

8.712

Introduction to Heavy-Ion Physics

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Gunther Roland

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In ultra-relativistic heavy-ion collisions, a saturated partonic state (Color Glass Condensate, CGC) is created.

Instantly, the CGC involves into a locally equilibrated strongly coupled plasma of quarks and gluons (sQGP).

The sQGP, with a temperature above 200MeV and the quantum numbers of the vacuum, undergoes a pressure driven expansion characteristic of an ideal liquid, before hadronizing at a cross-over temperature of about 170MeV.

Transport properties of the sQGP, like viscosity and parton energy loss parameters, can be estimated analytically using string theory and the AdS/CFT correspondence.

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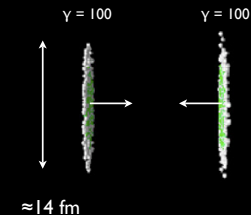
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Au+Au Collision at RHIC

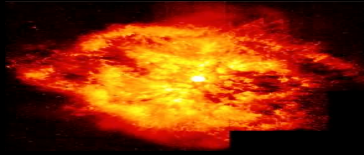
$197 \times (100\text{GeV} + 100\text{ GeV})$ in center of mass



1 GeV \approx mass of proton
1 fm (Fermi) $\approx 10^{-15}\text{m} \approx$ radius
of proton

approx. 6 μ J of kinetic energy

Au+Au Collision at RHIC



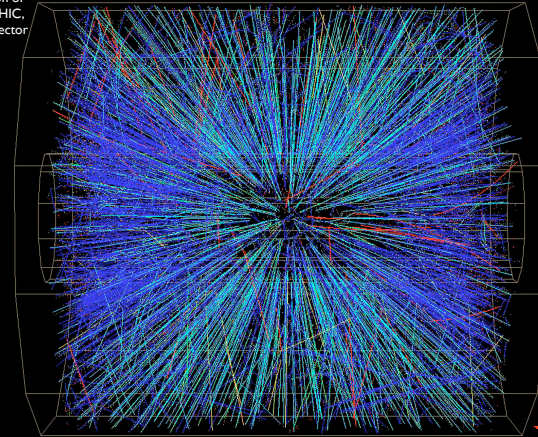
N.B. This picture is of course not QCD matter, but a Hubble picture of Nebula M1-67

80% of kinetic energy is converted to shortlived "Fireball"

Fireball proper lifetime $\Delta t \approx 10-15 \text{ fm}/c \approx 5 \times 10^{-23} \text{ s}$

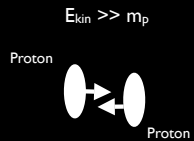
Au+Au Collision at RHIC

Trajectories of particles produced in a collision of two Gold nuclei at RHIC, seen by the STAR detector



Out of the fireball, thousands of particles emerge

Strong interaction

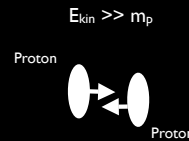


A collision of two protons (or more generally two *hadrons*) at high energies

Q: What will be the reaction products?

1950s - 1960s

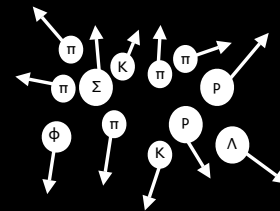
Strong interaction



A collision of two protons (or more generally two *hadrons*) at high energies

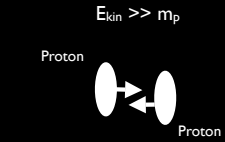
Q: What will be the reaction products?

1950s - 1960s



A: The reaction produces more hadrons

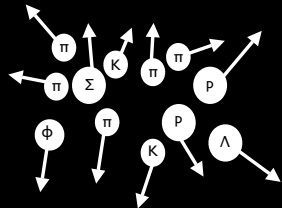
Strong interaction



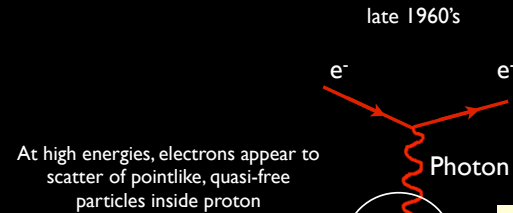
...if we look ... into the first 0.0001 sec of cosmic history when the temperature was above $10^{12}K$ we encounter problems of a difficulty beyond the range of modern statistical mechanics. At such temperatures...strongly interacting particles will be in a state of continual mutual interaction, and cannot reasonably be expected to obey any simple equation of state



Steven Weinberg (1972)
(from F.Wilczek, hep-th/9609099)



Strong interaction



At high energies, electrons appear to scatter off pointlike, quasi-free particles inside proton



1990 Nobel Prize to Jerry Friedman (MIT), Henry Kendall (MIT), Richard Taylor (SLAC)

Paradox: Weakly bound proton constituents can be seen in high-energy scattering, but can not be liberated even in most violent collisions

Quantum ChromoDynamics (QCD)

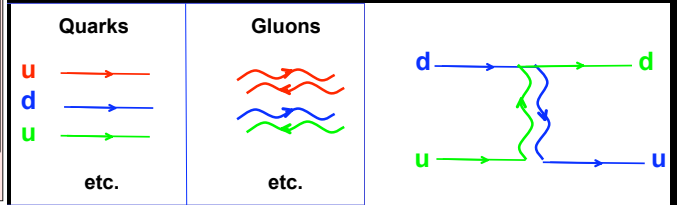
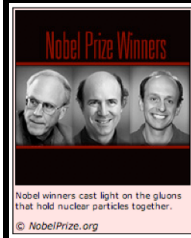
Quantum gauge theory (early 1970's)
- Point-like fermions (**Quarks**)
- Massless bosons (**Gluons**)

QCD particles carry 'Color' charge: red, green, blue
Quarks carry fractional ($\pm 1/3, \pm 2/3$) electric charge

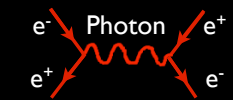
However, observed particles are **Hadrons** (no net color)
Baryons made of 3 quarks (e.g. proton)
Mesons made of quark + anti-quark (e.g. pion)

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c ²	Electric charge
u up	0.003	2/3
d down	0.006	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	175	2/3
b bottom	4.3	-1/3

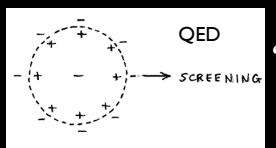
force carriers spin = 0, 1, 2, ...		
Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge
g gluon	0	0



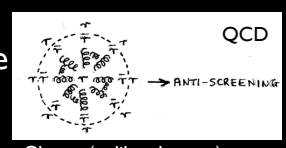
QED vs QCD



This looks rather similar. Making free electrons is easy. Why can't one make free quarks?



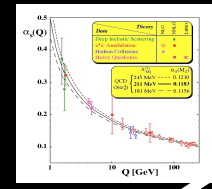
Vacuum fluctuations (e.g. e^+e^- pairs) screen electric charge



Gluons (unlike photons) carry (color-) charge

"Polarization of the Vacuum"

Electric charge appears stronger at smaller distance (e.g. $\alpha \approx 1/128$ at 90GeV)



Contribution of Gluons (Spin 1) to vacuum fluctuations leads to **anti-screening**


Color charge appears smaller at smaller distance (higher momentum interactions)

"Asymptotic Freedom"


Low Momentum: 0.2 GeV
Large Distance: 1fm

Momentum Scale


High Momentum: 10 GeV
Small Distance: 0.01 fm



Proton
 $r \sim 1\text{fm}$



Gluon



In high energy physics...
we distribute a higher and higher
amount of energy into a region of
with smaller and smaller size


...to study the question of "vacuum",
we must turn to a different direction;
we should investigate different
phenomena by distributing high
energy over a relatively large volume"

TD Lee, 1975

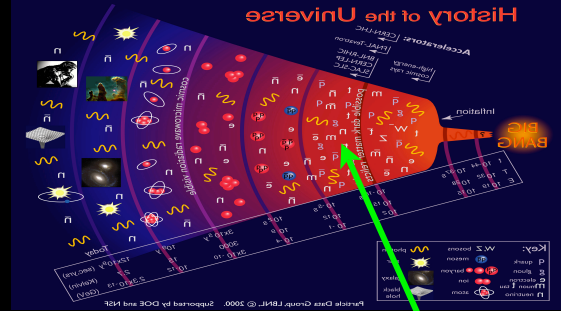
Low Momentum: 0.2 GeV
Large Distance: 1fm

Momentum Scale

High Momentum: 10 GeV
Small Distance: 0.01 fm



Proton
 $r \sim 1\text{fm}$



Superdense Matter: Neutrons or Asymptotically Free Quarks?


J. C. Collins and M. J. Perry
*Department of Applied Mathematics and Theoretical Physics, University of Cambridge,
Cambridge CB3 9EW, England*
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.


Low Momentum: 0.2 GeV
Large Distance: 1fm

Momentum Scale


High Momentum: 10 GeV
Small Distance: 0.01 fm



Proton
 $r \sim 1\text{fm}$



Gluon

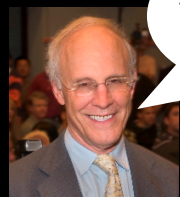


N.B. This picture is of course not
QCD matter, but a Hubble picture
of Nebula M1-67

**Bulk QCD Matter at
high temperature**

First experiments started in the mid-80's at
Brookhaven (Long Island) and CERN (Geneva)

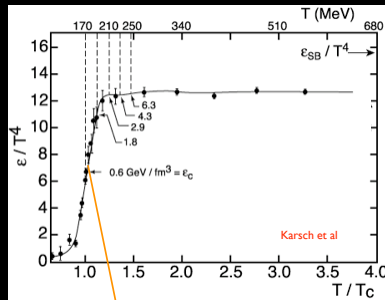
What we expected to find (since early 1980's):



If we were to heat the
world to a temperature of a
few hundred MeV, hadrons would melt
into a plasma of liberated quarks and
gluons
(D. Gross, 1998)

QCD Matter at high Temperature

John Negele's Blue Gene Supercomputer

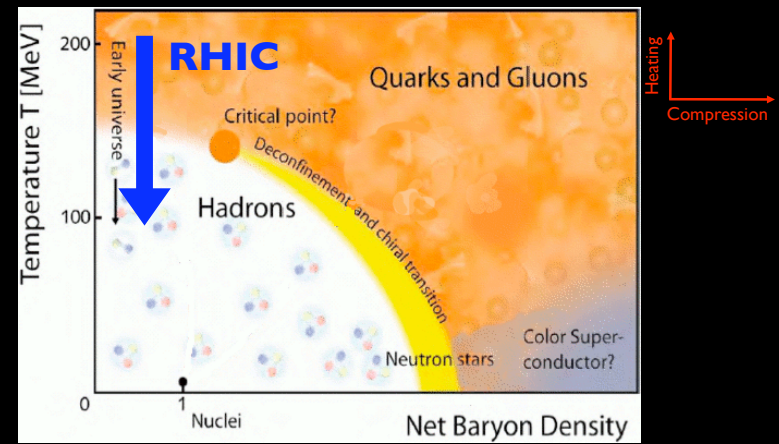


- Numerical Calculations: **Phase Transition** at high T
- Deconfinement: Quark-Gluon Plasma**

$T_{\text{critical}} \sim 170 \text{ MeV} \sim 2 \times 10^{12} \text{ K}$
 Energy density $\sim 0.7 \text{ GeV/fm}^3$

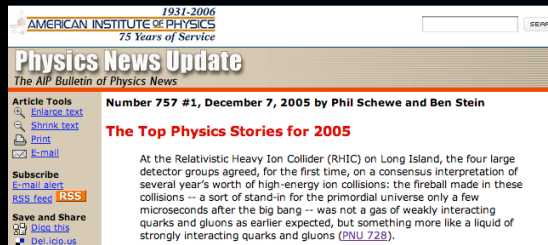
5 x nuclear matter density!

QCD Matter at high T and Density



RHIC events contain almost as much anti-matter and matter ($\bar{p}/p \approx 0.8$)
 RHIC explores cross-over region of phase diagram

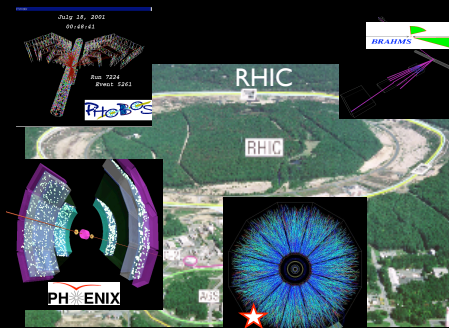
AIP Top Physics Story, Dec 2005



“...the fireball made in these [heavy-ion] collisions...was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid...”

based on Whitepapers by BRAHMS, PHENIX, PHOBOS and STAR collaborations at RHIC

Heavy Ion Experiments at RHIC



Superconducting collider
 3.8km circumference
 First beams in June 2000
 6 Runs: p+p, d+Au, Cu+Cu, Au+Au

4 Experiments:
 PHENIX, STAR (big)
 BRAHMS, PHOBOS (small)

	AGS	SPS	RHIC
CMS energy (GeV)	5	20	200
E increase		x4	x10
y range	± 1.6	± 3.0	± 5.3

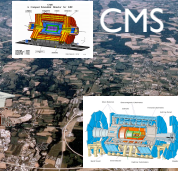
per nucleon-nucleon pair!

Heavy Ion Experiments at RHIC and LHC

RHIC



LHC

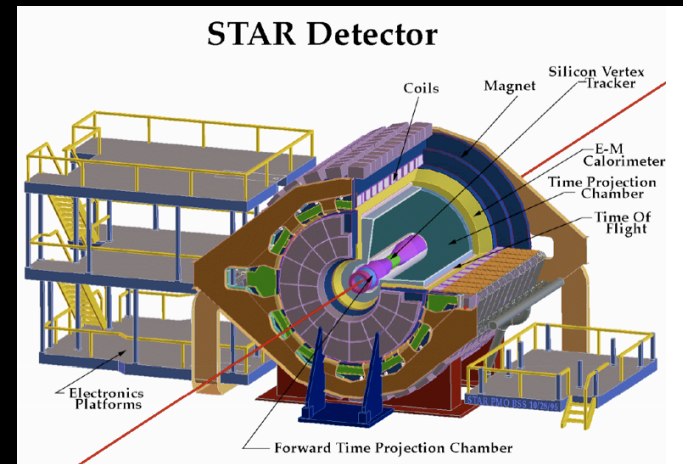


ALICE

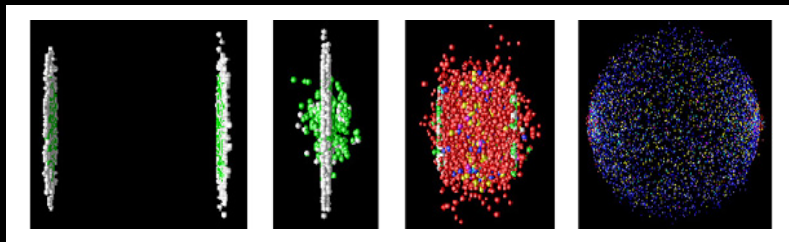
ATLAS

	AGS	SPS	RHIC	LHC
CMS Energy (GeV)	5	20	200	5500
E increase		x4	x10	x28
y range	±1.	±3.0	±5.3	±8.6

Anatomy of a Heavy Ion Detector

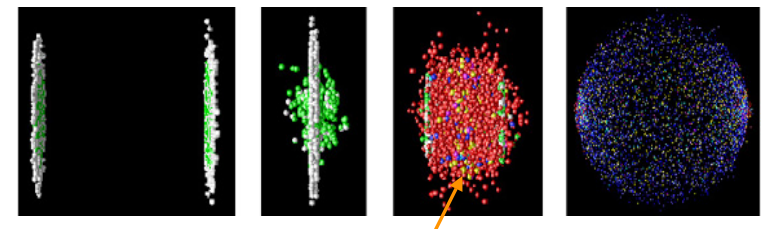


Heavy Ion Collision

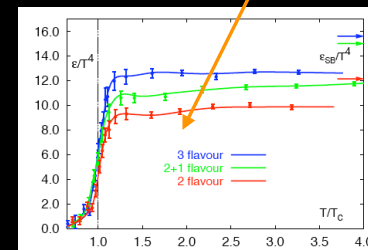


Time →

Heavy Ion Collision



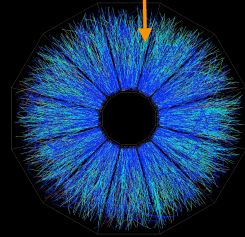
The Medium



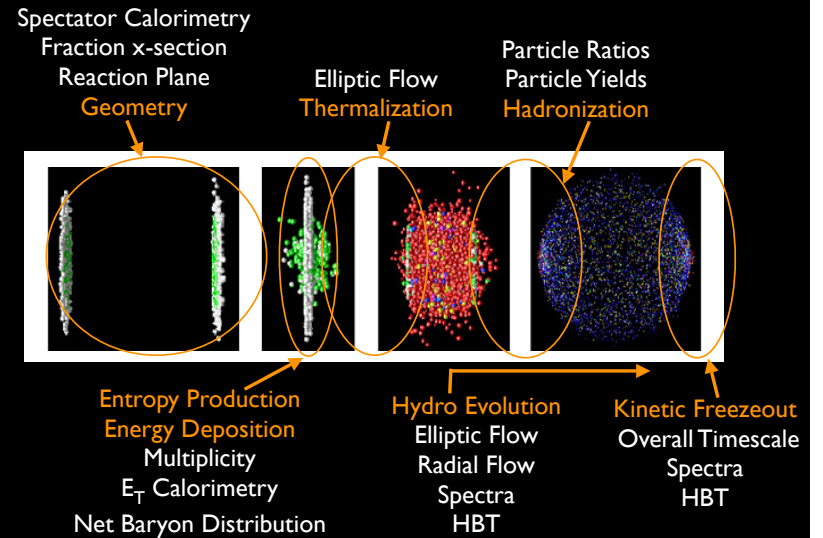
Heavy Ion Collision



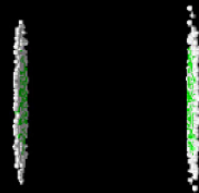
What we see:
"Ashes" of the Medium



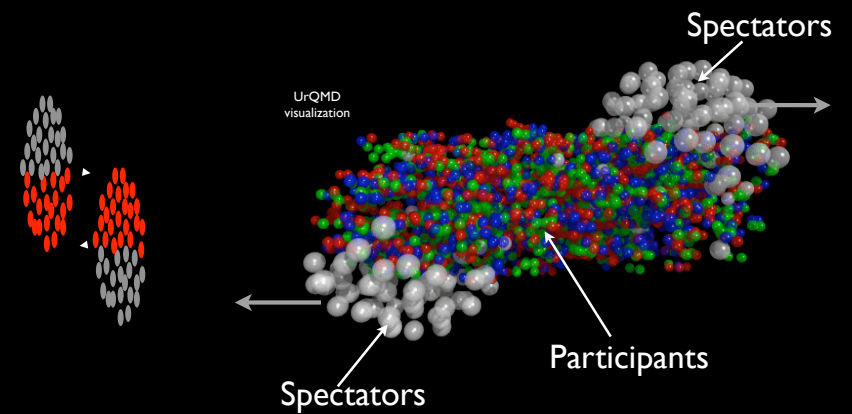
Anatomy of a Heavy Ion Collision



Collision Geometry

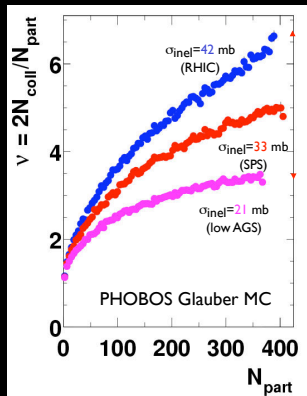


Collision Geometry and Centrality



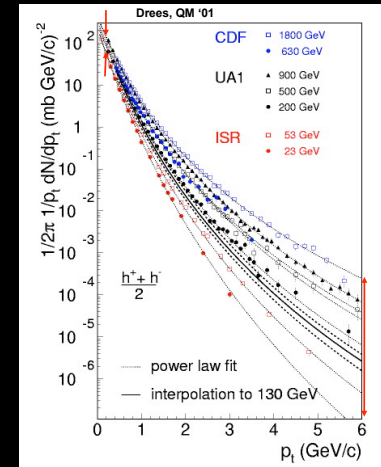
Use # of participants (" N_{part} ") to characterize collision centrality (impact parameter)

“Soft” and “Hard” Physics



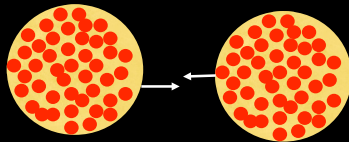
Use centrality to change Volume,
but also collisions/nucleon

“Soft” and “Hard” Physics



“Participant” Scaling

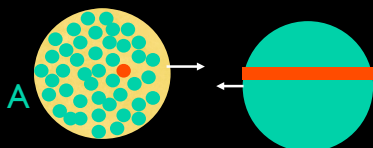
Volume



$$N_{part}/2 = \# \text{ of participating nucleons: } A$$

“Collision” Scaling

Point-like

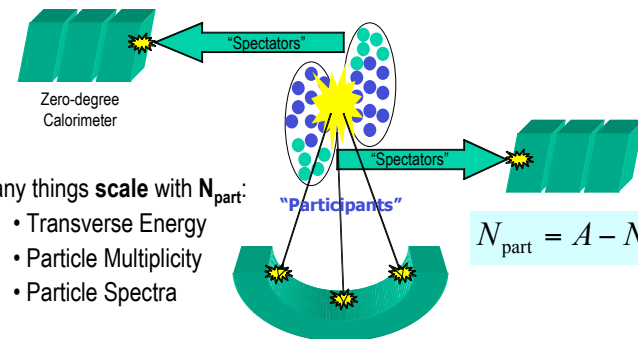


$$N_{coll} = \# \text{ of NN collisions: } \sim A^{4/3}$$

$$L \sim A^{1/3}$$

Measuring Centrality

The collision geometry (i.e. the impact parameter) determines the number of nucleons that **participate** in the collision



Many things **scale** with N_{part} :

- Transverse Energy
- Particle Multiplicity
- Particle Spectra

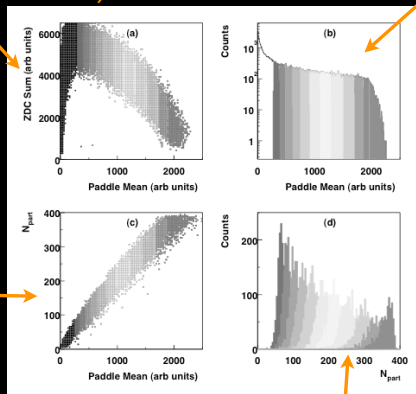
$$N_{part} = A - N_{spec}$$

Measuring "Centrality"

Tight cuts on geometry
difficult with RHIC ZCAL
(only neutrons)

Bin data in
Multiplicity

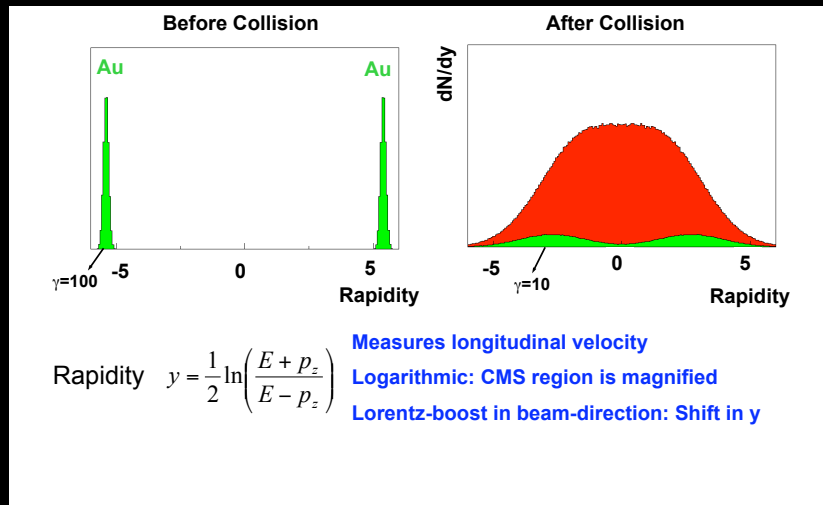
Multiplicity
monotonic
with N_{part}



Glauber MC: Fractional x-section to N_{part}

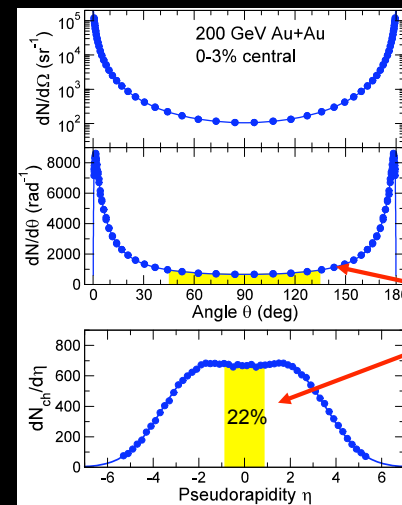
A few definitions

Rapidity



n.b.: I'm going to ignore the difference between rapidity and pseudorapidity

Angular Distribution

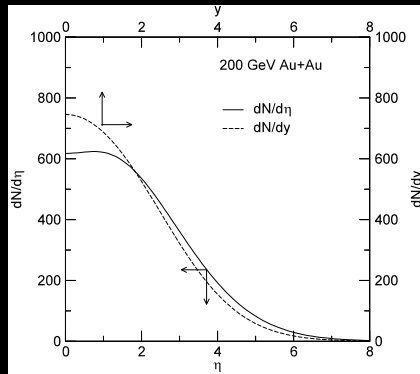


B. Back, Breckenridge '05

Only 22% emitted with $p_T > p_L$
However, these particles carry information about the densest region formed in the collisions

Rapidity vs Pseudo-Rapidity

$$\frac{dN}{d\eta d\mathbf{p}_T} = \beta \frac{dN}{dy d\mathbf{p}_T}$$



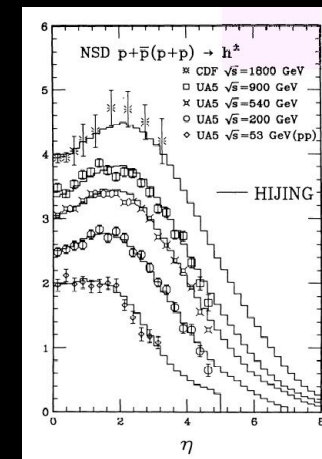
$$\eta = -\ln \tan \theta/2$$

Things to remember

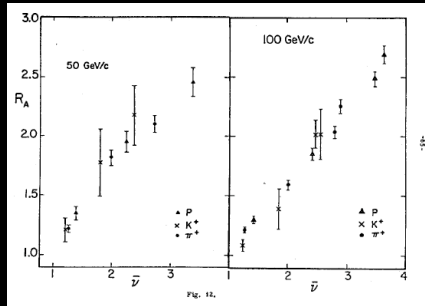
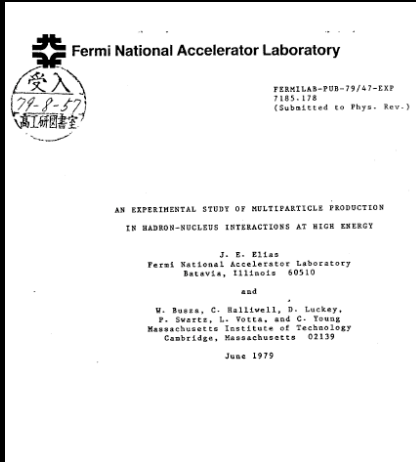
- Characterize centrality by number of participants N_{part} (\sim Volume) or number of collisions
- Use rapidity to describe longitudinal phase space
- Approximate rapidity with pseudo-rapidity (not identical!)

Interlude:
Some results from p+p
and p+A

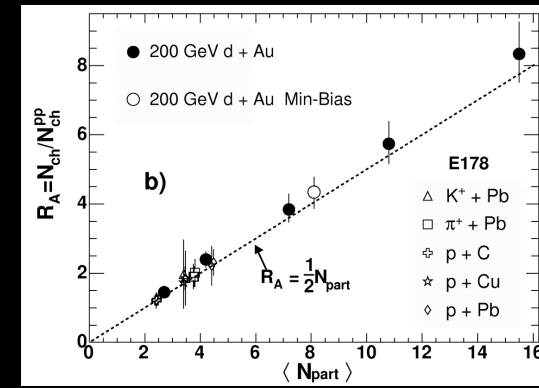
Pseudo-Rapidity Distributions in p+n



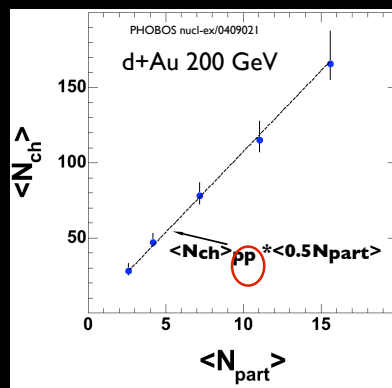
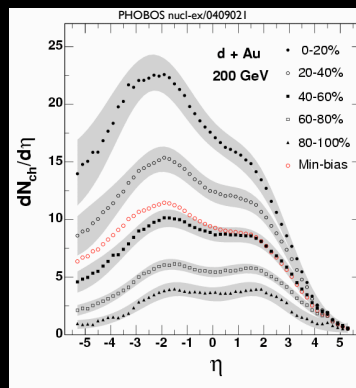
Centrality Dependence in p+A



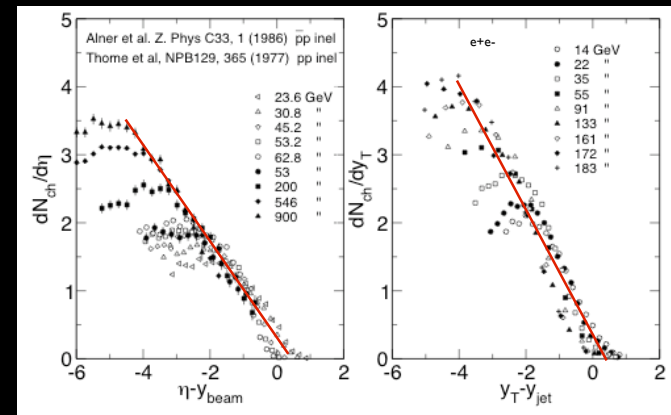
N_{part} Scaling in d+Au



N_{part} Scaling in d+Au

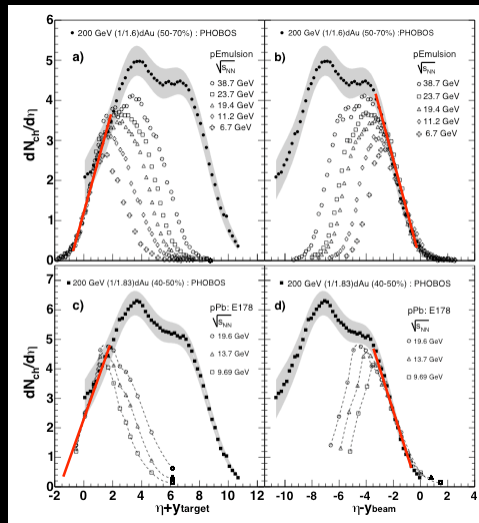


Limiting Fragmentation

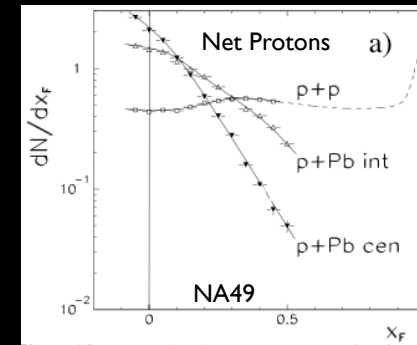


Particle production in restframe of one of the colliding particles

Limiting Fragmentation in d+Au



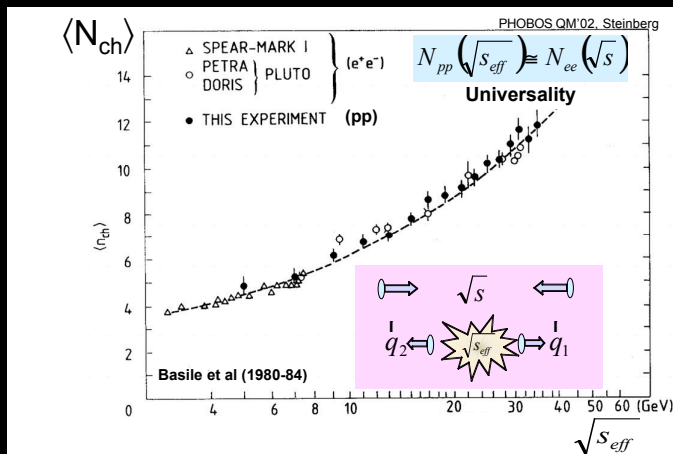
“Baryon-Stopping” in p+p and p+A



p+p: x_F distribution flat:
50% energy loss

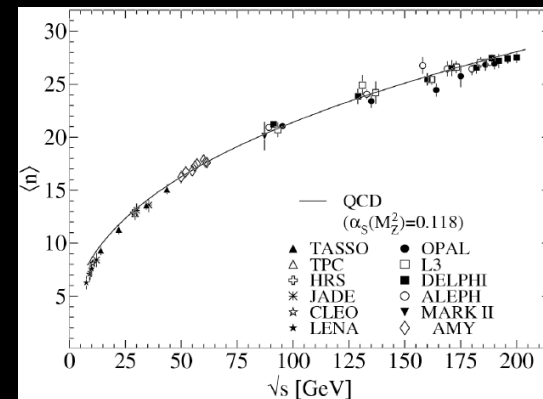
Defines available energy for particle production

Leading Particle Effect



Subtract energy of leading protons to define effective energy

pQCD Prediction of total multiplicity



Perturbative QCD can predict energy dependence of total multiplicity. Non-perturbative transition from partons to hadrons hidden in fragmentation functions

Things to remember

- In p+p collisions, about 50% of the energy available for particle production
- In p+A, total hadron multiplicity scales like $N_{part} * pp$ (same energy)
- Both p+p and p+A show limiting fragmentation scaling vs energy

Available Energy

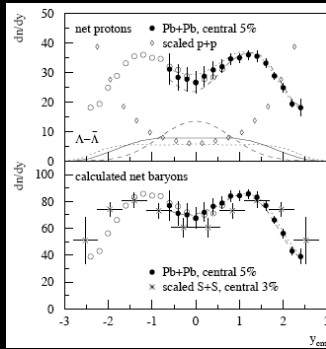


Net Baryon Distributions

Baryon Stopping and Charged Particle Distributions in Central Pb+Pb Collisions at 158 GeV per Nucleon

H. Appelshäuser¹, J. Bichler², S.J. Bailey³, L.S. Barzani⁴, J. Bartke⁵, R.A. Barton⁶, H. Bialkowska⁷, A. Bilmes⁸, C.O. Blyth⁹, R. Bock¹⁰, H. Boshatz¹¹, C. Boraschi¹², F.P. Brady¹³, H. Bräuninger¹⁴, R. Brusa¹⁵, P. Bunyat¹⁶, H.L. Casas¹⁷, D. Cebra¹⁸, G.E. Cooper¹⁹, J.G. Cruz²⁰, P. Cseri²¹, J. Dima²², V. Ekekezi²³, F. Eckardt²⁴, M.I. Ferrero²⁵, H.C. Fischer²⁶, D. Florko²⁷, Z. Fodor²⁸, P. Foka²⁹, P. Frymuth³⁰, V. Friese³¹, M. Fuchs³², J. Gabarró³³, J. Gao³⁴, R. Gao³⁵, M. Gaidarov³⁶, W. Geiss³⁷, E. Giacometti³⁸, J. Gózdrowski³⁹, J. Gutierrez⁴⁰, J.W. Harris⁴¹, S. Hagedorn⁴², T. Hasegawa⁴³, I.A. Hill⁴⁴, I. Horowitz⁴⁵, H. Hülsbosch⁴⁶, C. Iguchi⁴⁷, D. Irmshäuser⁴⁸, P. Janas⁴⁹, P.J. Jones⁵⁰, K. Kadzajko⁵¹, V.I. Karasik⁵², M. Kowalski⁵³, B. Latta⁵⁴, P. Leutz⁵⁵, A.I. Malakhov⁵⁶, S. Margazda⁵⁷, C. Markert⁵⁸, C.L. Melissinos⁵⁹, A. Mielke⁶⁰, J. Molit⁶¹, J.M. Nunez⁶², M. Oldenburg⁶³, C. Ouyang⁶⁴, C. Palla⁶⁵, A.D. Panagiotou⁶⁶, A. Pantziris⁶⁷, A. Pappas⁶⁸, B.J. Pater⁶⁹, A.M. Poskanzer⁷⁰, S. Putschke⁷¹, D.J. Prendergast⁷², J. Putschke⁷³, J.C. Rainey⁷⁴, R. Rapp⁷⁵, W. Rapp⁷⁶, H.G. Ritter⁷⁷, D. Ritzschke⁷⁸, C. Roland⁷⁹, C. Roland⁸⁰, H. Rostkova⁸¹, A. Rybczyk⁸², A. Sandwaś⁸³, H. Sano⁸⁴, A.Yu. Semenov⁸⁵, E. Sedykh⁸⁶, D. Sobczak⁸⁷, N. Sotkin⁸⁸, S. Stenlund⁸⁹, P. Szymanski⁹⁰, P. Sikler⁹¹, E. Skrzypczak⁹², C.T.A. Sogard⁹³, R. Stock⁹⁴, H. Strolz⁹⁵, J. Stropfer⁹⁶, J. Sukiak⁹⁷, M. Zuo⁹⁸, T.A. Trainor⁹⁹, S. Trznicki¹⁰⁰, T. Uehara¹⁰¹, M. Vanhaas¹⁰², C. Vassiliadis¹⁰³, D. Vassiliadis¹⁰⁴, F. Wang¹⁰⁵, H.D. Wiedemann¹⁰⁶, S. Wüthrich¹⁰⁷, C. Whitham¹⁰⁸, L. Wood¹⁰⁹, N. Xu¹¹⁰, T.A. Yanez¹¹¹, J. Zmeskal¹¹², X.Z. Zhu¹¹³, R. Zybair¹¹⁴

¹NA40 Collaboration
²Department of Physics, University of Alabama, Athens, Greece
³Lawrence Berkeley National Laboratory, University of California, Berkeley, USA
⁴Birmingham University, Birmingham, England
⁵KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
⁶CBR, Geneva, Switzerland
⁷Institute of Nuclear Physics, Cracow, Poland
⁸GSI Helmholtz Center for Heavy Ion Research (GSI), Darmstadt, Germany
⁹University of California at Davis, Davis, USA
¹⁰Joint Institute for Nuclear Research, Dubna, Russia
¹¹Glabochkovskiy Institute of Nuclear Physics, Frankfurt, Germany
¹²University of California at Los Angeles, Los Angeles, USA
¹³Hadronic Physics Department, GSI Helmholtz Center for Heavy Ion Research, Darmstadt, Germany
¹⁴Max-Planck-Institut für Physik, Munich, Germany
¹⁵Institute for Nuclear Studies, Warsaw, Poland
¹⁶Institute for Experimental Physics, University of Warsaw, Warsaw, Poland
¹⁷Nuclear Physics Laboratory, University of Washington, Seattle, WA, USA
¹⁸Tata University, New Haven, CT, USA
¹⁹Rutherford Appleton Laboratory, Didcot, Oxford, UK
²⁰July 20, 2004



Net proton and negative hadron spectra for central Pb+Pb collisions at 158 GeV per nucleus at the CERN SPS were measured and compared to spectra from lighter systems. Net baryon distributions were derived from those of net protons, utilizing model calculations of meson contributions as well as data and model calculations of strange baryon distributions. Despite rapidity shift with respect to the baryon and meson transverse momentum (p_T) of net baryons increases with system size. The rapidity density of negative hadrons scales with the number of participant nucleons for nuclear collisions, whereas their p_T is independent of system size. The p_T dependence upon particle mass and system size is consistent with larger transverse flow velocity at midrapidity for Pb+Pb compared to S+K central collisions.

Lattice QCD predicts that strongly interacting matter at an energy density greater than $1.2 \text{ GeV}/\text{fm}^3$ at finite baryon density and approximately chiral symmetry restored state known as the quark-gluon plasma (for an overview, see [1]). This state of matter existed in the early millisecond after the Big Bang and it may influence the dynamics of rotating neutron stars [2]. The collision of nuclei at ultrarelativistic energies offers the possibility in the laboratory of creating strongly interacting matter at sufficiently high energy density to form a quark-gluon plasma [3]. Evidence spectra from these reactions reflect the dynamics of the hot and dense state formed in the collision. The baryon density, established early by the reaction, is an important factor governing the evolution of the system [4]. Comparison of model predictions with measured rapidity and transverse momentum distributions and correlation functions constrains the possible dynamical scenarios of the reaction [5], such as those for longitudinal and transverse

Nuclear Stopping in Au+Au Collisions at $\sqrt{sNN} = 200 \text{ GeV}$

I. G. Bearden¹, D. Beavis², C. Boshuizen³, B. Boshuizen³, H. Beggel⁴, C. Chassagnon⁵, C. H. Christensen⁶, P. Christensen⁷, J. Cibot⁸, R. Dobie⁹, E. Engel¹⁰, J. J. Gaardhøje¹¹, M. Germainot¹², K. Hagel¹³, O. Hansen¹⁴, A. Holm¹⁵, A. K. Koba¹⁶, H. Koba¹⁷, A. J. Jaffe¹⁸, F. Jentsch¹⁹, J. J. Jurek²⁰, C. E. Jurek²¹, K. Karbowiak²², E. J. Kim²³, T. Koenig²⁴, T. M. Lacroix²⁵, J. H. Lee²⁶, Y. K. Lee²⁷, G. Lebedev²⁸, Z. Macha²⁹, A. Malakhov³⁰, M. Mielinski³¹, M. Murray³², J. Naudet³³, B. S. Nysen³⁴, J. Norwa³⁵, K. Oshikawa³⁶, D. Oussana³⁷, R. Pakter³⁸, F. Rapp³⁹, C. Rasmussen⁴⁰, D. Ratzke⁴¹, B. H. Raftoyiannis⁴², S. J. Randrup⁴³, S. J. Randrup⁴⁴, R. A. Schwarz⁴⁵, P. Sussler⁴⁶, T. S. Tsvetsov⁴⁷, F. Uecker⁴⁸, H. Wulke⁴⁹, Z. Xiao⁵⁰, and I. S. Zgura⁵¹

¹Brookhaven National Laboratory, Upton, New York 11975
²Institut de Recherches Subatomiques and Université Louis Pasteur, Strasbourg, France
³Institute of Nuclear Physics, Krakow, Poland
⁴Smoluchowski Inst. of Physics, Jagiellonian University, Krakow, Poland
⁵Johns Hopkins University, Baltimore 21218
⁶New York University, New York 10003
⁷Niels Bohr Institute, Blegdamervej 17, University of Copenhagen, Copenhagen 2100, Denmark
⁸Texas A&M University, College Station, Texas, 77843
⁹University of Bergen, Department of Physics, Bergen, Norway
¹⁰University of Bucharest, Romania
¹¹University of Kansas, Lawrence, Kansas 66045
¹²University of Oslo, Department of Physics, Oslo, Norway (Date-Venue: stopping, March 3, 2004)

Transverse momentum spectra and rapidity distribution, dN/dy , of protons, anti-protons, and neutrons ($p - \bar{p}$) from central (0-5%) Au+Au collisions at $\sqrt{sNN} = 200 \text{ GeV}$ were measured with the BRAHM3 spectrometer within the rapidity range $0.5 \leq y \leq 2.5$. The proton and anti-proton dN/dy decrease from mid-rapidity to $y = 2.5$. The net-proton yield is roughly constant for $y < 1$ at $dN/dy = 1$, and increases to $dN/dy = 12$ at $y = 1$. The data show that collisions at this energy exhibit a high degree of transparency and that the linear scaling of rapidity loss with rapidity observed at lower energies is broken. The energy loss per participant nucleon is estimated to be 72 MeV .

The energy loss of colliding nuclei is a fundamental quantity determining the energy available for particle production (excitation) in heavy ion collisions. This energy loss is essential for the possible formation of a deconfined quark-gluon phase of matter (QGP). Because baryon number is conserved, and rapidity distributions are only slightly affected by mesonizing in late stages of the collision, the measured net-baryon ($B - \bar{B}$) distribution retains information about the energy loss and allows the degree of nuclear stopping to be determined. Such measurements can also distinguish between different proposed phenomenological mechanisms of initial collective multiple interactions and baryon transport [1, 2].

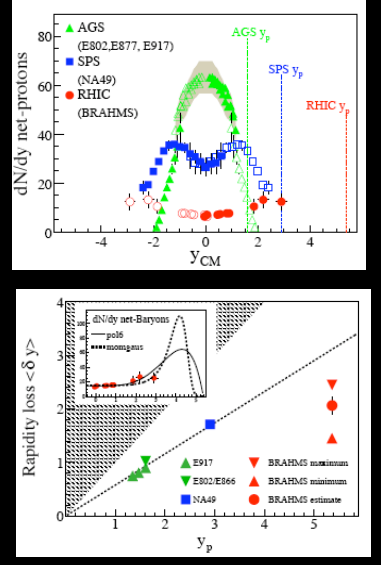
The average rapidity loss, $\langle \eta \rangle = \langle y - \bar{y} \rangle$, [3] is used to quantify stopping in heavy ion collisions [4]. Here, y_1 is rapidity of the incoming projectile and y_2 is the mean net-baryon rapidity after the collision:

$$\langle \eta \rangle = \frac{2}{N_{part}} \int_{y_1}^{y_2} \frac{p_T}{y} \frac{dN_{ch}(p_T, y)}{dy} dy, \quad (1)$$

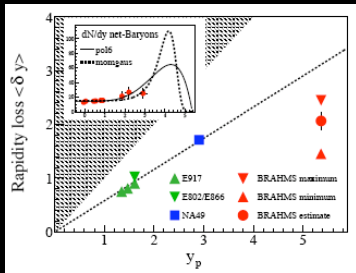
where N_{part} is the number of participating nucleons in the collision. The two extremes correspond to full stopping, where initial baryons lose all kinetic energy ($\langle \eta \rangle = y_1$), and full transparency, where they lose no kinetic energy ($\langle \eta \rangle = 0$). For fixed collision momentum (system size and centrality), at lower energy (SIS, AFS, and SPS) it was observed that $\langle \eta \rangle$ is proportional to the projectile rapidity. For central collisions between heavy nuclei (Pb, Au), $\langle \eta \rangle = 0.58 y_1$ [5].

It is often assumed that sufficiently high energy collisions are "transparent", thus the mid-rapidity region is approximately net-baryon free [6]. The energy density established early in the collision, ϵ , can then be related to a simple way to the final particle production. At RHIC it has been argued that at $\epsilon \sim 5 \text{ GeV}/\text{fm}^3$, will show the initial QGP production ($\epsilon_{QGP} \sim 1 \text{ GeV}/\text{fm}^3$) for the hadron gas to QGP phase transition.

In this letter, results on proton and anti-proton production, and baryon stopping in Au+Au collisions at $\sqrt{sNN} = 200 \text{ GeV}$ are presented. The data

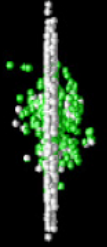


Things to remember

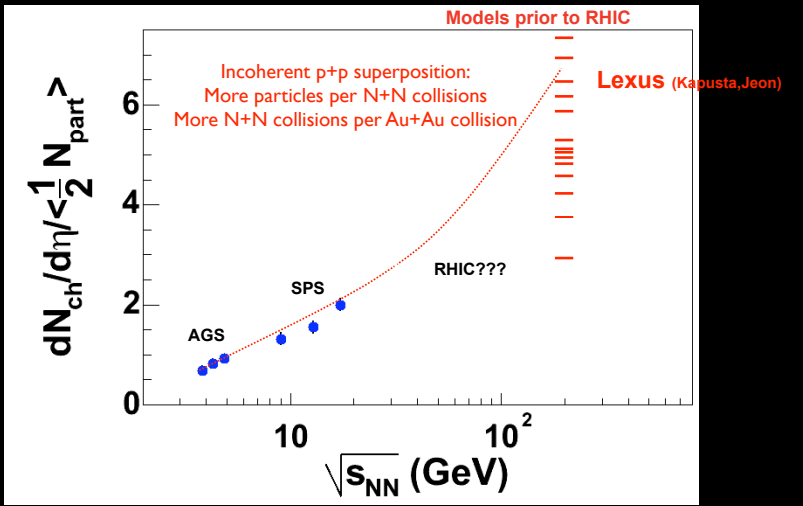


- In A+A collisions, about 70-80% of the energy available for particle production
- Stopping in A+A comparable to expectations from p+A

Hadron Multiplicities

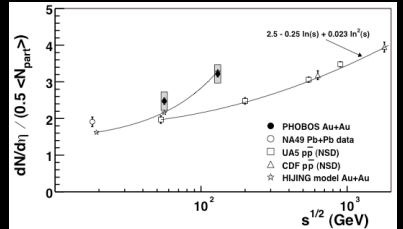


Particle Density near Mid-Rapidity in Au+Au



Charged particle multiplicity near mid-rapidity in central Au+Au collisions at $\sqrt{s} = 50$ and 130 AGeV

B. B. Back¹, M. D. Baker², D. S. Barton³, S. Bauder⁴, B. Baus⁵, R. Baur⁶, A. Bialas⁷, R. Bieschke⁸, W. Bizon⁹, A. Borkowski¹⁰, W. Bruns¹¹, A. Cerrito¹², M. Ceylan¹³, Y. H. Chang¹⁴, A. E. Chum¹⁵, T. Coughlan¹⁶, G. Csanos¹⁷, W. Czap¹⁸, B. Dabrowski¹⁹, M. P. Decowski²⁰, M. Dimpfer²¹, P. Fias²², J. Flork²³, M. Flisoi²⁴, K. Galanaka²⁵, R. Gans²⁶, E. Garcia-Solis²⁷, N. Garg²⁸, J. Gaudmy²⁹, C. Gatti³⁰, E. G. Gerasimov³¹, K. Gollner³², S. Gombor³³, J. Hauer³⁴, C. Hillenbrand³⁵, P. Hristova³⁶, A. Hoyer³⁷, C. A. Huhn³⁸, C. H. Hwang³⁹, C. H. Hwang⁴⁰, R. H. Hwang⁴¹, B. H. Hwang⁴², M. H. Hwang⁴³, J. Hwang⁴⁴, J. Hwang⁴⁵, J. Hwang⁴⁶, H. Hwang⁴⁷, H. Hwang⁴⁸, W. K. Hwang⁴⁹, P. Hwang⁵⁰, P. Hwang⁵¹, P. Hwang⁵², P. Hwang⁵³, P. Hwang⁵⁴, P. Hwang⁵⁵, P. Hwang⁵⁶, P. Hwang⁵⁷, P. Hwang⁵⁸, P. Hwang⁵⁹, P. Hwang⁶⁰, P. Hwang⁶¹, P. Hwang⁶², P. Hwang⁶³, P. Hwang⁶⁴, P. Hwang⁶⁵, P. Hwang⁶⁶, P. Hwang⁶⁷, P. Hwang⁶⁸, P. Hwang⁶⁹, P. Hwang⁷⁰, P. Hwang⁷¹, P. Hwang⁷², P. Hwang⁷³, P. Hwang⁷⁴, P. Hwang⁷⁵, P. Hwang⁷⁶, P. Hwang⁷⁷, P. Hwang⁷⁸, P. Hwang⁷⁹, P. Hwang⁸⁰, P. Hwang⁸¹, P. Hwang⁸², P. Hwang⁸³, P. Hwang⁸⁴, P. Hwang⁸⁵, P. Hwang⁸⁶, P. Hwang⁸⁷, P. Hwang⁸⁸, P. Hwang⁸⁹, P. Hwang⁹⁰, P. Hwang⁹¹, P. Hwang⁹², P. Hwang⁹³, P. Hwang⁹⁴, P. Hwang⁹⁵, P. Hwang⁹⁶, P. Hwang⁹⁷, P. Hwang⁹⁸, P. Hwang⁹⁹, P. Hwang¹⁰⁰



We present the first measurement of pseudorapidity densities of primary charged particles near mid-rapidity in Au+Au collisions at $\sqrt{s} = 50$ and 130 AGeV. For the most central collisions, we find the charged particle pseudorapidity density to be $dN_{ch}/d\eta_{ch} = 4.0 \pm 0.2$ (stat) ± 0.1 (sys) at 50 AGeV and 5.0 ± 0.2 (stat) ± 0.1 (sys) at 130 AGeV, values that are higher than any previously observed in nuclear collisions. Compared to proton-proton collisions, our data show an increase in the pseudorapidity density per participant by more than 40% at the higher energy.

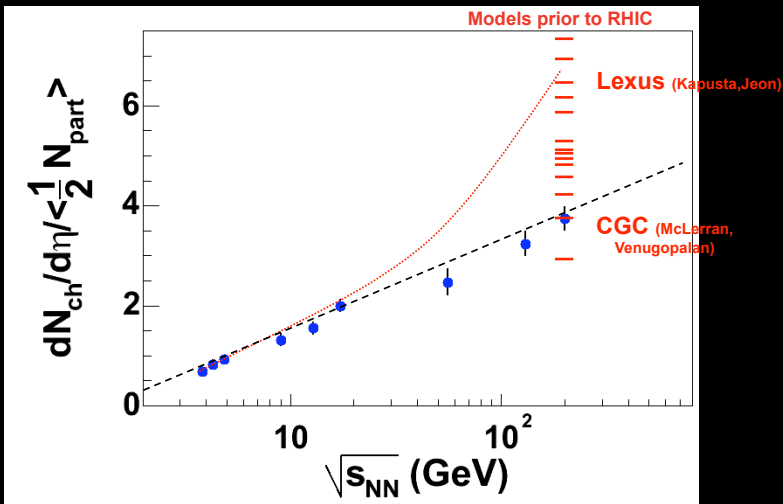
PACS number: 25.75.-q

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 $\sqrt{s} = 50$ 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 hadron-particle production 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 correlations in high-energy heavy-ion collisions, obtained from a variety of models, typically vary by up to a factor of two [2].

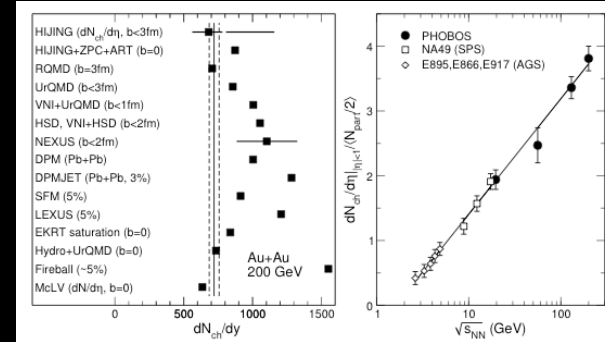
In this letter we report data for the most central Au+Au collisions detected in our spectrometer. We have determined the energy dependence of the density of primary charged particles emitted near 90° to the beam axis, characterized by the pseudorapidity density $dN/d\eta_{ch}$, where $\eta = -\ln|\tan(\theta/2)|$ 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



$dN/d\eta @ \eta=0$

PHOBOS Whitepaper

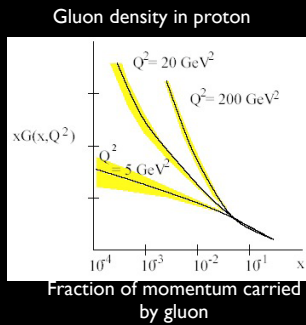


Oct 2004

Manifestation of Parton Saturation?

c.f. Blaizot, McLerran, Venugopalan, Kovchegov

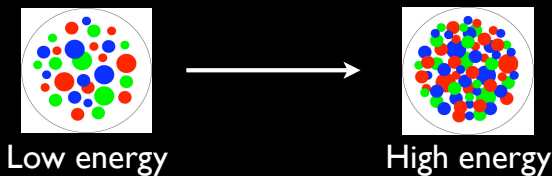
Parton Saturation



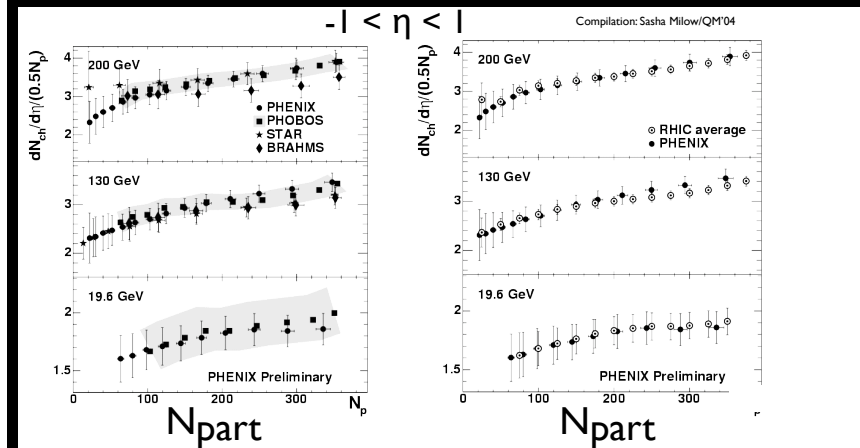
Idea(s): Entropy is not "created" but "liberated" from gluon distributions

Gluon density increases with x , Q^2

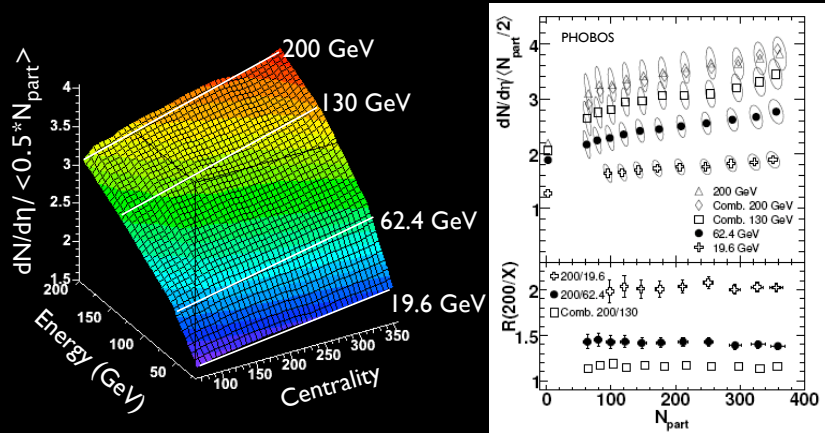
BUT: Gluons interact, limiting growth of gluon densities: Saturation



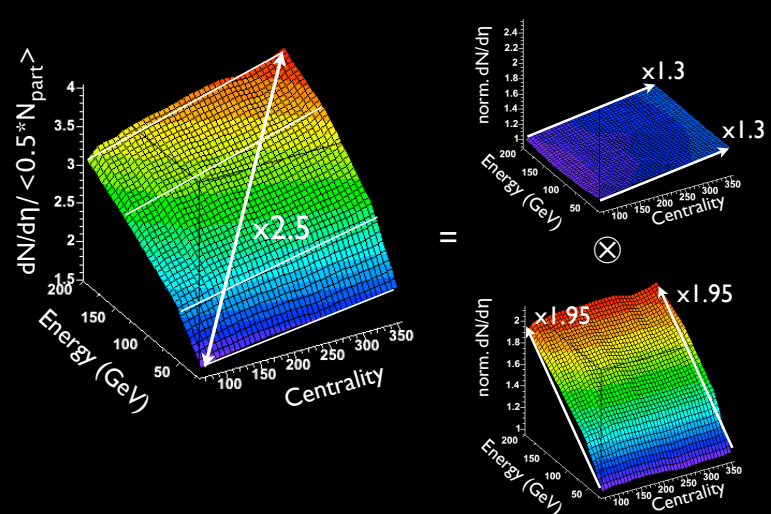
Mid-rapidity Multiplicity vs Centrality



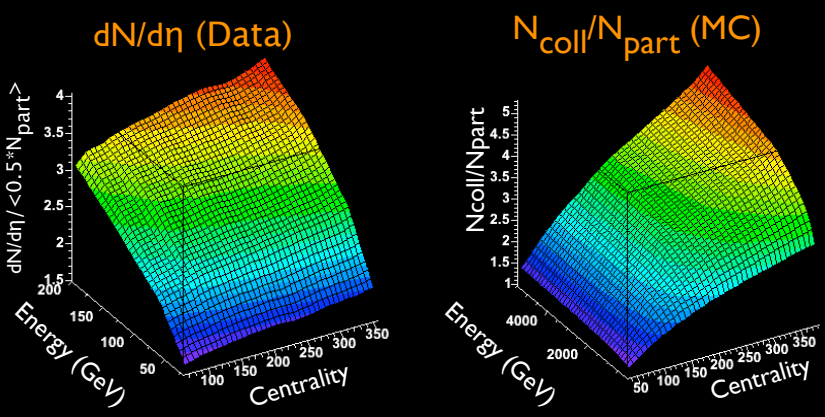
Mid-rapidity $dN/d\eta$ vs \sqrt{s} and N_{part}



$dN/d\eta$ vs \sqrt{s} and N_{part}

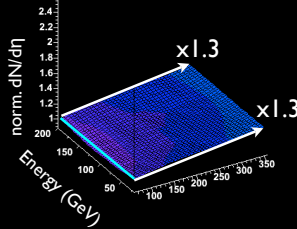


N_{coll}/N_{part} vs \sqrt{s} and N_{part}

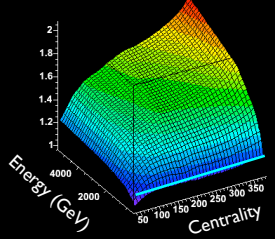
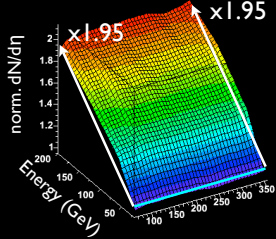
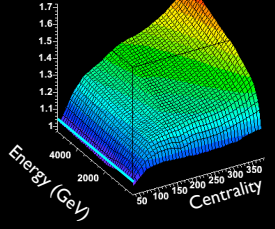


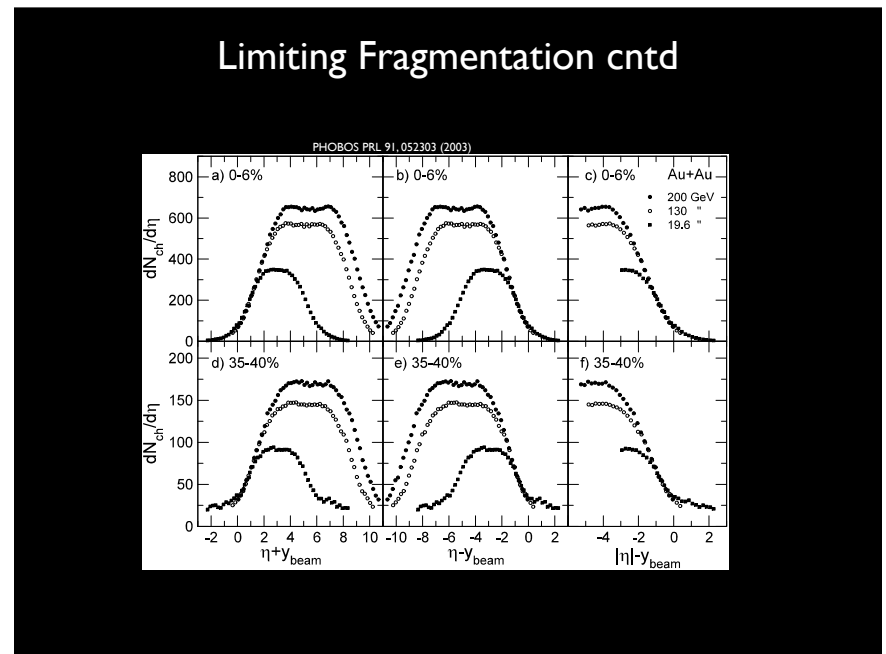
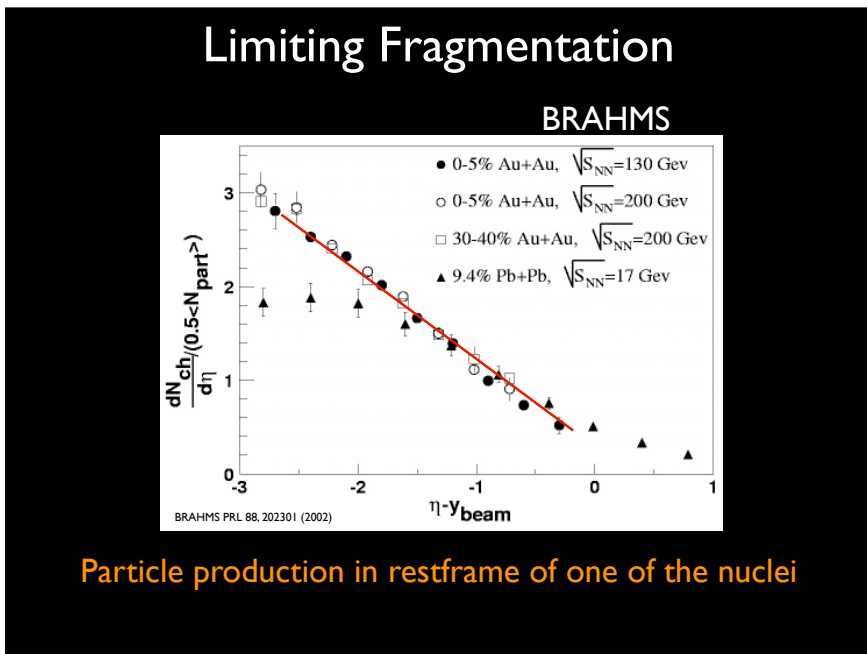
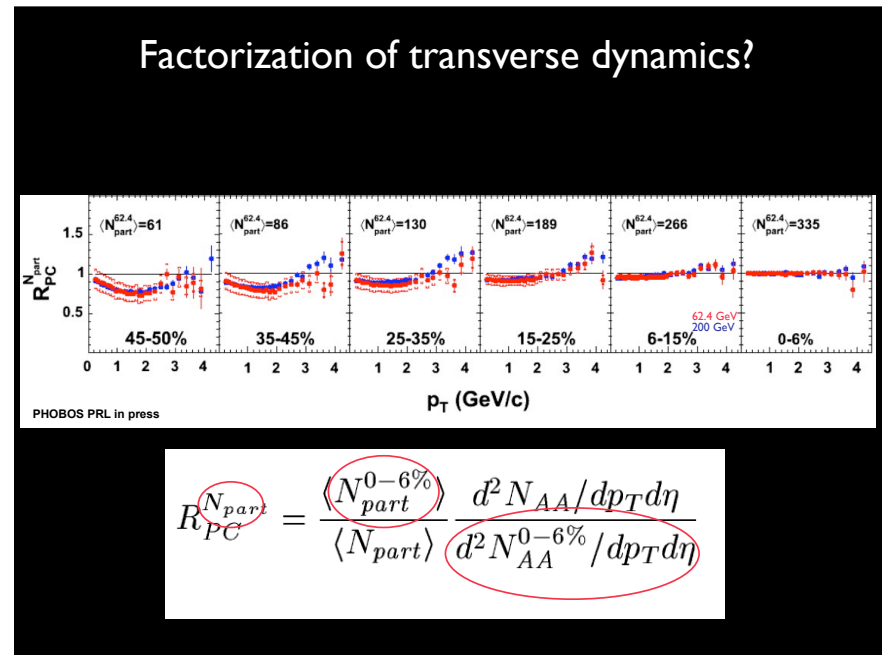
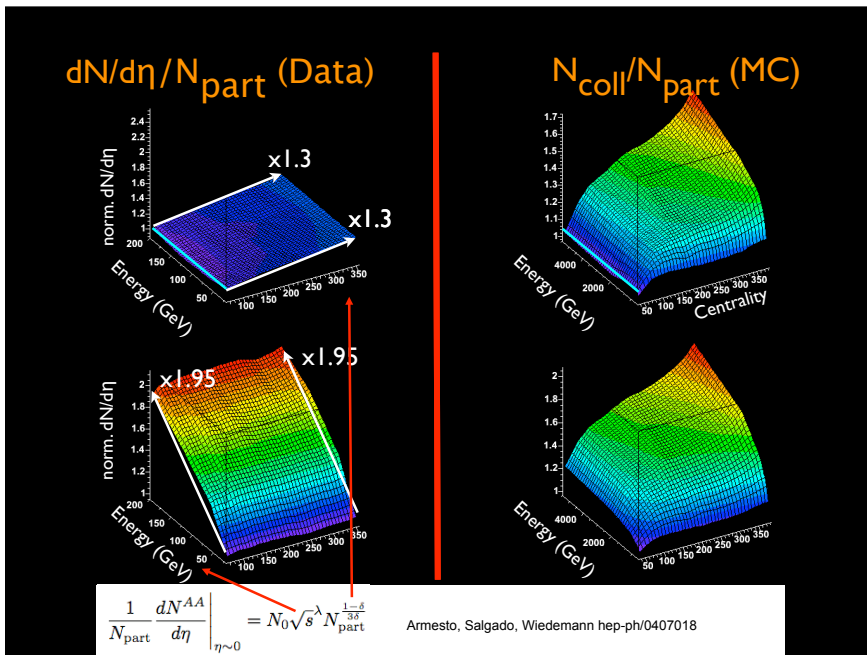
Factorization in a hard/soft picture?

$dN/d\eta / N_{part}$ (Data)

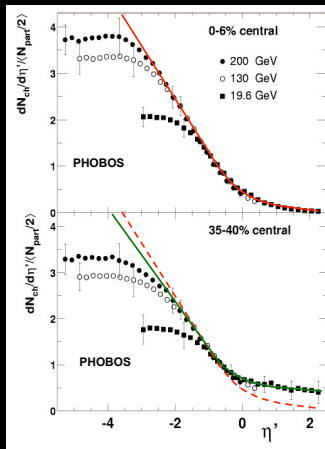


N_{coll}/N_{part} (MC)





Limiting Fragmentation vs Centrality



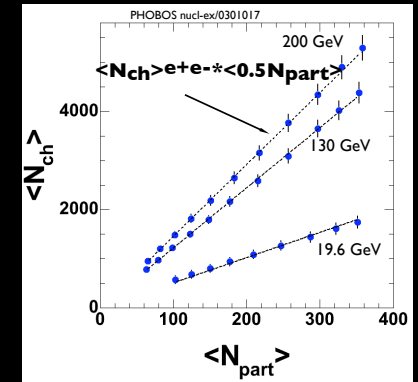
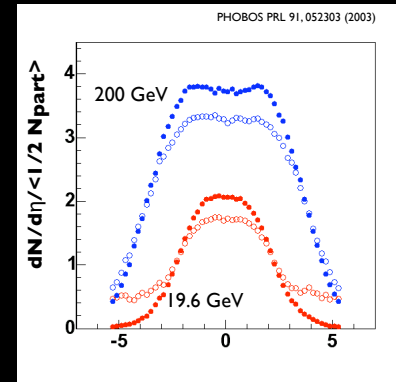
PHOBOS PRL 91, 052303 (2003)

Different Limiting Curves for Central and Peripheral Data

But both energy-independent

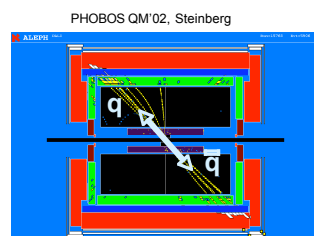
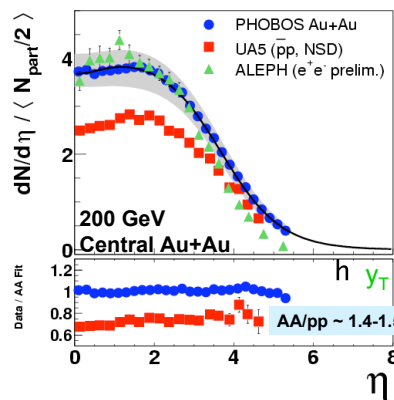
Dominance of Geometry?

Total Multiplicity $\langle N_{ch} \rangle$ in Au+Au



" N_{part} -Scaling"

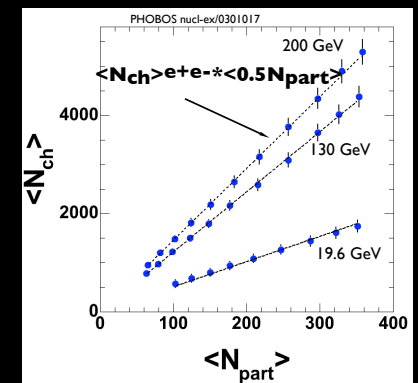
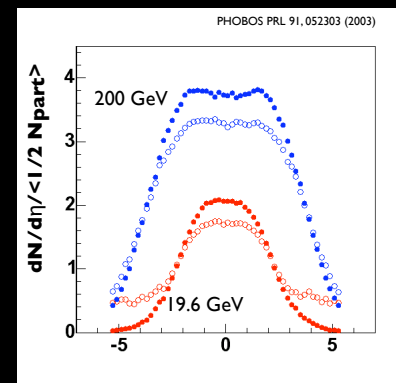
e^+e^- , p+p, A+A Correspondence?



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

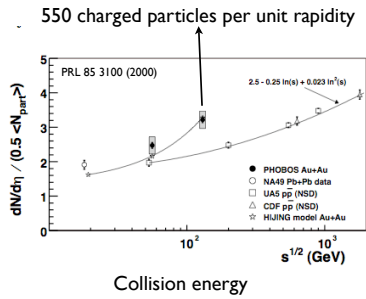
Surprising agreement in shape between AA/ e^+e^- /pp

Total Multiplicity $\langle N_{ch} \rangle$ in Au+Au

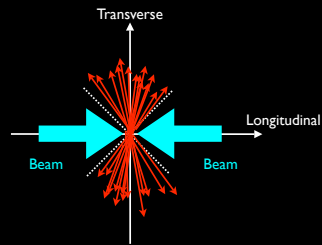


" N_{part} -Scaling"

Angular particle density near 90°
normalized per participant



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

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

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

But: Equilibration?

Things to remember

Slow, logarithmic growth of mid-y density

Parton saturation?

N_{part} scaling of total multiplicity

Parton saturation?

Limiting fragmentation scaling vs energy, centrality

Parton saturation?

Factorization of energy and centrality dependence ($\eta=0$, vs p_T vs η)

Parton saturation?

But:

Correspondence of multiplicity in A+A vs e+e- vs p+p ($1/2\sqrt{s}$)

Everything points to early (initial) determination of multiplicity distributions