筑波大学集中講義

相対論的流体力学の基礎と高エネルギー重イオン衝突反応への応用

東京大学大学院
理学系研究科物理学専攻
平野哲文

この講義でカバーしたいこと

1. クォーク･グルーオン･プラズマと相対論的重イオン衝突の物理の概観 (review) 2コマ
2. 相対論的完全/粘性流体 (lecture) 2コマ
3. Bjorkenスケーリング解 (lecture) 2コマ
4. 相対論的運動学 (lecture) 2コマ
5. 相対論的流体力学の応用としての重イオン衝突反応データの解析 (seminar) 2コマ

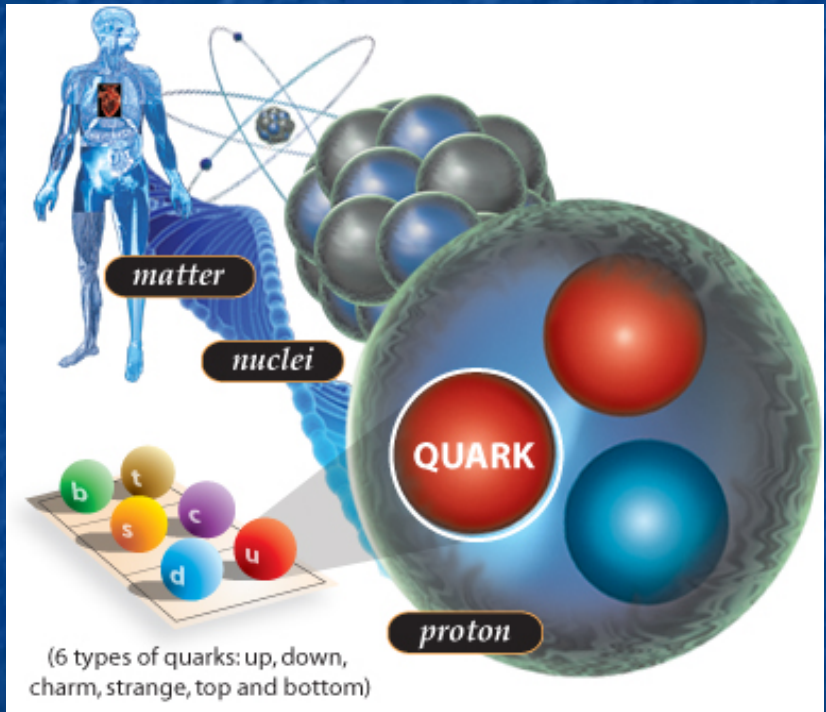
Introduction to the physics of the quark gluon plasma

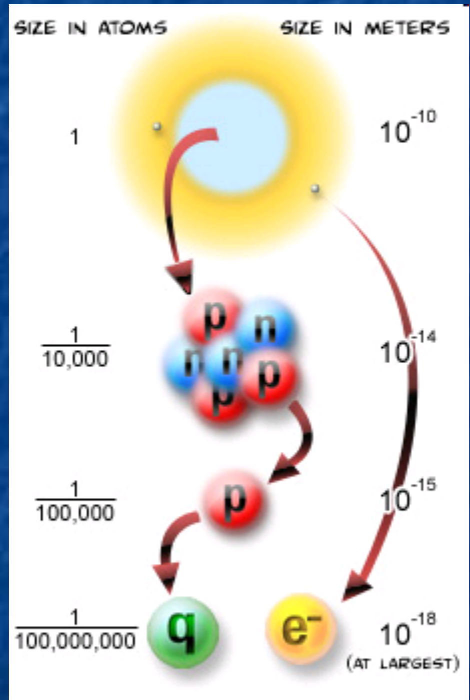
Lecture 1

Introduction

Q. What is the matter (in the sense of many body system) in which "building blocks" play a fundamental role?

Building Blocks





http://pdg.lbl.gov/
http://www.particleadventure.org/

Fermions in Standard Model

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Bosons in Standard Model

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Baryons as Composite Particles

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. These are a few of the many types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Mesons as Composite Particles

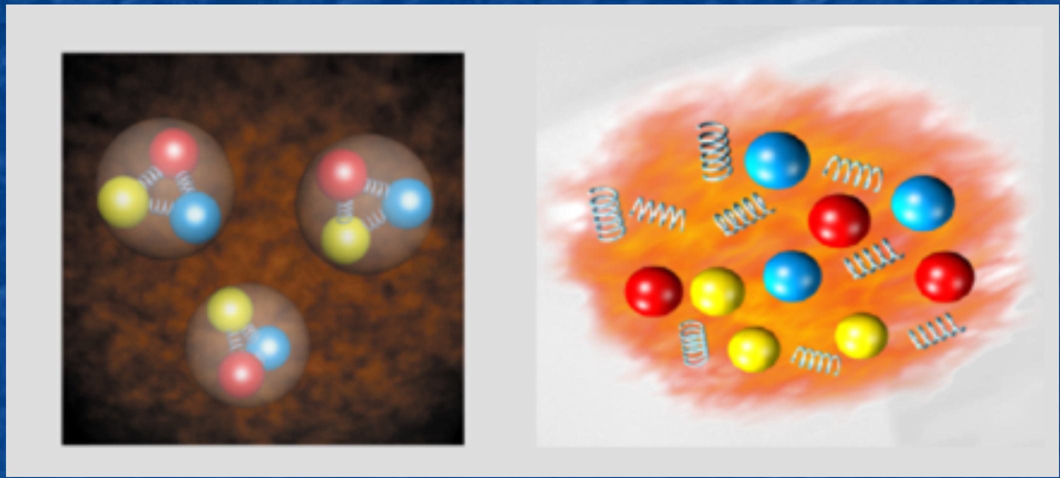
Mesons $q\bar{q}$ Mesons are bosonic hadrons These are a few of the many types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Physics of Many bodies

- "The whole is more than the sum of its parts." (Aristotle) http://en.wikipedia.org/wiki/Holism
- "More is different" (P.W. Anderson) http://www.sciencemag.org/cgi/pdf_extract/177/4047/393
- "Wholism is the way to proceed science in the 21st Century." (T.D. Lee, one of the founders of elementary particle physics) http://www.riken.jp/r-world/info/release/news/2000/dec/index.html#fro_01 (Original article in Japanese)

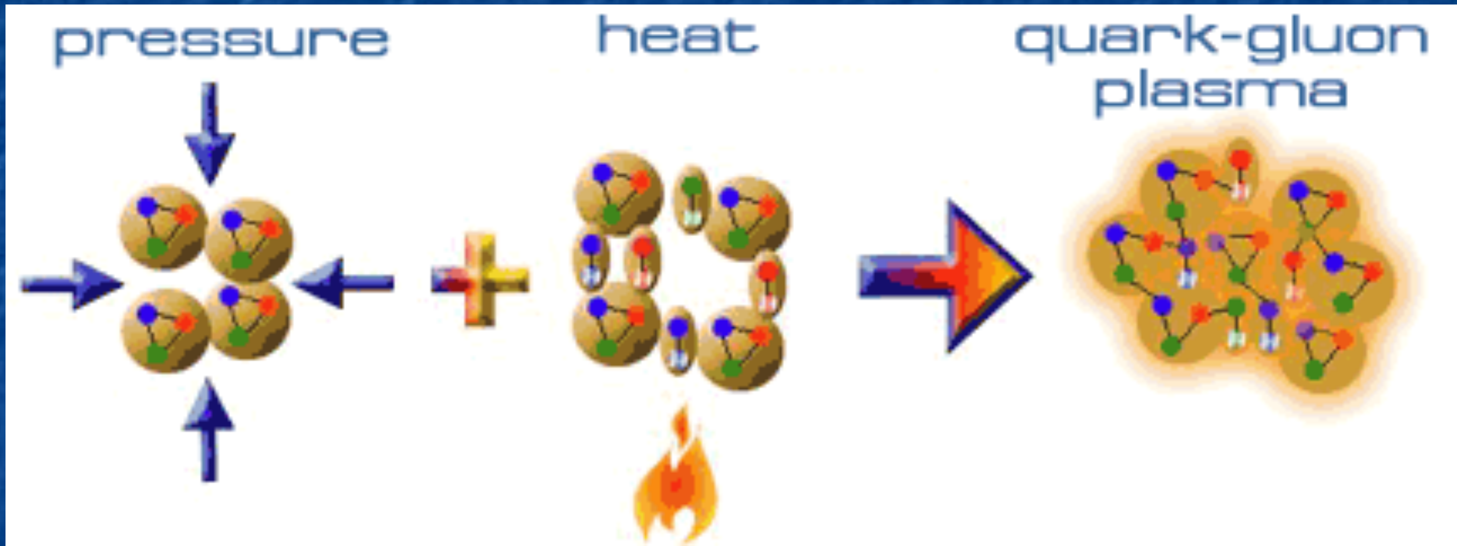
⟷ Elementary Particle Physics as "Reductionism"

Condensed Matter Physics of Elementary Particles



Quark Gluon Plasma QGP:
Many-body system of quarks and gluons under equilibrium
→ Statistical and thermodynamical physics of quarks and gluons

Recipes for Quark Gluon Plasma



How are colored particles set free from confinement?

Compress }
Heat up } hadronic many body system

Figure adopted from http://www.bnl.gov/rhic/QGP.htm

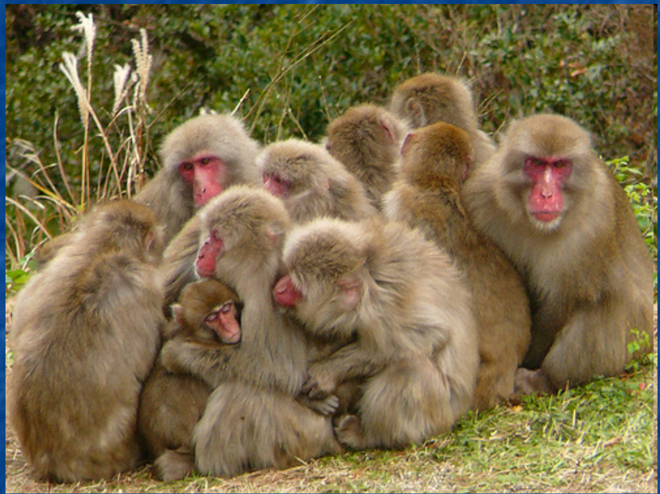
How High?

Suppose a closed-pack massless pion system,

$$n_\pi \approx \frac{1}{\frac{4}{3}\pi r_\pi^3}$$

$$\approx 3.6T^3$$

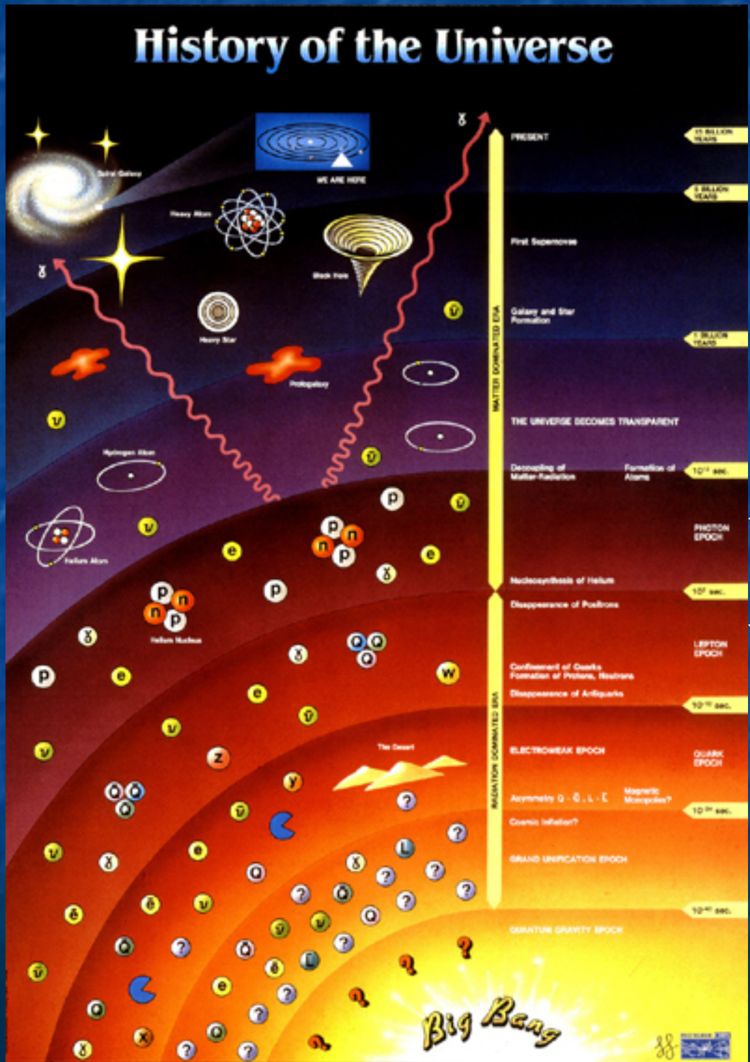
Or how low?



$\Rightarrow$ $T_c \sim 100 \text{ MeV} \sim 10^{12} \text{ K}$

for $r_\pi \sim 0.5 \text{ fm}$

Where WAS the QGP?



History of the Universe

History of the matter

Nucleosynthesis

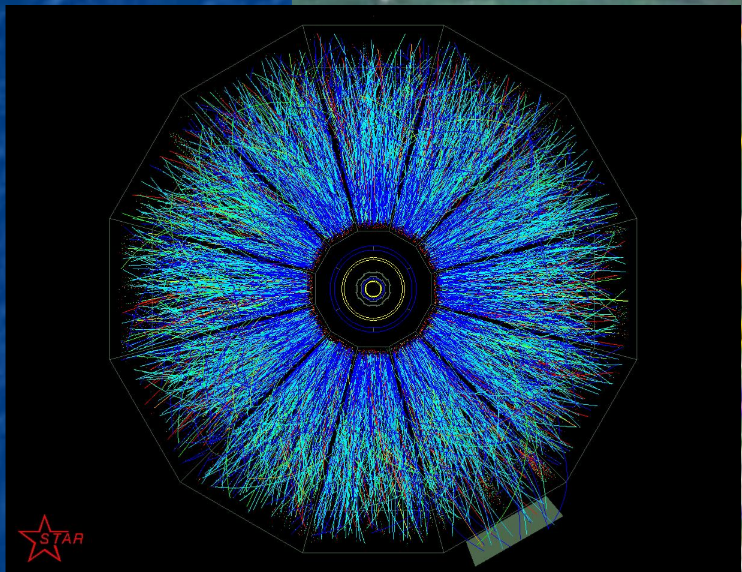
Hadronization

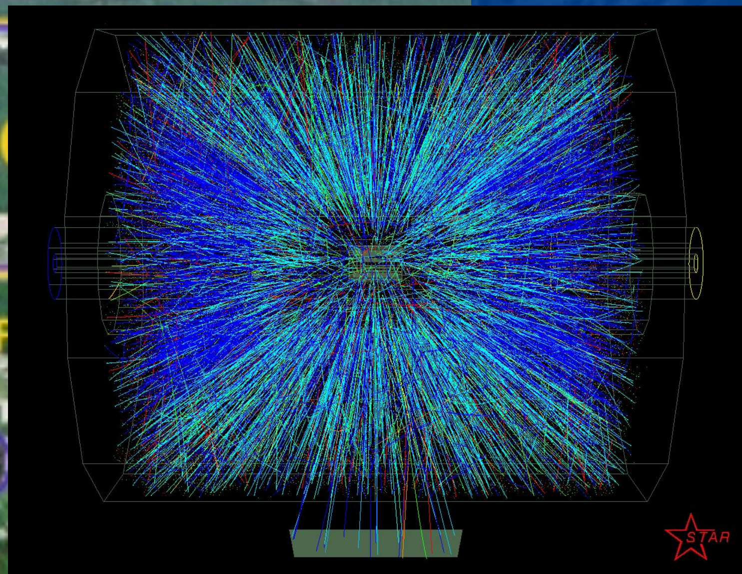
Quark Gluon Plasma

(after micro seconds of Big Bang)

Where IS the QGP?

Fate of Smashing Two Nuclei

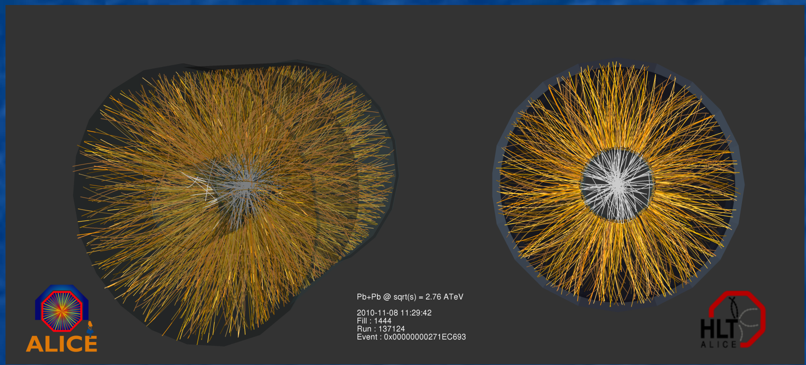


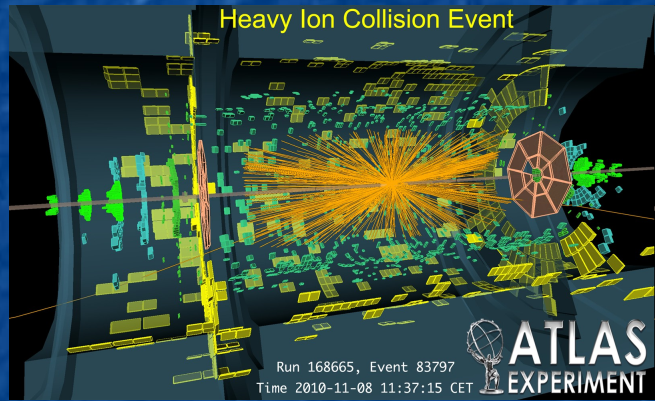


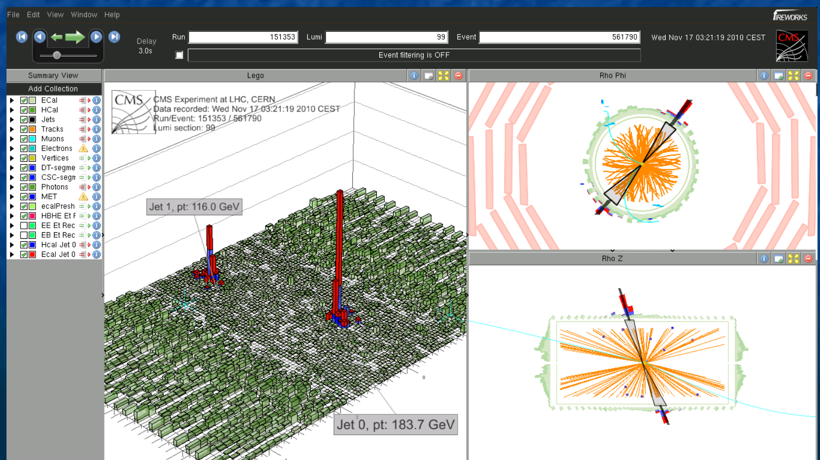
Front View Side View

Multiplicity of charged hadrons ~ 700 per unit rapidity in a head-on collision at $\mathrm{sqrt}(s_{NN})$=200 GeV

New Era Just Started!



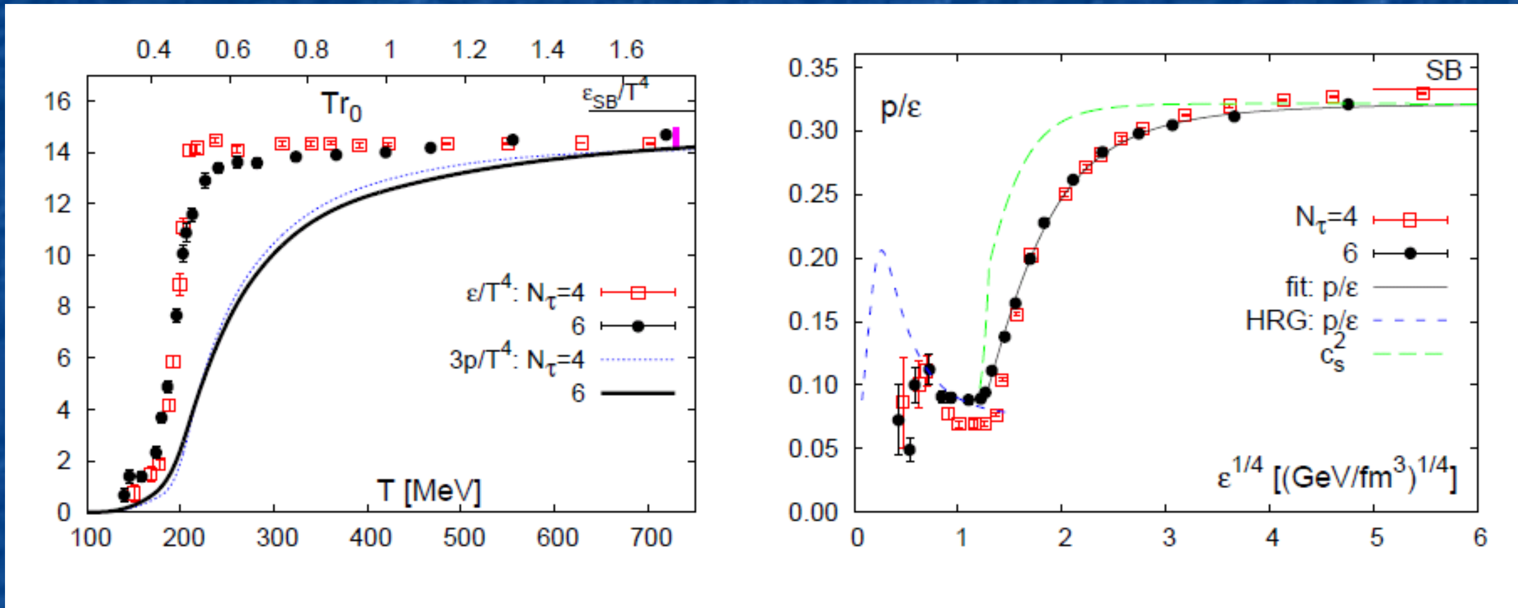




Multiplicity of charged hadrons ~ 1600 per unit rapidity in a head-on collision at $\sqrt{s_{NN}}$=2.76 TeV

M.Cheng et al., PRD77,014511 ('08)

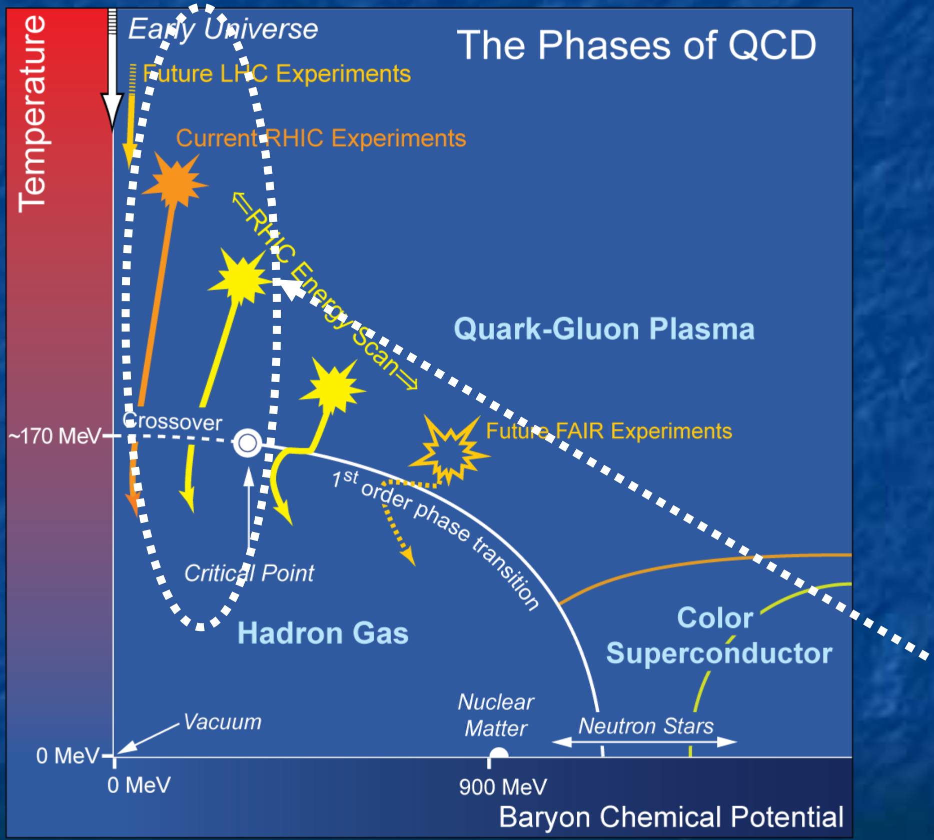
The QGP from the 1st Principle



Equation of state from lattice QCD

- Typical energy density scale of transition : ~1 GeV/fm^3
- Pseudo-critical temperature: ~190 MeV –> 170 MeV(?)
- Sound velocity is small in the vicinity of transition region
- Lattice QCD is NOT applicable for time evolution

Conjectured Phase Diagram of QCD



Understanding of phase diagram
→ "Condensed matter physics of QCD"

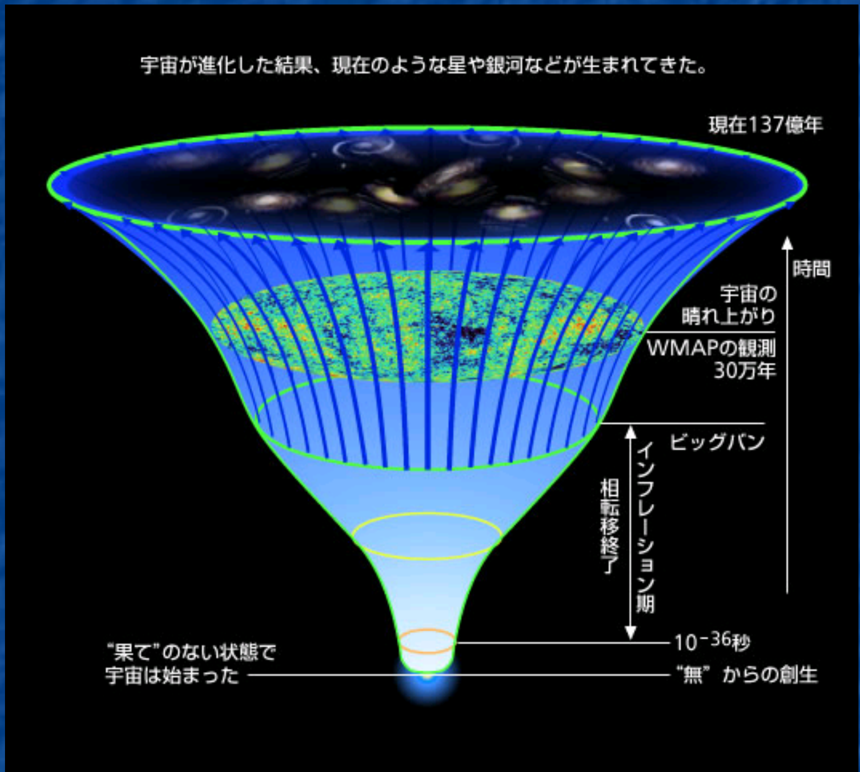
The region in which we can investigate by relativistic heavy ion collisions

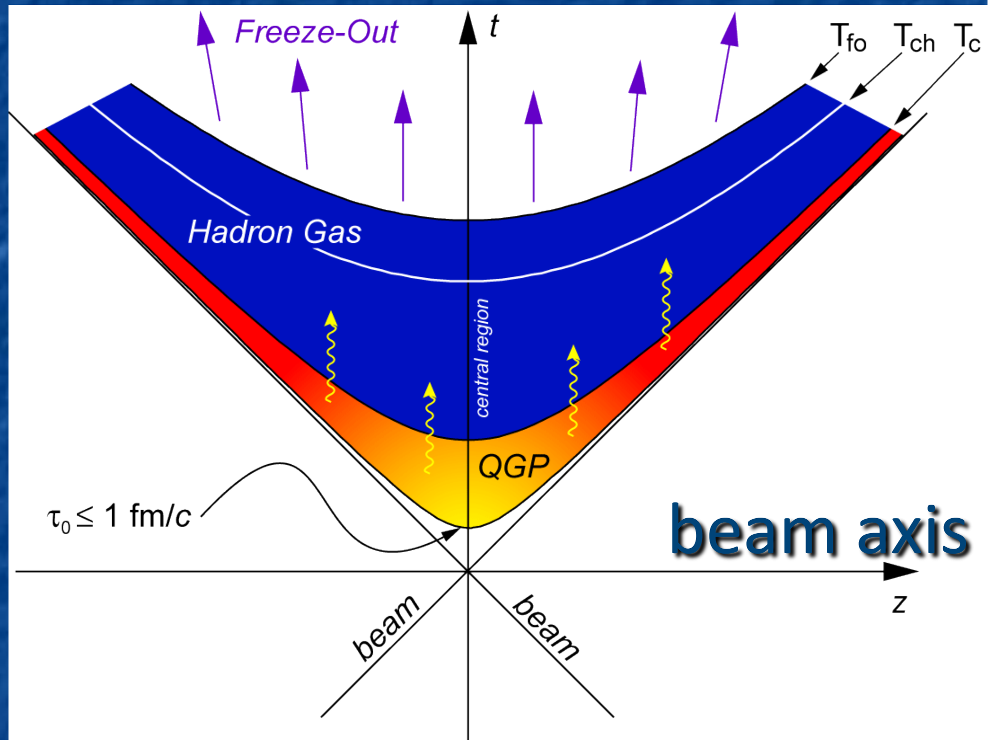
Physics of Relativistic Heavy Ion Collisions

Primary Goals of Heavy Ion Collisions at Ultrarelativistic Energies

- Understanding of QCD matter under extreme conditions (high T and low n_B)
  - Confinement, chiral symmetry breaking
  - Relevant to early universe
  - Unique opportunity
- Understanding of hadrons and nuclei at very high collision energy
  - Universal behavior (color glass condensate)
  - Not necessary unique, but give a good opportunity

Big Bang vs. Little Bang





3D Hubble expansion

Nearly 1D Hubble expansion*
+ 2D transverse expansion

Figure adopted from
http://www-utap.phys.s.u-tokyo.ac.jp/~sato/index-j.htm

*Bjorken('83)

Big Bang vs. Little Bang (contd.)

	Big Bang	Little Bang
Time Scale	10^{-5} sec >> m.f.p./c	10^{-23} sec ~ m.f.p./c
Expansion Rate	$10^{5\text{-}6}$/sec	$10^{22\text{-}23}$/sec

→ Local thermalization is not trivial in heavy ion collisions.

Spectrum	Red-shifted (CMB)	Blue-shifted (hadrons)

→ Collective flow is a key to see whether local thermalization is achieved.

Jargon: Centrality

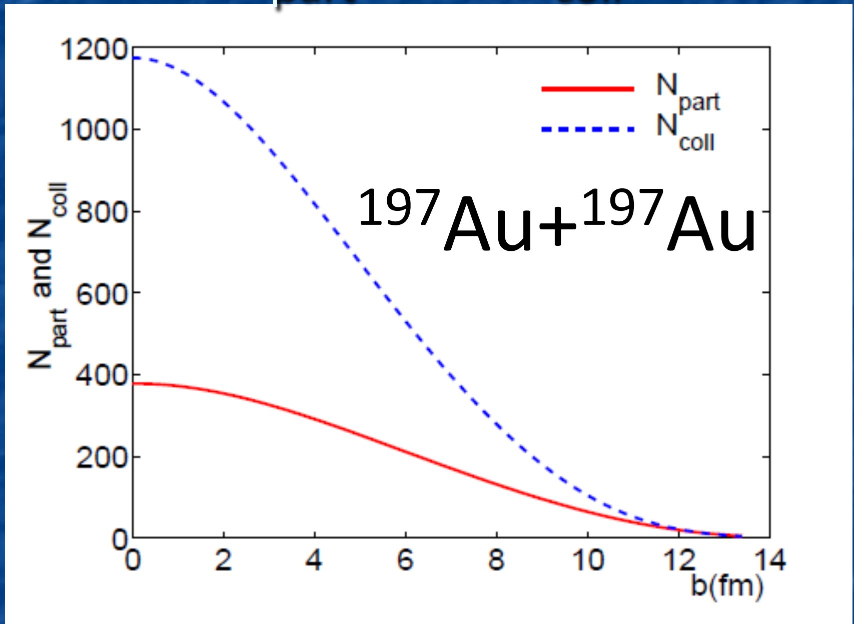
"Centrality" characterizes a collision and categorizes events.

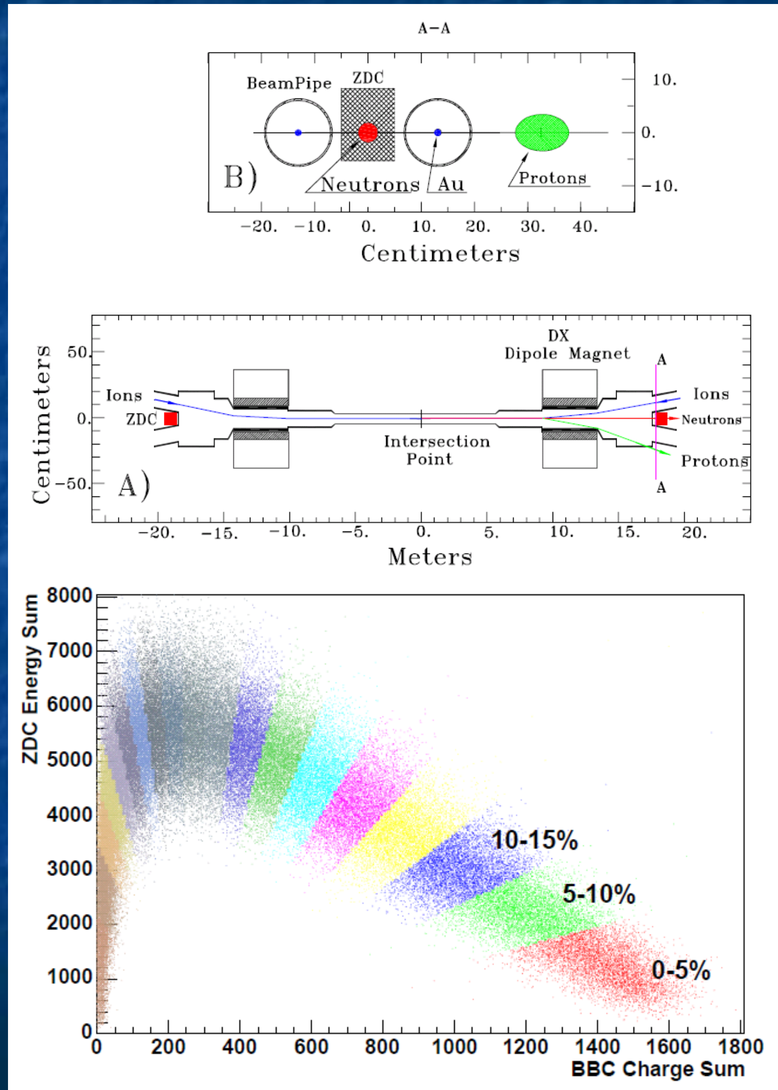
central event peripheral event

Participant-Spectator picture is valid

How to Quantify Centrality

N_{part} and N_{coll}





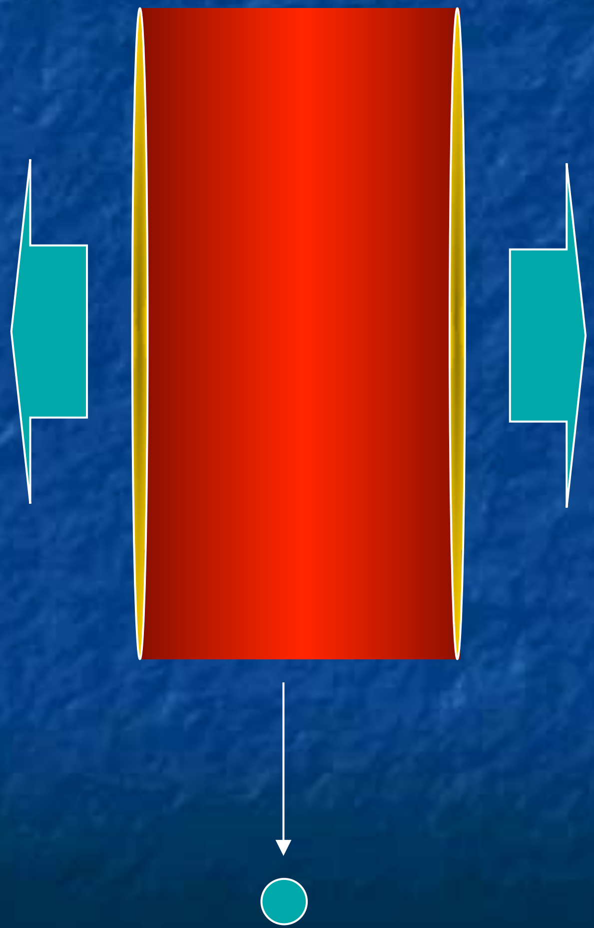
N_{part}: The number of participants

N_{coll}: The number of binary collisions

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

PHENIX: Correlation btw. BBC and ZDC signals

Sufficient Energy Density?



Bjorken('83)

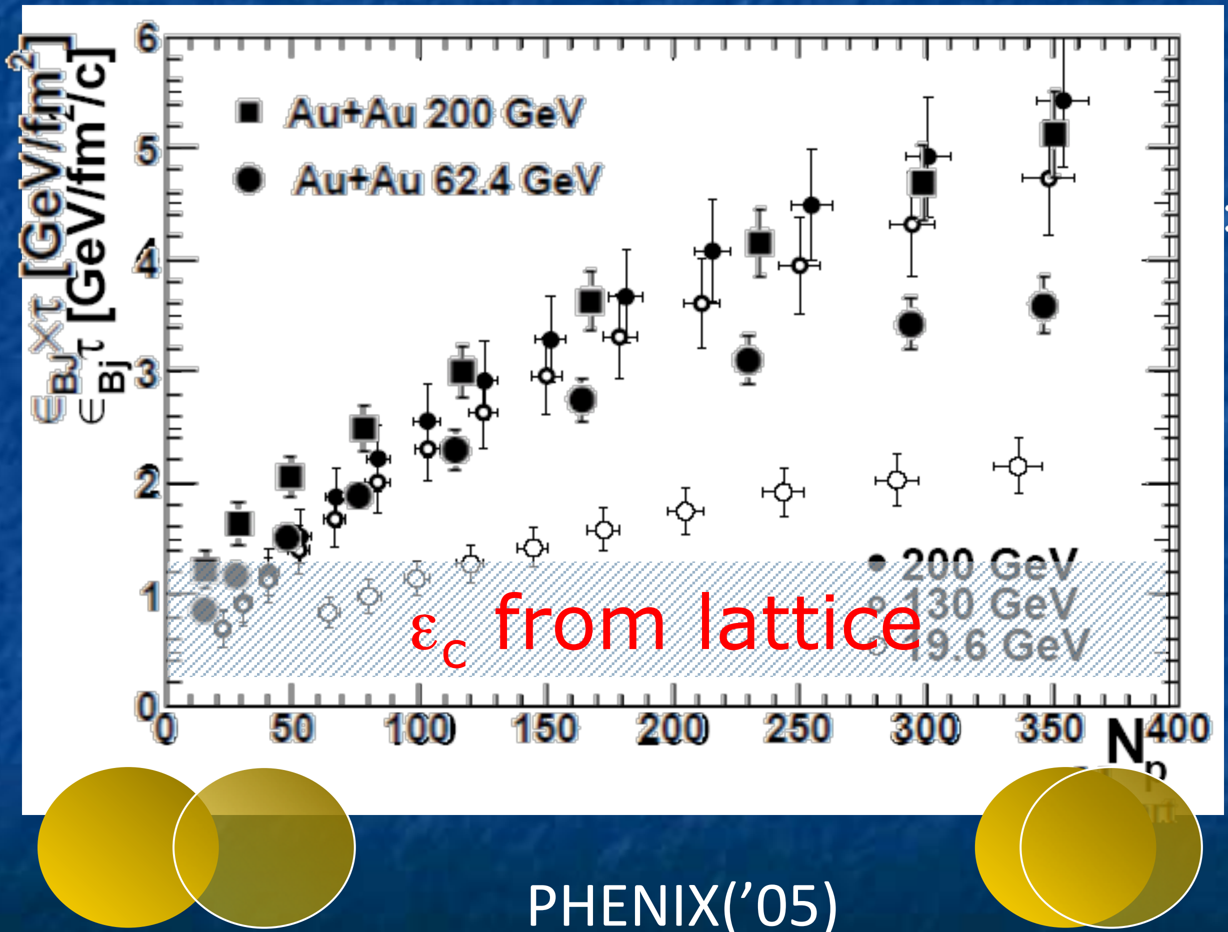
Bjorken energy density

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

total energy
(observables)

τ: proper time
y: rapidity
R: effective transverse radius
m_T: transverse mass

Estimated Energy Density at RHIC



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

Well above ε_c from lattice simulations in central collision at RHIC

PHENIX('05)
STAR('08)

Remarks on this Estimate

- Just a necessary condition in the sense that temperature (or pressure) is not measured.
- How to estimate tau?
- If the system is thermalized, the actual energy density is larger due to pdV work.
- Boost invariant?
- Averaged over transverse area. Effect of thickness? How to estimate area?

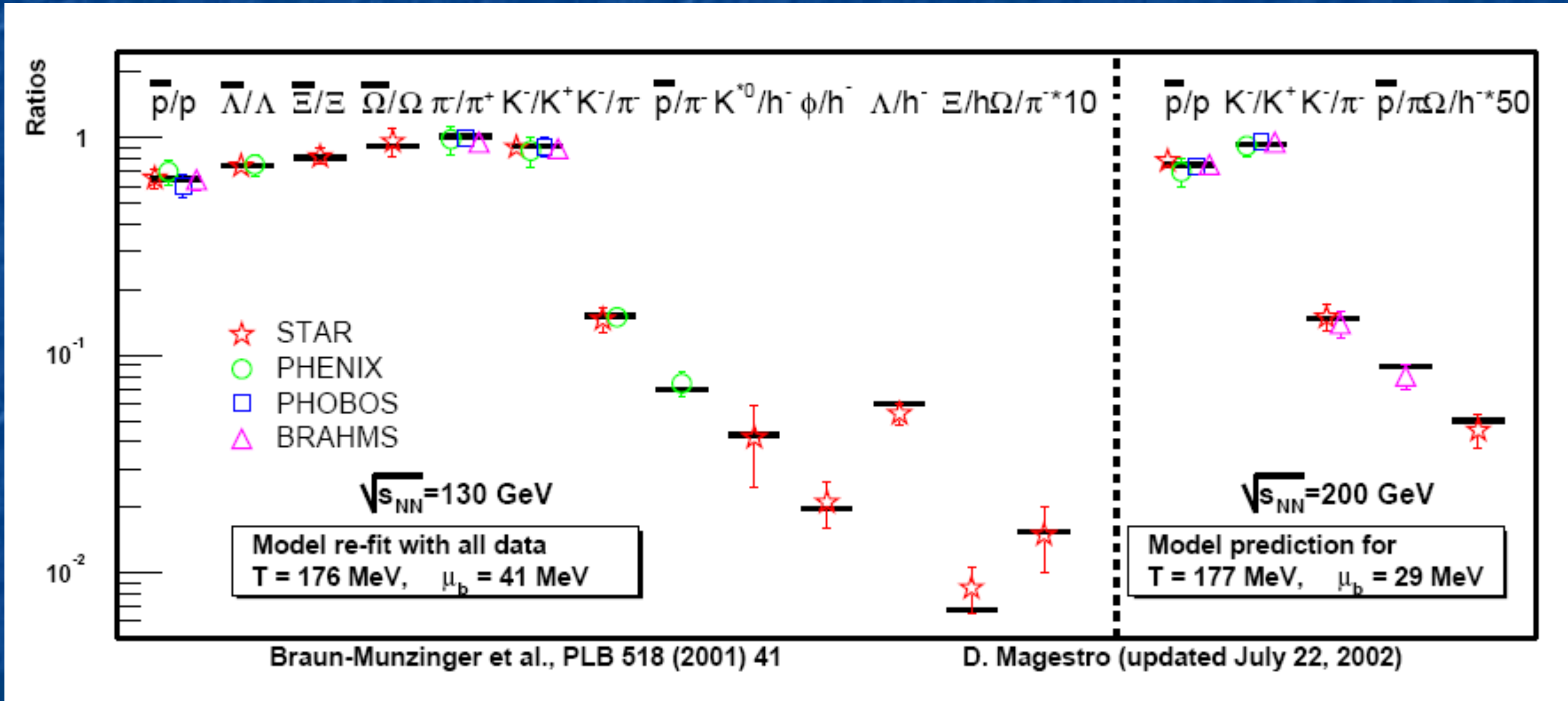
Matter in (Chemical) Equilibrium?

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

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

Two fitting parameters: T_{ch}, μ_B

Amazing Fit!



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

⇨ Close to T_c from lattice

Remarks on this Estimate

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

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

- What is the meaning of fitting parameters?

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

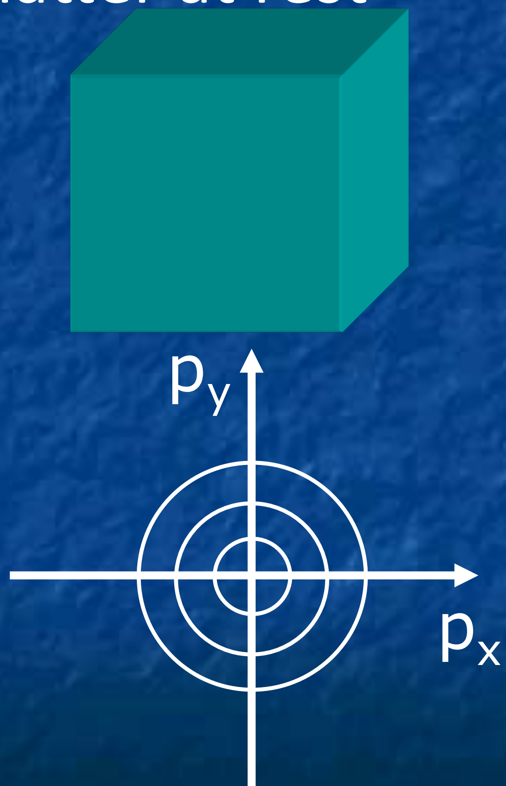
- Why so close to T_c?
  - → No chemical eq. in hadron phase!?
  - → Essentially dynamical problem!

$$\partial \cdot u(x) \Longleftrightarrow \sum_j \langle \sigma_{ij} v_{ij} \rangle \rho_j$$

expansion rate ⟷ reaction rate

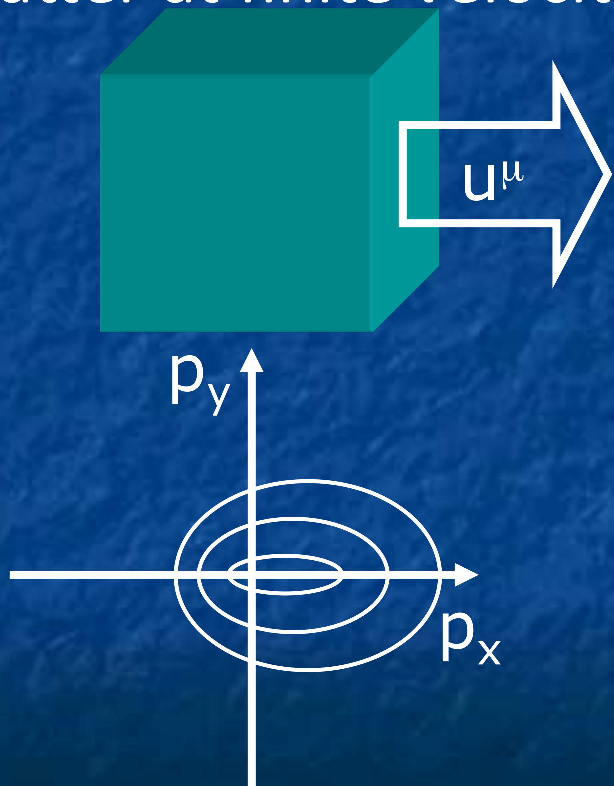
Matter in (Kinetic) Equilibrium?

Kinetically equilibrated matter at rest



Isotropic distribution

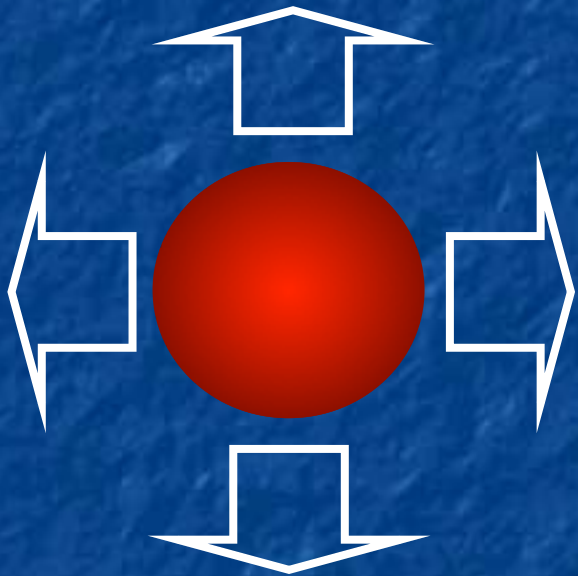
Kinetically equilibrated matter at finite velocity



Lorentz-boosted distribution

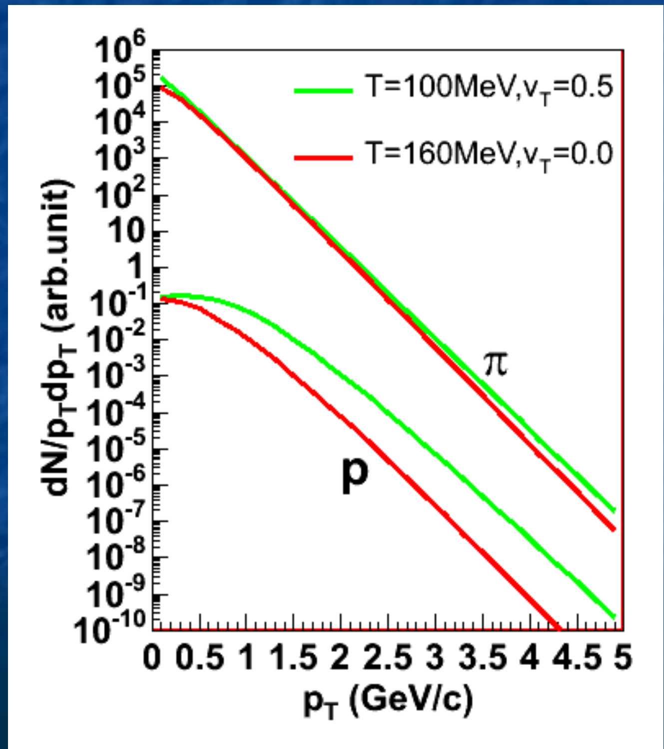
Radial Flow

Kinetic equilibrium
inside matter

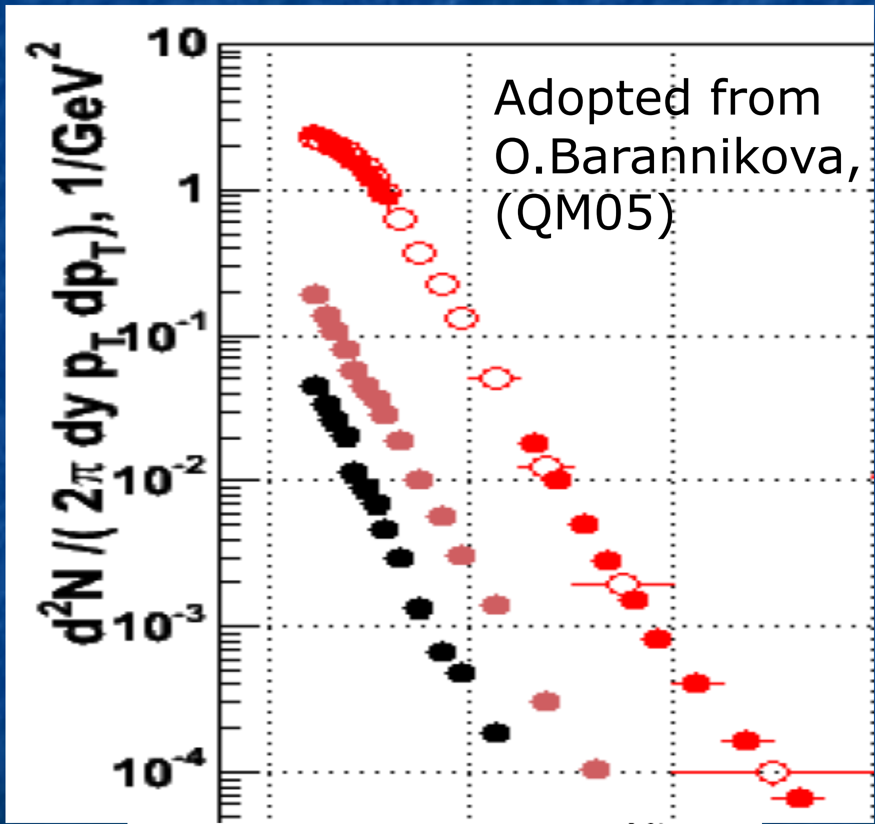


Pressure gradient
→ Driving force of flow
→ Flow vector points to
radial direction

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



Spectral change is seen in AA!



Power law in pp & dAu

Convex to Power law in Au+Au

- "Consistent" with thermal + boost picture
- Large pressure could be built up in AA collisions

Remarks on this Estimate

- Not necessary to be thermalized completely
  - Results from hadronic cascade models.
- How is radial flow generated dynamically?
- Finite radial flow even in pp collisions?
  - $(T,v_T)\sim(140\text{MeV},0.2)$
  - Is blast wave reliable quantitatively?
- Consistency?
  - Chi square minimum located a different point for f and W
- Flow profile? Freezeout hypersurface? Sudden freezeout?

Basic checks cleared

- Energy density can be well above e_c.
  - Thermalized?
- "Temperature" can be extracted.
  - Why freezeout happens so close to T_c?
- High pressure can be built up.
  - Completely equilibrated?

Importance of systematic study
based on dynamical framework

Major Discovery at Relativistic Heavy Ion Collider (RHIC)

Hydrodynamics for QGP at Work

asahi.com

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。

The Washington Post

Universe May Have Begun as Liquid, Not Gas

Associated Press
Tuesday, April 19, 2005; Page A05

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence.

新华网 XINHUANET.com

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。

nature

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

by Mark Peplow
news@nature.com

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

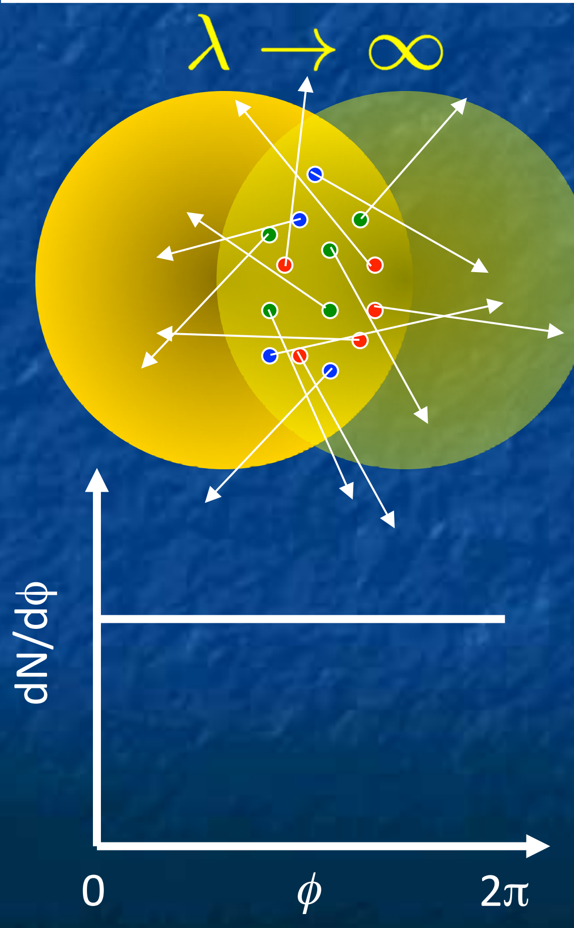
Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

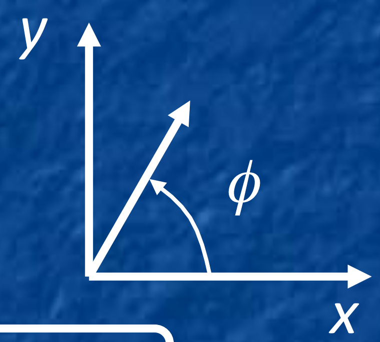
Ollitrault ('92)

What is Elliptic Flow?

How does the system respond to spatial anisotropy?

No secondary interaction





INPUT

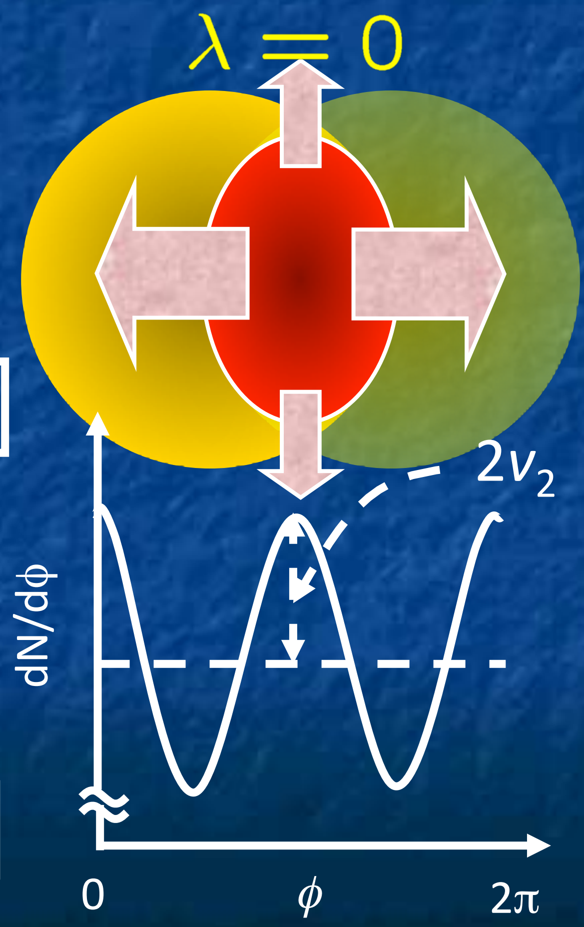
Spatial Anisotropy

Interaction among produced particles

OUTPUT

Momentum Anisotropy

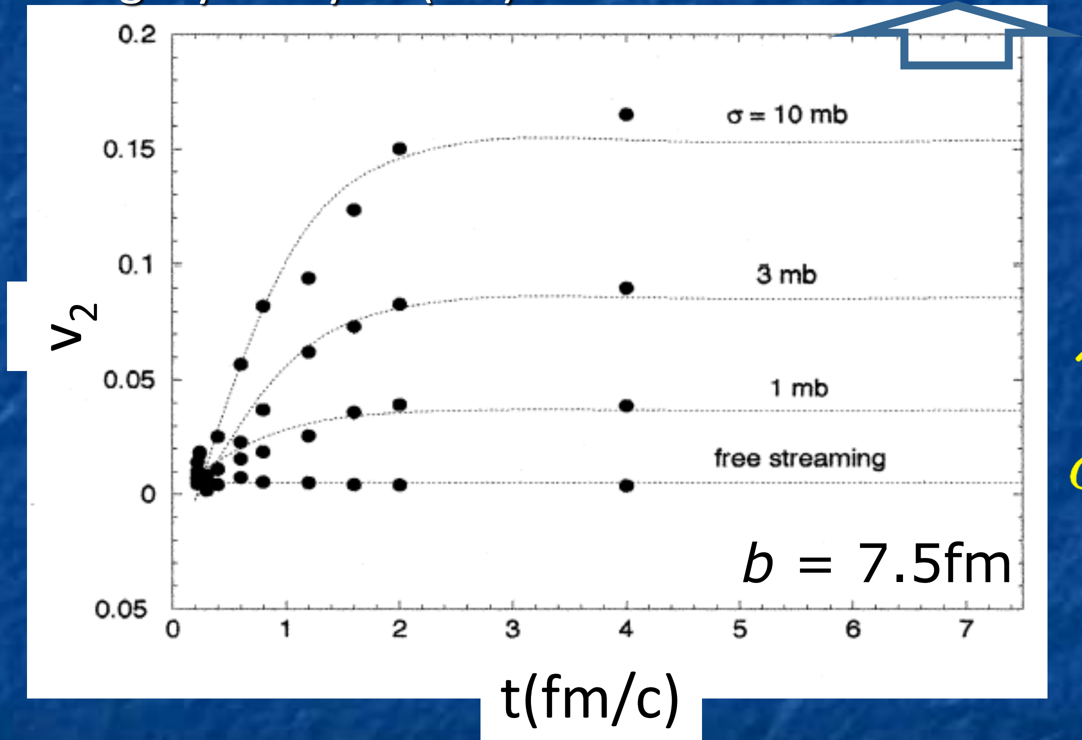
Hydro behavior



Elliptic Flow in Kinetic Theory

Zhang-Gyulassy-Ko('99)

ideal hydro limit



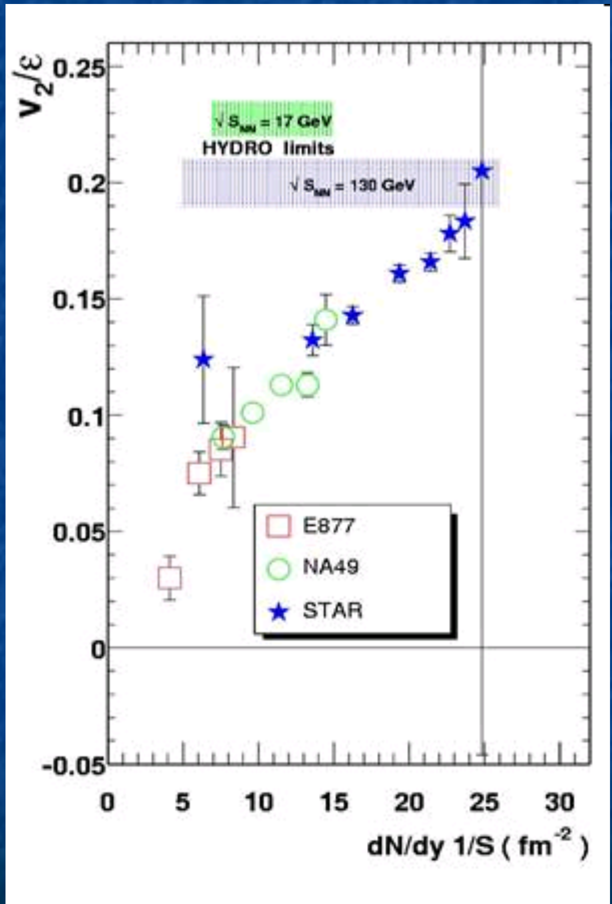
$$\lambda = \frac{1}{\sigma\rho} \propto \eta$$

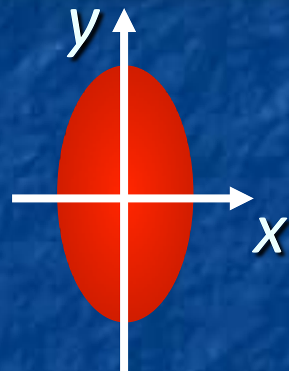
$\lambda \to 0$: Ideal hydro

$\sigma \to \infty$: 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)

Arrival at Hydrodynamic Limit





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

$$\frac{v_2}{\varepsilon} = \frac{\text{momentum anisotropy}}{\text{spatial anisotropy}} = \frac{\text{output}}{\text{input}} = \text{response}$$

Experimental data reach hydrodynamic limit curve for the first time at RHIC.

RHIC Scientists Serve Up "Perfect" Liquid - Netscape Browser

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http://www.bnl.gov/bnlweb/pubaf/pr/PR_display.asp?prI

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RHIC Scientists Serve Up "Perfect" Li...

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- Management Bios
- About Brookhaven

:: RHIC News

Answer from 'Dusty Shelf' Aids Quest to See Matter as it Was

Contact: Karen McNulty Walsh, (631) 344-8350 or Mona S. Rowe, (631) 344-5056

Print-friendly | E-mail Article

RHIC Scientists Serve Up "Perfect" Liquid

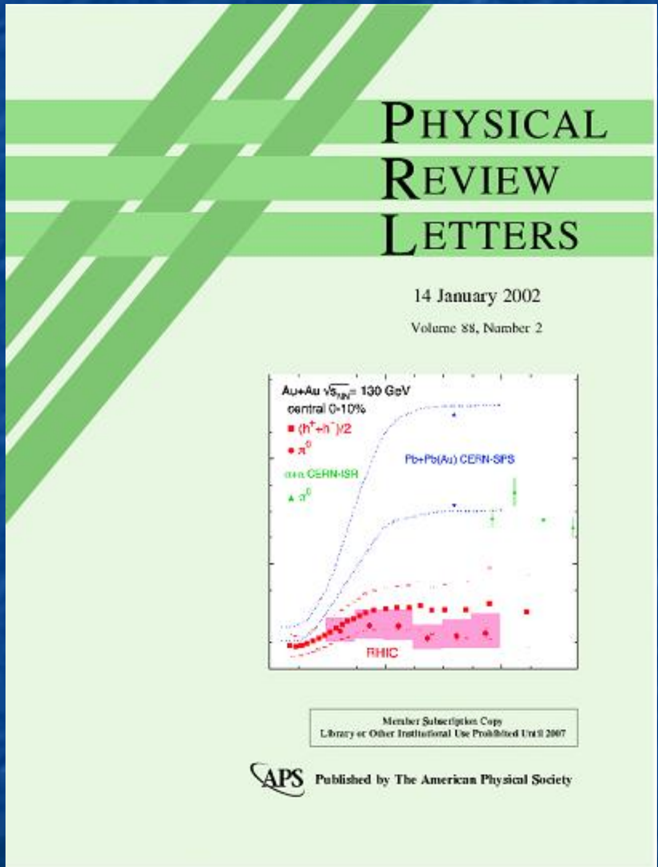
New state of matter more remarkable than predicted -- raising many new questions

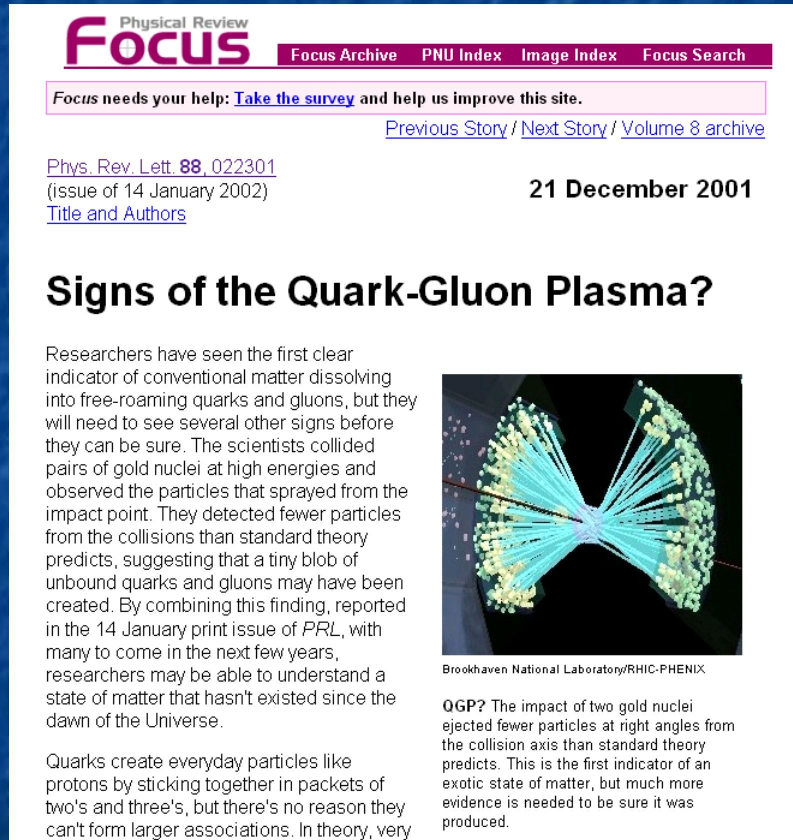
April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions

Done

QGP as Opaque QCD Matter

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Phys. Rev. Lett. **88**, 022301
(issue of 14 January 2002)
Title and Authors

21 December 2001

Signs of the Quark-Gluon Plasma?

Researchers have seen the first clear indicator of conventional matter dissolving into free-roaming quarks and gluons, but they will need to see several other signs before they can be sure. The scientists collided pairs of gold nuclei at high energies and observed the particles that sprayed from the impact point. They detected fewer particles from the collisions than standard theory predicts, suggesting that a tiny blob of unbound quarks and gluons may have been created. By combining this finding, reported in the 14 January print issue of *PRL*, with many to come in the next few years, researchers may be able to understand a state of matter that hasn't existed since the dawn of the Universe.

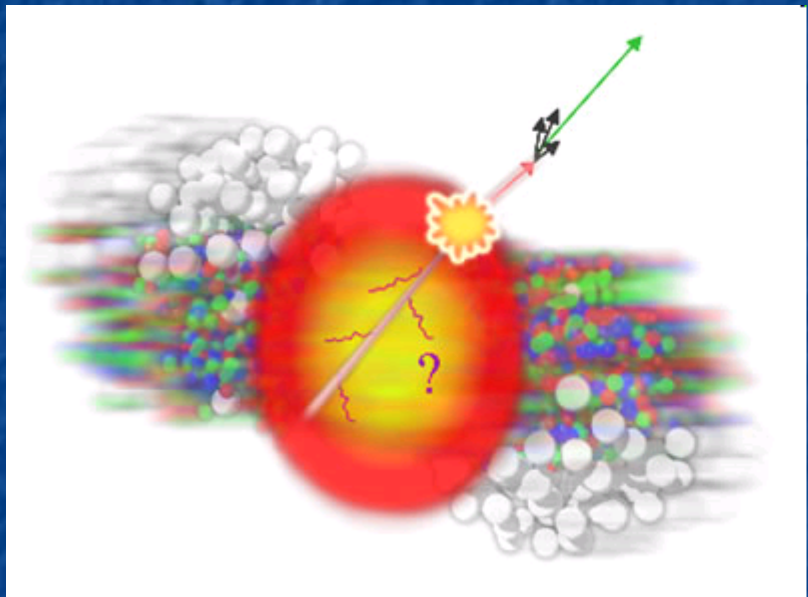
Brookhaven National Laboratory/RHIC-PHENIX

QGP? The impact of two gold nuclei ejected fewer particles at right angles from the collision axis than standard theory predicts. This is the first indicator of an exotic state of matter, but much more evidence is needed to be sure it was produced.

Quarks create everyday particles like protons by sticking together in packets of two's and three's, but there's no reason they can't form larger associations. In theory, very

Perfect liquid is something like
a black ink in a sense of QED.

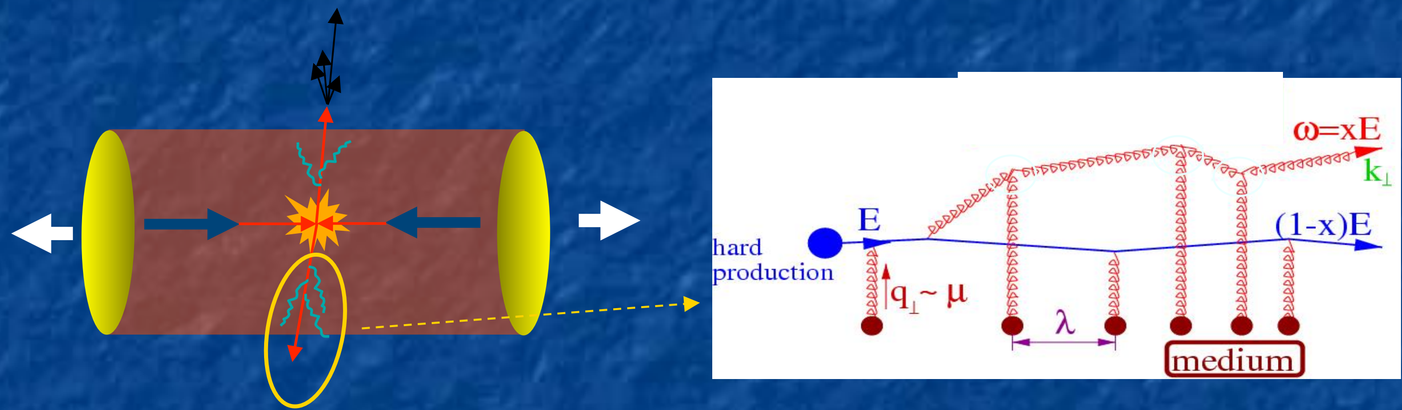
Jet Tomography



1. Suppression of inclusive yields at high p_T
2. Modification of back-to-back correlation

Adopted from
http://www.lbl.gov/Science-Articles/Archive/sabl/2008/Feb/jets.html

Jet Quenching

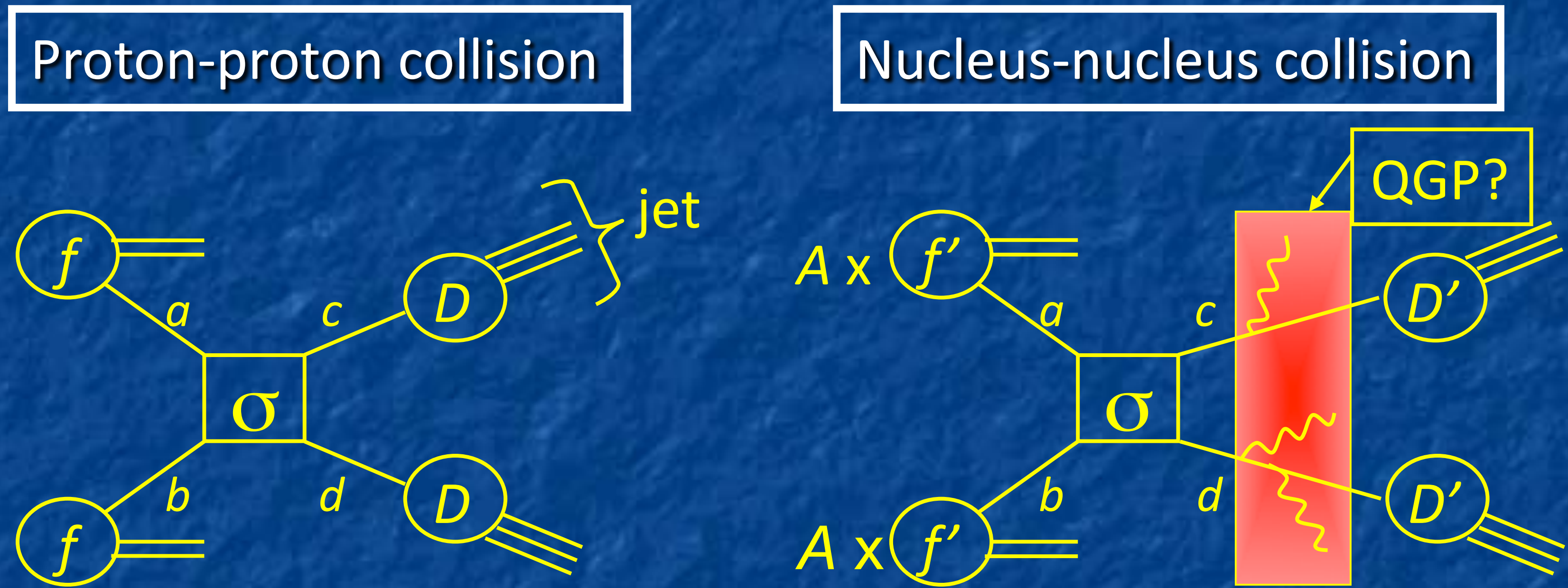


An energetic parton loses its energy by emitting gluons during traversing medium.

- Emitted gluons also interact with medium.
- Interference effect (LPM effect)
- Medium evolves dynamically.

Figure adopted from M. van Leeuwen, talk at QM2005.

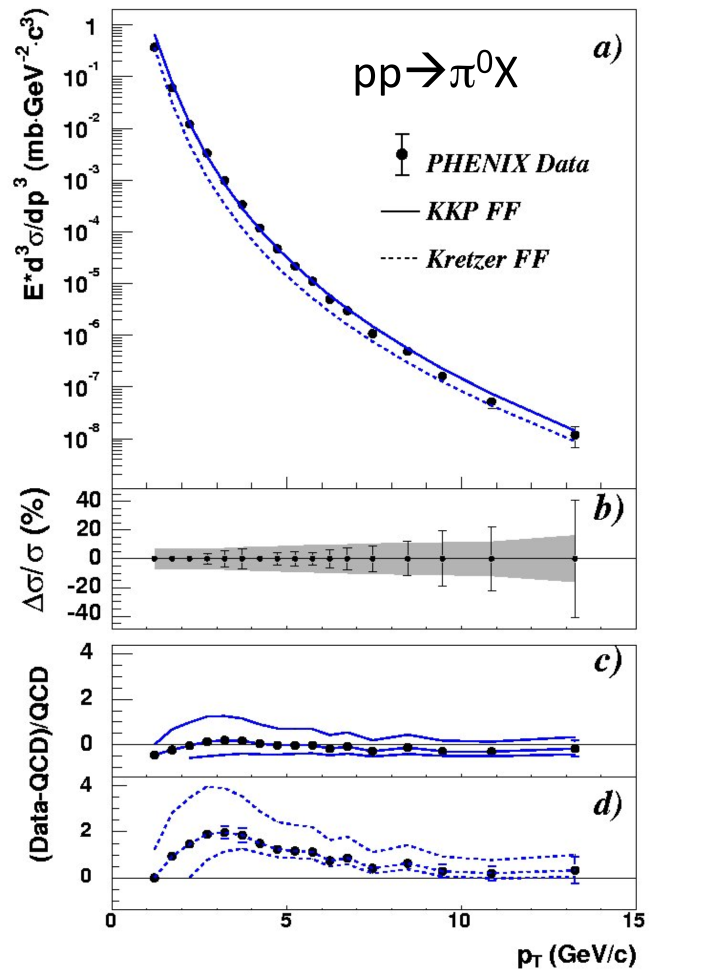
High p_T Spectra



f: Parton distribution function
D: Fragmentation function

A: Mass number
f′ : Parton distribution in a nucleus
D′: Modified fragmentation function

Perturbative QCD



PHENIX data and
NLO QCD results

Leading order

$$q + q' \to q + q', q + \bar{q} \to q + \bar{q}$$

$$q + \bar{q} \to g + g, q + g \to q + g$$

$$g + g \to g + g, g + g \to q + \bar{q}$$

$$E\frac{d\sigma_h^{pp}}{d^3p}$$

$$= \quad K \sum_{ab} \int f_a(x_1, Q^2) dx_1 f_b(x_2, Q^2) dx_2$$

$$\times \quad \frac{d\sigma^{ab\to cd}}{d\hat{t}}(Q^2)$$

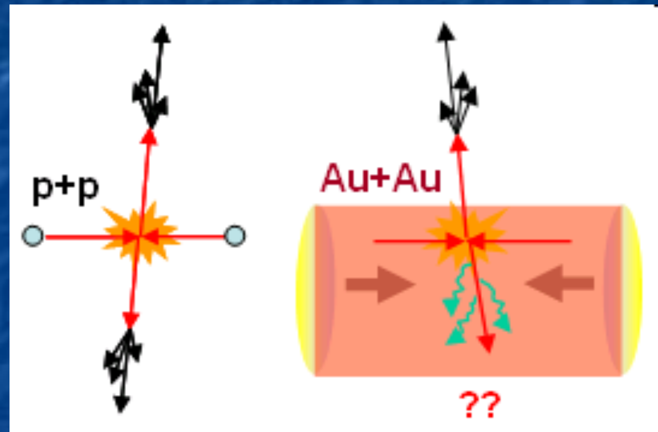
$$\times \quad \frac{D_{c\to h}(z_c)}{\pi z_c}$$

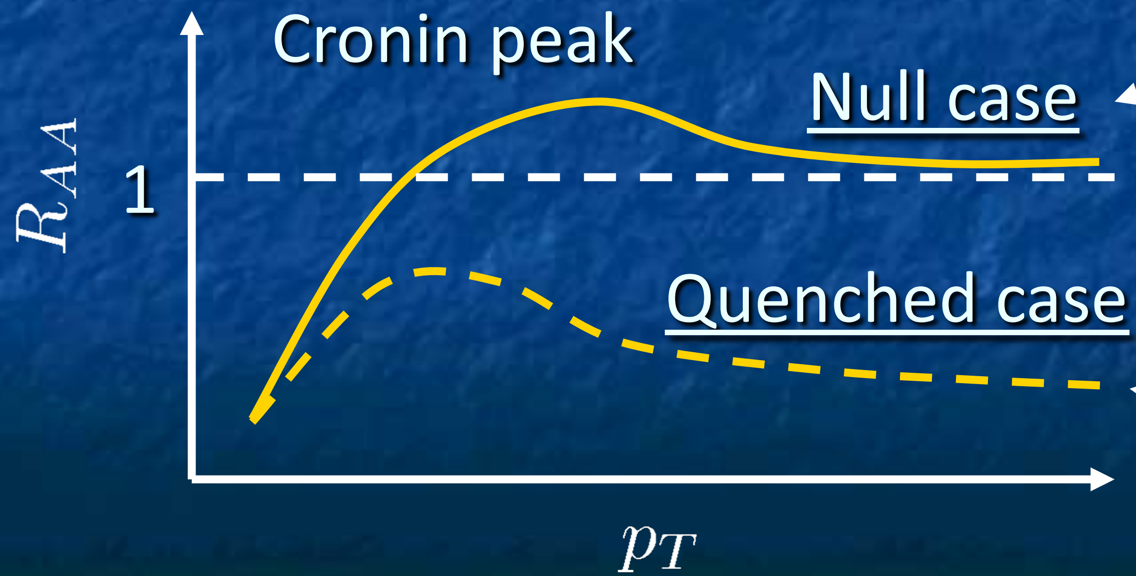
Figure adopted from http://www.star.bnl.gov/central/focus/highPt/

How to Quantify Jet Quenching

Nuclear modification factor

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

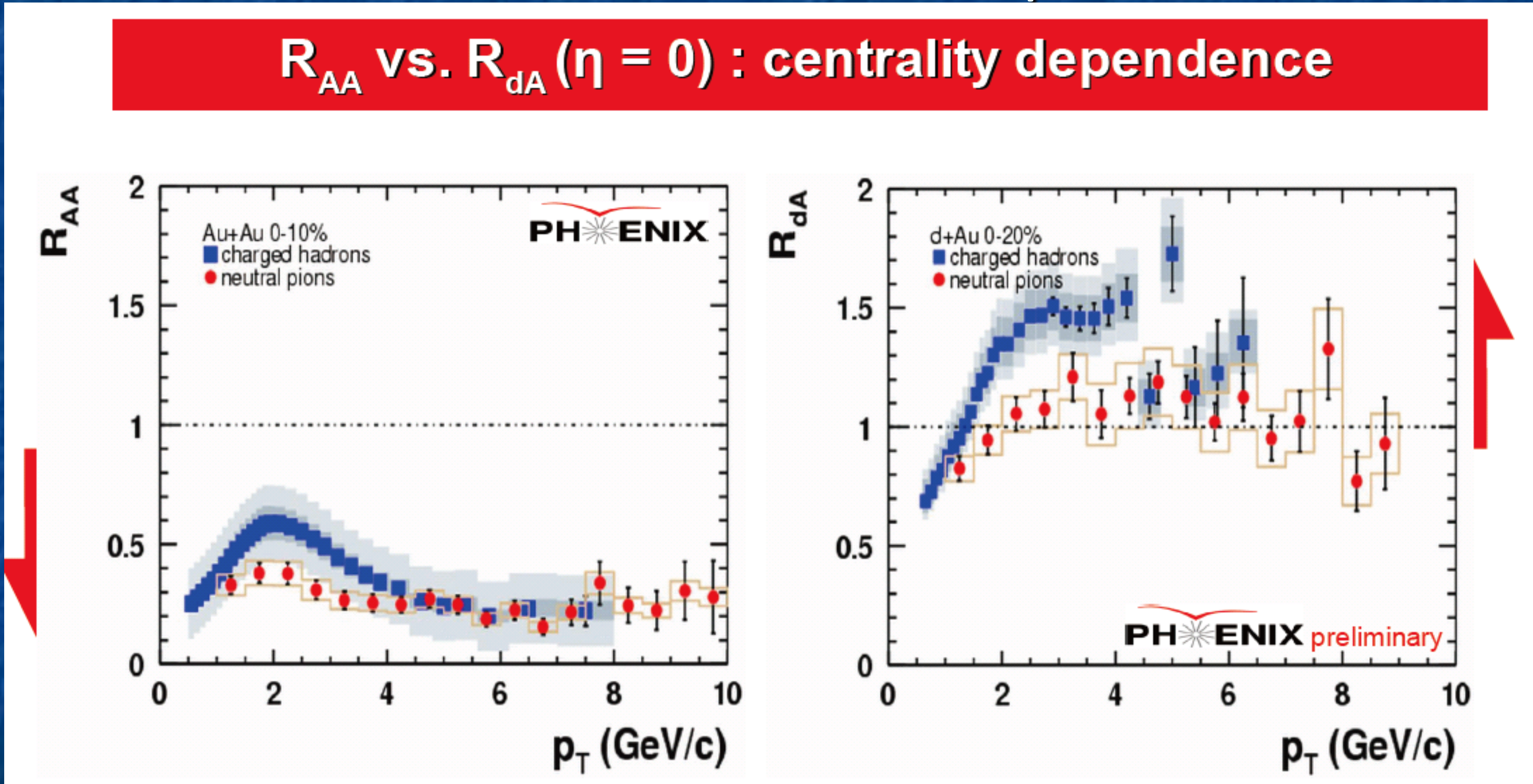




Yield scales with N_{coll} ?

Yield suppresses?

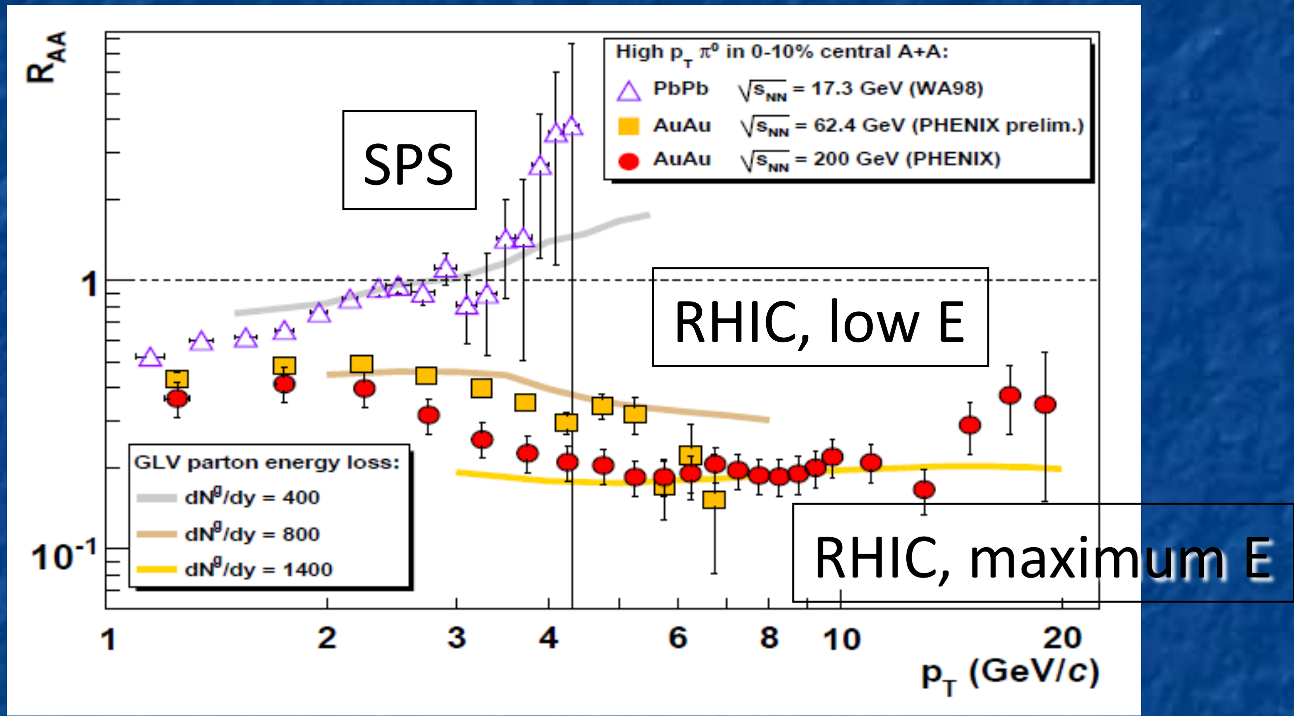
Suppression of High p_T Hadrons



Large suppression in central Au+Au collisions!

Slide adopted from D.d'Enterria, talk at QM2004.

Onset of Jet Quenching

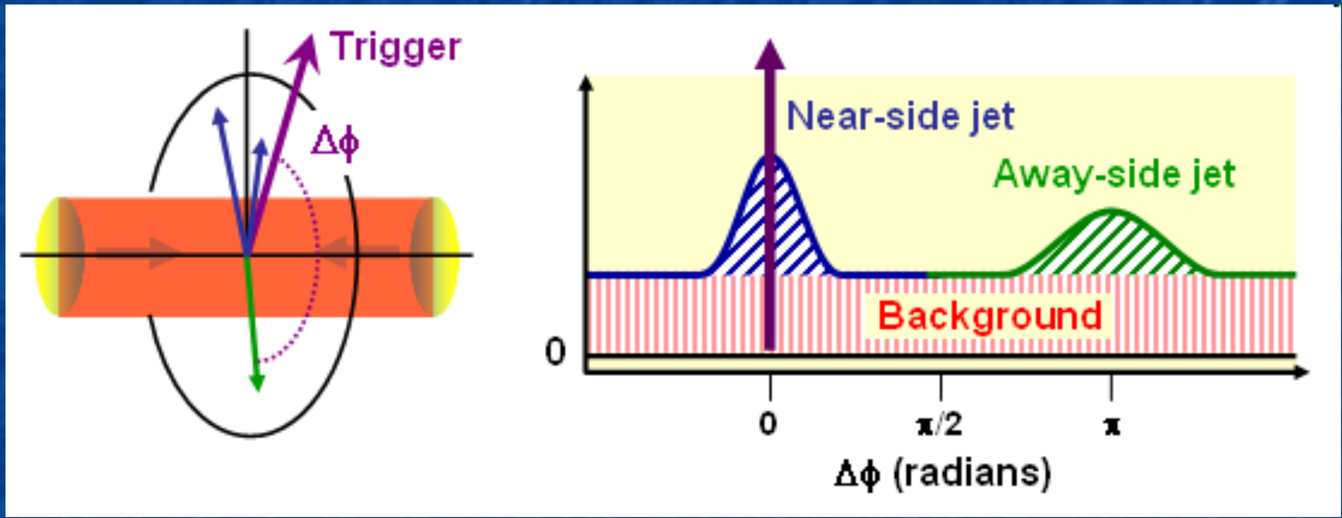


D.d'Enterria, 0902.2011[nucl-ex]

(Almost) no jet quenching at SPS

Jet quenching was discovered for the first time at RHIC.

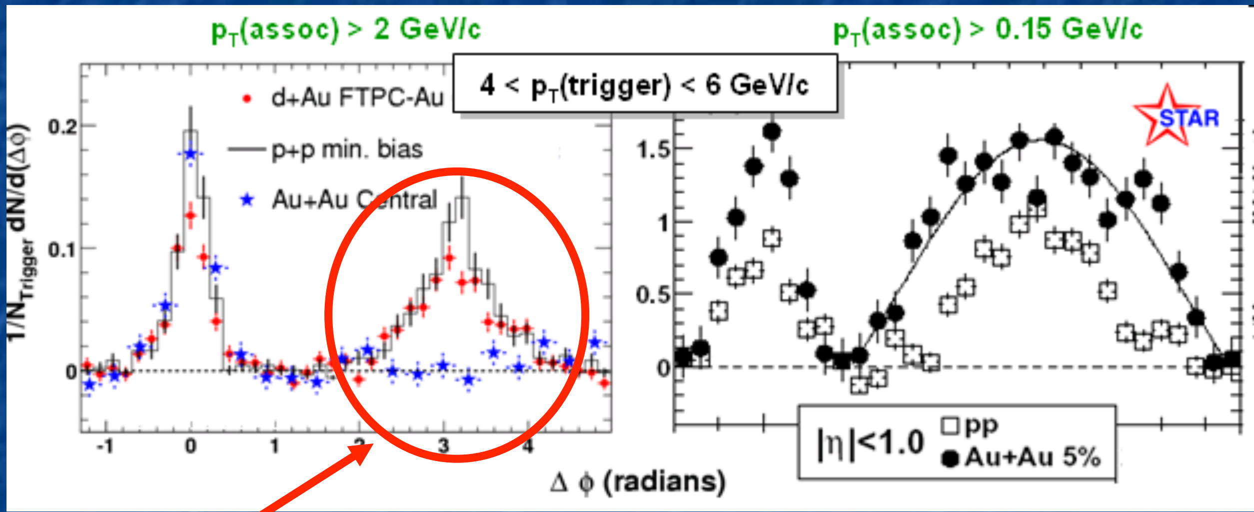
Jet Accoplanarity



What happens to away side peak in azimuthal angle distribution for associated hadrons?

Figure adopted from
http://www.star.bnl.gov/central/focus/highPt/

Disappearance of Away-Side Peak



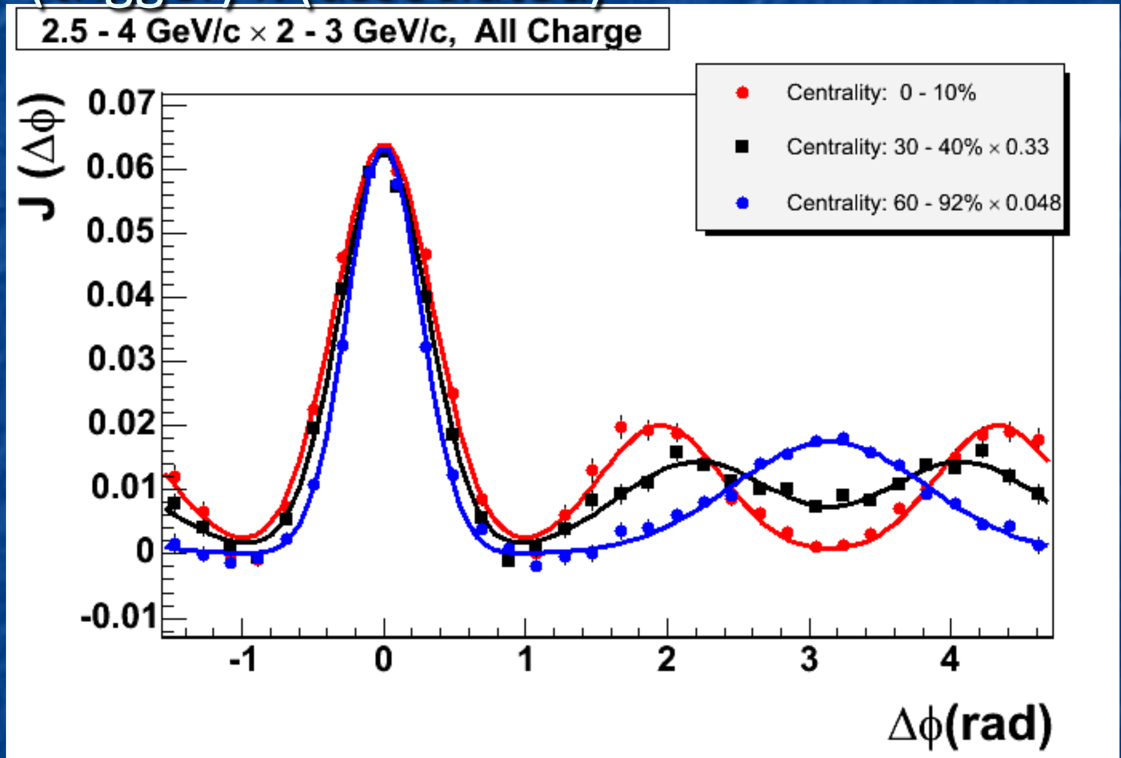
Away-side peak:
Exists in p+p and d+Au collisions, but disappears in Au+Au collisions

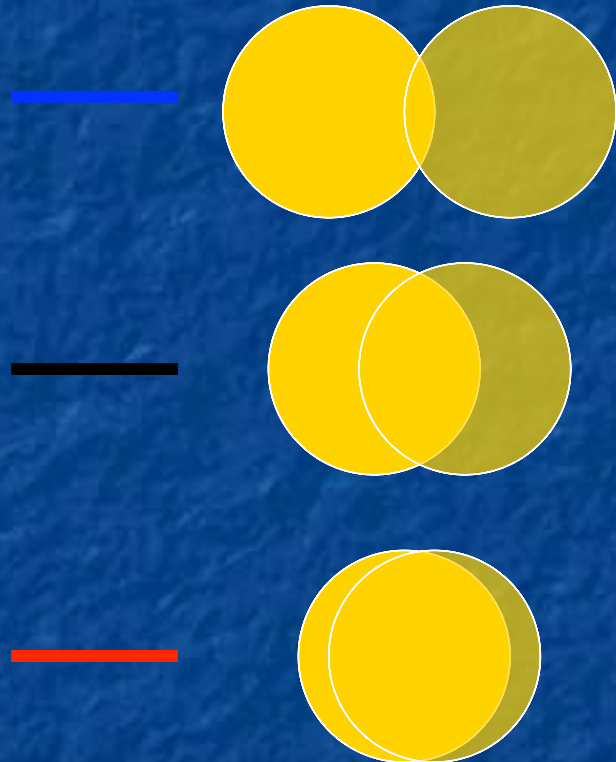
Where does the lost energy go?
→ Distributed among soft particles?

Figure adopted from http://www.star.bnl.gov/central/focus/highPt/

Split of Away-Side Peak

(trigger) x (associated)



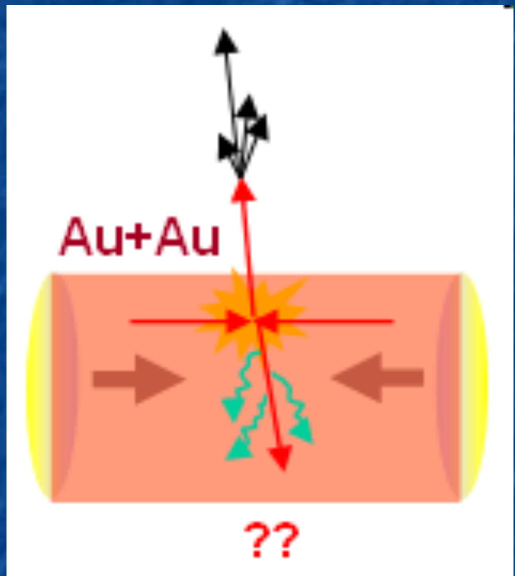


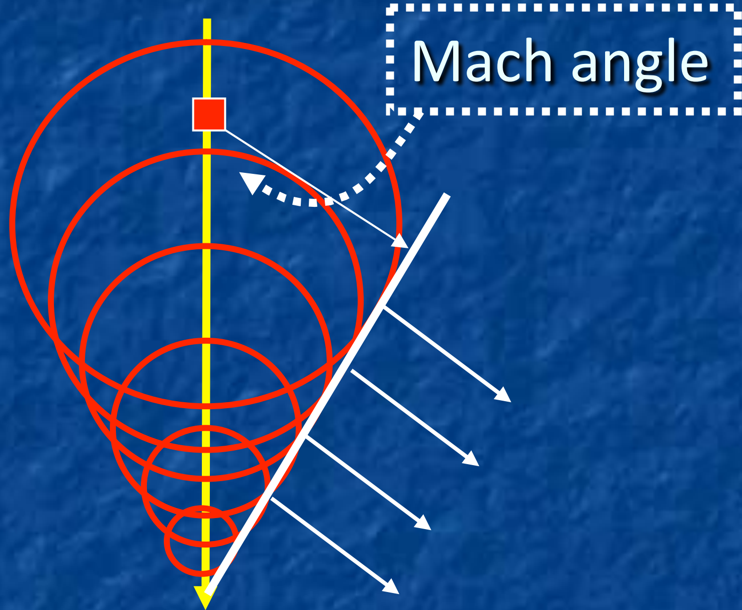
*Background subtracted

One away-side peak → Two peaks!?

Figure adopted from H. Büsching, talk at QM2005.

Mach-Cone in QGP?

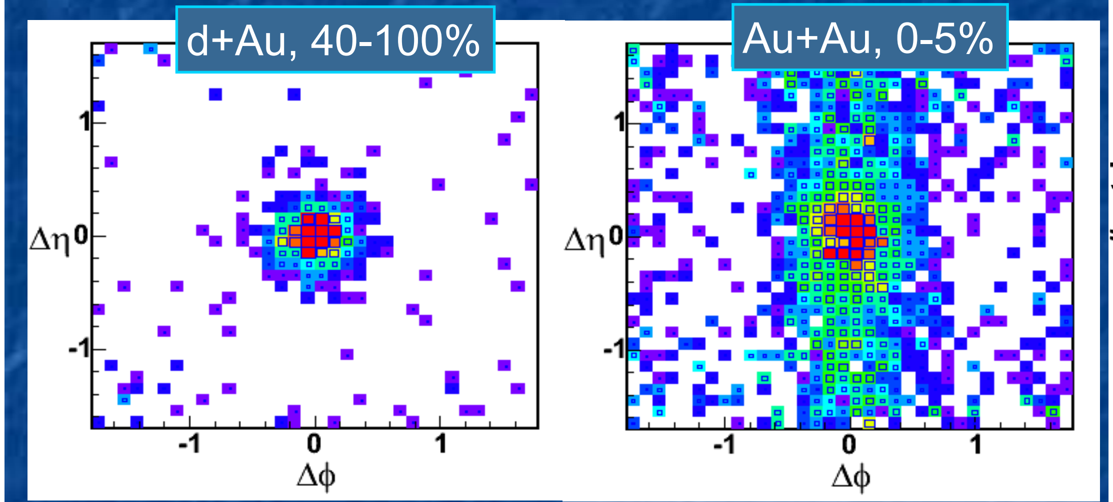


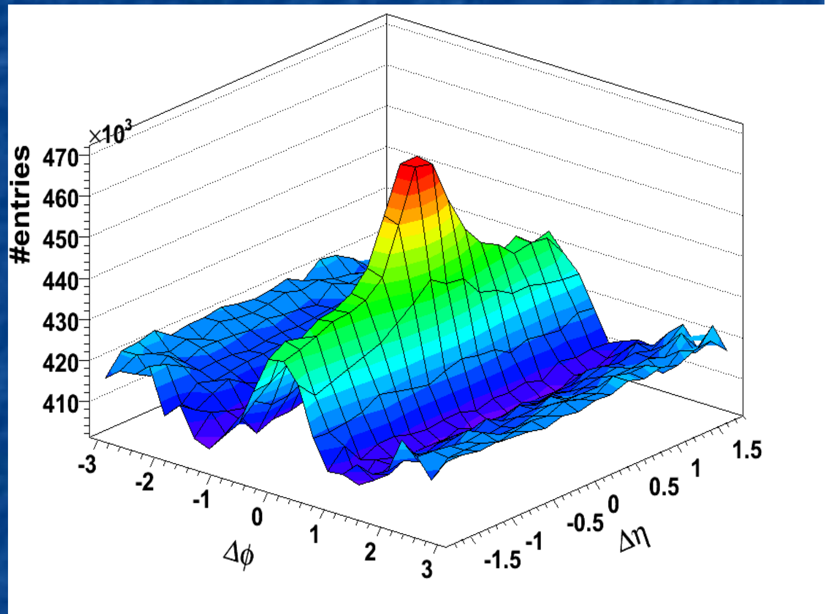


(Sound velocity) < (Velocity of a high energy parton)
Information about sound velocity in the medium
→Mach angle ~ 75 deg.
→(Average) sound velocity $c_s^2 < 0.1$
→ Very soft equation of state?

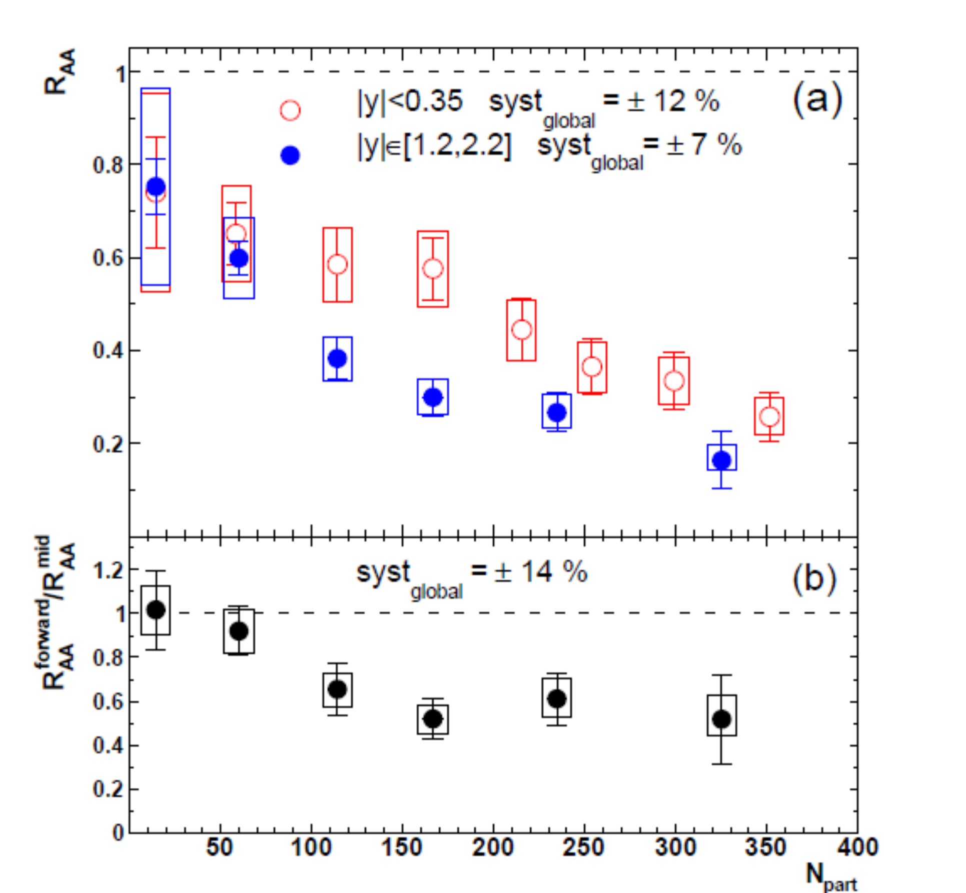
Near Side Jet Structure

Ridge structure in pseudorapidity direction (STAR)

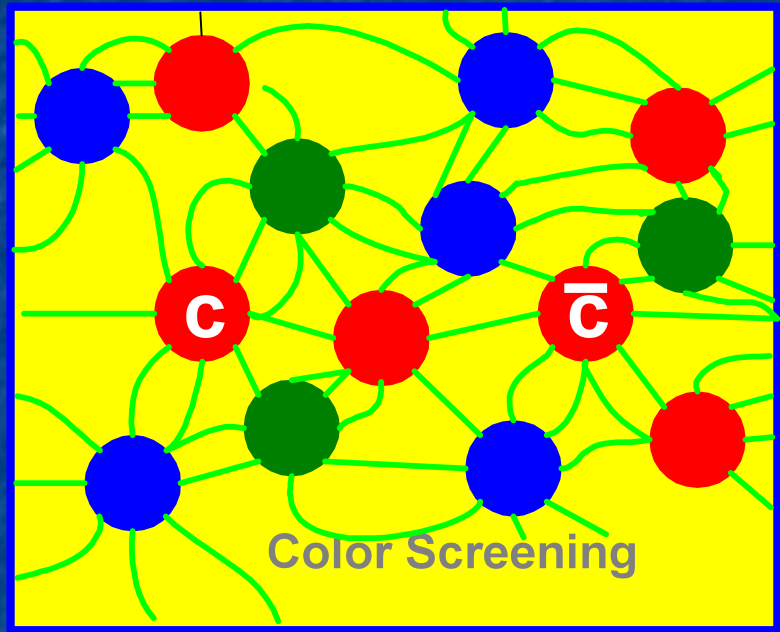




J/psi suppression



(PHENIX)

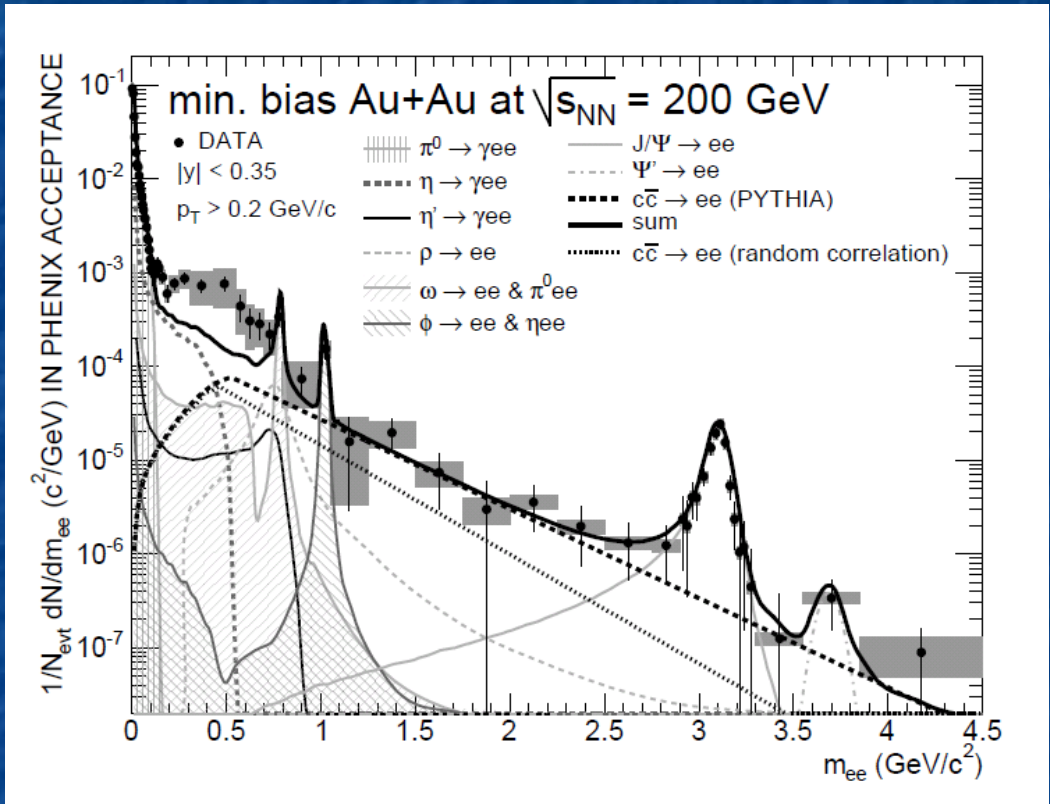


Color Debye screening
(Matsui-Satz)

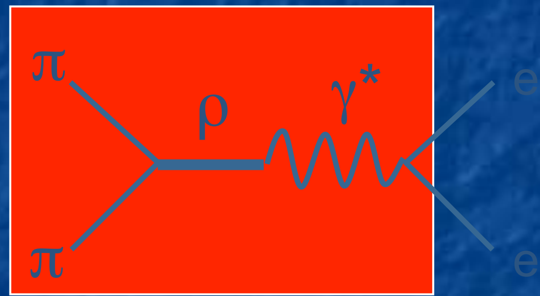
Lattice studies:

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?



(PHENIX)



Mass shift?
Broadening of peak?
Other mechanism?

Other Probes

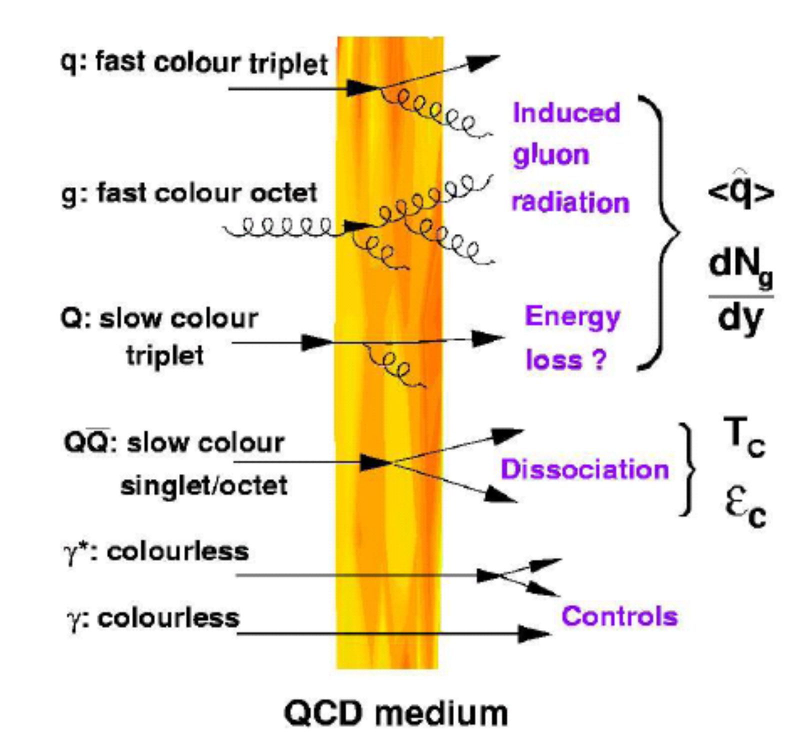


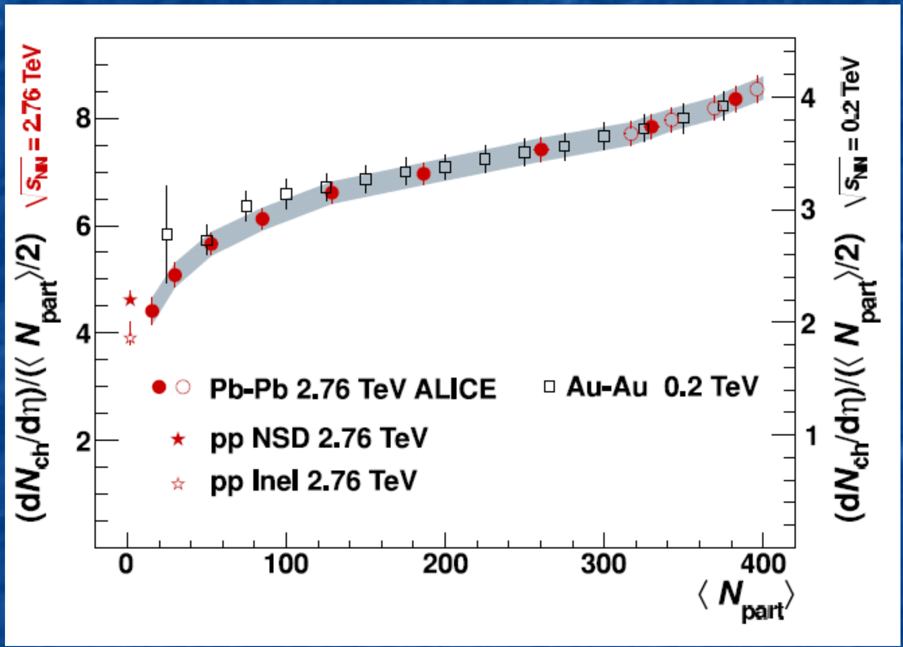
Figure adopted from D.d'Enterria, 0902.2011[nucl-ex]

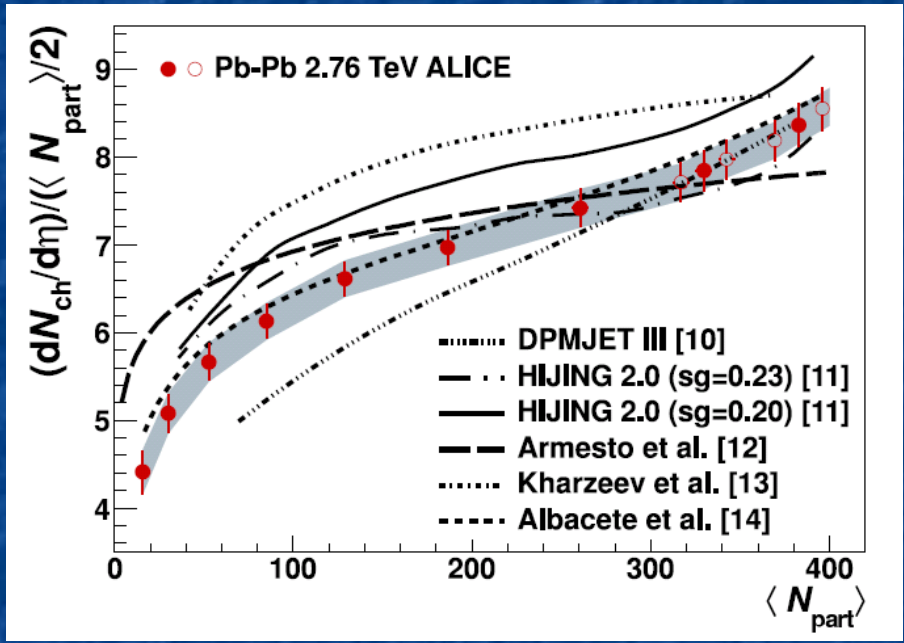
Rare particles
at the RHIC energies
- heavy quarks
- quarkonia
- photons
- di-leptons…

Rare probes will be important at LHC.

New Results
at LHC

Multiplicity

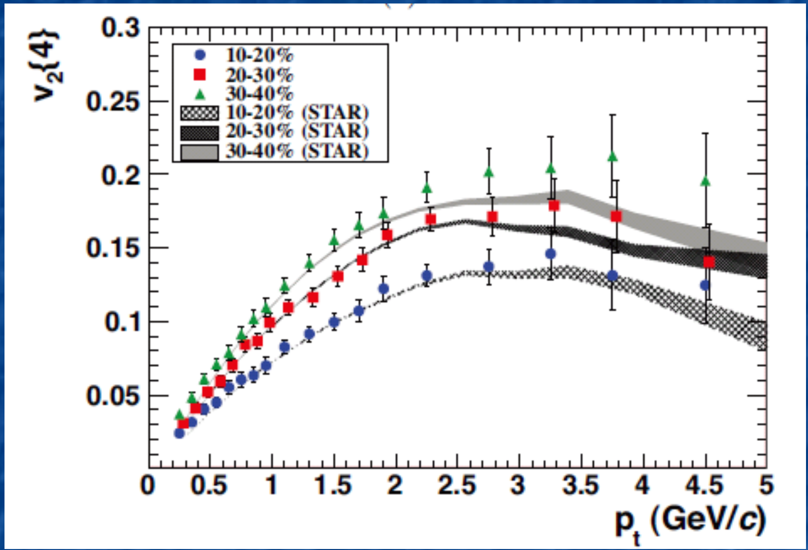


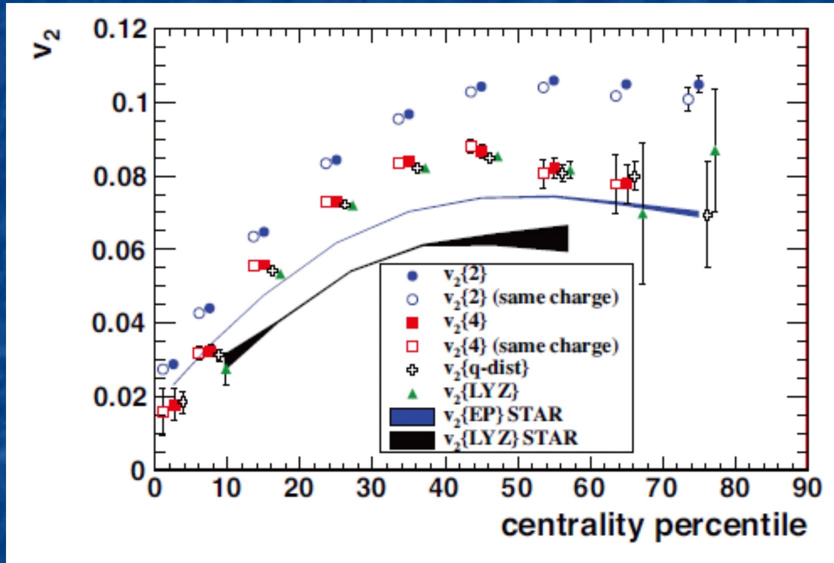


One data point kills most of models

ALICE, arXiv:1011.3916, arXiv:1012.1657

Elliptic Flow



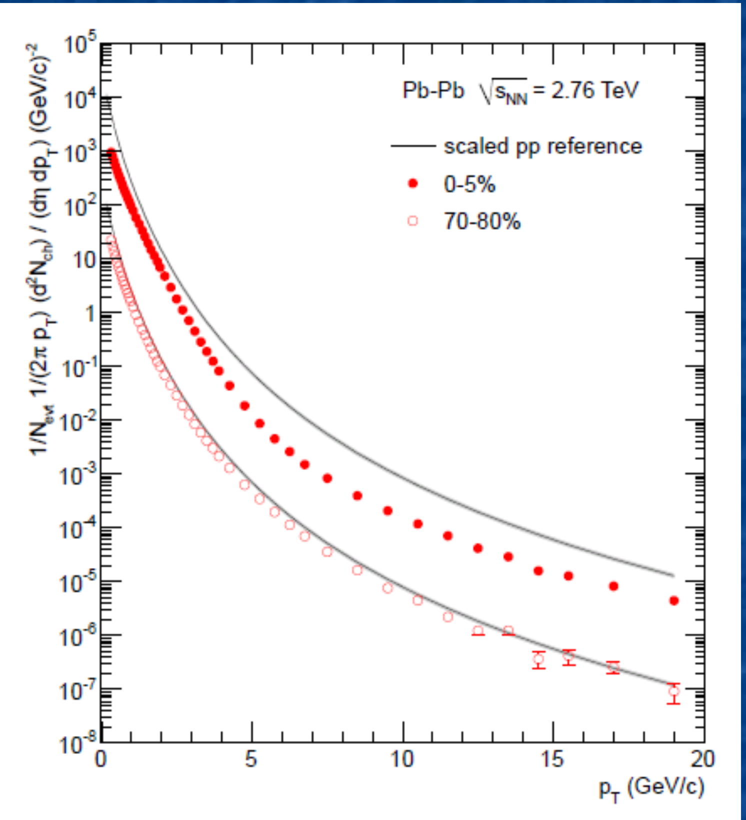


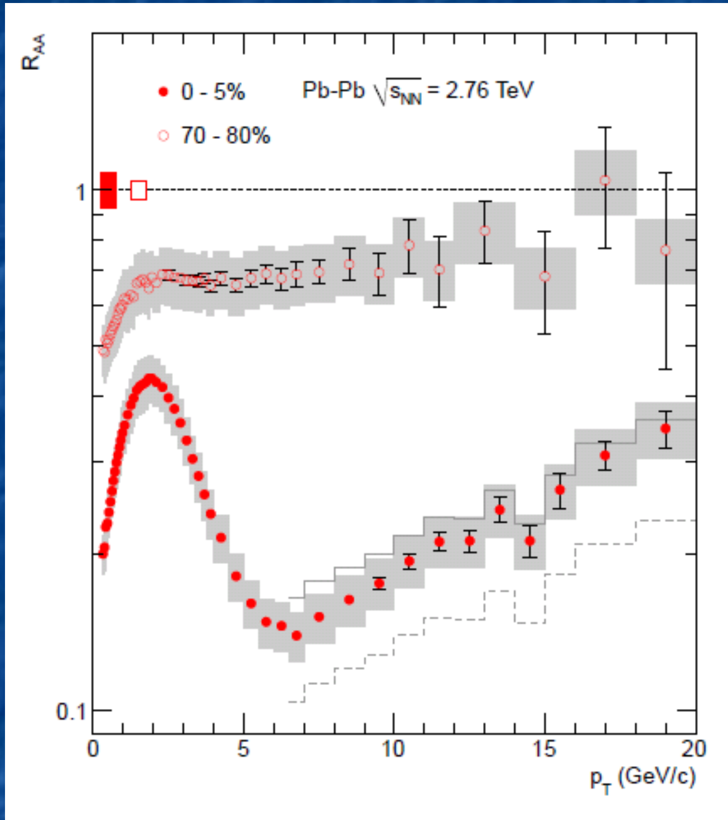
Almost identical to RHIC!?

~30% increase from RHIC to LHC

ALICE, arXiv:1011.3914

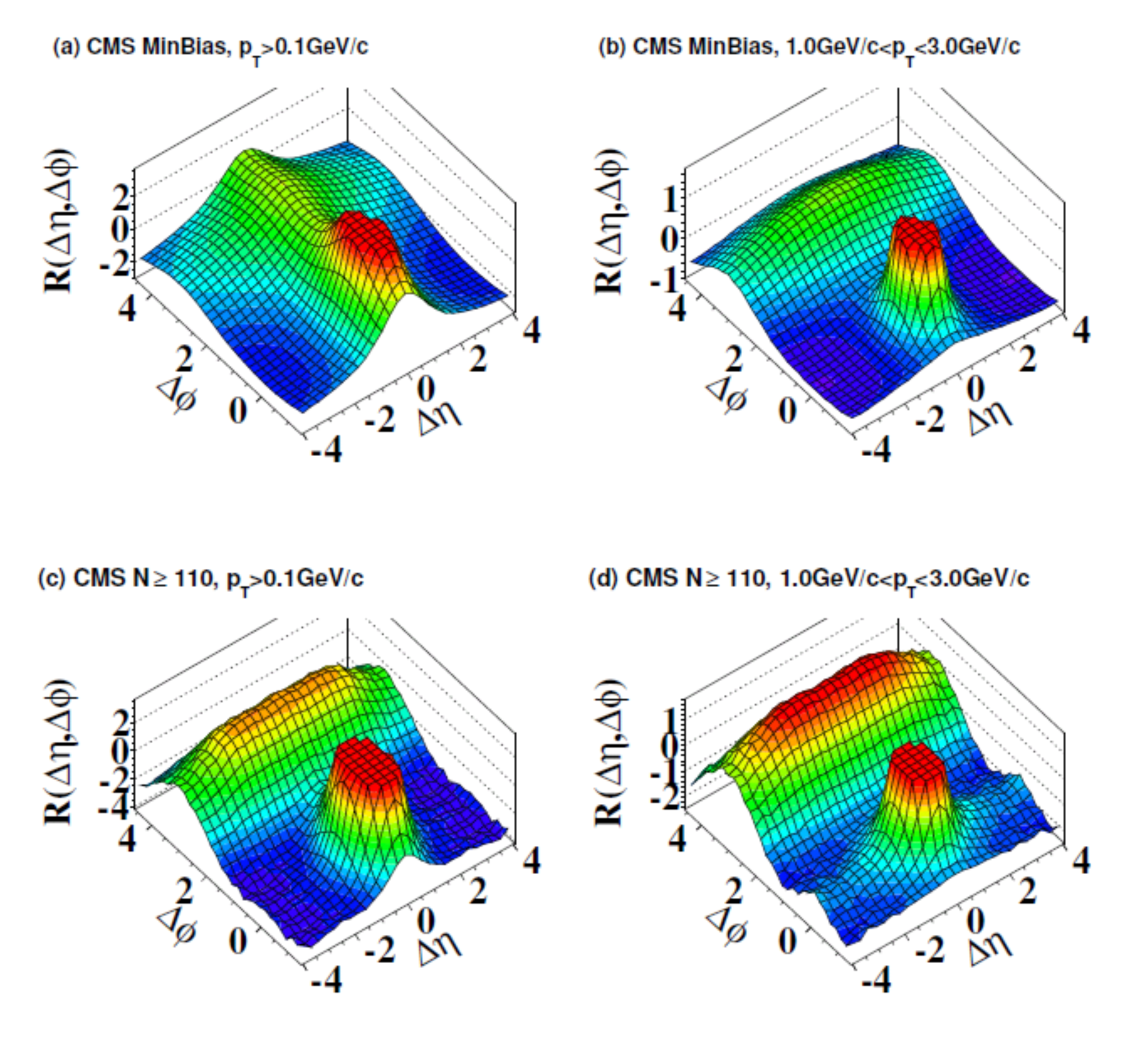
Jet Quenching





High pT hadrons are suppressed again!

QGP in pp collisions!?



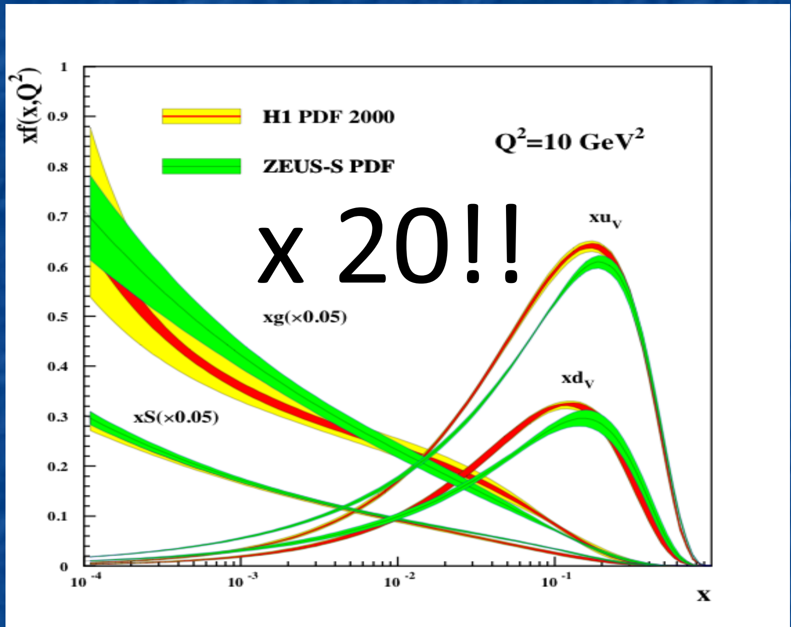
Ridge in pp collisions!?

CMS,JHEP09(2010)091

Understanding of Full Evolution at LHC Era

- After some initial time, space-time evolution of created matter is described by hydrodynamics reasonably well.
- What happens at first contact? (Or how does the hadron/nucleus look at very high energy?)
- If we would know the particle/entropy production at first contact, how does the QCD matter under local equilibrium form?

Parton Distribution in Proton at Small x



- Gluons are dominant at small x.
- Small x = High energy
- Hadron/Nucleus as a bunch of gluons at high energy

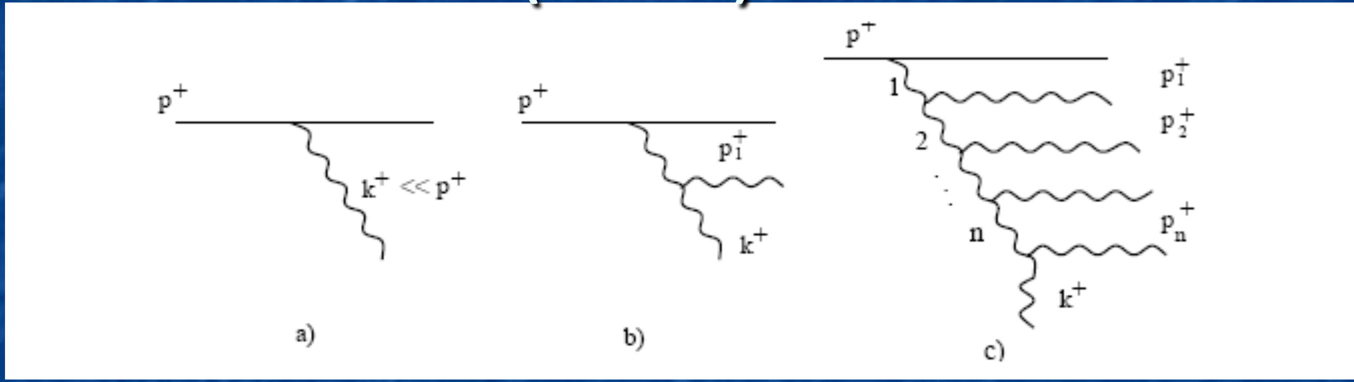
Bjorken x ~ Fraction of longitudinal momentum in proton

Kinematics in gg→ g

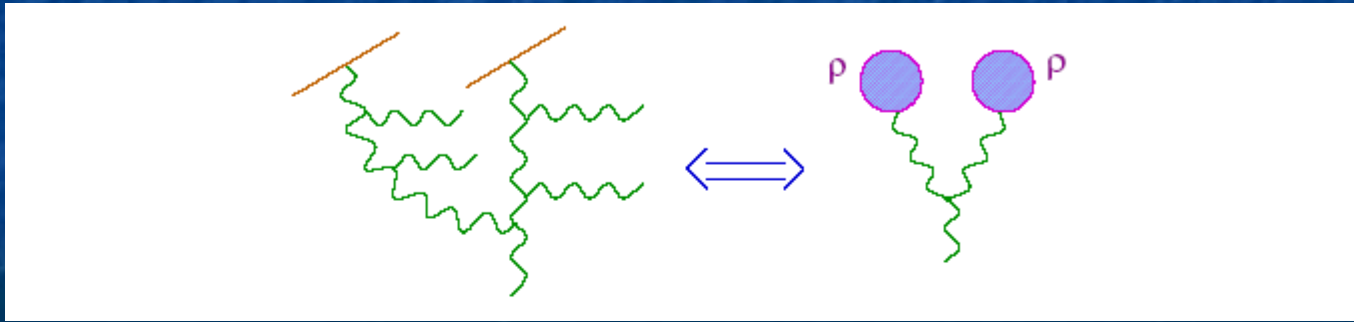
$$x_{1,2} = \frac{p_T}{\sqrt{s}} e^{\pm y}$$

Interplay btw. Emission and Recombination at Small x

Linear effect (BFKL)



Non-linear effect

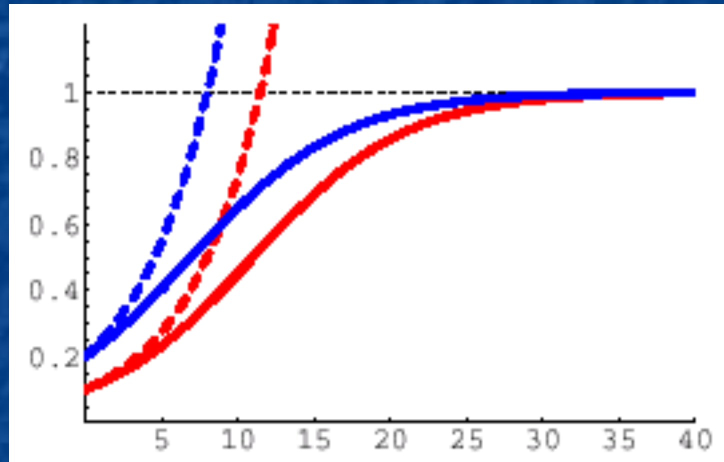


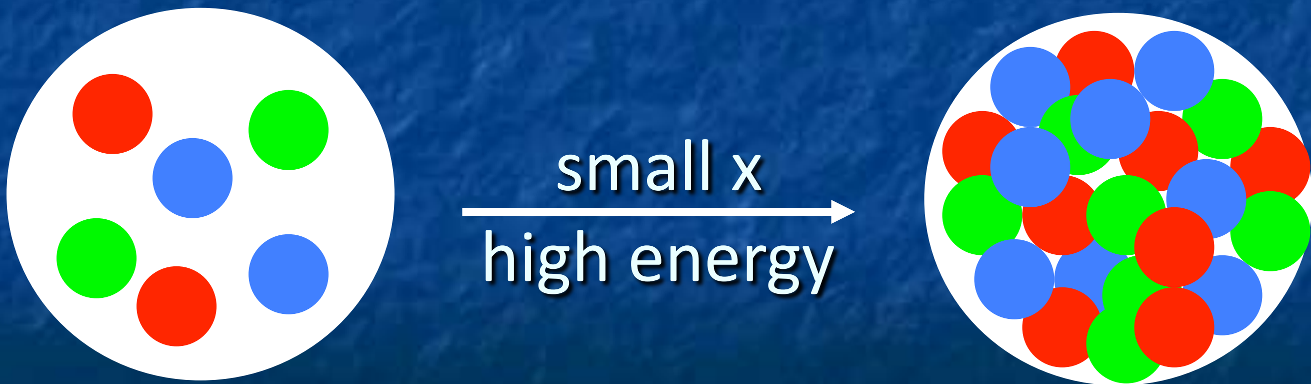
Figures adopted from
E.Iancu and R.Venugopalan, in Quark Gluon Plasma 3 (world scientific)

Non-Linear Evolution and Color Glass Condensate (CGC)

Rate eq.*

$$\frac{d\mathcal{N}}{d\ln s} = \kappa(\mathcal{N} - \mathcal{N}^2)$$

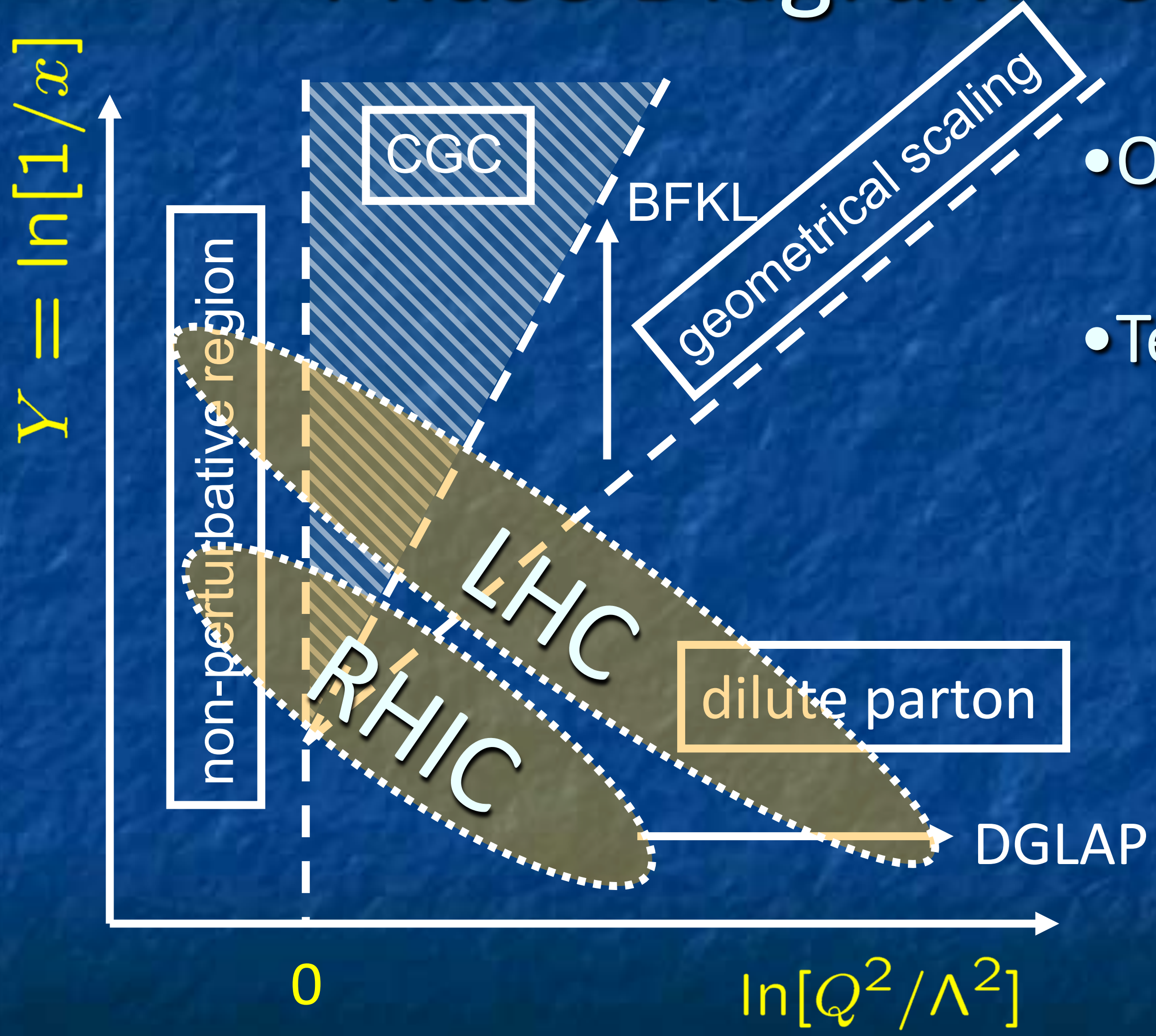




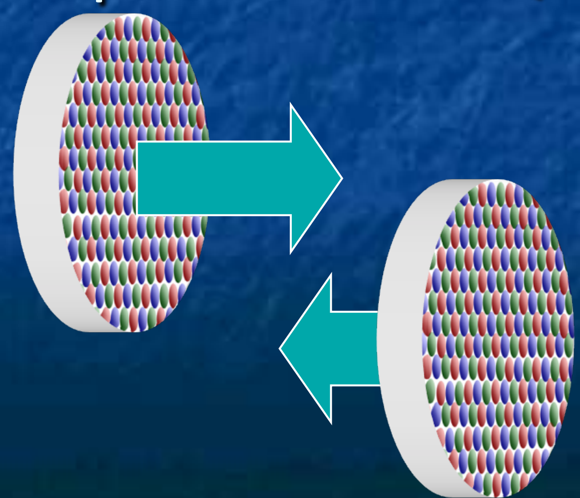
*More sophisticated equation (BK or JIMWLK) based on QCD has been solved.

Figures adopted from K.Itakura, talk at QM2005.

“Phase Diagram” of hadrons

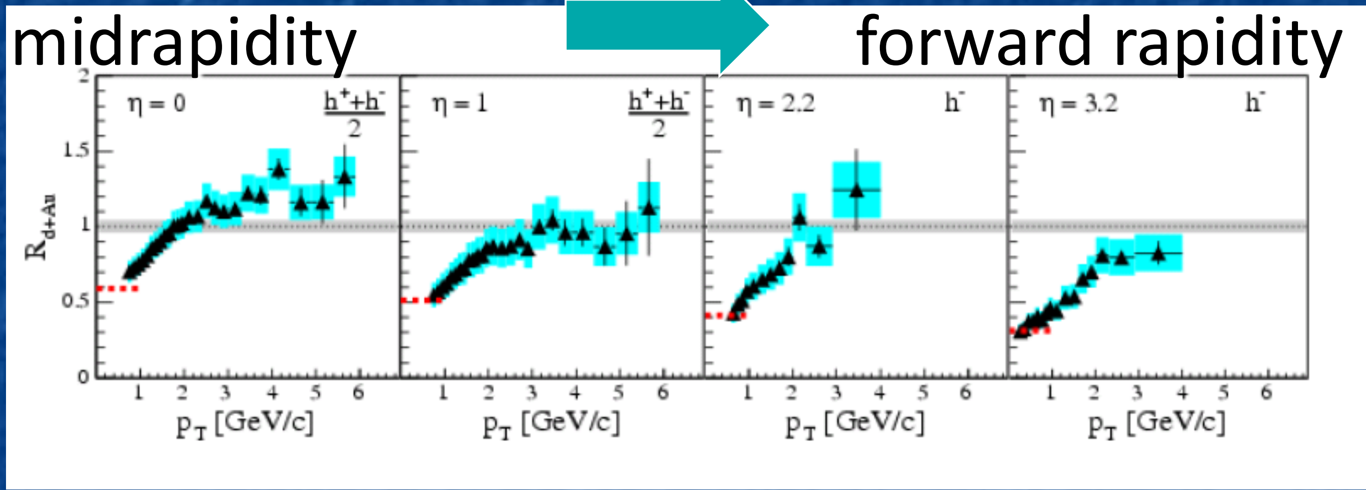


- Onset of CGC at RHIC
  - Some evidences exist.
- Test of CGC at LHC
  - How to describe perturbative CGC to non-perturbative QGP?



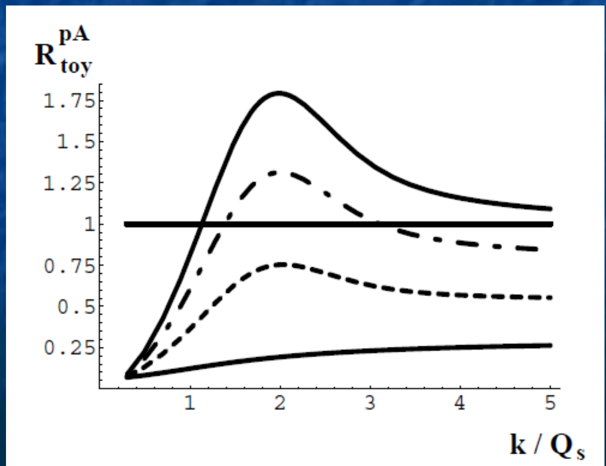
Onset of CGC in d+Au Collisions at RHIC

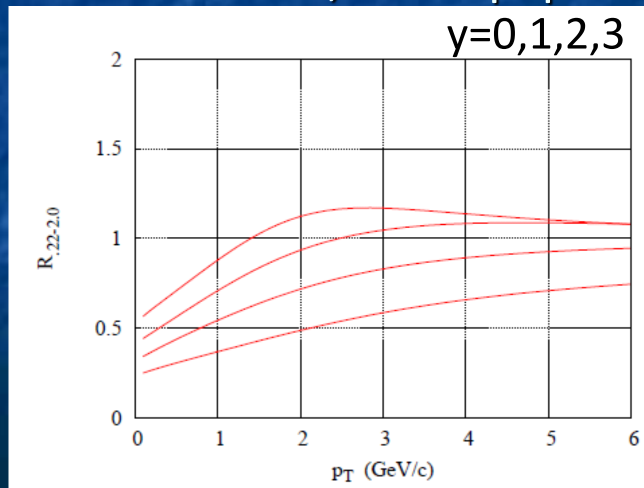
data



BRAHMS Collaboration, white paper

theory (CGC)





D.Kharzeev et al., PRD68,094013('03).

H.Fujii, talk at RCNP workshop('07)

Summary

- An almost perfect fluid and opaque QCD matter is created at RHIC for the first time.
  - Concept of strongly interacting quark-gluon many body system is established.
- Toward comprehensive understanding of the collision as a whole and the QGP at LHC
  - CGC is the key concept at ultrarelativistic energy.
- Some exotic phenomena are anticipated.
  - Something like perfect fluidity or shock wave (Mach cone) at RHIC