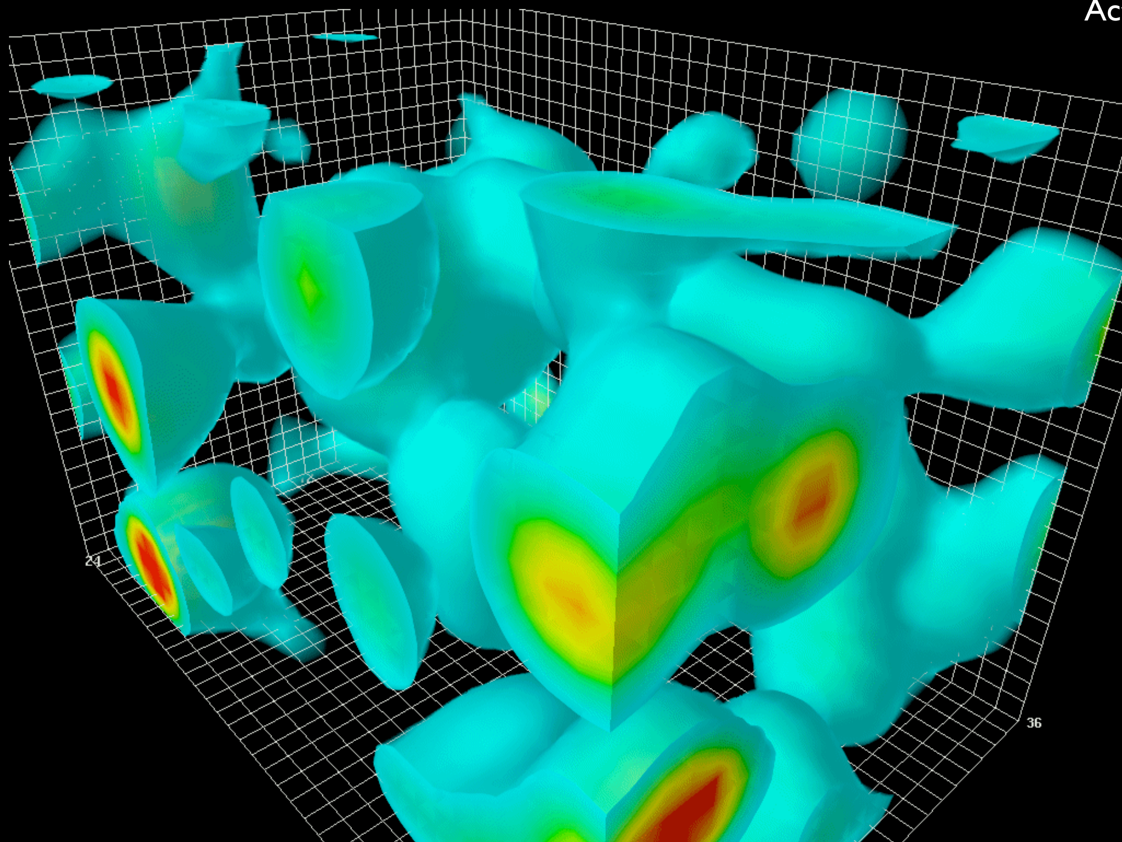
8.712
Introduction to Heavy-Ion Physics
Part II

3/18/2008

Gunther Roland

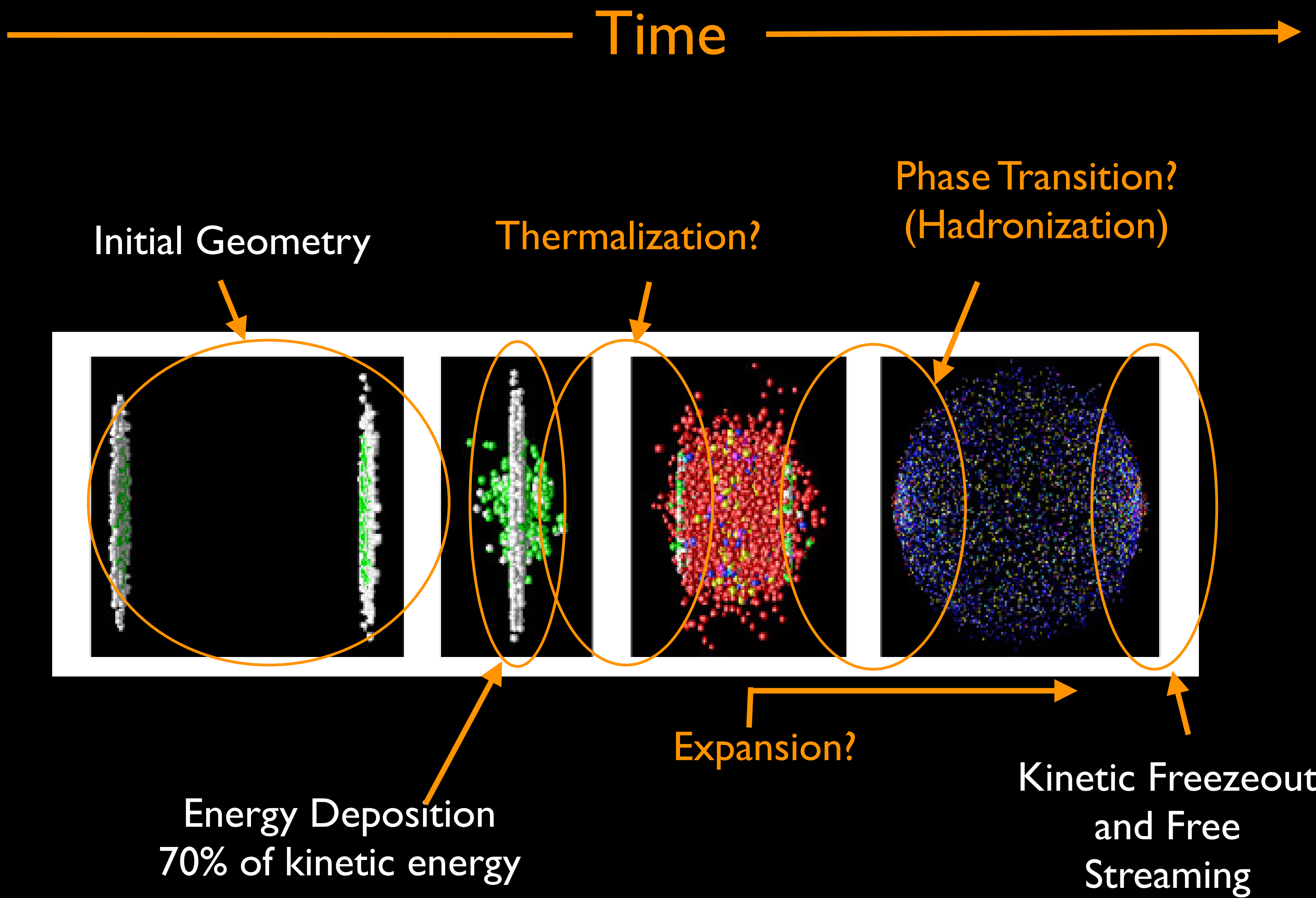
What are the properties of the vacuum at 10^{12}K? → CMS@LHC

Action density on ≈15fm^3 lattice
D. Leinweber, Adelaide

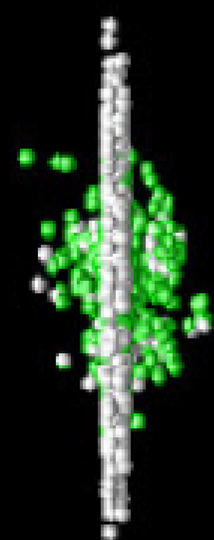


QCD vacuum

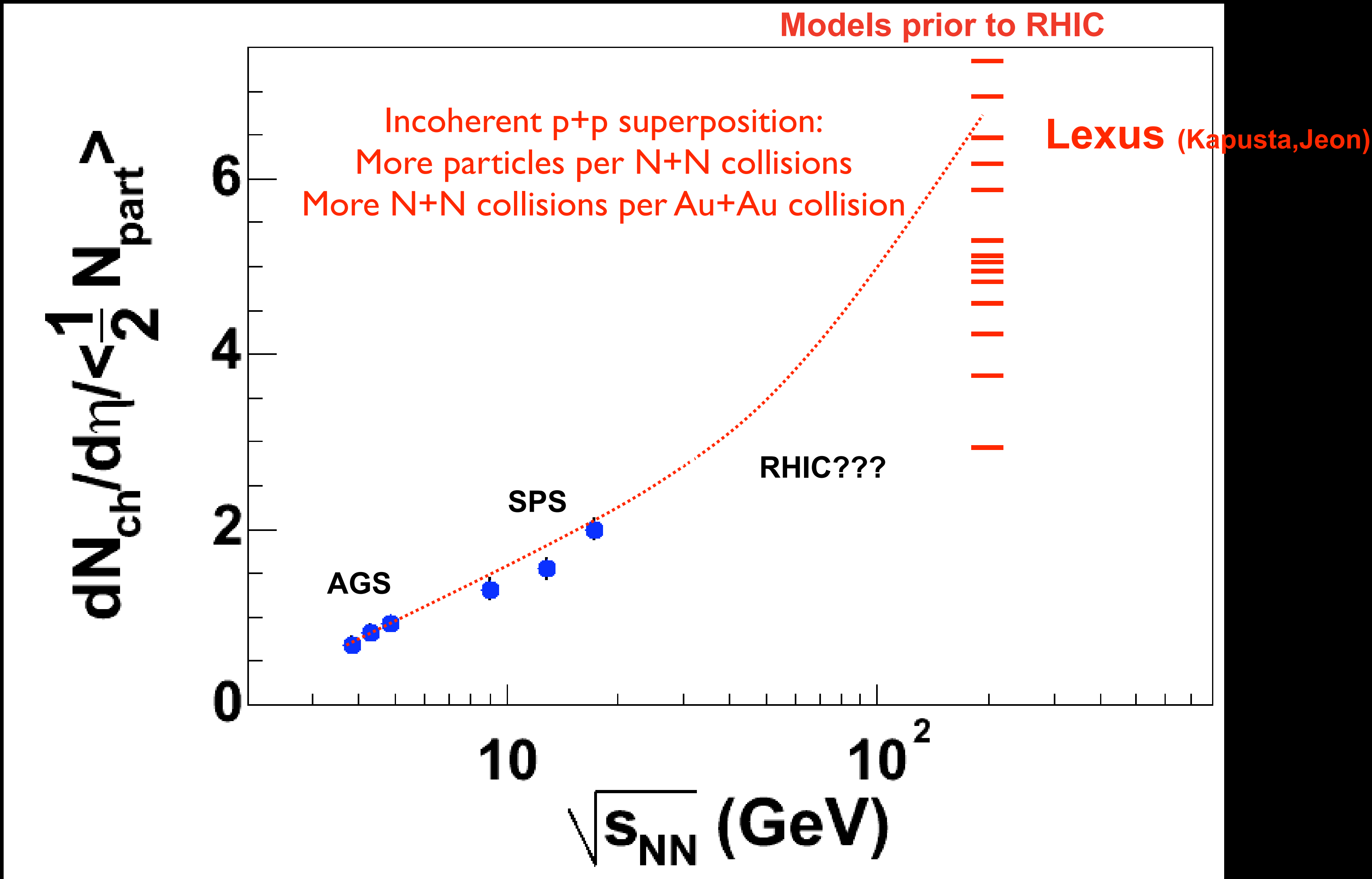
Time Evolution of a Heavy Ion Collision



Hadron Multiplicities



Particle Density near Mid-Rapidity in Au+Au



First RHIC Physics Paper

Charged particle multiplicity near mid-rapidity in central Au+Au collisions at $\sqrt{s} = 56$ and 130 AGeV

B.B.Back[1], M.D.Baker[2], D.S.Barton[2], S.Basilev[5], R.Baum[8], R.R.Betts[1,7], A.Bialas[4], R.Bindel[8], W.Bogucki[3], A.Budzanowski[3], W.Busza[5], A.Carroll[2], M. Ceglia[2], Y.-H.Chang[6], A.E.Chen[6], T.Coghen[3], C. Conner[7], W.Czyz[4], B.Dabrowski[3], M.P.Decowski[5], M.Despet[3], P.Fita[5], J.Fitch[5], M.Friedl[5], K.Galuszka[3], R.Ganz[7], E.Garcia-Solis[8], N.George[1], J.Godlewski[3], C.Gomes[5], E.Griesmayer[5], K.Gulbrandsen[5], S.Gushue[2], J.Halik[3], C.Halliwell[7], P.Haridas[5], A.Hayes[9], G.A.Heintzelman[2], C.Henderson[5], R.Hollis[7], R.Holynski[3], B.Holzman[7], E.Johnson[9], J.Kane[5], J.Katzy[5,7], W.Kita[3], J.Kotula[3], H.Kraner[2], W.Kucewicz[7], P.Kulinich[5], C.Law[5], M.Lemler[9], J.Ligocki[3], W.T.Lin[6], S.Manly[9,10], D.McLeod[7], J.Michalowski[3], A.Mignerey[8], J.Mülmenstädt[5], M.Neal[5], R.Nouicer[7], A.Olszewski[2,3], R.Pak[2], I.C.Park[9], M.Patel[5], H.Pernegger[5], M.Plesko[5], C.Reed[5], L.P.Remsberg[2], M.Reuter[7], C.Roland[5], G.Roland[5], D.Ross[5], L.Rosenberg[5], J.Ryan[5], A.Sanzgiri[10], P.Sarin[5], P.Sawicki[3], J.Scaduto[2], J.Shea[8], J.Sinacore[2], W.Skulski[9], S.G.Steadman[5], G.S.F.Stephans[5], P.Steinberg[2], A.Straczek[3], M.Stodulski[3], M.Strek[3], Z.Stopa[3], A.Sukhanov[2], K.Surowiecka[5], J.-L.Tang[6], R.Teng[9], A.Trzupek[3], C.Vale[5], G.J.van Nieuwenhuizen[5], R.Verdier[5], B.Wadsworth[5], F.L.H.Wolfs[9], B.Wosiek[3], K.Wozniak[3], A.H.Wuosmaa[1], B.Wyslouch[5], K.Zalewski[4], P.Zychowski[3]

(PHOBOS collaboration)

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(July 21, 2000)

We present the first measurement of pseudorapidity densities of primary charged particles near mid-rapidity in Au+Au collisions at $\sqrt{s} = 56$ and 130 AGeV. For the most central collisions, we find the charged particle pseudorapidity density to be $dN/d\eta|_{|\eta|<1} = 408 \pm 12(stat) \pm 30(syst)$ at 56 AGeV and $555 \pm 12(stat) \pm 35(syst)$ at 130 AGeV, values that are higher than any previously observed in nuclear collisions. Compared to proton-antiproton collisions, our data show an increase in the pseudorapidity density per participant by more than 40% at the higher energy.

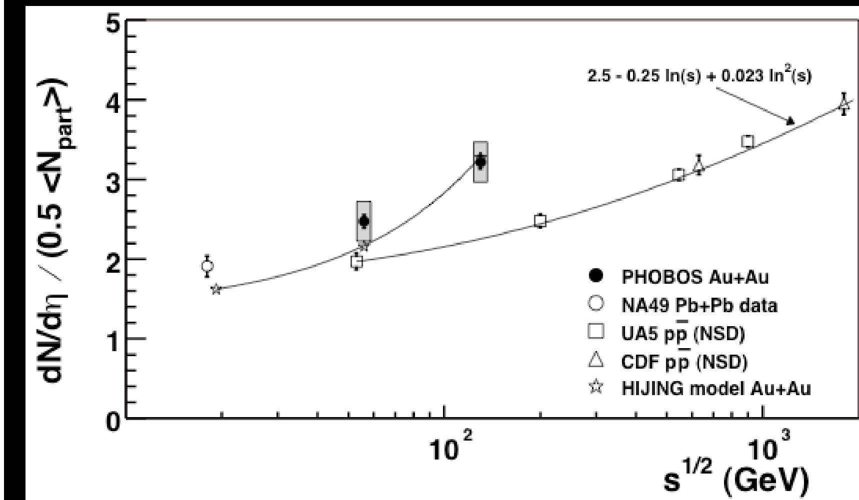
PACS numbers: 25.75.-q

In June 2000, the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory delivered the first collisions between Au nuclei at the highest center of mass energies achieved in the laboratory to date. In this paper we present data taken with the PHOBOS detector during the first collider run at energies of $\sqrt{s} = 56$ and 130 AGeV. The ultimate goal of our work is to understand the behavior of strongly interacting matter at conditions of extreme density and temperature. Quantum chromodynamics (QCD), the fundamental theory of strong interactions, predicts that for sufficiently high energy density a new state of matter will be formed, the so-called quark-gluon plasma (QGP) [1]. The measurements shown here represent the first step toward the development of a full picture of the dynamical evolution of nucleus-nucleus collisions at RHIC energies.

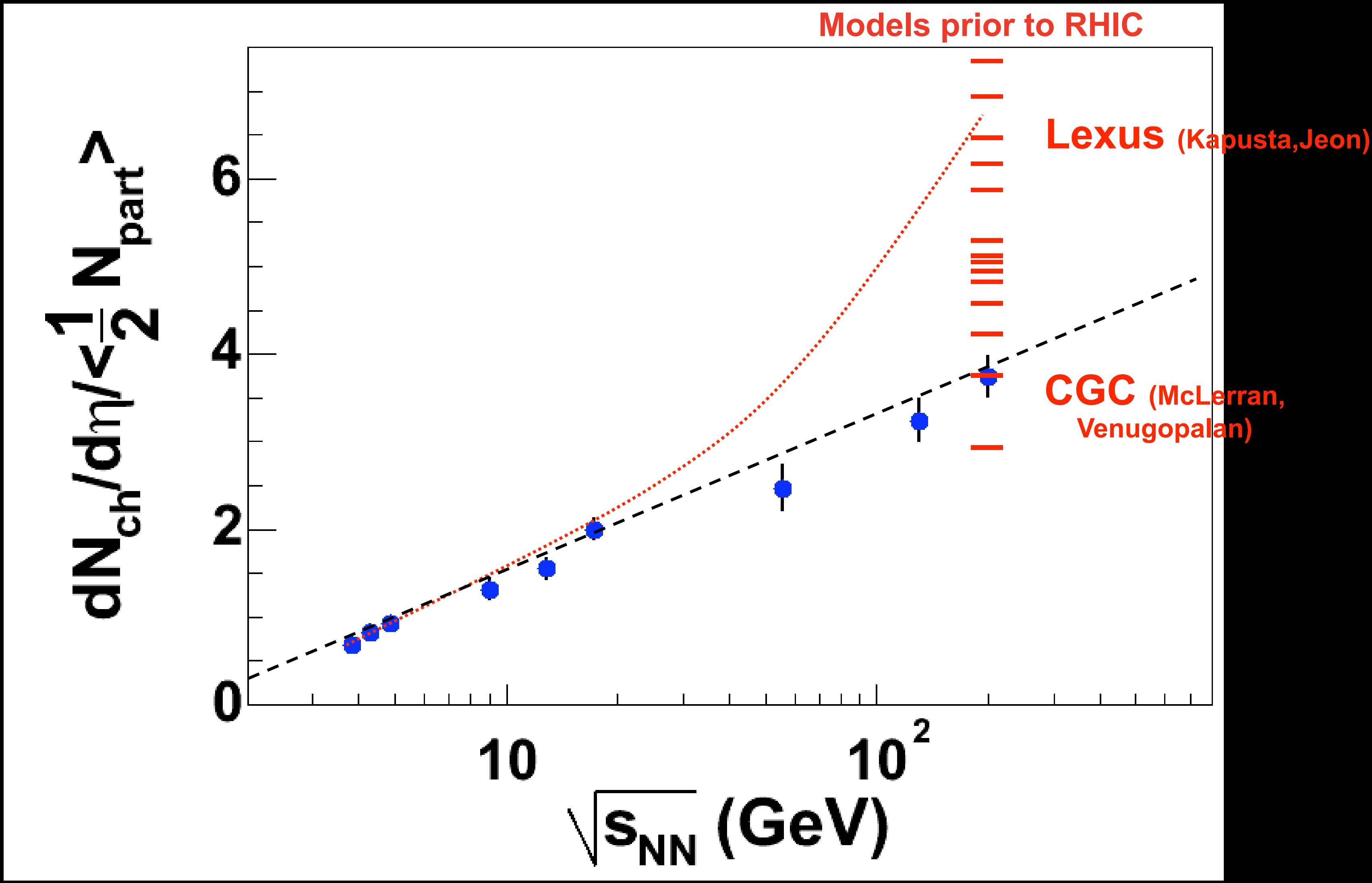
Studying the dependence of charged particle densities on energy and system size provides information on the interplay between hard parton-parton scattering processes, which can be calculated using perturbative QCD, and soft processes, which are treated by phenomenological models that describe the non-perturbative sector of QCD. Predictions for multi-particle production in high-energy heavy-ion collisions, obtained from a variety of models, typically vary by up to a factor of two [2].

In this letter we report data for the most central Au+Au collisions detected in our apparatus. We have determined the energy dependence of the density of primary charged particles emitted near 90° to the beam axis, characterized by the pseudorapidity density $dN/d\eta|_{|\eta|<1}$, where $\eta = -\ln\tan(\theta/2)$ and θ is the polar angle from the beam axis. These data provide the first means to constrain models of heavy-ion collisions at RHIC energies. They will allow the extraction of basic information about the initial conditions in these collisions, in particular the energy density, and thus form an essential element for the proper prediction or description of other observables.

The PHOBOS detector employs silicon pad detectors to perform tracking, vertex detection and multiplicity measurements. Details of the setup and the layout of the silicon sensors can be found elsewhere [3,4]. For the initial running period of the accelerator only a small fraction of the full setup was installed. It included the first 6 layers of the silicon spectrometer (SPEC), part of the two-layer silicon vertex detector (VTX) and

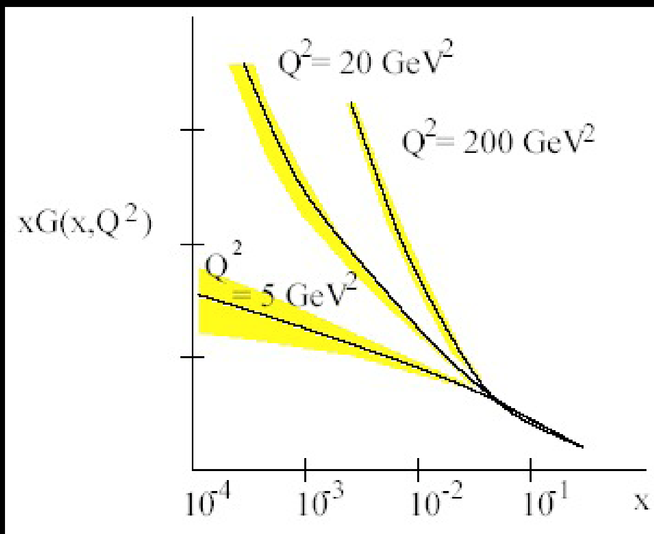


Particle Density near Mid-Rapidity



Parton Saturation

Gluon density in proton

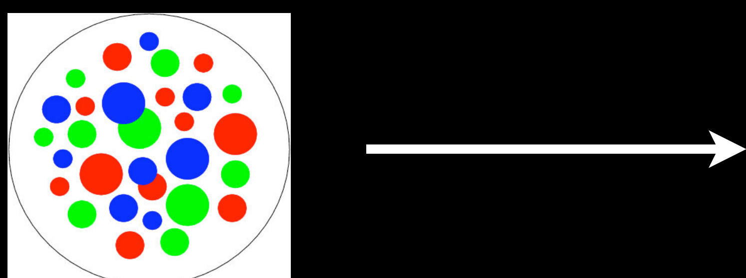


Fraction of momentum carried by gluon

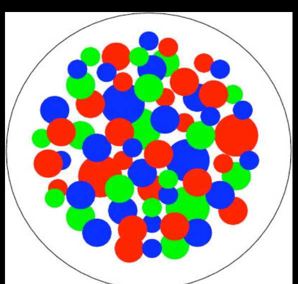
Idea(s):
Entropy is not "created" but "liberated" from gluon distributions

Gluon density increases with x, Q^2

BUT: Gluons interact, limiting growth of gluon densities: Saturation



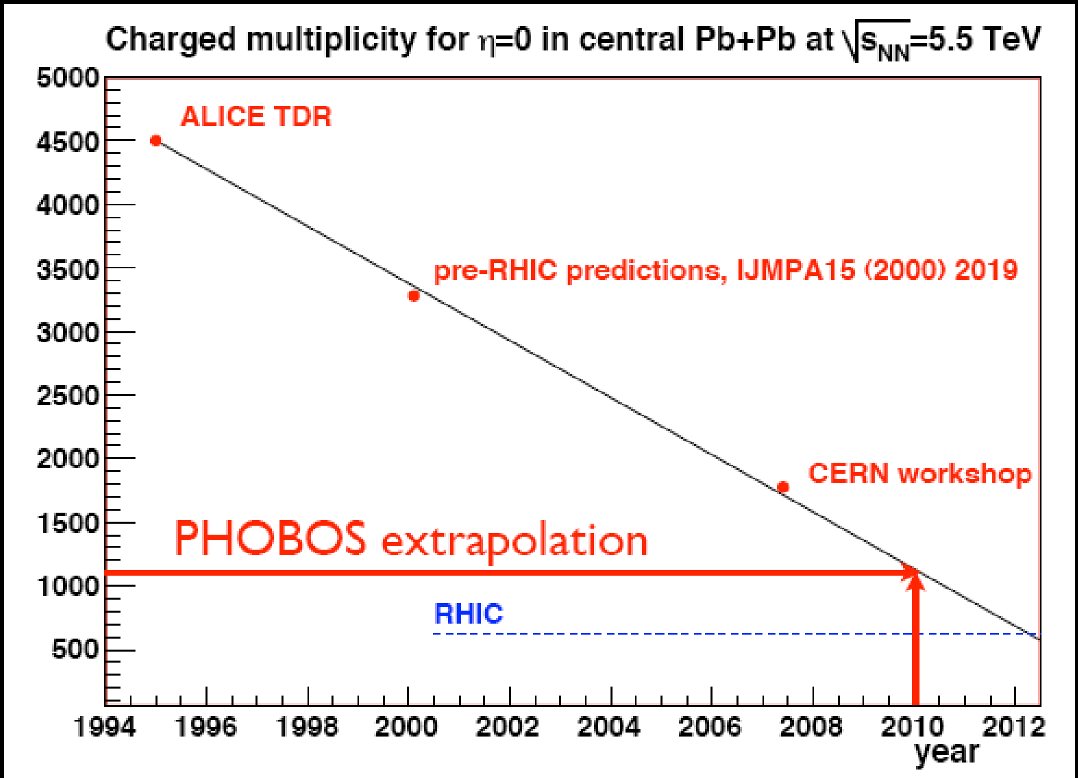
Low energy



High energy

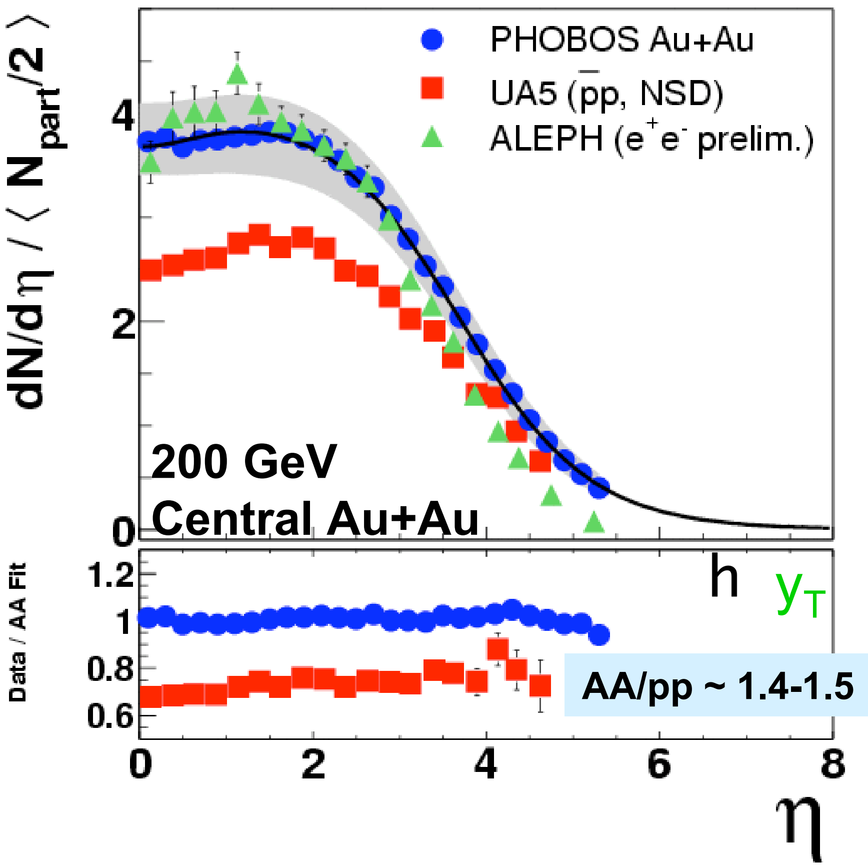
One important lesson

from Nestor Armesto, QM 2008

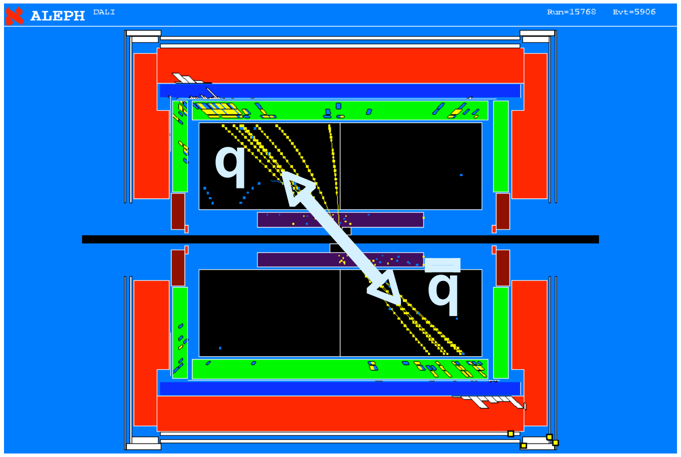


Don't bet your experiment on predictions....

e^+e^-, p+p, A+A Correspondence ?

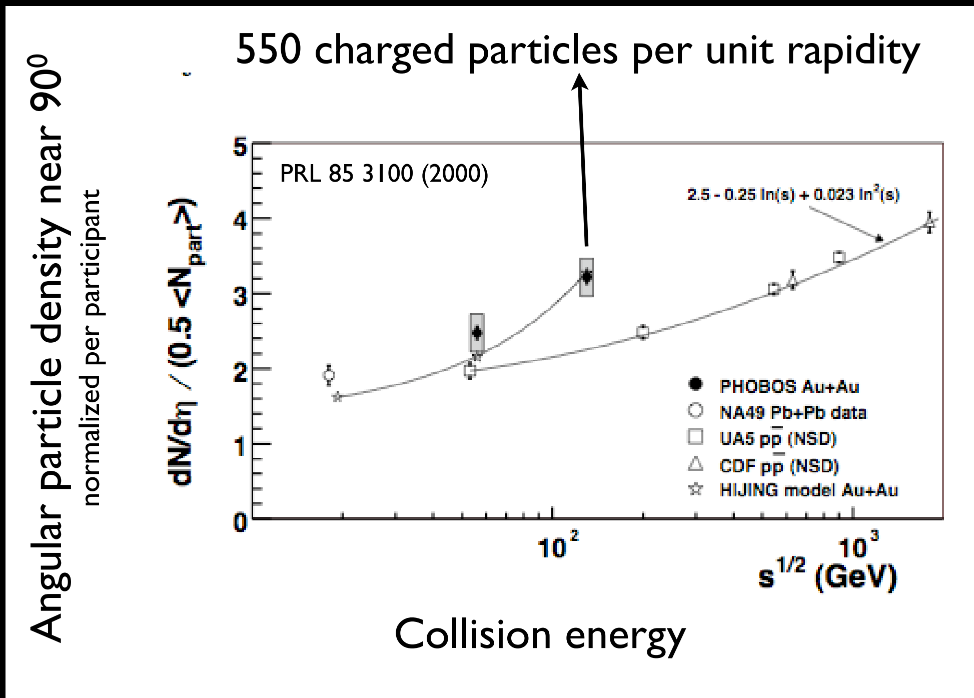


PHOBOS QM'02, Steinberg

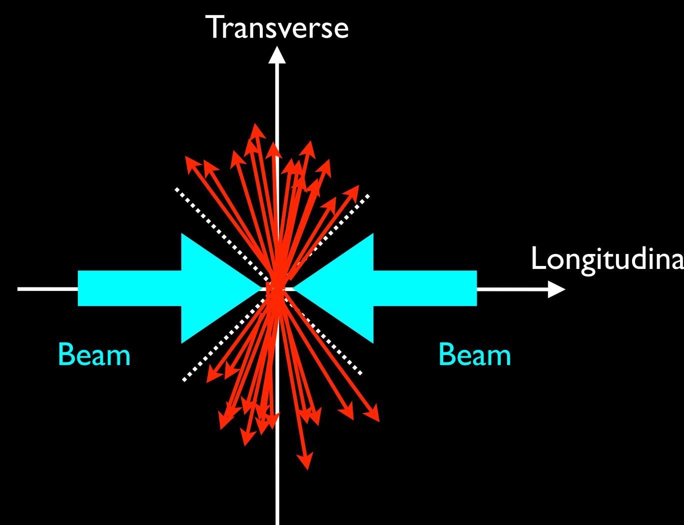


e^+e^- measures dN/dy_T (rapidity relative to "thrust" axis)

Surprising agreement in shape between AA/e^+e^-/pp



RHIC delivered first collisions on June 12th, 2000
PHOBOS submitted first paper July 19th, 2000



Use "energy flow" from longitudinal (=beam) to transverse direction to estimate energy/volume

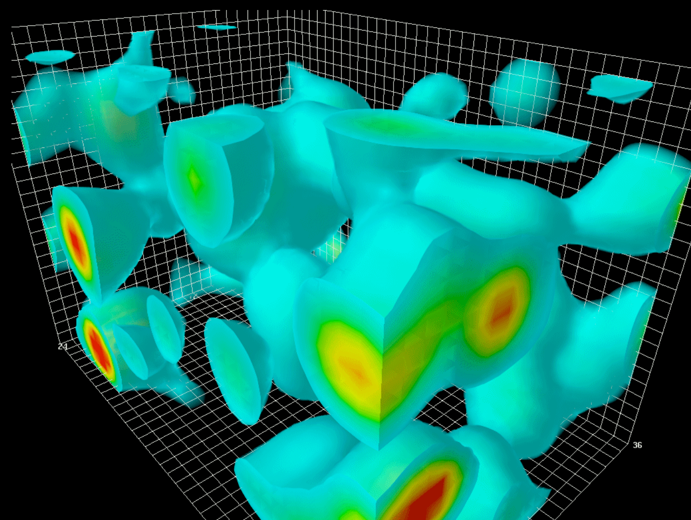
$$\frac{1000 \text{ particles x } 0.5 \text{ GeV/particle}}{\pi \times (7 \text{ fm})^2 * 1 \text{ fm}} \approx 3 \text{GeV/fm}^3$$

Much larger than $\epsilon_{crit} \approx 0.7$ GeV/fm^3

But: Equilibration?

What are the transport properties of the vacuum at 10^{12}K?

What are the transport properties of the vacuum at 10^{12}K?



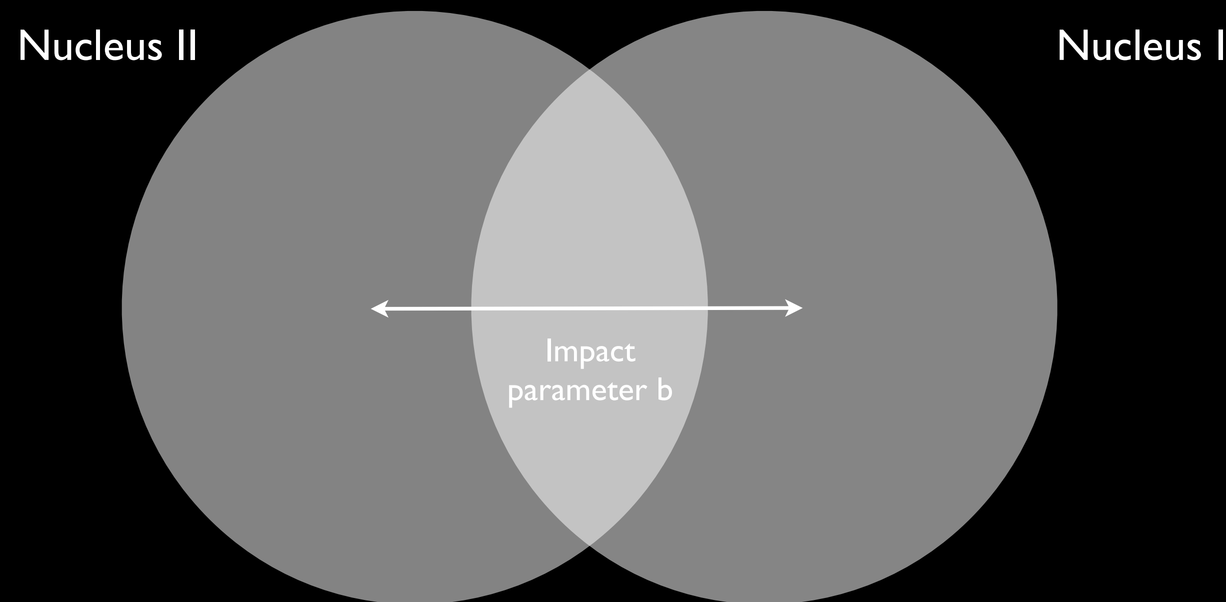
Action density on ≈$15 fm^3$ lattice
D. Leinweber, Adelaide

e.g. can one measure or calculate the viscosity of a system at T > 200MeV?

first we need to show that we indeed produce an interacting system at such temperatures

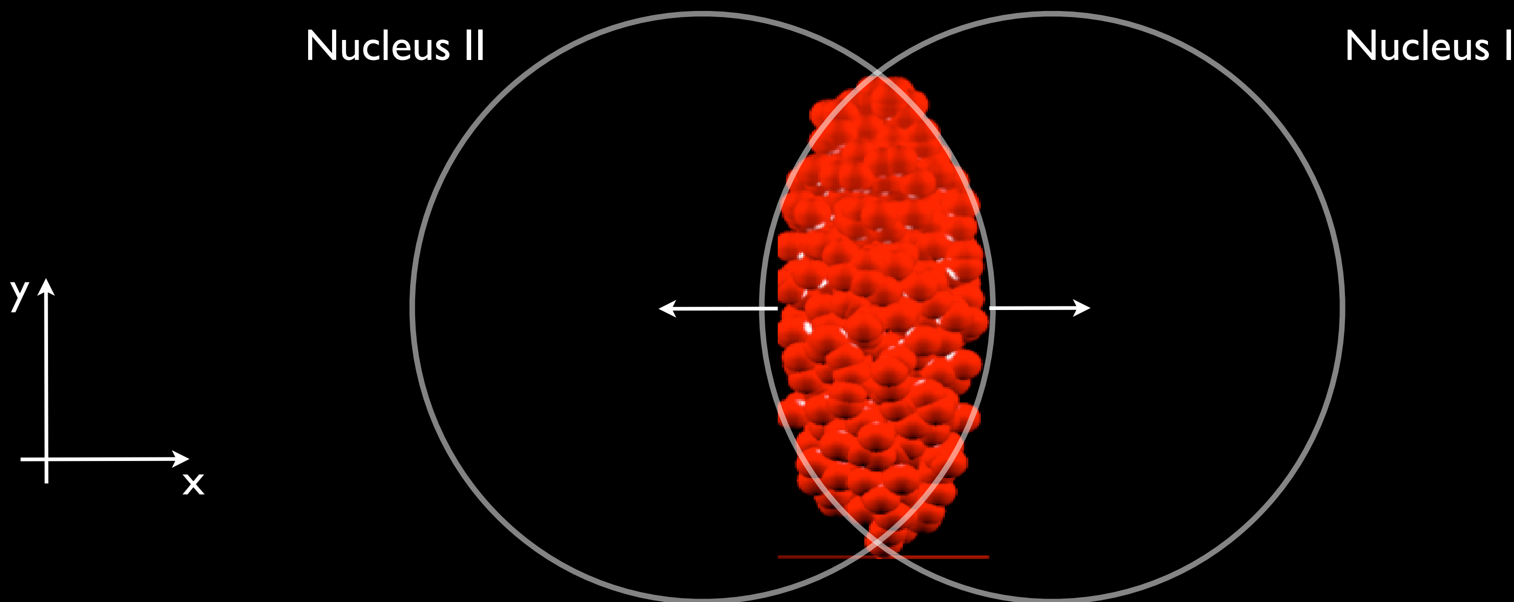
How do we prove that we make "matter"?

Non-central collision (Transverse plane)



How do we prove that we make “matter”?

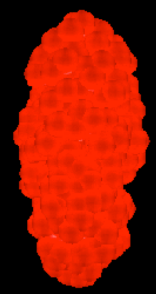
Non-central collision (Transverse plane)



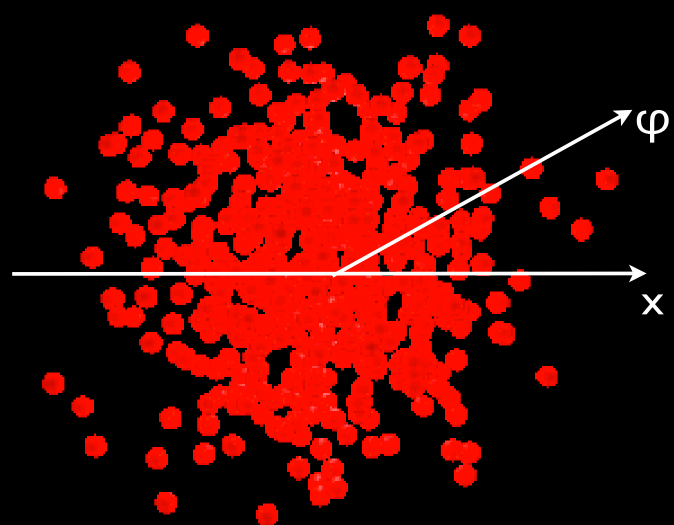
“Hot” overlap zone is asymmetric in azimuthal angle

Define: $\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$ “Initial State Eccentricity”

Non-interacting particles

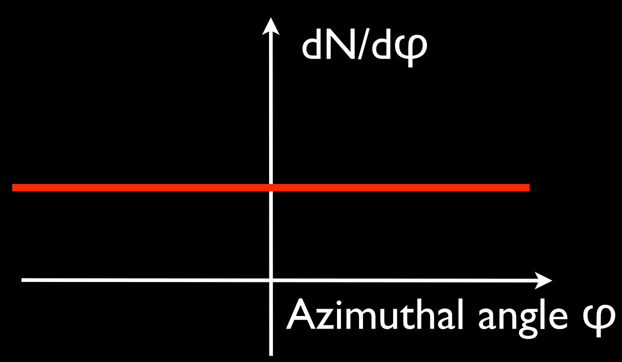


Non-interacting particles



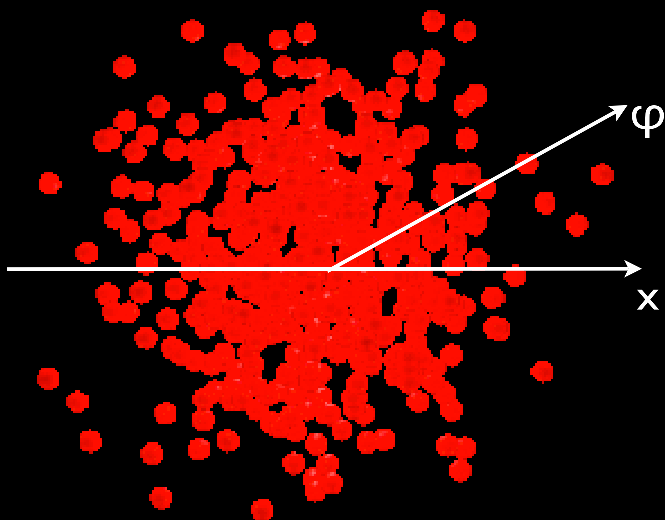
Shape information is not transfered to momentum space

Flat azimuthal distribution



Collective expansion of Matter

Non-interacting particles



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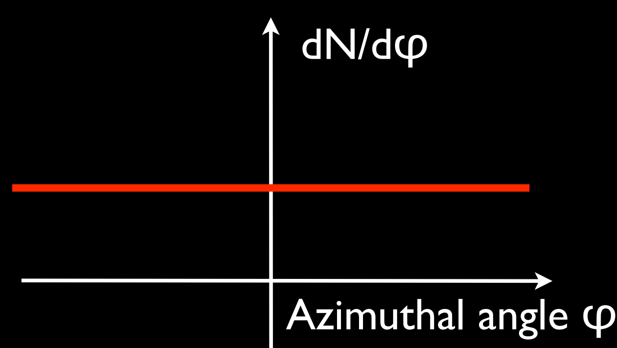
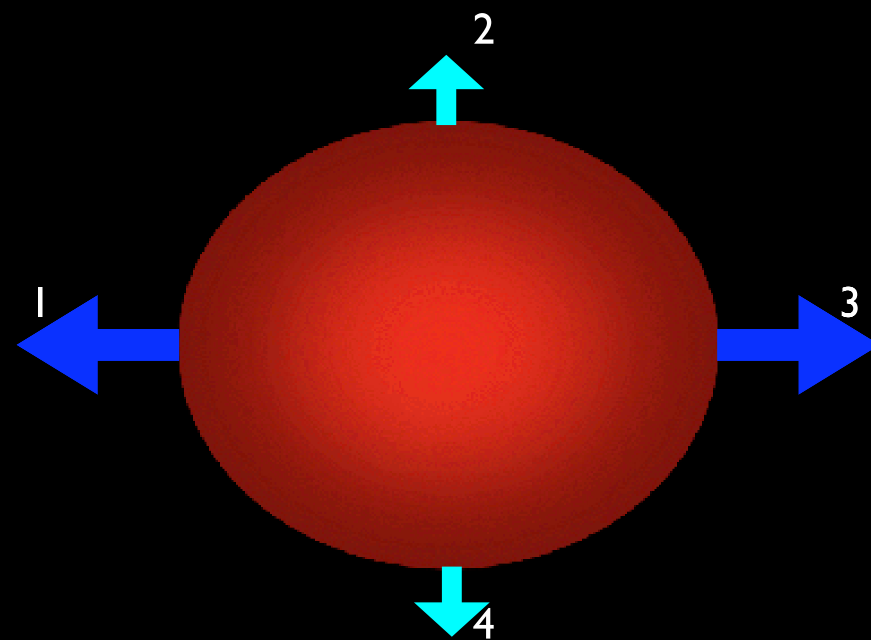
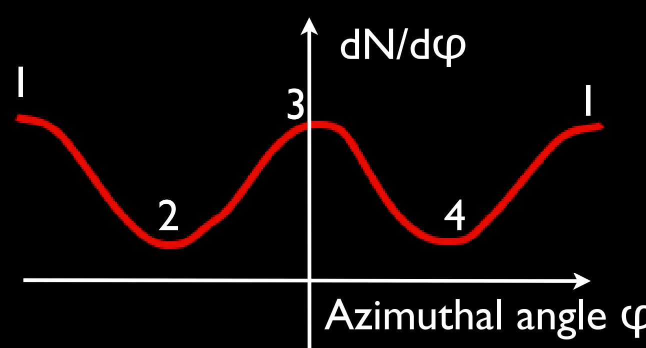


Collective expansion of Matter



Shape information transformed into momentum space

cos(2 φ) modulation of azimuthal distribution

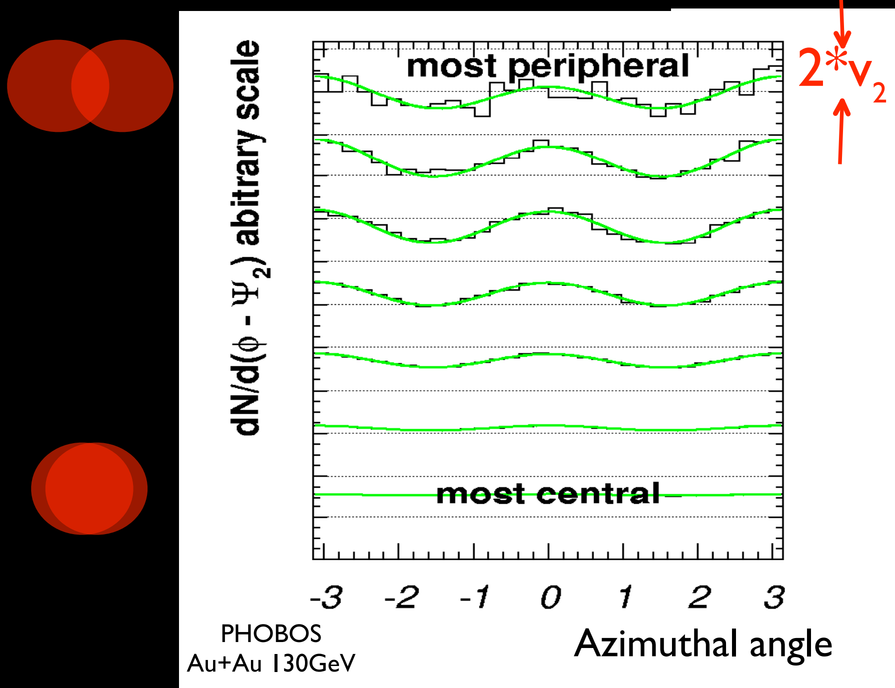


How do we prove that we make "matter"?

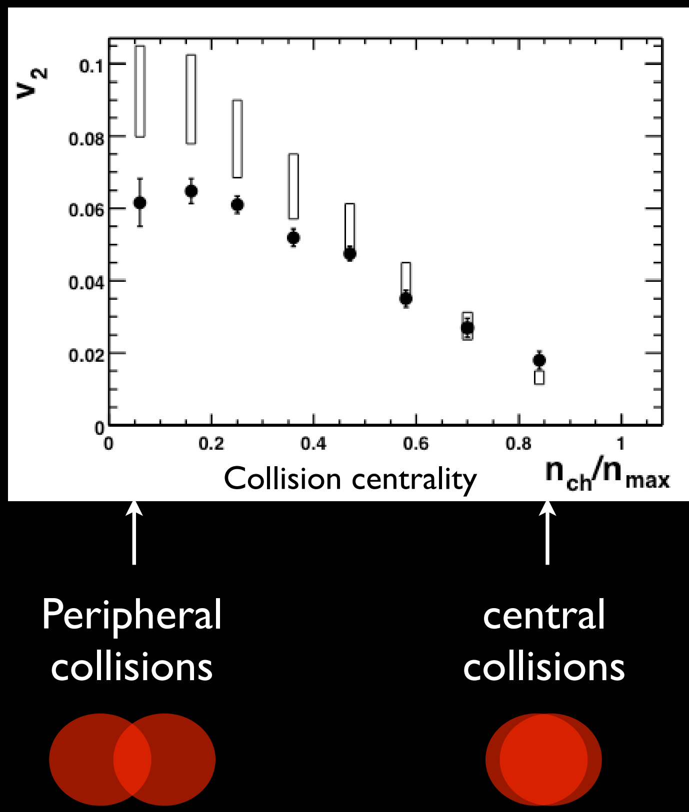
Azimuthal distribution

$dN/d\varphi = 1 + 2\, v_2 \cos(2(\varphi - \varphi0))$

"Elliptic Flow"



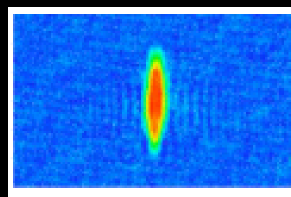
STAR PRL 2000



The initial anisotropy in coordinate space is translated into momentum space: Interactions → Equilibration (?)

Hydrodynamic Evolution

Initial State



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Energy/Momentum Conservation

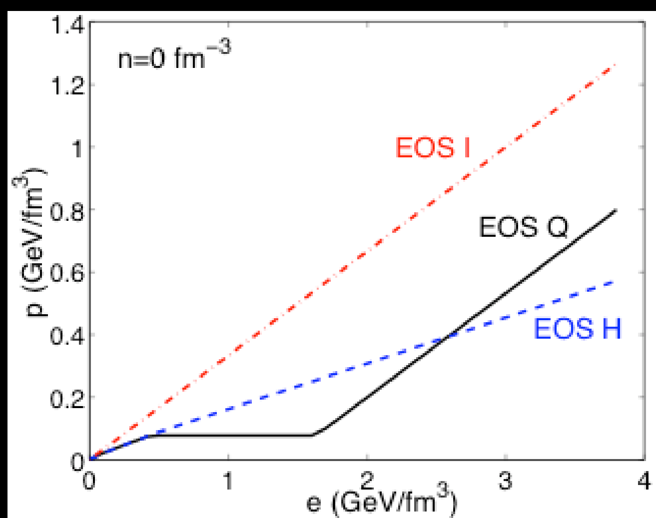
$$\partial_\mu T^{\mu\nu} = 0$$

Baryon number Conservation

$$\partial_\mu j^\mu = 0$$

+

Equ. of State



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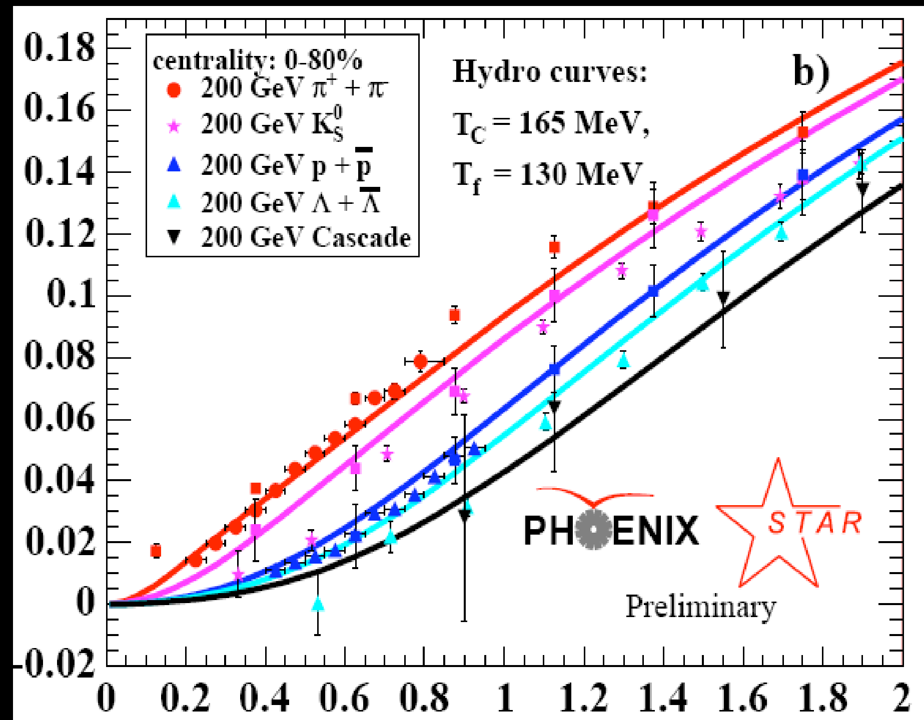


<u>Ideal Hydro</u>

local equilibrium

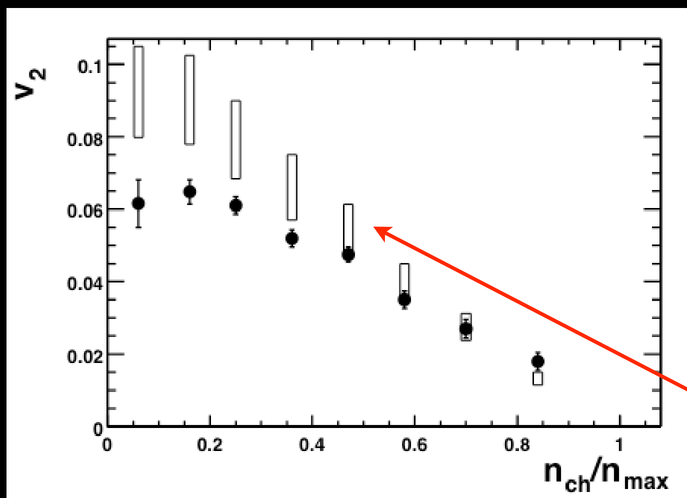
vanishing λ_{MFP}

no viscosity

Hydrodynamics

"Ideal hydrodynamics"

STAR PRL 2000



Assumption:

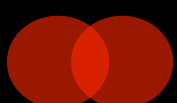
Shortly after initial collision (<1-2fm/c) a system in local equilibrium with very small mean free path is created

Local equilibrium ⇔ small λ_{mfp} ⇔ small shear viscosity

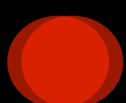
$v_2 \propto \epsilon$ (i.e. initial geometric eccentricity)

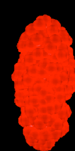
Mid-central data reach hydro prediction (calculated using $\lambda_{mfp} = 0$)

Peripheral collisions



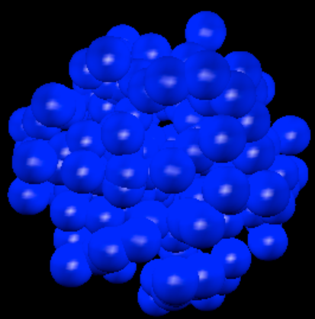
central collisions





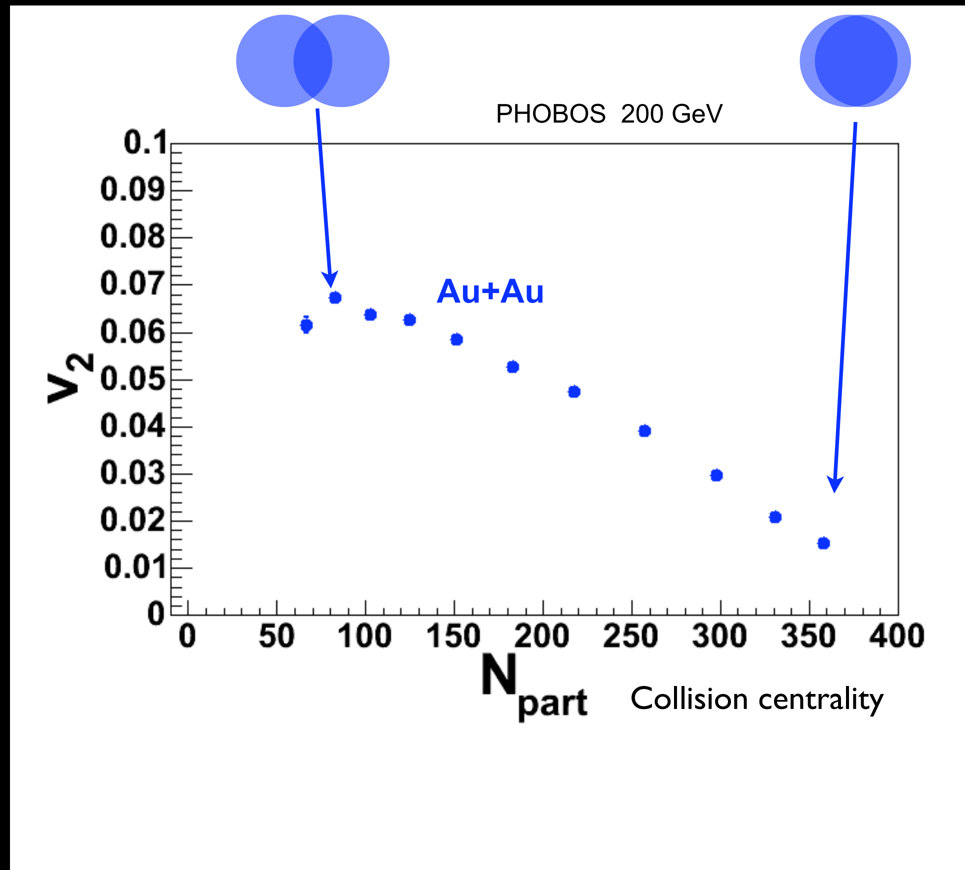
Once shape info is lost in free streaming, can't be recovered

Elliptic Flow and Geometry, I

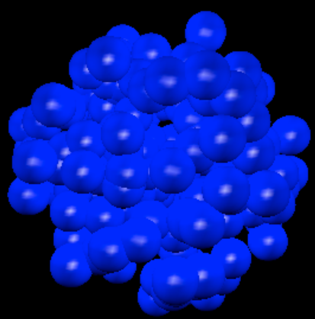


Gold
A=197

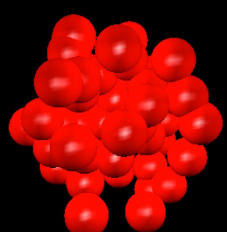
Test connection between geometry and elliptic flow
by comparing Au+Au to Cu+Cu



Elliptic Flow and Geometry, I

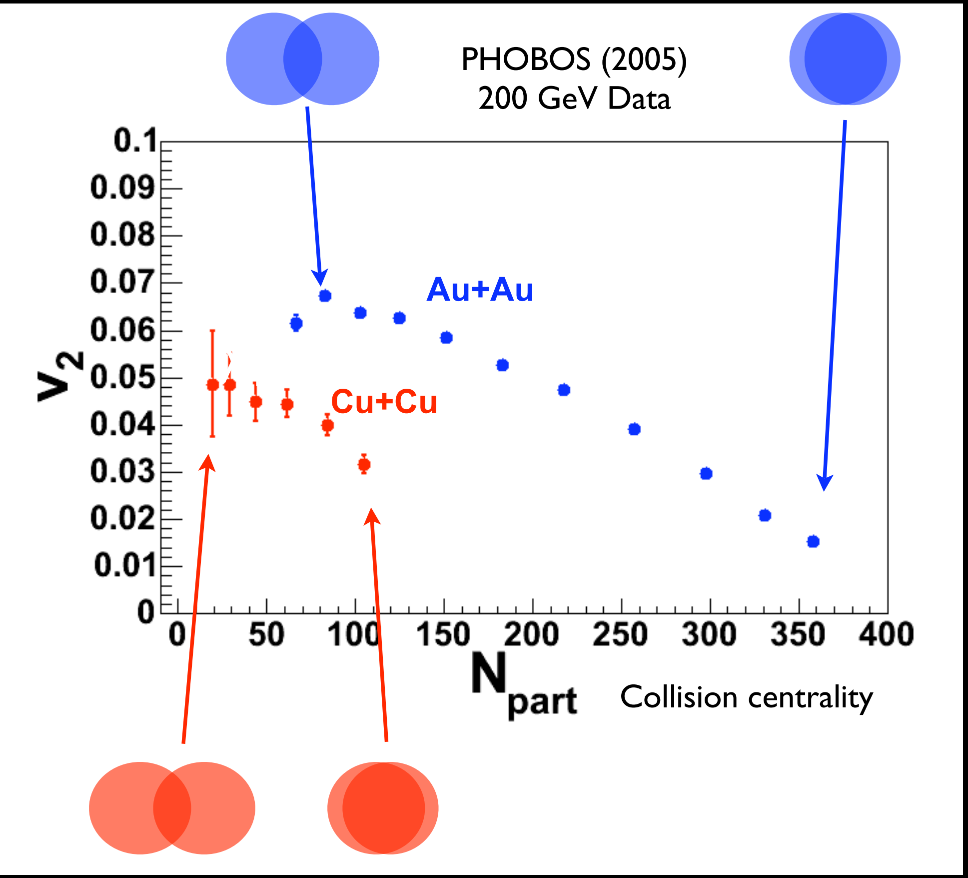


Gold
A=197



Copper
A=64

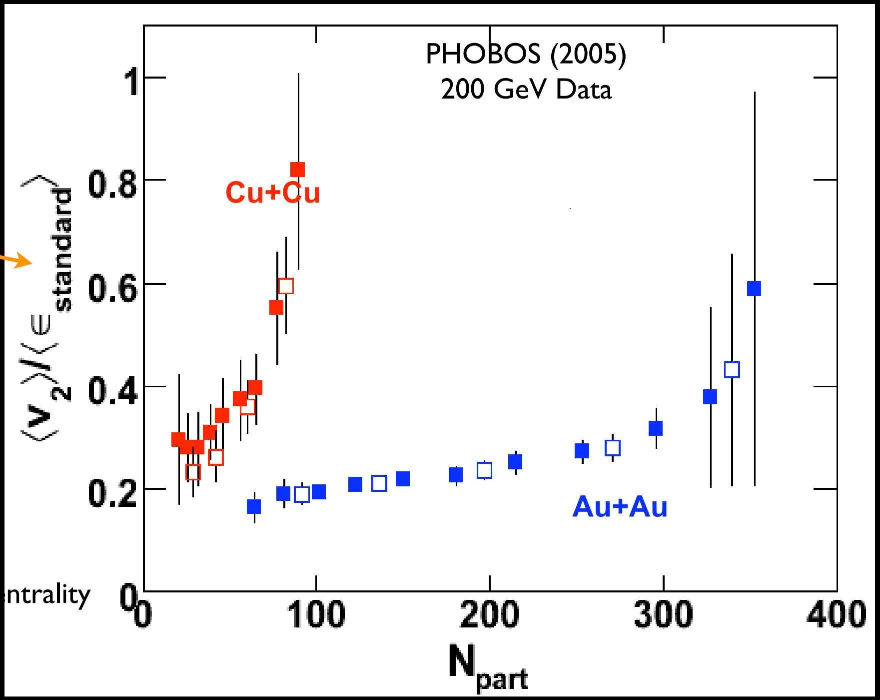
Test connection between geometry and elliptic flow by comparing Au+Au to Cu+Cu



v_2 is large even for central Cu+Cu

Challenge: System Size Scaling

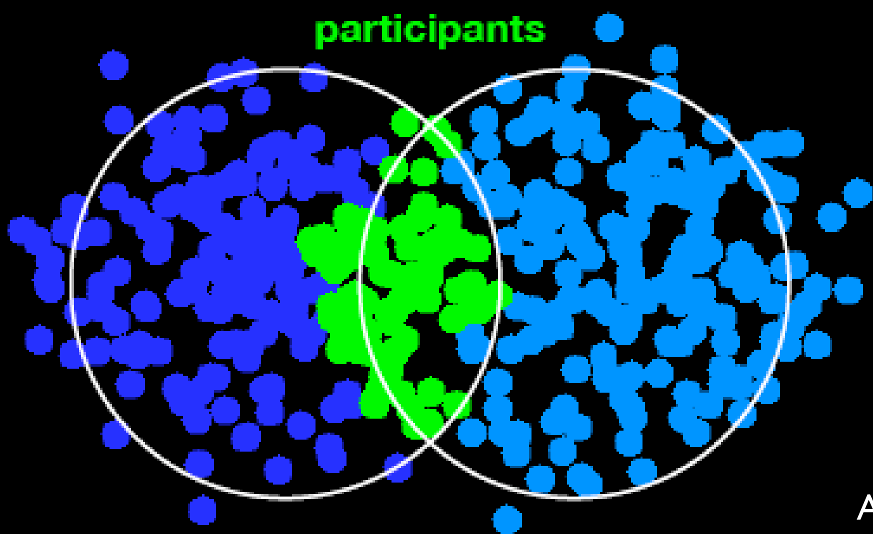
$$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$



For same N_{part} (~ same initial density), v_2/ϵ_{std} is much larger in Cu+Cu than in Au+Au collisions

Re-thinking ϵ

At fixed b



In Glauber MC model, geometry is sampled by finite number of nucleons

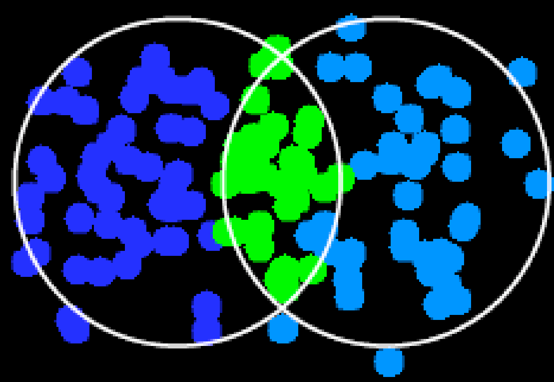
➞

Geometry varies from event-to-event, even at fixed b

Aguiar, Hama, Kodama, Osada, hep-ph/0106266 (QM 2001)
Miller, Snellings, nucl-ex/0312008
(4 citations until 2005, 28 since then)
Broniowski et al, arXiv:0706.4266

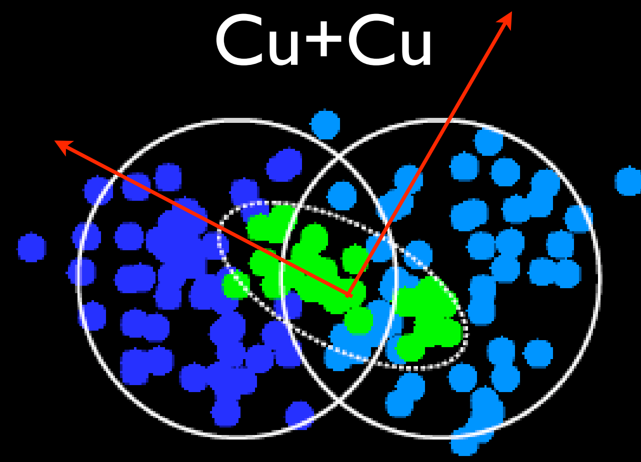
Collision Geometry Fluctuations

Cu+Cu



Plots from Richard Bindel, Maryland, using PHOBOS Glauber MC

Cu+Cu



$$\epsilon_{part} = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4(\sigma_{xy}^2)^2}}{\sigma_y^2 + \sigma_x^2}$$

"Participant Eccentricity"

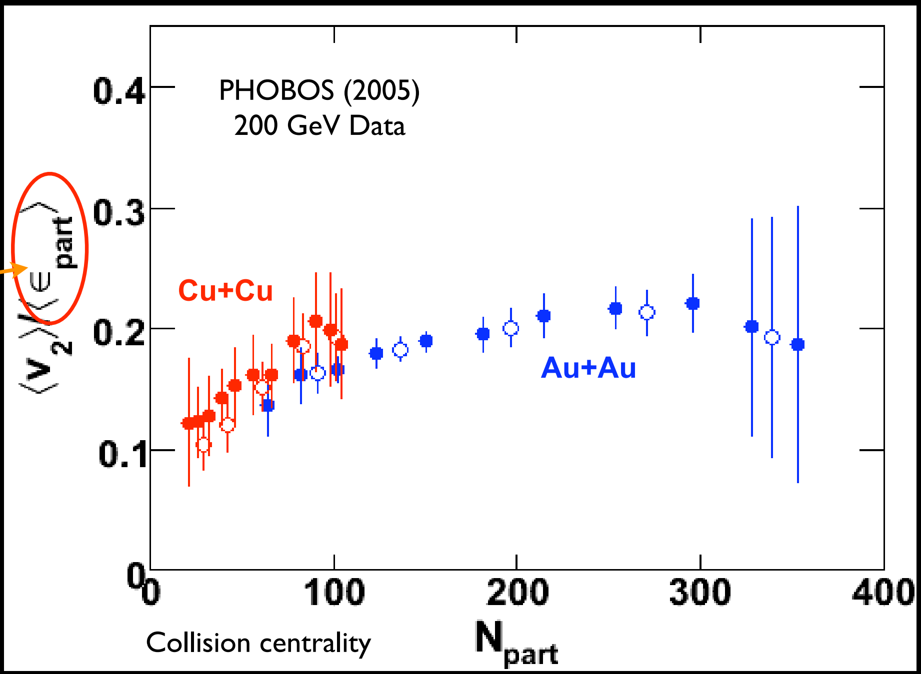
PHOBOS 2005, see also

Broniowski et al, arXiv:0706.4266

If flow is driven by initial matter distribution, the orientation (and shape) of that distribution should determine direction and magnitude of flow

System Size Scaling

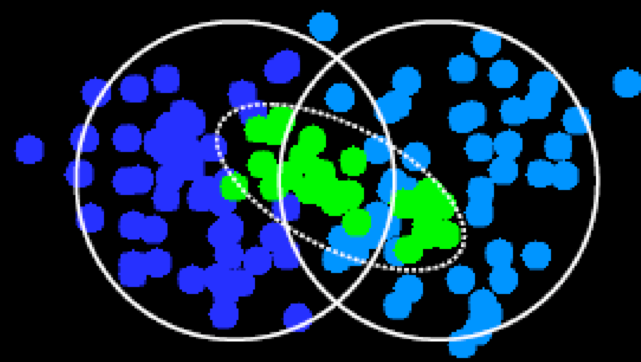
$$\epsilon_{part} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4(\sigma_{xy}^2)^2}}{\sigma_y^2 + \sigma_x^2}$$



Re-interpretation of Glauber MC initial states yields v_2 scaling between Cu+Cu and Au+Au

Collision Geometry Fluctuations

Cu+Cu



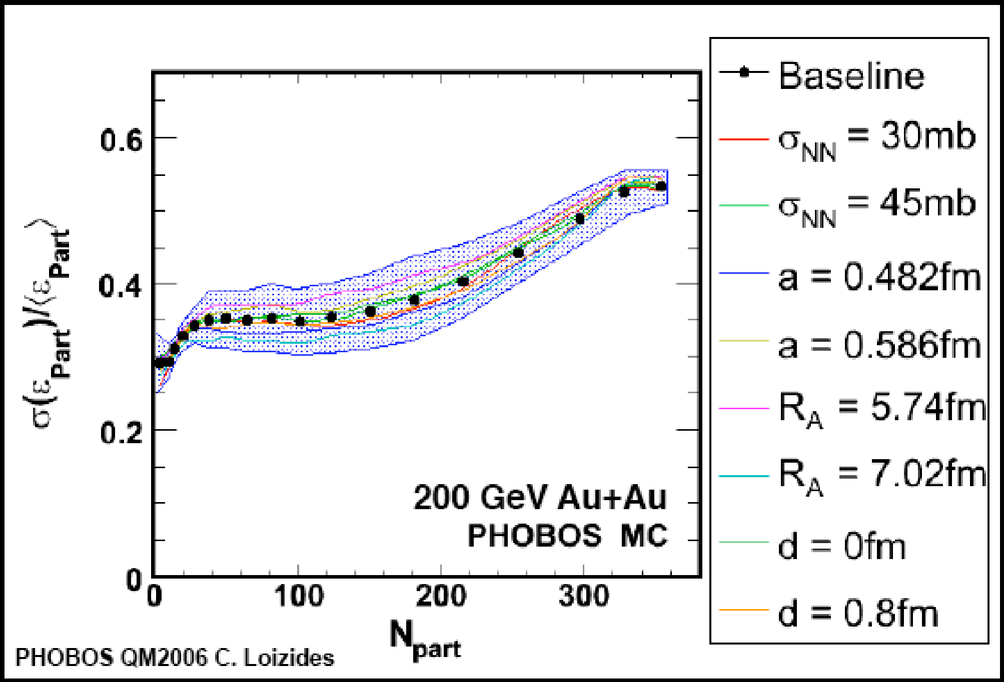
How do we know the Glauber shapes and shape fluctuations are real?

Measure them directly!
If $v_2 \propto \epsilon$, then:

$$\frac{\sigma(v_2)}{<v_2>} = \frac{\sigma(\epsilon)}{<\epsilon>}$$

i.e. relative fluctuations in v_2 should be determined by relative fluctuations in ϵ

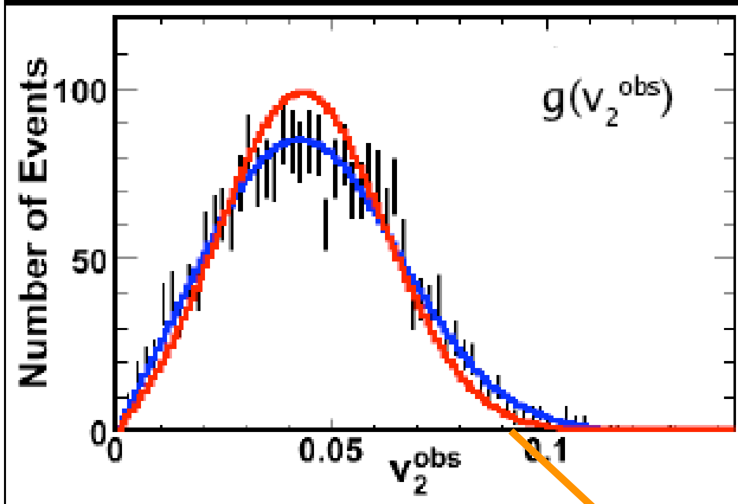
ϵ_{part} Fluctuations in Glauber MC



Large event-by-event variation of ϵ_{part} (~40%)

Robust against variation of Glauber MC parameters

Extracting v_2 Fluctuations



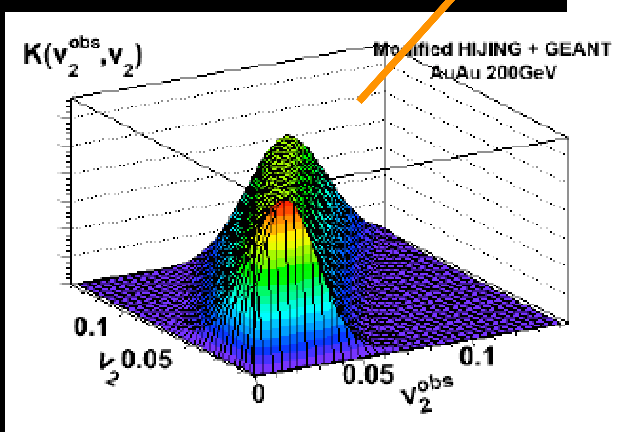
Measured

PHOBOS: event-by-event fit of (v_2,ϕ_0) over ~ 4π

$$g(v_2^{obs}) = \int_0^1 K(v_2^{obs}, v_2)\, f(v_2)\, dv_2$$

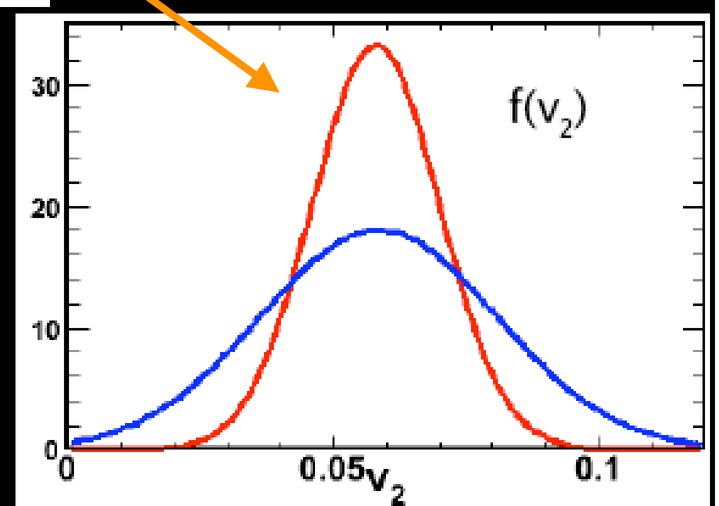
Measured

Constructed from MC

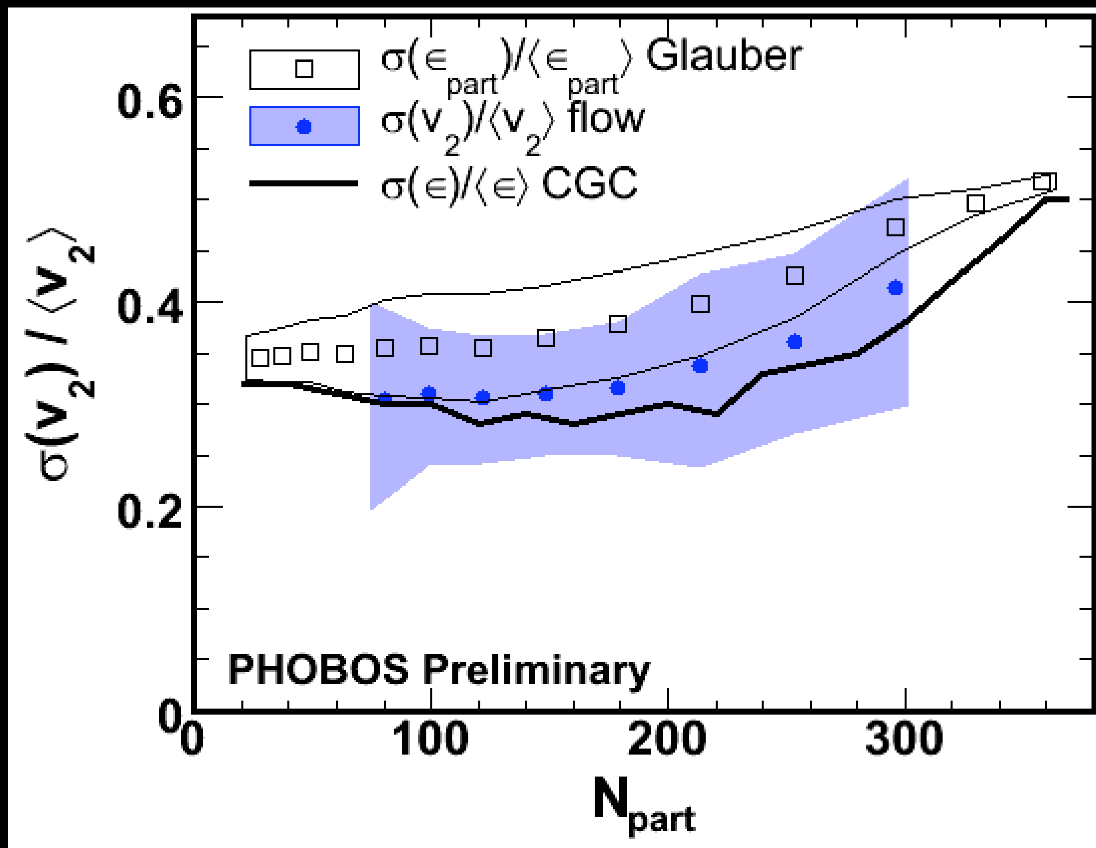


Correction function

Corrected

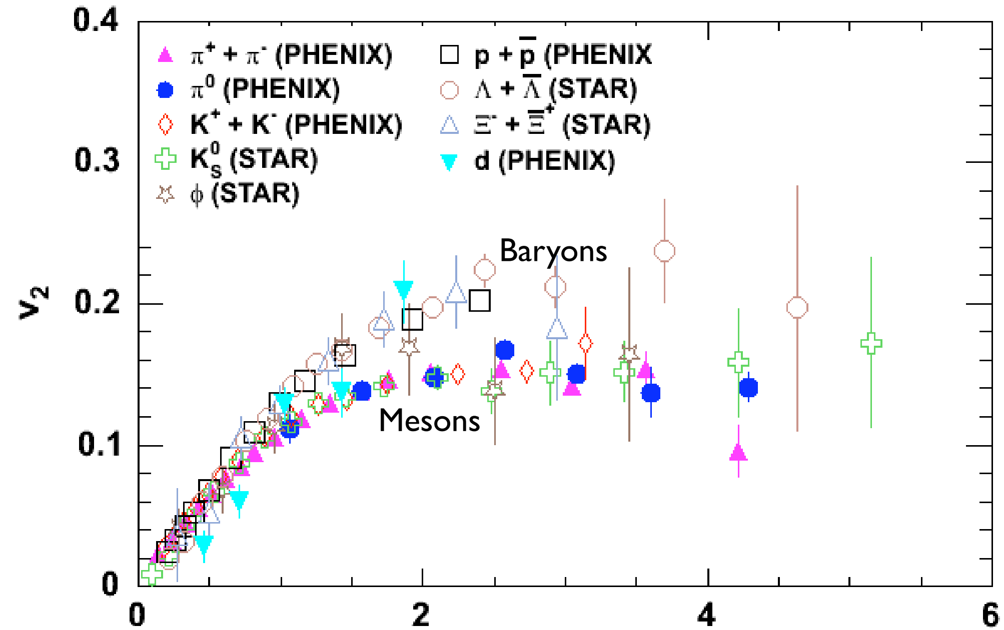


Observed Elliptic Flow Fluctuations



What is the nature of this matter?

Plot from M. Isaah
CIPANP '06

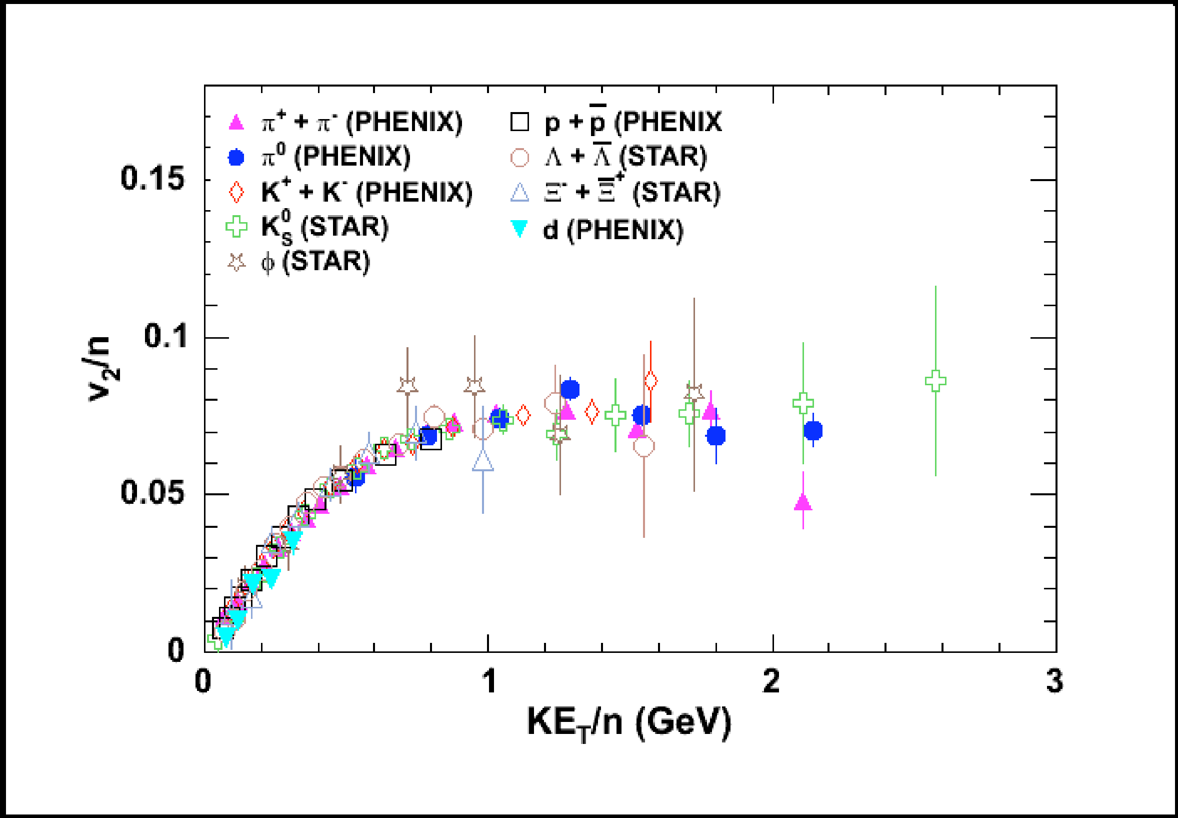


$KE_T = \sqrt{p_T^2 + m_0^2} - m_0$ (GeV)

Elliptic flow as a function of "transverse kinetic energy"

What is the nature of this matter?

Plot from M. Isaah
CIPANP '06



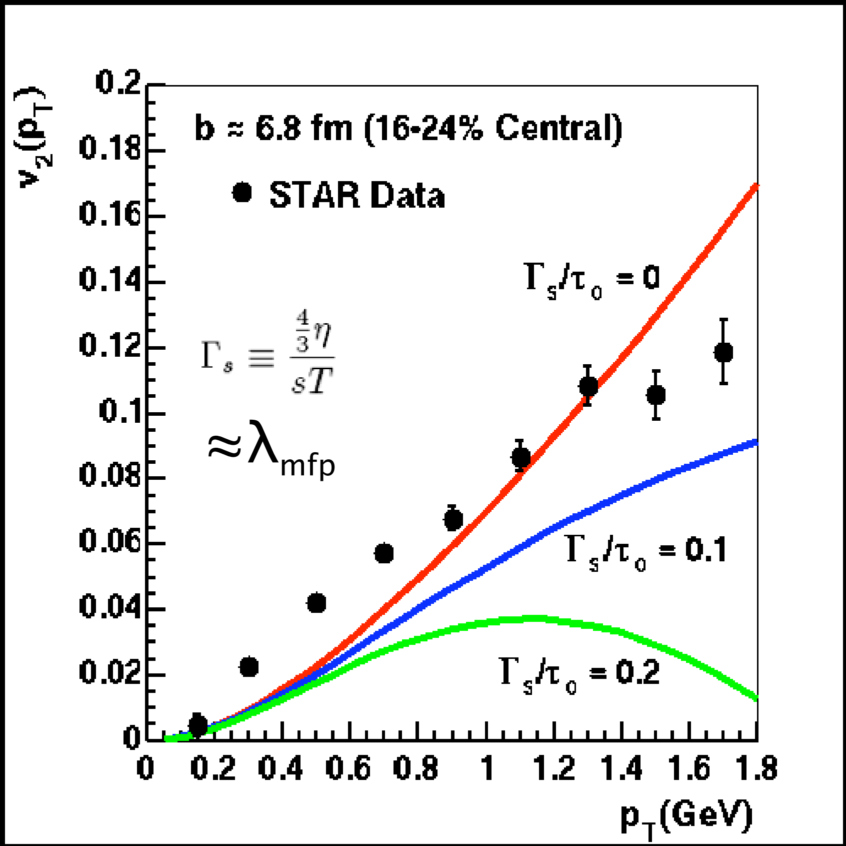
Baryons: n=3
Mesons: n=2

Flow mechanism "knows" about quarks

But: detailed microscopic dynamics that lead to "quark-number scaling" are not yet understood

How well does our fluid flow?

D. Teaney, 2003: Estimated viscous corrections to ideal hydro calculations

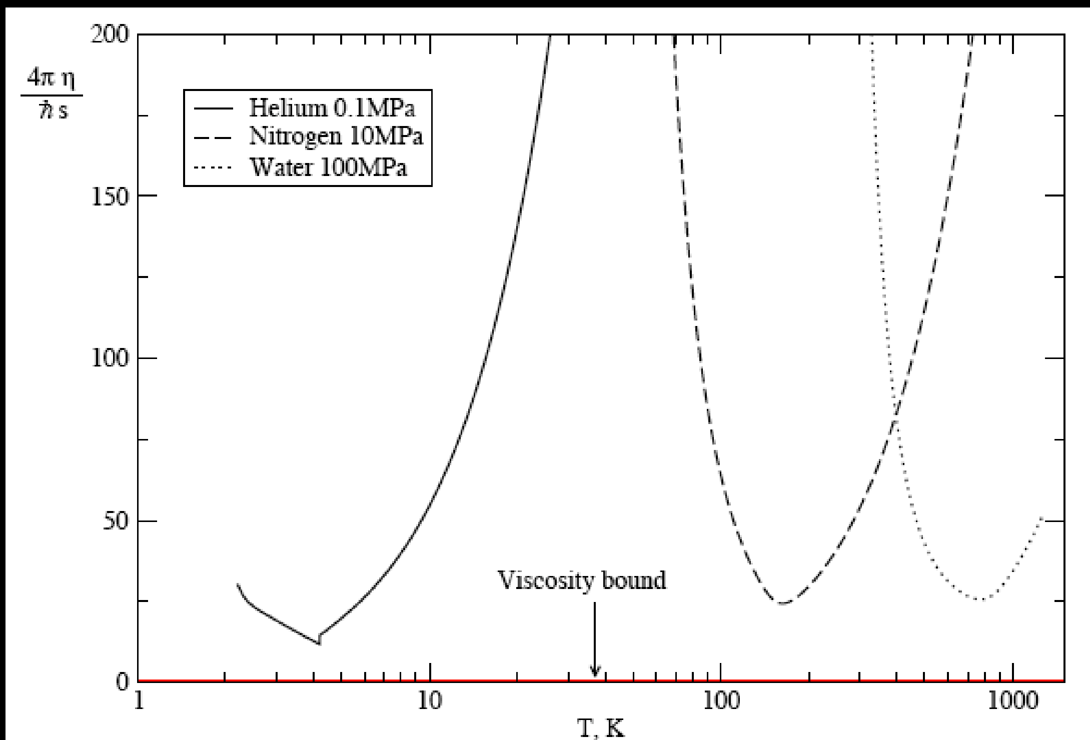


Comparing shear viscosity/entropy density, RHIC matter is **100× better** fluid than water

Large elliptic flow implies very small viscosity ⇔ small λ_{mfp} ⇔ strong coupling

Perfect liquid at RHIC?

Data from RHIC suggest that $\eta/s < 0.2$ (possibly < 0.1)



⟵ RHIC @ $4\pi\ \eta/s \approx 1$

How can one calculate η/s?

How can one calculate η/s?

Perturbative QCD gives $\eta/s \approx 1$

Liquid → vanishing λ_{mfp} → strong coupling
pQCD is the right theory, but wrong approximation

Lattice QCD: hard (see later)

String theory:

Shear Viscosity of Strongly Coupled $\mathcal{N} = 4$ Supersymmetric Yang-Mills Plasma

G. Policastro[1,2], D.T. Son[3,4], and A.O. Starinets[1]
[1] *Department of Physics, New York University, New York, New York 10003*
[2] *Scuola Normale Superiore, Piazza dei Cavalieri 7, 56100, Pisa, Italy*
[3] *Physics Department, Columbia University, New York, New York 10027*
[4] *RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973*
(April 2001)

String Theory to the Rescue?

Using the anti–de Sitter/conformal field theory correspondence, we relate the shear viscosity η of the finite-temperature $\mathcal{N} = 4$ supersymmetric Yang-Mills theory in the large N, strong-coupling regime with the absorption cross section of low-energy gravitons by a near-extremal black three-brane. We show that in the limit of zero frequency this cross section coincides with the area of the horizon. From this result we find $\eta = \frac{\pi}{8} N^2 T^3$. We conjecture that for finite 't Hooft coupling $g_{\mathrm{YM}}^2 N$ the shear viscosity is $\eta = f(g_{\mathrm{YM}}^2 N) N^2 T^3$, where $f(x)$ is a monotonic function that decreases from $\mathcal{O}(x^{-2} \ln^{-1}(1/x))$ at small x to $\pi/8$ when $x \to \infty$.

The ratio of shear viscosity to volume density of entropy can be used to characterize how close a given fluid is to being perfect. Using string theory methods, we show that this ratio is equal to a universal value of $\hbar/4\pi k_B$ for a large class of strongly interacting quantum field theories whose dual description involves black holes in anti–de Sitter space. We provide evidence that this value may serve as a lower bound for a wide class of systems, thus suggesting that black hole horizons are dual to the most ideal fluids.

AdS/CFT correspondence

Maldacena (1997), Gubser, Klebanov,Polyakov; Witten (1998)

$\mathcal{N}$ = 4 Super-Yang-Mills theory in 4d with SU(N_C)	⟺	A string theory in 5d AdS
Finite temperature	⟺	Black hole in AdS_5
Large N_C and strong coupling limit	⟺	Classical gravity limit

YM observables at infinite N_C and infinite coupling can be computed using classical gravity

Apply to both dynamical and thermodynamic observables.

Viscosity Bound

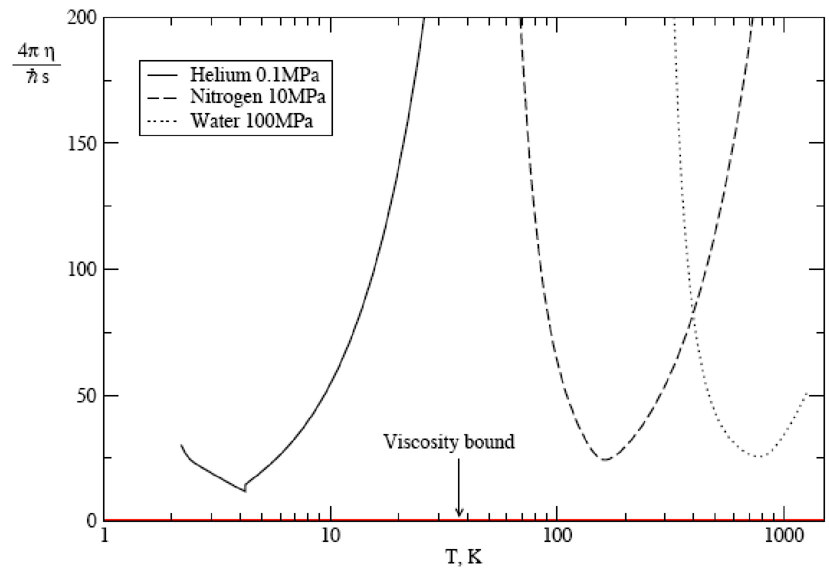


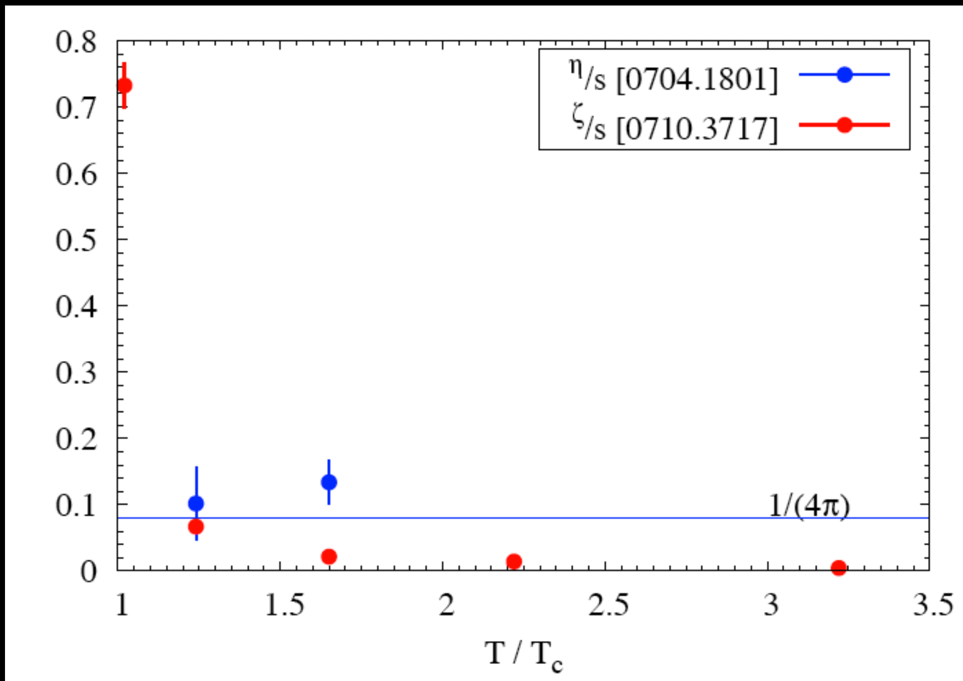
Figure 2: The viscosity-entropy ratio for some common substances: helium, nitrogen and water. The ratio is always substantially larger than its value in theories with gravity duals, represented by the horizontal line marked "viscosity bound."

All field theories with a gravity dual were found to have
$\eta/s > 1/4\pi$

Universal bound?

"Black hole horizons (in 5-d anti-de-Sitter space...) are dual to the most ideal liquids"

Lattice QCD Calculation of η/s

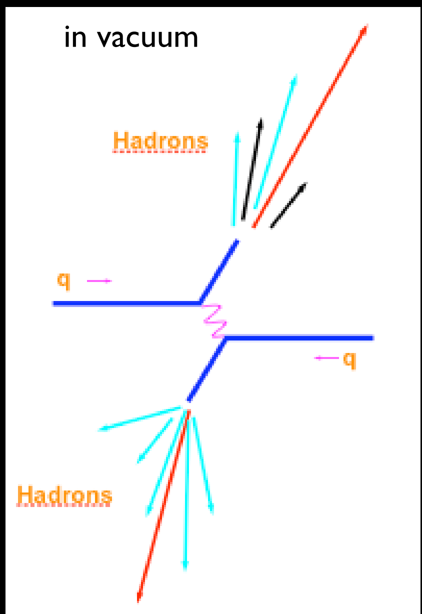


Harvey Meyer (MIT)

Lattice calculations agree with small shear viscosity for QCD plasma

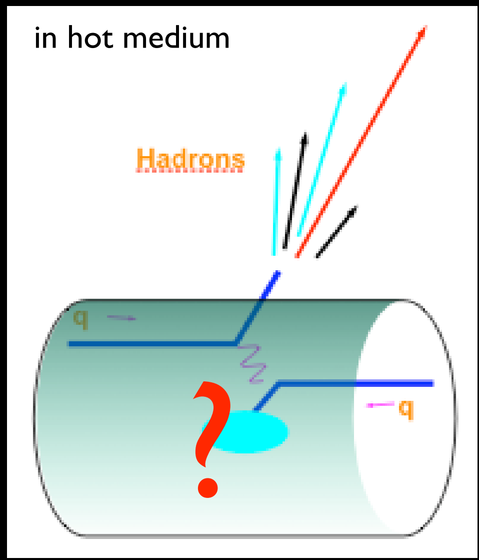
Require bold extrapolations to extract η

What else can one learn about the medium?

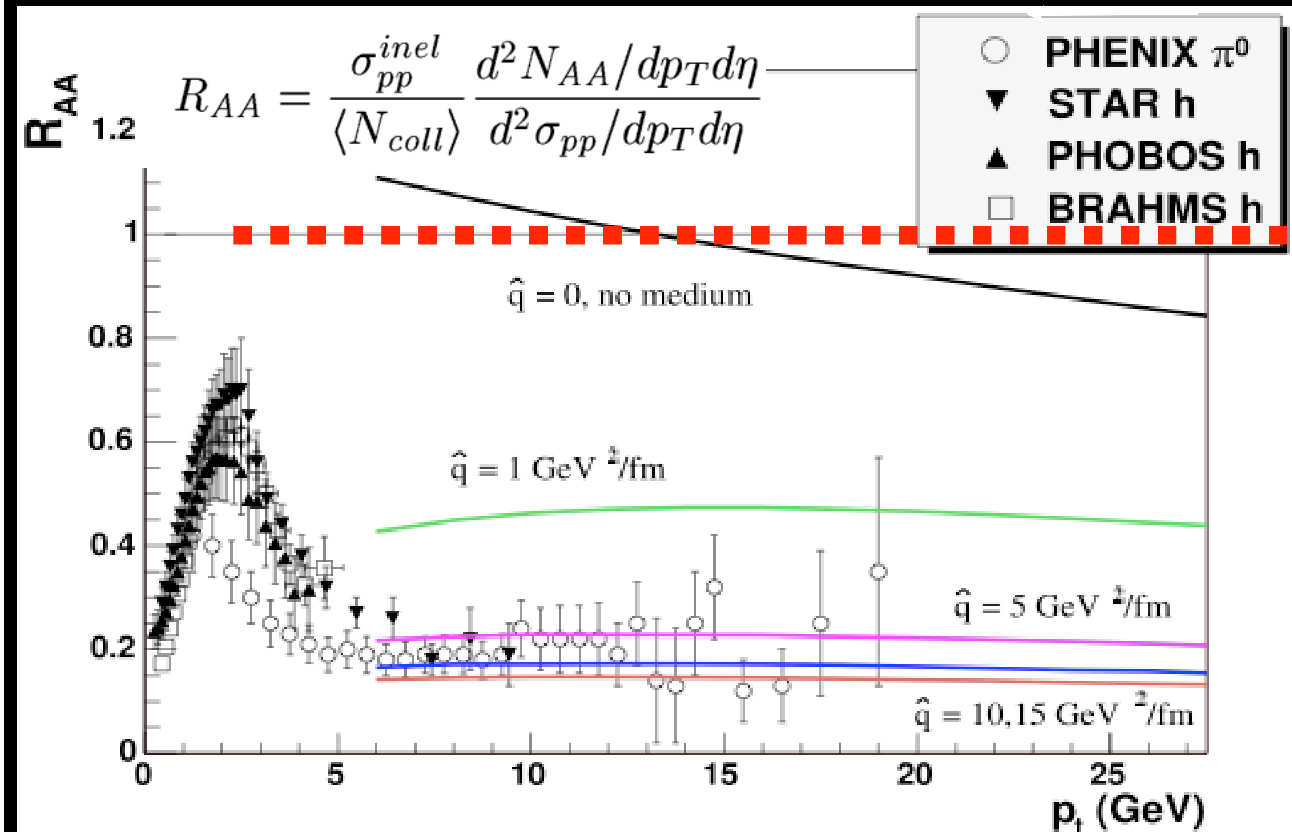


Hadrons at high p_T (>>T) originate from "fragmentation" of high p_T quarks (or gluons)

What happens when high p_T partons traverse the medium?



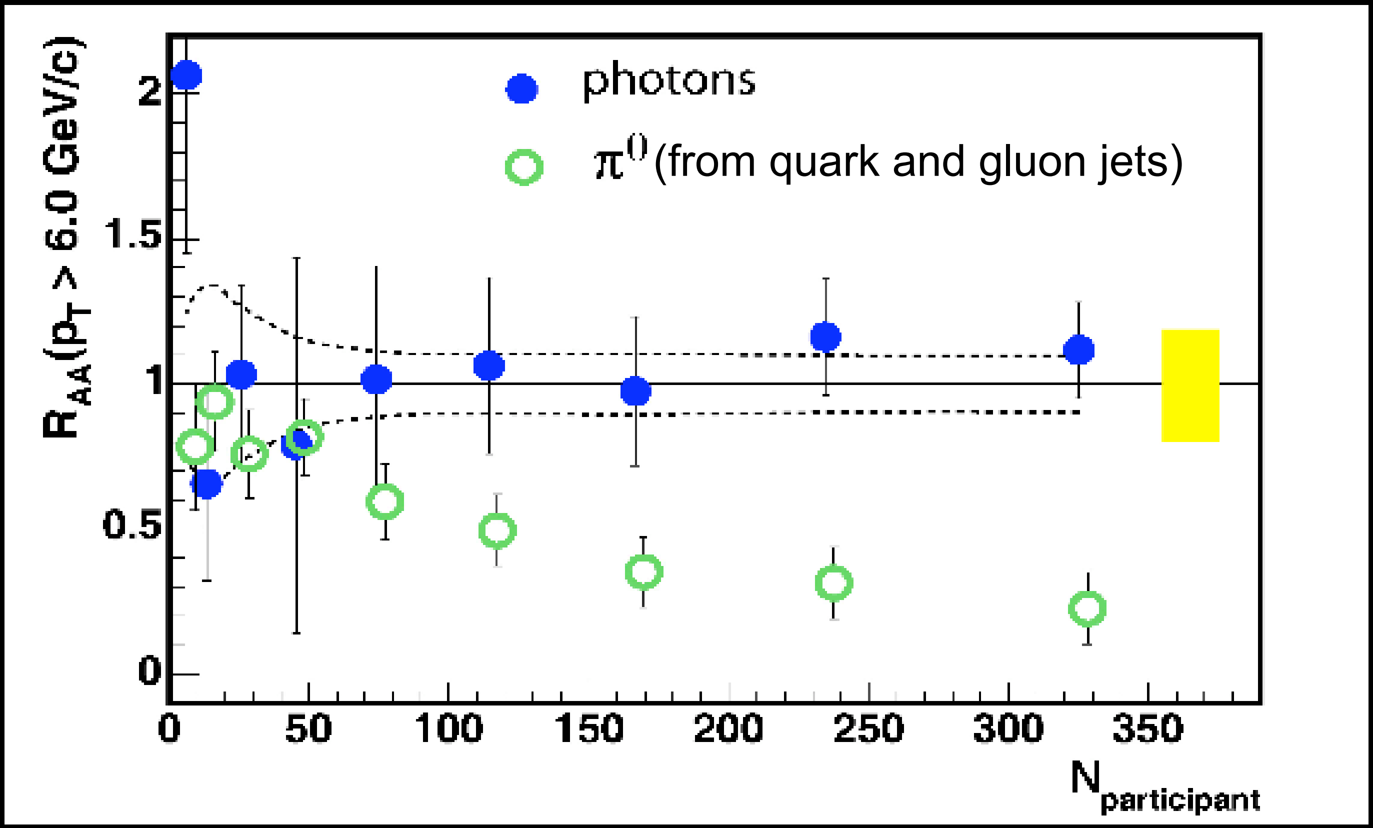
The Medium is "black": Jet Quenching



Expected yield in Au+Au, relative to p+p

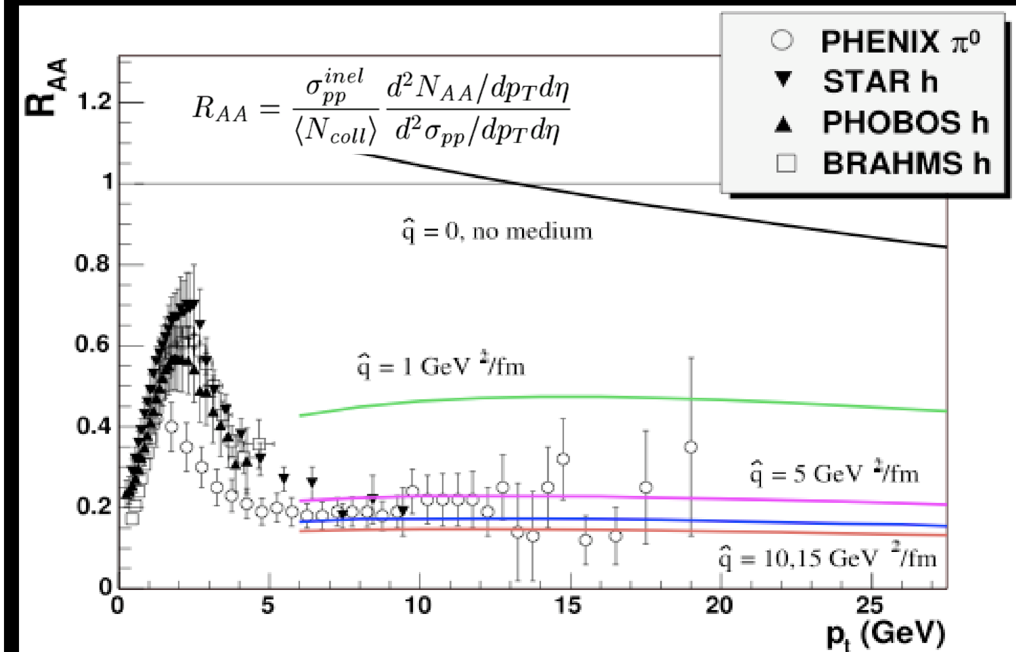
Observe a suppression ("jet quenching") by factor 5-6!

N_{coll}-Scaling ?



High pT photons (which don't suffer energy loss in the medium) are produced with the expected rate relative to p+p

The Medium is “black”: Jet Quenching



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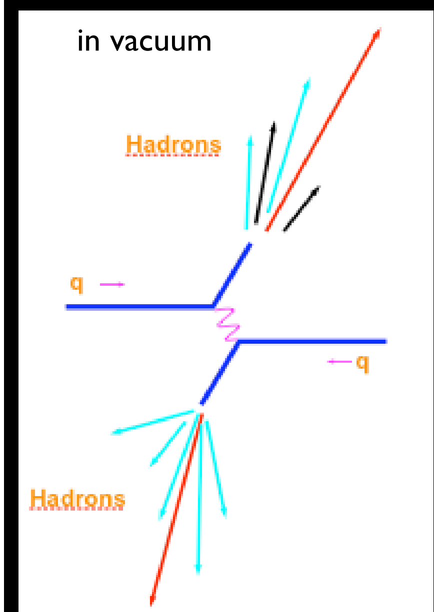
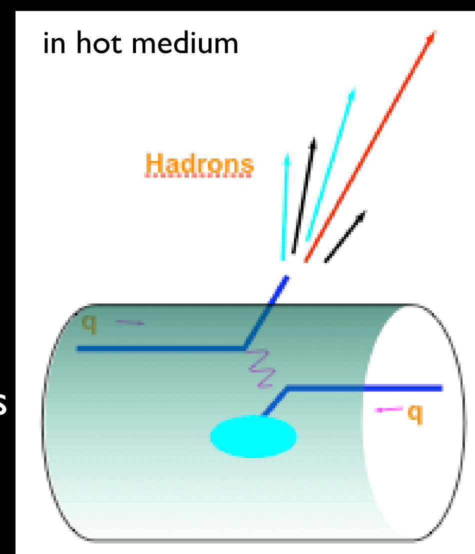
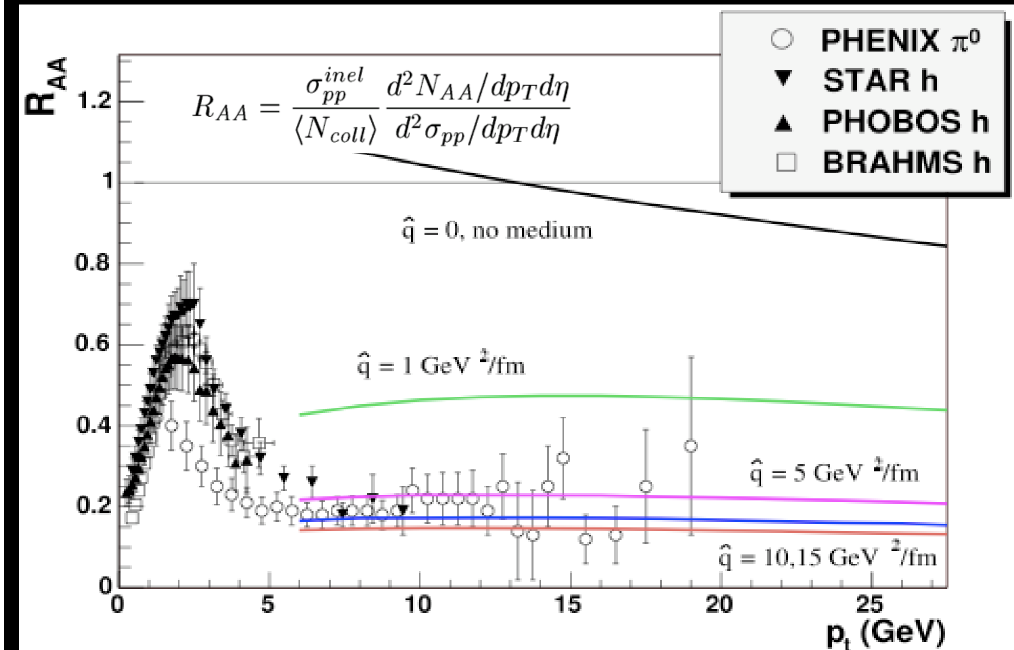


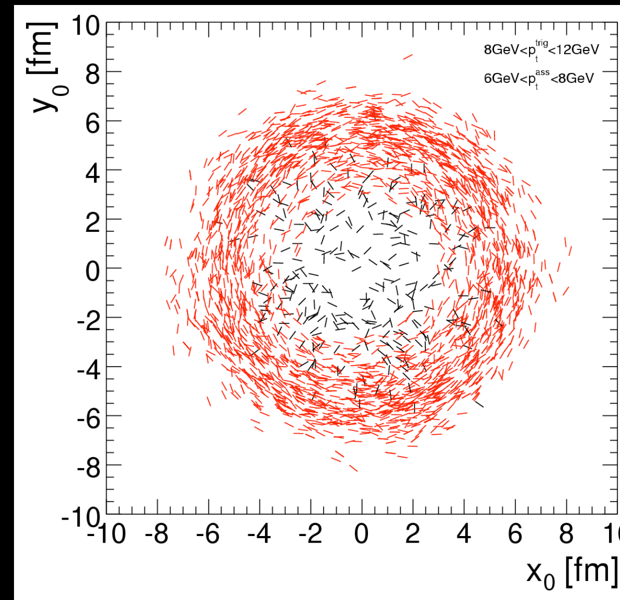
Hadrons at high p_T originate from “fragmentation” of high p_T quarks (or gluons)

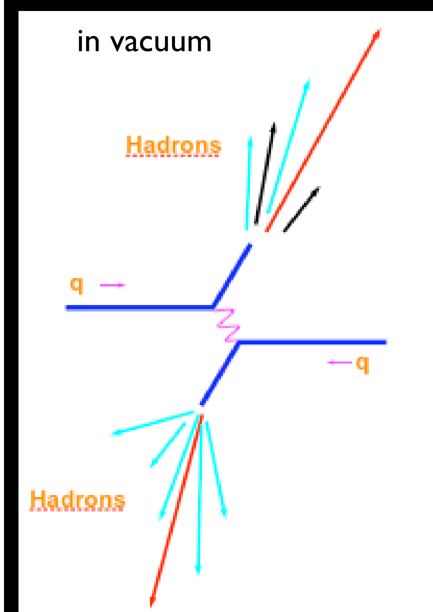
In medium, only “surface radiation” escapes. Partons traversing medium are “swallowed” by medium.



The Medium is "black": Jet Quenching







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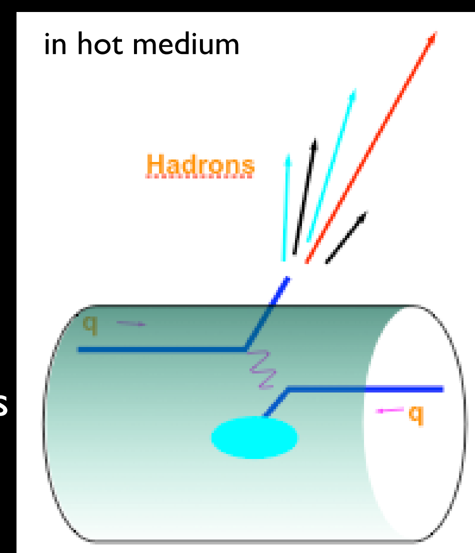
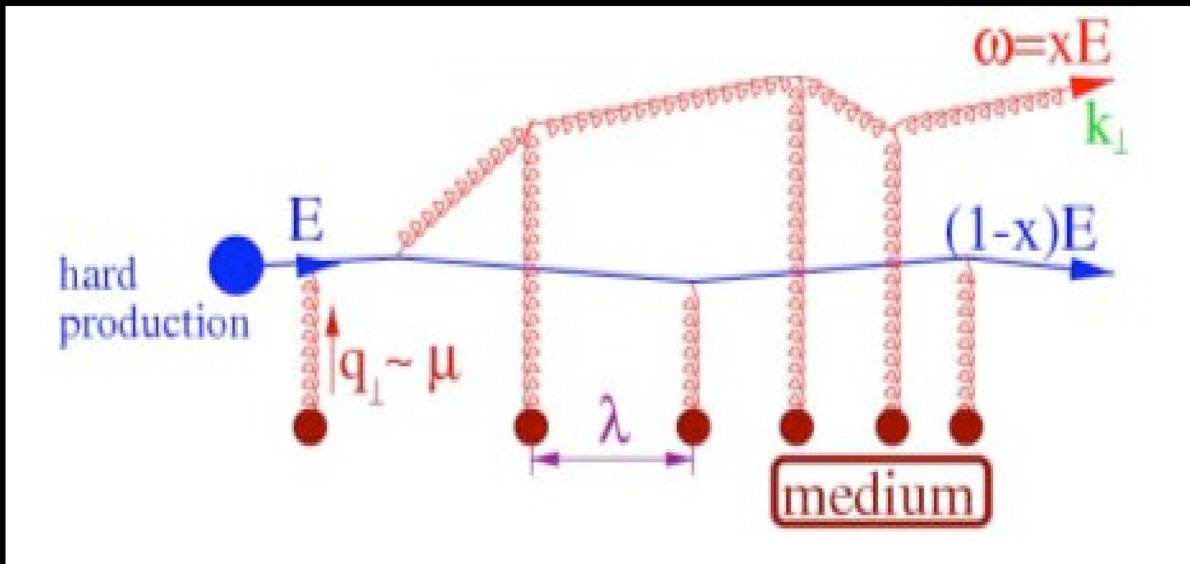


Gluon Bremsstrahlung



$$\Delta E \approx -\frac{\alpha_S}{2\pi} N_C \, \hat{q} \, L^2$$

k_T kick per unit path length

pQCD calculations give $\hat{q} \approx$ 1-3 GeV^2/fm

Energy Loss in String Theory

$\hat{q}$ of $\mathcal{N}$=4 SYM theory

BDMPS transport coefficient reads: $\lambda = g_{YM}^2 N_c$

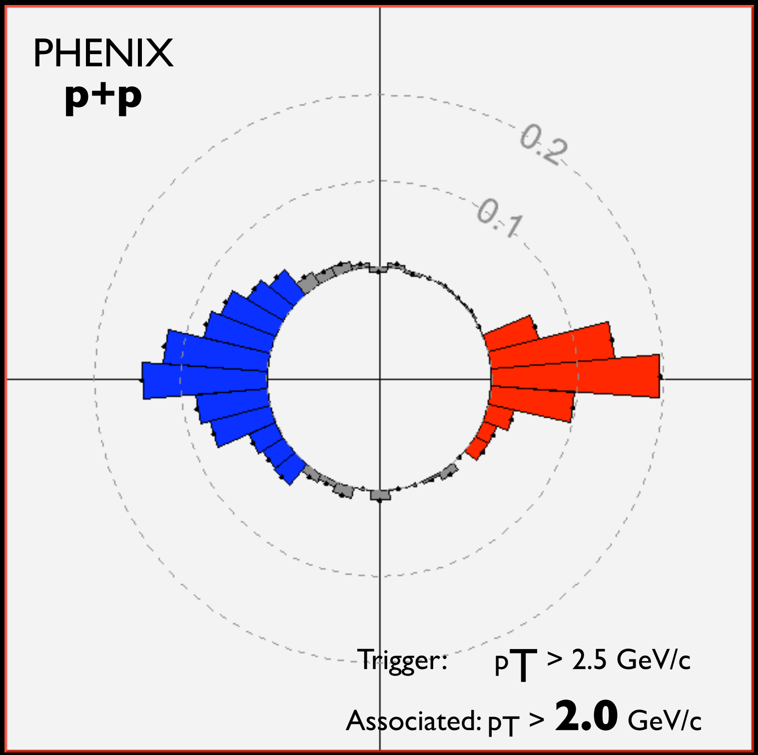
$$\hat{q}_{SYM} = \frac{\pi^{3/2}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3 \approx 26.69\sqrt{\alpha_{SYM} N_c}T^3$$

- It is not proportional to number of scattering centers
- Take: $N_C = 3, \alpha_s = \frac{1}{2}, T = 300\ MeV$

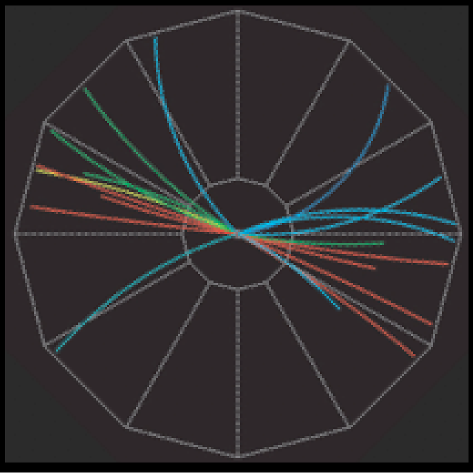
$$\hat{q}_{SYM} = 4.5\ \mathrm{GeV}^2/\mathrm{fm}.$$

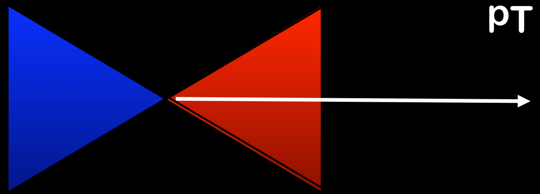
- Experimental estimates: 5-15 GeV^2/fm

Jets and Angular Correlations



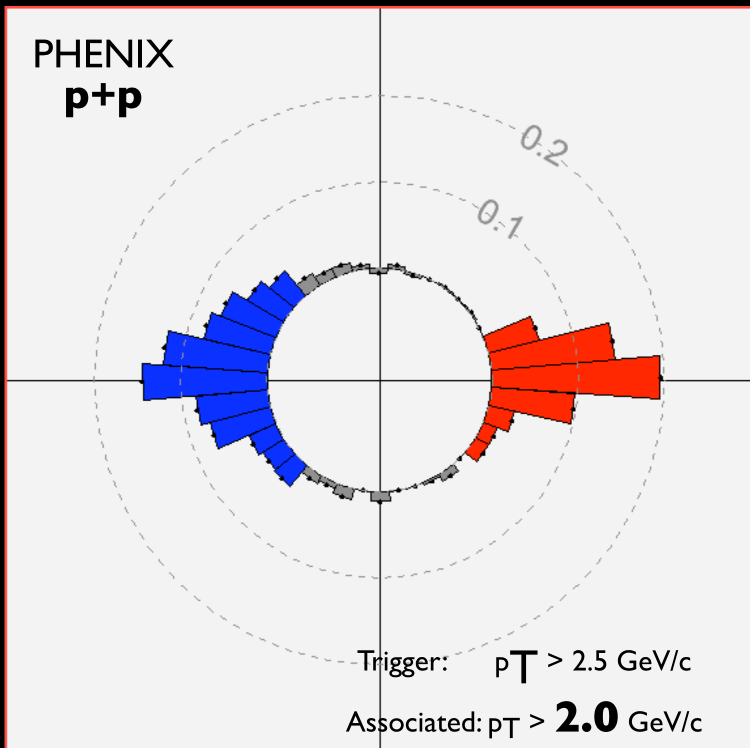
STAR
200 GeV p+p
p_T > 2.0 GeV/c

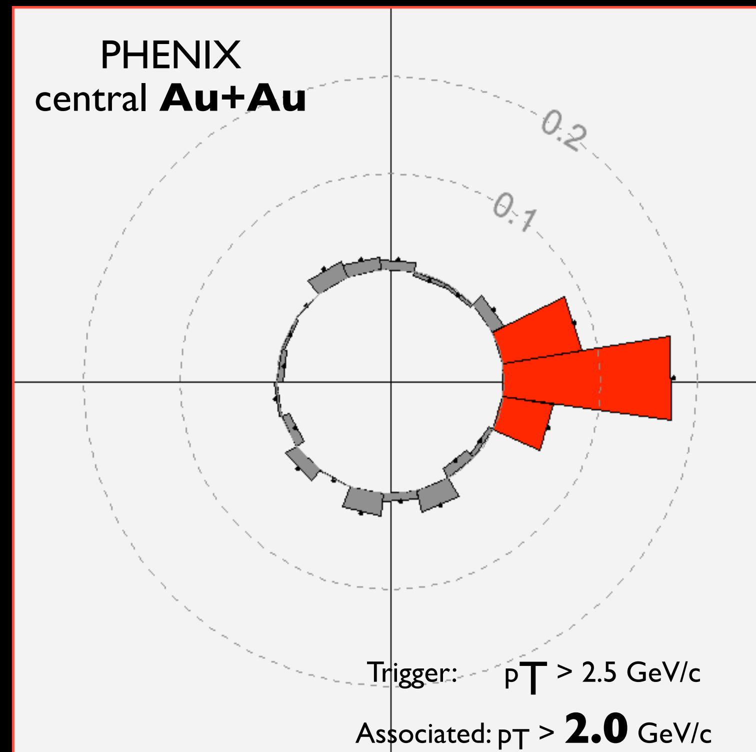




Plot angle of associated particles above p_T threshold relative to trigger

Jets and Angular Correlations





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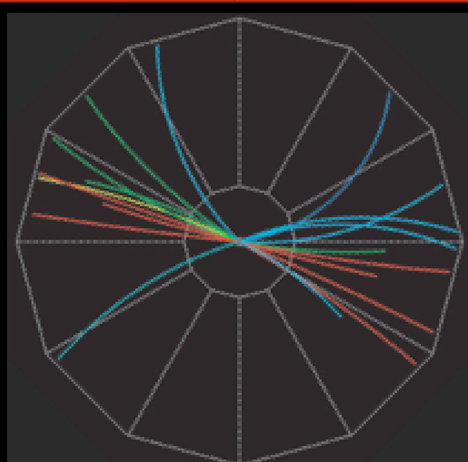
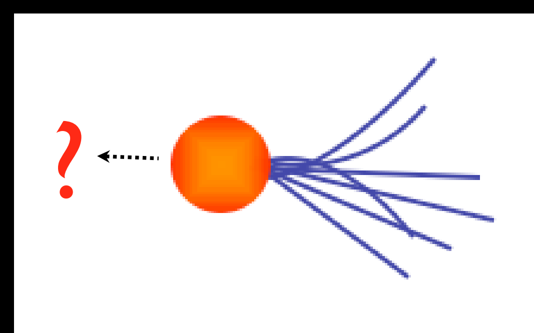
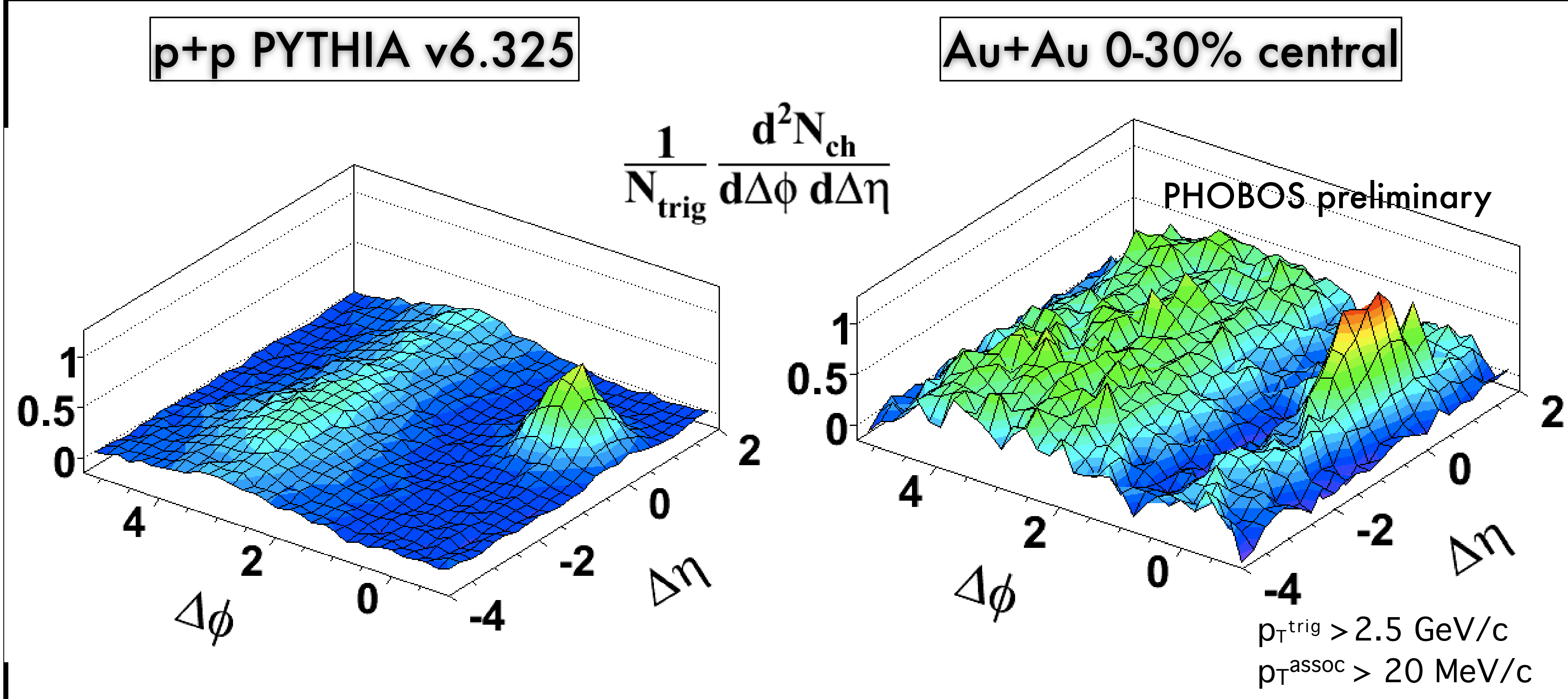




[redacted]

Where does the energy go?



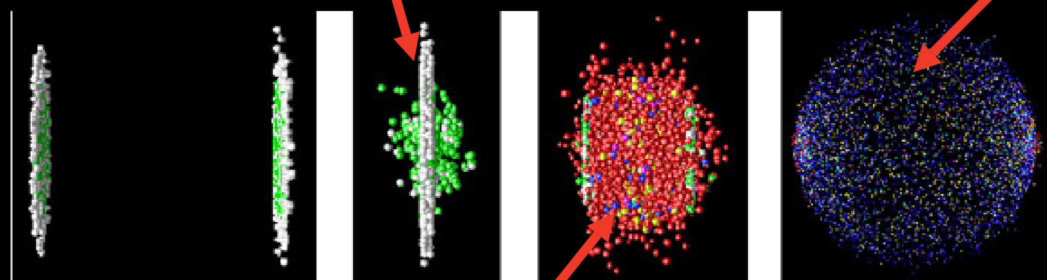
"Lost" energy found in quasi-thermal low p_T particles, even far in rapidity from trigger particle

Initial Collisions

- Hard Scattering takes place [direct γ]
- High p_T partons are produced [d+Au]
- Overall Entropy defined [$dN/d\eta$]
- Geometrical asymmetry [Geometry]

Hadronization

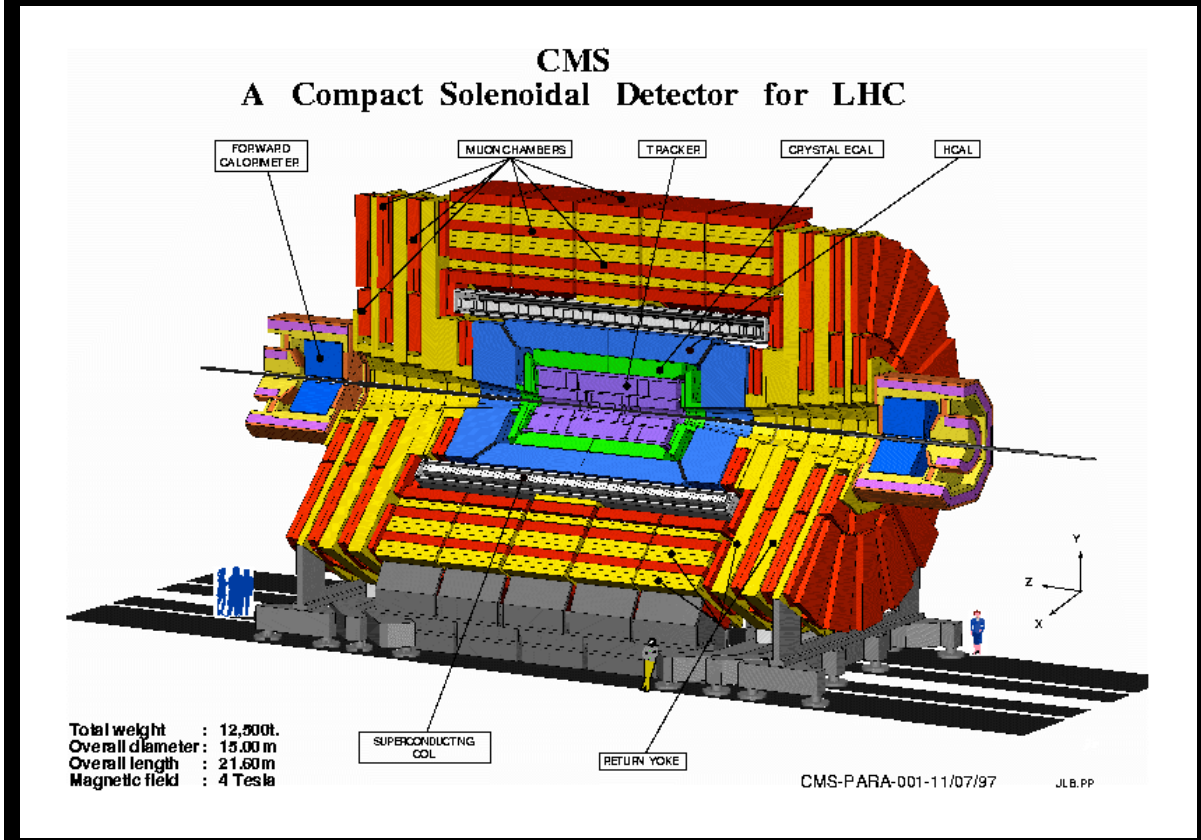
- Recombination from quark soup [proton-non suppression, quark-scaling of v_2]
- Global statistical hadron formation at T_{ch} = 170 MeV [particle ratios]
- Radial expansion with β_T ~ 0.6c [PID spectra]
- Particle emission after 10fm/c for few fm/c [HBT]



Early Stage (~ few fm/c)

- High Density (~ 5 GeV/fm^3) [$dN/d\eta$, high p_T suppression]
- Local thermal equilibration[Elliptic Flow v_2]
- Pressure driven expansion [Elliptic Flow v_2, HBT]
- Opaque for fast partons [Back-to-Back jets]

Heavy Ions at LHC



CMS: Big experiment

2600 Physicists
$500M construction
Designed for p+p

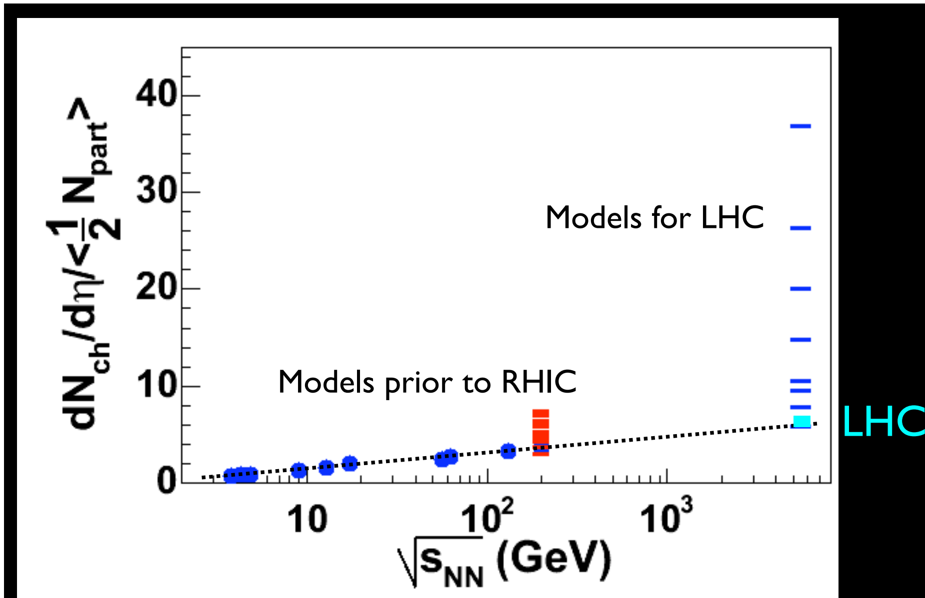
12500 tons
1 GHz interaction rate
1 TByte/sec data flow
World's largest magnet (2.6 GJ)
200 m^2 Si Detectors

LHC Tunnel will close Sep 1 2007

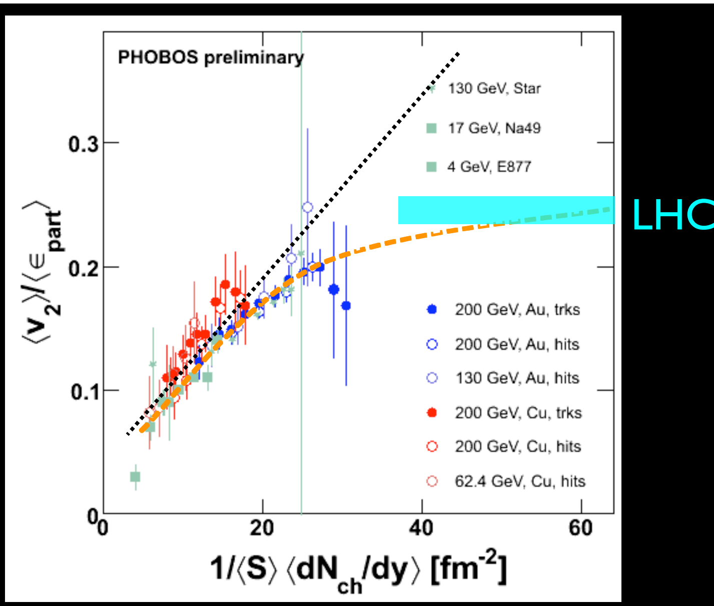
<u>Heavy ions at LHC</u>

Unprecedented change in initial conditions

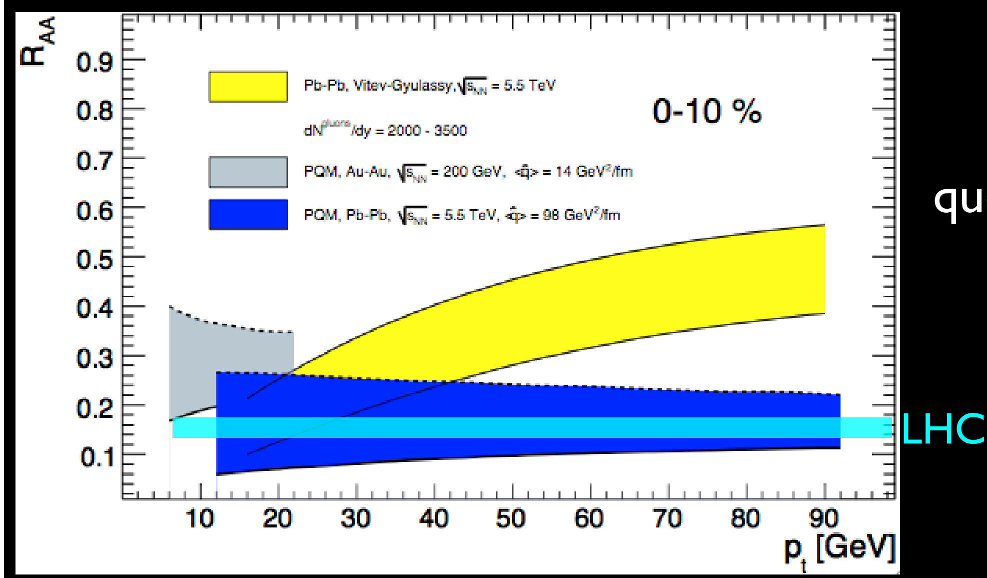
Qualitatively new probes of the medium, e.g. Jets



1 Day: Multiplicity ⇒ Initial Density



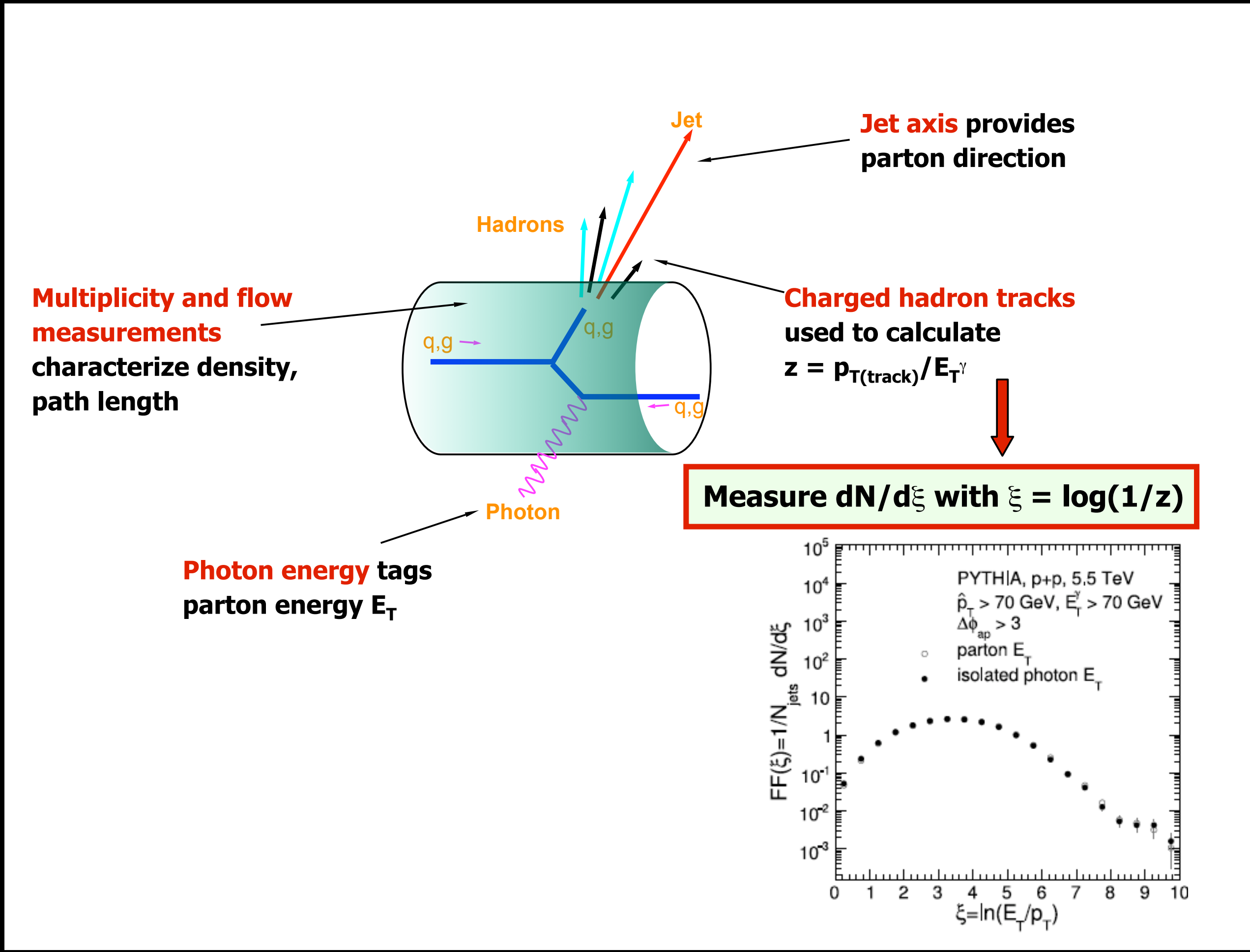
1 Week: Does elliptic flow saturate, indicating equilibrium?



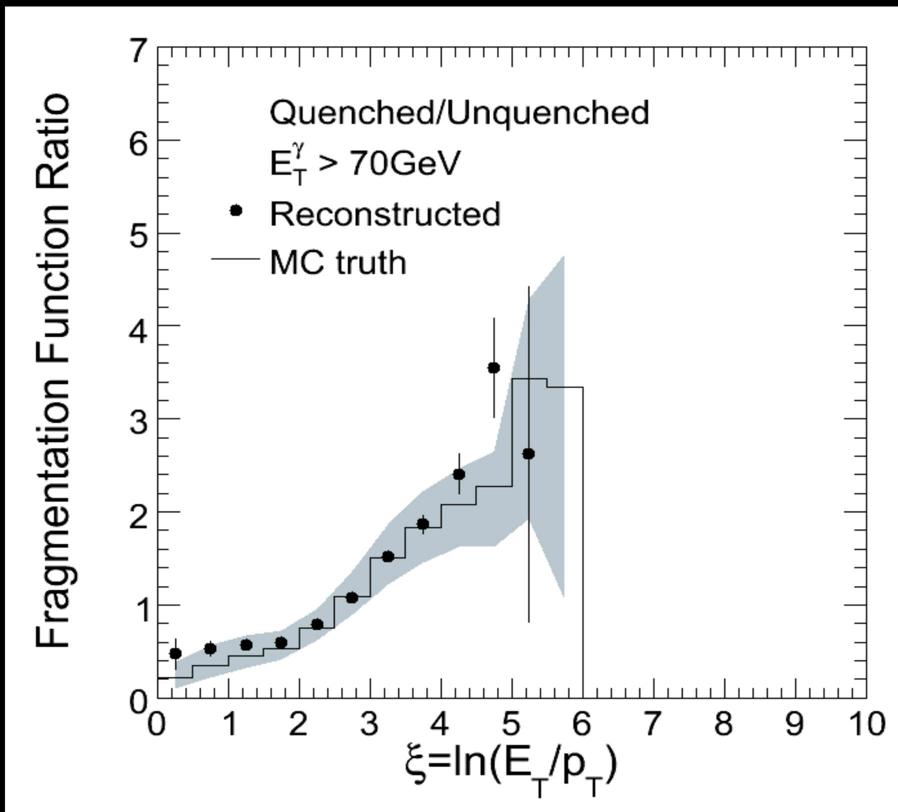
1 Month: What is the jet quenching parameter? Is the medium "black"?

Once we have these qualitative answers:
→ program of precision measurements of medium properties

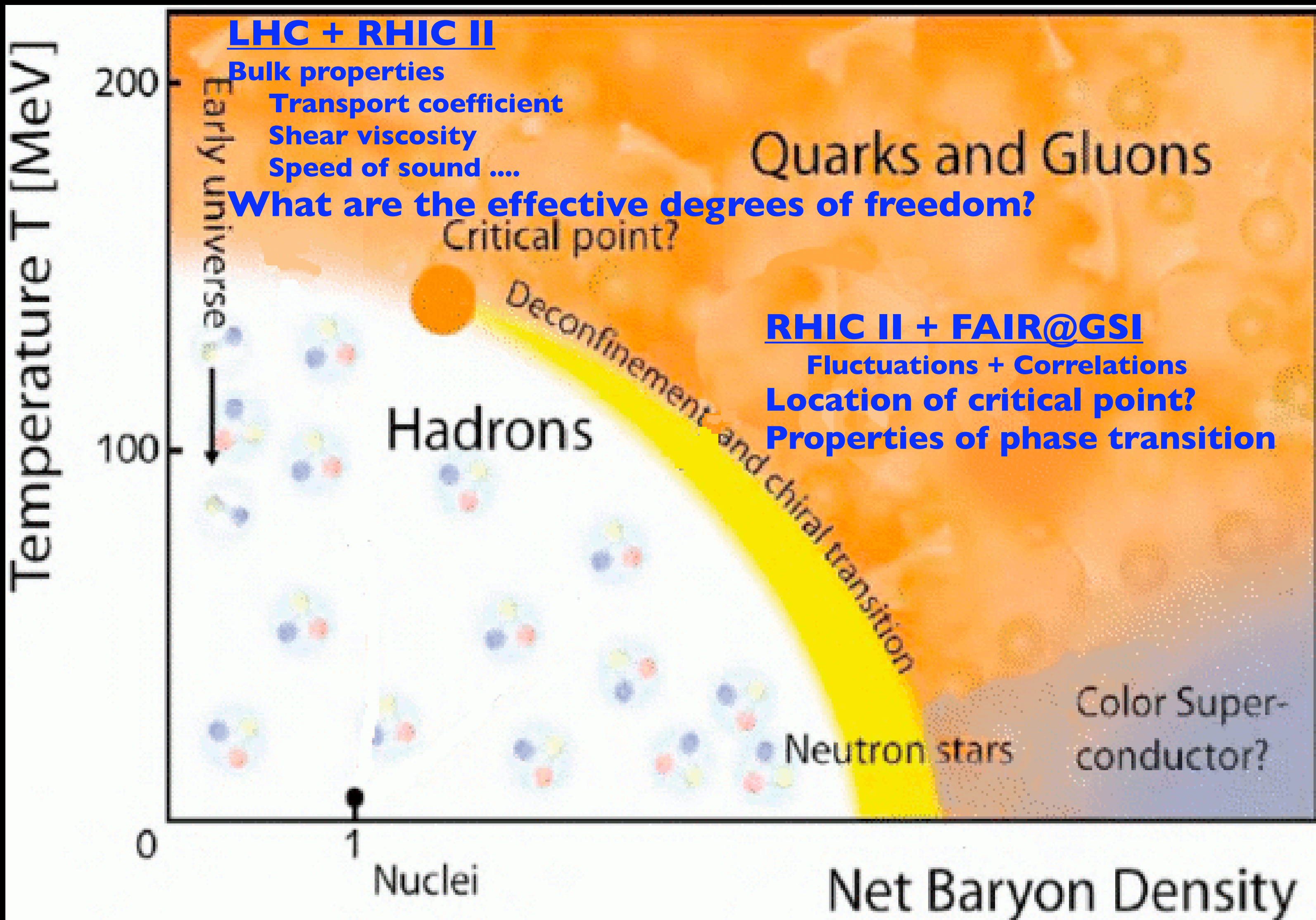
Measuring energy loss at LHC



Higher collision energy allows to find jets and photons at high p_T (>70 GeV/c)

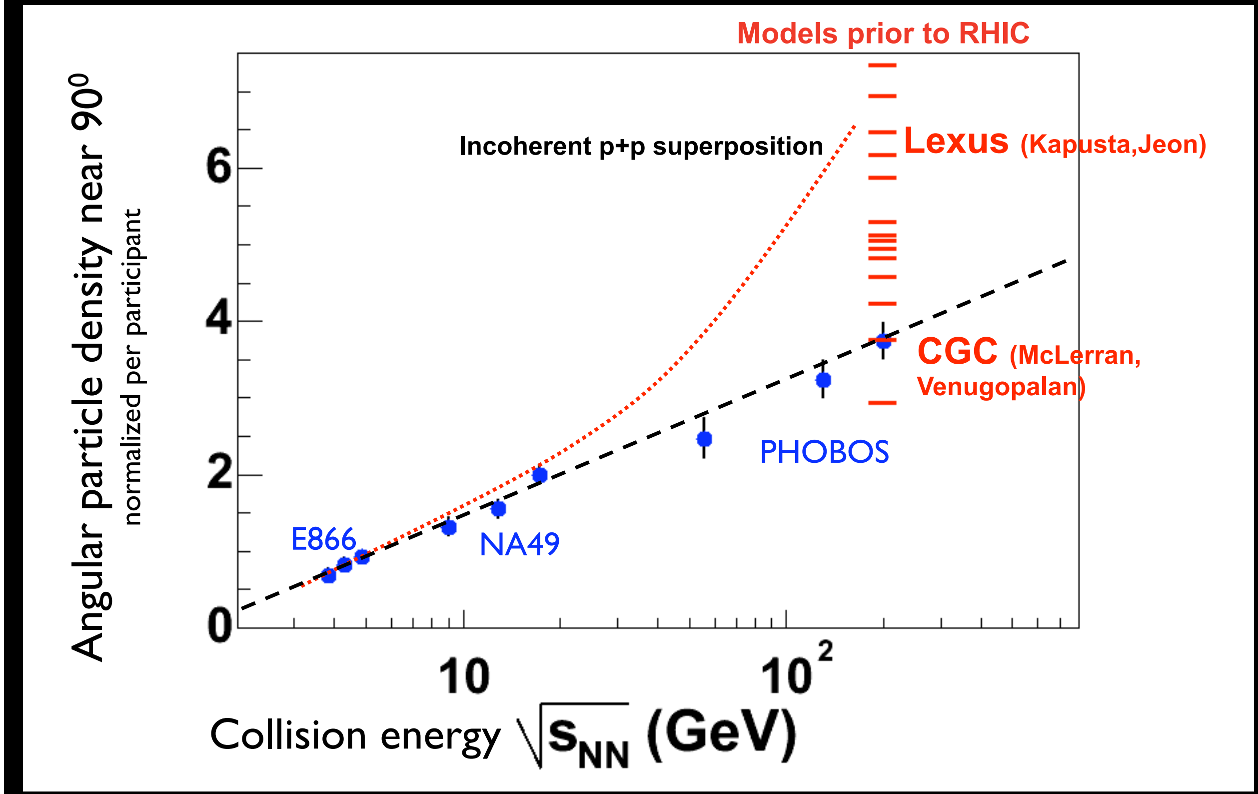


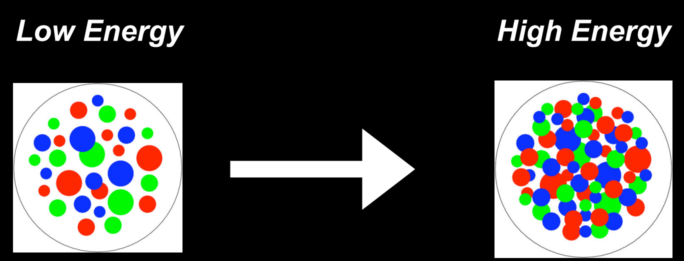
Quenched/Unquenched
E_T^γ > 70GeV
Reconstructed
MC truth
Fragmentation Function Ratio
$\xi=\ln(E_T/p_T)$
0
1
2
3
4
5
6
7
8
9
10



LHC + RHIC II
Bulk properties
Transport coefficient
Shear viscosity
Speed of sound ....
What are the effective degrees of freedom?
RHIC II + FAIR@GSI
Fluctuations + Correlations
Location of critical point?
Properties of phase transition
Quarks and Gluons
Critical point?
Deconfinement and chiral transition
Hadrons
Early universe
Neutron stars
Color Super-conductor?
Temperature T [MeV]
200
100
0
1
Nuclei
Net Baryon Density


See you next week!





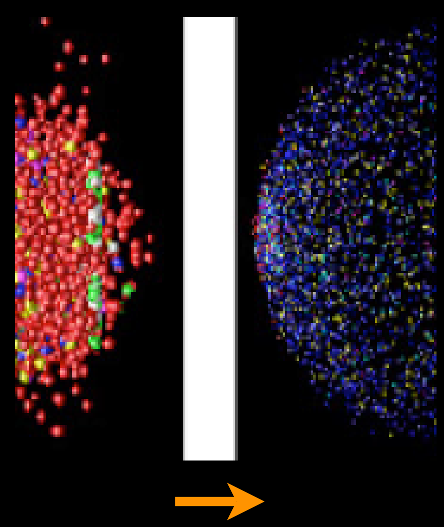
Parton Saturation

Particle production by "liberation" of gluons already present in incoming nuclei

Effective gluon density increases with energy, but saturates when gluons below Q_{sat} overlap in transverse plane

This "Color Glass Condensate" describes nuclei at high energies

Hadronization



Enhancement of Multi-Strange Baryons

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–EP/98–64
22 April 1998

Enhancement of central Λ, Ξ and Ω yields in Pb-Pb collisions at 158 A GeV/c

E. Andersen[3], F. Antinori[6,12], N. Armenise[2], H. Bakke[3], J. Bán[8], D. Barberis[7], H. Beker[6], W. Beusch[6], I.J. Bloodworth[5], J. Böhm[14], R. Caliandro[2], M. Campbell[6], E. Cantatore[6], N. Carrer[12], M.G. Catanesi[2], E. Chesi[6], M. Dameri[7], G. Darbo[7], A. Diaczek[13], D. Di Bari[2], S. Di Liberto[15], B.C. Earl[5], D. Elia[2], D. Evans[5], K. Fanebust[3], R.A. Fini[2], J.C. Fontaine[10], J. Ftáčnik[8], B. Ghidini[2], G. Grella[16], M. Guida[16], E.H.M. Heijne[6], H. Helstrup[4], A.K. Holme[6], D. Huss[10], A. Jacholkowski[2], G.T. Jones[5], P. Jovanovic[5], A. Jusko[8], V.A. Kachanov[17], T. Kachelhoffer[18], J.B. Kinson[5], A. Kirk[5], W. Klempt[6], B.T.H. Knudsen[3], K. Knudson[6], I. Králik[8], J.C. Lassalle[6], V. Lenti[2], R. Lietava[8], R.A. Loconsole[2], G. Løvhøiden[6,11], M. Lupták[8], V. Mack[10], V. Manzari[2], P. Martinengo[6], M.A. Mazzoni[15], F. Meddi[15], A. Michalon[18], M.E. Michalon-Mentzer[18], P. Middelkamp[6], M. Morando[12], M.T. Muciaccia[2], E. Nappi[2], F. Navach[2], P.I. Norman[5], B. Osculati[7], B. Pastirčák[8], F. Pellegrini[12], K. Piška[14], F. Posa[2], E. Quercigh[6], R.A. Ricci[9], G. Romano[16], G. Rosa[16], L. Rossi[7], H. Rotscheidt[6], K. Šafařík[6], S. Saladino[2], C. Salvo[7], L. Šándor[6,8], T. Scognetti[2], G. Segato[12], M. Sené[13], R. Sené[13], S. Simone[2], A. Singovski[17], W. Snoeys[6], P. Staroba[14], S. Szafran[13], M. Thompson[5], T.F. Thorsteinsen[3], G. Tomasicchio[2], G.D. Torrieri[5], T.S. Tveter[11], J. Urbán[8], G. Vassiliadis[1], M. Venables[5], O. Villalobos Baillie[5], T. Virgili[16], A. Volte[13], M.F. Votruba[5] and P. Závada[14]

Abstract

Λ, Ξ and Ω yields and transverse mass spectra have been measured at central rapidity in Pb-Pb and p-Pb collisions at 158 A GeV/c. The yields in Pb-Pb interactions are presented as a function of the collision centrality and compared with those obtained from p-Pb collisions. Strangeness enhancement is observed which increases with centrality and with the strangeness content of the hyperon.

To be submitted to Physics Letters B

1) Nuclear Physics Department, Athens University, Athens, Greece
2) Dipartimento I.A. di Fisica dell'Università e del Politecnico di Bari and Sezione INFN, Bari, Italy
3) Fysisk institutt, Universitetet i Bergen, Bergen, Norway
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5) University of Birmingham, Birmingham, UK
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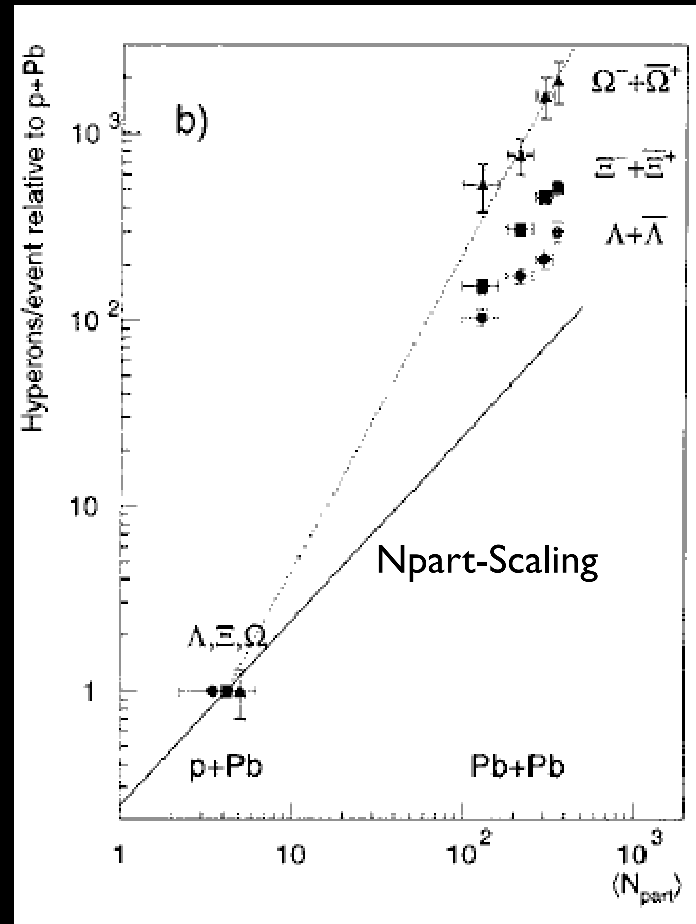
8) Institute of Experimental Physics, Košice, Slovakia
9) INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy
10) GRPHE, Université de Haute Alsace, Mulhouse, France
11) Fysisk institutt, Universitetet i Oslo, Oslo, Norway
12) Dipartimento di Fisica dell'Università and Sezione INFN, Padua, Italy
13) Collège de France and IN2P3, Paris, France
14) Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic
15) Dipartimento di Fisica dell'Università "La Sapienza" and Sezione INFN, Rome, Italy
16) Dipartimento di Scienze Fisiche "E.R. Caianiello" dell'Università and INFN, Salerno, Italy
17) Institute of High Energy Physics, Protvino, Russia
18) Centre de Recherches Nucléaires, Strasbourg, France



Large Enhancement for e.g. Ω/participant, relative to p +Pb

Spectrum of Produced Hadrons

Temperature

Chemical Potential

$$\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^3} \int \mathrm{d}^3\mathrm{p} \left[\mathrm{e}^{\sqrt{\mathrm{p}^2+m_j^2}/T + \boldsymbol{\mu}\cdot \mathbf{q}_j/T} \pm 1 \right]^{-1}$$

Yield

Mass

Quantum Numbers

- Statistical *Description* of Observed Yields in Gibbs Grand-Canonical Ensemble

– Many Different Implementations

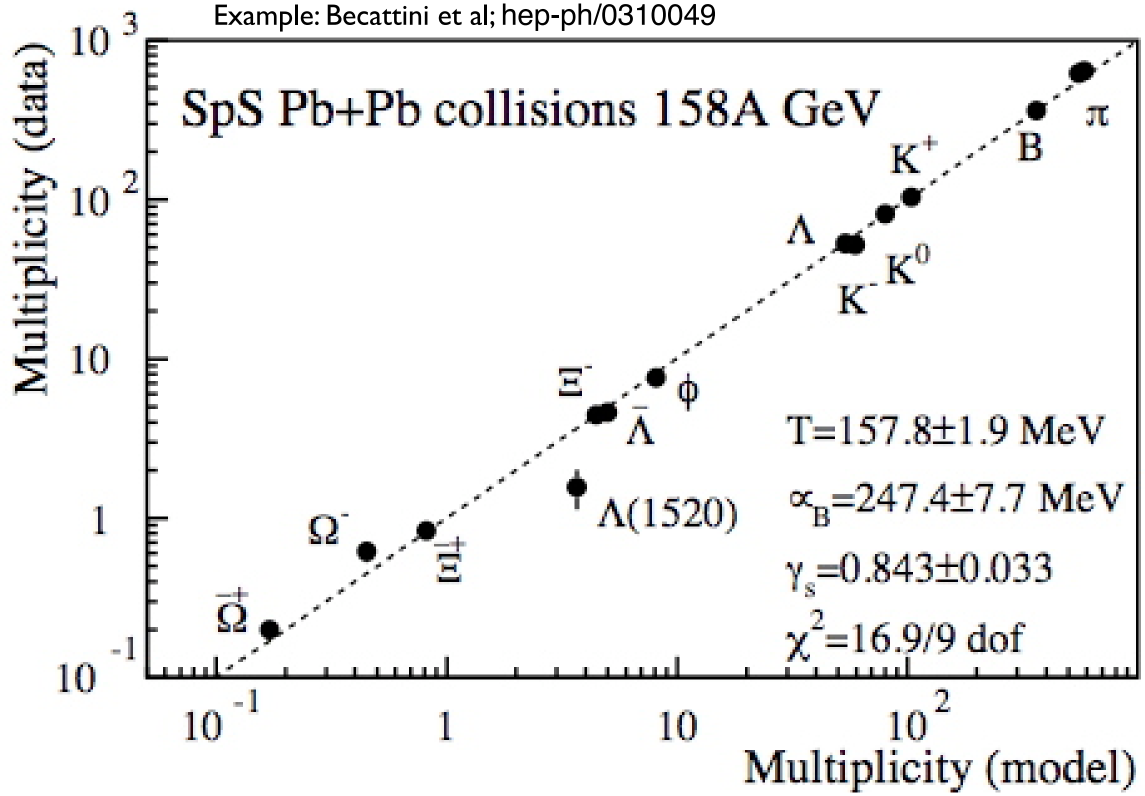
c.f. Hagedorn, Becattini, Braun-Munzinger, Cleymans, Heinz, Letessier, Mekijan, Rafelski, Redlich, Satz, Sollfrank, Stachel, Tounsi + many others

- Mid-Rapidity vs 4-π yields
- Non-Equilibrium (γ_s, γ_q)
- Numerical Implementation

- Here: Common Features of Different Approaches

Spectrum of Produced Hadrons

Example: Becattini et al; hep-ph/0310049

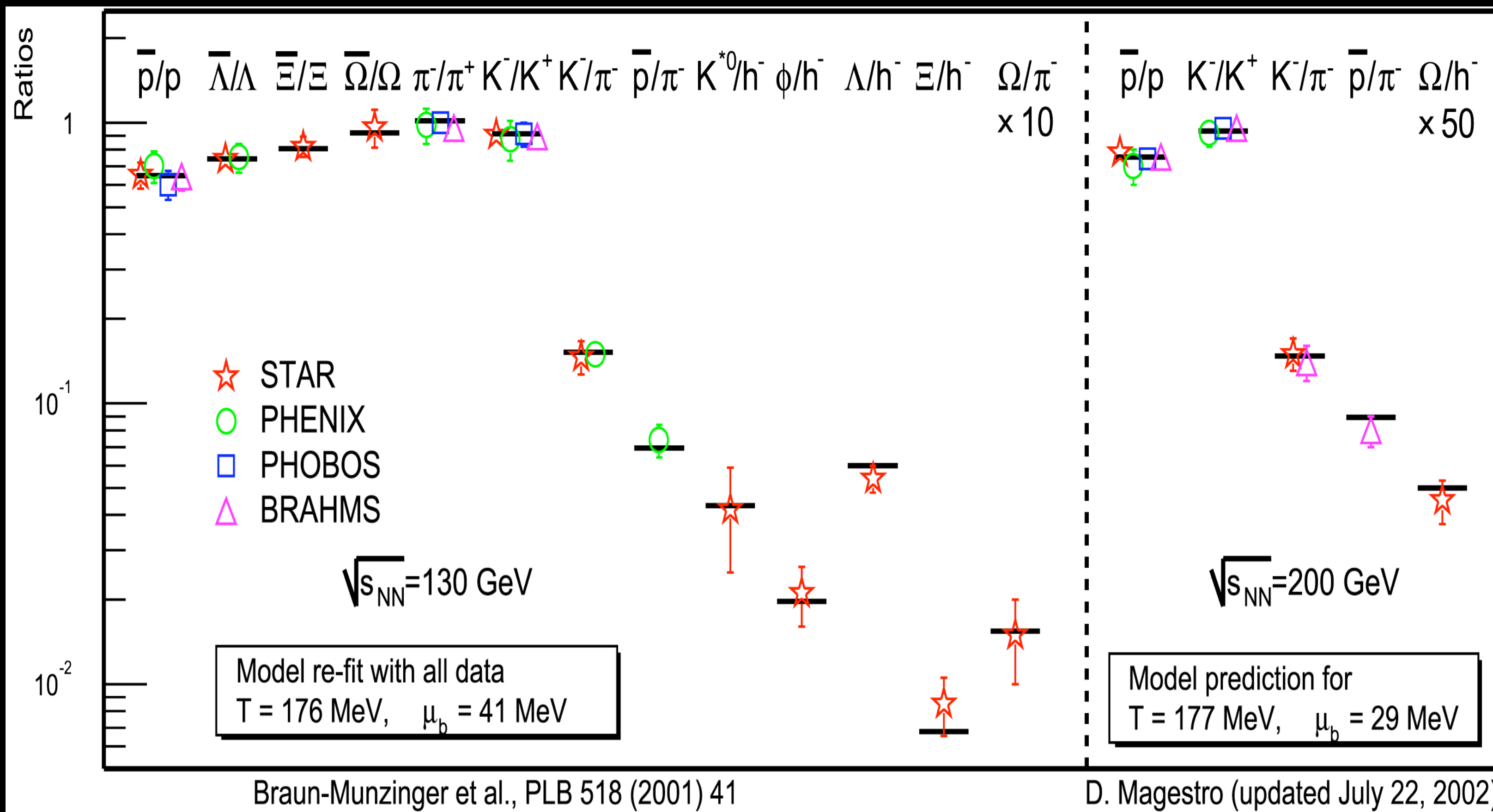


NA49 data,

4-π yields,

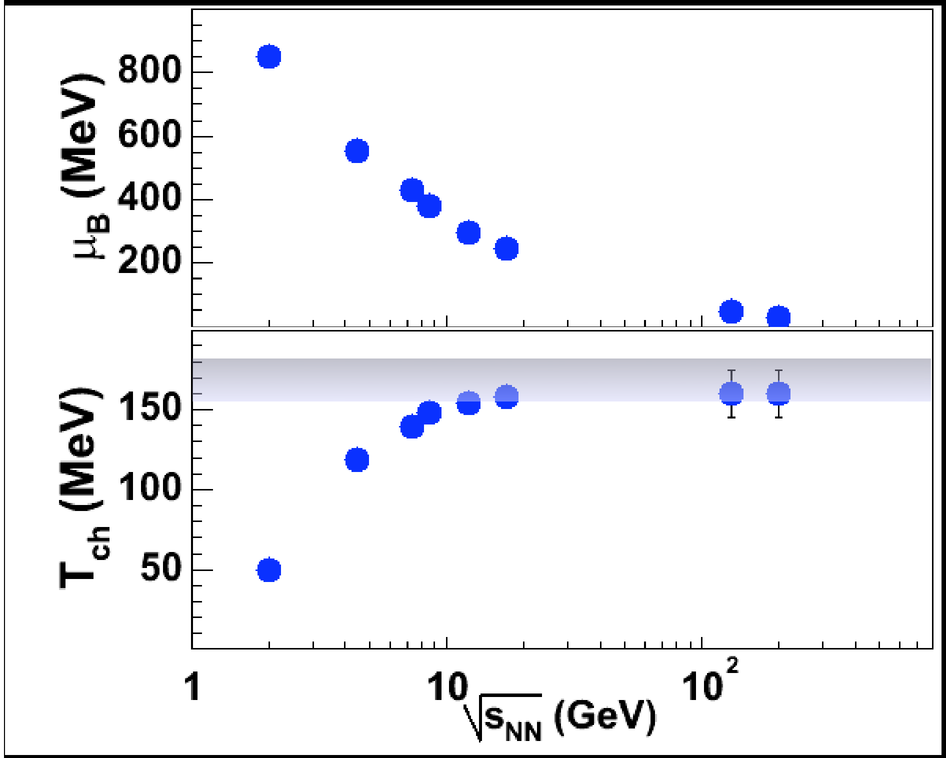
γ_s ~ 0.85

Statistical Model Fit



Relative Abundance: Two Parameters !

"Thermal Fit" Parameters vs sqrt(s)



μ_B drops with collision energy

T_{ch} approaches limiting value

Size (Mass, Volume)

Microcanonical ensemble. All conservation laws including energy-momentum (angular momentum, parity), charges enforced.

$V > 20\ fm^3$, $M > 10$ GeV (F. Liu et al., Phys. Rev. C 68 (2003) 024905) F. B., L. Ferroni, talk in ISMD 2003)

Canonical ensemble. Energy and momentum conserved on average, charges exactly. Temperature is introduced

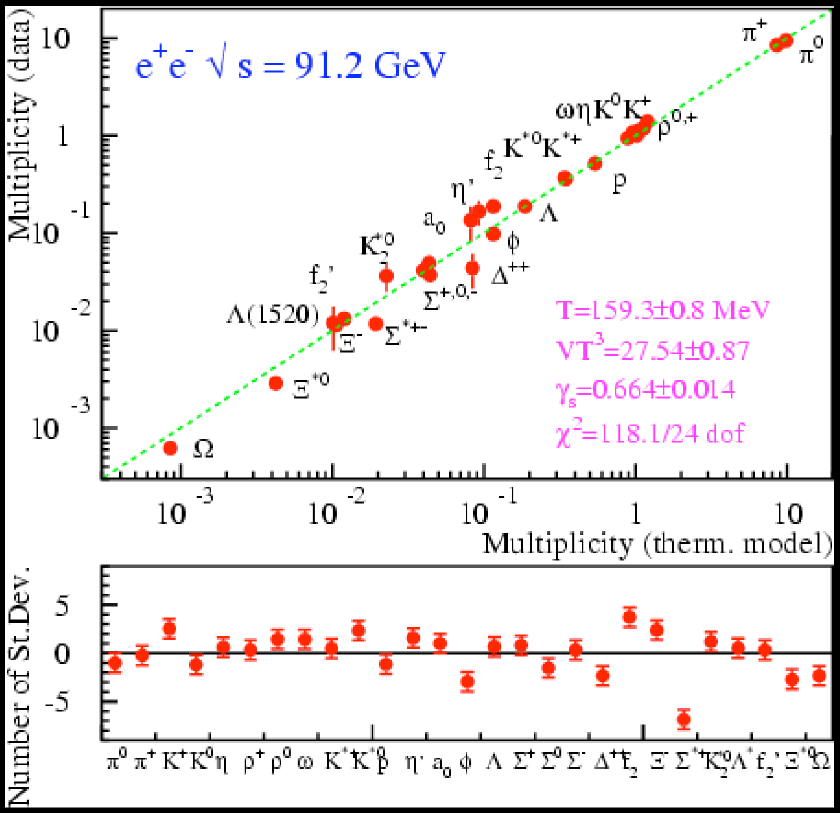
$V > 100\ fm^3$, $M > 50$ GeV (A. Keranen, F.B., Phys. Rev. C 65 (2002) 044901)

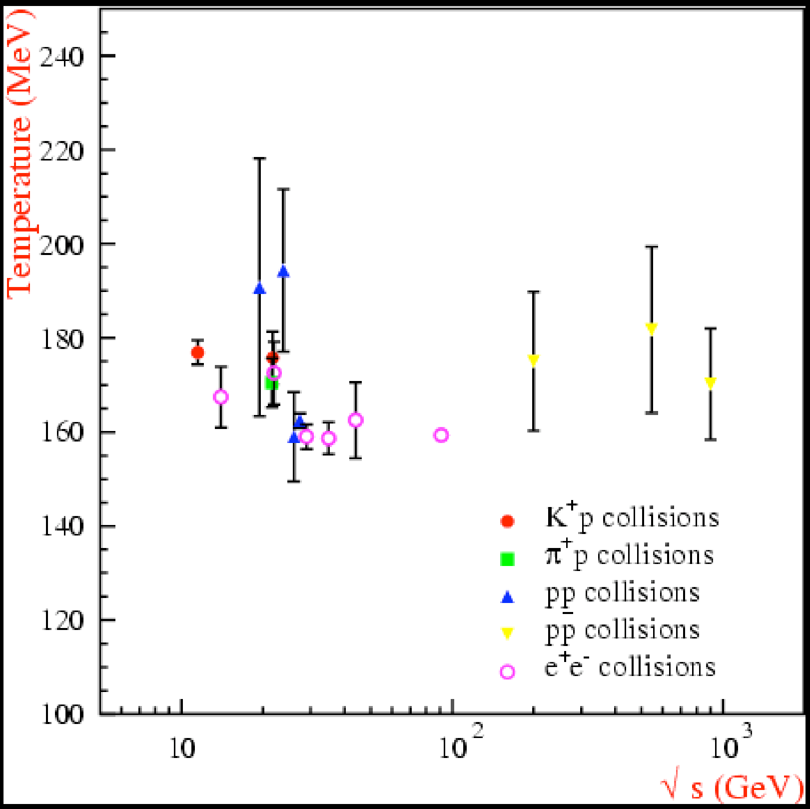
Grand-canonical ensemble. Also charges are conserved on average. Chemical potentials are introduced

Difficulty of computing

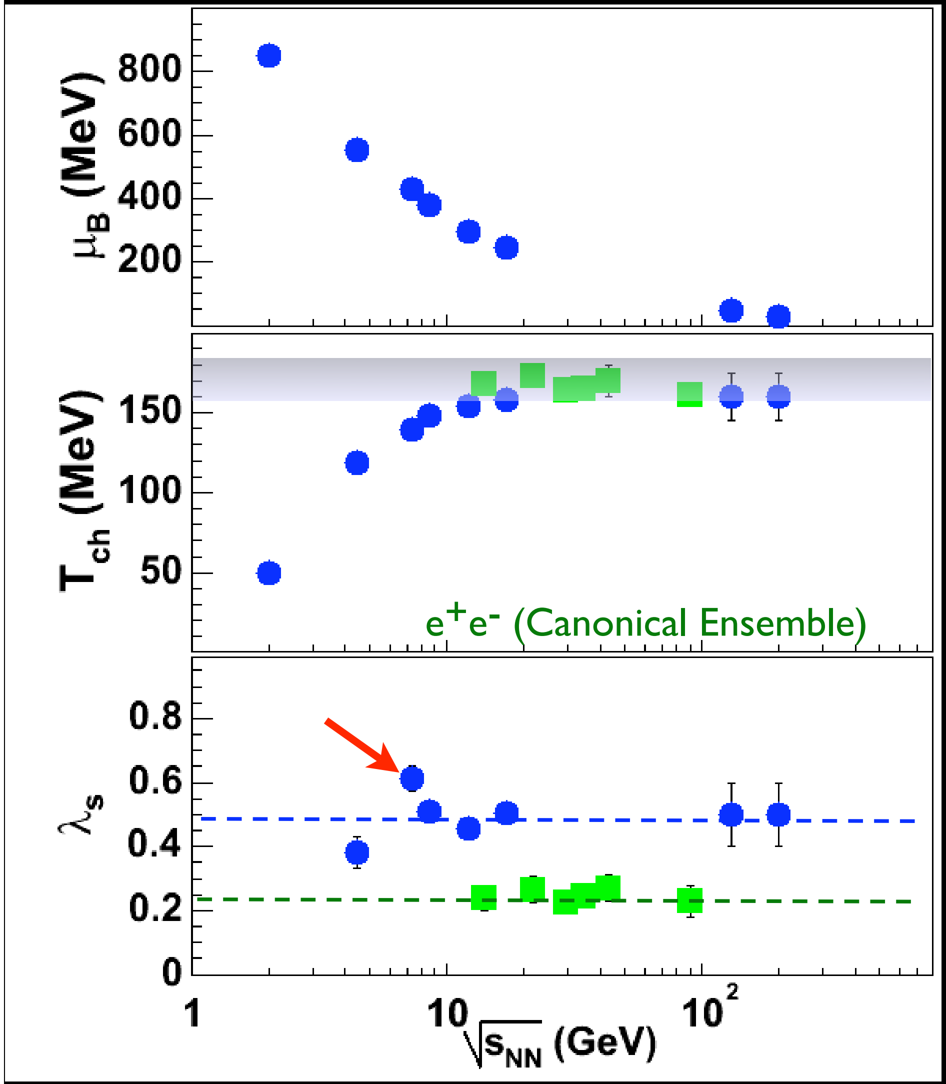
from Francesco Becattini

Statistical Model for Elementary Collisions





“Thermal Fit” Parameters vs sqrt(s)



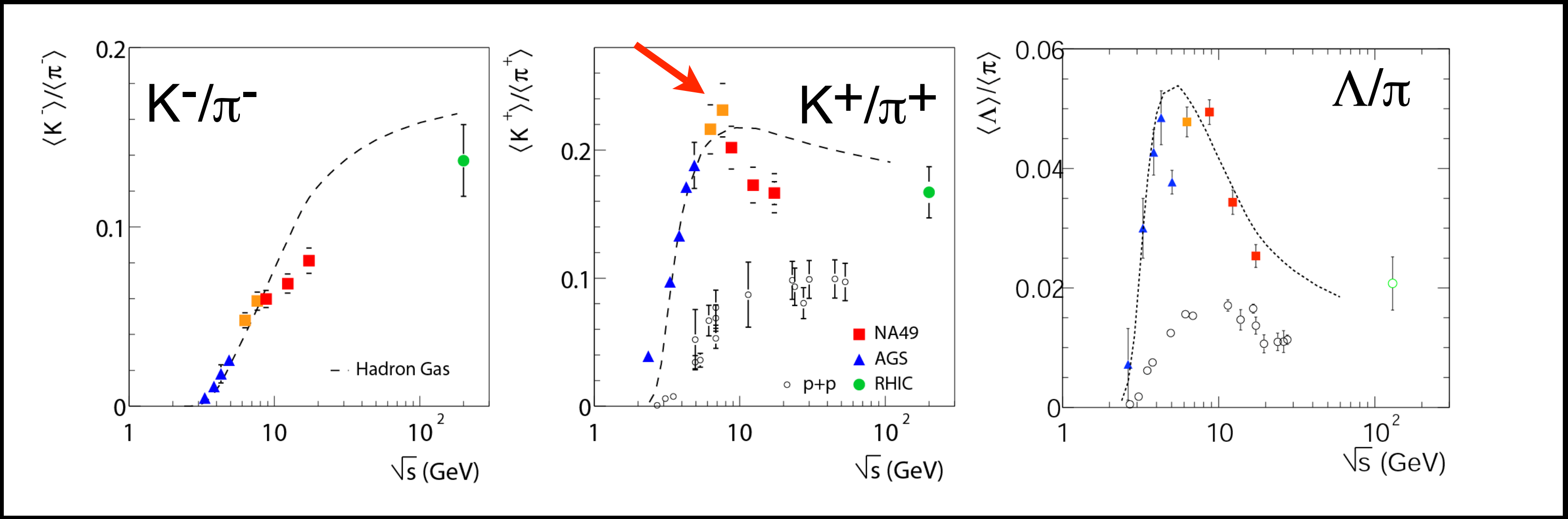
e^+e^- hadronizes at same T_{ch}

Are we looking at a *local* or *global* property?

Strangeness enhancement unique to AA

Global (or at least large) correlation volume

The “Horn”



NA49: Sharp maximum in K/π ratio at low SPS energy

Broad maximum from μ_B and p+p √s dependence, but no sharp structure in models