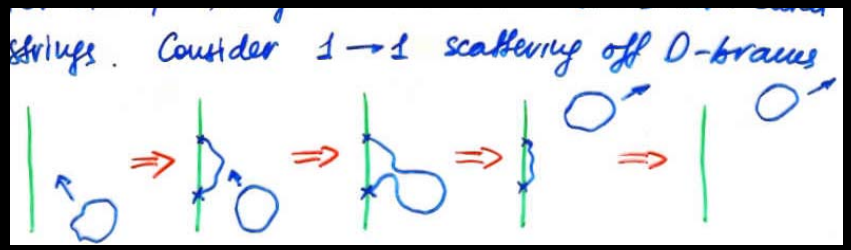
Compare the three models of viscosity:



The minimal model of η and the Const X.-section model of η yield the same amount of radial flow.

Klebanov: AdS/CFT

Closed Strings scatter
from Black D3-Branes
in Anti-deSitter Space
(AdS)



Gravity theory in
9+1 dimensions

"Dual" to a 3+1D "N=4 SYM" Supersymmetric Yang-Mills Theory

Lives on the "boundary" of the 9+1D space

Entropy & Viscosity from AdS/CFT

$$\boxed{S_{BH} = \frac{2\pi A}{\kappa^2} = \frac{\pi^2}{2} N^2 T^3 V}$$

T^3 scaling as expected in a CFT;

N^2 scaling characteristic of $SU(N)$ gauge theory.

On general field theory grounds we have

$$S = f(g_{YM}^2 N)\frac{2\pi^2}{3} N^2 T^3 V,$$

power of T fixed by scale invariance

and perturbative calculations give

$$f = 1 - \frac{3}{2\pi^2} g_{YM}^2 N + \frac{3+\sqrt{2}}{\pi^3}(g_{YM}^2 N)^{3/2} + \ldots$$

AdS

A calculation for low-energy scattering off a black hole (black D3-Brane…)

In general, $\sigma(0)$ = Horizon Area

For 3-branes,

$\sigma(0) = \pi^3 r_0^3 R^2$

The viscosity at $g^2 N \to \infty$,

$$\eta = \frac{1}{2\kappa^2}\sigma(0) = \frac{\pi}{8} N^2 T^3,$$

where again we used $T = \frac{r_0}{\pi R^2}$.

Since $s = \frac{S}{V} = \frac{\pi^2}{2} N^2 T^3$,

$$\frac{\eta}{s} = \frac{1}{4\pi} \quad \text{for } g^2 N \to \infty.$$

Is this the lowest possible value? (Kovtun, Son, Starinets)

$$\frac{\eta}{s} = \frac{\hbar}{4\pi k_B} \approx 6.08 \times 10^{-13}\ K\text{-}s$$

For water under normal conditions, $\eta/s \approx 2.3 \times 10^{-10}$ K-s (400 Larger than $\frac{\hbar}{4\pi k_B}$)

Liquid ^{4}He at 1 MPa, T=10K $\Rightarrow \approx 6 \times 10^{-12}$ K-s.

CFT

…gives information about the dual YM theory

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

Gauge-String Duality & Us

Duality:

Weakly-Coupled QCD (pQCD) ←→ Strongly coupled strings

<u>Weakly coupled strings ←→ Strongly-Coupled QCD</u>

1000's of papers working on strongly-coupled (S)QCD(s)
(unfortunately not "our" QCD)

"Simple" AdS equations ←→ Infinitely summed SYM diagrams

Will this help us understand the apparently simple principles behind soft RHIC physics?

Bulk Dynamics 2004

- ∇ Experimental Input
  - Scaling rules for multiplicities
  - Utility of blast wave for radial & elliptic flow
- ∇ Theoretical Issues
  - Thermalization (why so robust in small systems?)
  - Difficulties with dynamical transport models
  - EOS (DOF vs. ε) may be difficult to access
  - Hydrodynamic evolution is generic
    - How does QCD (esp. pQCD) fit into this story?
  - Boost invariance not a good assumption anymore
- ∇ Interesting input from strings (branes!) via AdS/CFT
  - Entropy, Viscosity, Confinement from…gravity?