Explore the QCD Phase Diagram

- Partonic Equation of State at RHIC

Nu Xu
Lawrence Berkeley National Laboratory

Many Thanks to the Organizers

Outline

1) Introduction
   - Hydrodynamic approach
   - Collectivity vs. local thermalization

2) Recent experimental data
   - Transverse momentum distributions
   - Partonic collectivity at RHIC

3) Outlook
   - Heavy quark measurements
     ➔ ***thermalization***
   - RHIC energy scan
     ➔ ***QCD tri-critical point***

Physics Goals at RHIC

- Identify and study the properties of the matter (EOS) with partonic degrees of freedom.

- Explore the QCD phase diagram.

Hydrodynamic Flow = *Collectivity* ⊗ Local Thermalization

Pressure, Flow, …

$$\tau d\sigma = dU + pdV$$

σ– entropy; p – pressure; U – internal energy; V – volume
$\tau = k_B T$, thermal energy per dof

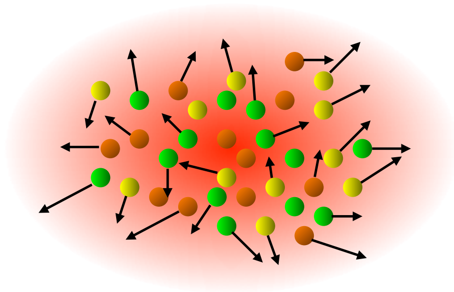
In high-energy nuclear collisions, *interaction* among *constituents* and *density distribution* will lead to:

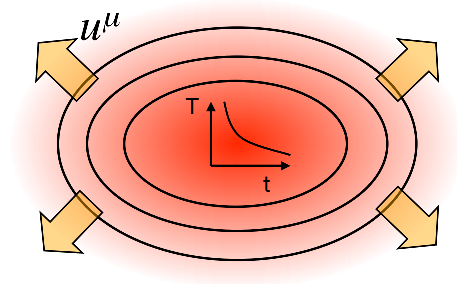
pressure gradient ⇔ collective flow

⇔ number of degrees of freedom (dof)
⇔ Equation of State (EOS)
⇔ No thermalization is needed – pressure gradient only depends on the ***density gradient and interactions***.
⇒ Space-time-momentum correlations!

Timescales of Expansion Dynamics

microscopic view vs **macroscopic view**





scattering rate $\nu_{ab} \sim$

$$\int \frac{d^3 p_a}{(2\pi)^3} \frac{d^3 p_b}{(2\pi)^3} f_a(p_a) f_b(p_b) \sigma_{ab}(s) \left| \vec{v}_a - \vec{v}_b \right|$$

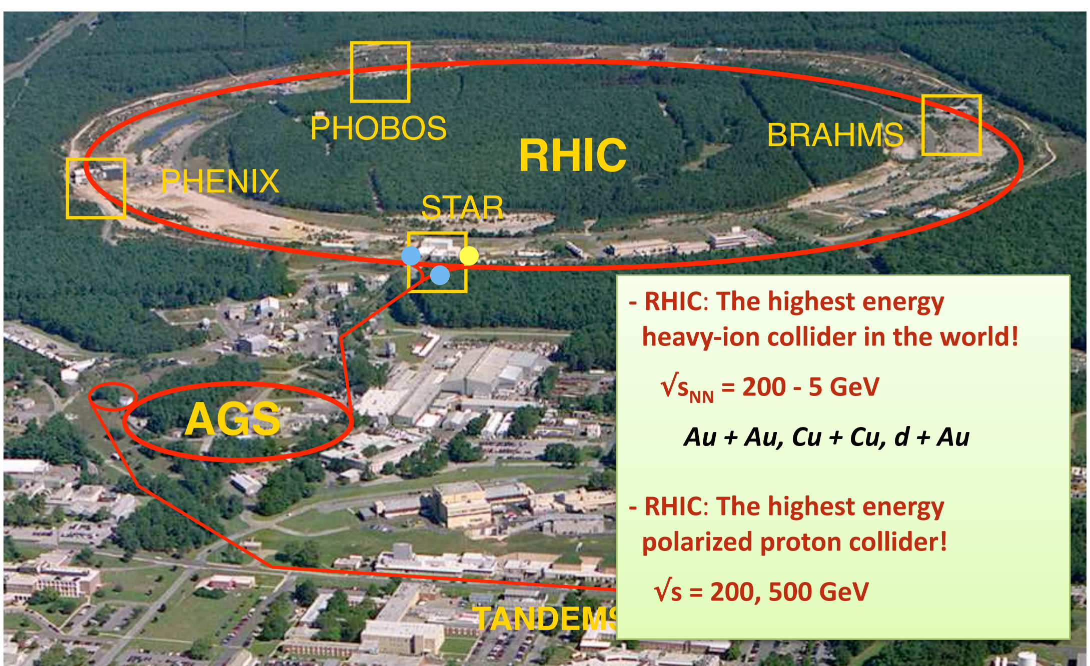
expansion rate $\partial_\mu u^\mu$

dilution rate $\partial_\tau s$

A macroscopic treatment requires that the scattering rate is larger than macroscopic rates

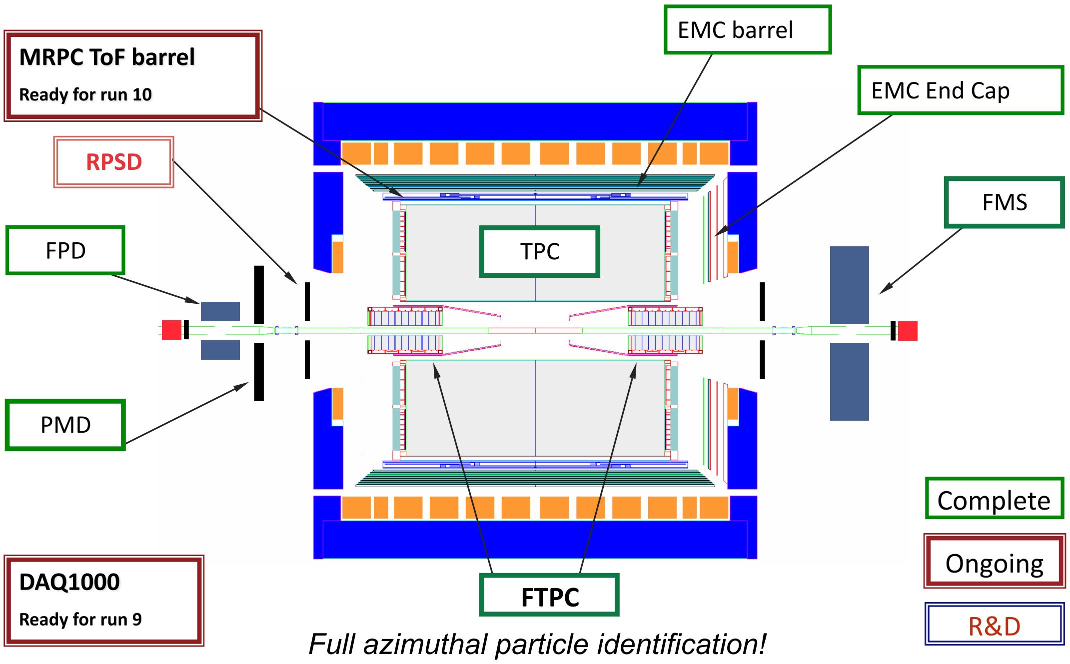
Relativistic Heavy Ion Collider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY



Animation M. Lisa

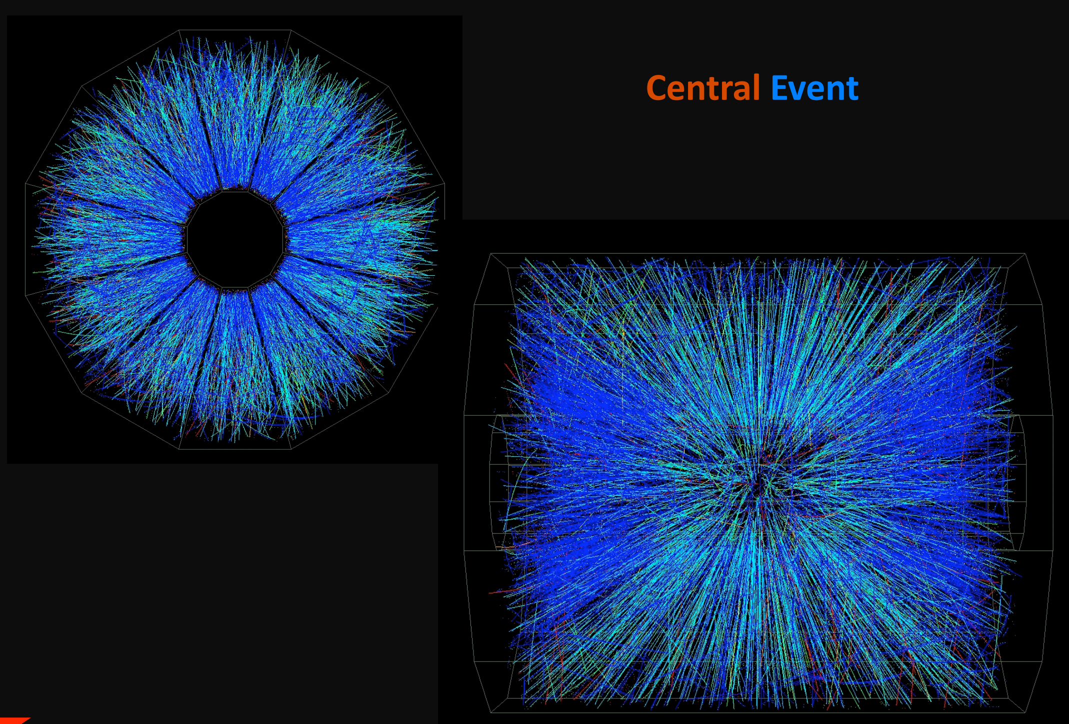
STAR Detector



Full azimuthal particle identification!

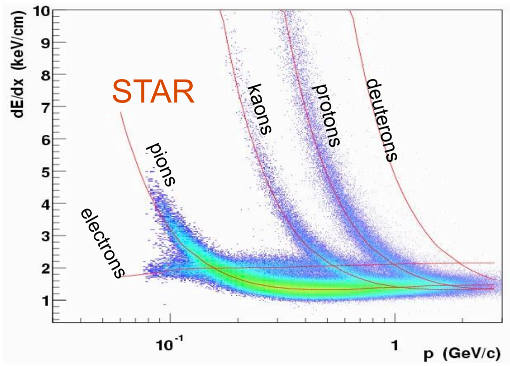
$e, \pi, \boldsymbol{\rho}, K, \boldsymbol{K^*}, p, \boldsymbol{\varphi}, \Lambda, \Delta, \Xi, \Omega, D, \Lambda_C, \boldsymbol{J/\psi}$ …

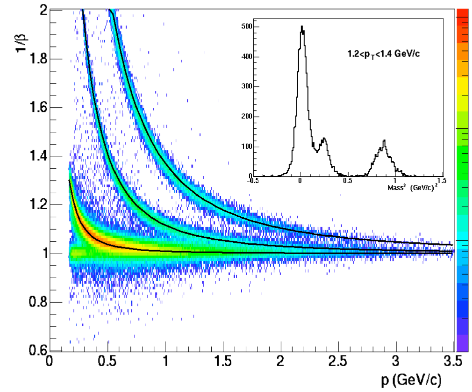
Au + Au Collisions at RHIC



STAR (real-time Level 3)

Particle Identification (i)





STAR TPC:
1) dE/dx PID up to p ~ 1 GeV/c
$|y| < 0.5$; $p_T \sim 1$ GeV/c
2) Azimuthal acceptance: ~ 2π
3) Tracking efficiency: ~ 90%, homogenous

STAR MRPC TOF: nucl-ex/0309012
1) Timing resolution: ~ 85 ps
2) PID: π and K ~ 1.9 GeV/c
p and π/K ~ 3 GeV/c
3) Efforts on R&D by ALICE at CERN

Other methods: conversion, EMCal, SVT, Si-μ vertex detector, …

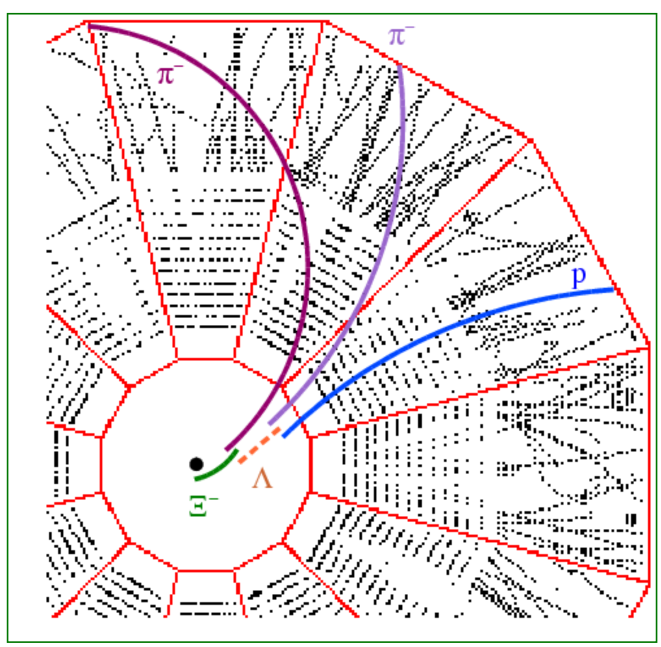
Reconstruction V^0

Multi-strange particles are reconstructed via the decay mode：

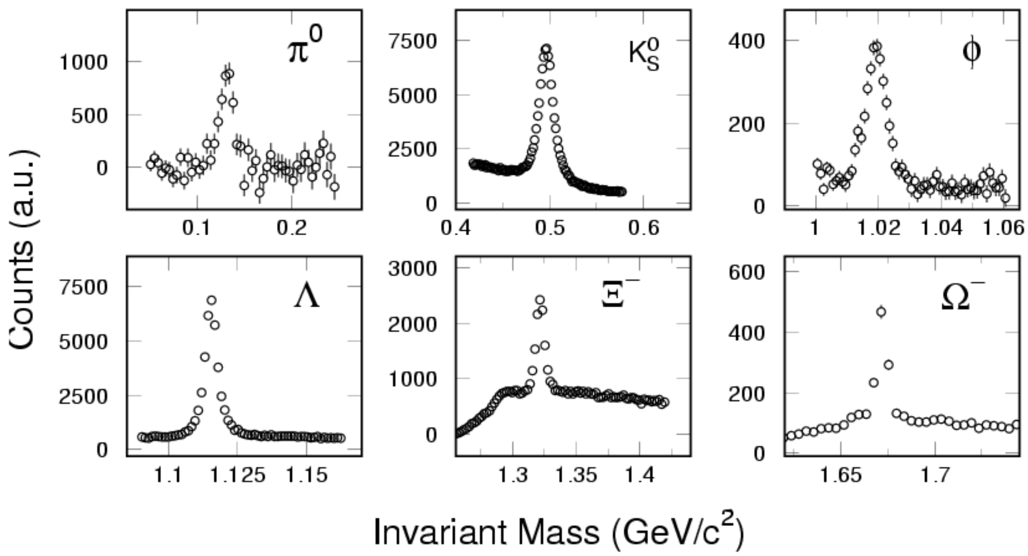
$$\Xi \Rightarrow \Lambda + \pi$$
$$\hookrightarrow p + \pi$$

Combination of momenta of the daughter particles

⇒ invariant mass spectra



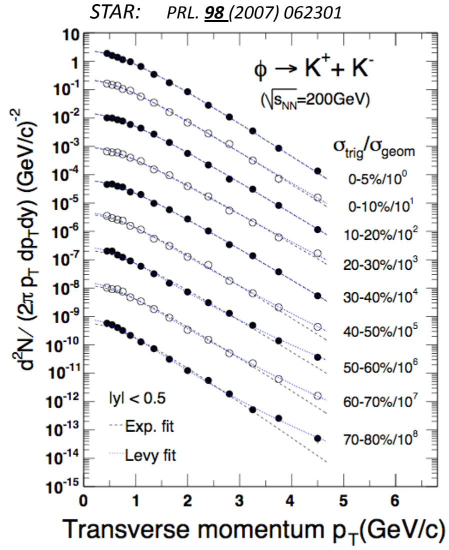
Particle Identification (ii)

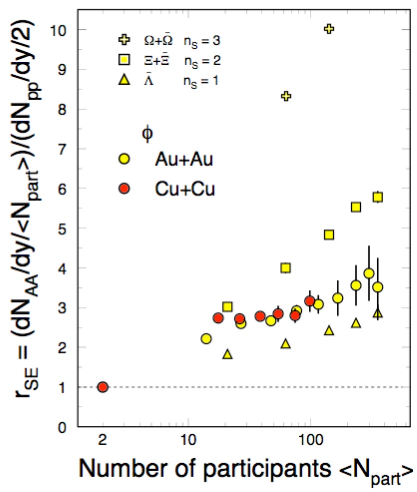


Reconstruct particles in full azimuthal acceptance of STAR!

ϕ-mesons from Au+Au Collisions

STAR: PRL. __98__ (2007) 062301





ssbar fusion ⇨ ϕ-meson formation!

STAR: Phys. Lett. *B612*, 81(2005)

The observed strangeness enhancement is NOT due to the Canonical suppression!

STAR: Preliminary

Transverse Flow Observables

$$\frac{d\sigma}{d\Omega} = \frac{d^3\sigma}{dp_x dp_y dp_z} = \frac{dN}{p_T dp_T dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left[1 + \sum_{i=1} 2v_i \cos(i\varphi)\right]$$

$$p_T = \sqrt{p_x^2 + p_y^2}, \qquad m_T = \sqrt{p_T^2 + m^2}$$

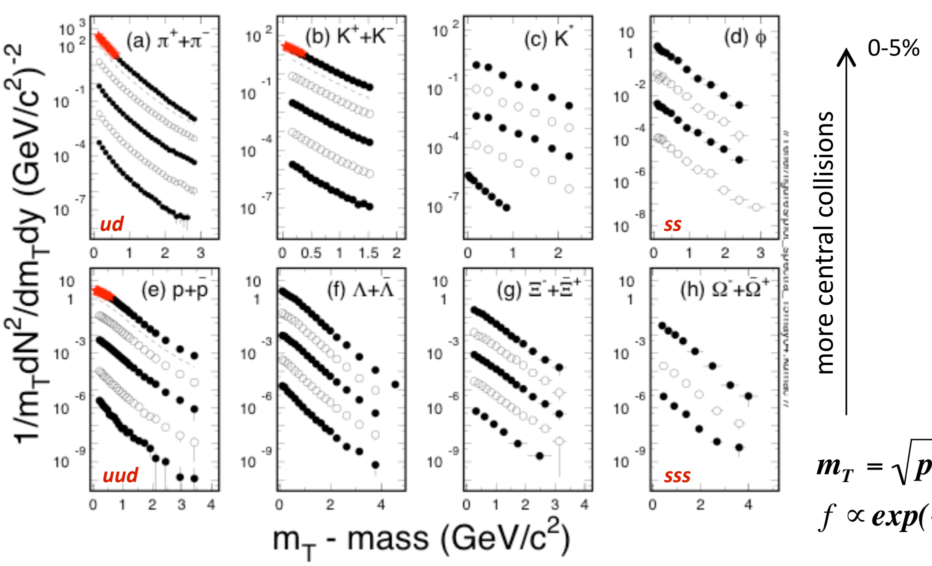
$$v_i = \langle \cos(i\varphi) \rangle_{event} \qquad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

1) Radial flow – integrated over whole history of the evolution
2) Directed flow (v_1) – relatively early
3) Elliptic flow (v_2) – relatively early

- Mass dependent: characteristic of hydrodynamic behavior.

Hadron Spectra from RHIC

p+p and Au+Au collisions at 200 GeV



$$m_T = \sqrt{p_T^2 + m^2}$$

$$f \propto exp(-m_T/T_{slope})$$

Multi-strange hadron spectra are exponential in their shapes.

STAR white papers - Nucl. Phys. A757, 102(2005).

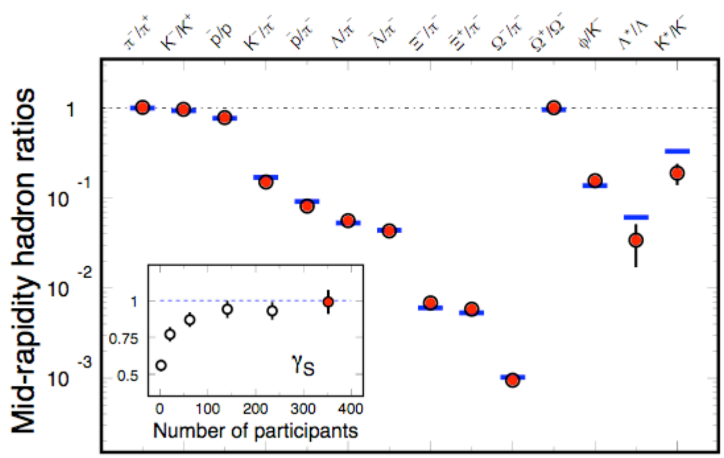
Statistical Model

- Assume thermally (constant T_{ch}) and chemically (constant n_i) equilibrated system at chemical freeze-out
- System composed of non-interacting hadrons and resonances
- Given T_{ch} and m 's (+ system size), n_i's can be calculated in a grand canonical ensemble

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

- Obey conservation laws: Baryon Number, Strangeness, Isospin
- Short-lived particles and resonances need to be taken into account

Yields Ratio Results



200 GeV ^{197}Au + ^{197}Au central collision

data

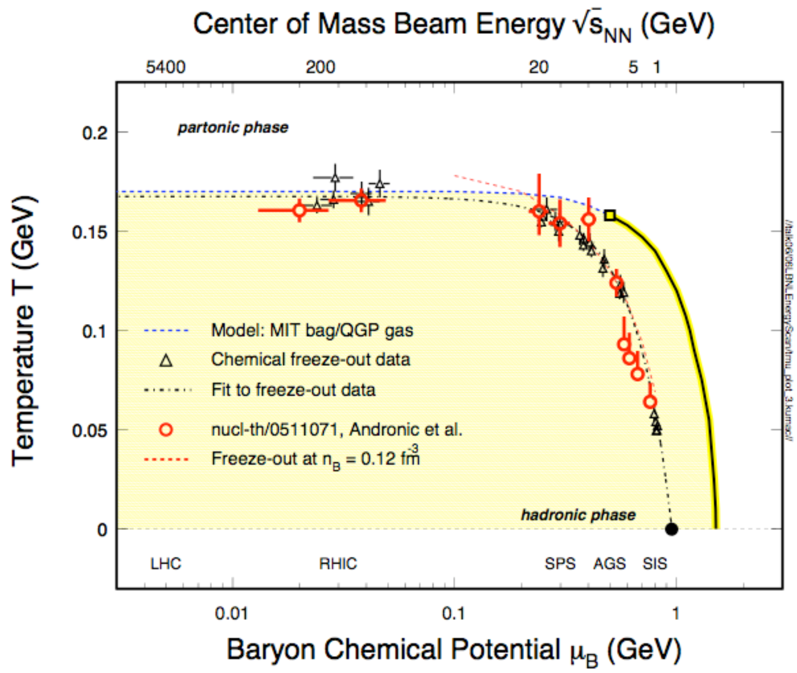
Thermal model fits

T_{ch} = 163 ± 4 MeV

μ_B = 24 ± 4 MeV

- In central collisions, thermal model fit well with $\gamma_S = 1$. **The system is thermalized at RHIC.**
- Short-lived resonances show deviations. **There is life after chemical freeze-out.** RHIC white papers - 2005, Nucl. Phys. *A757*, STAR: p102; PHENIX: p184.

The QCD Phase Diagram



$T_{ch} \sim T_C$ (LGT) at RHIC

*Thermalization is assumed!

Recent review:
A. Andronic, et al, NP ***A772,*** *B. 167(06)*

Thermal Model Fits (Blast-Wave)

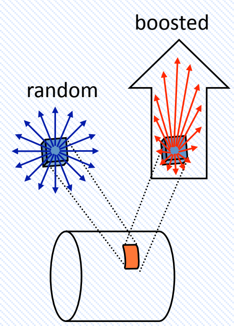
Source is assumed to be:
- Locally thermal equilibrated
- Boosted in radial direction

E.Schnedermann, J.Sollfrank, and U.Heinz, Phys. Rev. ***C48****, 2462(1993)*

$$E\frac{d^3N}{dp^3} \propto \int_\sigma e^{-(u^\mu p_\mu)/T_{fo}} p d\sigma_\mu \Rightarrow$$

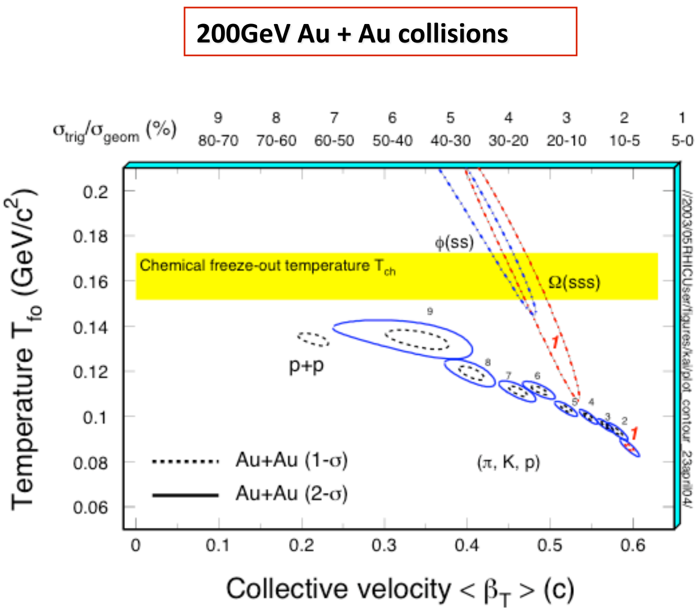
$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)$$

$$\rho = \tanh^{-1}\beta_T \qquad \beta_T = \beta_S\left(\frac{r}{R}\right)^\alpha \qquad \alpha = 0.5,\ 1,\ 2$$



Extract thermal temperature T_{fo} and velocity parameter $\langle\beta_T\rangle$

Blast Wave Fits: T_{fo} vs. $\langle \beta_T \rangle$



1) *π*, *K*, and *p* change smoothly from peripheral to central collisions.

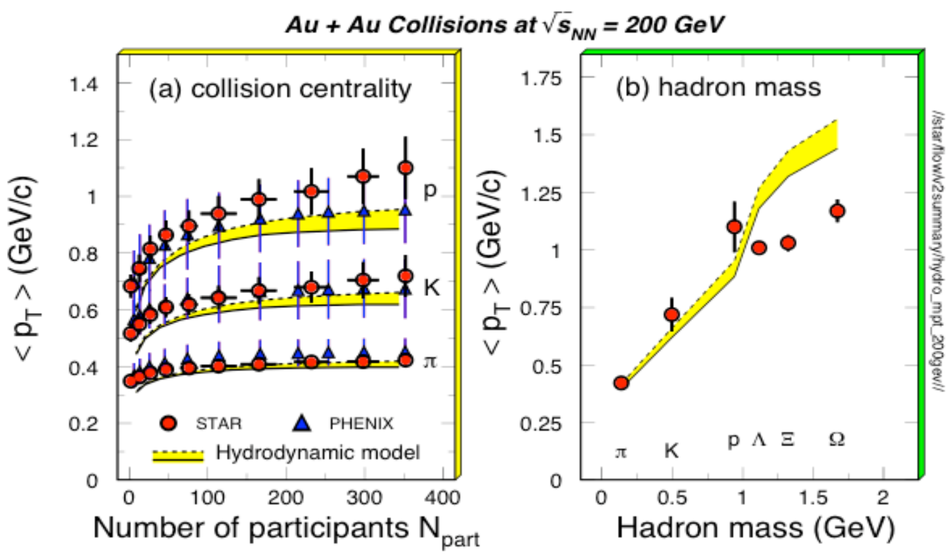
2) At the most central collisions, $\langle \beta_T \rangle$ reaches 0.6c.

3) Multi-strange particles φ, Ω are found at higher T_{fo} and lower $\langle \beta_T \rangle$

➪ light hadrons move with higher velocity compared to strange hadrons

STAR: NP**A715**, 458c(03); *PRL* ***92**, 112301(04); **92**, 182301(04).*

Compare with Model Results

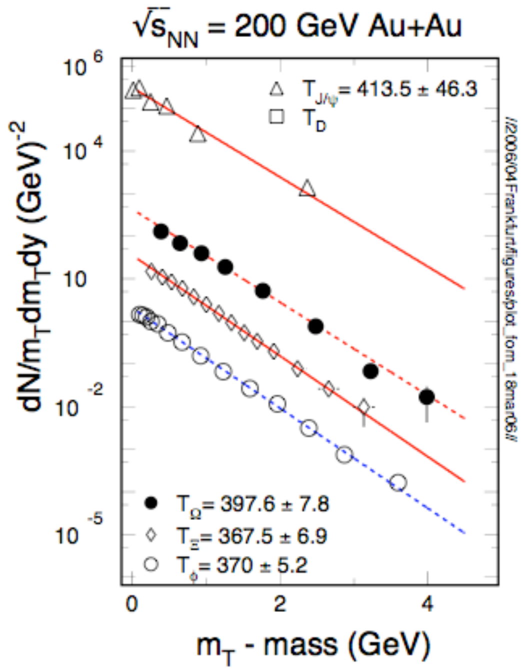


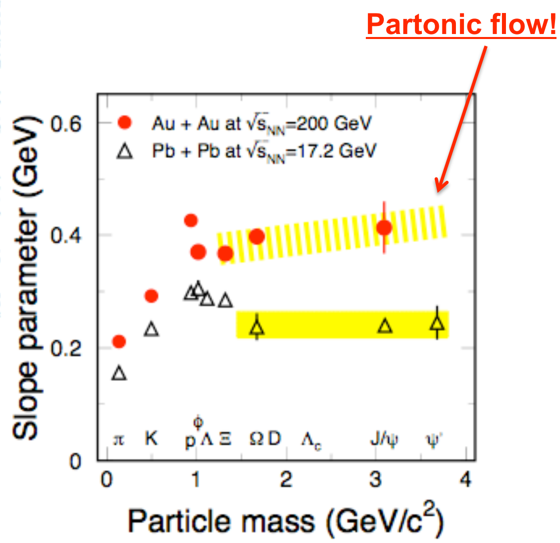
- Hydro model works well for *π, K, p*, but over-predicts flow for **multi-strange hadrons** - partonic flow only?!
- Initial 'collective kick' introduced *(P. Kolb and R. Rapp, PRC67)*

Slope Parameter Systematics

$$m_T = \sqrt{p_T^2 + m^2}$$

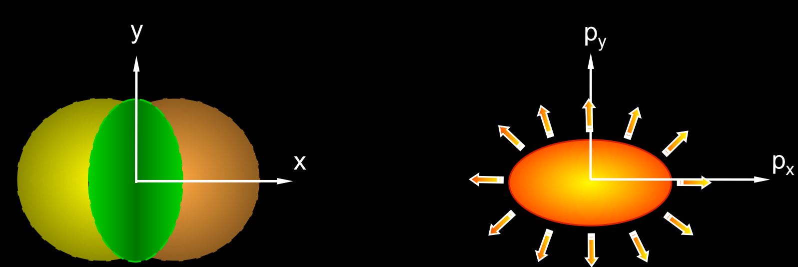
$$f \propto exp(-m_T / T_{slope})$$





Anisotropy Parameter v_2

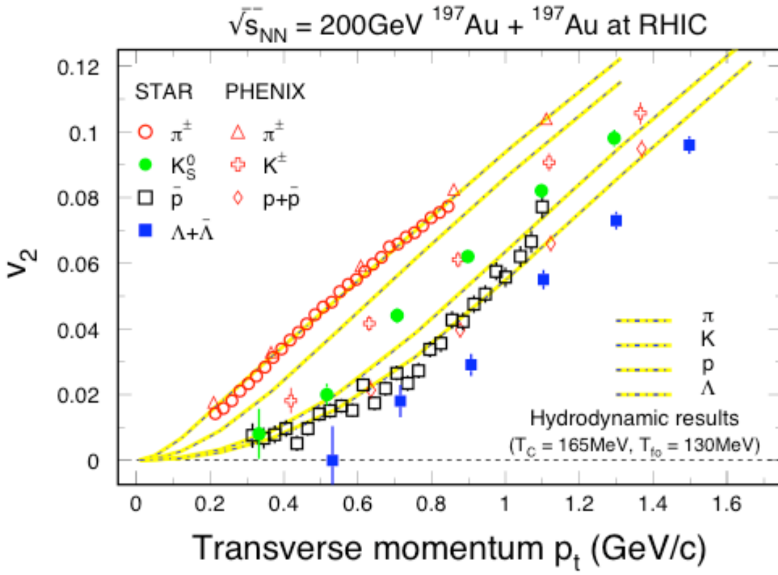
coordinate-space-anisotropy ⇨ momentum-space-anisotropy



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

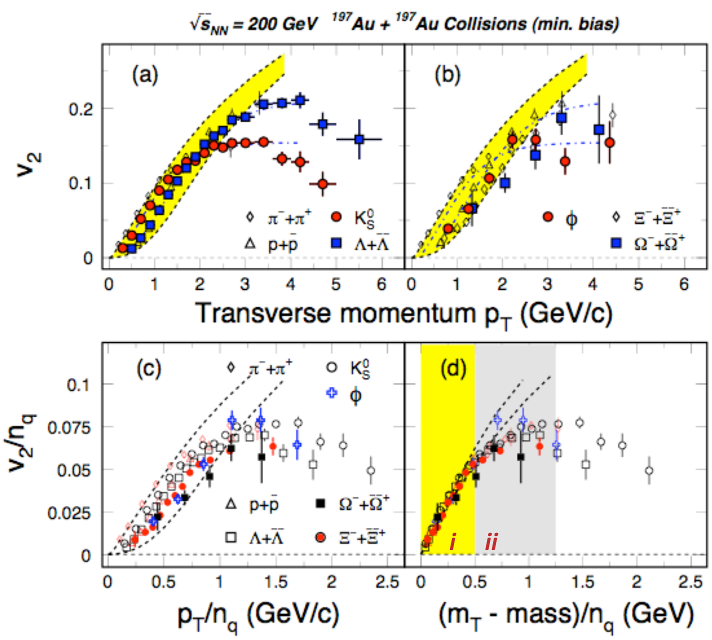
v_2 at Low p_T Region



P. Huovinen, private communications, 2004

- Minimum bias data!
- At low p_T, model result fits mass hierarchy well - *Collective motion at RHIC*
- More work needed to fix the details in the model calculations.

Collectivity, Deconfinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

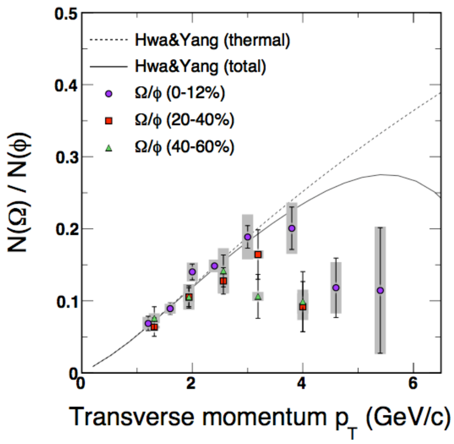
➪ **N_q scaling**
novel hadronization process

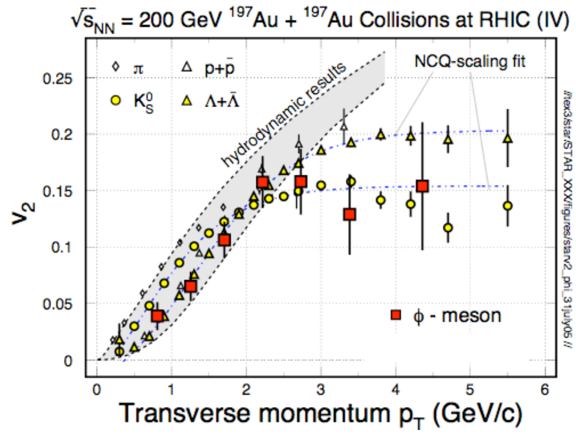
➪ **Parton flow**
De-confinement

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05)*
nucl-ex/0405022, QM05

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
....

ϕ -meson Flow: Partonic Flow





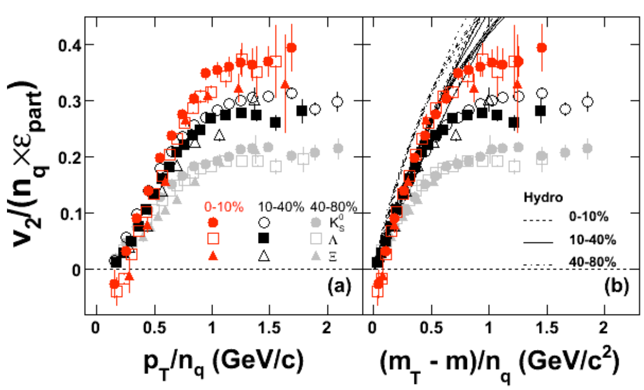
"**ϕ-mesons are produced via coalescence of seemingly thermalized quarks in central Au+Au collisions. This observation implies *hot and dense matter with partonic collectivity* has been formed at RHIC**"

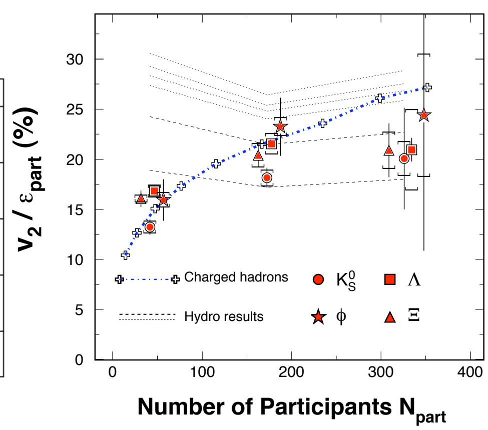
STAR: Phys. Rev. Lett. ***99*** (2007) 112301// * STAR, Duke, TAMU
** OZI rule

Centrality Dependence

*STAR: Phys. Rev. **C77**, 54901(2008)*

200 GeV Au+Au





*S. Voloshin, A. Poskanzer, PL **B474**, 27(00).*
D. Teaney, et. al., nucl-th/0110037

- Larger v_2/ε_{part} indicates stronger flow in more central collisions.
- NO ε_{part} scaling.
- The observed n_q-scaling does not necessarily mean thermalization.

EoS Parameters at RHIC

In central Au+Au collisions at RHIC

- partonic freeze-out:

$^*T_{pfo}$ = 165 ± 10 MeV weak centrality dependence

$v_{pfo} \geq 0.2$ (c)

- hadronic freeze-out:

$^*T_{fo}$ = 100 ± 5 (MeV) strong centrality dependence

v_{fo} = 0.6 ± 0.05 (c)

Systematic study, understand the centrality dependence of the EoS parameters

** Thermalization assumed*

sQGP and the QCD Phase Diagram

200 GeV Au+Au collisions at RHIC, strongly interacting matter formed:

Jet energy loss: R_{AA}
Strong collectivity: v_0, v_1, v_2
Hadronization via coalescence: n_q-scaling

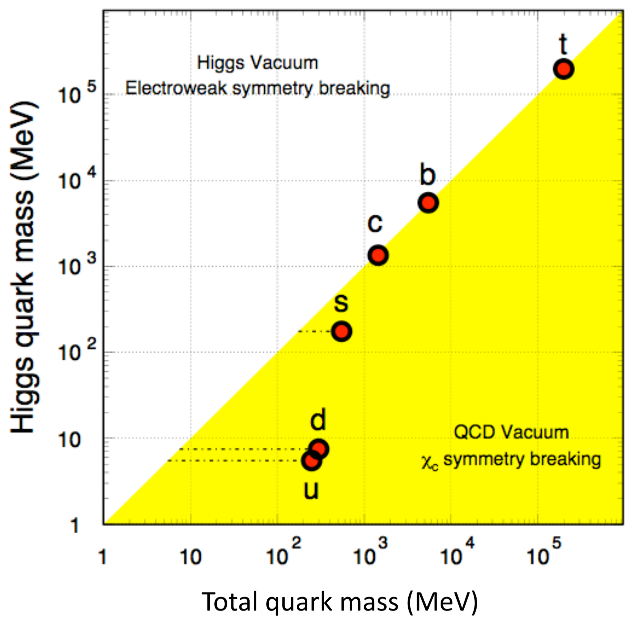
Questions:

Has the thermalization reached, or how large is the η at RHIC?

When (at which energy) does this transition happen?

What does the QCD phase diagram look like?

Quark Masses



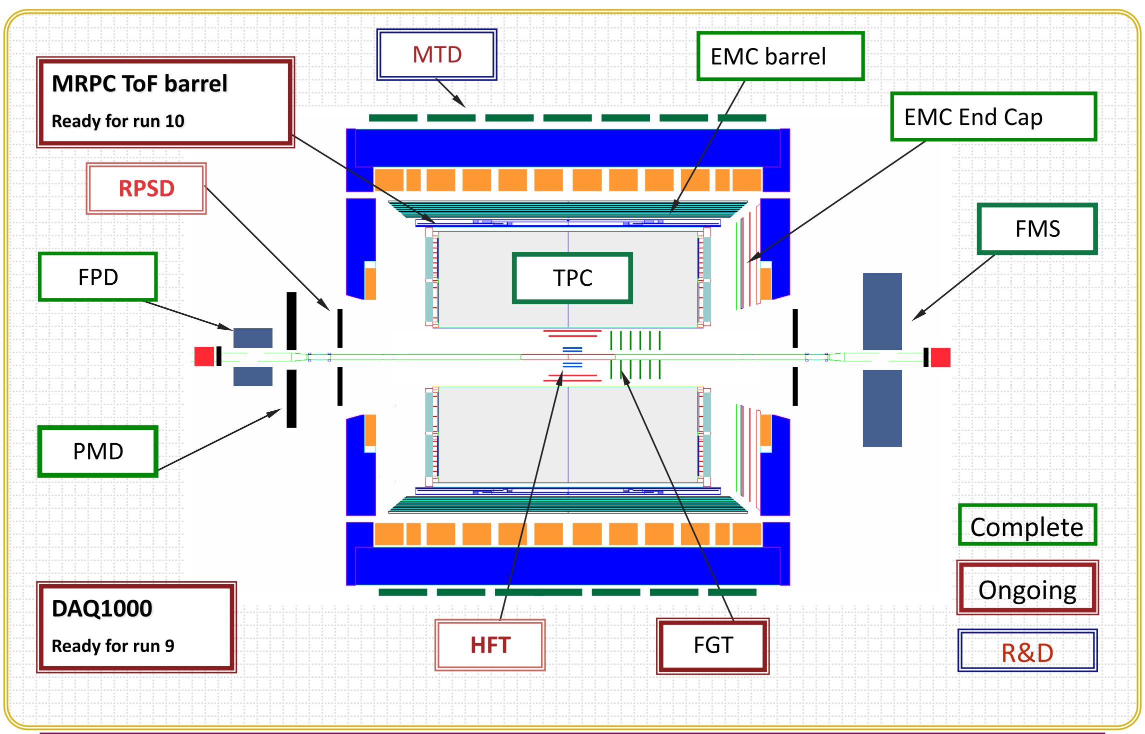
1) Higgs mass: electro-weak symmetry breaking. (current quark mass)
2) QCD mass: Chiral symmetry breaking. (constituent quark mass)

⇨ New mass scale compared to the excitation of the system.

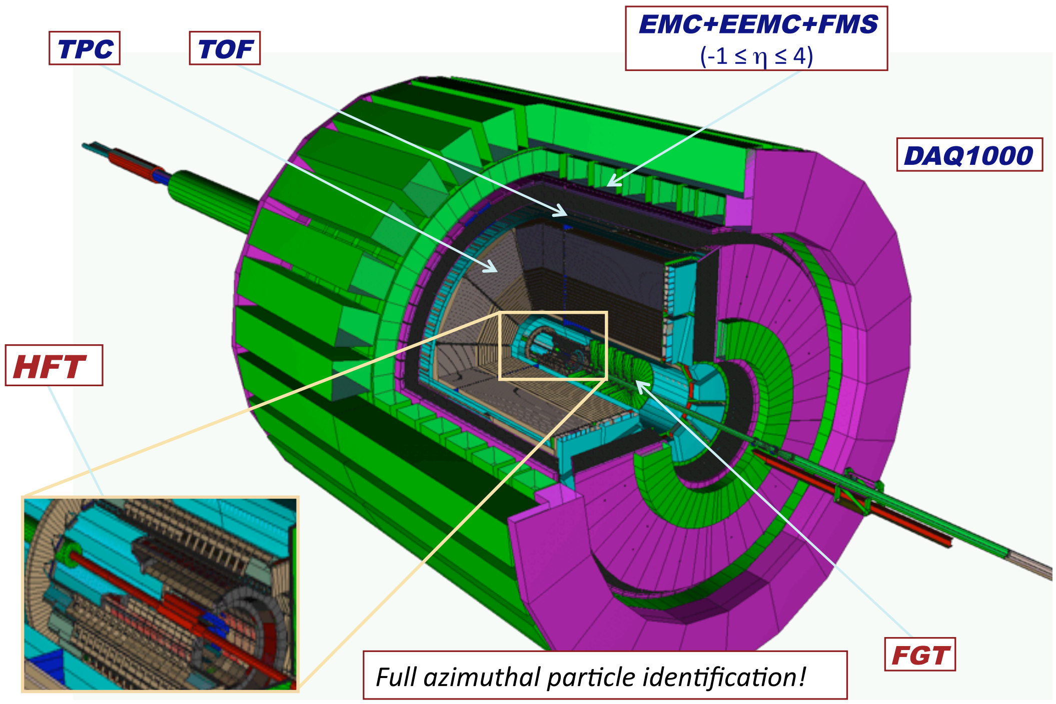
⇨ Important tool for studying properties of the hot/dense medium at RHIC.

⇨ Test pQCD predictions at RHIC.

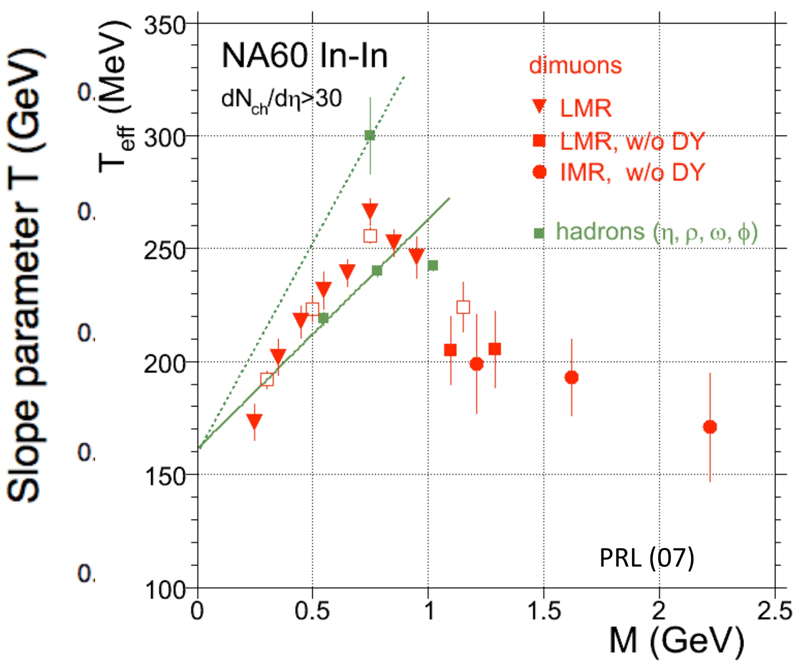
STAR Detector



STAR Detectors



Direct Radiation



Di-leptons allow us to measure the direct radiation from the matter with partonic degrees of freedom, no hadronization!

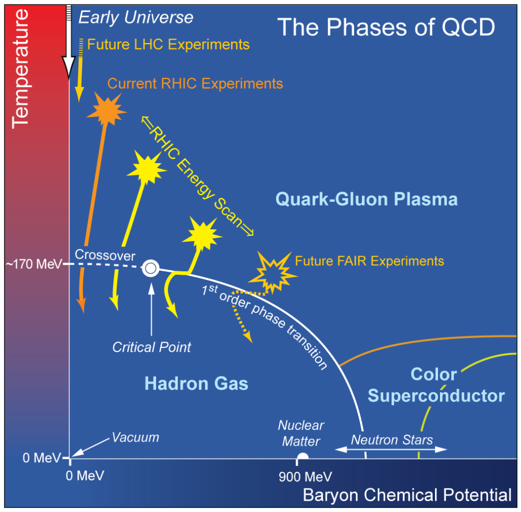
- Low mass region:
  ρ, ω, φ ⇒ **e^-e^+**
  m_{inv} ⇒ **e^-e^+**

  medium effect
  Chiral symmetry

- High mass region:
  J/ψ ⇒ **e^-e^+**
  m_{inv} ⇒ **e^-e^+**

  Direct radiation

The QCD Critical Point



- **LGT prediction on the transition temperature T_C is robust.**

- **LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram* at finite baryon chemical potential.**

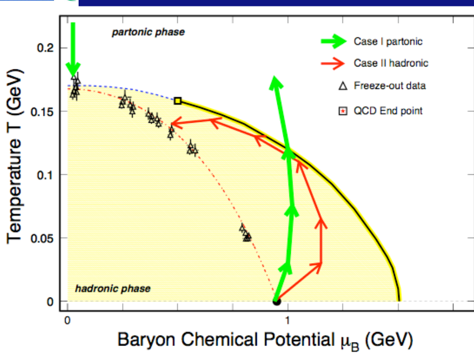
- **Experimental evidence for either the critical point or 1st order transition is important for our knowledge of the QCD phase diagram*.**

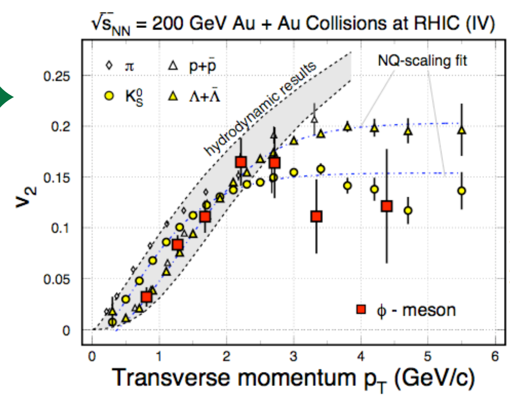
*** Thermalization has been assumed**

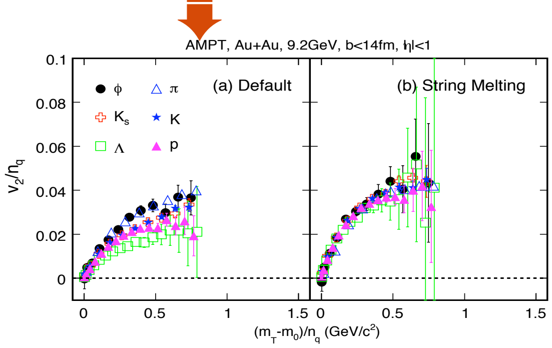
*M. Stephanov, K. Rajagopal, and E. Shuryak, PRL **81**, 4816(98)*
*K. Rajagopal, PR **D61**, 105017 (00)*

- http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf

Observable I: Quark Scaling





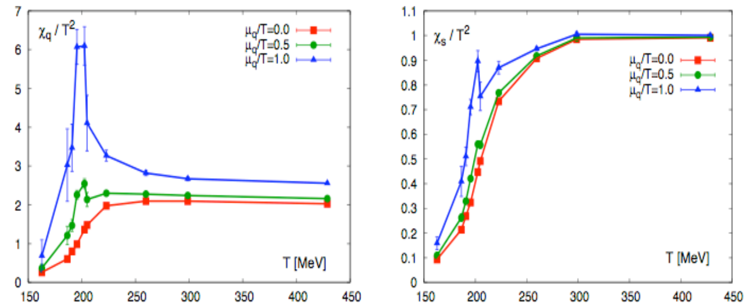


- $m_\phi \sim m_p \sim 1$ GeV
- $s\bar{s} \Rightarrow \phi$ not $K^+K^- \Rightarrow \phi$
- $\sigma_{\phi h} << \sigma_{p\pi, \pi\pi}$

In the hadronic case, no number of quark scaling and the value of v_2 of ϕ will be small.

Observable II: χ_q, χ_S

F. Karsch, 2008.



Event by event:

$$K_p = \frac{\langle N_p^4 \rangle - 3\langle N_p^2 \rangle^2}{\langle N_p^2 \rangle}$$

1. net-proton Kurtosis $K_p(E)$
2. two proton correlation functions $C_2(E)$
3. ratio of the d/p
4. ratio of K/p

sQGP and the QCD Phase Diagram

200 GeV Au+Au collisions at RHIC, strongly interacting matter formed:

Jet energy loss: R_{AA}
Strong collectivity: v_0, v_1, v_2
Hadronization via coalescence: n_q-scaling

Questions:

Has the thermalization reached, or how large is the η at RHIC?

When (at which energy) does this transition happen?

What does the QCD phase diagram look like?