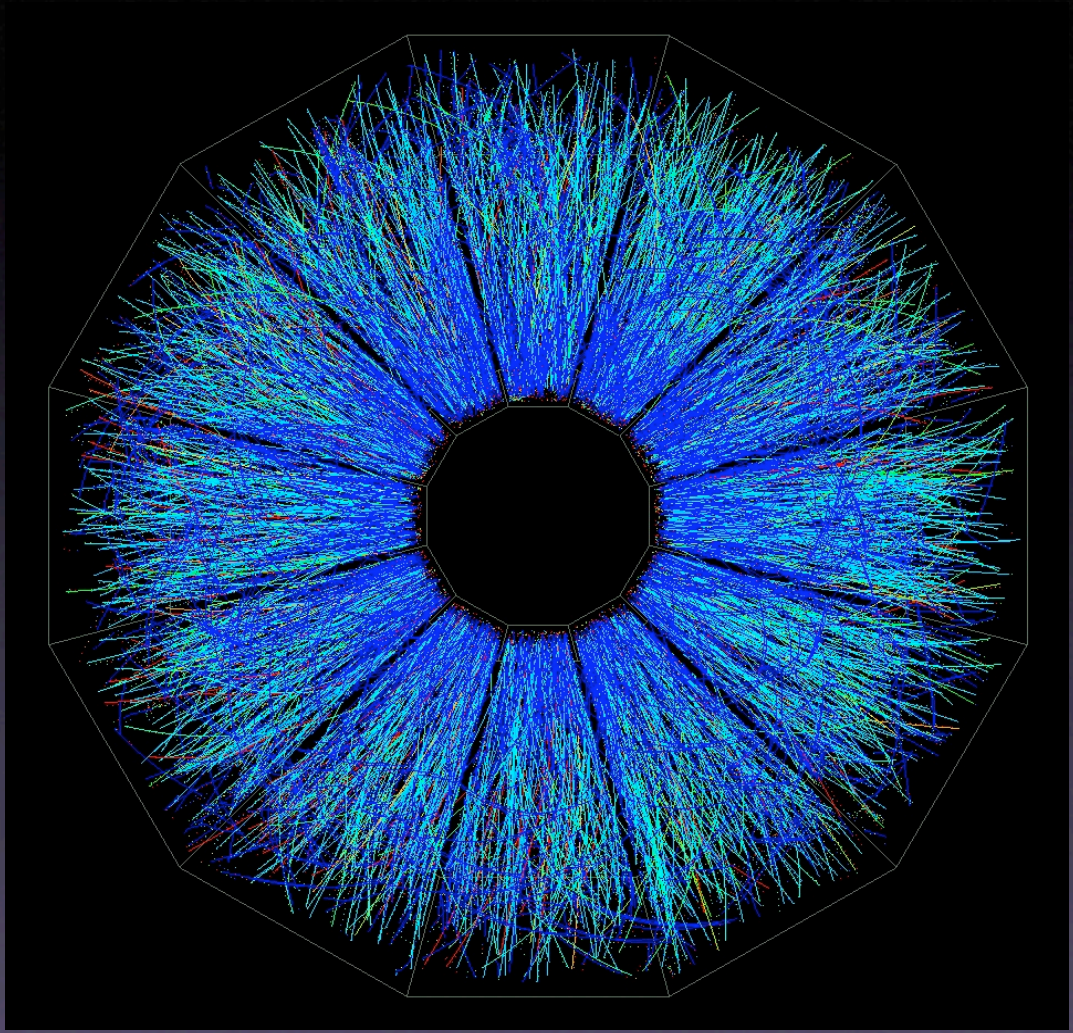
Hadron Multiplicities in High-Energy Collisions

Prague May 2005

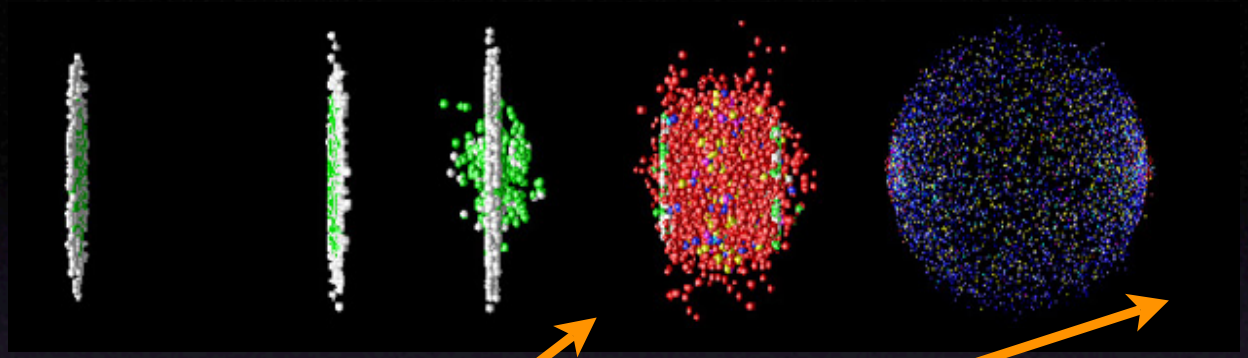
Gunther Roland
MIT

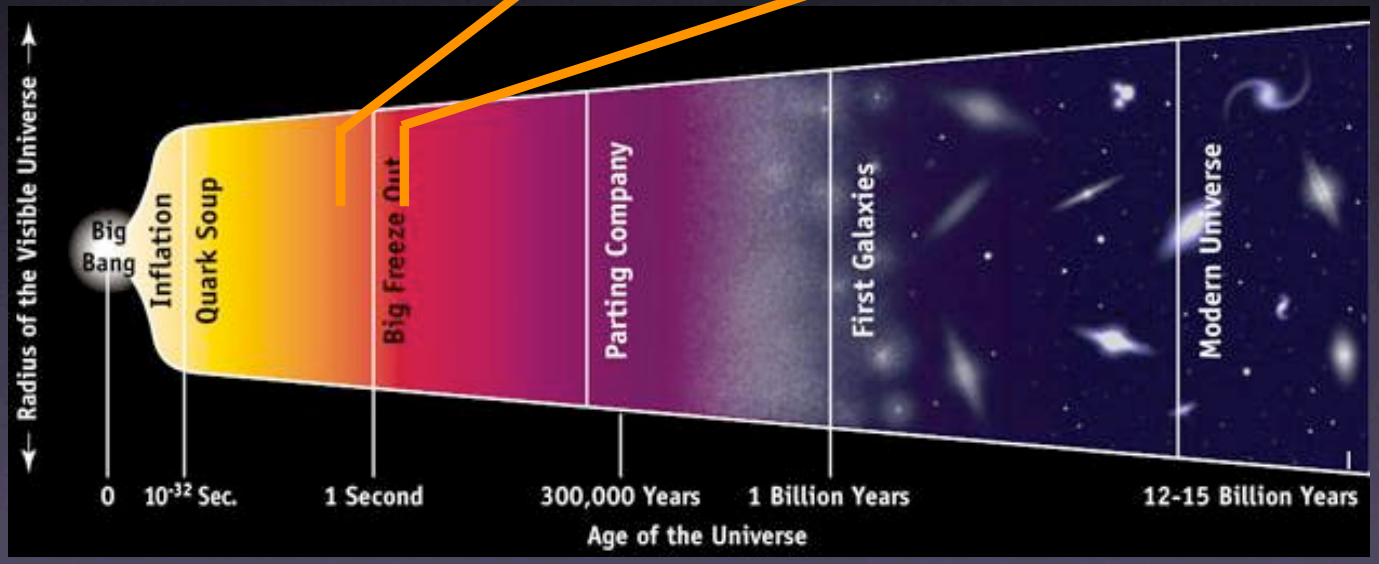
Au+Au Collision at RHIC



Going back in time

Heavy-Ion Collision



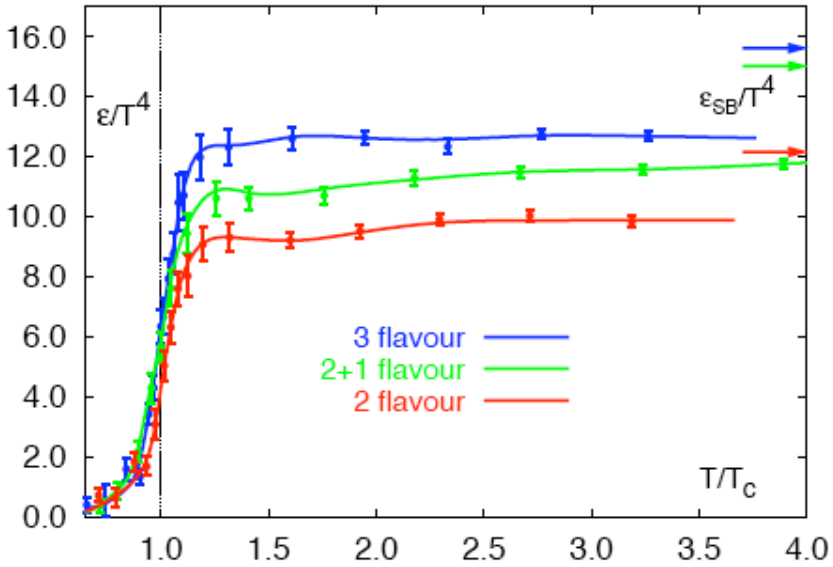


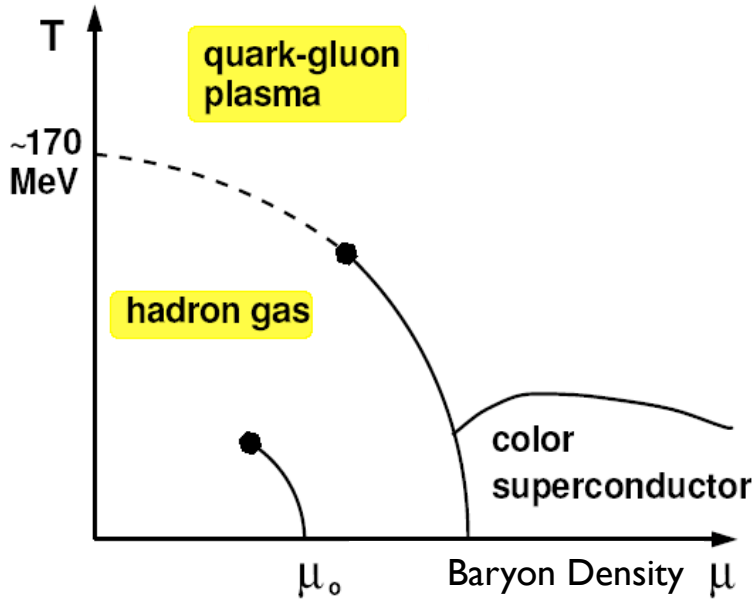
Universe

Quark Gluon Plasma

ε/T^4

(F. Karsch, hep-lat/0106019)





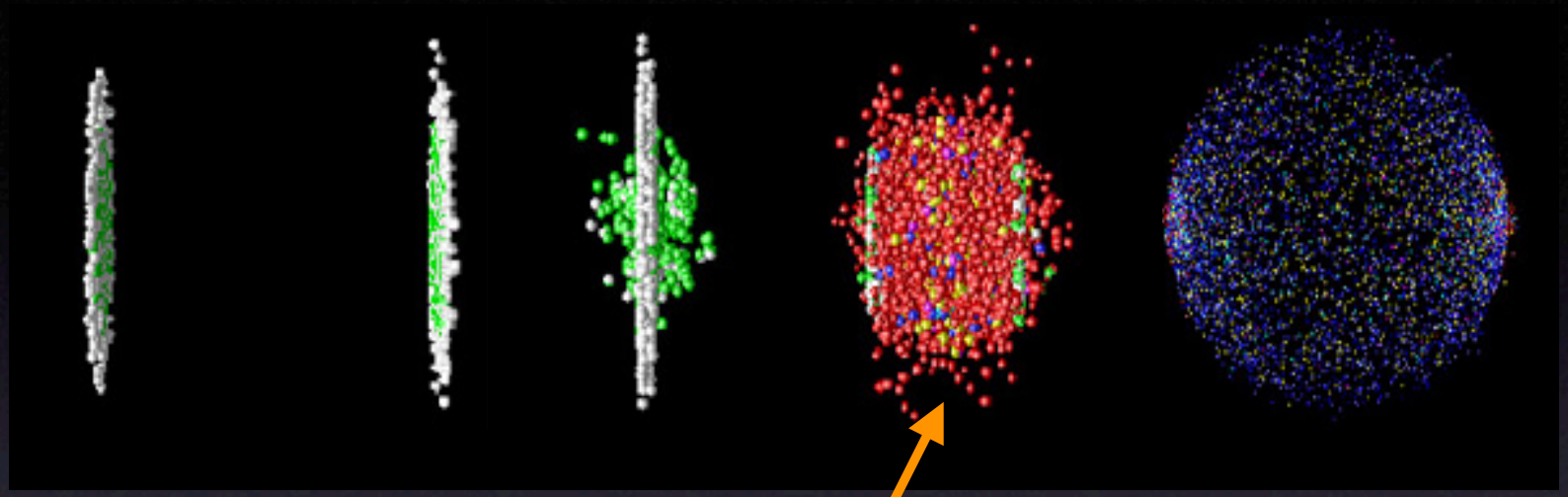
Phase Transition at high T

~ 170 MeV

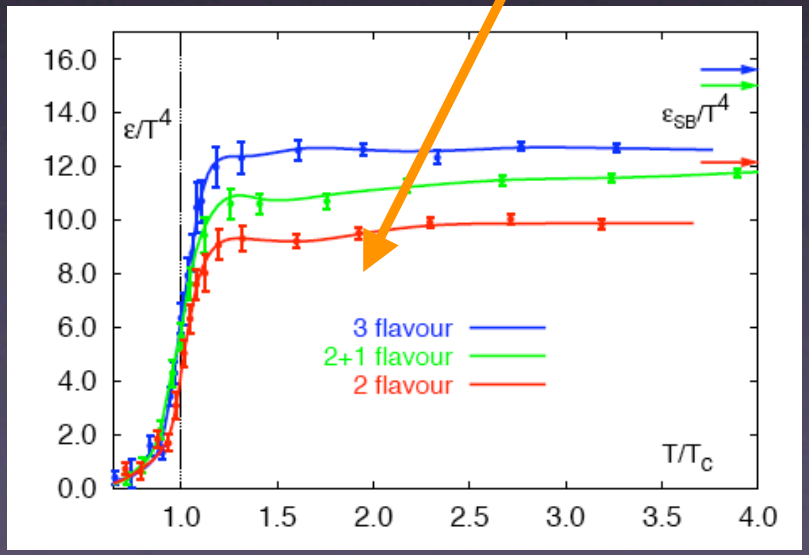
~ 1 GeV/fm^3

Deconfinement: Quark-Gluon Plasma

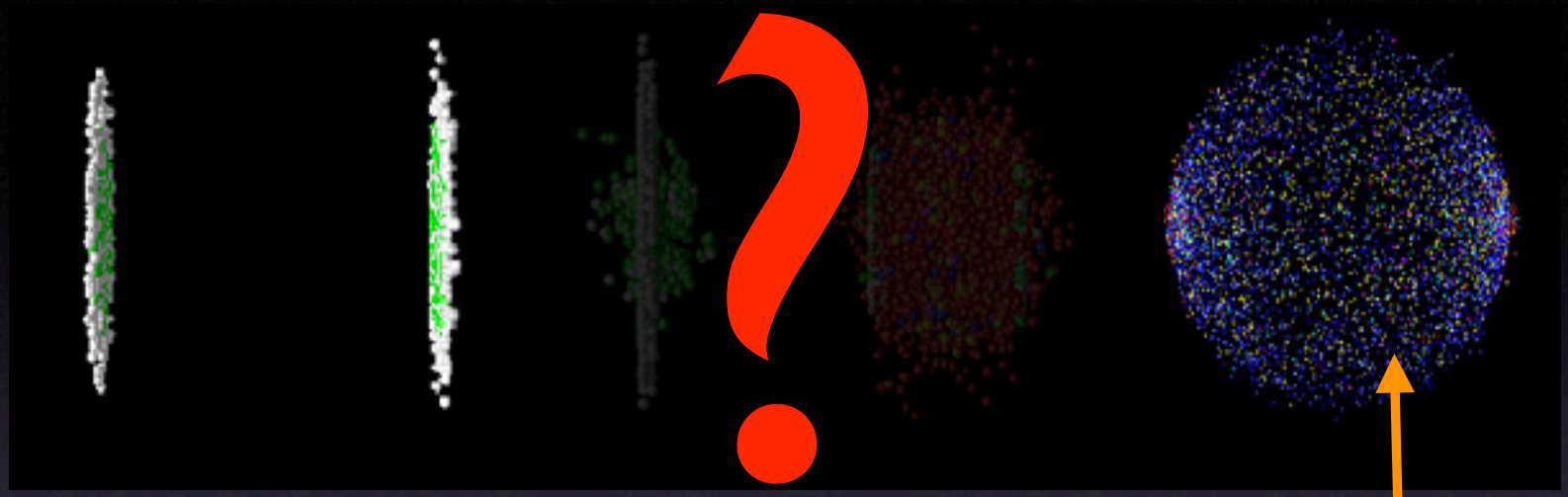
Heavy Ion Collision

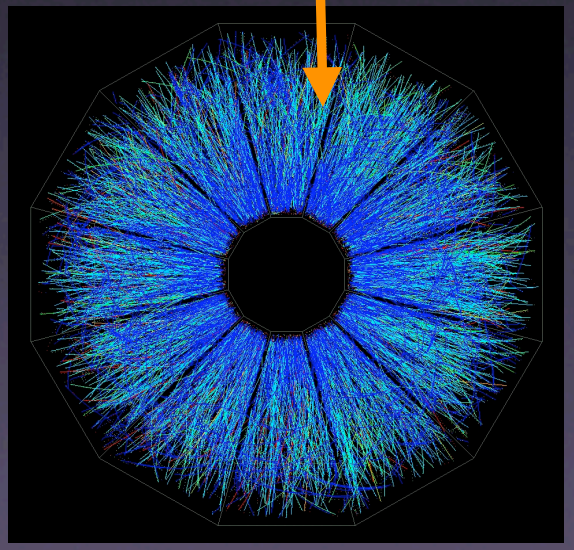


Medium? QGP?



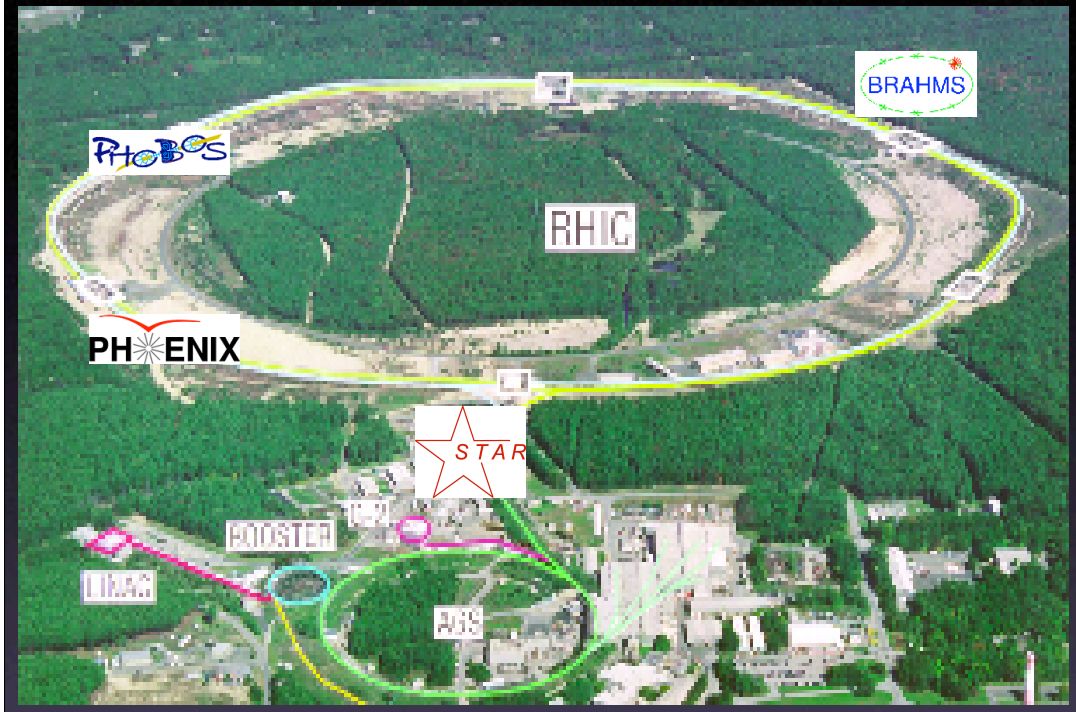
Heavy Ion Collision





What we see:
"Ashes" of the Medium

Relativistic Heavy Ion Collider



- 4 Experiments
  - 2 big
  - 2 small
- Complementary capabilities

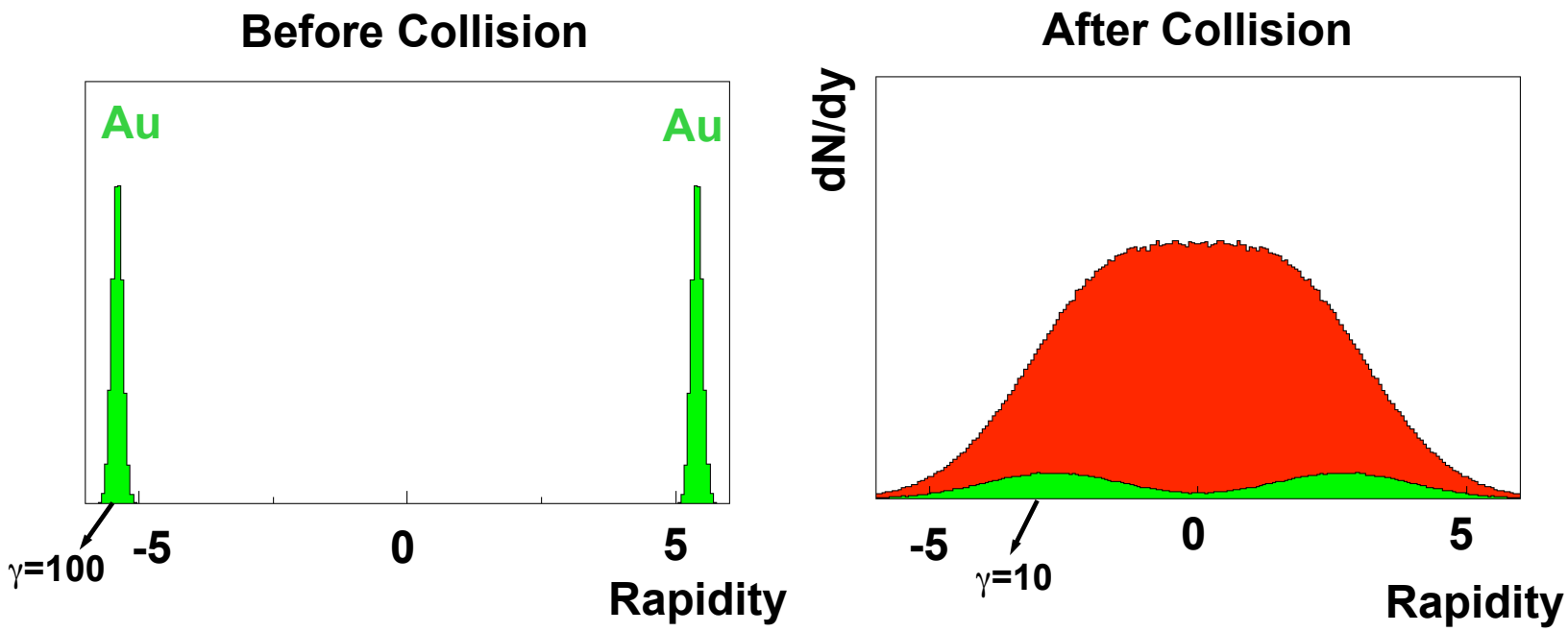
First Physics in '00

Versatile machine

- Au+Au ('00-'02, '04)
  - 19.6 GeV
  - 56 GeV
  - 62 GeV
  - 130 GeV
  - 200 GeV
- p+p ('02,'03,'05)
  - 200 GeV polarized
  - 410 GeV
- d+Au ('03)
  - 200 GeV
- Cu+Cu ('05)
  - 22 GeV
  - 62 GeV
  - 200 GeV

A few definitions

Rapidity



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

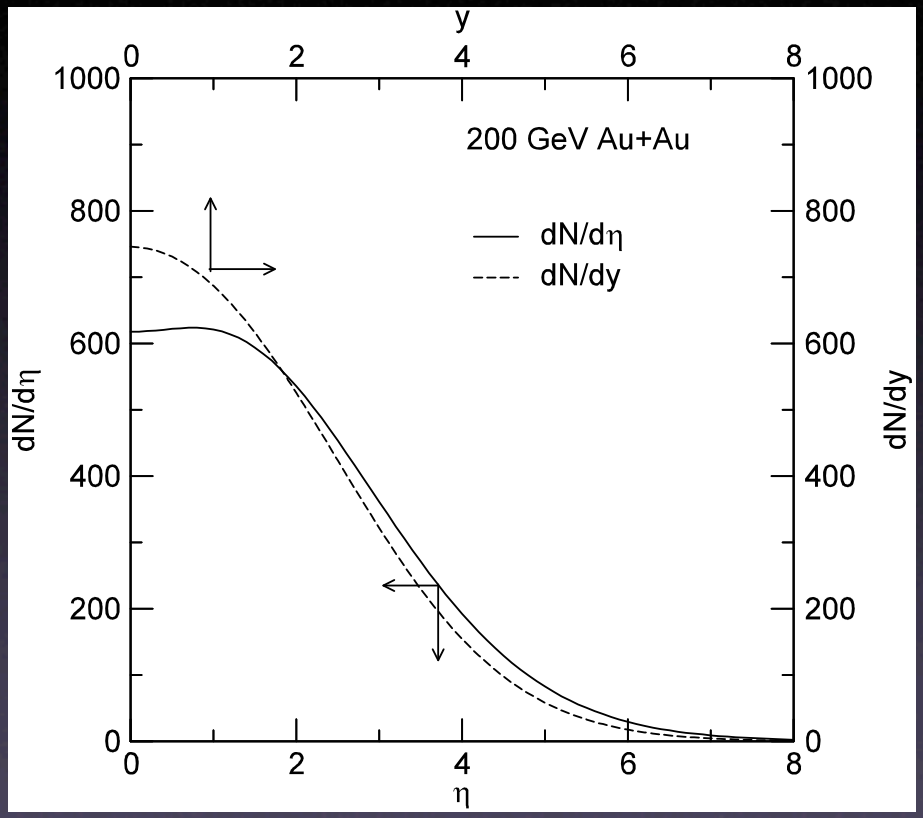
Measures longitudinal velocity

Logarithmic: CMS region is magnified

Lorentz-boost in beam-direction: Shift in y

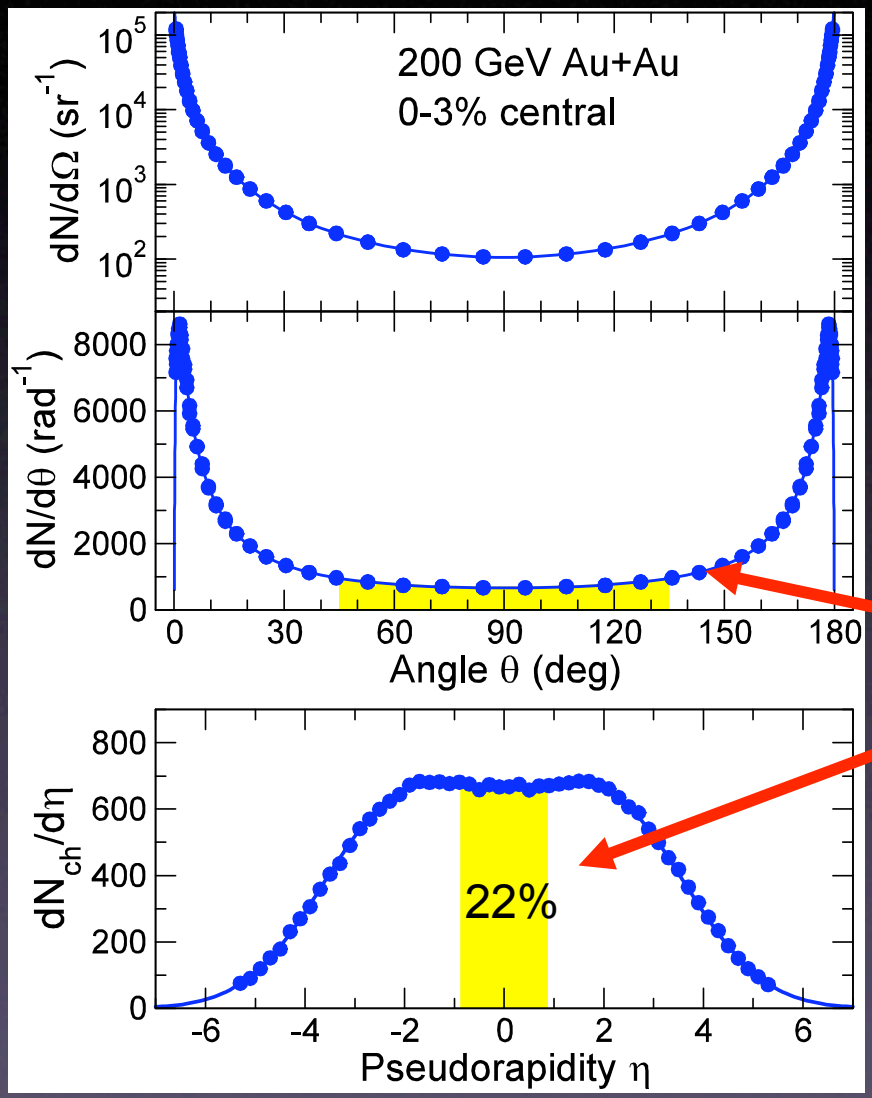
Rapidity vs Pseudo-Rapidity

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



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

Angular Distribution



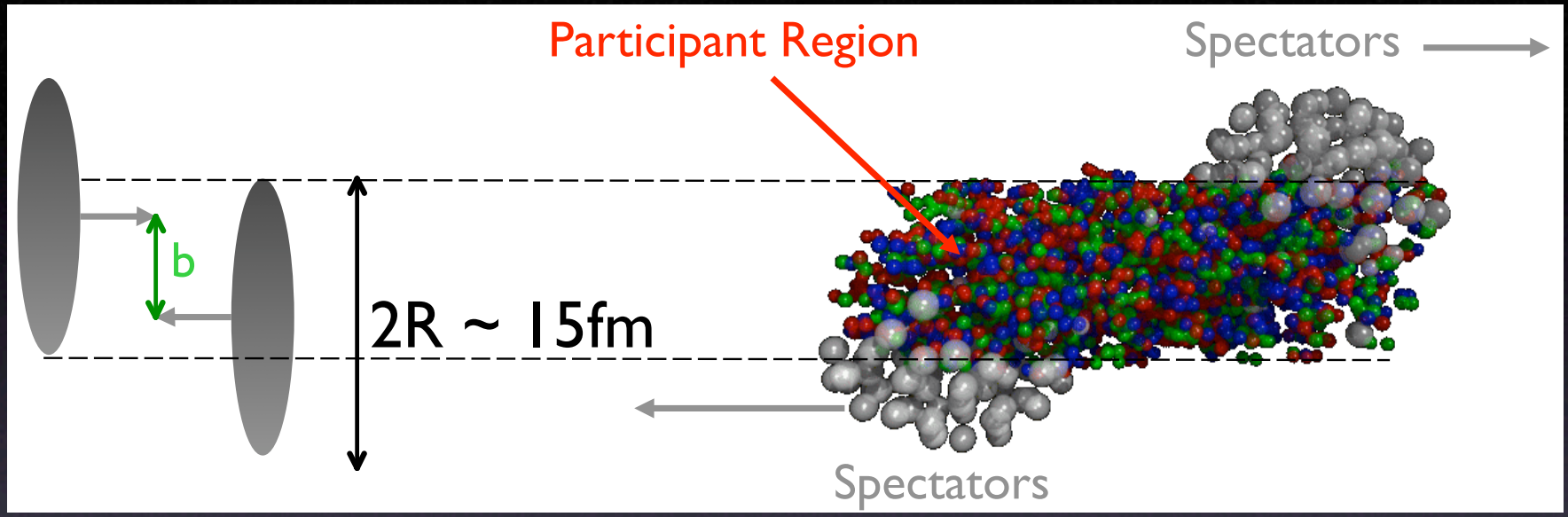
B. Back, Breckenridge '05

Only 22% emitted with $p_T > p_L$

However, these particles carry information about the densest region formed in the collisions

Collision Geometry

Collision Geometry



Smaller Impact Parameter b

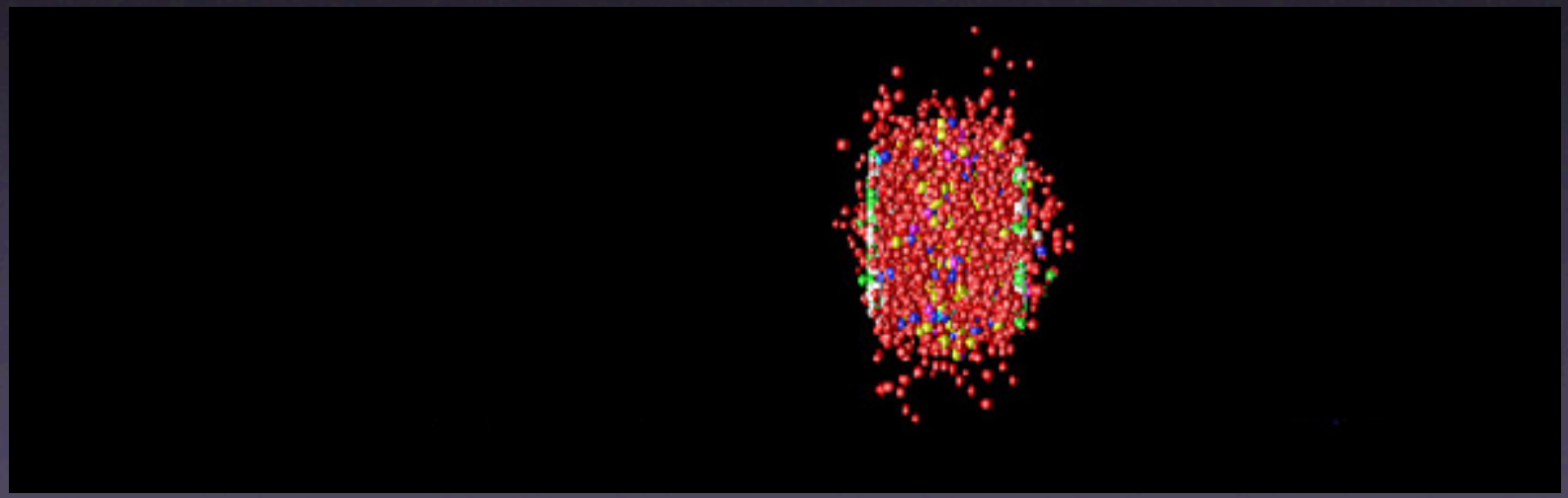
↓

More Participants (N_{part})

↓

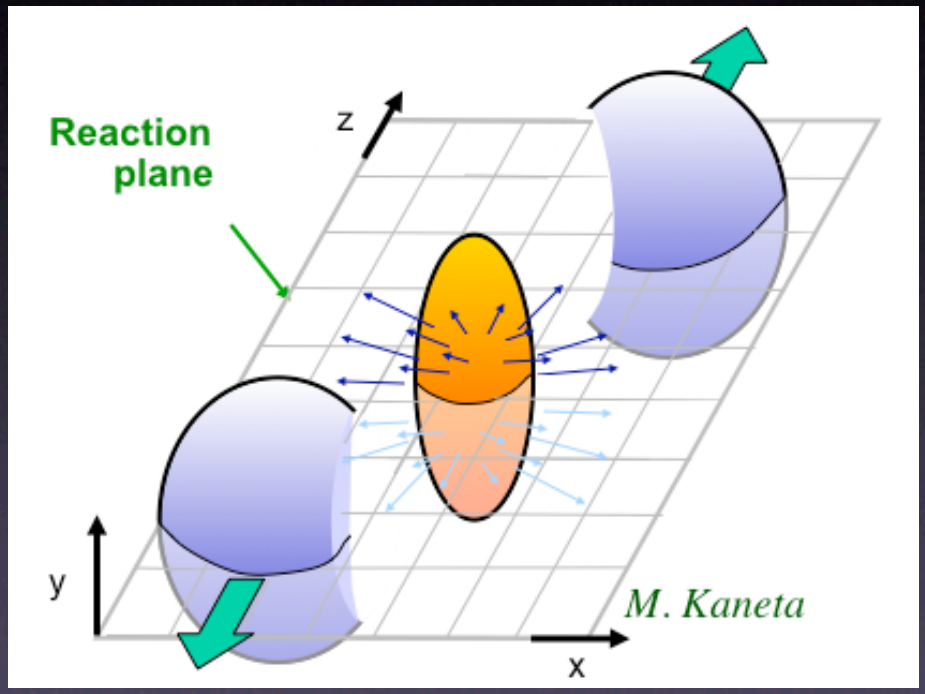
Bigger Collision System → More Produced Particles!

Dense *Matter*?



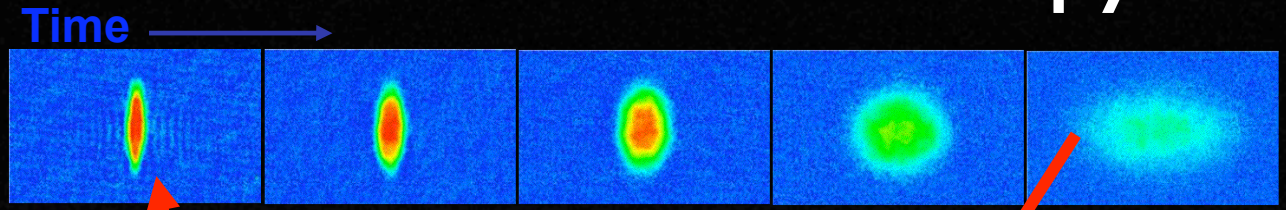
~1 fm/c

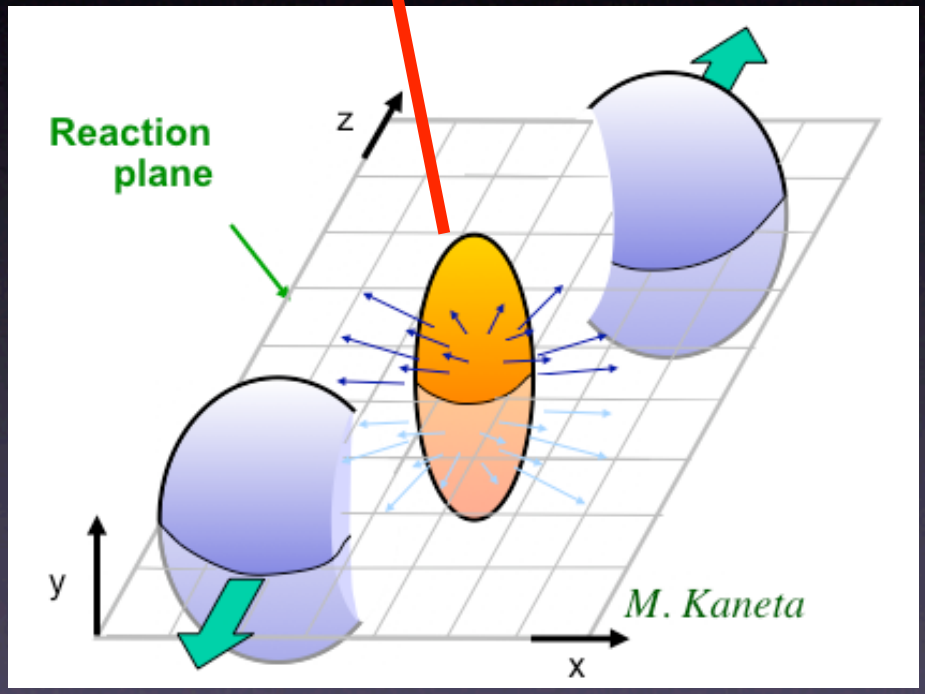
Azimuthal Anisotropy

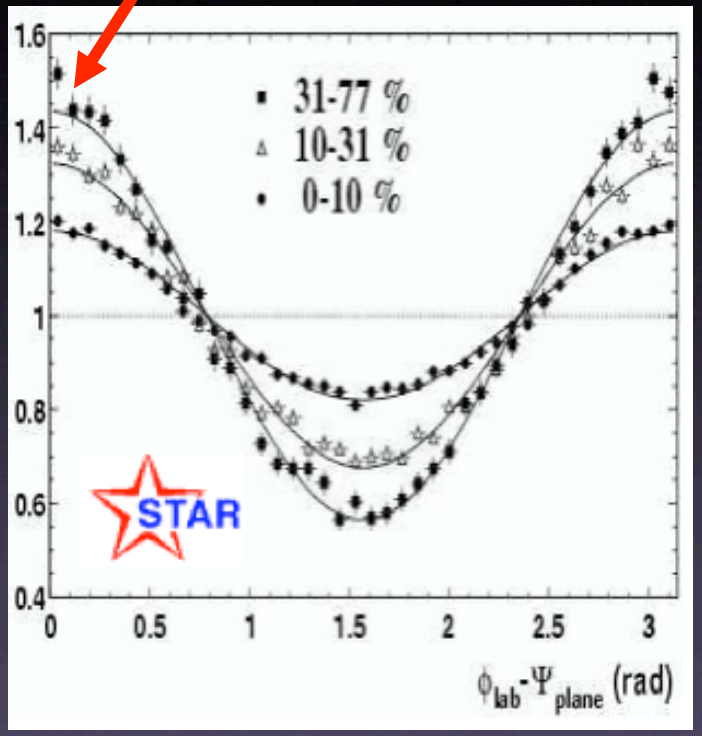


Initial State Anisotropy
Coordinate Space

Azimuthal Anisotropy







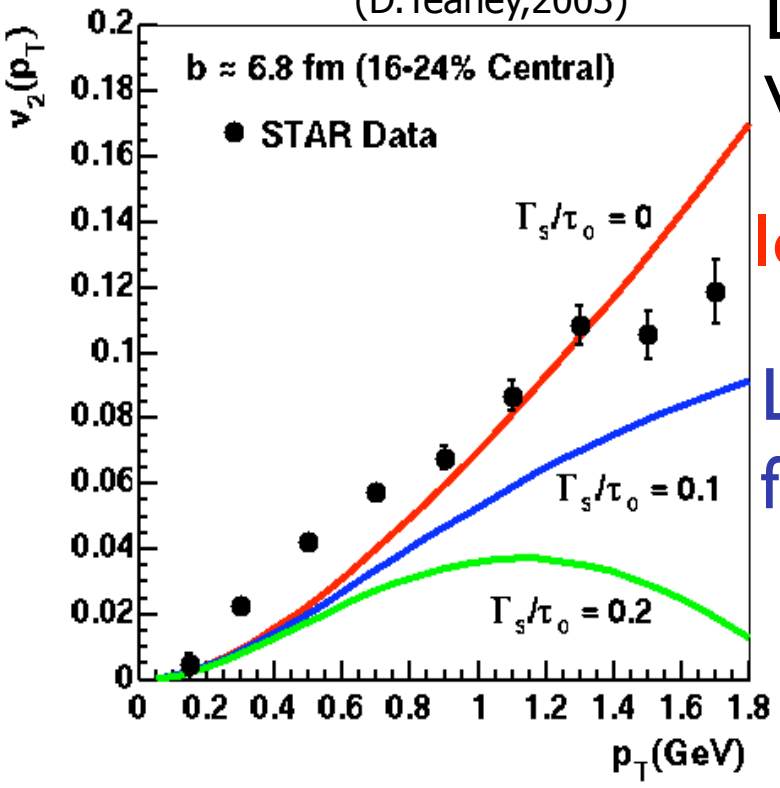
Initial State Anisotropy
Coordinate Space

Interaction!

Final State Anisotropy
Momentum Space

Hydrodynamics and Flow

(D.Teaney,2003)



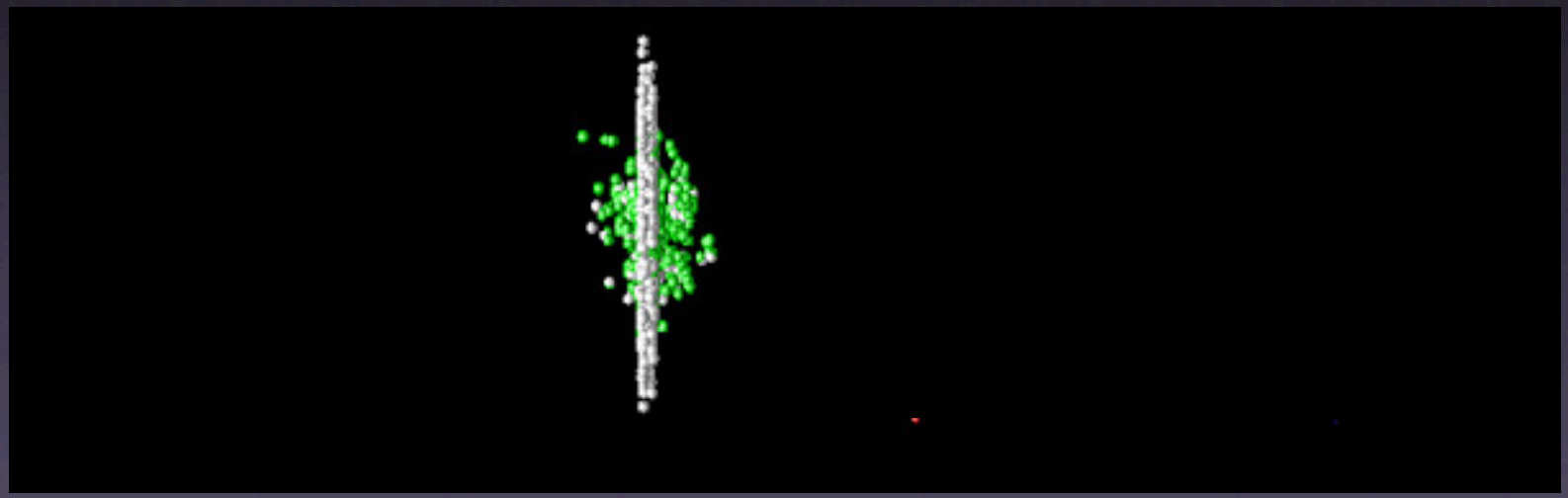
Lines:
Viscosity/Entropy

Ideal Hydro

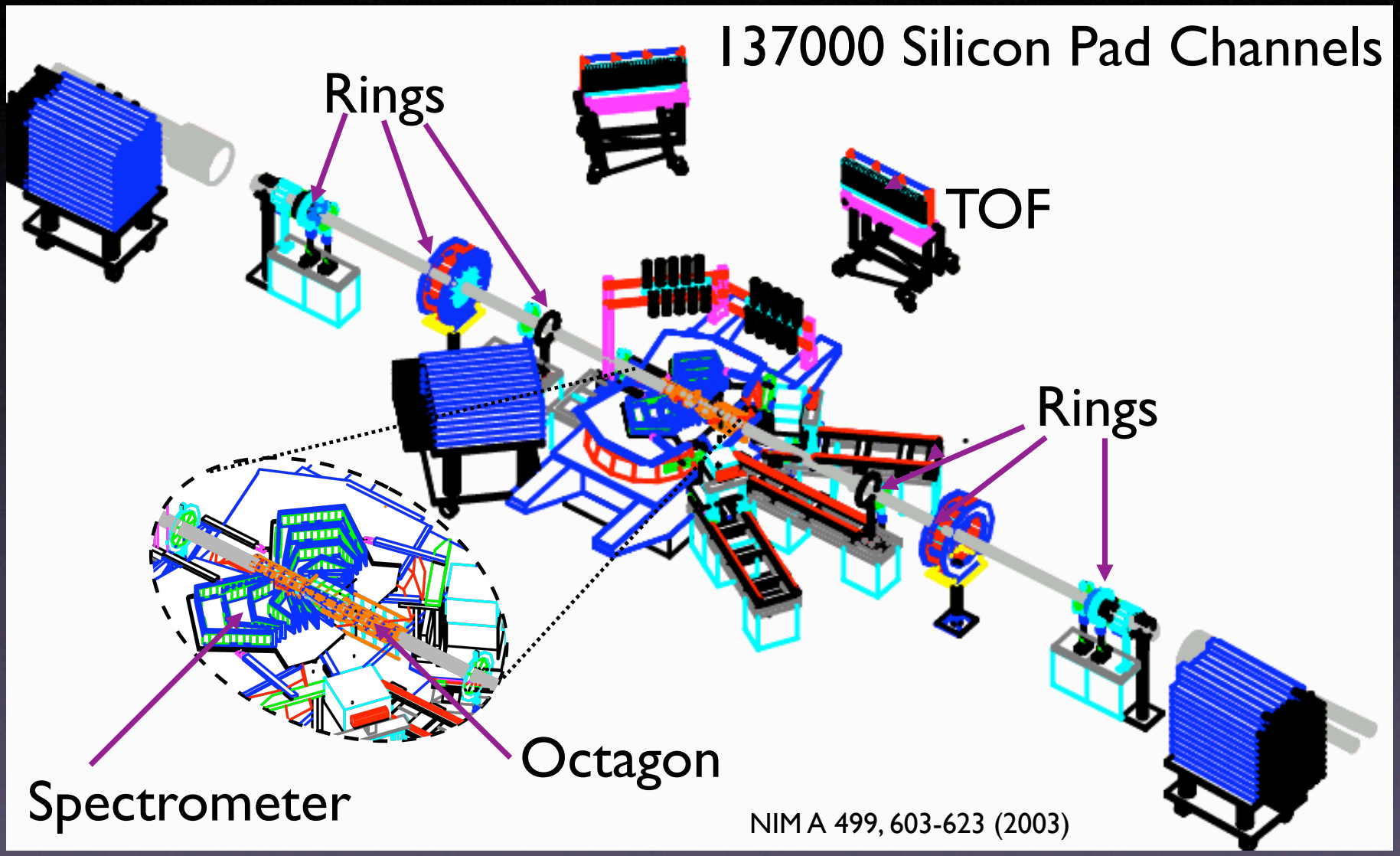
Lower Bound
from String Theory

The QGP as an ideal fluid?

Hadron Multiplicities

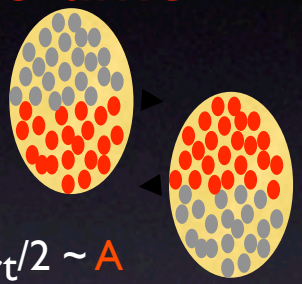


PHOBOS Detector at RHIC

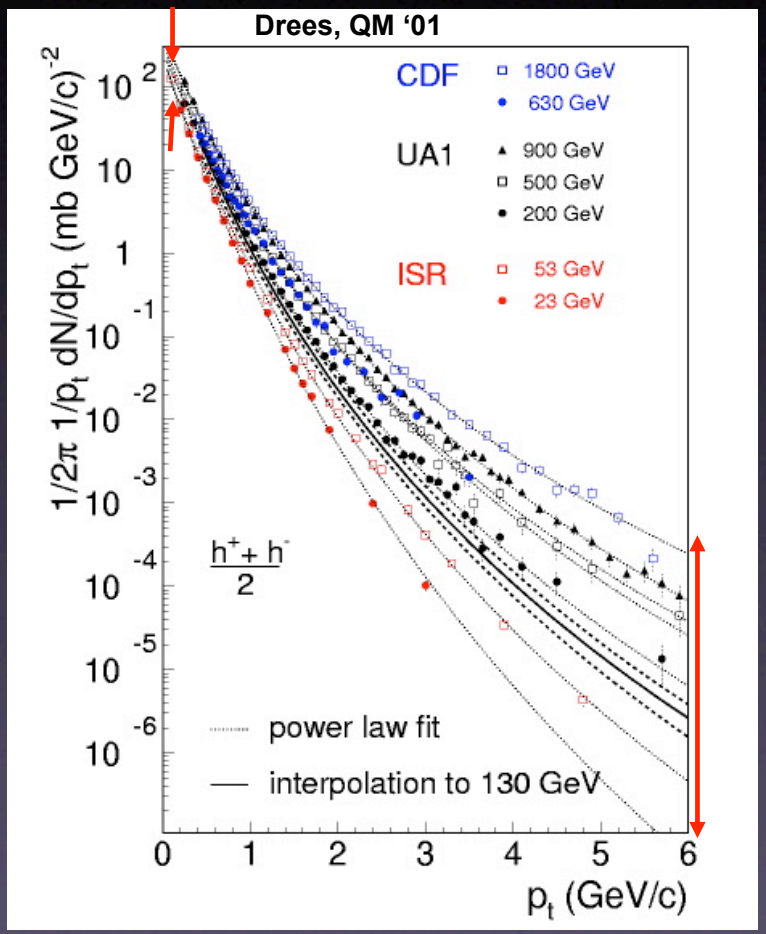


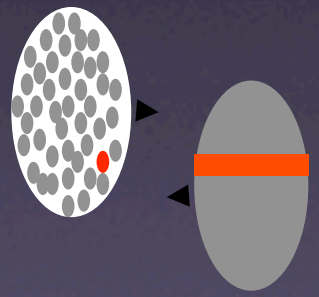
"Soft" and "Hard" Physics

"Volume"



$N_{part}/2 \sim A$





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

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

"Collisions"

First RHIC 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.Bastlev[3], R.Baum[6], R.R.Betts[1,7], A.Bialas[4], R.Bindel[8], W.Bogucki[3], A.Budzanowski[3], W.Busza[3], A.Carroll[2], M. Ceglia[2], Y.-H.Chang[6], A.E.Chen[6], T.Coghen[2], C. Conner[7], W.Czyż[4], B.Dąbrowski[3], M.P.Decowski[3], M.Despet[3], P.Fita[3], J.Fitch[2], M.Friedl[3], K.Gałuszka[3], R.Ganz[7], E.Garcia-Solis[8], N.George[1], J.Godlewski[3], C.Gomes[3], E.Gratsmayer[3], K.Gulbrandsen[3], S.Gushue[2], J.Hałik[3], C.Halliwell[7], P.Hartidas[2], A.Hayes[9], G.A.Heintzelman[2], C.Henderson[3], R.Hollis[7], R.Hołyński[3], B.Holzman[7], E.Johnson[9], J.Kane[3], J.Katzy[3,7], W.Kita[3], J.Kotuła[3], H.Kraner[2], W.Kucewicz[7], P.Kulinich[3], C.Law[3], M.Lemler[2], J.Ligocki[3], W.T.Lin[6], S.Manly[9,10], D.McLeod[7], J.Michałowski[3], A.Mignerey[5], J.Mulmenstädt[3], M.Neal[3], R.Nouicer[7], A.Olszewski[2,3], R.Pak[2], I.C.Park[9], M.Patel[3], H.Pernegger[3], M.Płoskoń[3], C.Reed[3], L.P.Remsberg[2], M.Reuter[7], C.Roland[3], G.Roland[3], D.Ross[2], L.Rosenberg[3], J.Ryan[3], A.Sanzgiri[10], P.Sarin[3], P.Sawicki[3], J.Scaduto[2], J.Sheu[8], J.Sinacore[2], W.Skulski[9], S.G.Steadman[3], G.S.F.Stephans[3], P.Steinberg[2], A.Stanczak[3], M.Stodulski[3], M.Strąk[3], Z.Stopa[3], A.Sukhanov[2], K.Surowiecka[3], J.-L.Tang[6], R.Teng[9], A.Trzupek[3], C.Vale[3], G.J.van Nieuwenhuizen[3], R.Verdier[3], B.Wadsworth[3], F.L.H.Wolfs[9], B.Wosiek[3], K.Woźniak[3], A.H.Wuosmaa[1], B.Wysłouch[3], K.Zalewski[3], P.Żychowski[3]

(PHOBOS collaboration)

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[8] Department of Chemistry, University of Maryland, College Park, MD 20742
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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 $dN/d\eta|_{|\eta|<1} = 408 \pm 12(\text{stat}) \pm 30(\text{syst})$ at 56 AGeV and $555 \pm 12(\text{stat}) \pm 38(\text{syst})$ 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.

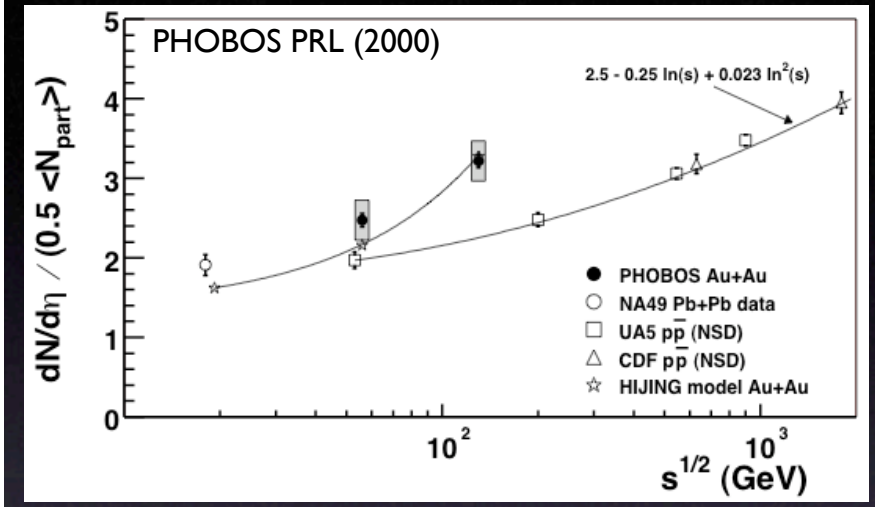
PACS numbers: 25.75.-q

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.

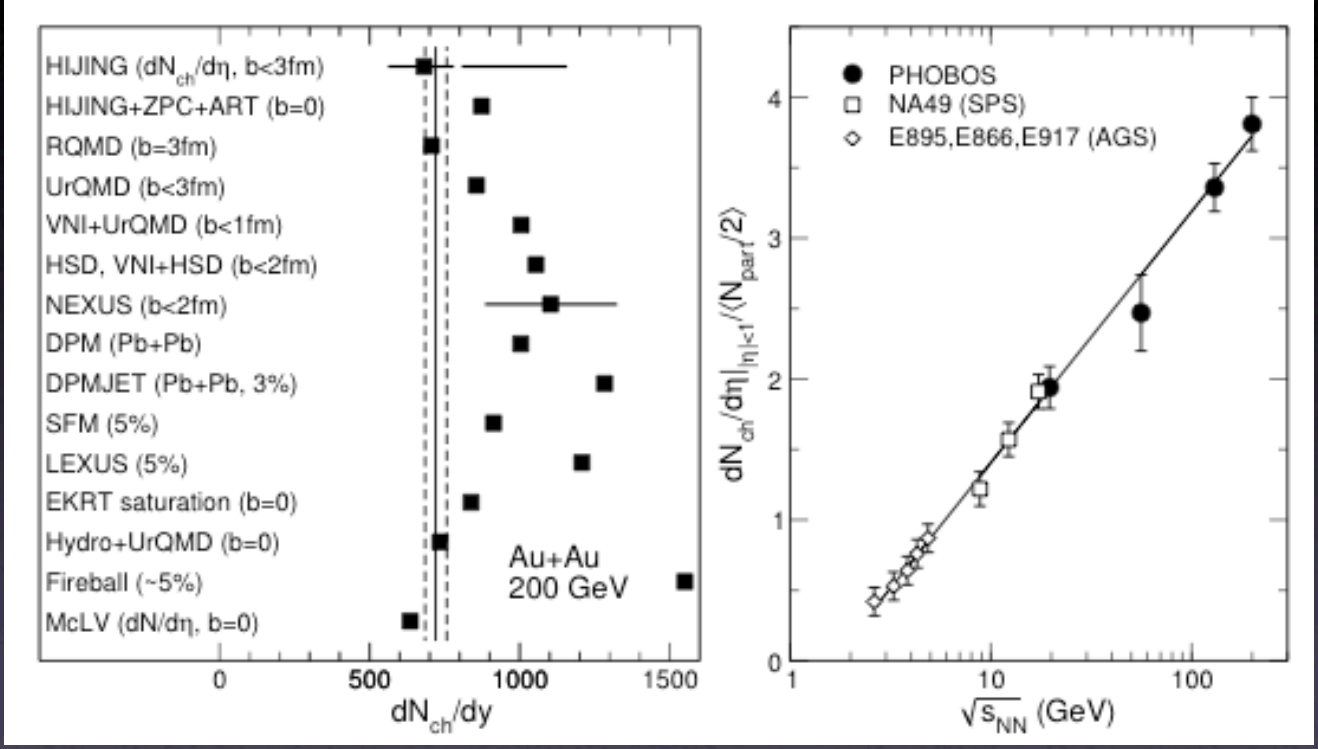
The PHOBOS detector employs silicon pad detectors to perform tracking, vertex detection and multiplicity measurements. Details of the setup and the layout of the silicon sensors can be found elsewhere [3,4]. For the initial running period of the accelerator only a small fraction of the full setup was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



Mid-Rapidity Multiplicity surprisingly low

dN/dη@η=0

PHOBOS Whitepaper

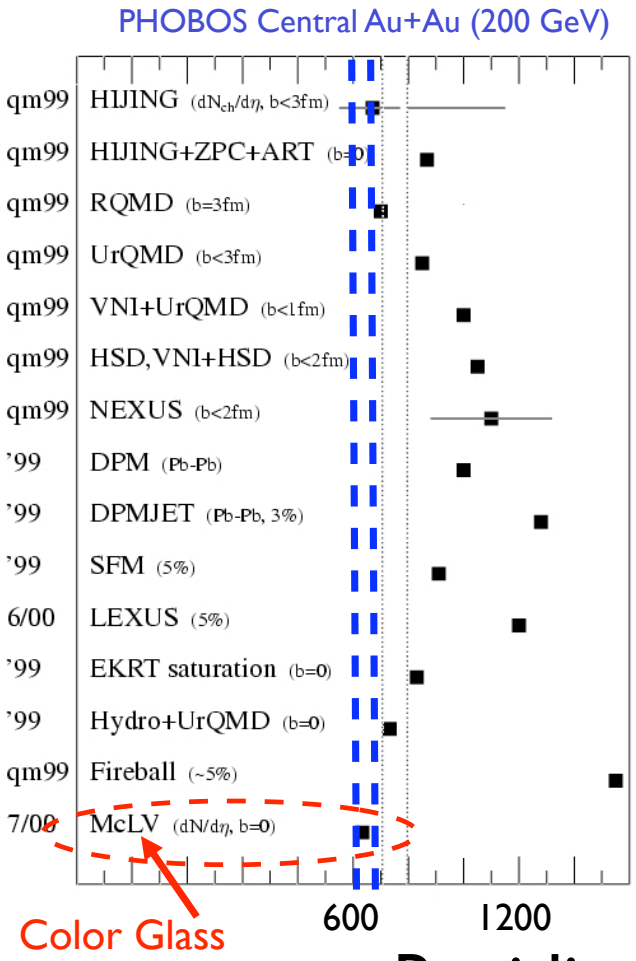


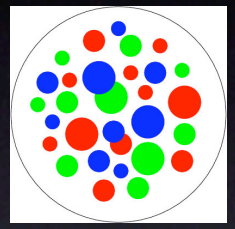
Oct 2004

Manifestation of Parton Saturation?

c.f. Blaizot, McLerran, Venugopalan, Kovchegov, Kharzeev, Nardi, Levin, Mueller, Salgado, Wiedemann, Eskola, Tuchin + many others

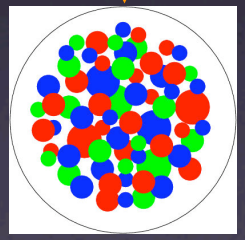
Particle Multiplicity at RHIC





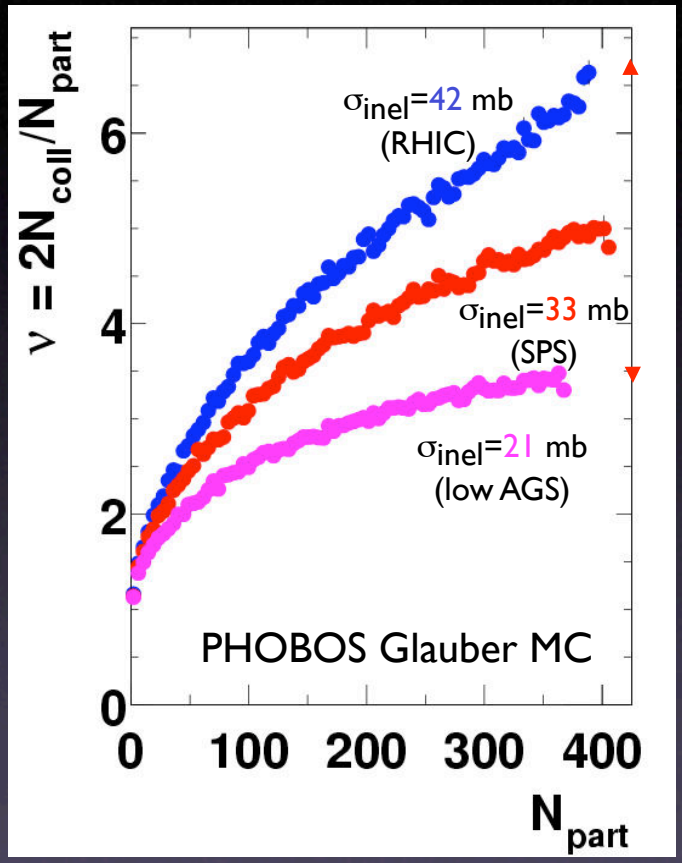
Low Energy

Parton Saturation



High Energy

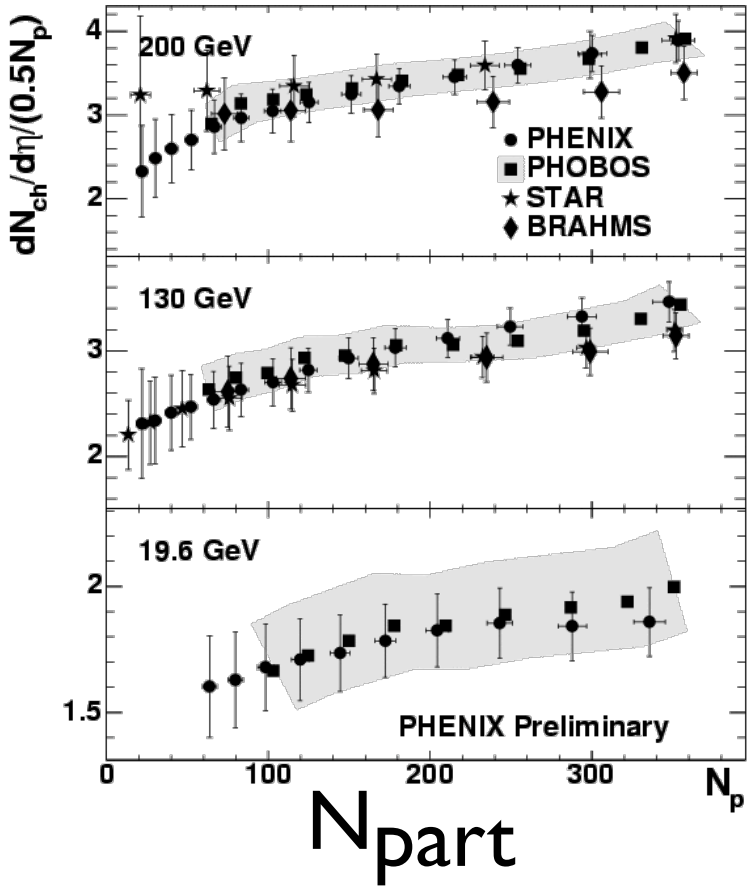
"Soft" and "Hard" Physics



Use centrality, energy to change balance of soft and hard particle production

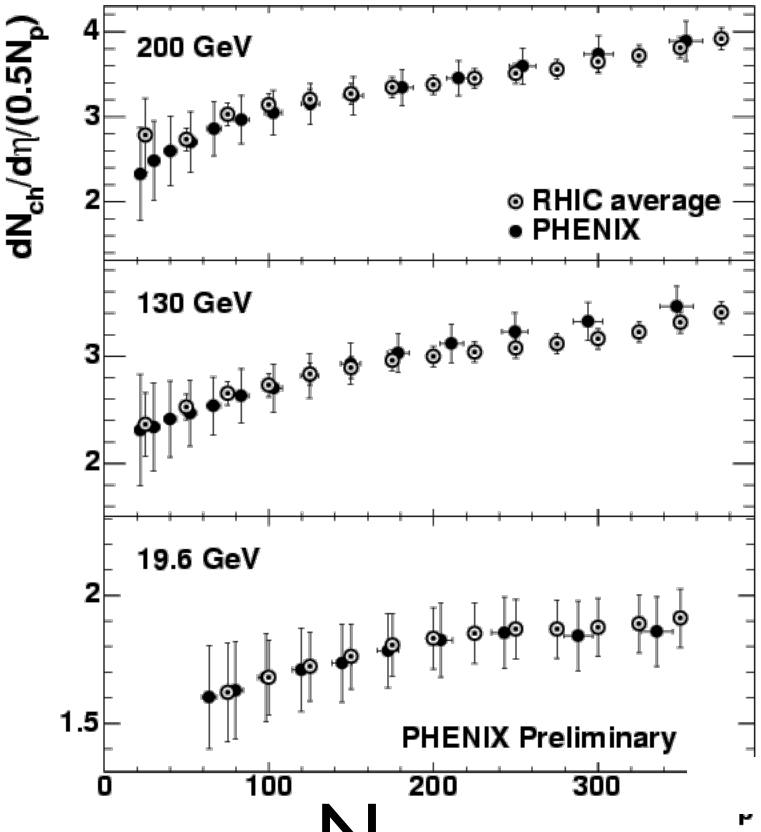
Mid-rapidity Multiplicity vs Centrality

$-1 < \eta < 1$



N_{part}

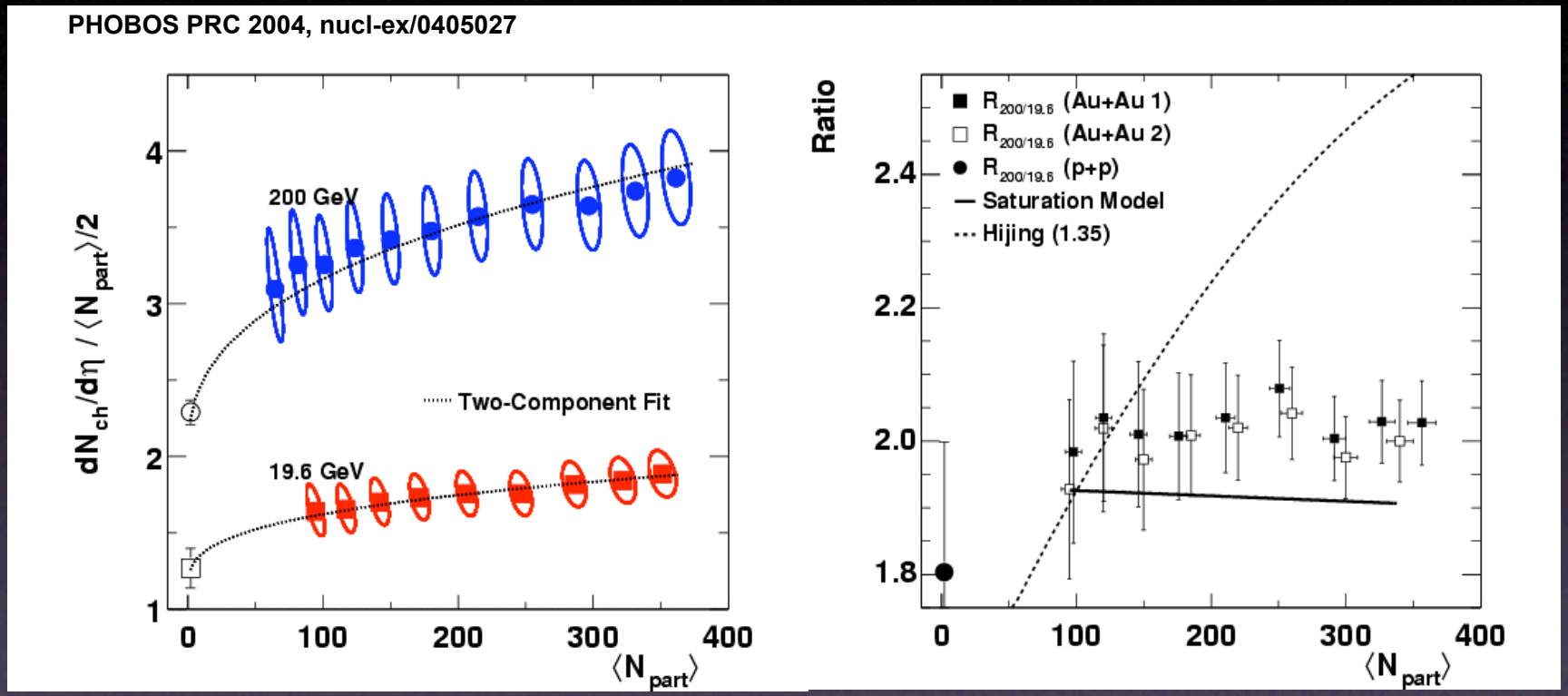
Compilation: Sasha Milow/QM'04



N_{part}

Energy + Centrality Dependence

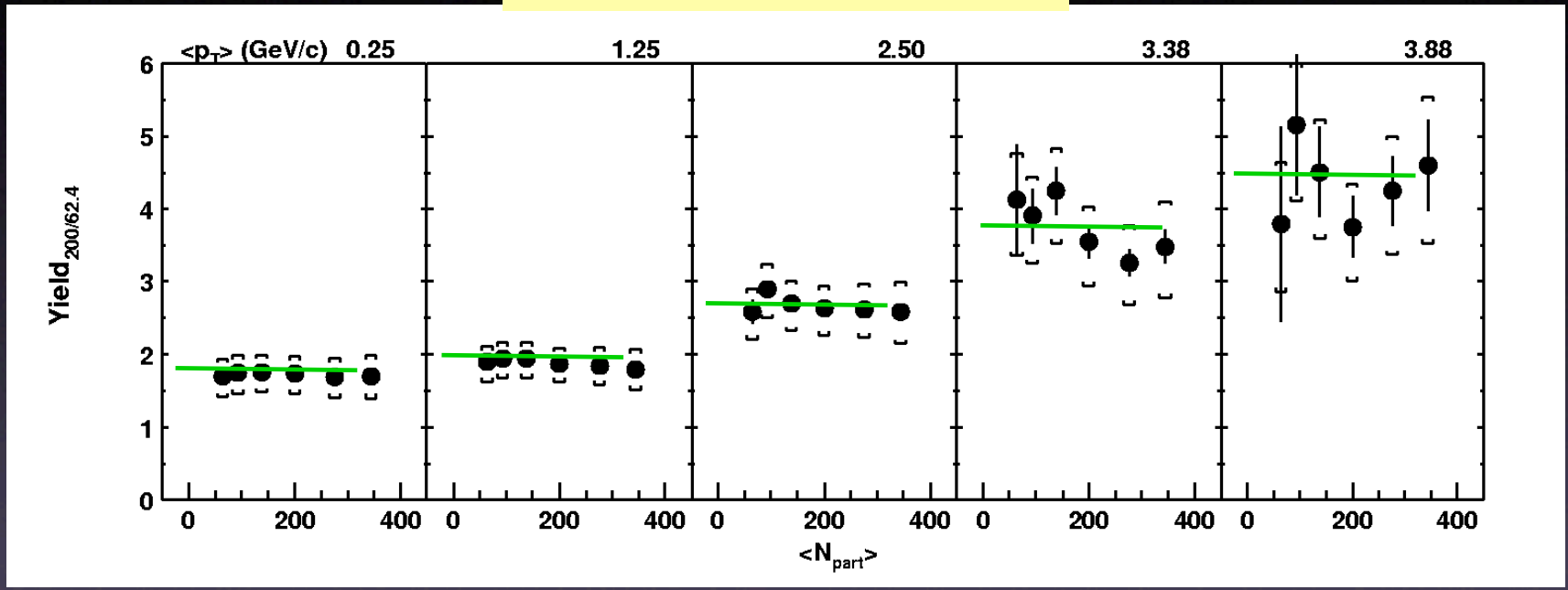
PHOBOS PRC 2004, nucl-ex/0405027



"Factorization of Energy and Centrality Dependence"

Factorization of transverse dynamics?

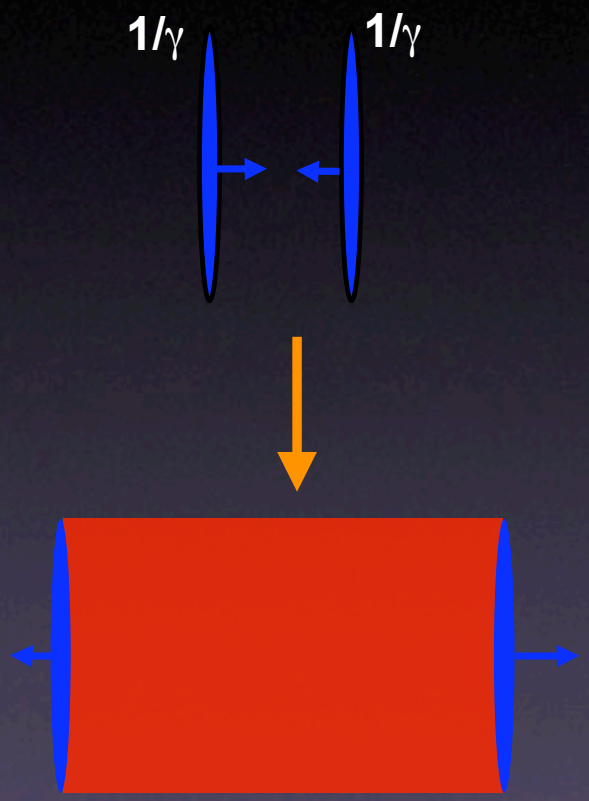
Au+Au: Ratio 200/62.4 GeV



Factorization of Energy and
Centrality Dependence over large range in p_T

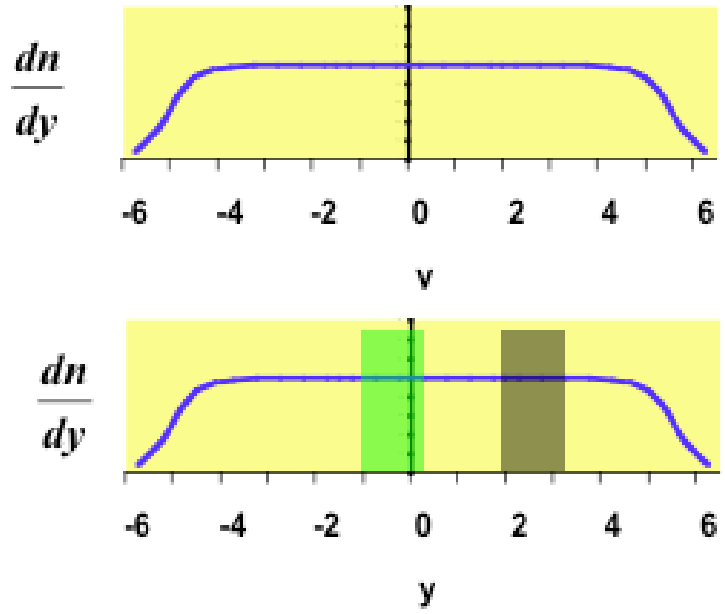
Rapidity Distributions

Bjorken Picture

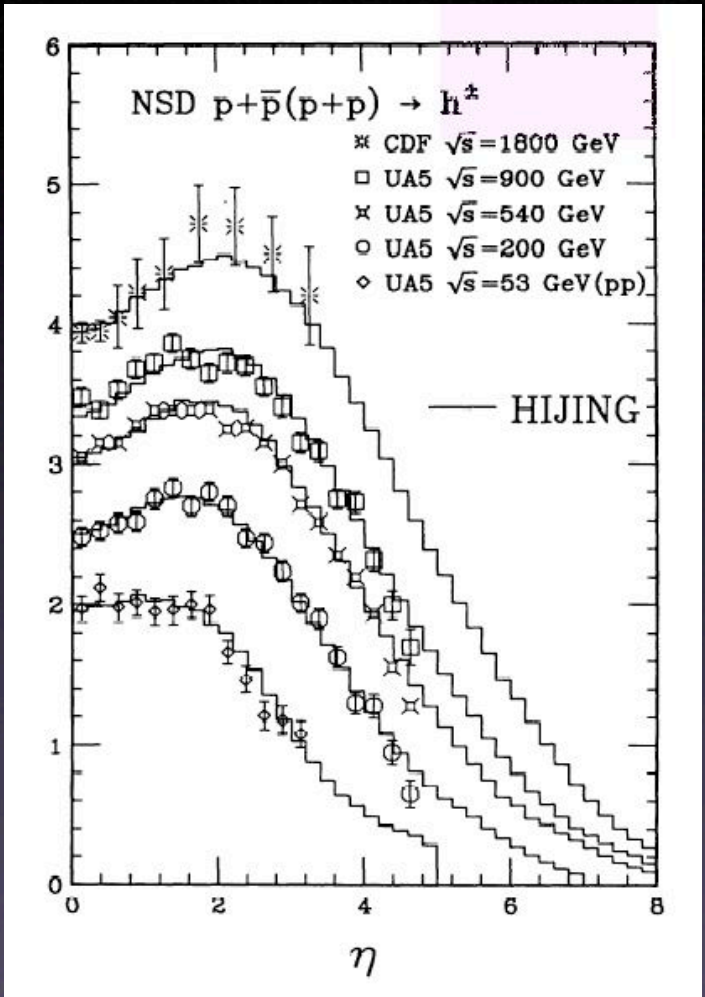


"Boost-invariant" Expansion

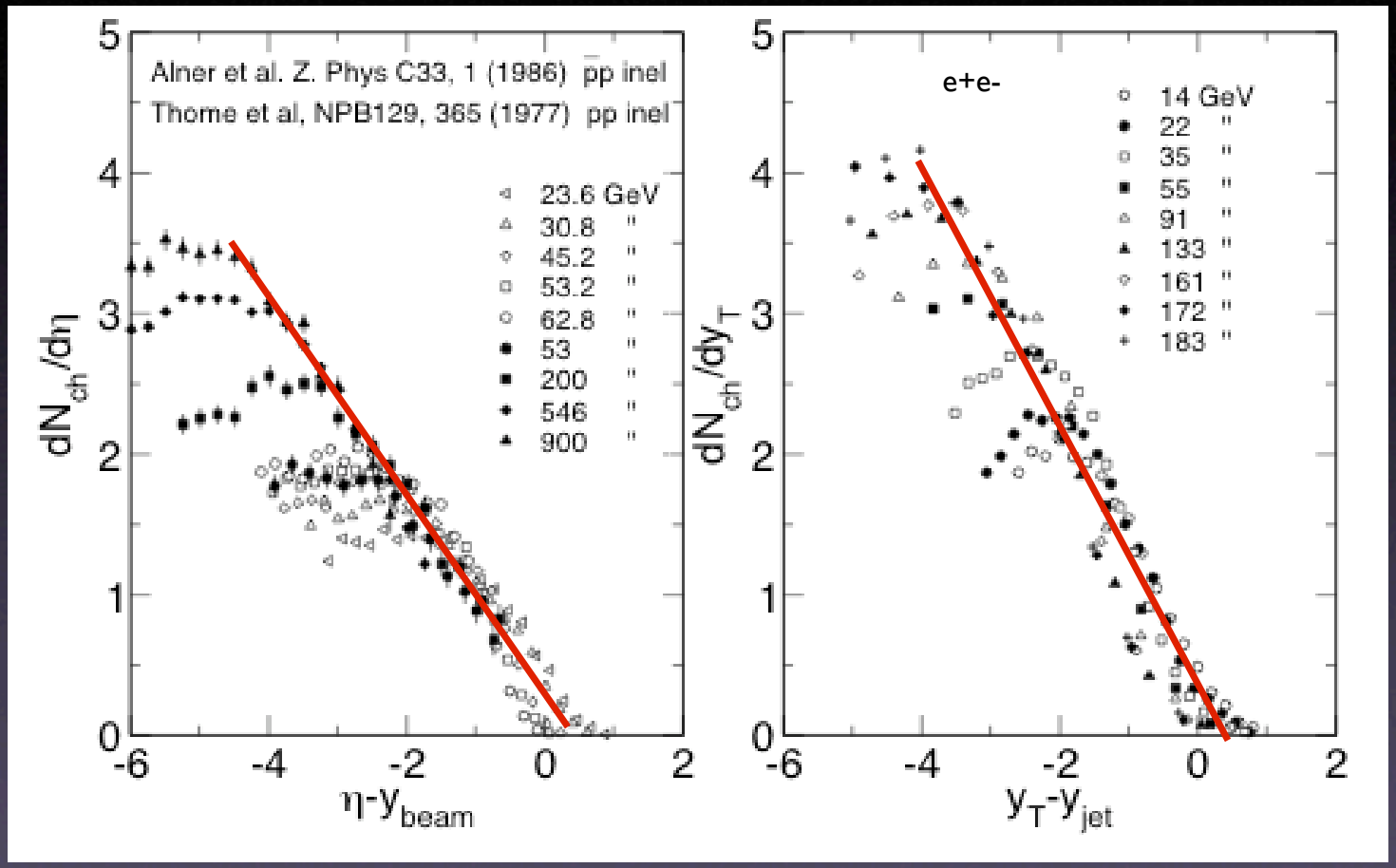
$$\frac{d^3\sigma}{d^2p_T\,dy} \qquad \frac{d^2\sigma}{d^2p_T}\cdot\frac{dn}{dy}$$



Pseudo-Rapidity Distributions in p+p



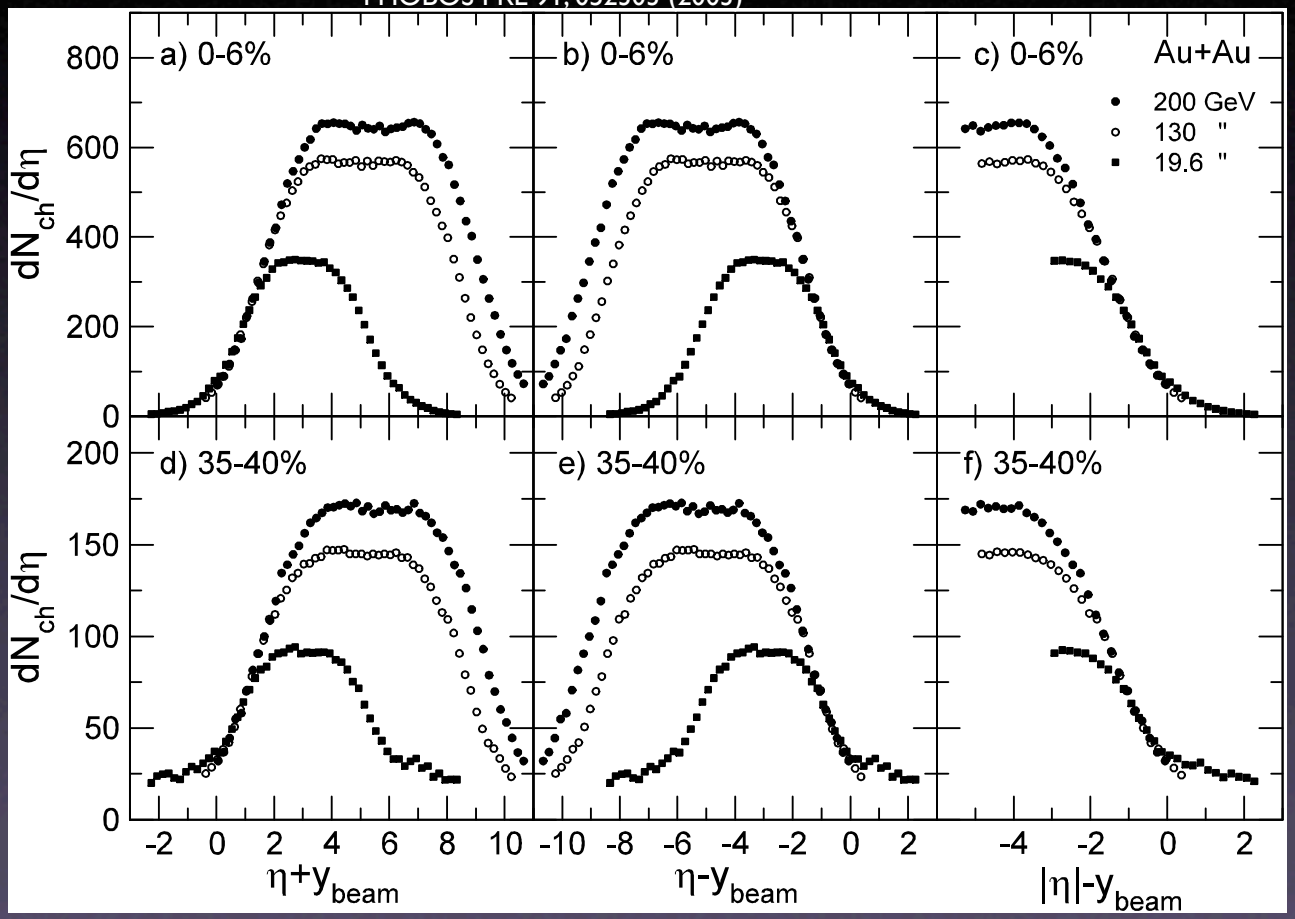
Limiting Fragmentation



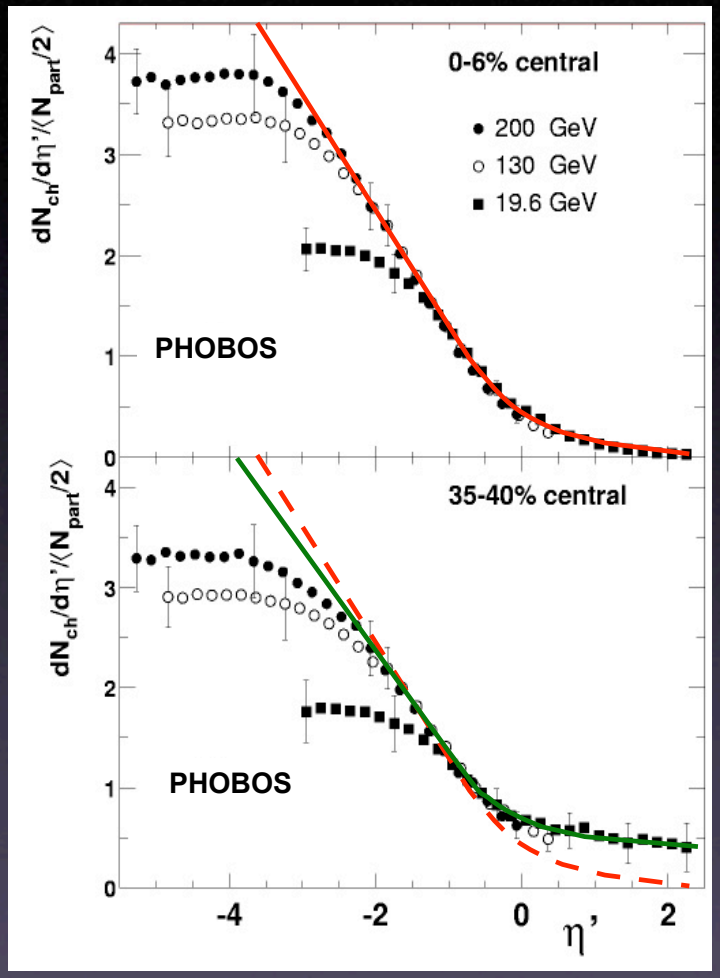
Particle production in restframe of one of the colliding particles

Limiting Fragmentation cntd

PHOBOS PRL 91, 052303 (2003)



Limiting Fragmentation vs Centrality



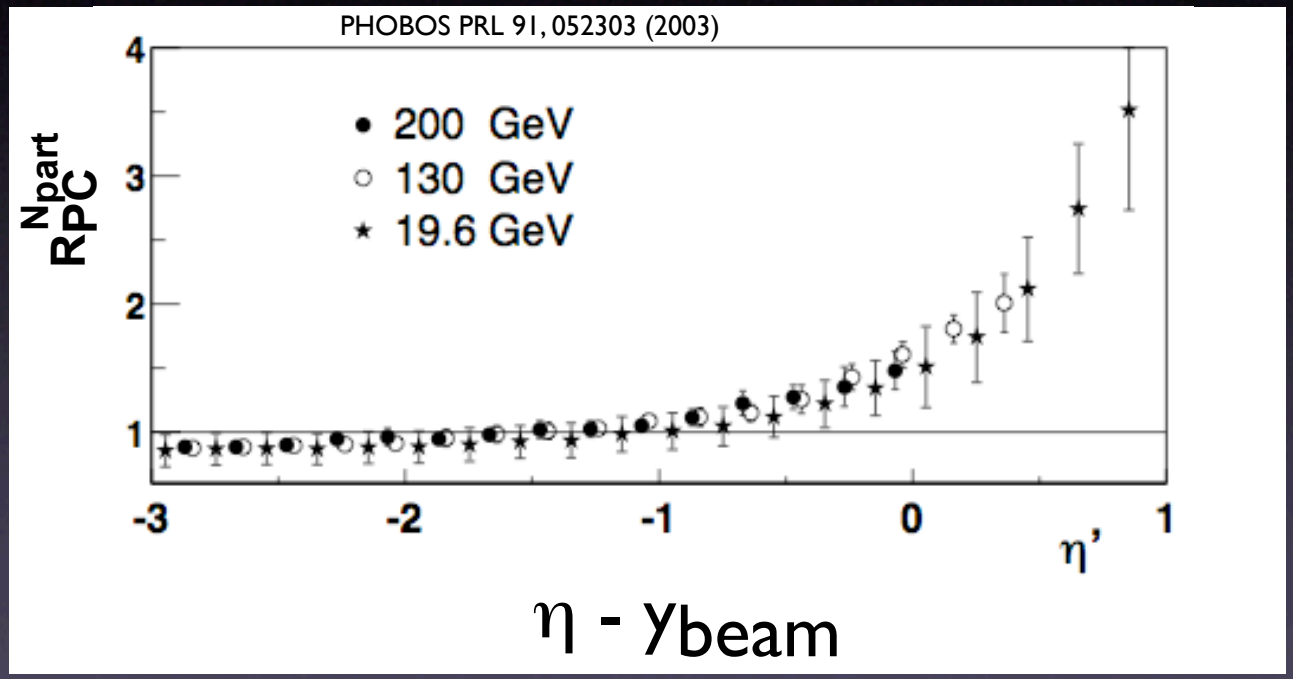
PHOBOS PRL 91, 052303 (2003)

Different Limiting Curves for Central and Peripheral Data

But *both* energy-independent

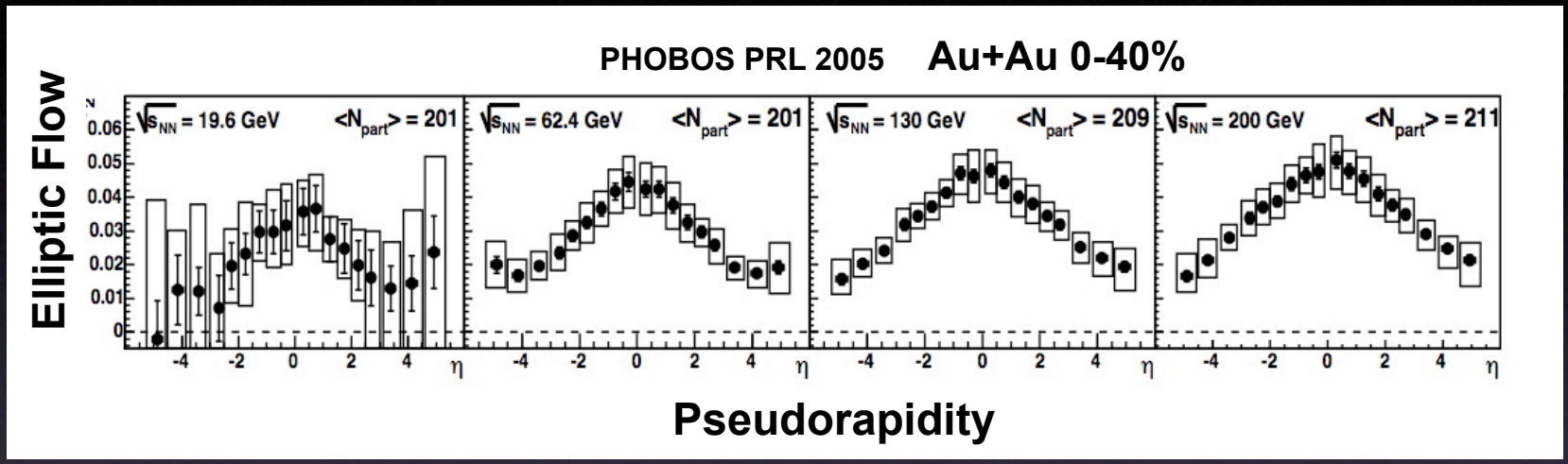
Dominance of Geometry?

Factorization of Longitudinal Dynamics



Dominance of Collision Geometry?

Rapidity Dependence of v_2

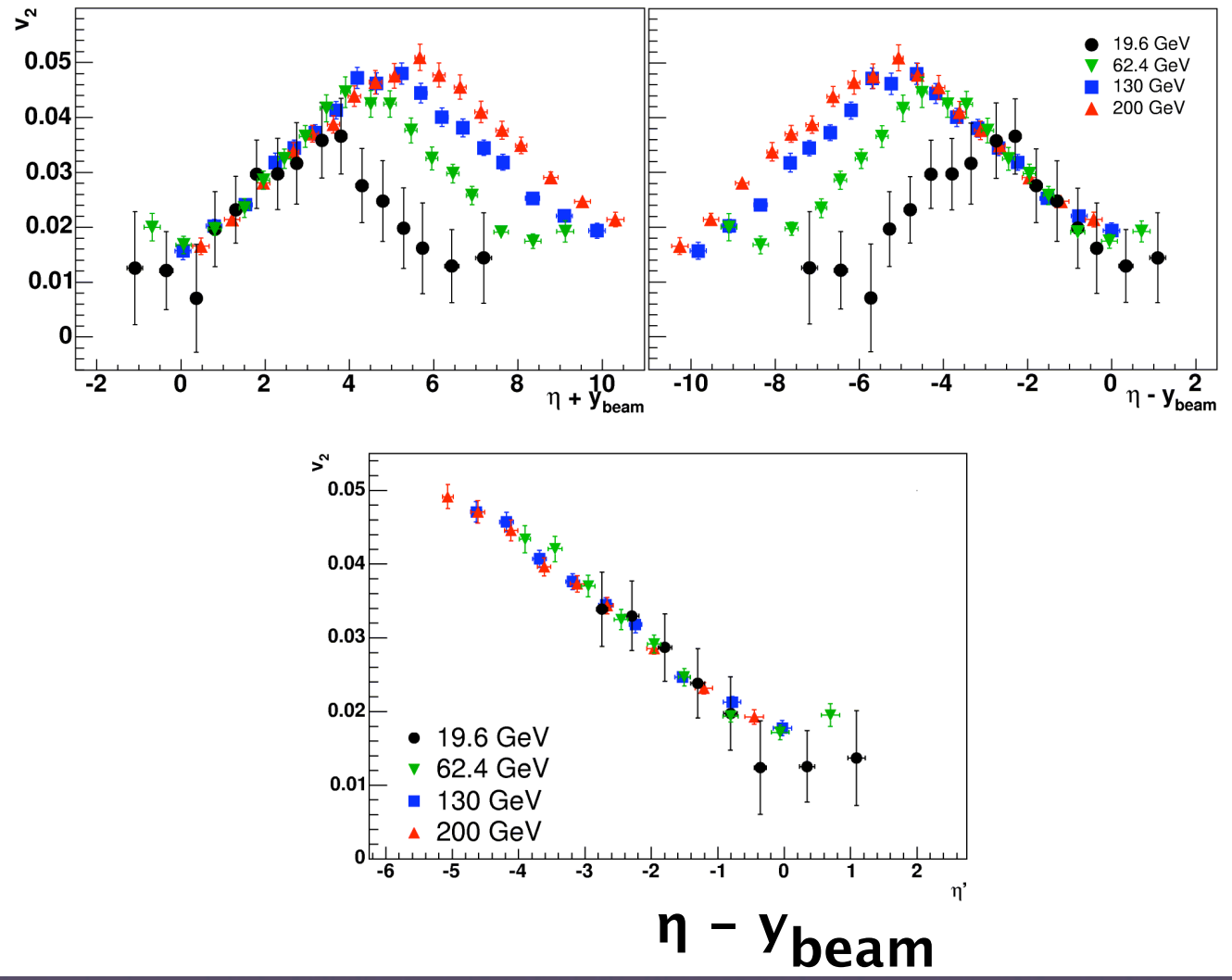


No Boost-invariant plateau:
Same initial asymmetry leads to different final state v2 vs y at all √s

Limiting Fragmentation for Elliptic Flow?

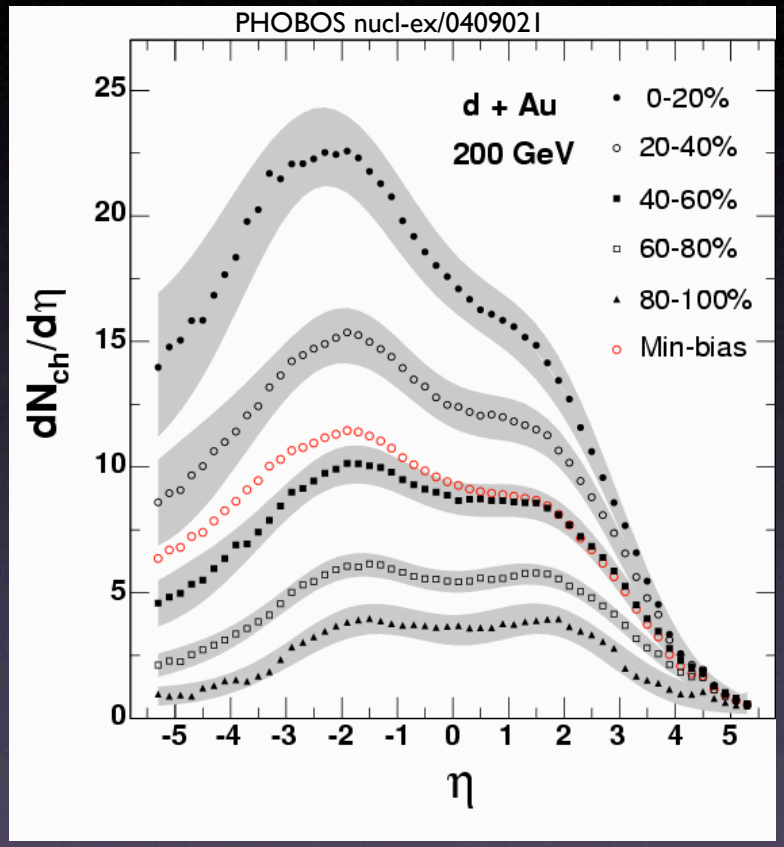
Au+Au

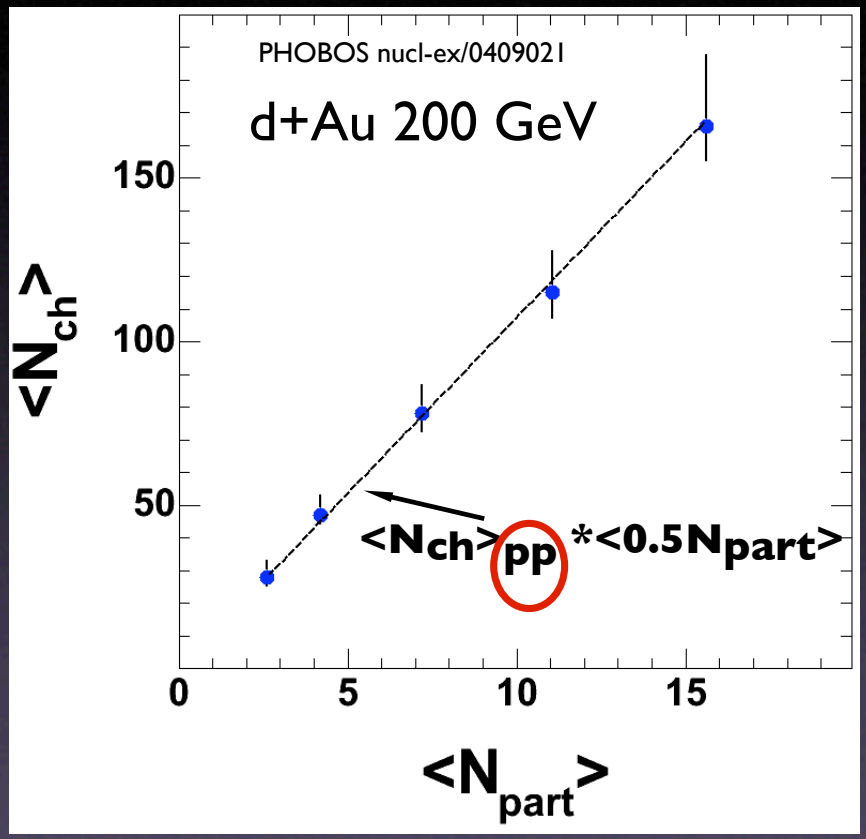
PHOBOS nucl-ex/0406021



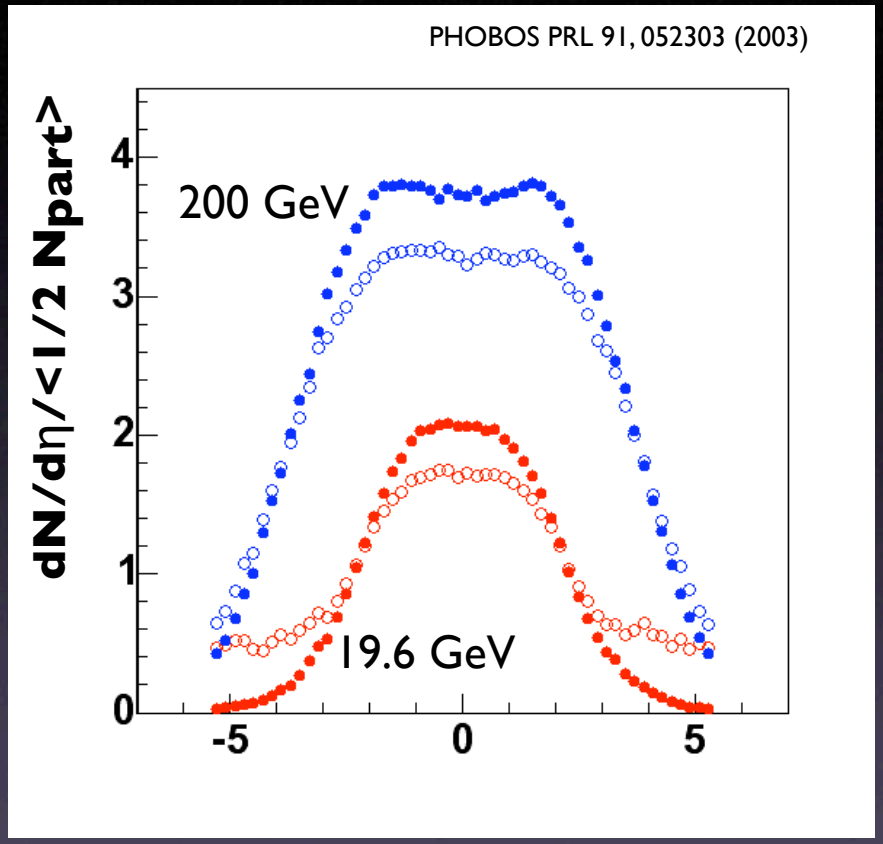
Total Multiplicity

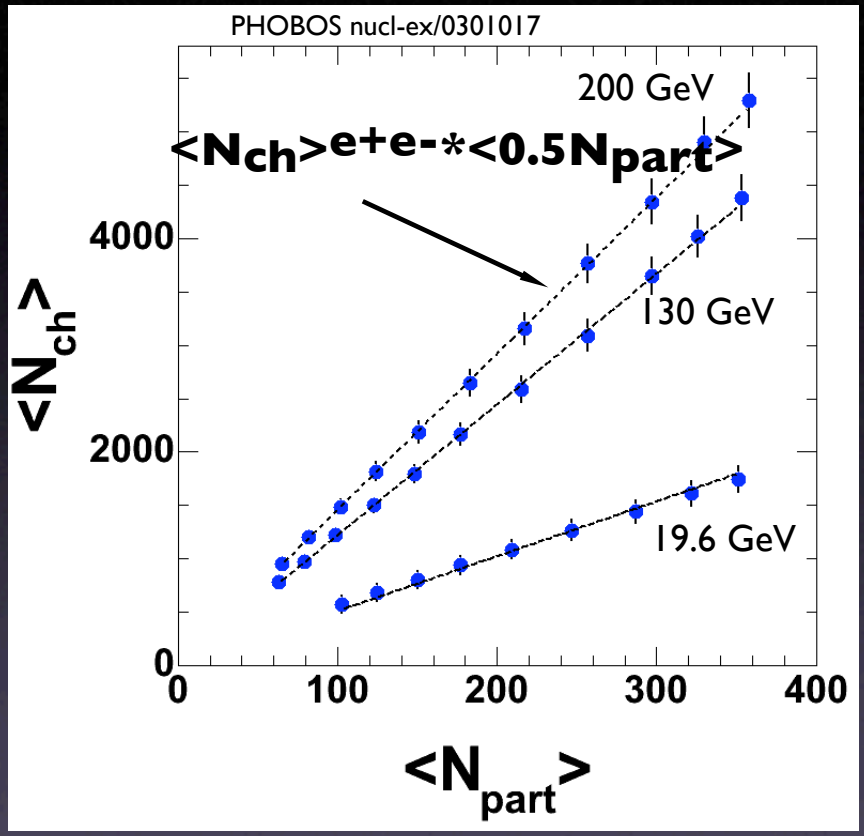
Npart Scaling in d+Au





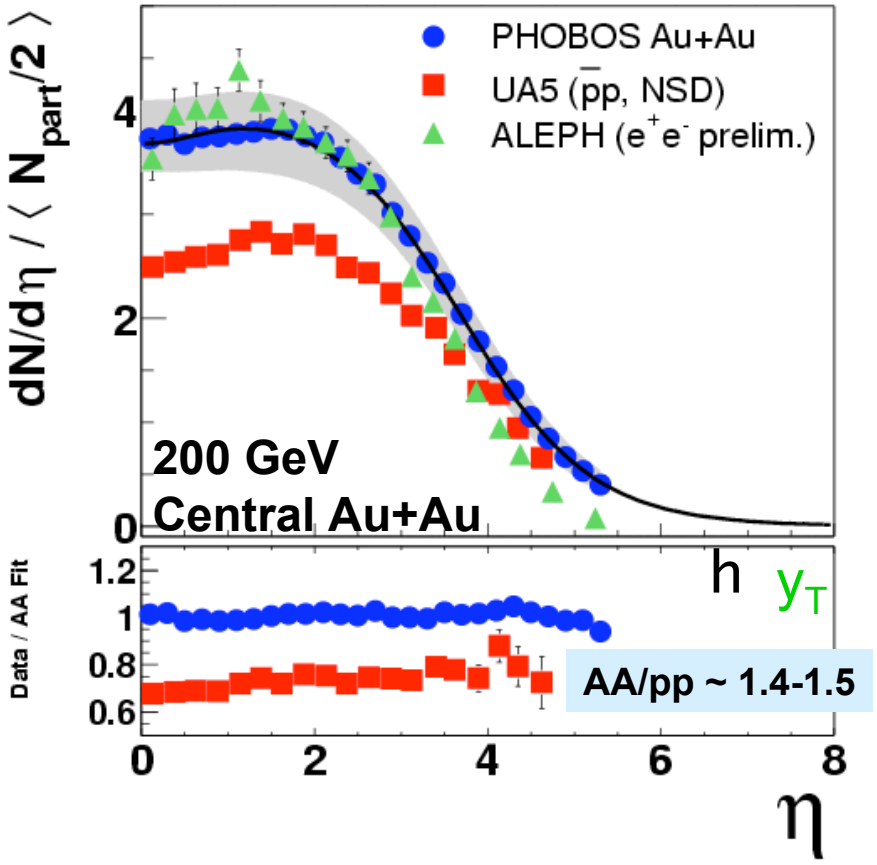
Total Multiplicity $\langle N_{ch} \rangle$ in Au+Au



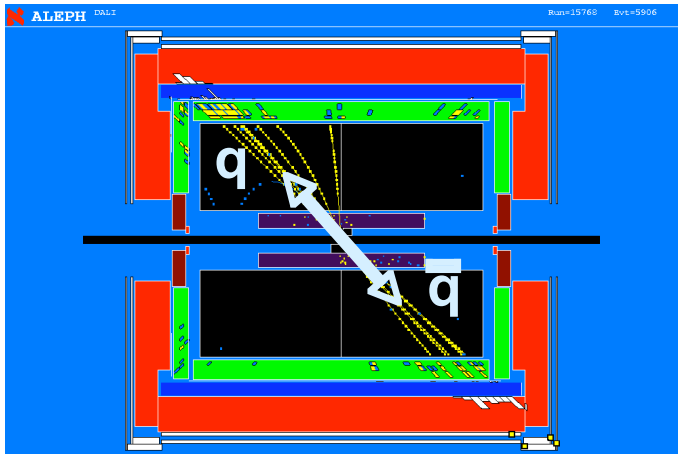


"N_{part} -Scaling"

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



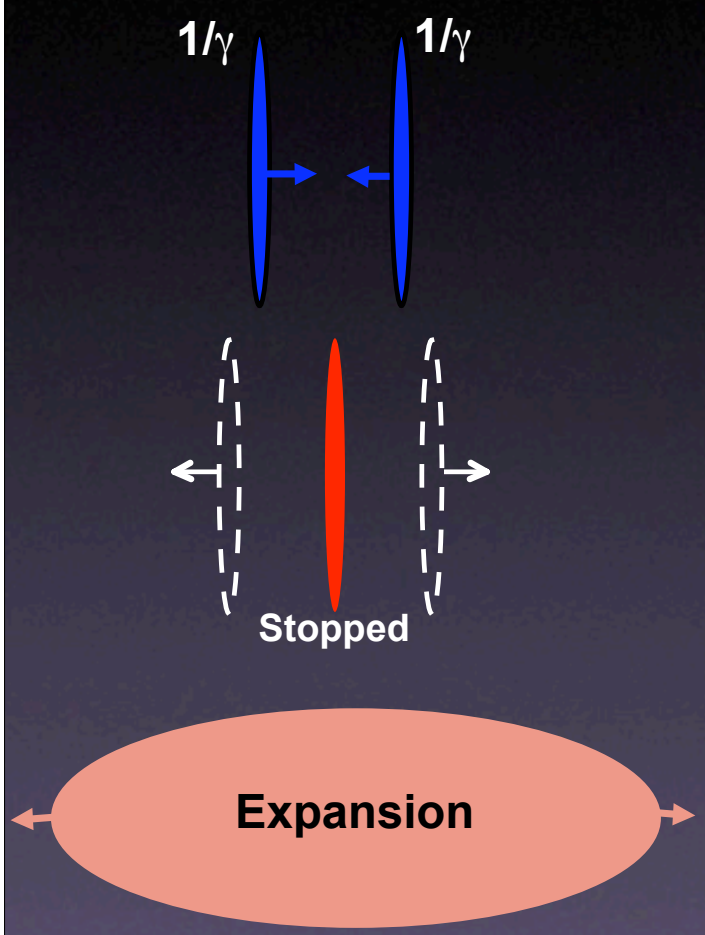
PHOBOS QM'02, Steinberg



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

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

Landau Hydrodynamics



Carruthers, Duong-Van on pp data in 1973:

surprisingly well described by Landau's energy-dependent Gaussian rapidity distribution [see Eq. (2.1) for the definition of y]

$$\frac{1}{\sigma_{\text{in}}}\frac{d\sigma}{dy} = \frac{dN}{dy}$$

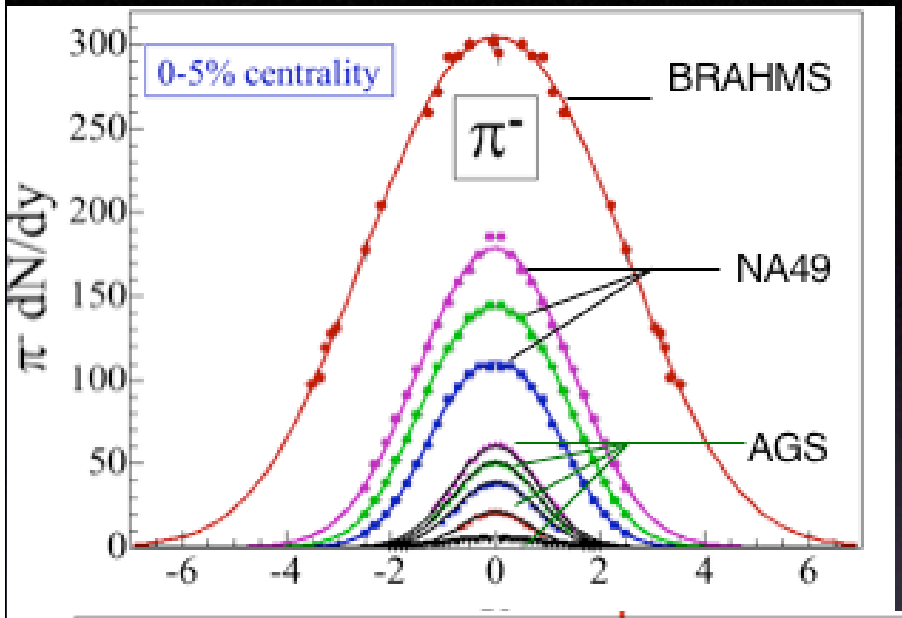
$$= N \exp(-y^2/2L)/(2\pi L)^{1/2}, \qquad (1.5)$$

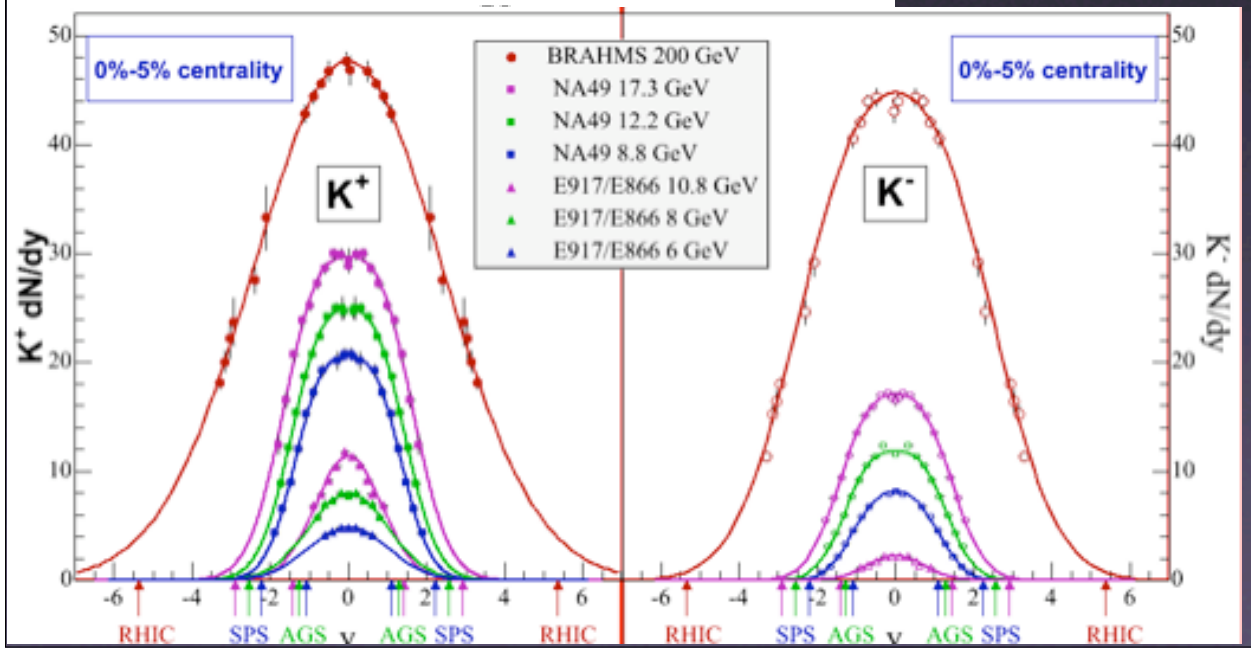
where the parameter L is

$$L = \tfrac{1}{2}\ln(s/4m_p{}^2), \qquad (1.6)$$

where s is the squared total c.m. energy.

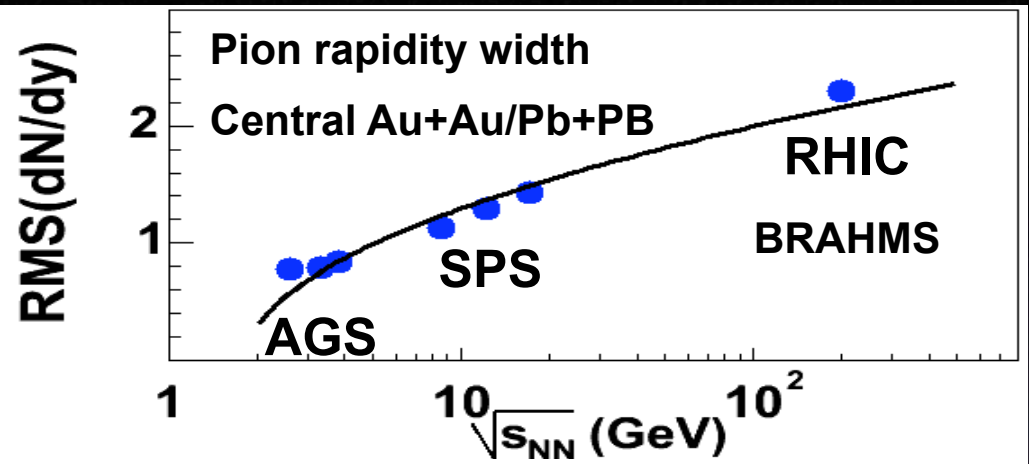
Rapidity Distributions

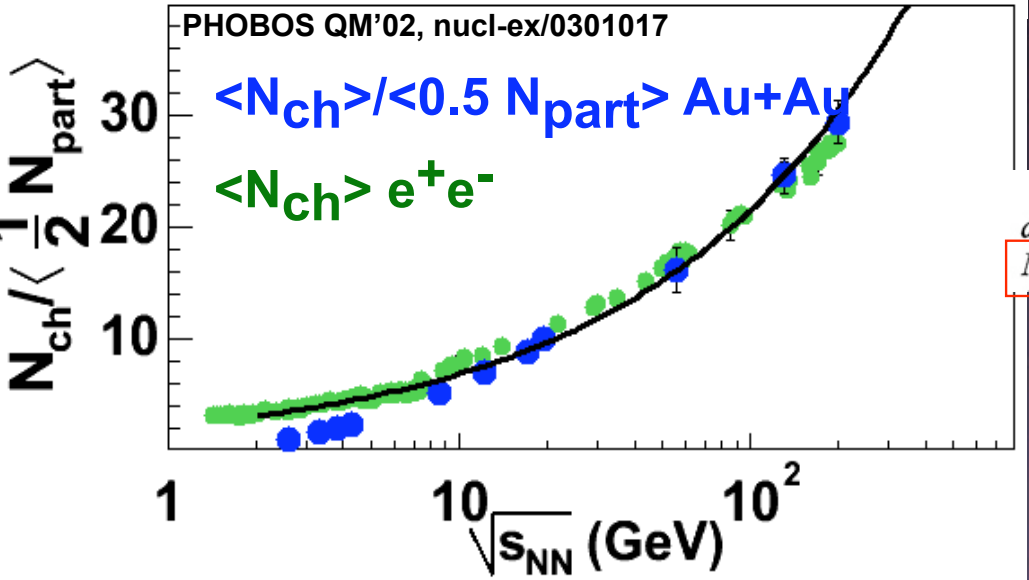




Meson rapidity distributions are approximately Gaussian - reminiscent of Landau?

Landau Hydrodynamics?





surprisingly well described by Landau's energy-dependent Gaussian rapidity distribution [see Eq. (2.1) for the definition of y]

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$$=N\exp(-y^2/2L)/(2\pi L)^{1/2}, \qquad (1.5)$$

where the parameter L is

$$L=\tfrac{1}{2}\ln(s/4m_p{}^2), \qquad (1.6)$$

where s is the squared total c.m. energy.

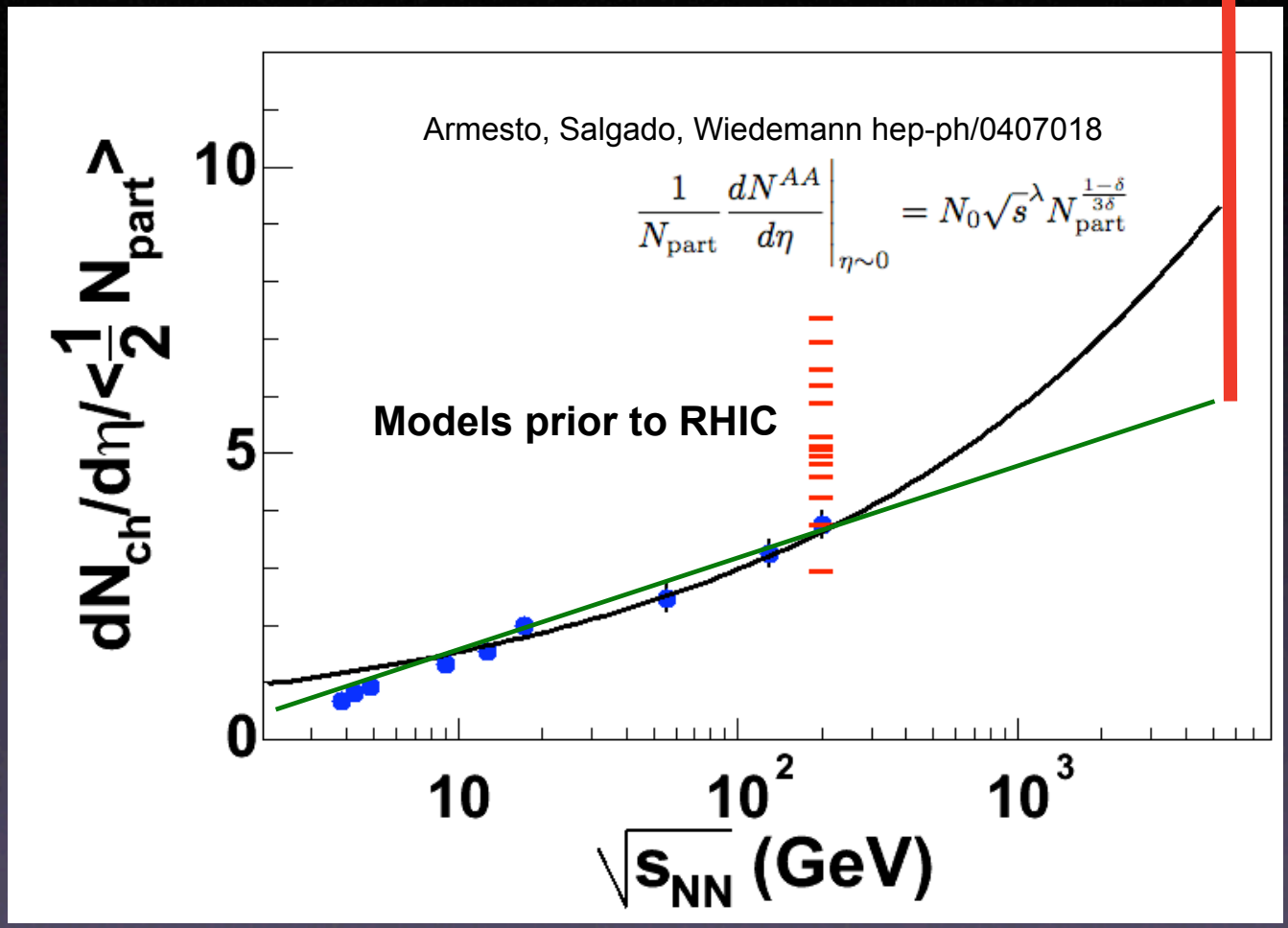
Secondly, we wish to stress that as a function of *available energy* W_{had} the hadronic multiplicity varies as $N\approx 2.2\ W_{had}{}^{1/2}$ over a vast range of initial energies.[25]

Carruthers, Duong-Van

on pp and e^+e^- data in 1983

The Future

Energy Dependence

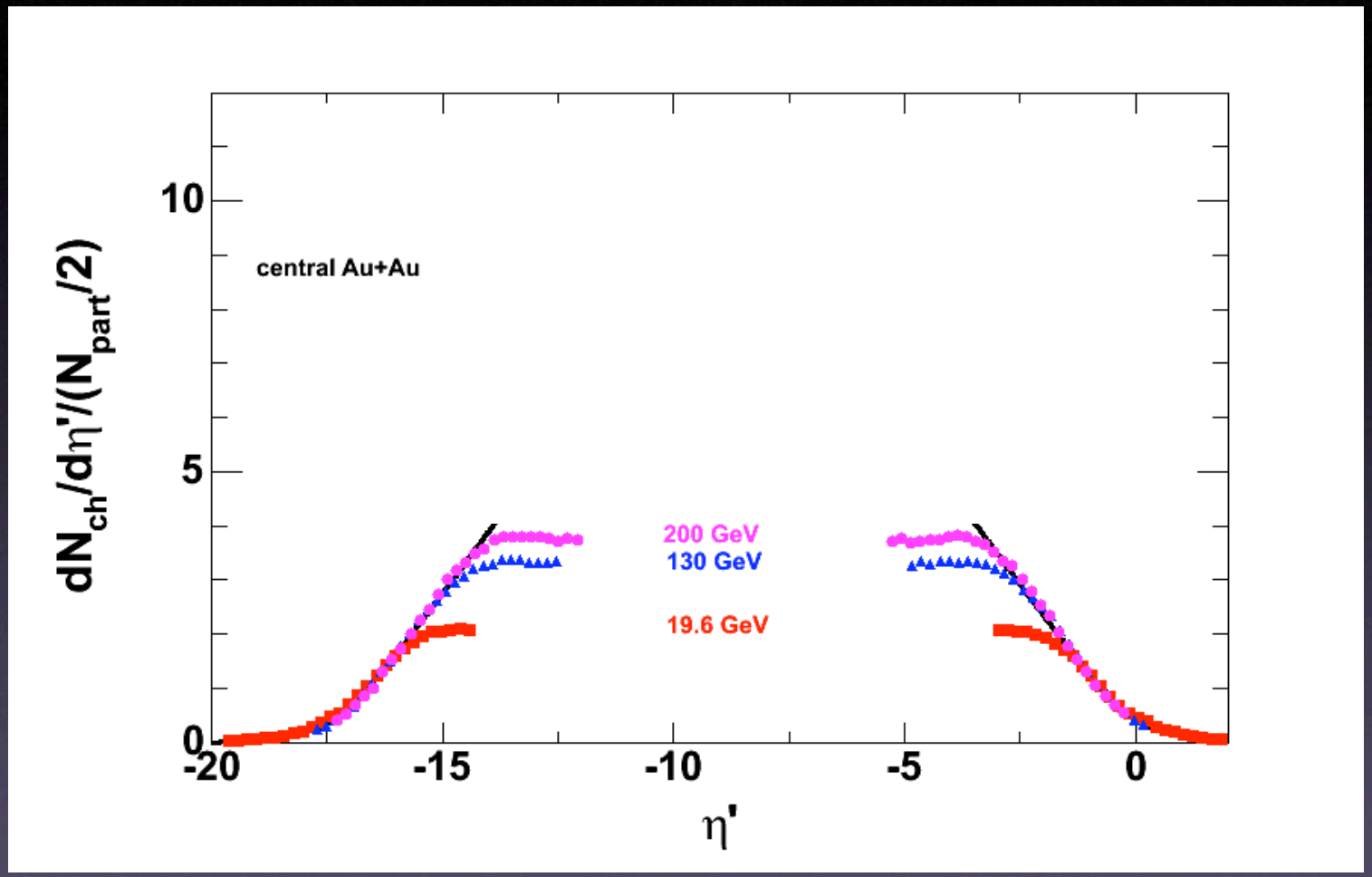


Detectors planned for dN/dy > 5000!

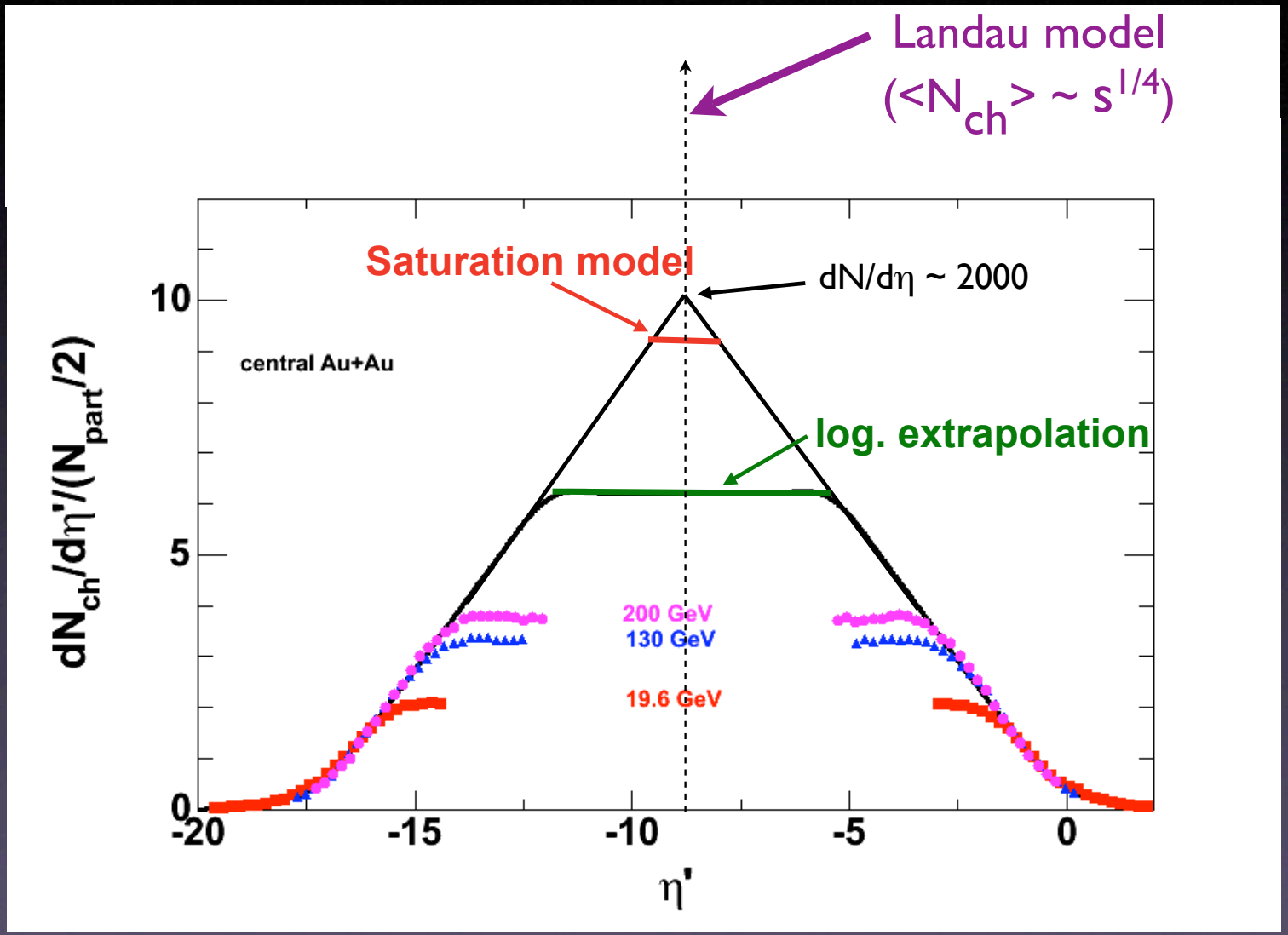
dN/dη ~ 1800

dN/dη ~ 1100

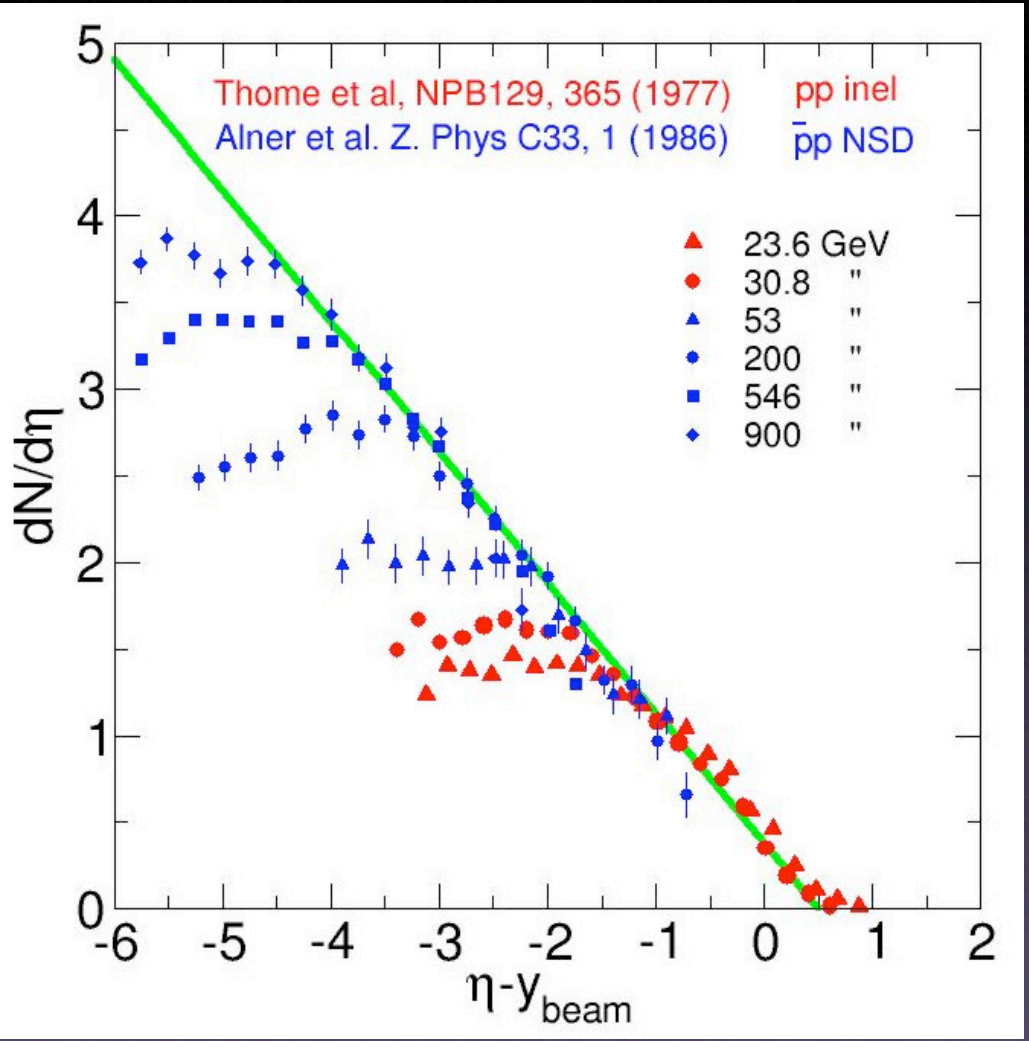
Limiting Fragmentation and LHC



Extrapolation to LHC



Limiting Fragmentation in p+p



Holds up to 900 GeV!

Summary

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 pT, vs η)

Parton saturation?

But:

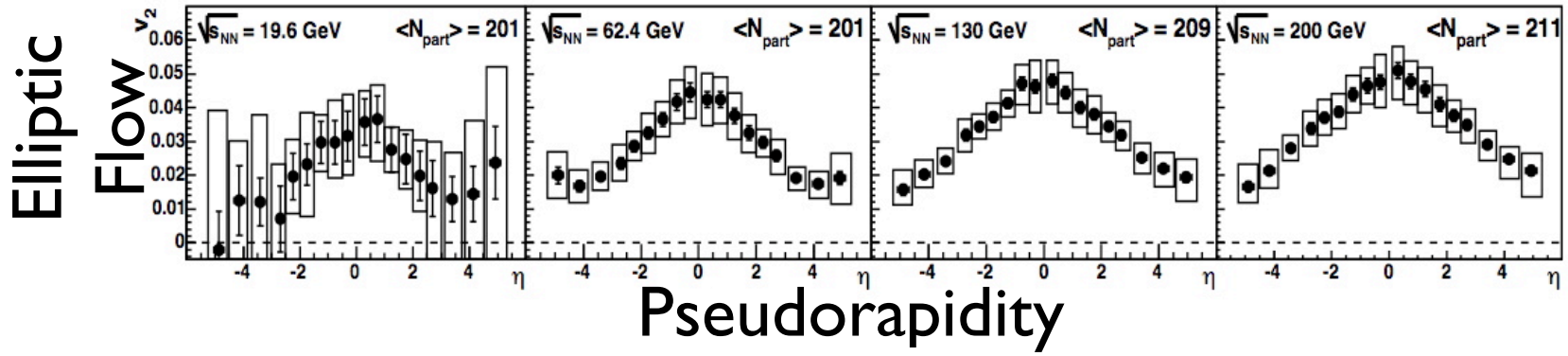
Correspondence of multiplicity in A+A vs e+e- vs p+p ($1/2\sqrt{s}$)

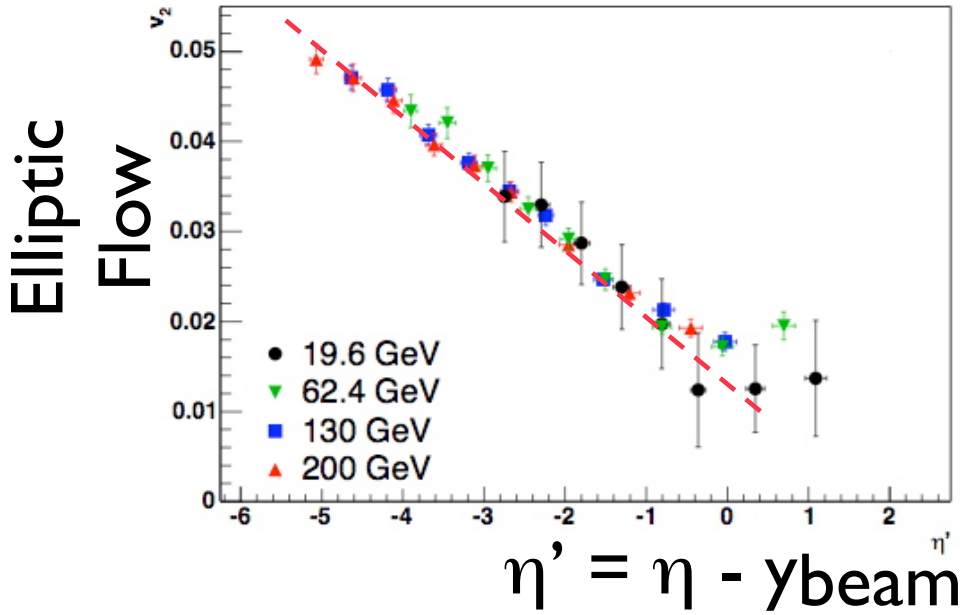
Everything points to early (initial) determination of multiplicity distributions

LHC will provide definitive answers!

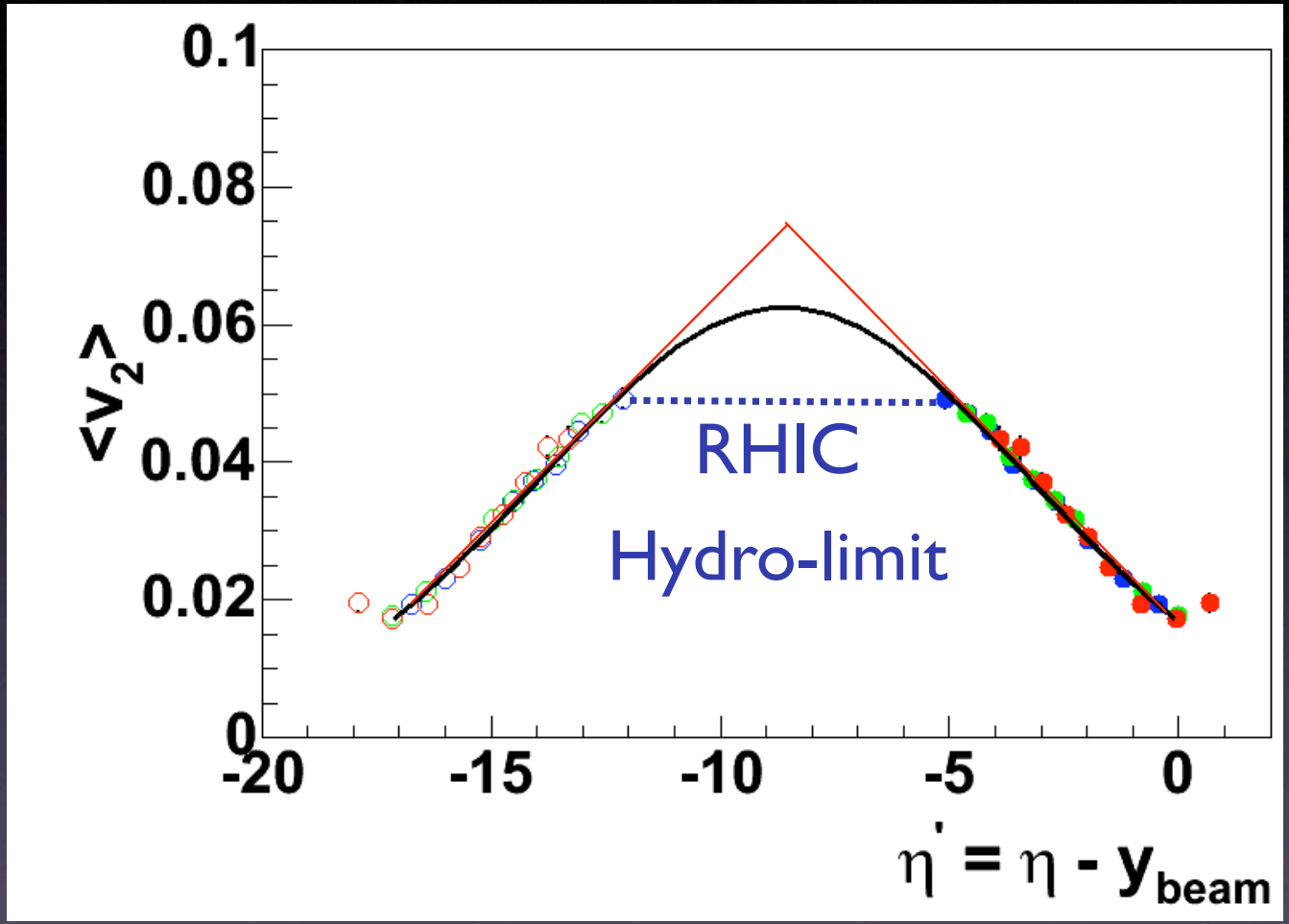
Elliptic Flow at LHC

PHOBOS nucl-ex/0406021 Au+Au 0-40%

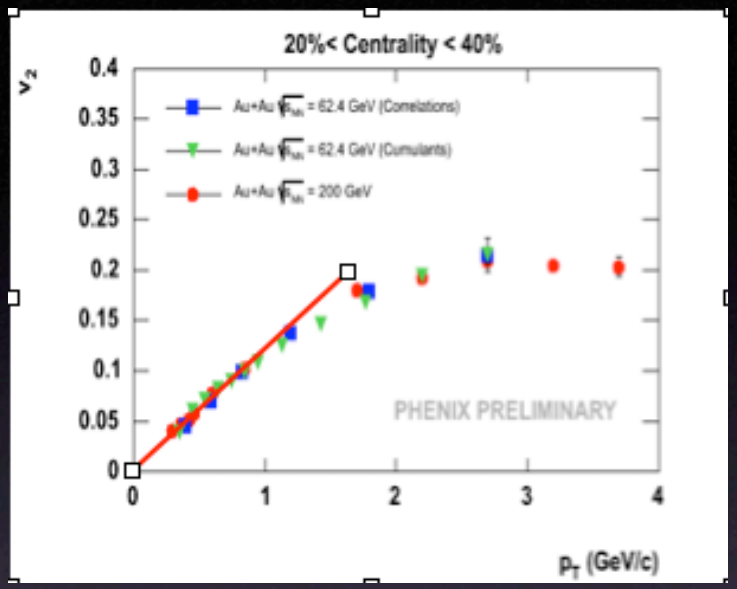




Elliptic Flow at LHC

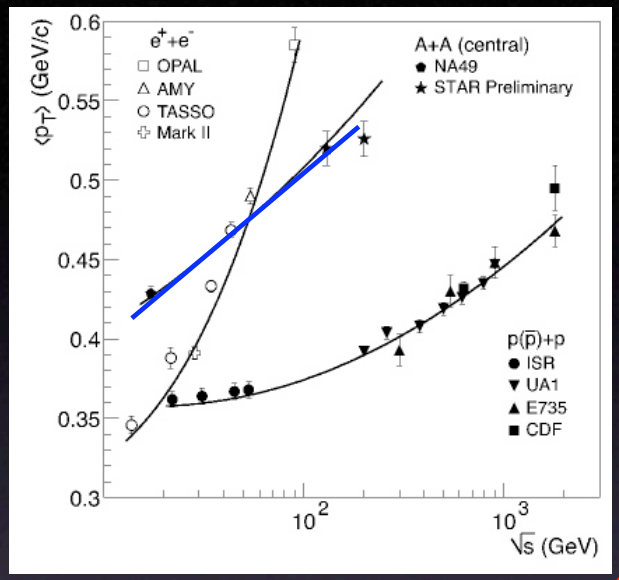


v_2 vs p_T



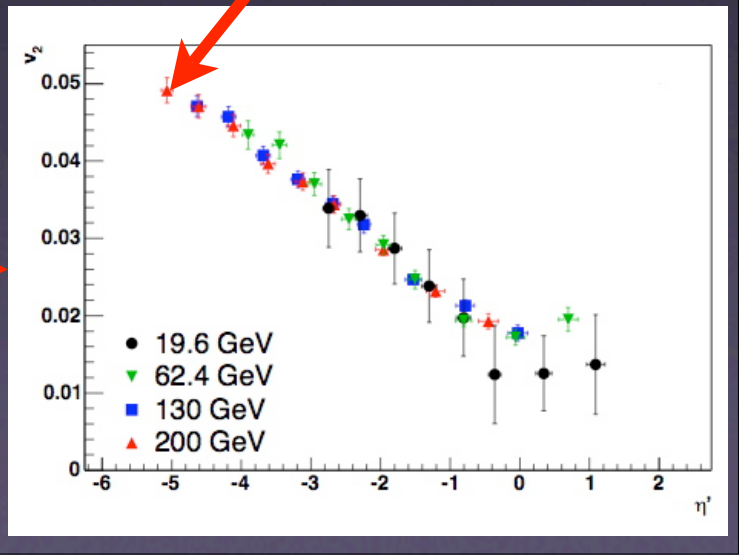
+

$\langle p_T \rangle$ vs $\sqrt{s}$

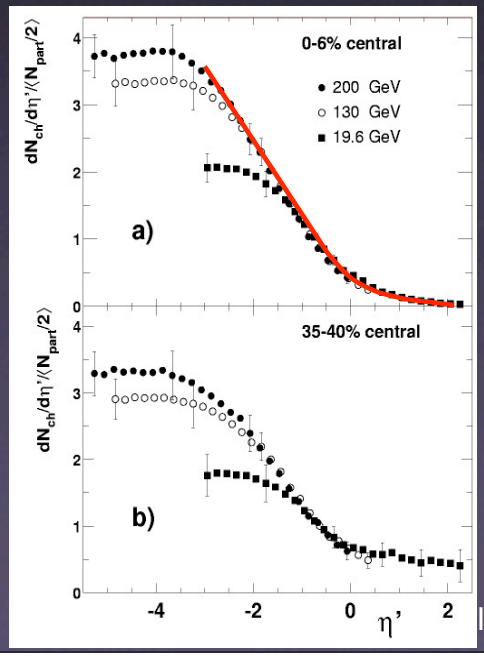


=

$v_2(\eta')$ vs $\sqrt{s}$



dN/dη' vs $\sqrt{s}$



land/MIT