CNS Summer School 2007

Toward understanding of Quark-Gluon Plasma in relativistic heavy ion collisions

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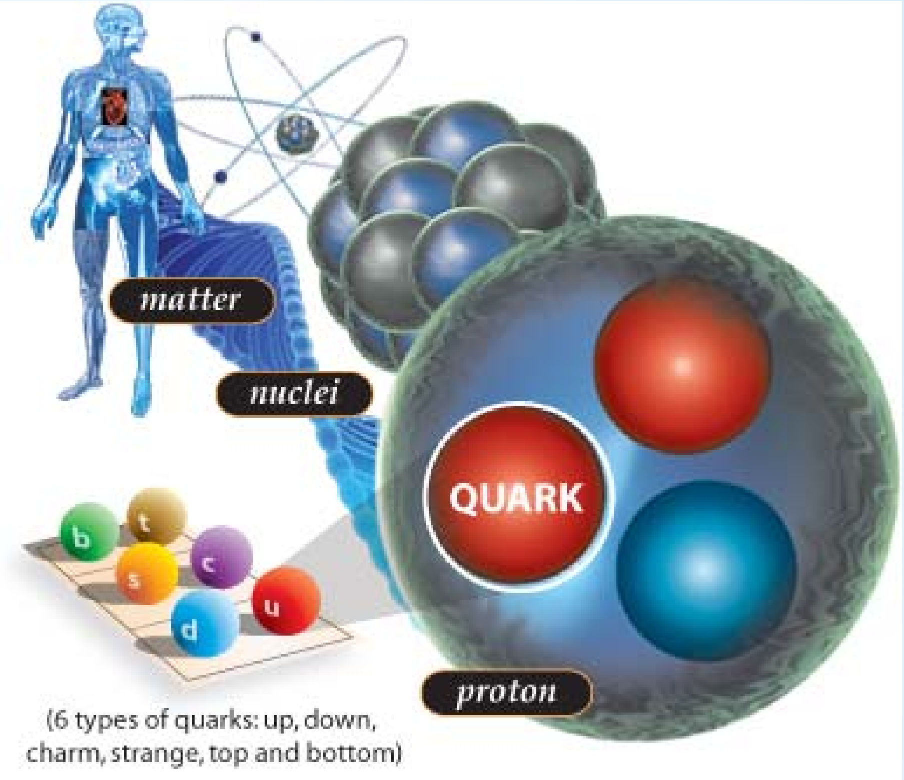
Outline

- Introduction
- Dynamics of Relativistic Heavy Ion Collisions
- Basic Checks
- Two Big Discoveries
  - Bulk Dynamics: Elliptic Flow
  - Probe: Jet Quenching
  - (Highlight of new data)
- Summary

Disclaimer
~200 papers from 4 collaborations at RHIC since 2000. Impossible to cover all of them in one-hour lecture!

Introduction

Q. What are our building blocks?

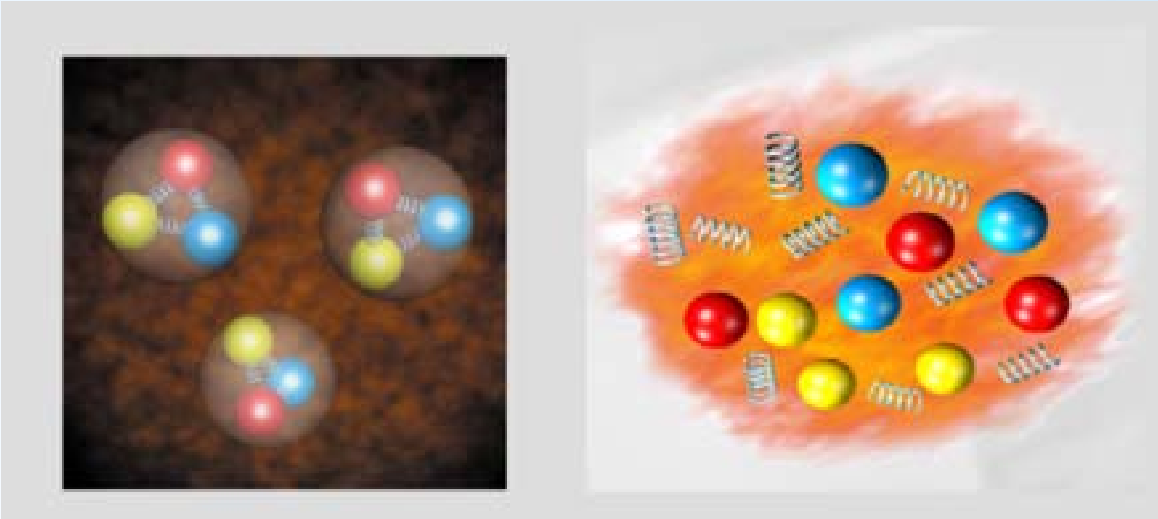


A. Quarks, leptons, and gauge particles

If you would answer "open and closed strings, …",
you should go to another summer school…

Introduction (contd.)

Q. What is the matter in which quarks and gluons play a direct role?



A. The Quark Gluon Plasma (QGP)
Quarks and gluons are moving almost freely out of hadrons.

Introduction (contd.)

Main Casts

Matter: Quarks

Gauge: Gluons

Sub-Casts

Hadrons (Quarks are confined.)

Fundamental principle

QCD (QuantumChromo Dynamics)

Form of Matter

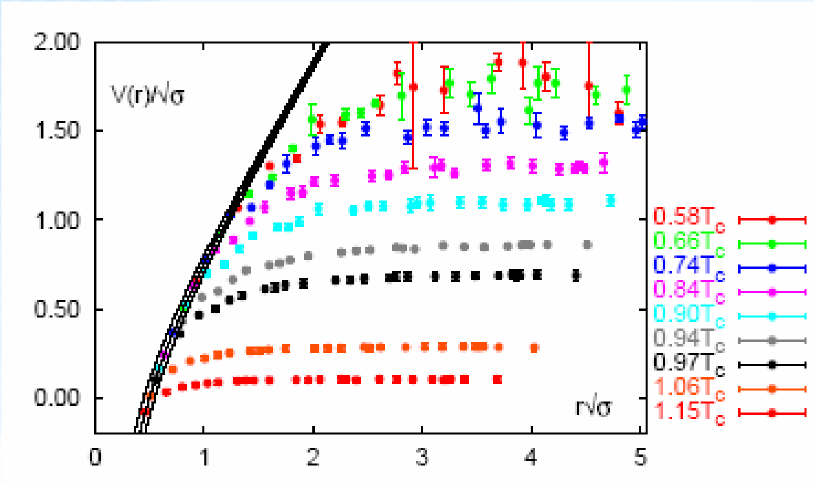
QGP (Quark Gluon Plasma)

QGP study =
"Condensed matter in particle physics"

Two Faces of QCD

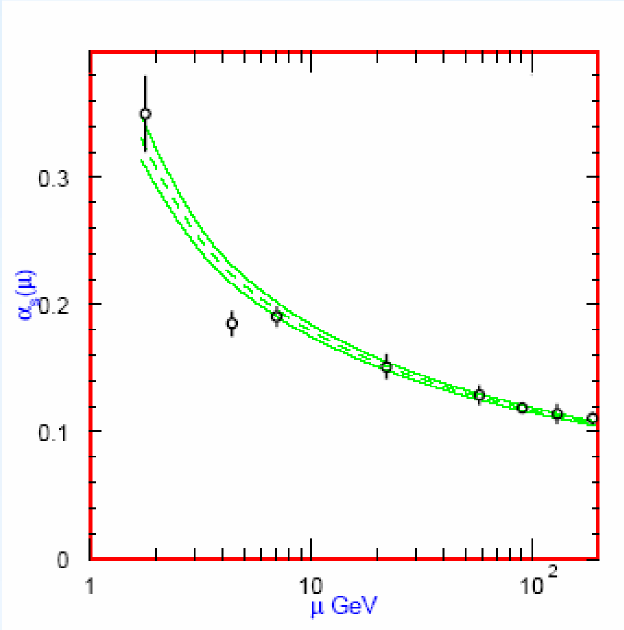
$$\mathcal{L} = \bar{\psi}_i (i\gamma_\mu D^\mu_{ij} - m\delta_{ij})\psi_j - \frac{1}{4} F_{\mu\nu a} F^{\mu\nu a}$$

Quark-Antiquark potential



Quark confinement

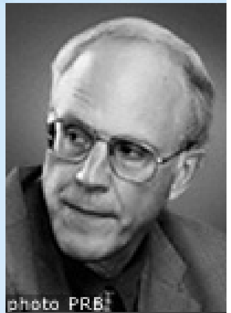
Running Coupling

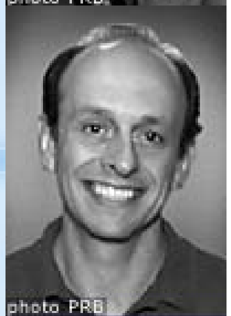


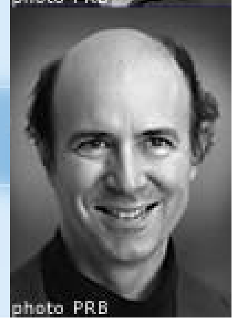
Asymptotic freedom

Gross, Politzer, Wilczek

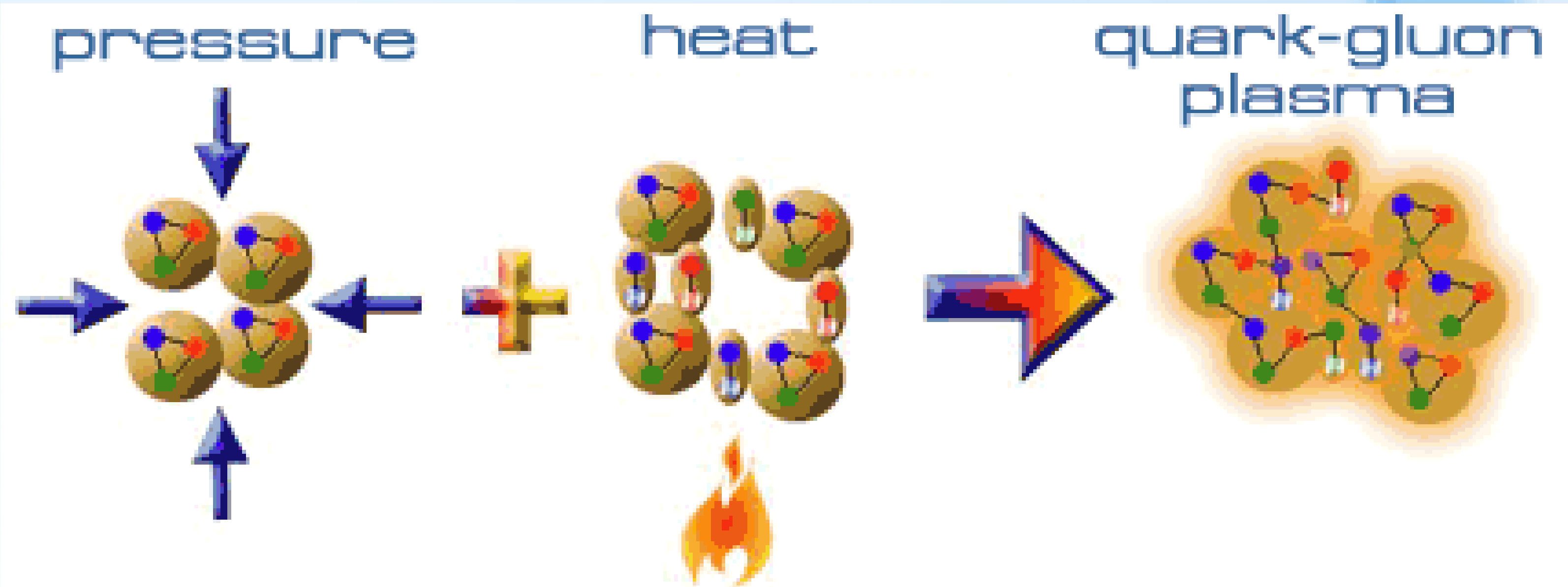
Nobel Prize(2004)







Recipe for "Quark-Gluon Soup"



For system of many nucleons,

1. Compress them!

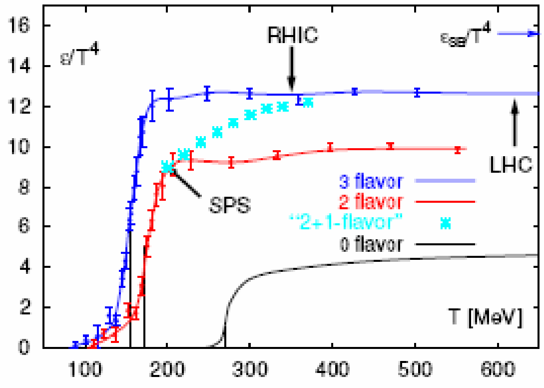
→ Density increases

2. Heat them up!

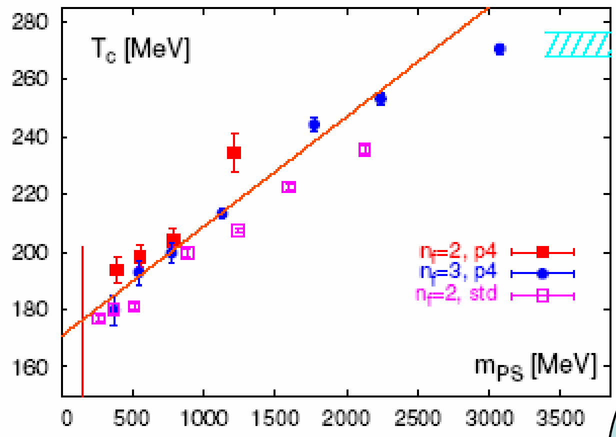
→ Temperature increases

Critical Energy Density from Lattice

Equation of State and T_c



QCD EoS



transition temperature

- ϵ/T^4 for $m_\pi \simeq 770$ MeV; $(m_\pi/m_\rho \simeq 0.7, TV^{1/3} = 4)$ $\epsilon_c/T_c^4 = 6 \pm 2$ $\Rightarrow$
- $T_c = (173 \pm 8 \pm sys)$ MeV (T_c for $m_\pi \gtrsim 300$ MeV) $\epsilon_c = (0.3 - 1.3)\mathrm{GeV/fm}^3$

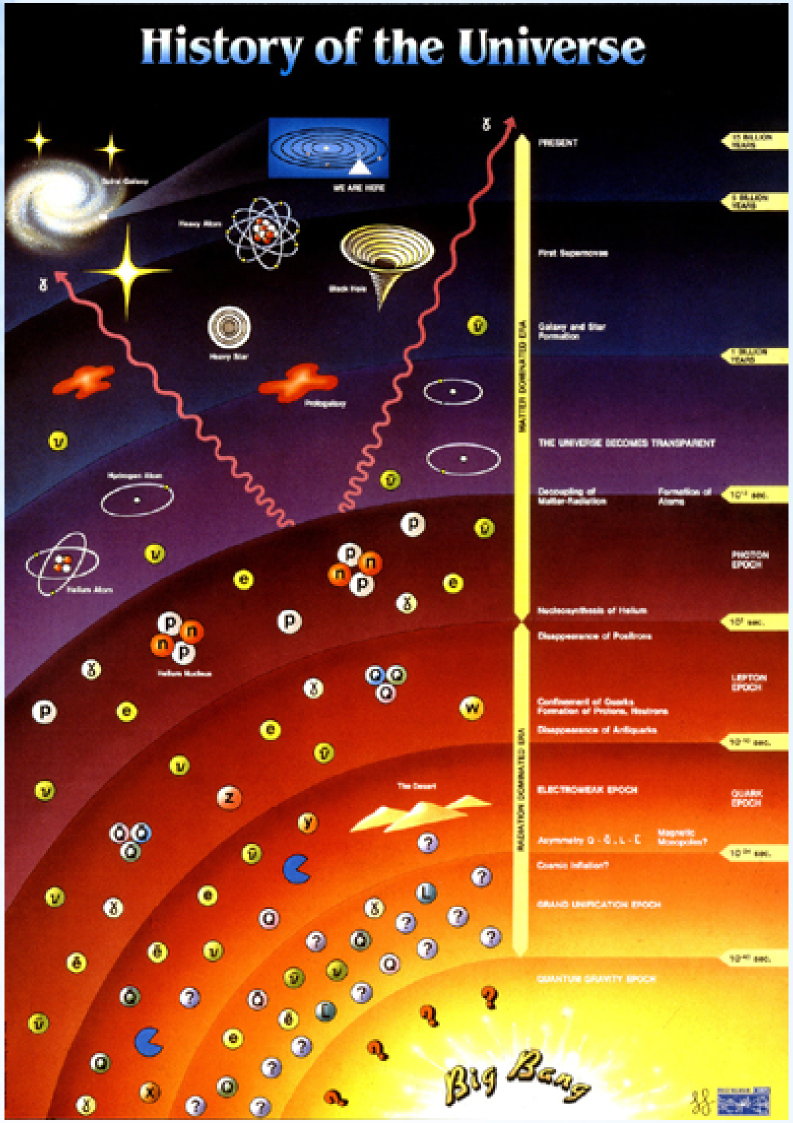
Keep in mind

- improved staggered fermions but still on rather coarse lattices: $N_\tau = 4$, i.e. $a^{-1} \simeq 0.8$ GeV

FK, E. Laermann, A. Peikert, Nucl. Phys. B605 (2001) 579

Stolen from Karsch(PANIC05);
Note that recent results seem to be $T_c \sim 190$MeV

Matter evolves with our Universe

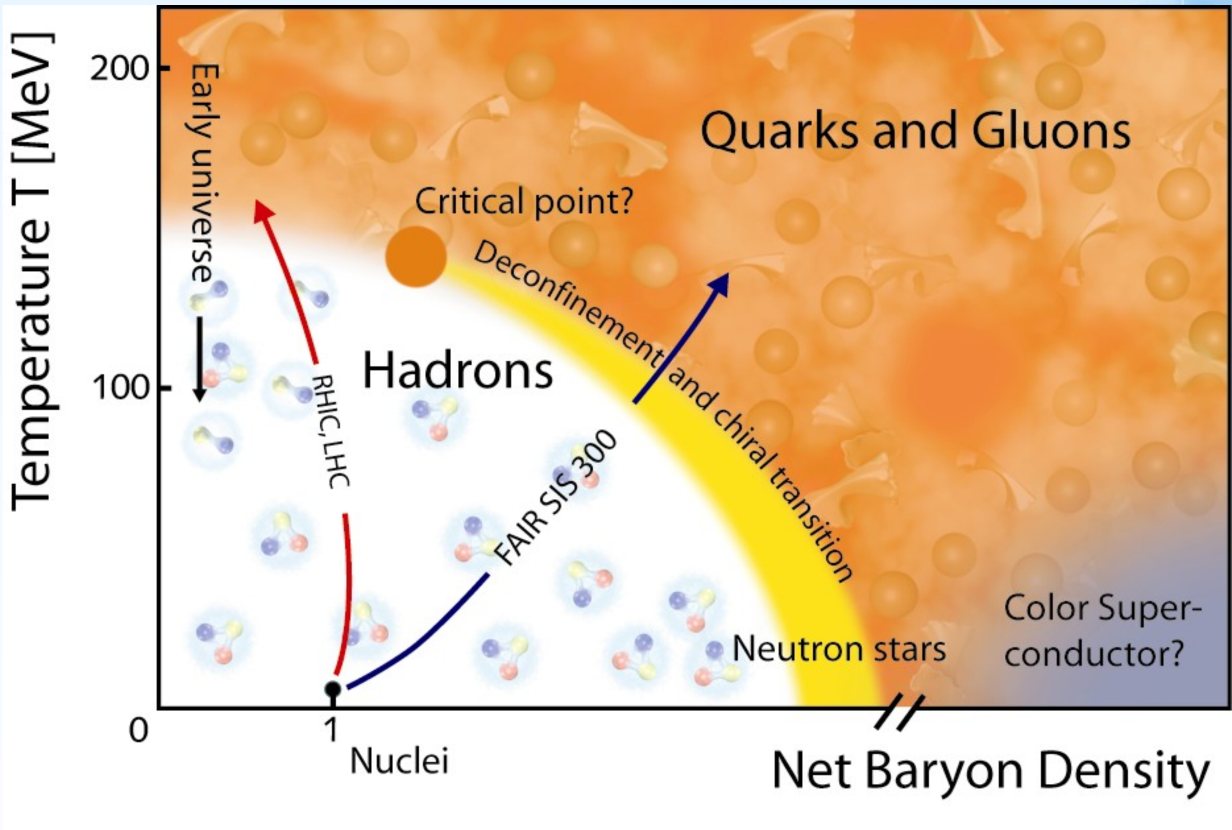


To understand QGP

To understand origin of matter as well as early universe

Schematic Phase Diagram of QCD

high temperature



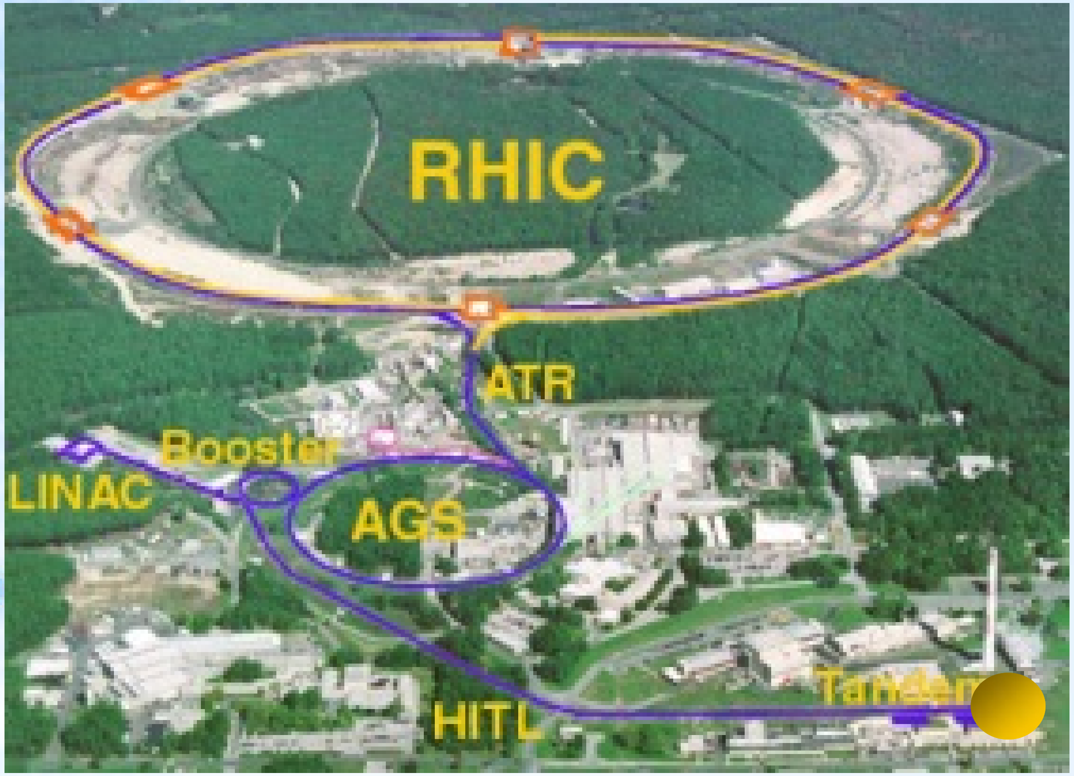
high density*

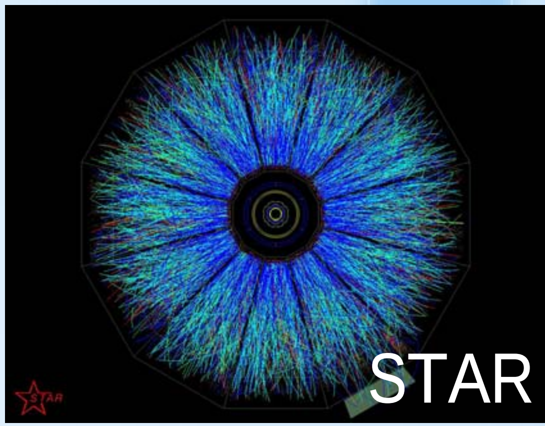
*Density means “baryon” density

Little Bang!

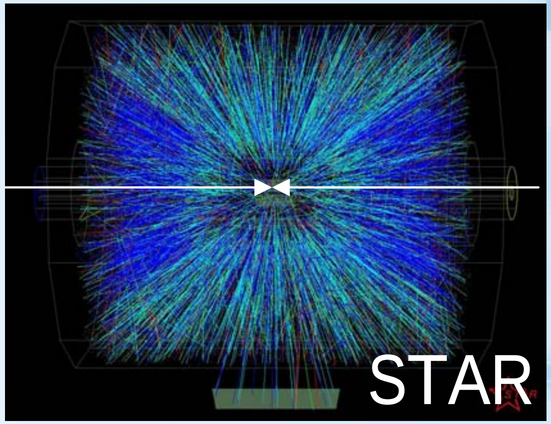
RHIC: Relativistic Heavy Ion Collider(2000-)

RHIC as a time machine!





front view



side view

100 GeV per nucleon

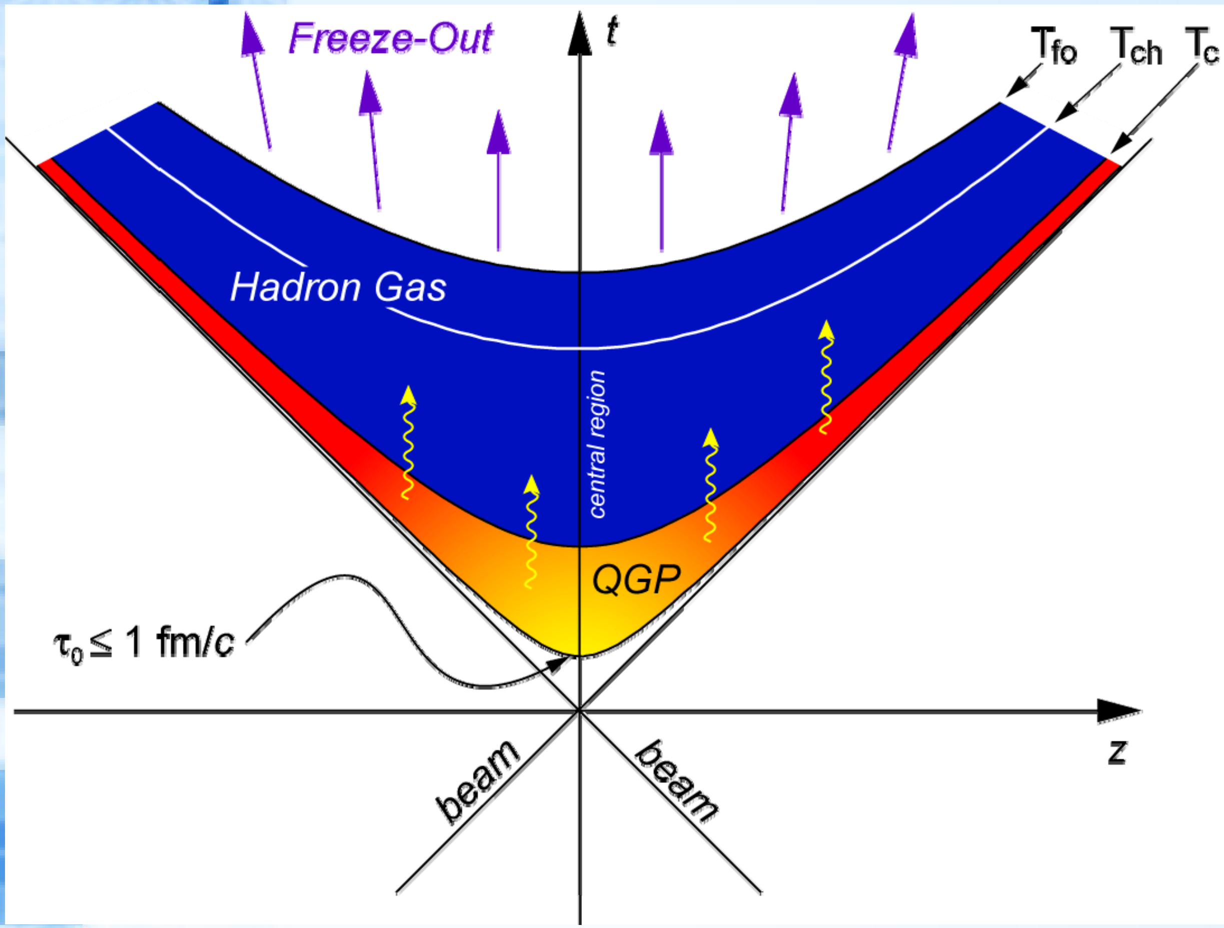
Au(197×100)+Au(197×100) collisions

Energy frontier as of today

→ Large Hadron Collider (LHC) will start soon.

Dynamics of Heavy Ion Collisions

Dynamics of Heavy Ion Collisions



Freezeout

“Re-confinement”

Expansion, cooling

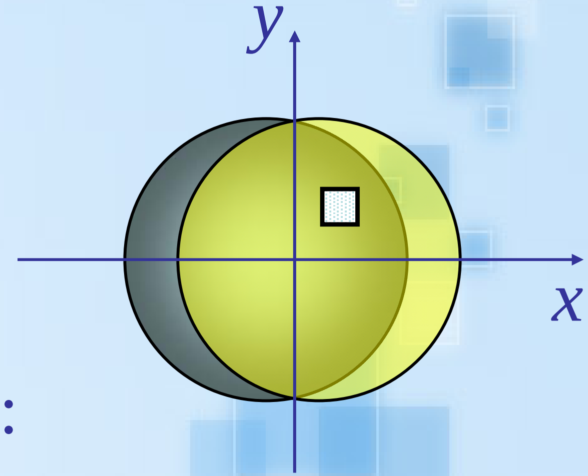
Thermalization

First contact
(two bunches of gluons)

Time scale
10fm/c~10^{-23}sec
<<10^{-4}(early universe)

Temperature scale
100MeV~10^{12}K

N_{coll} & N_{part}



Thickness function:

$$T(\mathbf{r}) = \int dz \rho(\sqrt{\mathbf{r}^2 + z^2})$$

Woods-Saxon nuclear density:

$$\rho(r) = \frac{\rho_0}{\exp[(r-R)/\delta] + 1}$$

Gold nucleus:

ρ_0=0.17 fm^{-3}

R=1.12$A^{1/3}$-0.86$A^{-1/3}$

d=0.54 fm

of binary collisions

$$T_{AA} = \int d^2\mathbf{r} T(\mathbf{r} - \mathbf{b}/2) T(\mathbf{r} + \mathbf{b}/2)$$

$$N_{\rm coll} = T_{AA}(b)\sigma_{\rm in}$$

σ_{in} = 42mb @200GeV

of participants

$$\frac{d^2 N_{\rm part}}{d^2\mathbf{r}}(\mathbf{r};\mathbf{b})$$

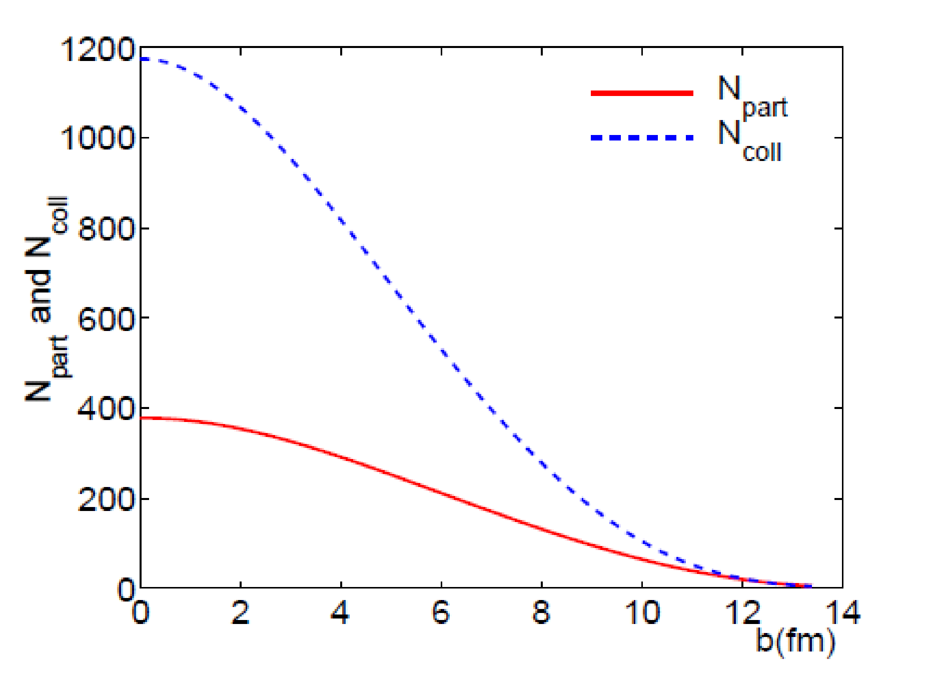
$$= T_a\left(\mathbf{r} + \frac{1}{2}\mathbf{b}\right)\left\{1 - \exp\left[-\sigma_{\rm in} T_b\left(\mathbf{r} - \frac{1}{2}\mathbf{b}\right)\right]\right\}$$

$$+ T_b\left(\mathbf{r} - \frac{1}{2}\mathbf{b}\right)\left\{1 - \exp\left[-\sigma_{\rm in} T_a\left(\mathbf{r} + \frac{1}{2}\mathbf{b}\right)\right]\right\}$$

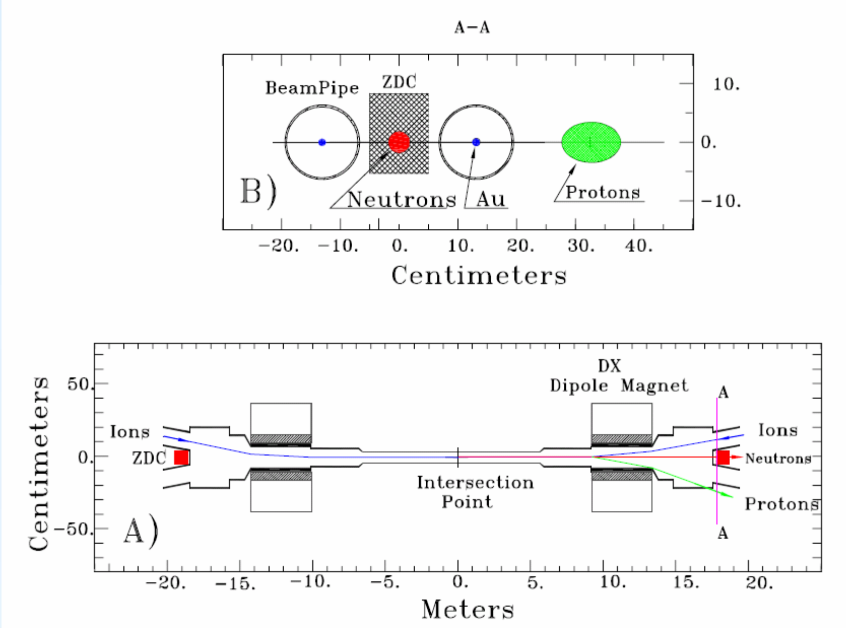
1 − (survival probability)

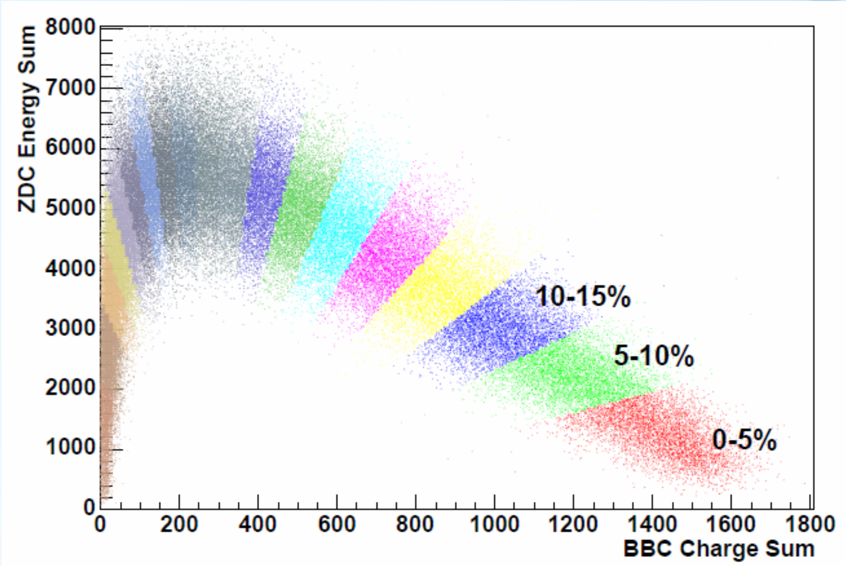
$$N_{\rm part} = \int d^2\mathbf{r} \frac{d^2 N_{\rm part}}{d^2\mathbf{r}}$$

Centrality



N_{part} and N_{coll} as a function of impact parameter

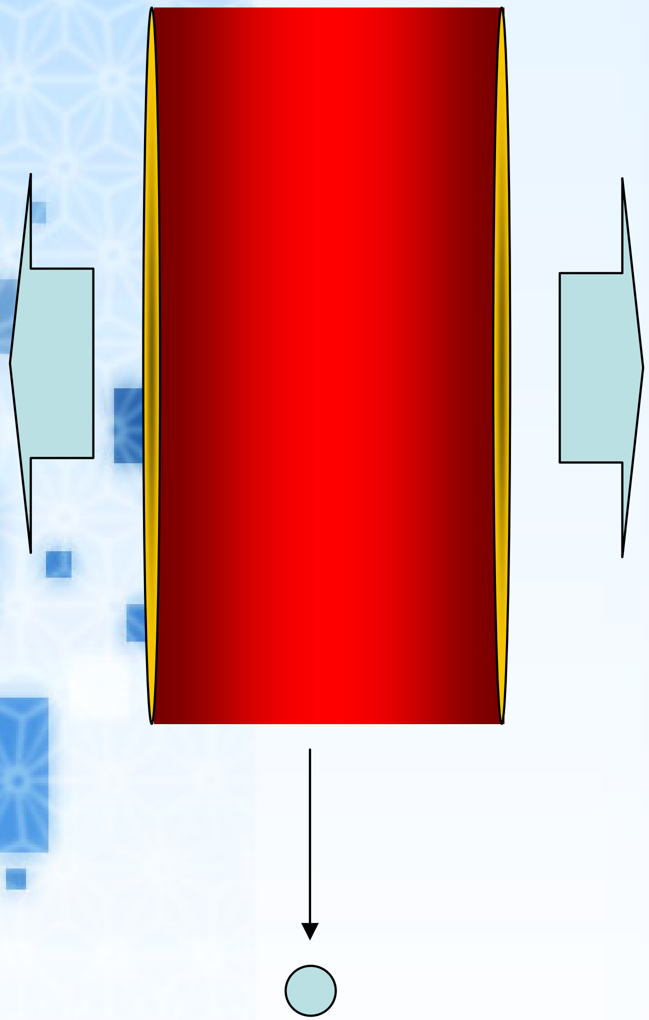




PHENIX: Correlation btw. BBC and ZDC signals

BASIC CHECKS

Basic Checks (I): Energy Density



Bjorken('83)

Bjorken energy density

$$\epsilon_{Bj}(\tau) = \frac{\langle m_T \rangle}{\tau \pi R^2} \frac{dN}{dy}$$

total energy (observables)

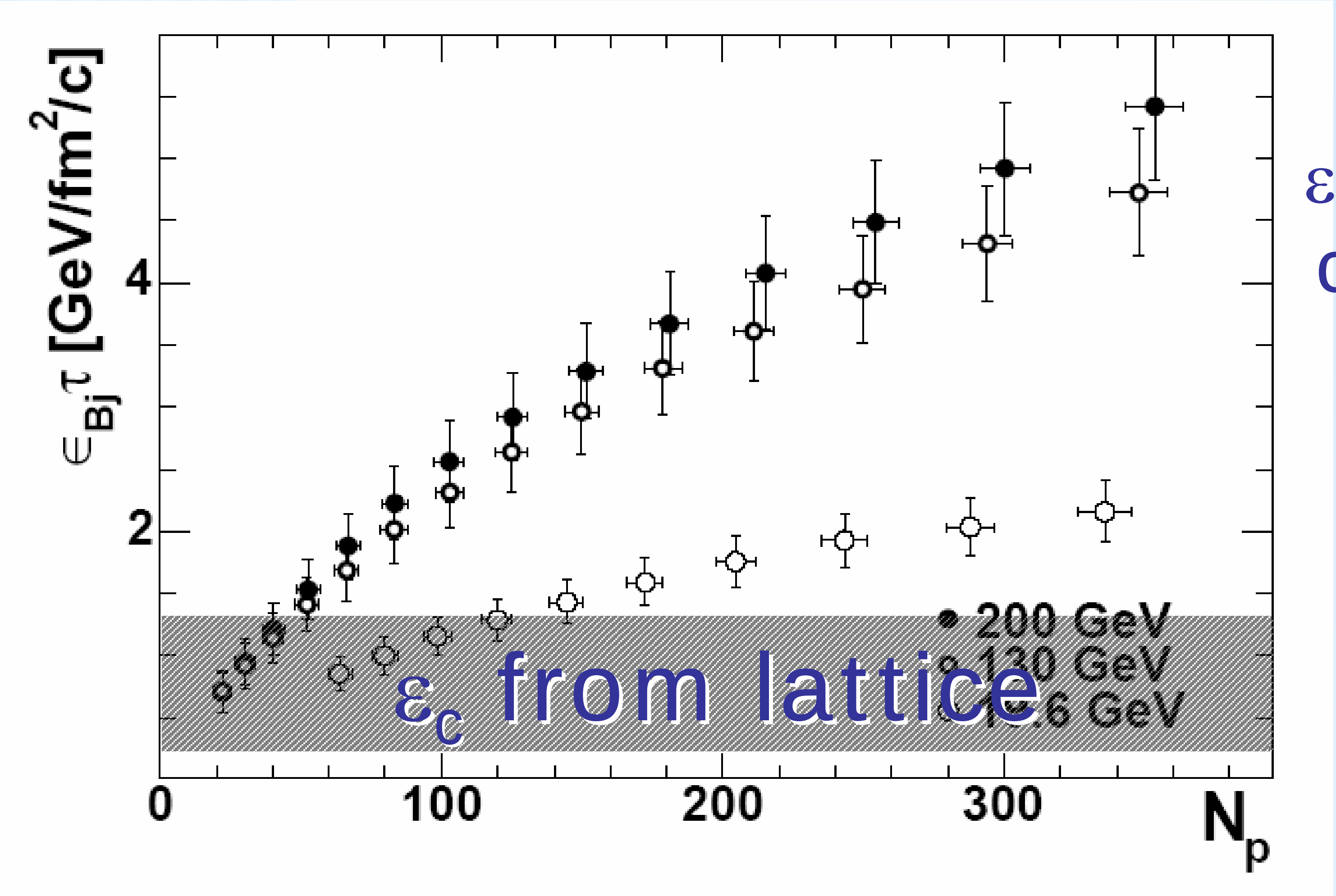
τ: proper time

y: rapidity

R: effective transverse radius

m_T: transverse mass

Centrality Dependence of Energy Density



Well above ε_c from lattice in central collision at RHIC, <u>if assuming τ=1fm/c.</u>

PHENIX('05)

CAVEATS (I)

- Just a necessary condition in the sense that temperature (or pressure) is not measured.
- How to estimate tau?

Basic Checks (II): Temperature

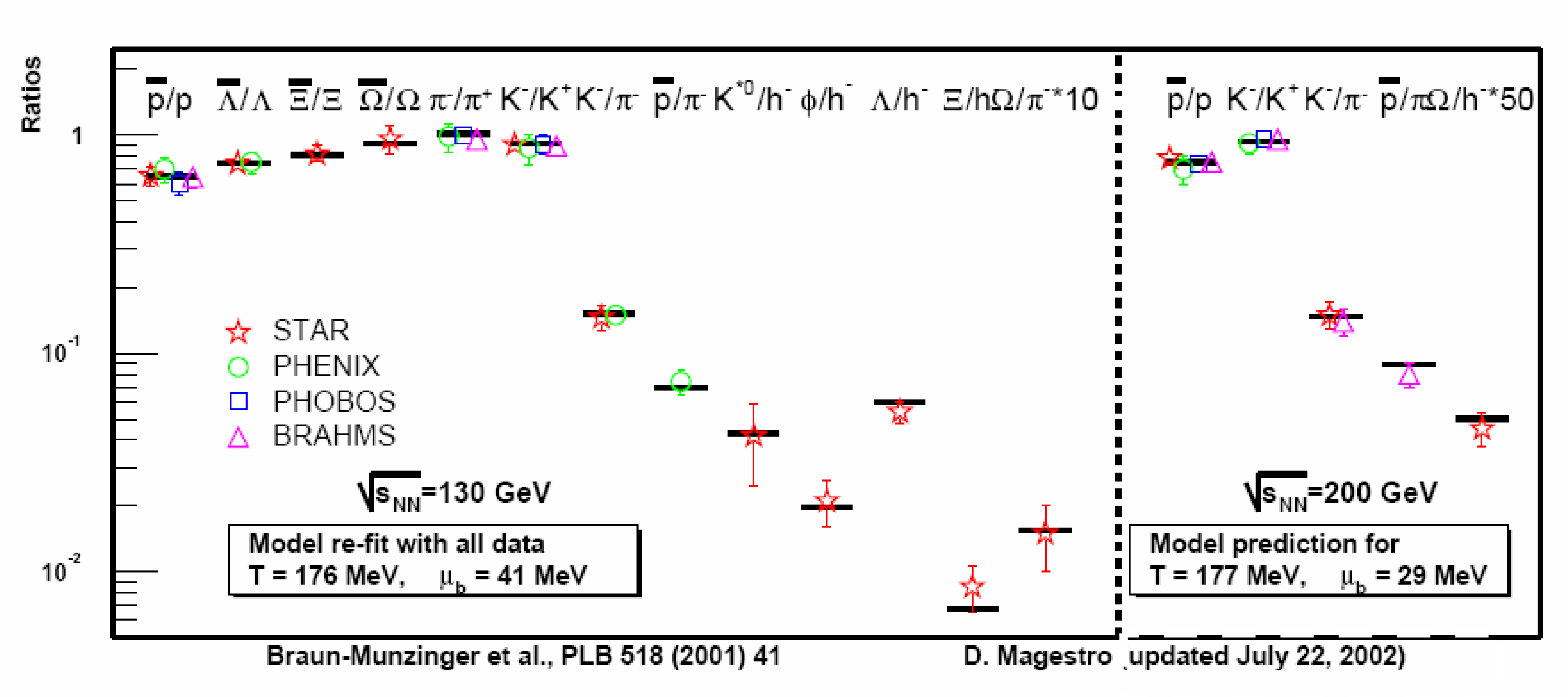
$$n_i(T,\mu) = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(E_i-\mu_i)/T] \pm 1}$$

$$\langle N_i \rangle = V\left[\underbrace{n_i^{\text{th}}(T,\mu)}_{\text{direct}} + \underbrace{\sum_R \Gamma_{R\to i} n_R(T,\mu)}_{\text{Resonance decay}}\right]$$

$\Delta \to N\pi$, $\rho \to \pi\pi$, etc.

Two fitting parameters: T_{ch}, μ_B

Amazing fit!



$T=177 MeV$, $\mu_B = 29$ MeV

→ Close to T_c from lattice

CAVEATS (II)

- Even e^+e^- or pp data can be fitted well!

See, e.g., Becattini&Heinz('97)

- So, what is the meaning of fitting parameters?
- Just Lagrange multiplier?

See, e.g., Rischke('02),Koch('03)

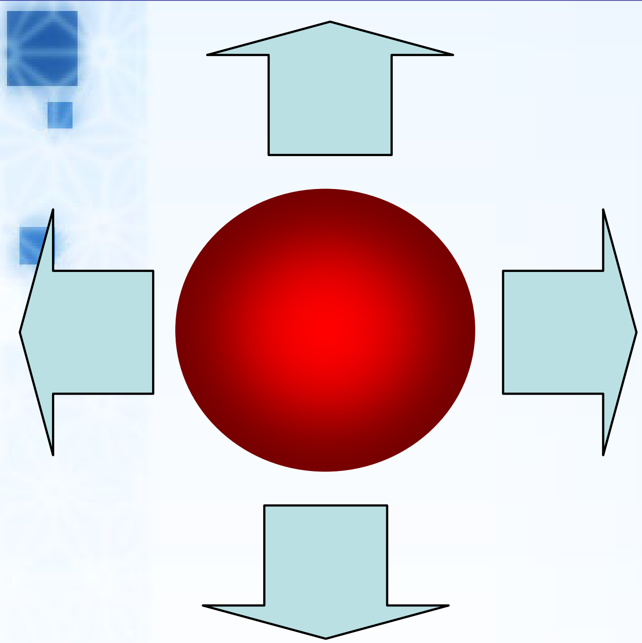
- Why so close to T_c?
  - → No chemical eq. in hadron phase!?
  - → Essentially dynamical problem!

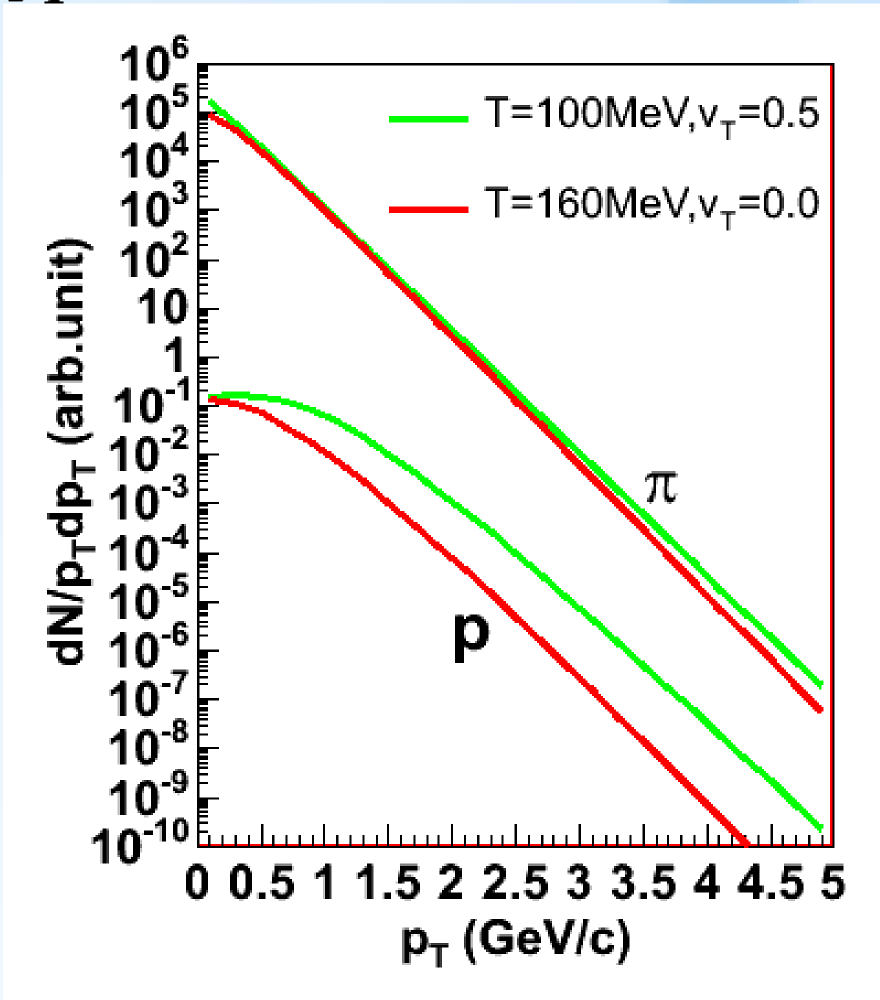
Basic Checks (III): Pressure

Blast wave model (thermal+boost)
Sollfrank et al.('93)

$$\frac{dN}{p_T dp_T} \propto m_T K_1\left(\frac{\gamma m_T}{T}\right) I_0\left(\frac{\gamma v_T p_T}{T}\right)$$

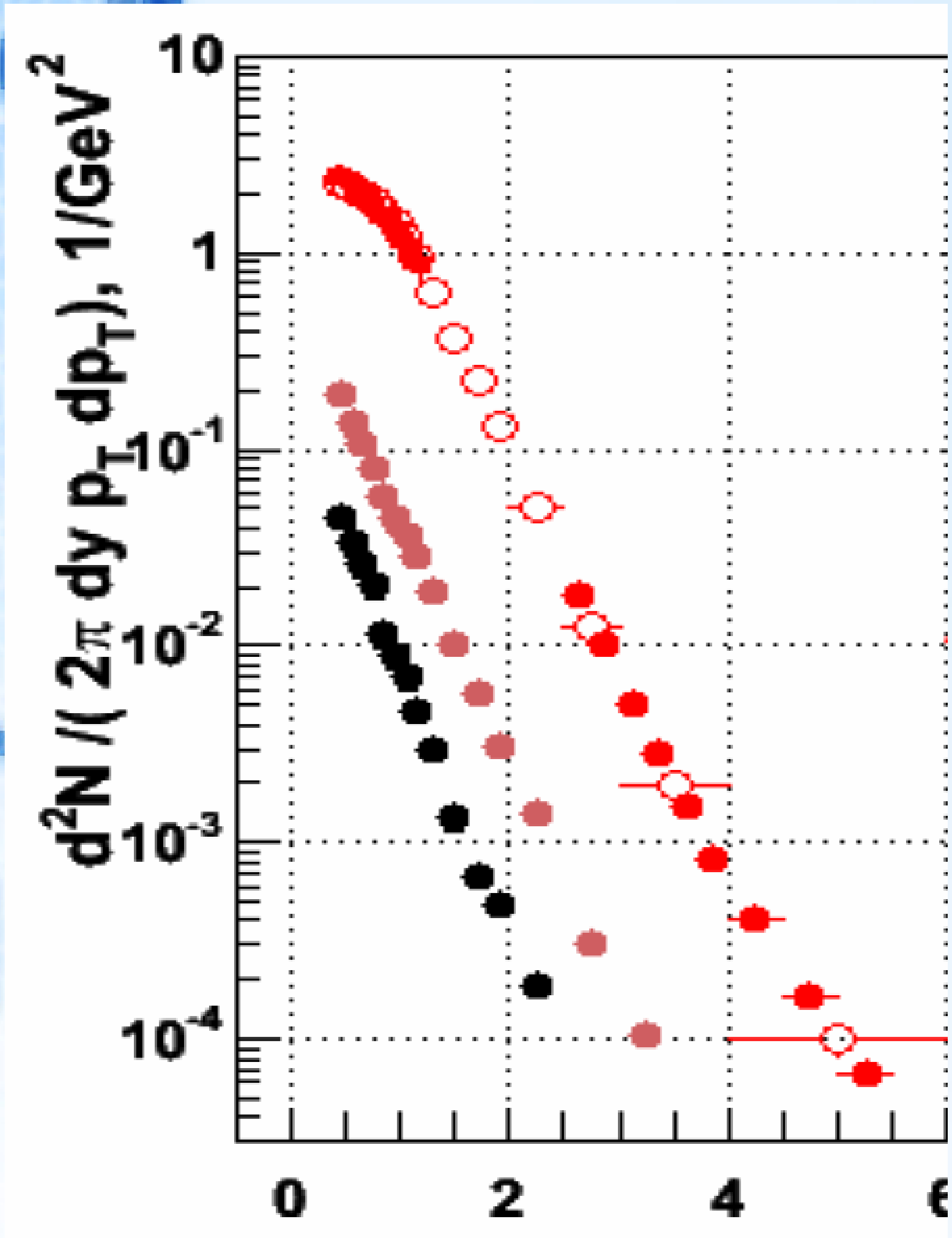
Driving force of flow
→pressure gradient
Inside: high pressure
Outside: vacuum (p=0)

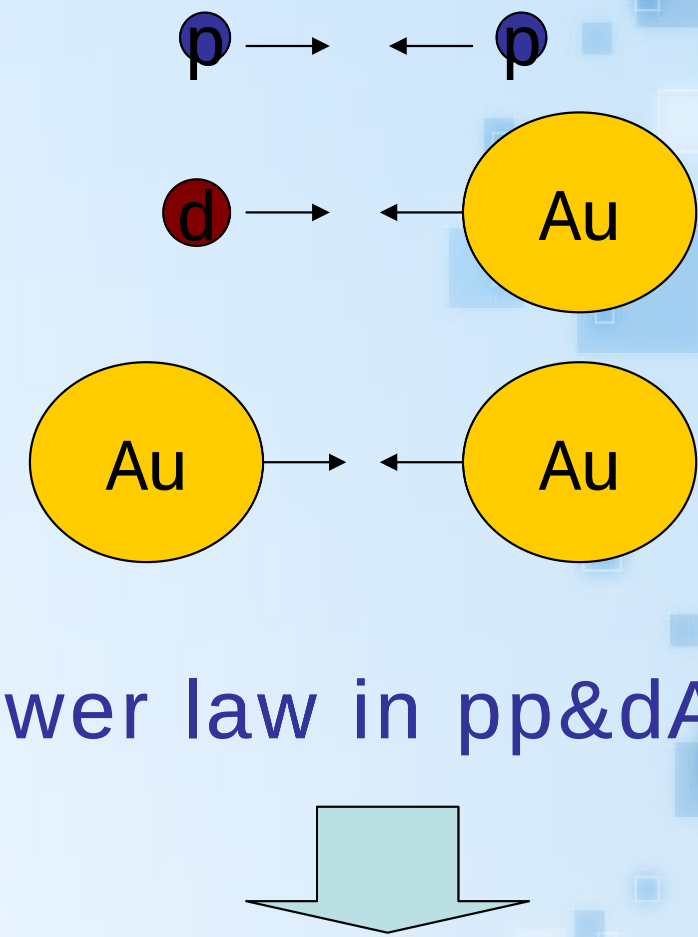




Spectral change is seen!

O.Barannikova, talk at QM05





Power law in pp&dAu

Convex to Power law in Au+Au

High pressure!?

CAVEATS (III)

- Not necessary to be thermalized completely
  - Results from non-equilibrium model also show similar shapes.
- How is radial flow generated dynamically?

Necessary Conditions to Study QGP at RHIC

- Energy density can be well above ε_c.
  - How large locally?
- Temperature can be extracted.
  - How high inside the matter?
- High pressure can be built up.
  - How high?

Importance of systematic study based on dynamical framework

Two Big Discoveries:

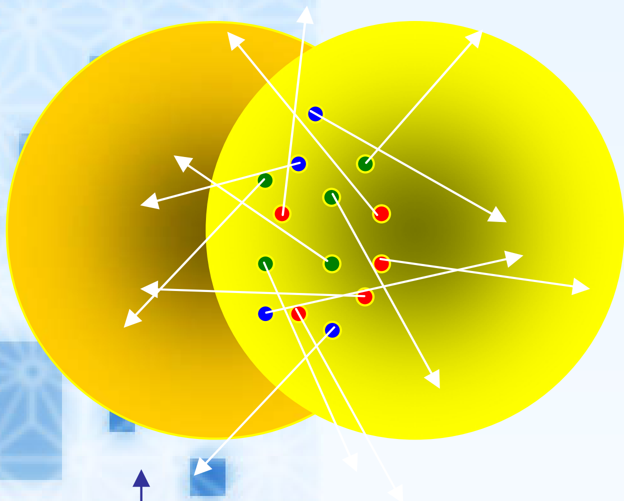
1. Elliptic Flow
2. Jet Quenching

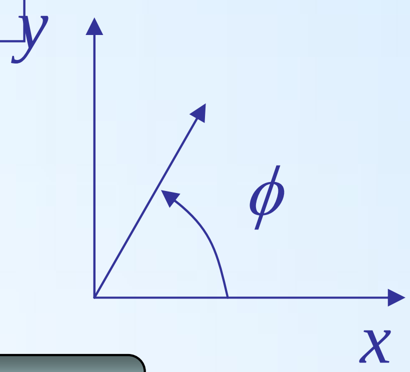
What is Elliptic Flow?

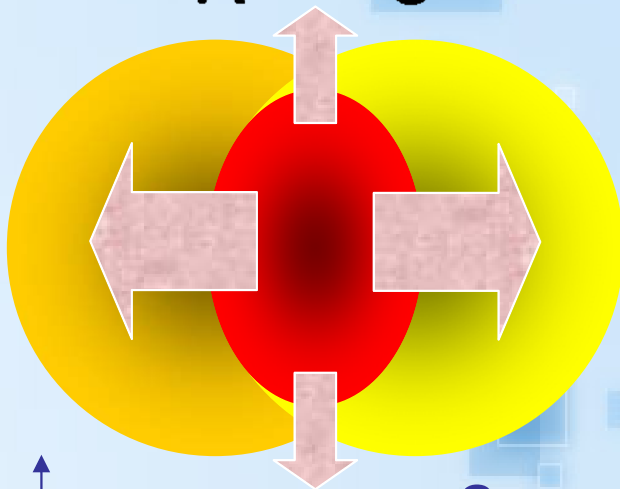
Ollitrault ('92)

How does the system respond to spatial anisotropy?

No secondary interaction	Hydro behavior
$\lambda \to \infty$	$\lambda = 0$







INPUT

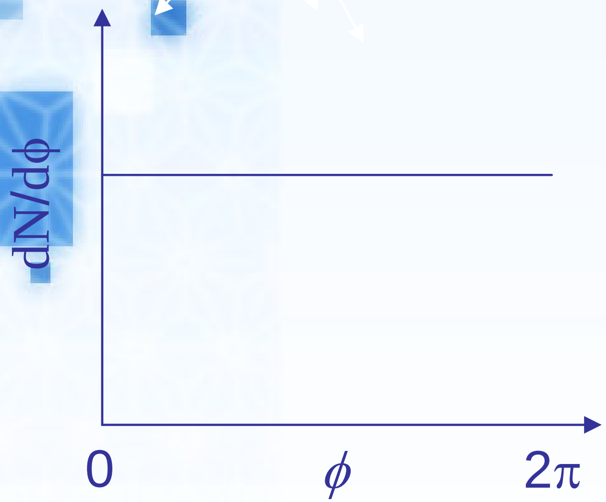
Spatial Anisotropy

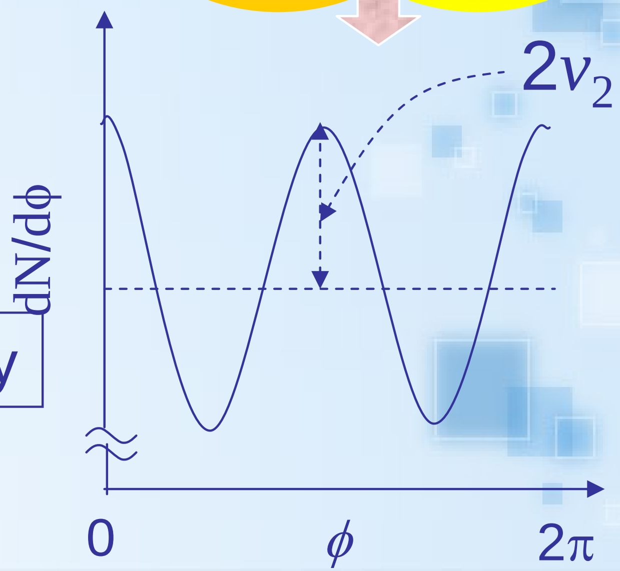
Interaction among produced particles

OUTPUT

Momentum Anisotropy

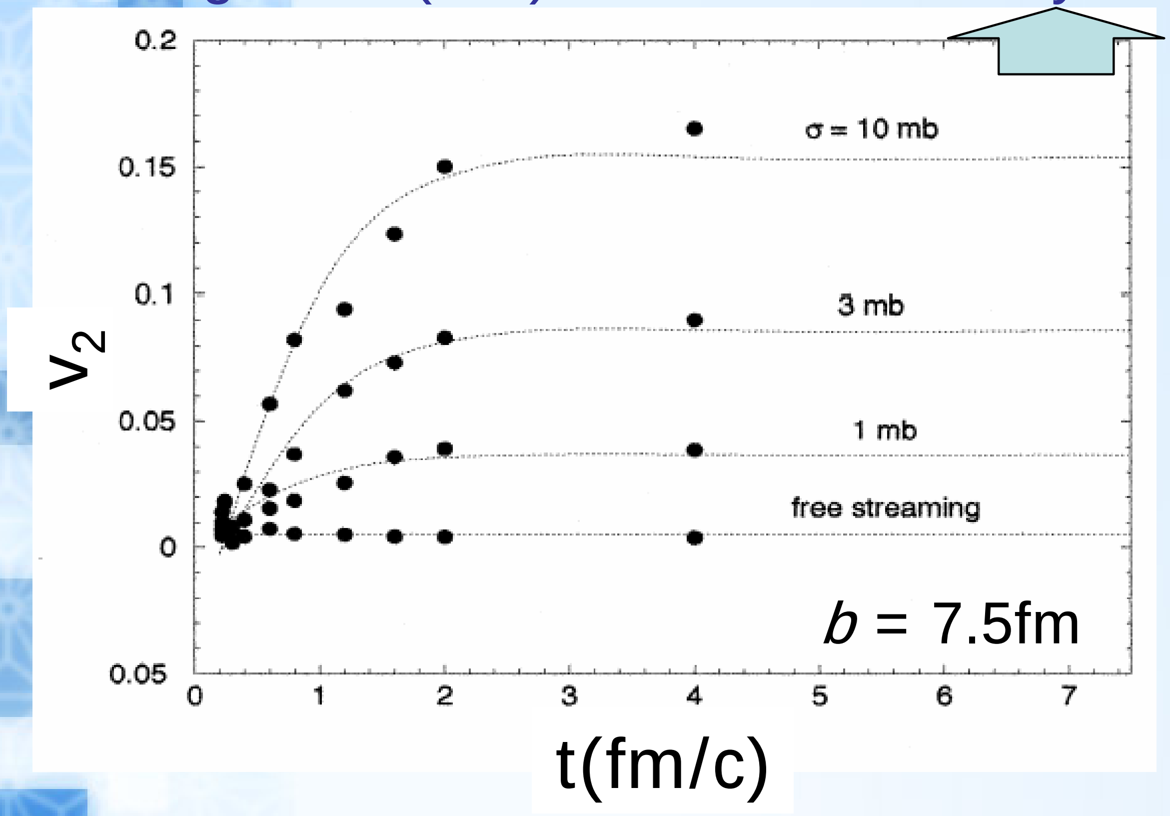
$$v_2 = \langle \cos(2\phi) \rangle$$





v_2 from a Boltzmann Simulation

Zhang et al.('99) ideal hydro limit



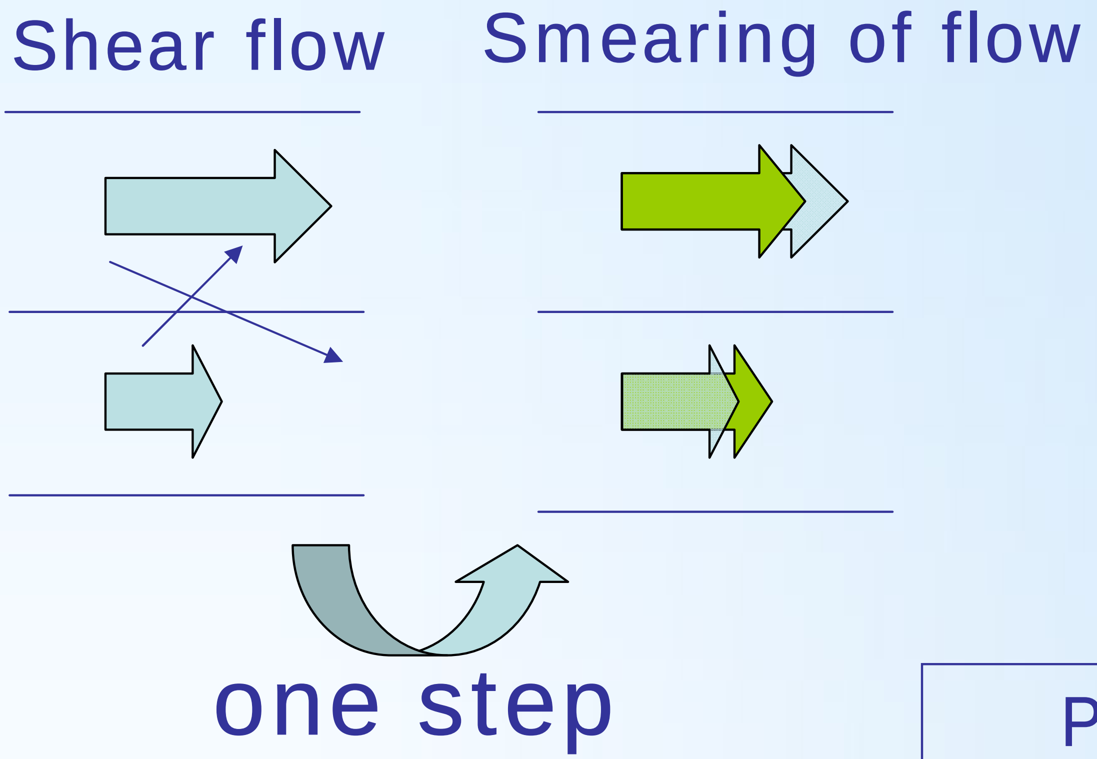
$$\lambda = \frac{1}{\sigma\rho} \propto \eta$$

$\lambda \to 0$: Ideal hydro

$\sigma \to \infty$: strongly interacting system

v_2 is
- generated through secondary collisions
- saturated in the early stage
- sensitive to cross section (~1/m.f.p.~1/viscosity)

Schematic Picture of Shear Viscosity



Perfect fluid:
$\lambda = 1/\sigma\rho \rightarrow 0$

shear viscosity $\rightarrow$ 0

Primer of Hydrodynamics

Non-relativistic Navier-Stokes eq. (a simple form)

Neglecting external force and assuming incompressibility.

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\vec{\nabla}P + \frac{\eta}{\rho}\nabla^2\vec{u}$$

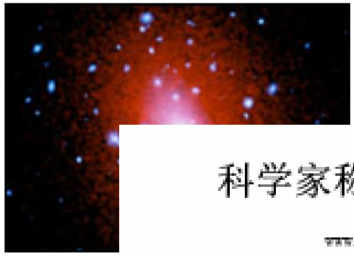
Pressure gradient generates flow

Shear viscosity diffuses flow.

Interplay btw. these two effects

Caveat: In the actual calculations, relativistic version of (ideal) hydro equations is solved.

Early Universe Went With the Flow



Posted April 18, 2005 5:57PM

Between 2000 and 2003 the lab's Relativistic Heavy Ion Collic repeatedly smashed the nuclei of gold atoms together with s that their energy briefly generated trillion-degree temperature

科学家称初生宇宙可能是液体状的而非气体状

www.XINHUANET.com 2005年04月20日 07:45:55 来源：新京报

【字体：大 中 小】【打印本稿】【读后感言】【进入论坛】【推荐 Go 】 【关闭】

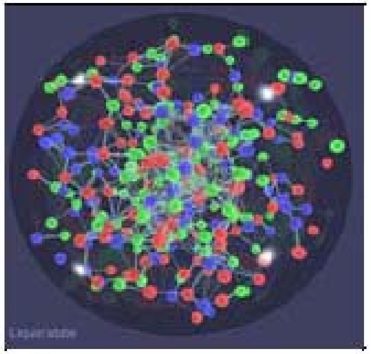
本报综合报道 4月18日，在美国佛罗里达州坦帕市举行的美国物理协会会议上，有科学家提出，对粒子碰撞的最新研究结果表明，在宇宙诞生的最初百万分之一秒，宇宙可能是液体状的，而不是像过去所认为的那样是炽热的气体状的。

BNL

www.geographic.hu Tudomány

Magyar részvétellel fedezték fel az univerzum ősanyagát

Az univerzum keletkezése utáni néhány milliomod másodperc állapotát sikerült modelleznünk amerikai és magyar tudósoknak. Az Ősrobbanás utáni anyag forró, sűrű és folyékony lehetett.



Az amerikai Brookhaven Nemzeti Laboratórium (BNL) RHIC gyorsítója (Relativistic Heavy Ion Collider, Relativisztikus Nehézion-Ütköztető) mellett működő négy kísérleti csoport közös bejelentést tett: az ütköztetett nagyenergiás nehéz atommagokból sikerült előállítaniuk az anyagnak egy új, forró és sűrű állapotát. Az anyagnak ez az új formája az atommagok már ismert elemi építőköveiből, kvarkokból és gluonokból áll, viszont tulajdonságai jelentősen eltérnek az elméleti jóslatoktól, és igen figyelemreméltóak mivel a nehézion-ütközésekben keletkezett anyag nem szabad kvarkok és gluonok alkotta ideális gázként, hanem folyadékként viselkedik– olvasható a kfki.hu-n. A négy cikket, amelyeken a RHIC négy nagy nemzetközi kísérleti együttműködése közel egy éve dolgozik, a *Nuclear Physics* folyóirat egyszerre fogja közölni.

science ORF.at ANMELDEN & VISITKARTE ÄNDERN

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Neues aus der Welt der Wissenschaft

[ORF ON Science : News : Wissen und Bildung . Kosmos]

Das Universum war am Anfang "flüssig"

Das Universum war direkt nach dem Urknall vermutlich einem Fluidum ähnlich. Das schließen dänische Forscher aus Experimenten am weltstärksten Kernbeschleuniger RHIC am Brookhaven National Laboratory.

Mit seiner enormen Kollisionsenergie bildet der RHIC rund 1.000 Milliarden Grad Celsius heiße Urmaterie vom Anbeginn der Zeit vor rund 13,7 Milliarden Jahren nach.

Post

as 'liquid-l

have hot, ng old

社会 asahi.comトップ > 社会 > その他・話題

宇宙の始まりはしずく？「クオークは液体」と発表

2005年04月18日23時34分

宇宙誕生の大爆発「ビッグバン」直後に相当する超高温・高密度の状態を再現する実験をしてきた日米などの国際チームは18日、物質を形づくる究極の基本粒子クオークは超高温でバラバラになるが、気体のように自由に跳び回るのでなく、しずくのような液体状態にあったと考えられる、と発表した。理論的に予想外の発見で、宇宙や物質のなりたちを説明するシナリオに影響を与える可能性がある。

...mage: BNL

When they a clear ization arly

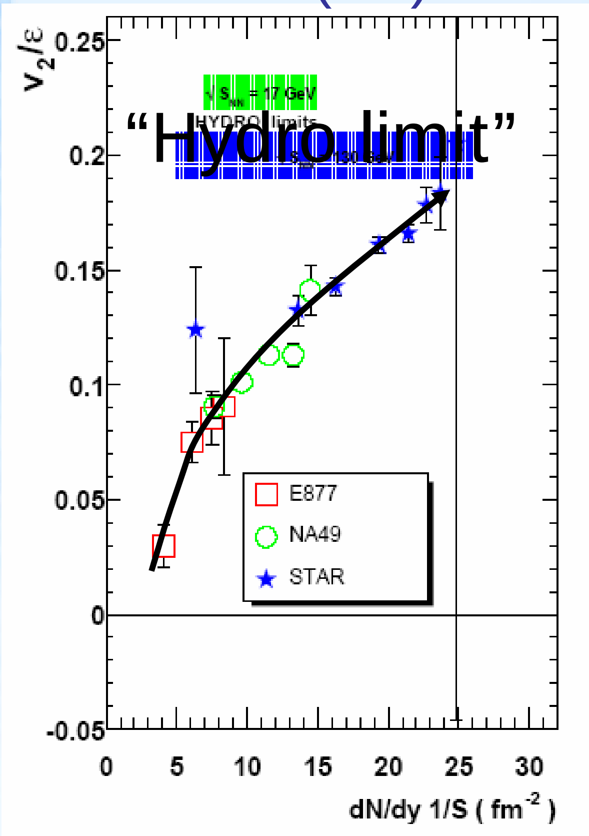
...markable than had been predicted. In ...marizing the first three years of RHIC findings, ...t instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions

microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

Agreement btw. hydro and data

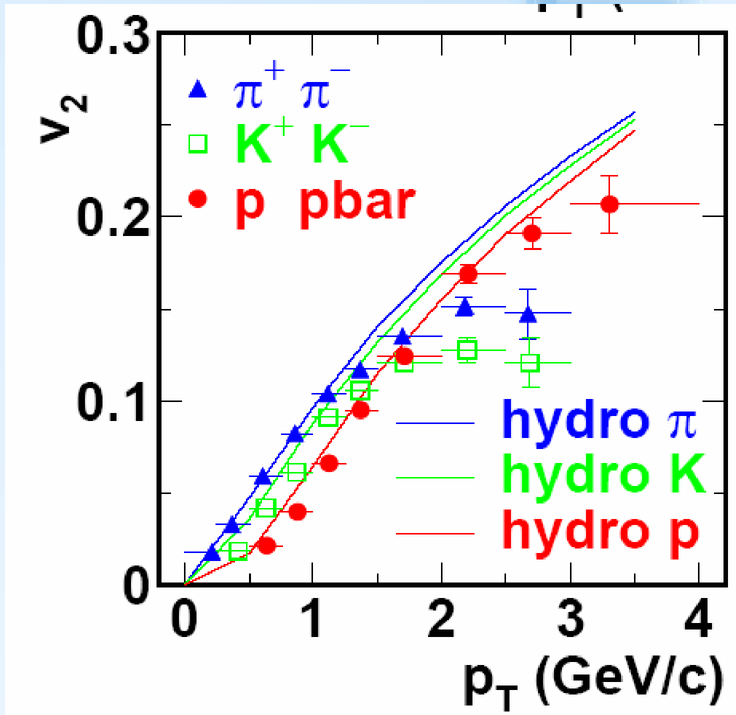
response = (output)/(input)

STAR('02)



Multiplicity dependence

PHENIX('03)

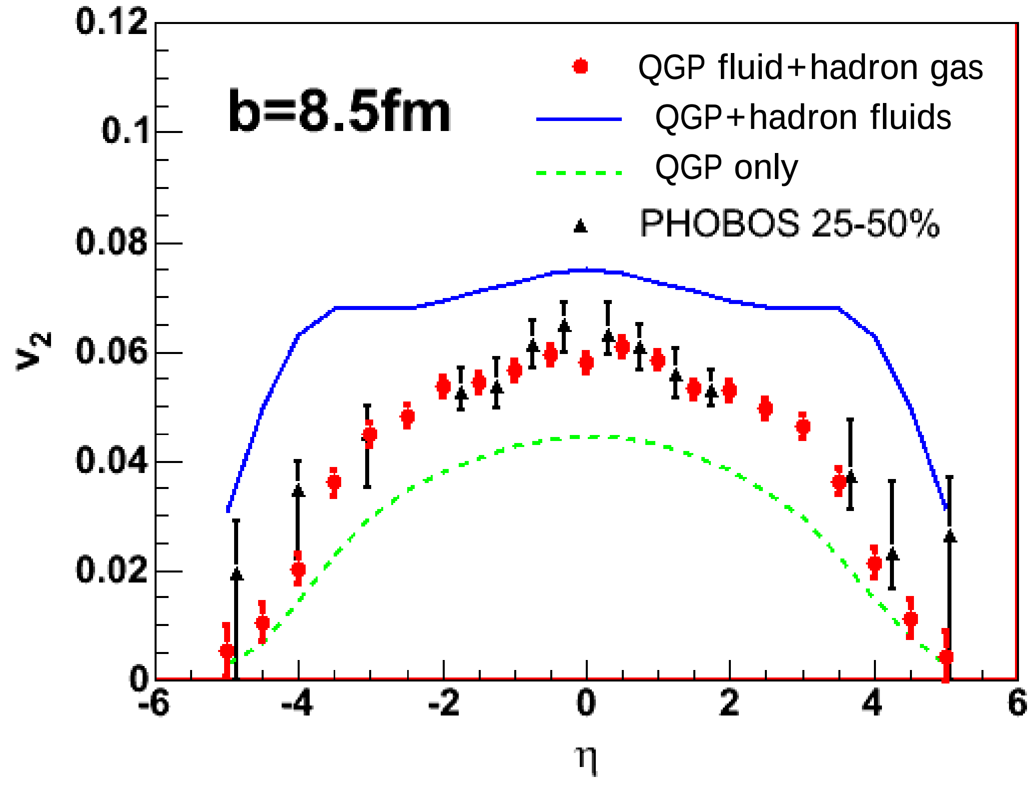


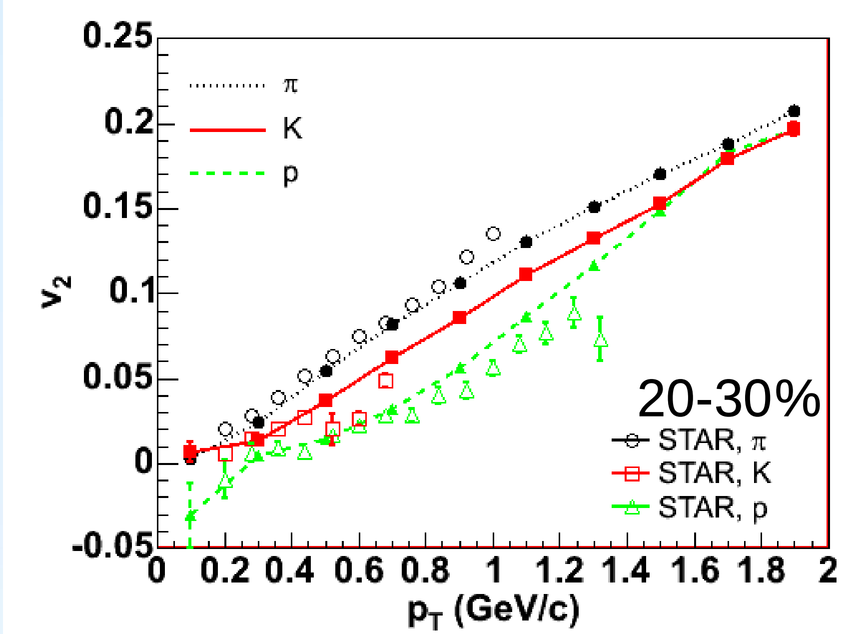
p_T dependence and mass ordering

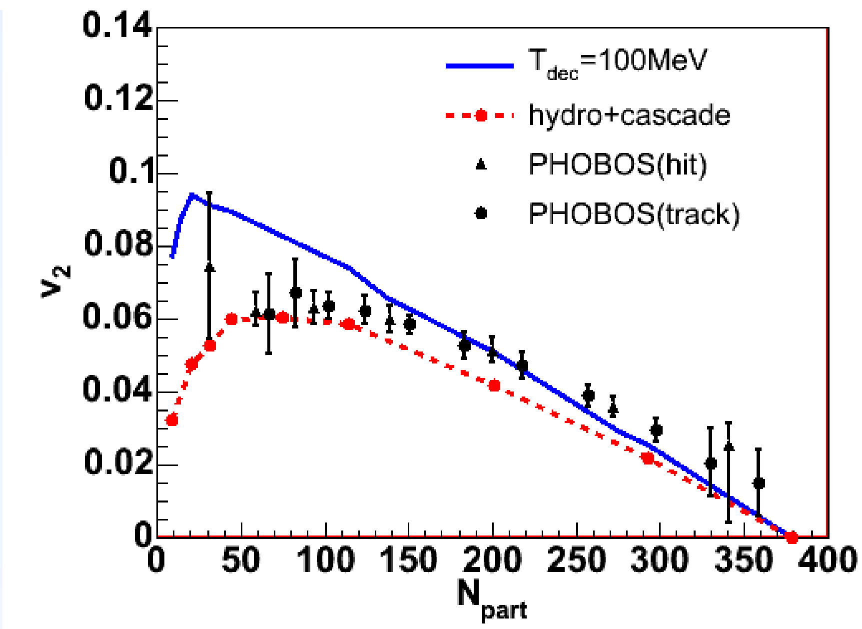
Hydro results: Huovinen, Kolb, Heinz,...

TH,U.Heinz,D.Kharzeev,R.Lacey,Y.Nara

Results from our Group







(Upper-left)
Pseudorapidity dependence
(Upper-right)
Transverse momentum dep.
(Lower-right)
Centrality dependence

Summary of Elliptic Flow

- Experimetal data are consistent with perfect fluid (neglecting viscosity) QGP picture.
- Remember

(shear viscosity) ~ (mean free path)

~1/(cross section),

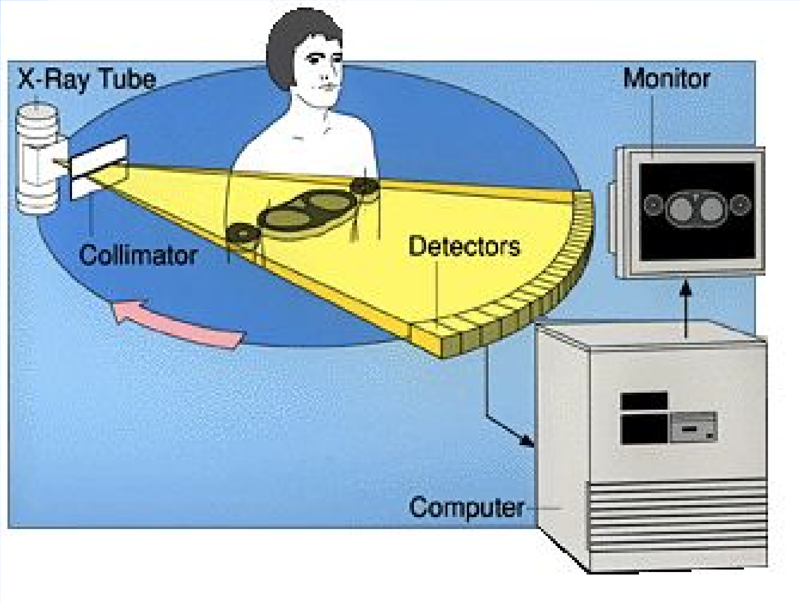
quarks and gluons interact with each other strongly.

Two Big Discoveries:

1. Elliptic Flow
2. Jet Quenching

Tomography

CT (computed tomography) scan

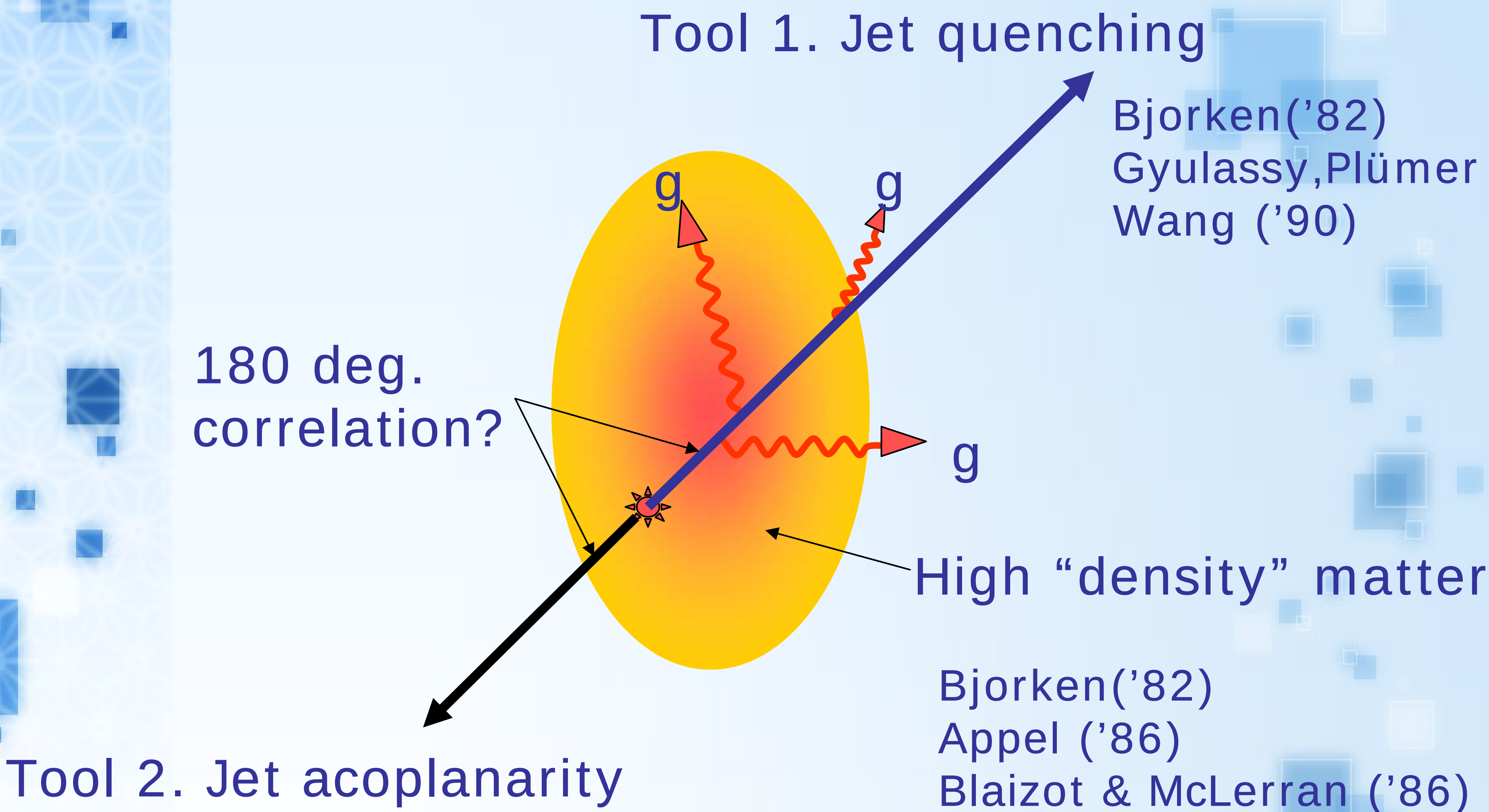


- “Tomography”
  1. Known probes: Spectra reliably calculable via pQCD
  2. Good detector: RHIC experiments!
  3. Interaction btw. probes and unknowns:

     Recent development in this field

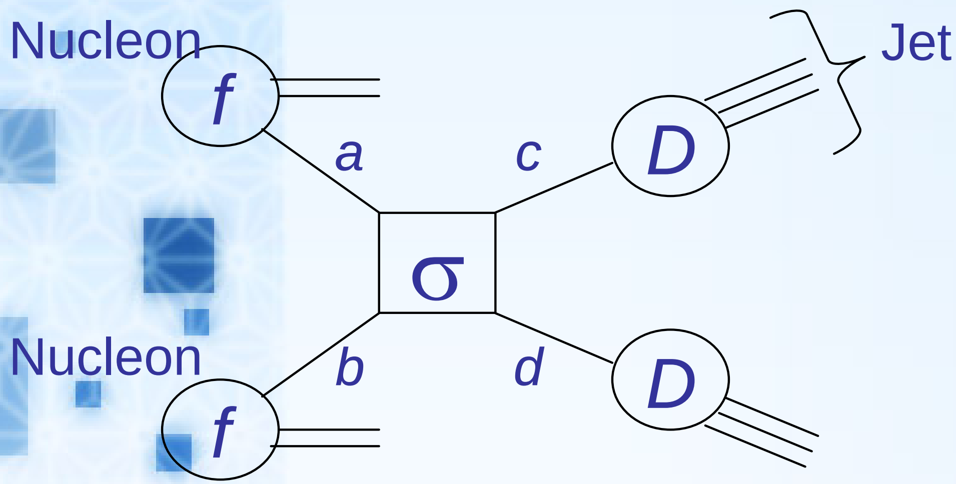
*平野哲文、浜垣秀樹、「ジェットで探るクォークグルーオンプラズマ」、日本物理学会誌2004年12月号

Jet Tomography



Difference btw. pp and AA

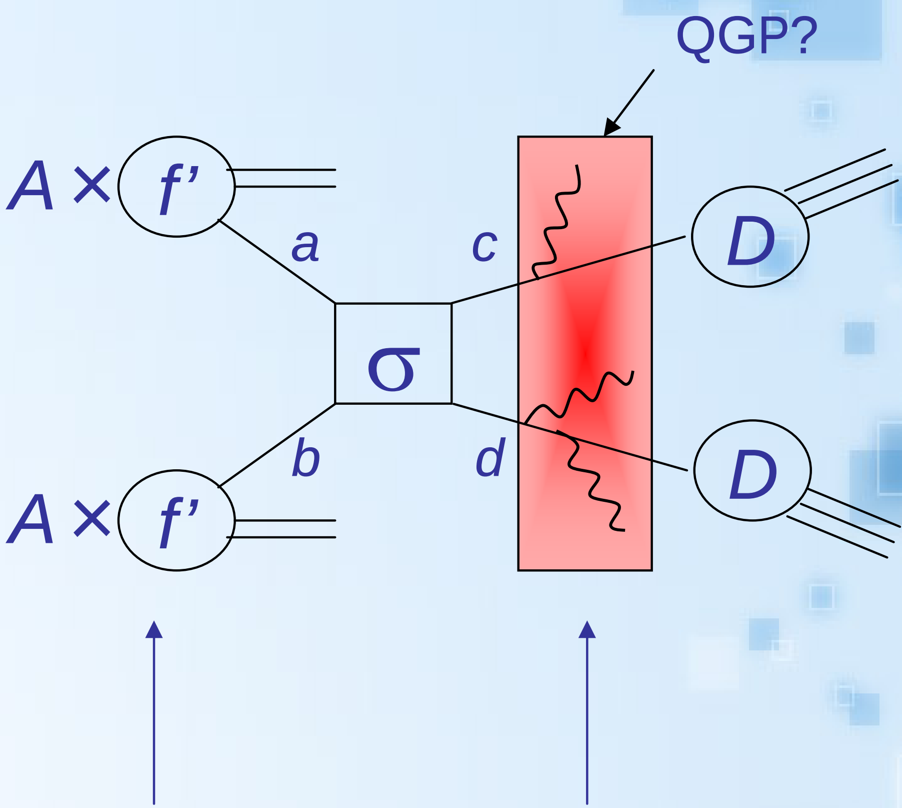
pp collisions



f: parton dist.

D: Frag. dist.

AA collisions

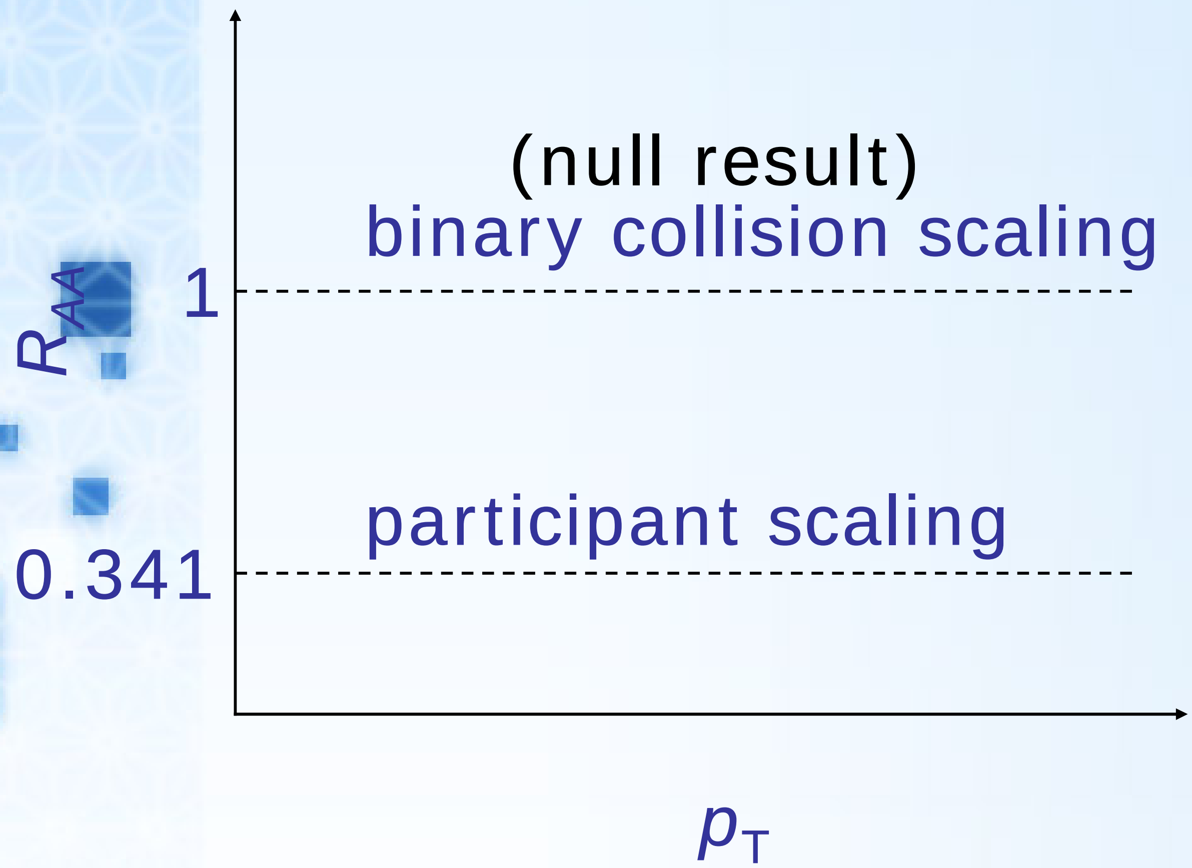


Initial effects

Final effects

Nuclear Modification Factor

$$R_{AA} = \frac{dN^{AA}/dp_{\mathrm{T}}d\eta}{\langle N_{\mathrm{coll}}\rangle dN^{pp}/dp_{\mathrm{T}}d\eta}$$



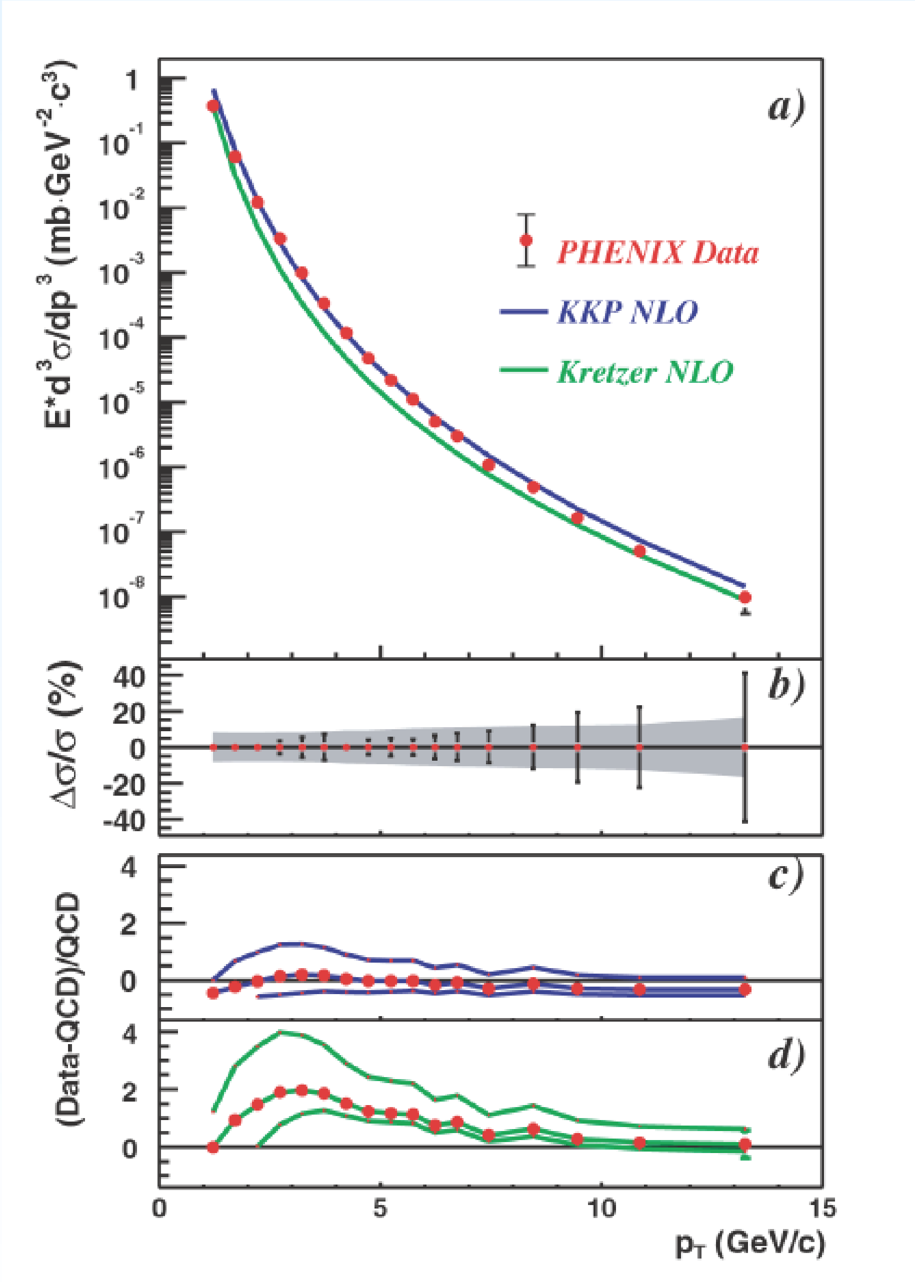
Au+Au 0-10% central

- b=2.8 fm

- N_{coll} = 978
- N_{part} = 333

- $N_{\mathrm{part}}/N_{\mathrm{coll}}$ = 0.341

pQCD at Work



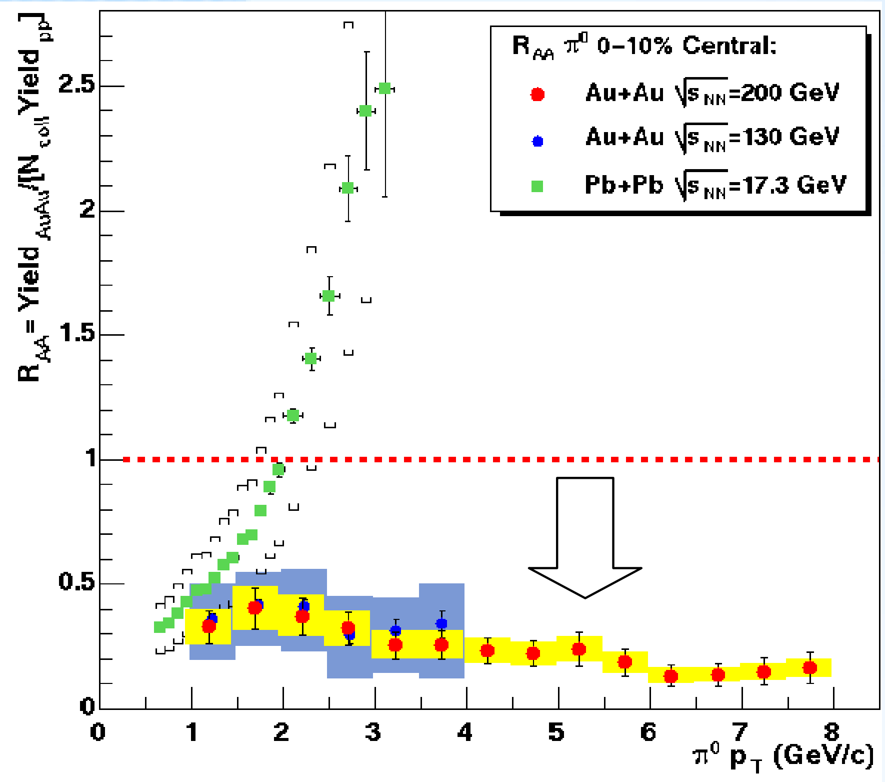
π_0 p_T distribution in pp collisions at sqrt(s) = 200 GeV

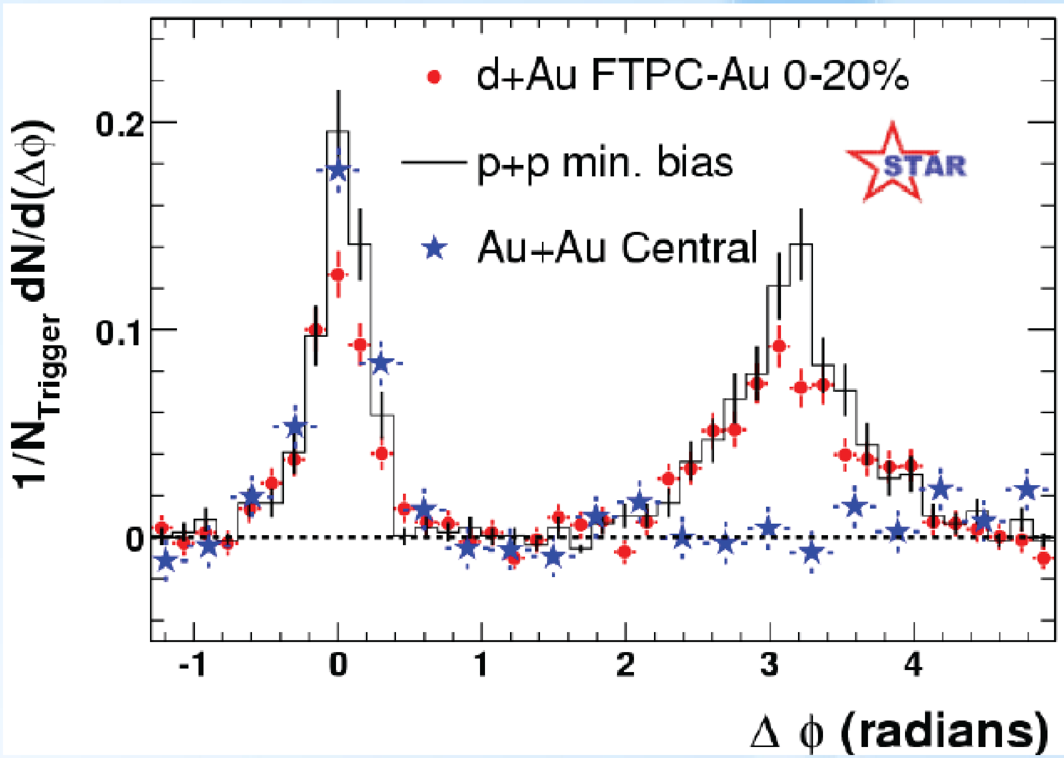
High pT particles can be utilized as probes of matter

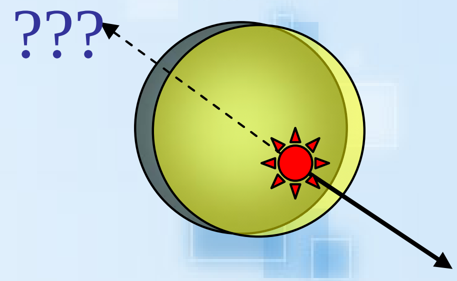
High p_T data at RHIC

$$R_{AA} = \frac{dN^{AA}/dp_T d\eta}{\langle N_{coll} \rangle dN^{pp}/dp_T d\eta}$$

$$\frac{1}{N_{trigger}}\frac{dN}{d\Delta\phi} = \frac{1}{N_{trigger}}\int d\Delta\eta \frac{dN}{d\Delta\phi d\Delta\eta}$$







S.S.Adler et al.(PHENIX), PRL91,072301(2003).

C.Adler et al. (STAR), PRL90,082302(2003).

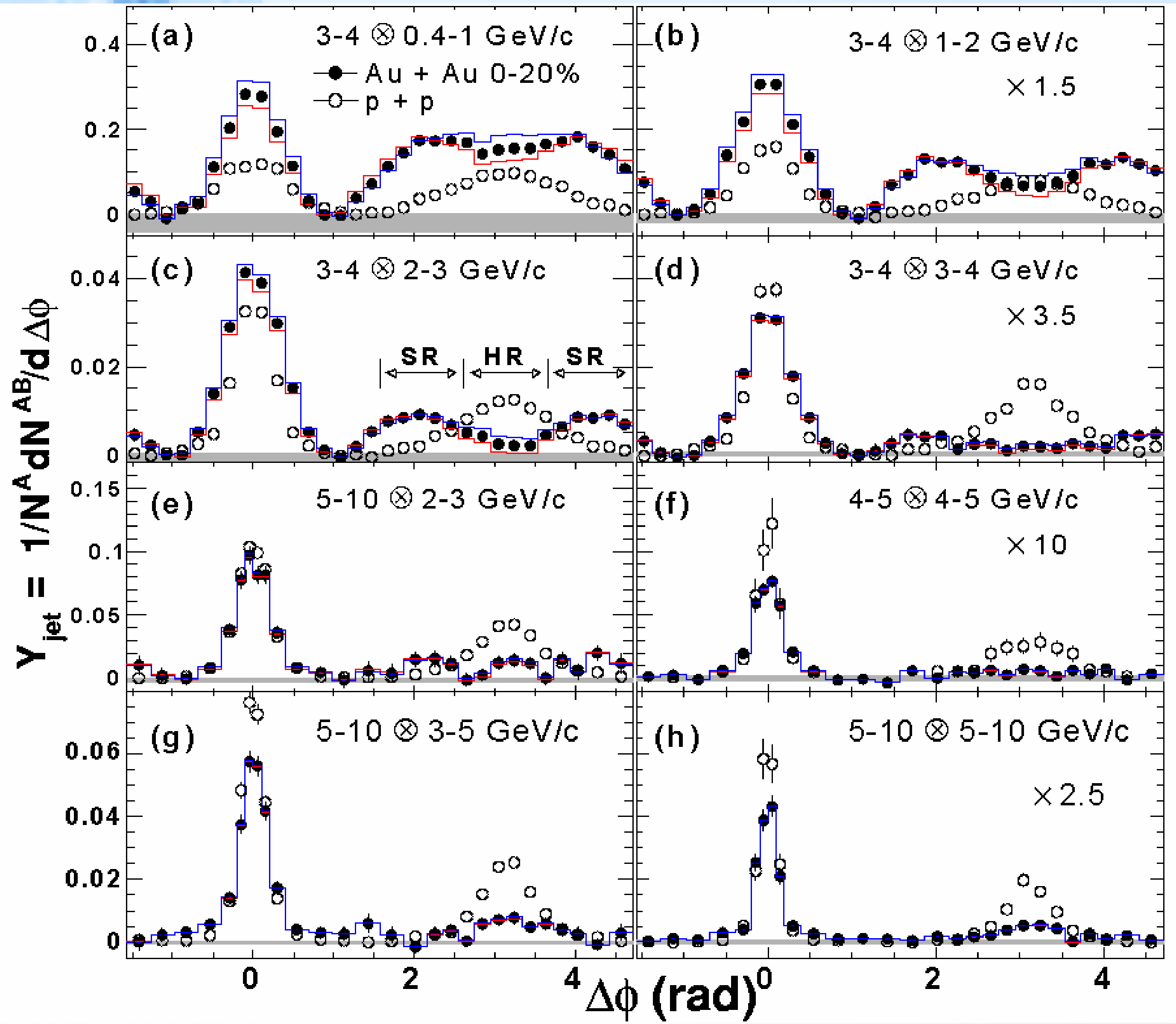
Summary of Jet Quenching

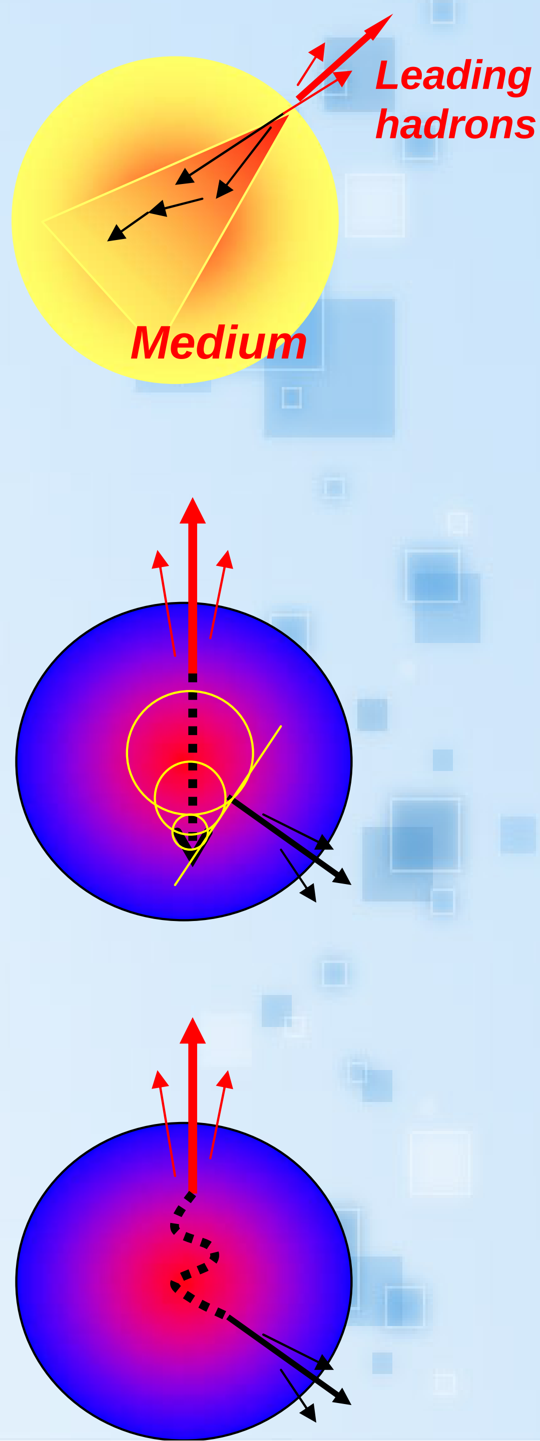
- Yields of high pT hadrons are suppressed.
- Correlation btw. two jets is lost.
- Suggesting “opaque” matter (in the sense of QCD) is created at RHIC.

Highlights of New Intriguing Data

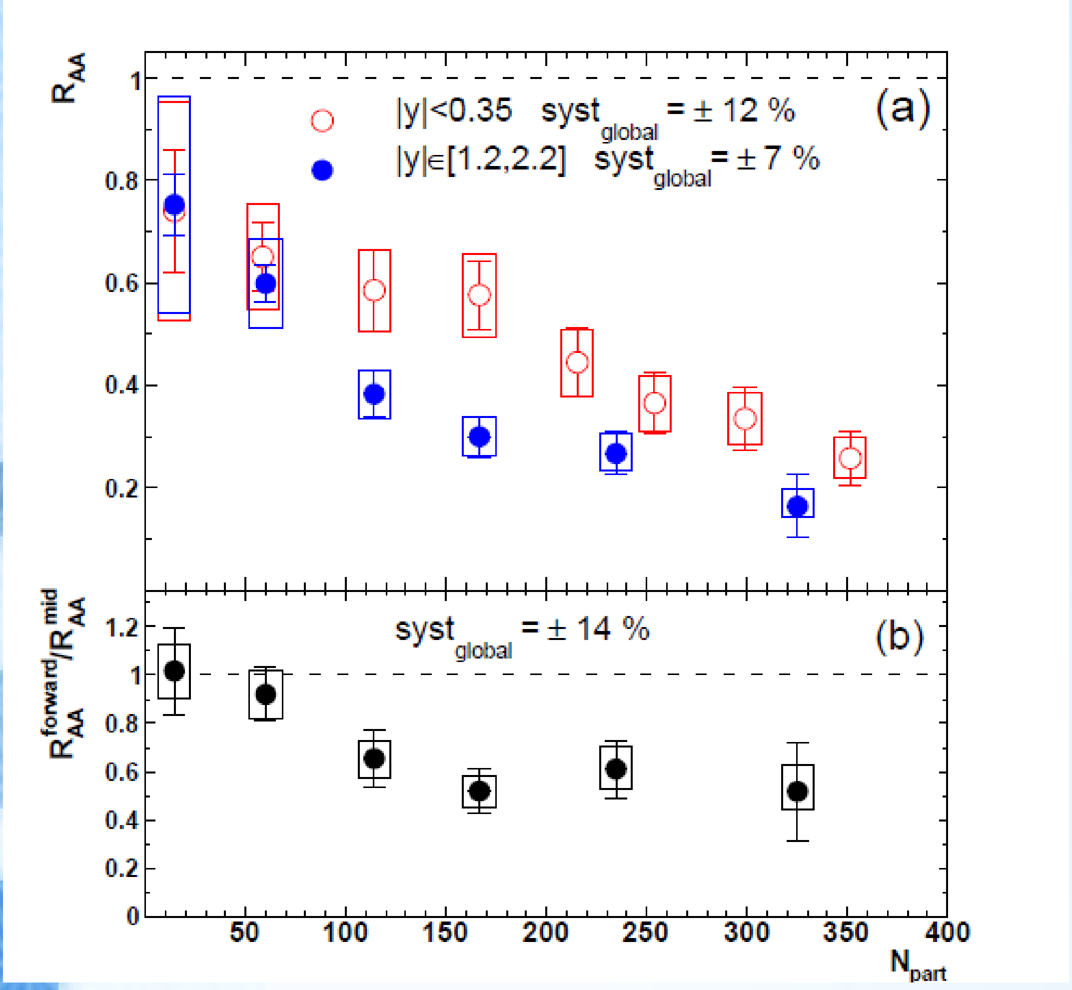
Jet Structure

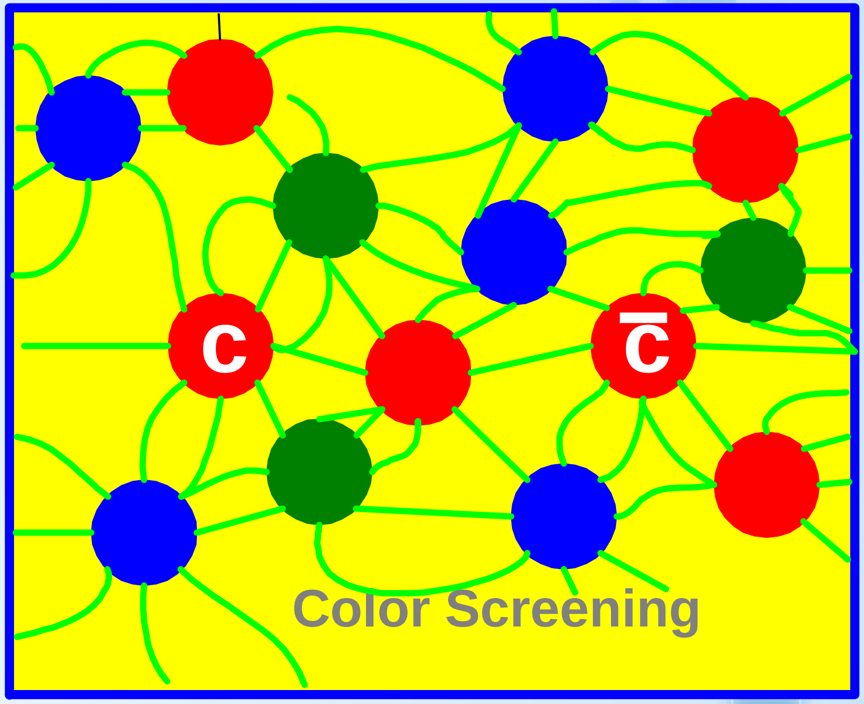
Cone-like structure? (PHENIX)





J/psi suppression





Color Debye screening
(Matsui-Satz)

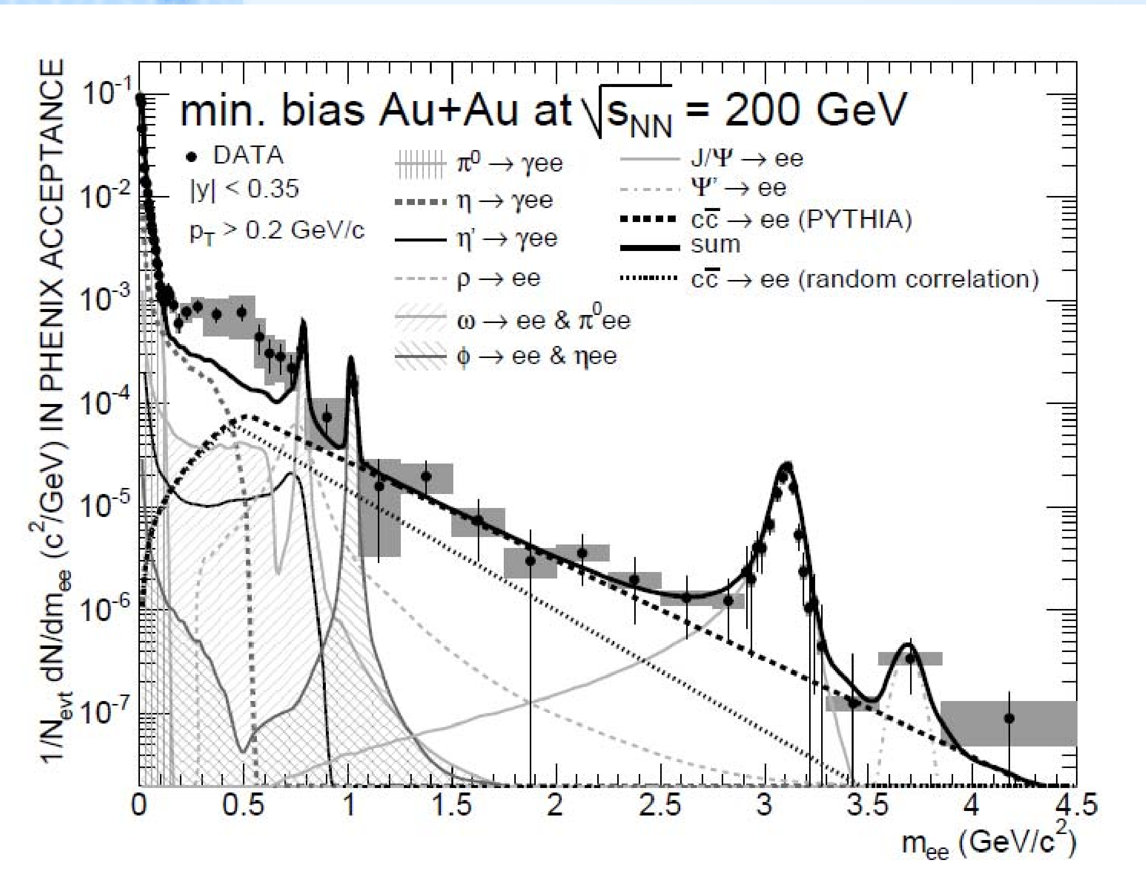
(PHENIX)

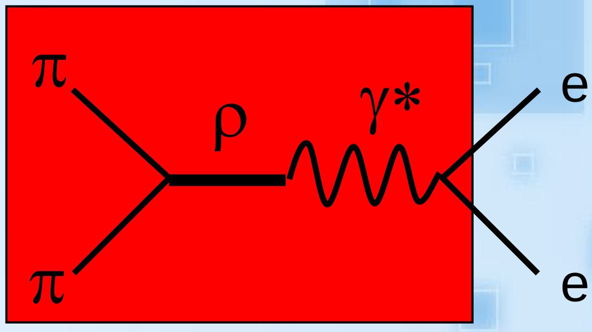
→ talk by S.Oda

Lattice studies:

M.Asakawa and T.Hatsuda, PRL. 92, 012001 (2004)
A. Jakovac et al. PRD 75, 014506 (2007)
G.Aarts et al. arXiv:0705.2198 [hep-lat]. (Full QCD)
...

Spectral Change of Hadrons?





Mass shift of ρ mesons?
Broadening of peak?
Evidence of partial restoration of chiral symmetry?

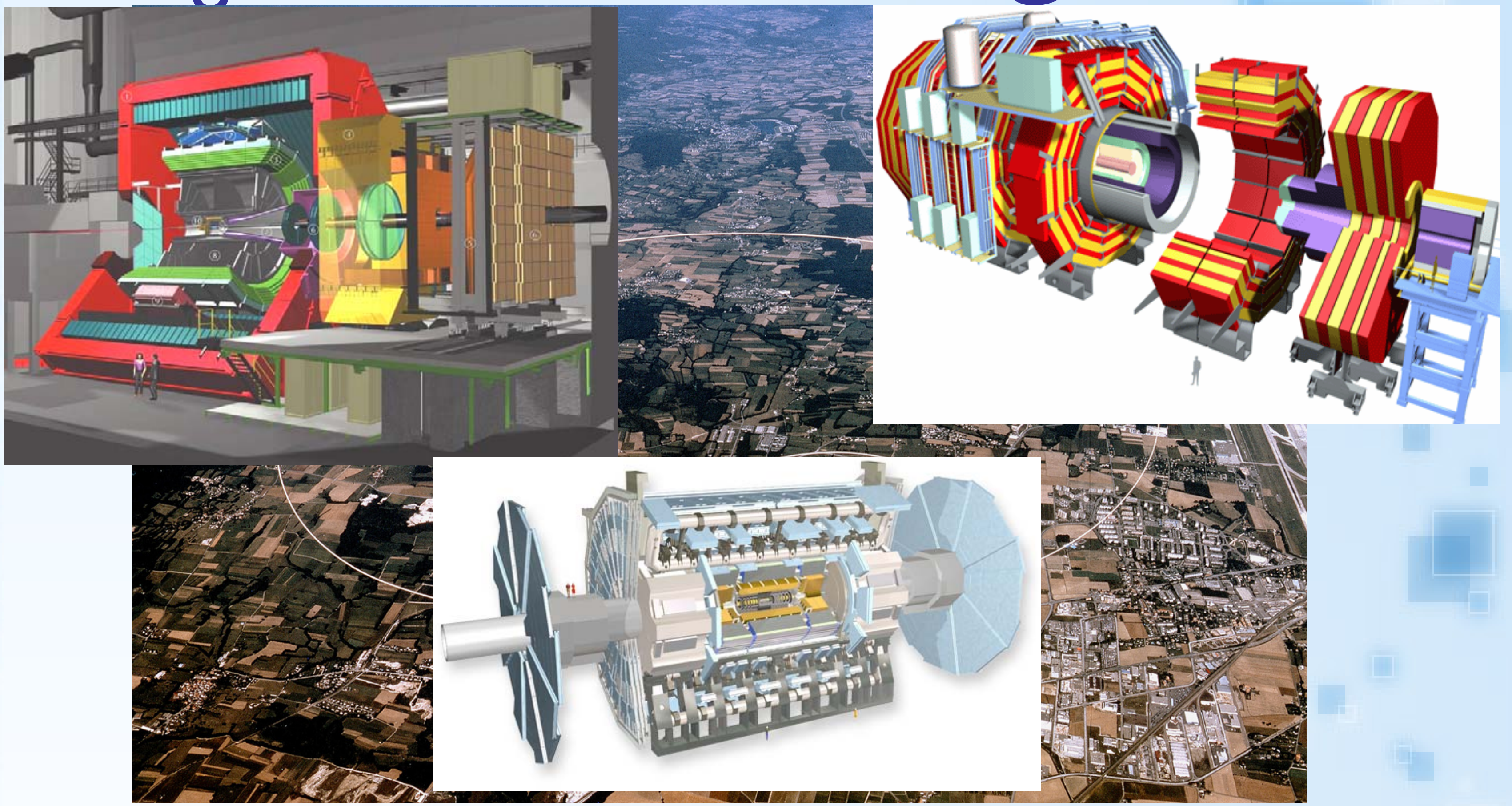
(PHENIX)
Posted on arXiv in this May!

Summary

- Basic checks suggest that it is promising to create the QGP at RHIC
- Two big discoveries indicate the matter produced in heavy ion collisions is strongly interacting and dense (opaque) system.
- The tip of the iceberg! Many other observables support this picture.
- More quantitative analyses are under way.

Outlook

Large Hadron Collider @ CERN



Higher collision energy, higher initial temperature, longer life time of QGP, smaller baryon density, ...