8.712
Introduction to Heavy-Ion Physics

3/11/2008

Gunther Roland

Introduction to Heavy-Ion Physics

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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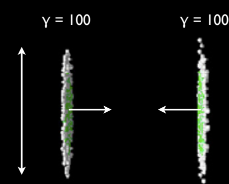
Au+Au Collision at RHIC

197 × (100GeV + 100 GeV) in center of mass

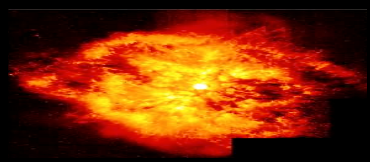


1 GeV ≈ mass of proton
1fm (Fermi) =10^{-15}m ≈ radius of proton

≈14 fm

approx. 6μJ of kinetic energy

Au+Au Collision at RHIC



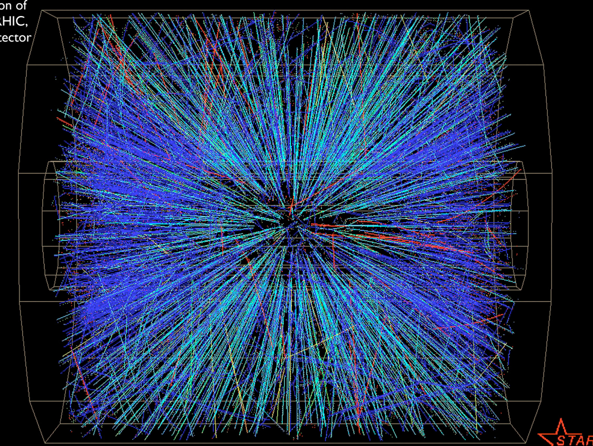
N.B. This picture is of course not QCD matter, but a Hubble picture of Nebula M1-67

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

Fireball proper lifetime $\Delta t \approx$ 10-15fm/c $\approx 5\times10^{-23}$ s

Au+Au Collision at RHIC

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

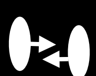


Out of the fireball,
thousands of particles emerge

Strong interaction

$E_{kin} >> m_p$

Proton



Proton

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

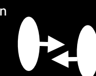
Q: What will be the reaction products?

1950s - 1960s

Strong interaction

$E_{kin} >> m_p$

Proton



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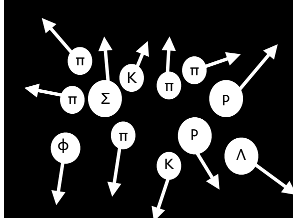
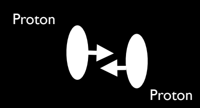


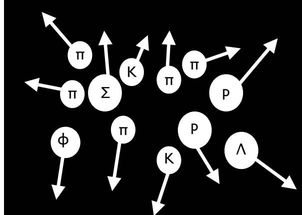
A: The reaction produces more hadrons

Strong interaction

$E_{kin} >> m_p$



...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

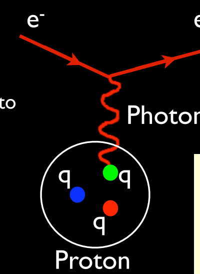


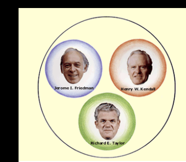
Steven Weinberg (1972)
(from F. Wilczek, hep-th/9609099)

Strong interaction

late 1960's

At high energies, electrons appear to scatter of 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 (±1/3, ±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)

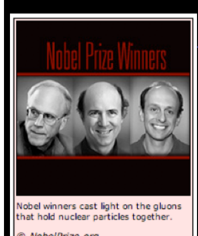
Quarks spin = 1/2

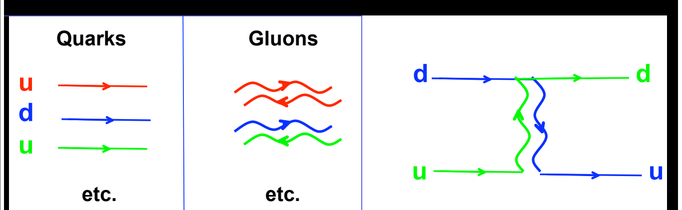
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

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

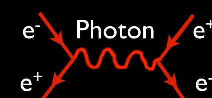
Strong (color) spin = 1

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

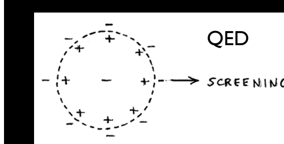




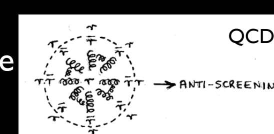
QED vs QCD



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

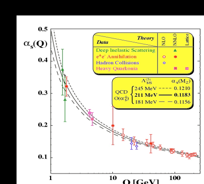


"Polarization of the Vacuum"



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

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

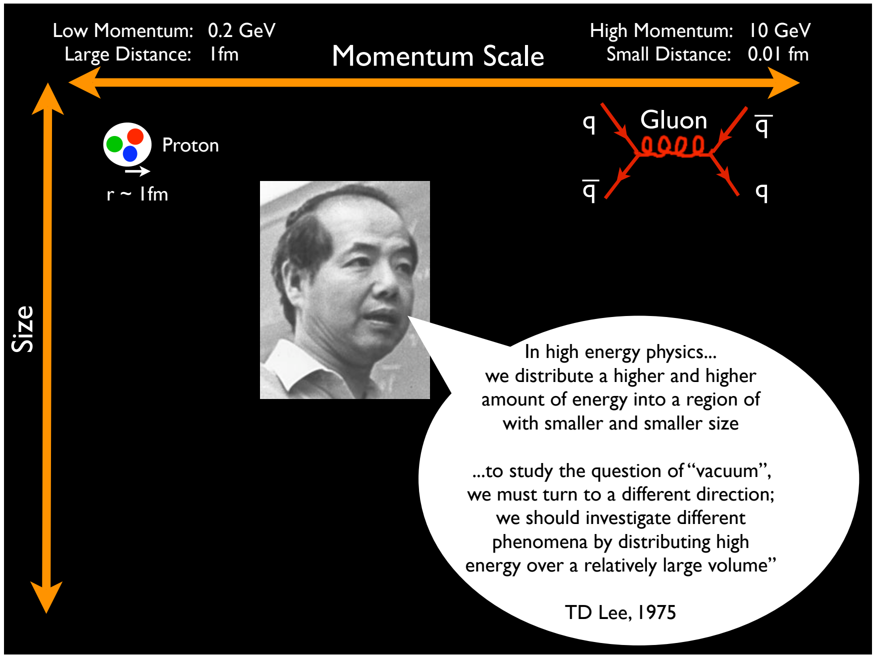


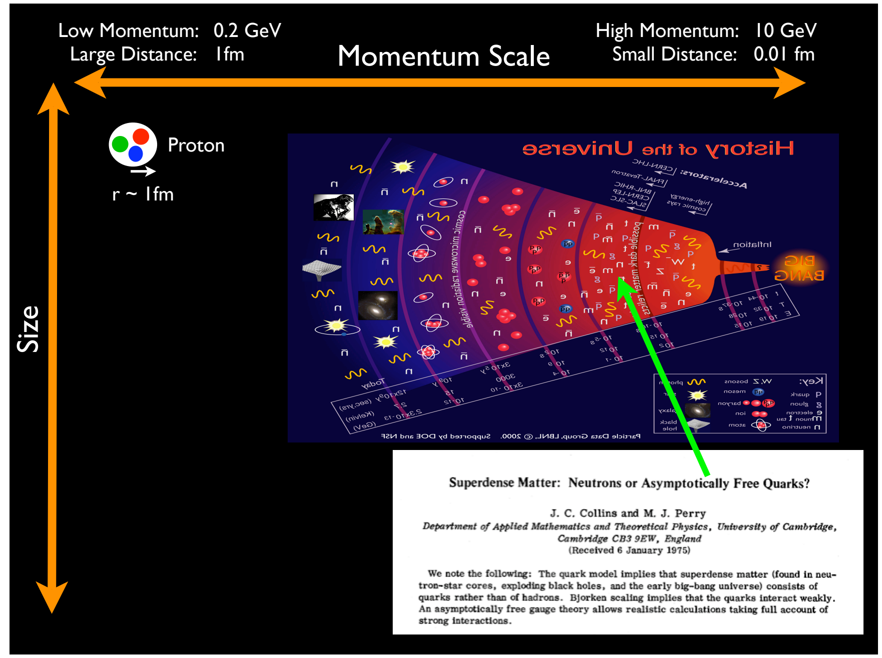
Gluons (unlike photons) carry (color-) charge

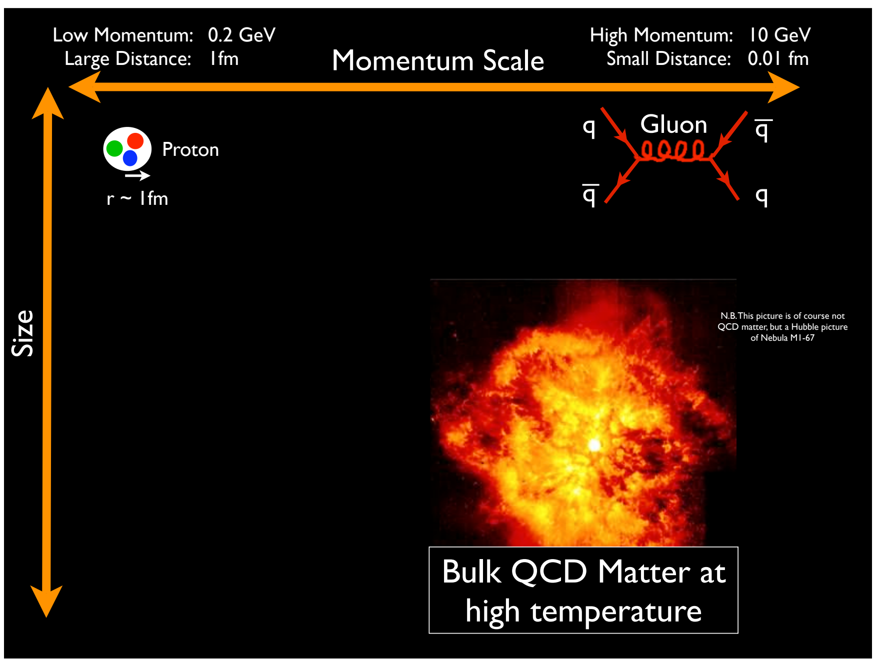
Contribution of Gluons (Spin 1) to vacuum fluctuations leads to **anti-screening**

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
Size
Proton
r ~ 1fm
q
Gluon
q̄
q̄
q
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
Size
Proton
r ~ 1fm
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
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Size
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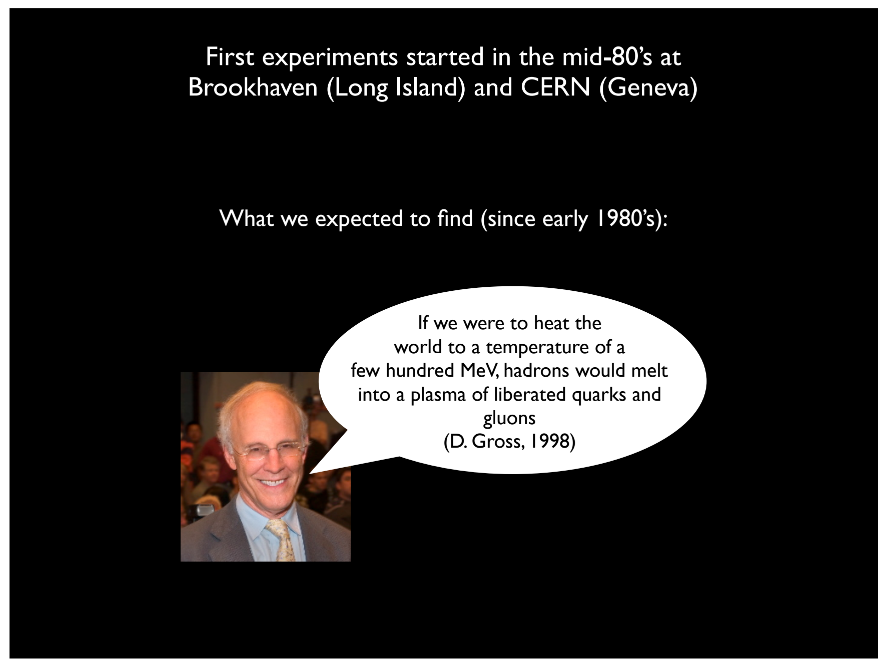
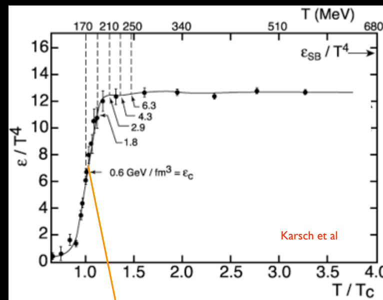
q
Gluon
q̄
q̄
q
N.B. This picture is of course not QCD matter, but a Hubble picture of Nebula M1-67
Bulk QCD Matter at high temperature


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



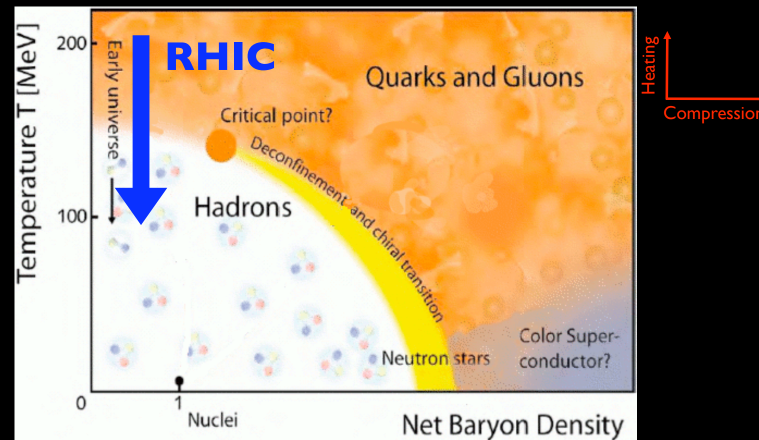
- **Numerical Calculations: Phase Transition at high T**
- **Deconfinement: Quark-Gluon Plasma**

$T_{critical}$ ~ 170 MeV ~ 2×10^{12}K

Energy density ~ 0.7 GeV/fm^3

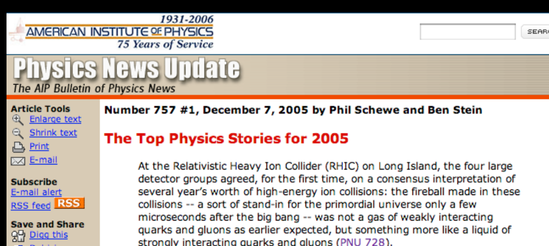
5 x nuclear matter density!

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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Number 757 #1, December 7, 2005 by Phil Schewe and Ben Stein

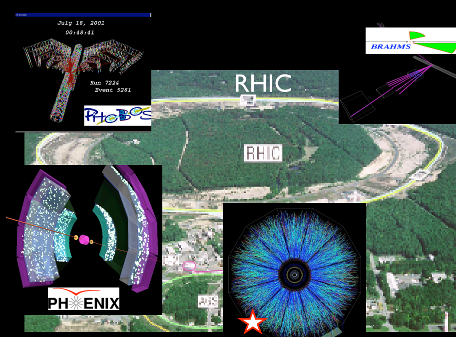
The Top Physics Stories for 2005

At the Relativistic Heavy Ion Collider (RHIC) on Long Island, the four large detector groups agreed, for the first time, on a consensus interpretation of several year's worth of high-energy ion collisions: the fireball made in these collisions -- a sort of stand-in for the primordial universe only a few microseconds after the big bang -- was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid of strongly interacting quarks and gluons (PNU 728).

"...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

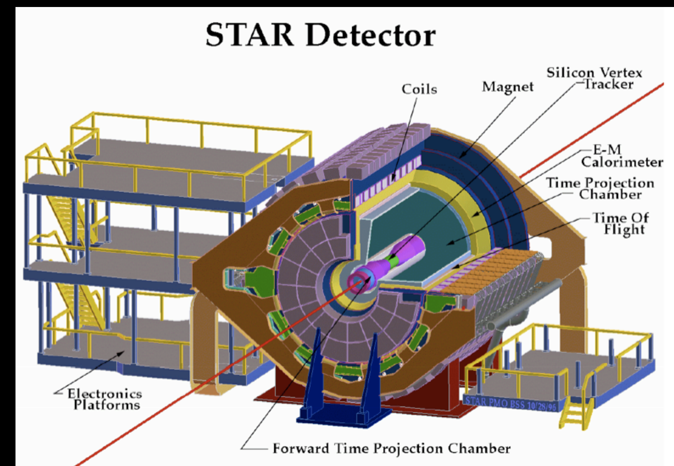
per nucleon-nucleon pair!

Heavy Ion Experiments at RHIC and LHC

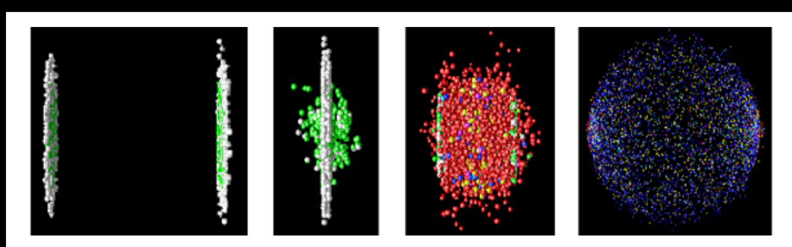
RHIC

	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

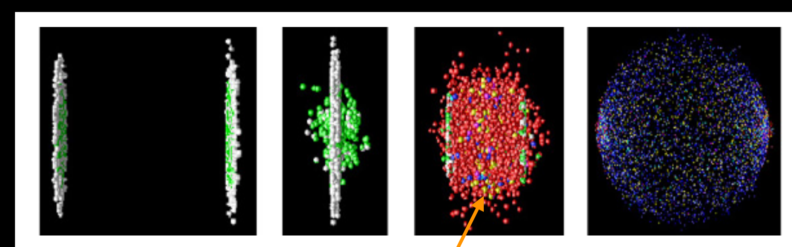


Heavy Ion Collision

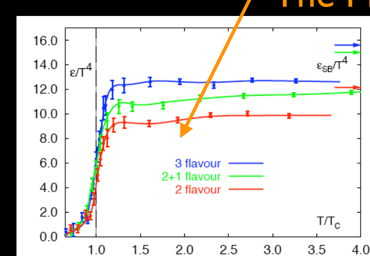


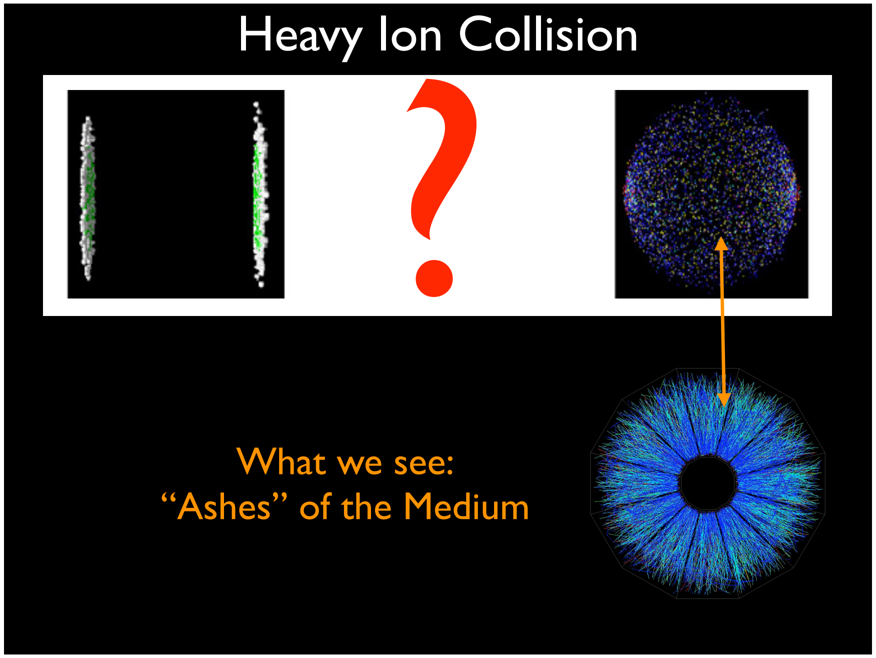
Time →

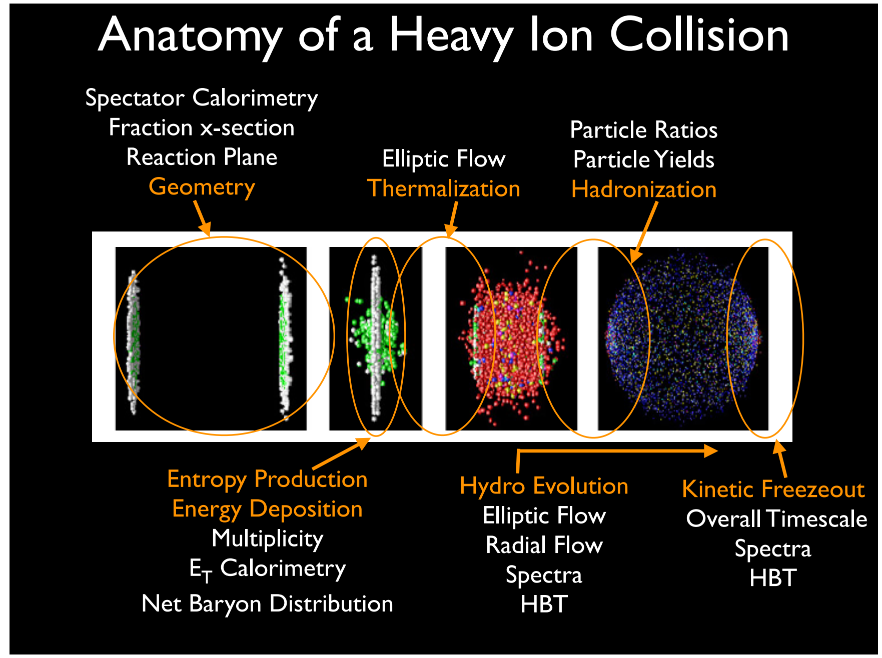
Heavy Ion Collision

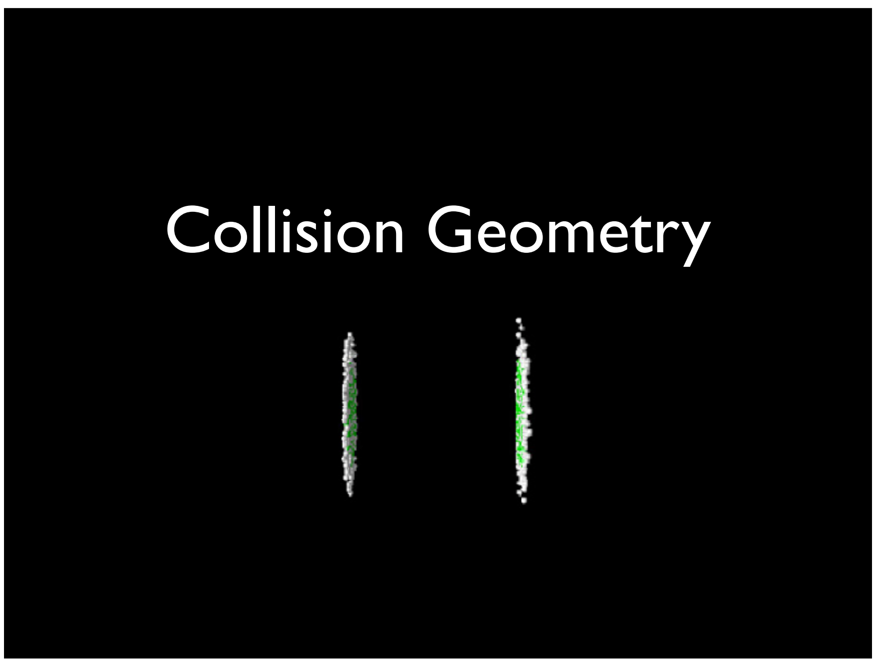


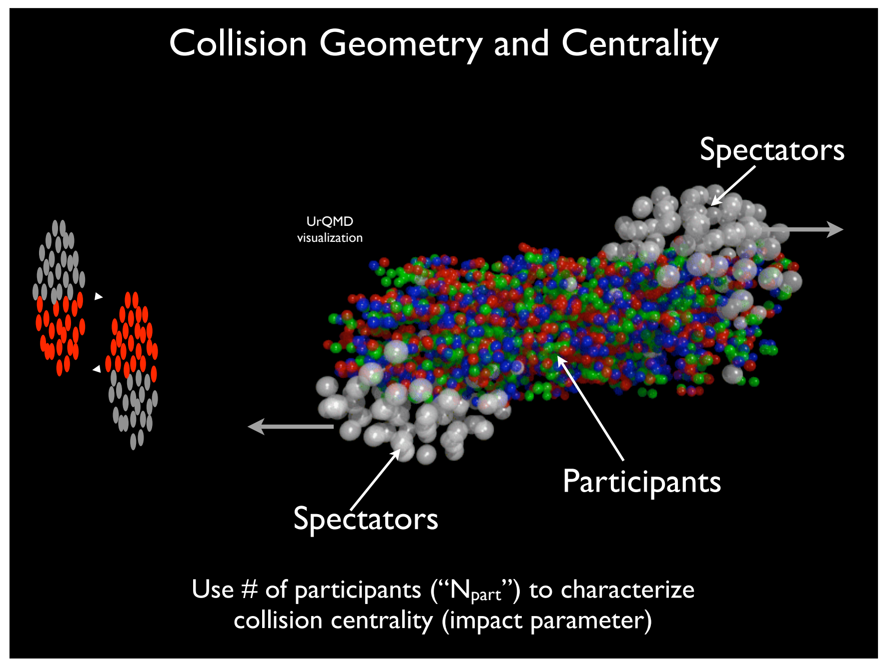
The Medium



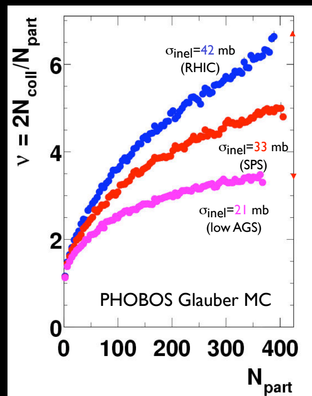

Heavy Ion Collision
?
What we see:
"Ashes" of the Medium


Anatomy of a Heavy Ion Collision
Spectator Calorimetry
Fraction x-section
Reaction Plane
Geometry
Elliptic Flow
Thermalization
Particle Ratios
Particle Yields
Hadronization
Entropy Production
Energy Deposition
Multiplicity
E_T Calorimetry
Net Baryon Distribution
Hydro Evolution
Elliptic Flow
Radial Flow
Spectra
HBT
Kinetic Freezeout
Overall Timescale
Spectra
HBT


Collision Geometry

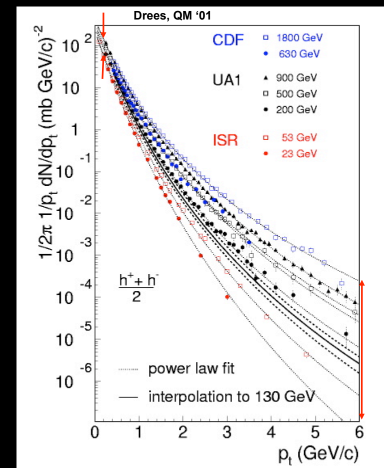

Collision Geometry and Centrality
UrQMD visualization
Spectators
Participants
Spectators
Use # of participants ("N_{part}") to characterize collision centrality (impact parameter)

"Soft" and "Hard" Physics



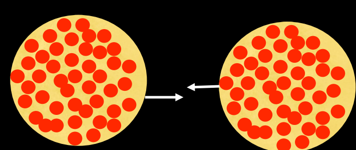
Use centrality to change Volume, but also collisions/nucleon

"Soft" and "Hard" Physics



"Participant" Scaling

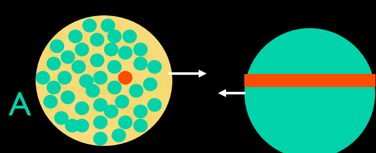
Volume



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

"Collision" Scaling

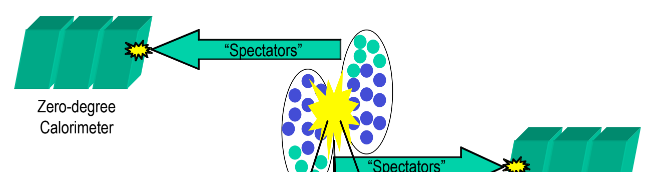
Point-like



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

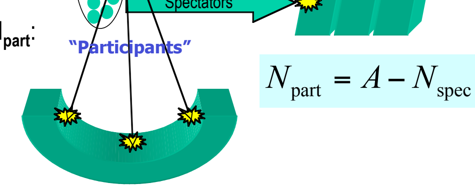
Measuring Centrality

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

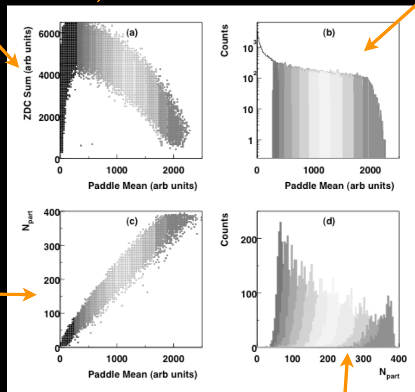


$$N_{part} = A - N_{spec}$$

Measuring "Centrality"

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

Bin data in Multiplicity

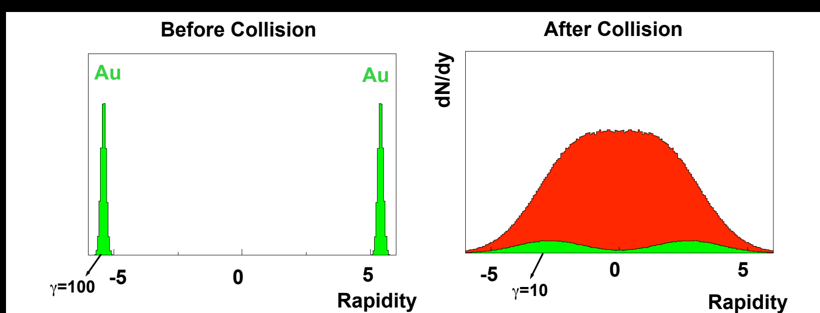


Multiplicity monotonic with N_{part}

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

A few definitions

Rapidity



Rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

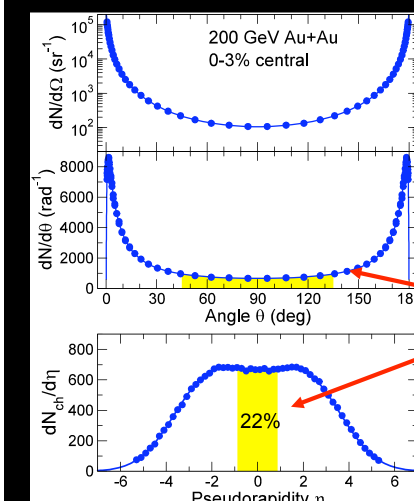
Measures longitudinal velocity

Logarithmic: CMS region is magnified

Lorentz-boost in beam-direction: Shift in y

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

Angular Distribution



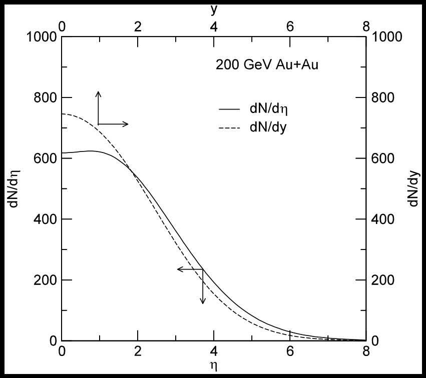
B. Back, Breckenridge '05

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

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



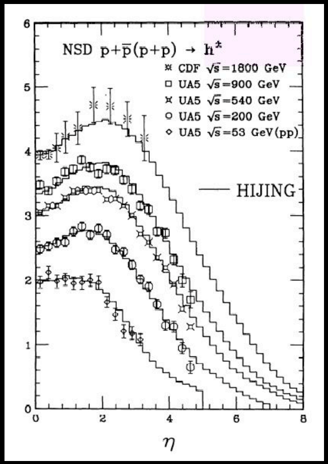
$$\eta = -\ln\tan\theta/2$$

Things to remember

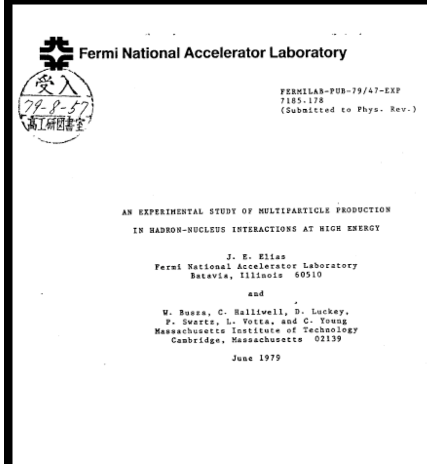
- Characterize centrality by number of participants N_{part} (~ Volume) or number of collisions
- Use rapidity to describe longitudinal phase space
- Approximate rapidity with pseudo-rapidity (not identical!)

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

Pseudo-Rapidity Distributions in p+p



Centrality Dependence in p+A



Fermi National Accelerator Laboratory

FERMILAB-PUB-79/47-EXP
7185.178
(Submitted to Phys. Rev.)

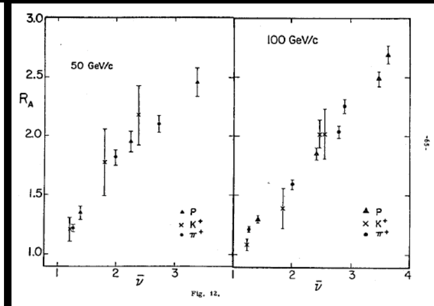
AN EXPERIMENTAL STUDY OF MULTIPARTICLE PRODUCTION
IN HADRON-NUCLEUS INTERACTIONS AT HIGH ENERGY

J. E. Elias
Fermi National Accelerator Laboratory
Batavia, Illinois 60510

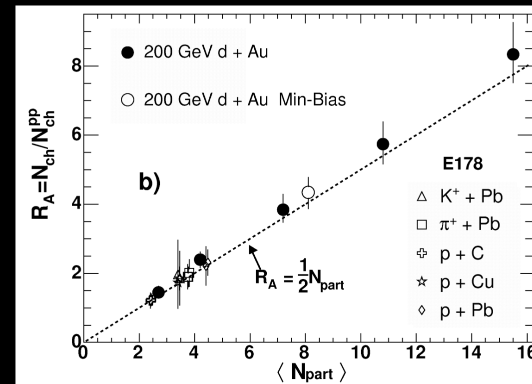
and

W. Busza, C. Halliwell, D. Luckey,
P. Swartz, L. Votta, and C. Young
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

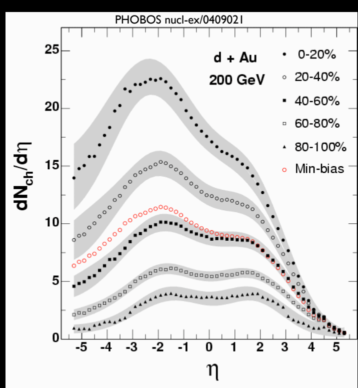
June 1979

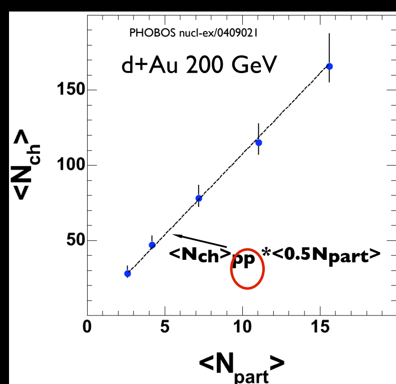


Npart Scaling in d+Au

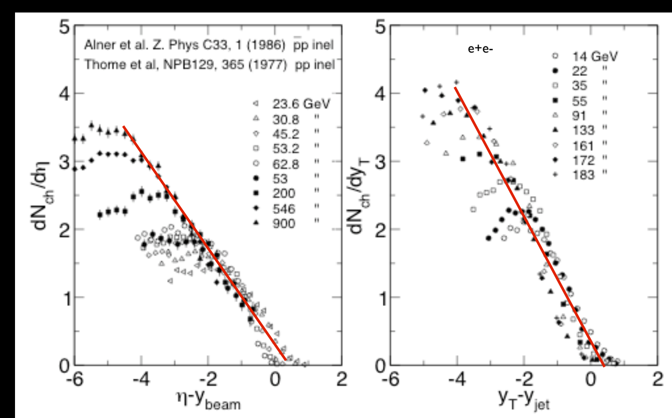


Npart Scaling in d+Au



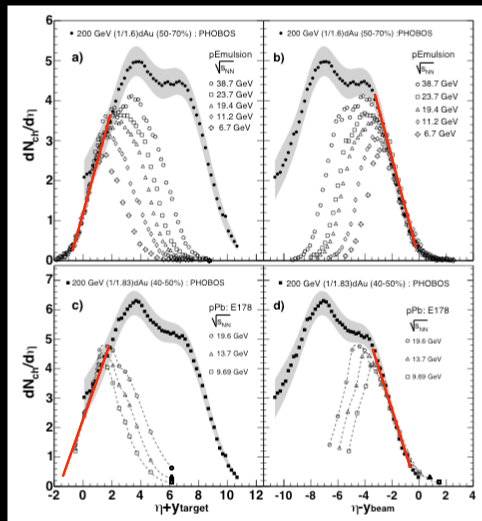


Limiting Fragmentation

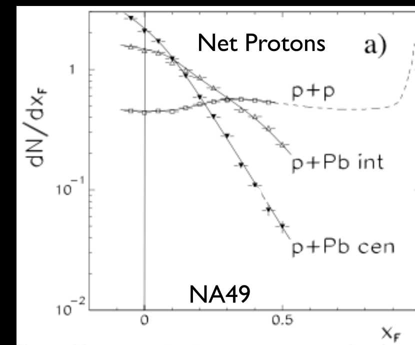


Particle production in restframe of one of the colliding particles

Limiting Fragmentation in d+Au



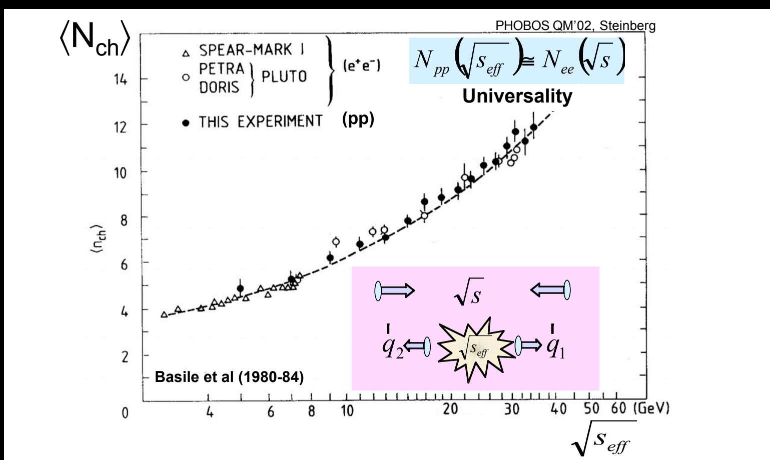
“Baryon-Stopping” in p+p and p+A



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

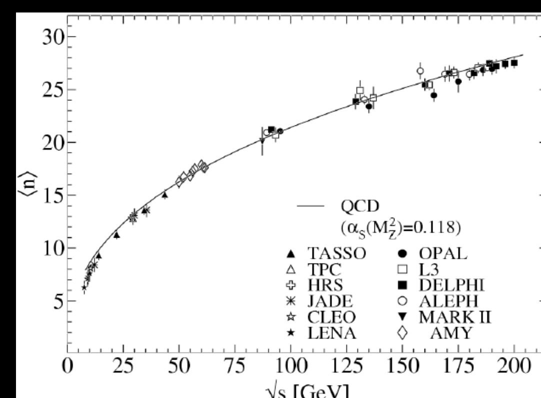
Defines available energy for particle production

Leading Particle Effect



Subtract energy of leading protons to define effective energy

pQCD Prediction of total multiplicity

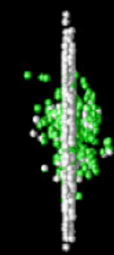


Perturbative QCD can predict energy dependence of total multiplicity. Non-perturbative transition from partons to hadrons hidden in fragmentation functons

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

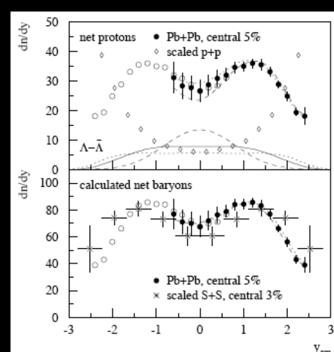


Net Baryon Distributions

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

(NA49 Collaboration)

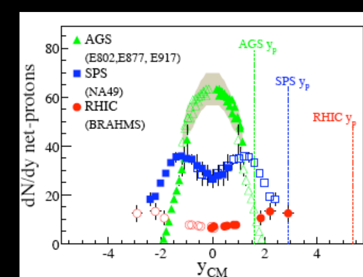
arXiv:nucl-ex/9810014 v3 15 Feb 1999

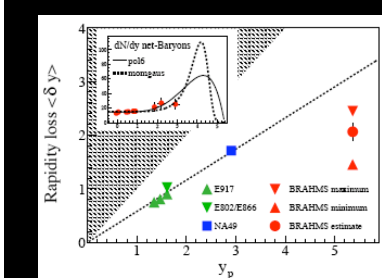


Nuclear Stopping in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

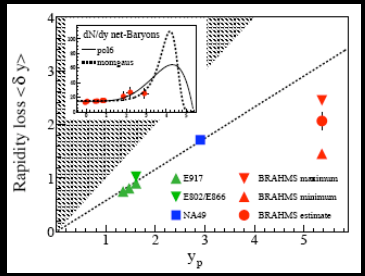
The BRAHMS Collaboration

arXiv:nucl-ex/0312023 v2 3 Sep 2004





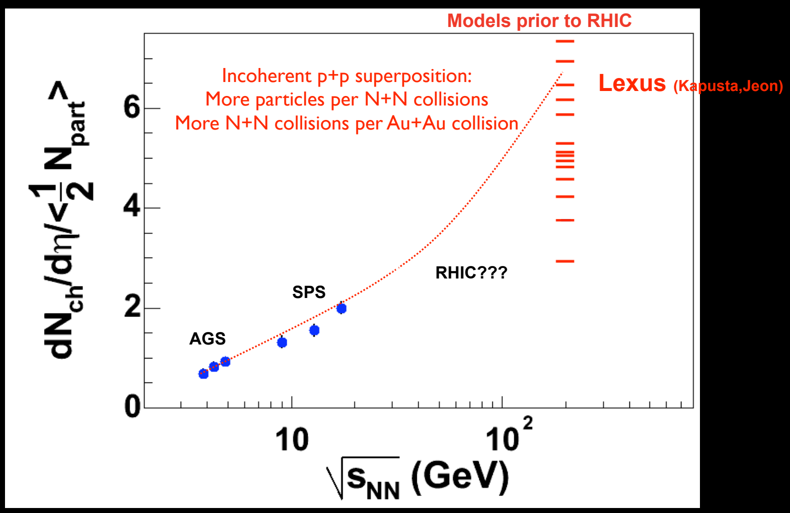
Things to remember



- 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 $\sqrt{s} = 56$ 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.Białas[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.Czyż[4], B.Dąbrowski[3], M.P.Decowski[5], M.Despet[3], P.Fita[5], J.Fitch[5], M.Friedl[5], K.Gałuszka[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.Hołyński[3], B.Holzman[7], E.Johnson[9], J.Kane[5], J.Katzy[5,7], W.Kita[3], J.Kotuła[3], H.Kraner[2], W.Kucewicz[7], P.Kulinich[5], C.Law[5], M.Lemler[8], J.Ligocki[3], W.T.Lin[6], S.Manly[9,10], D.McLeod[7], J.Michałowski[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.Strączek[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.Woźniak[3], A.H.Wuosmaa[1], B.Wysłouch[5], K.Zalewski[4], P.Żychowski[3]
(PHOBOS collaboration)
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[2] Chemistry Department, Brookhaven National Laboratory, Upton, NY 11973-5000
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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.

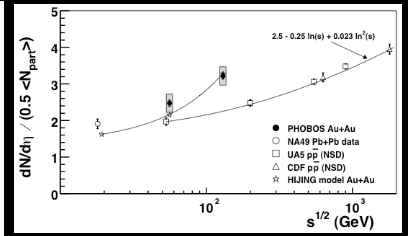
PACS numbers: 25.75.-q

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.

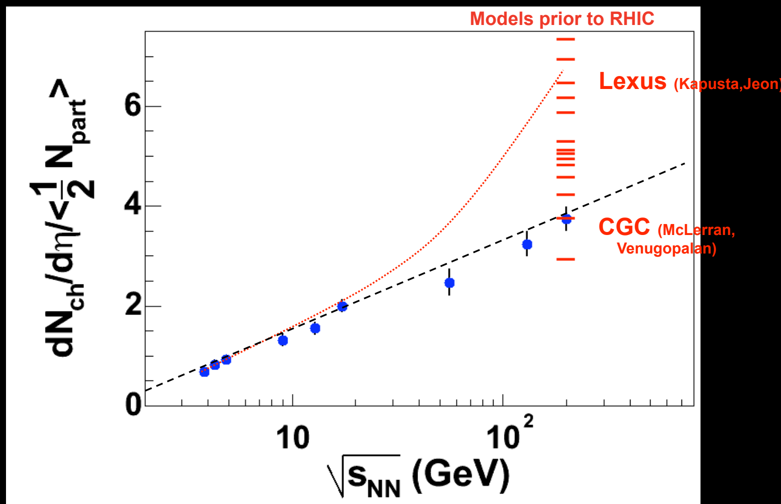
Studying the dependence of charged particle densities on energy and system size provides information on the interplay between hard parton-parton scattering processes, which can be calculated using perturbative QCD, and soft processes, which are treated by phenomenological models that describe the non-perturbative 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

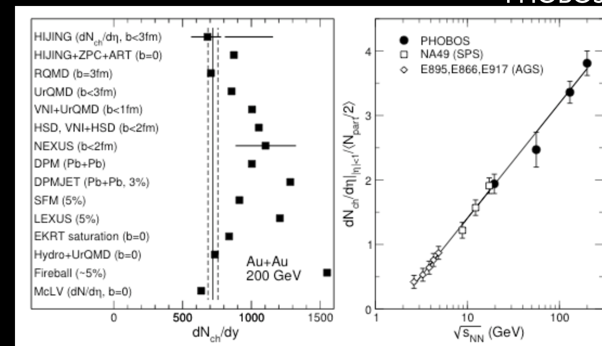


Particle Density near Mid-Rapidity



dN/dη@η=0

PHOBOS Whitepaper



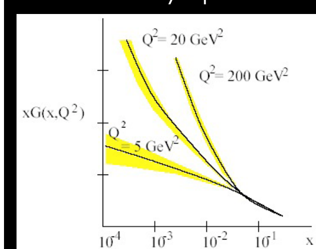
Oct 2004

Manifestation of Parton Saturation?

c.f. Blaizot, McLerran, Venugopalan, Kovchegov

Parton Saturation

Gluon density in proton



Fraction of momentum carried by gluon

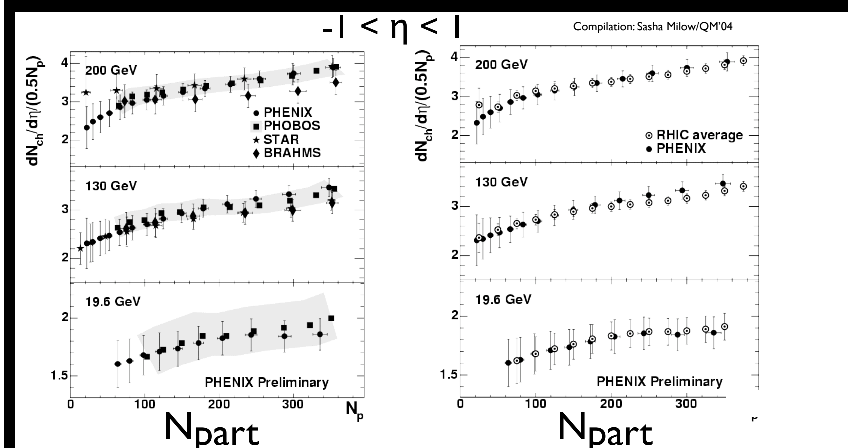
Idea(s):
Entropy is not "created" but "liberated" from gluon distributions

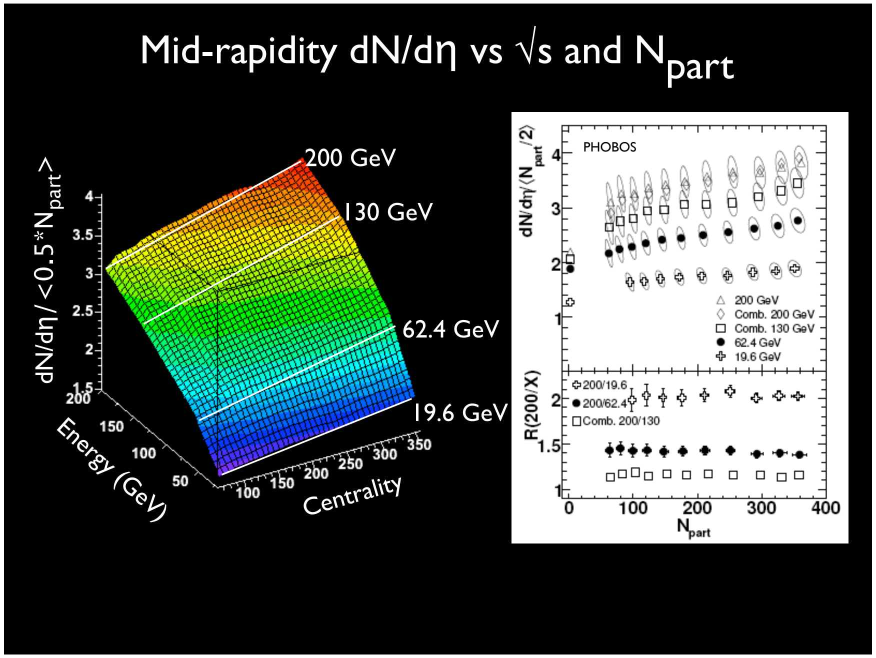
Gluon density increases with x, Q^2

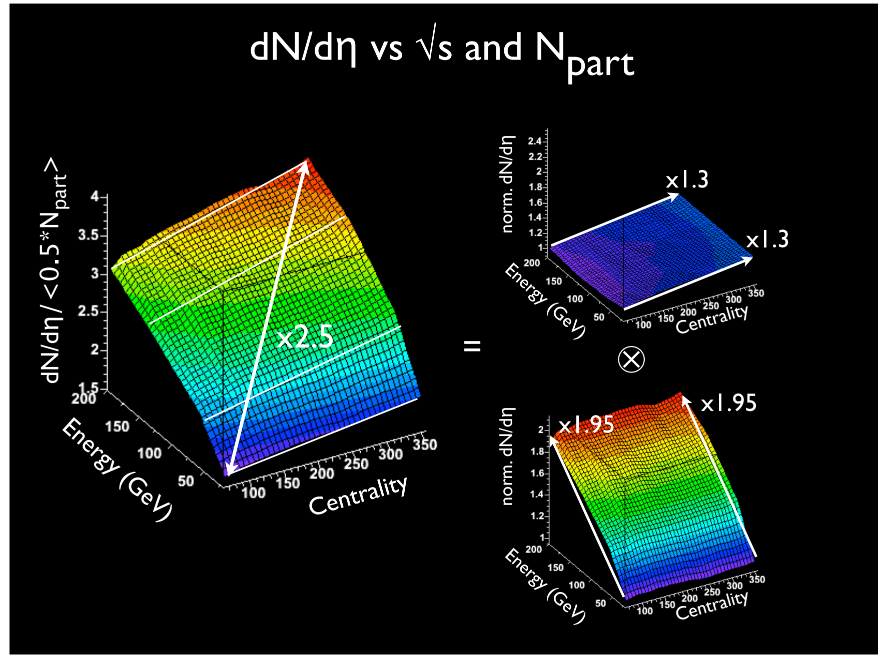
BUT: Gluons interact, limiting growth of gluon densities: Saturation

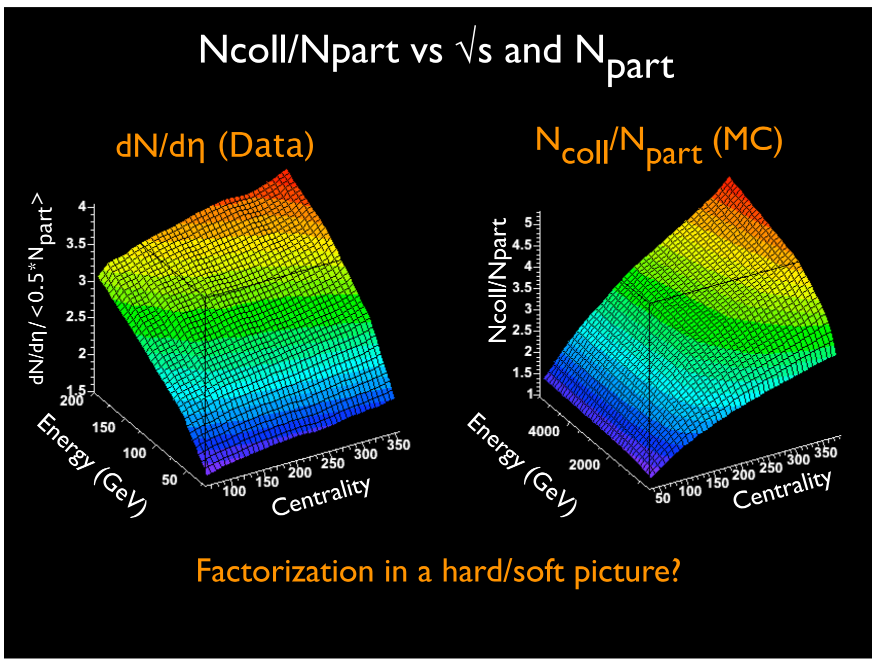
Low energy High energy

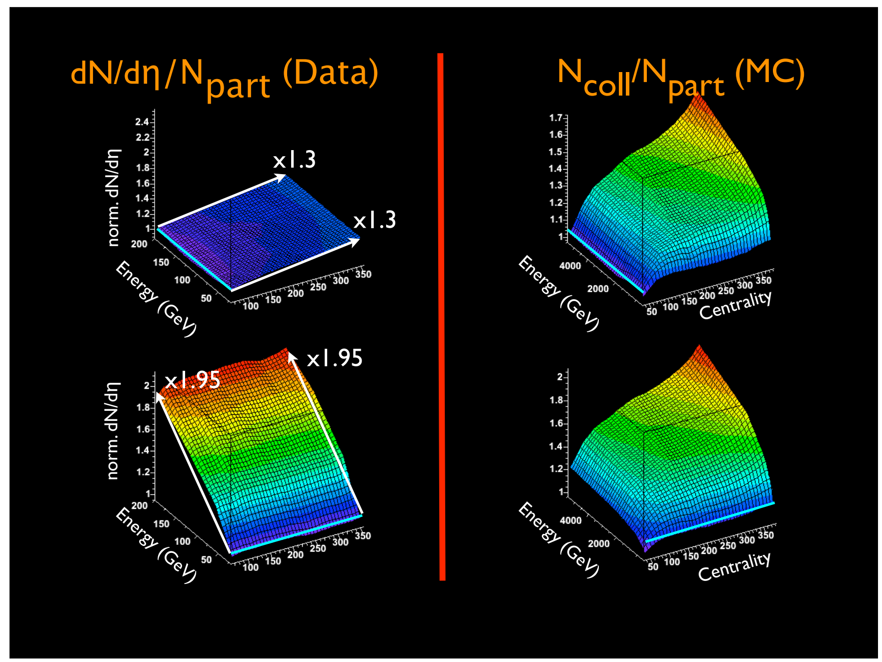
Mid-rapidity Multiplicity vs Centrality



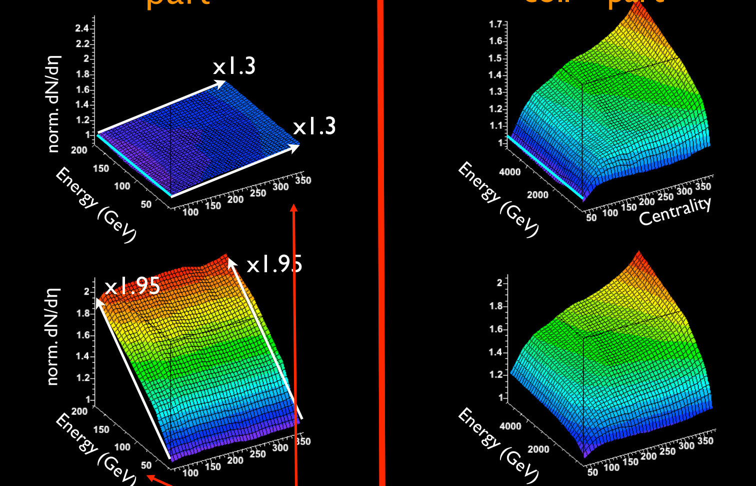

Mid-rapidity dN/dη vs √s and N_part
200 GeV
130 GeV
62.4 GeV
19.6 GeV
dN/dη/<0.5*N_part>
Energy (GeV)
Centrality
PHOBOS
200 GeV
Comb. 200 GeV
Comb. 130 GeV
62.4 GeV
19.6 GeV
200/19.6
200/62.4
Comb. 200/130
R(200/X)
N_part


dN/dη vs √s and N_part
dN/dη/<0.5*N_part>
x2.5
=
x1.3
x1.3
⊗
x1.95
x1.95
norm. dN/dη
Energy (GeV)
Centrality


Ncoll/Npart vs √s and N_part
dN/dη (Data)
N_coll/N_part (MC)
dN/dη/<0.5*N_part>
Ncoll/Npart
Energy (GeV)
Centrality
Factorization in a hard/soft picture?


dN/dη/N_part (Data)
N_coll/N_part (MC)
x1.3
x1.3
x1.95
x1.95
norm. dN/dη
Energy (GeV)
Centrality

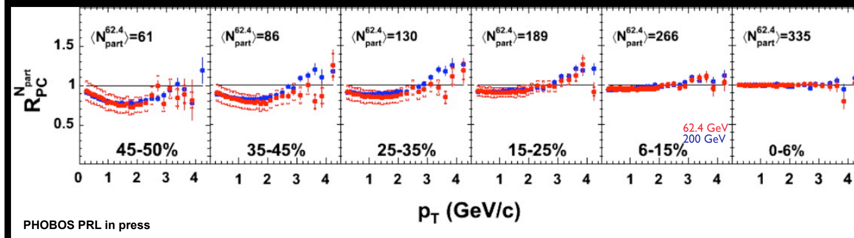
dN/dη/N_part (Data) — N_coll/N_part (MC)



$$\frac{1}{N_{\rm part}}\frac{dN^{AA}}{d\eta}\Big|_{\eta\sim 0} = N_0\sqrt{s}^{\lambda} N_{\rm part}^{\frac{1-\delta}{3\delta}}$$

Armesto, Salgado, Wiedemann hep-ph/0407018

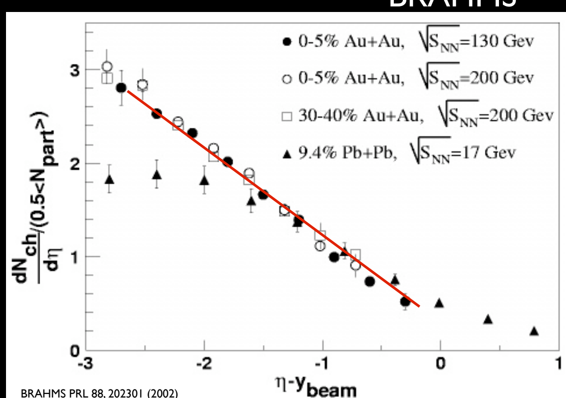
Factorization of transverse dynamics?



$$R_{PC}^{N_{part}} = \frac{\langle N_{part}^{0-6\%}\rangle}{\langle N_{part}\rangle}\,\frac{d^2N_{AA}/dp_T d\eta}{d^2N_{AA}^{0-6\%}/dp_T d\eta}$$

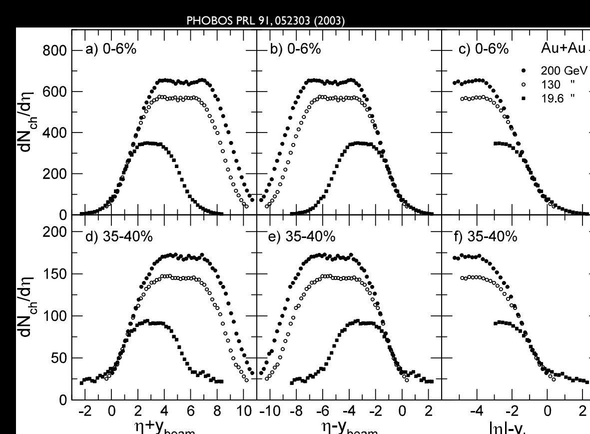
Limiting Fragmentation

BRAHMS

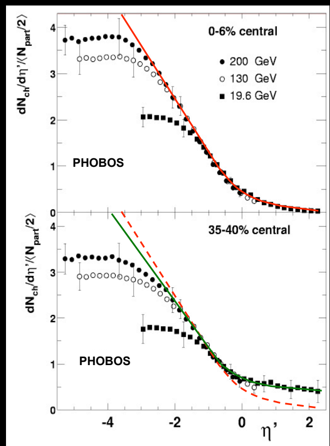


Particle production in restframe of one of the nuclei

Limiting Fragmentation cntd



Limiting Fragmentation vs Centrality



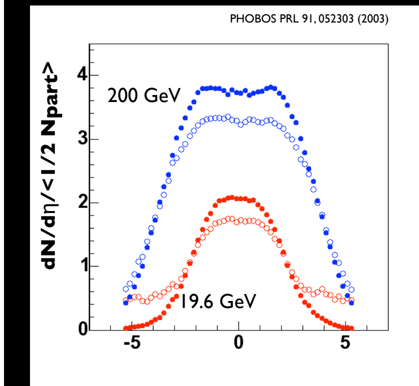
PHOBOS PRL 91, 052303 (2003)

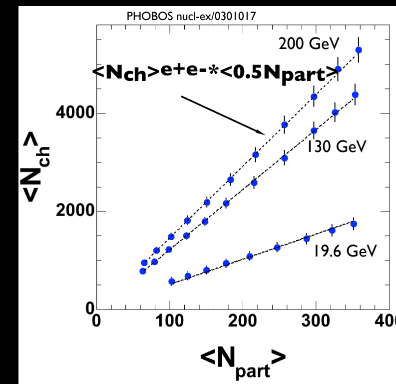
Different Limiting Curves for Central and Peripheral Data

But *both* energy-independent

Dominance of Geometry?

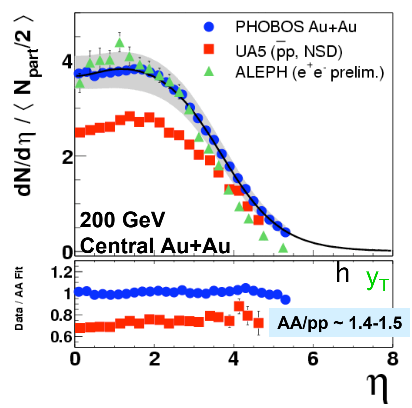
Total Multiplicity 〈N_{ch}〉 in Au+Au



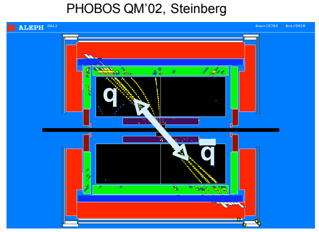


"N_{part} -Scaling"

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



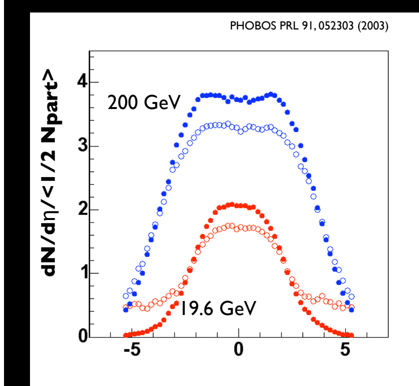
PHOBOS QM'02, Steinberg

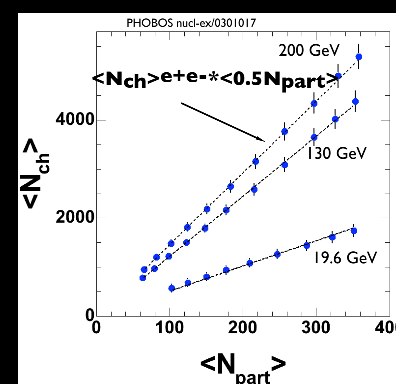


e^+e^- measures dN/dy_T (rapidity relative to "thrust" axis)

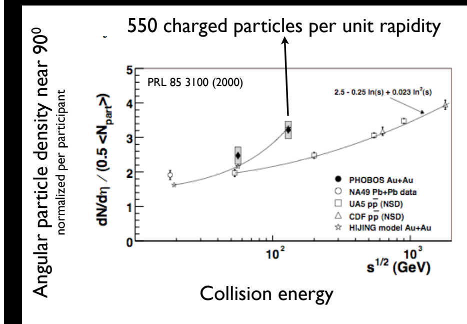
Surprising agreement in shape between AA/e^+e^-/pp

Total Multiplicity 〈N_{ch}〉 in Au+Au

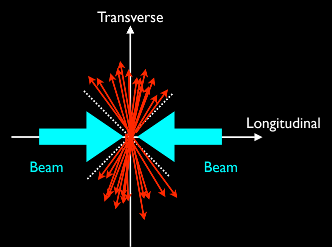




"N_{part} -Scaling"



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

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

Much larger than $\epsilon_{crit} \approx 0.7$ 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 (η=0, vs pT vs η)

Parton saturation?

But:

Correspondence of multiplicity in A+A vs e+e- vs p+p (1/2√s)

Everything points to early (initial) determination of multiplicity distributions