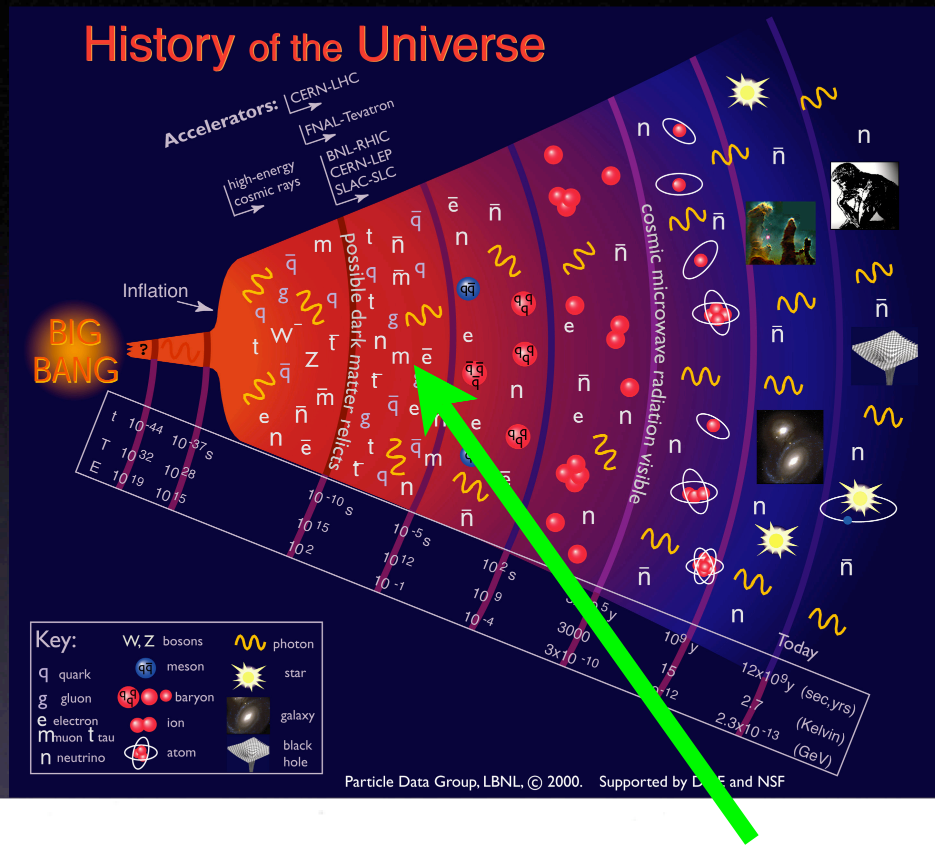
Hot Matter at RHIC and LHC

LNS Colloqium
Nov 7 2005

Gunther Roland

Have you found the Quark-Gluon Plasma yet?



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.

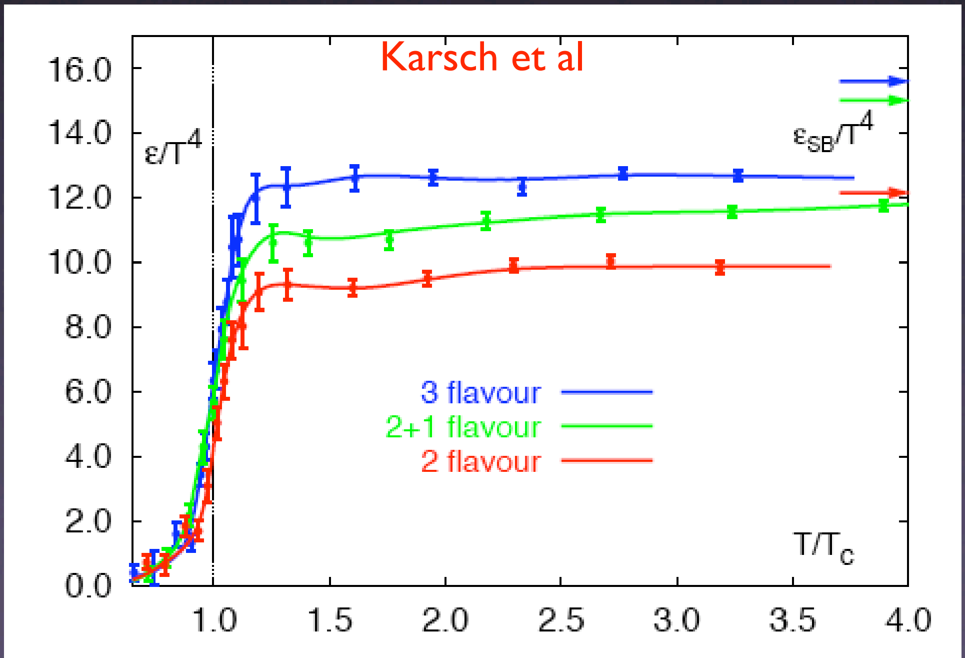
QCD Phase Diagram

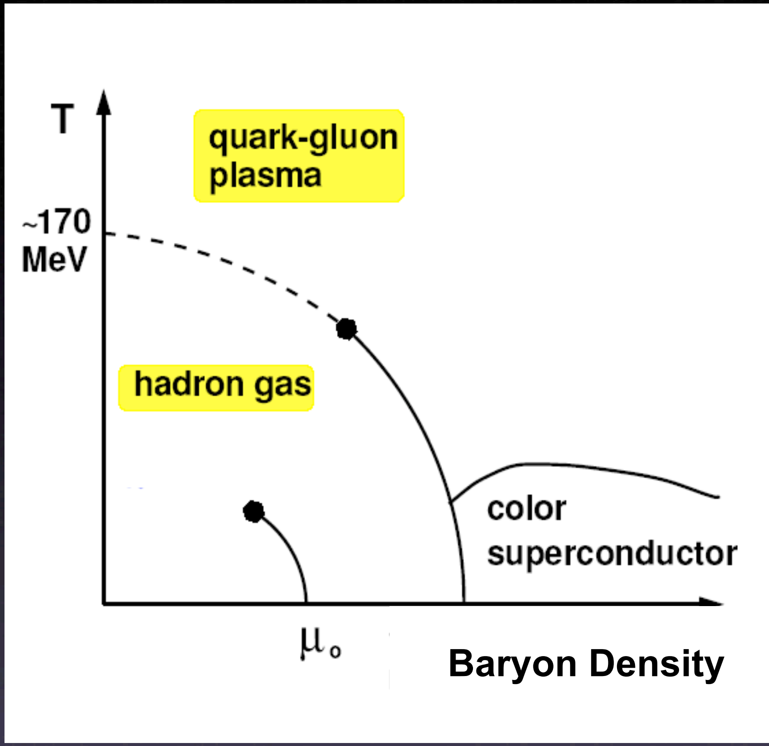
Phase Transition at high T

~ 170 MeV

~ 1 GeV/fm^3

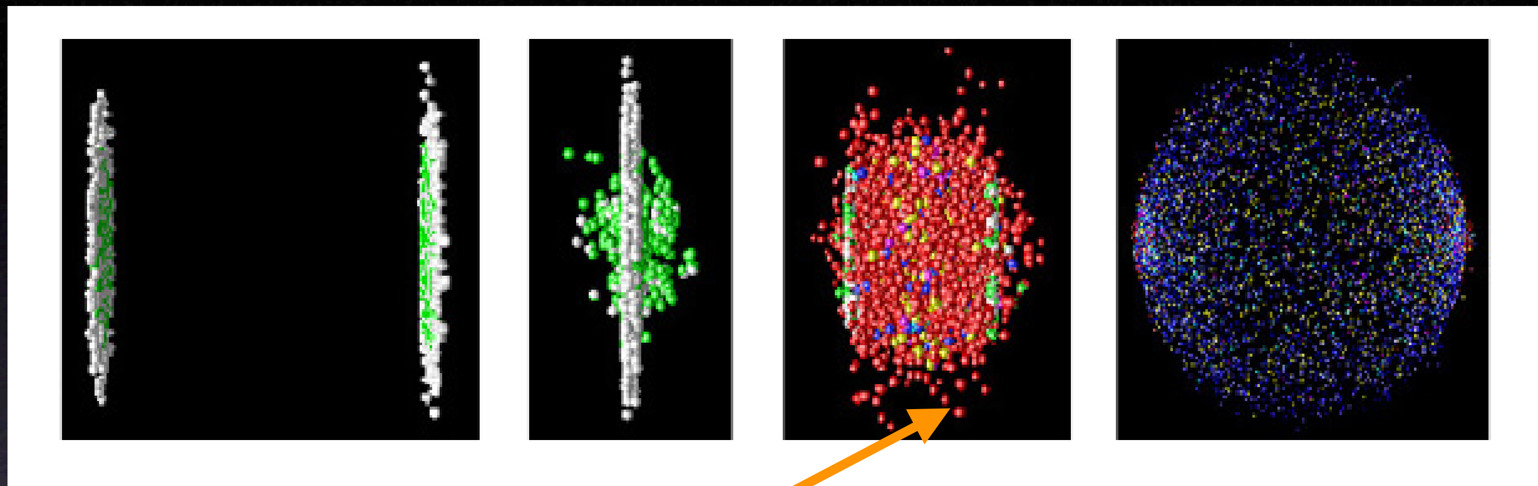
Deconfinement:
Quark-Gluon Plasma

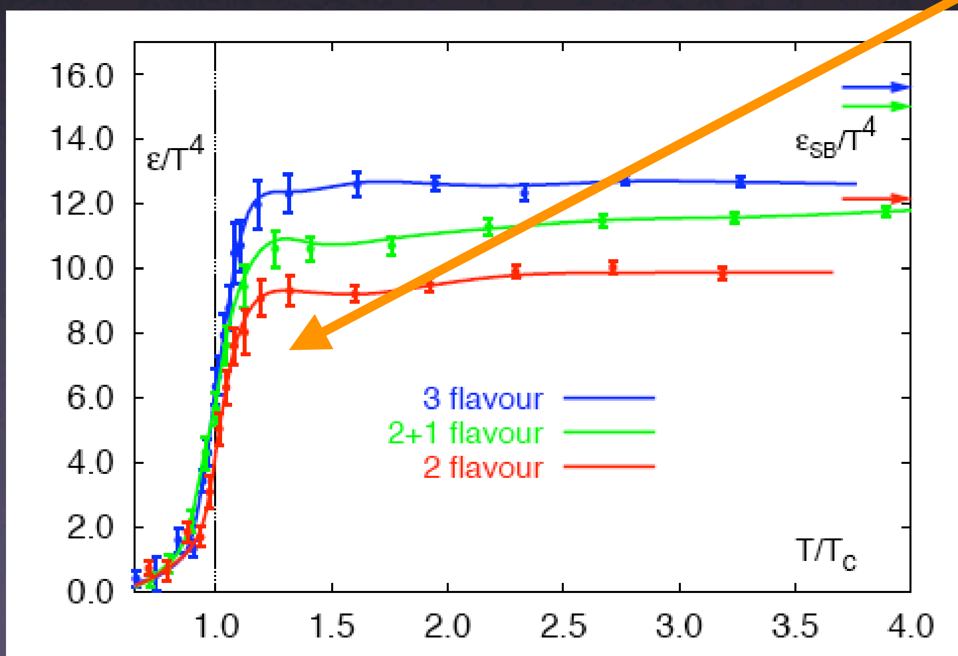




QCD Phase Diagram

Time

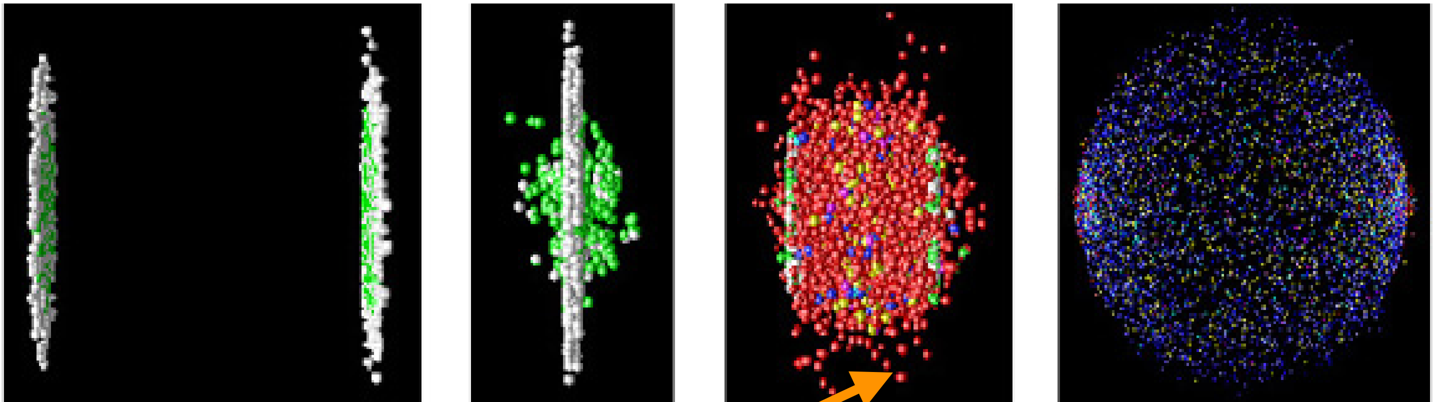




The Medium

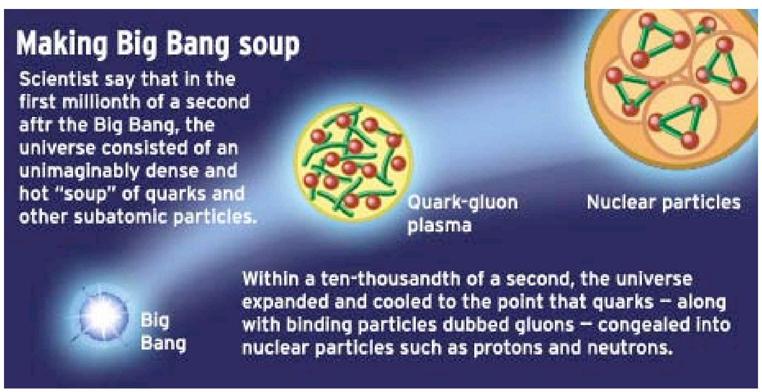
QCD Phase Diagram

Time



In the beginning was ... a perfect liquid?

'Big Bang soup' really behaves like fluid, scientists say



Duane Hoffmann / MSNBC

REUTERS

Updated: 2:29 p.m. ET April 18, 2005

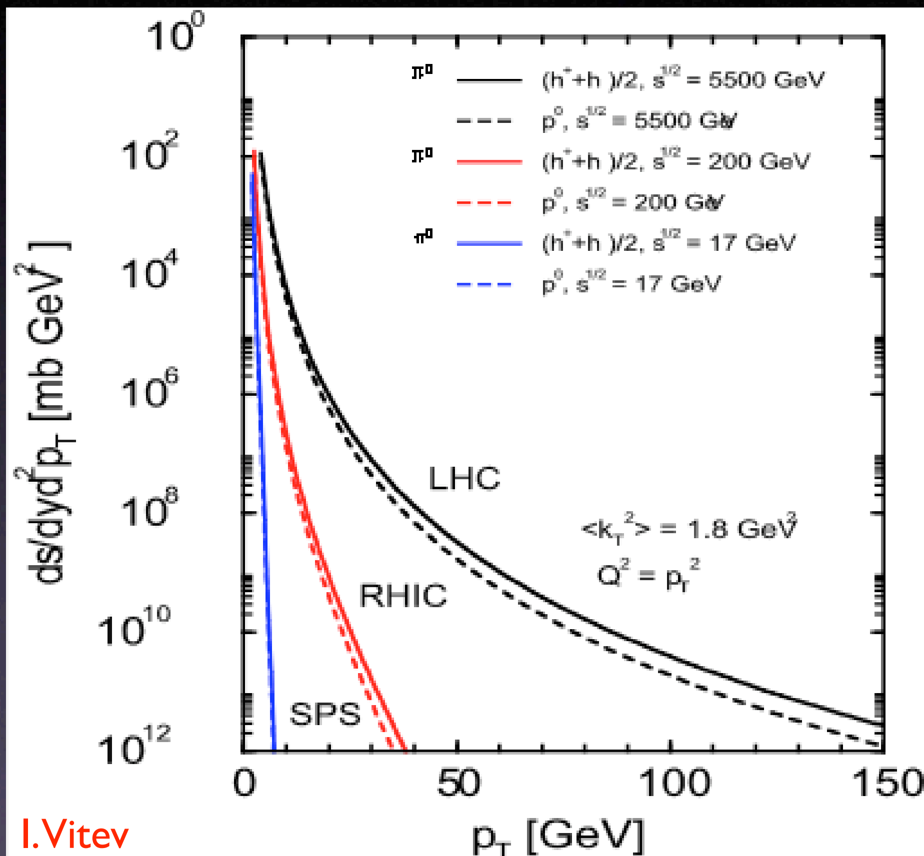
WASHINGTON - Scientists using a giant atom smasher said on Monday they have created a new state of matter — a hot, dense liquid

The Medium

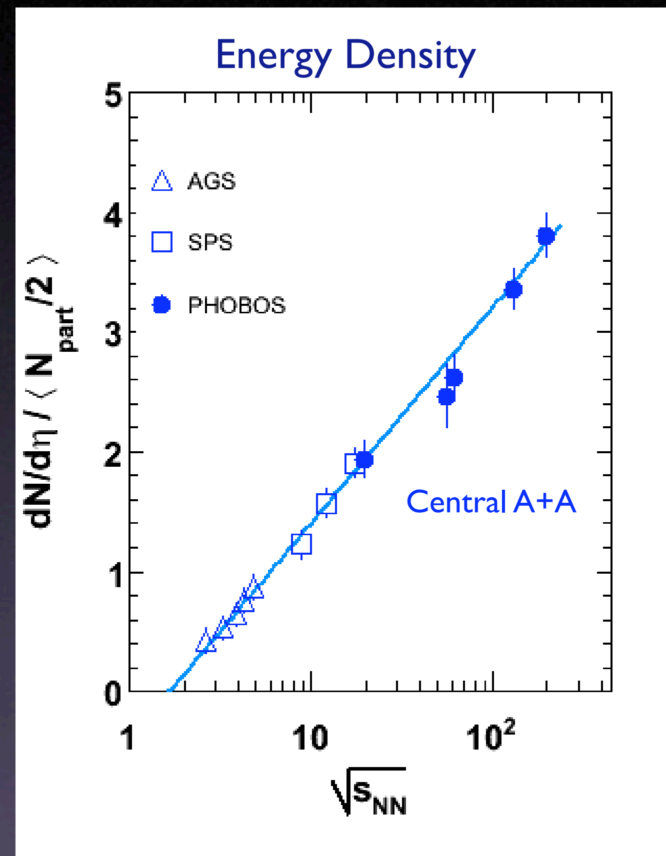
2004/5: Whitepapers from 4 RHIC experiments

PHOBOS whitepaper
Nucl Phys A 757, 28 (2005)

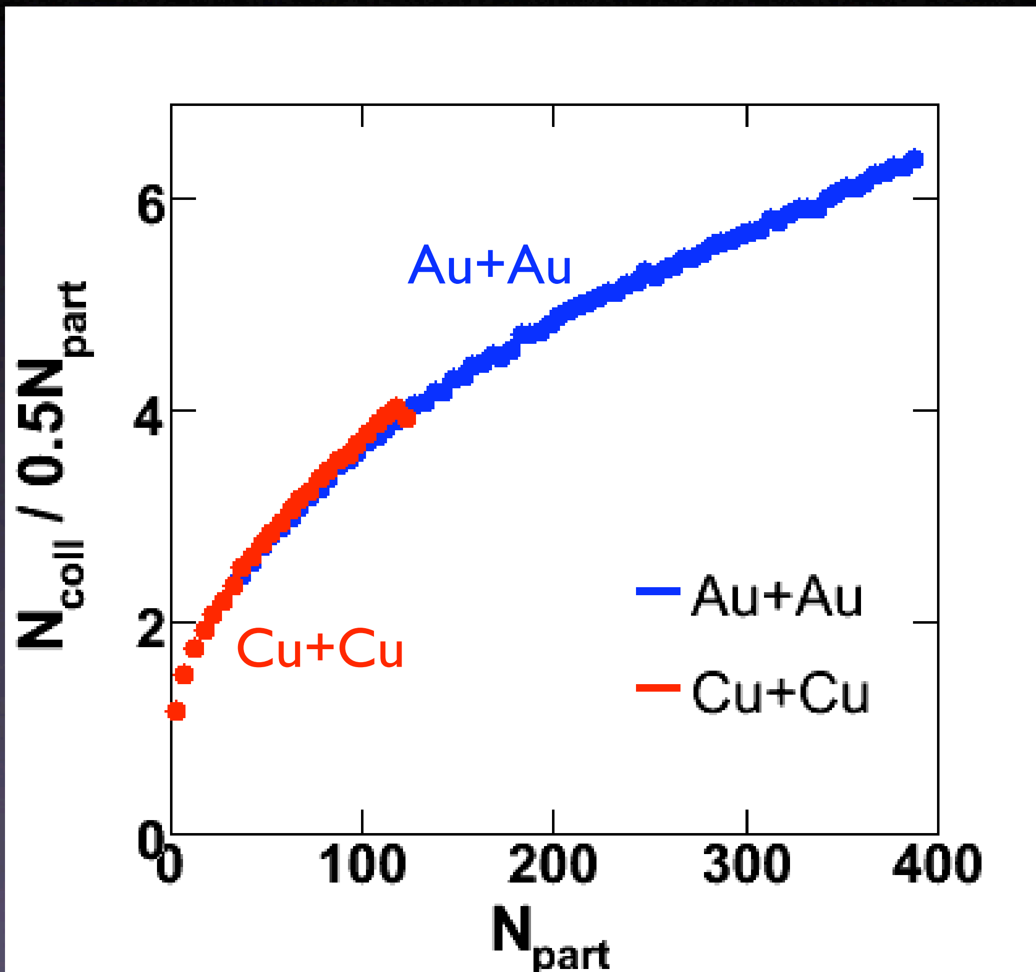
MSNBC
April '05



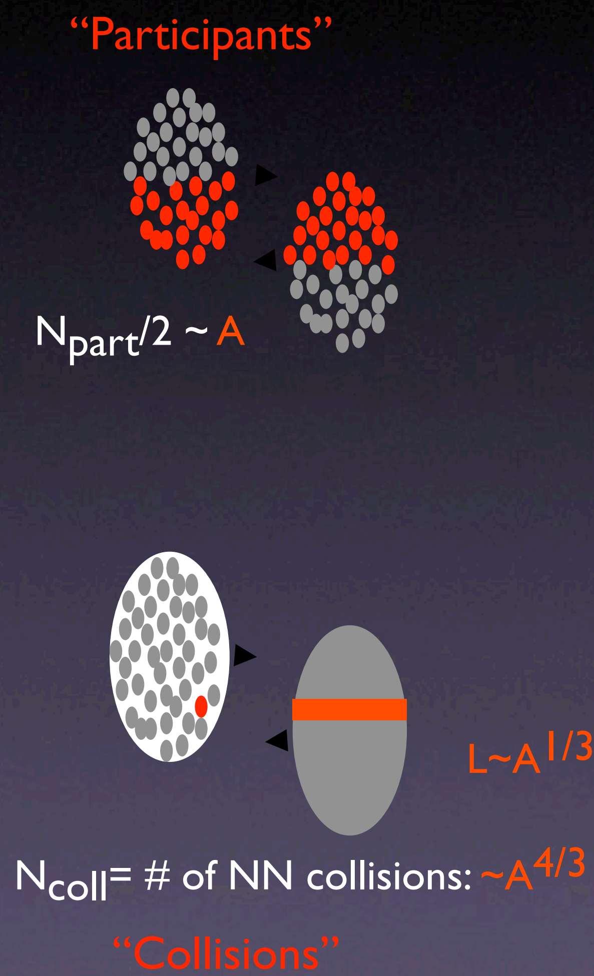
ds/dyd²p_T [mb GeV²]
p_T [GeV]
LHC
RHIC
SPS
<k_T²> = 1.8 GeV²
Q² = p_T²
I.Vitev



Energy Density
AGS
SPS
PHOBOS
Central A+A
dN/dη / ⟨ N_part /2 ⟩
√s_NN

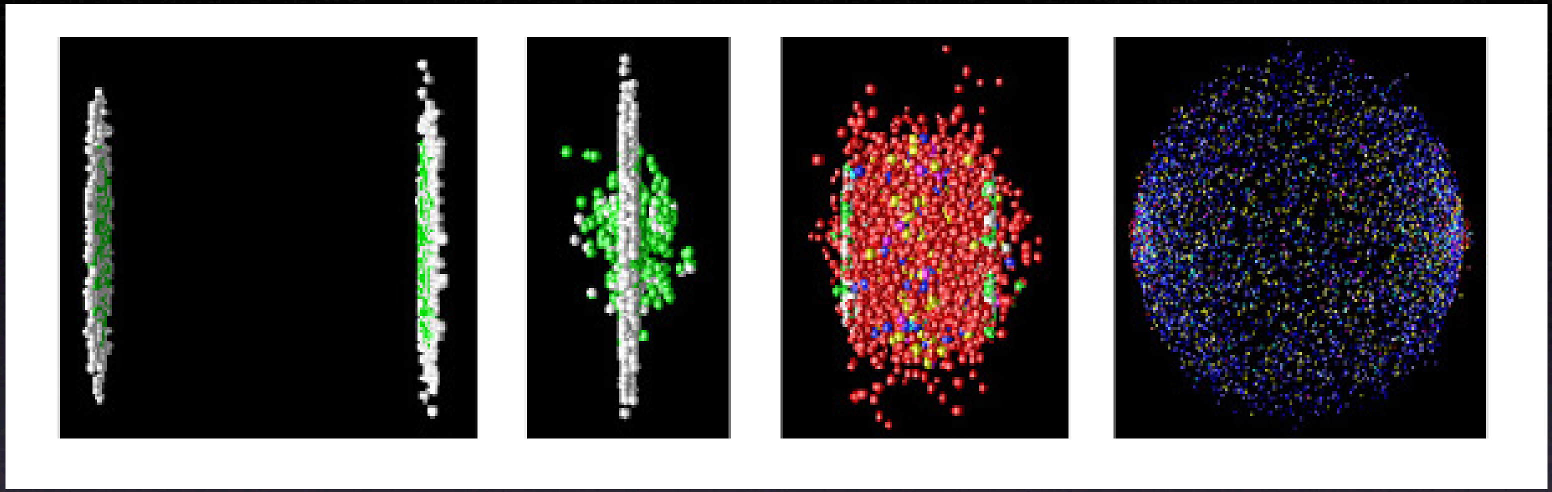


Au+Au
Cu+Cu
Au+Au
Cu+Cu
N_{coll} / $0.5N_{part}$
N_{part}
0
2
4
6
0
100
200
300
400



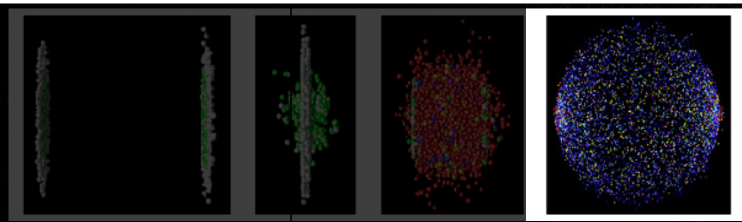
"Participants"
$N_{part}/2 \sim A$
$L \sim A^{1/3}$
N_{coll}= # of NN collisions: $\sim A^{4/3}$
"Collisions"

QCD Phase Diagram

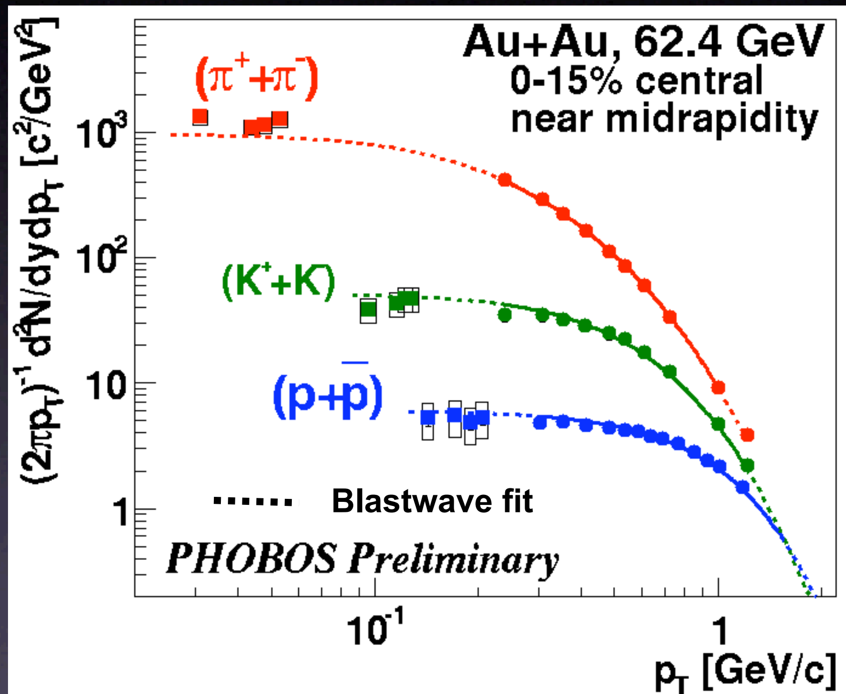


This Talk

Examine different stages of the collision process
Look at key evidence for our current picture
Point out interesting puzzles



Collective transverse expansion

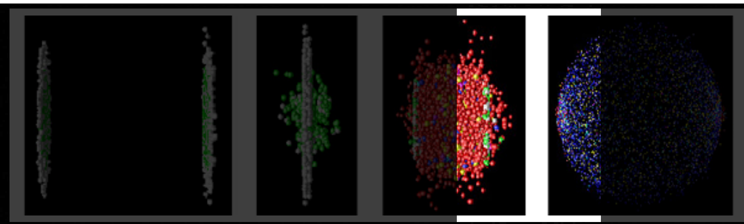


Effective Temperature

$T_{eff} = T + <\beta_T>^2 * mass$

Simultaneous fit constrains expansion parameters:

$T_f \approx 120MeV, \beta_T \approx 0.6c$



Hadronization

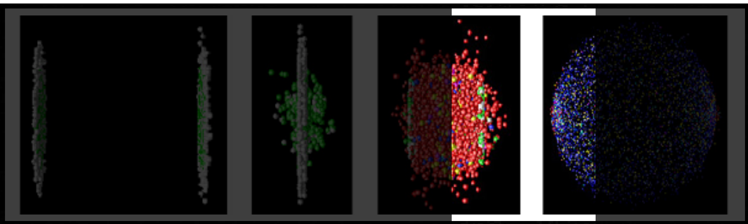
Statistical Hadronization in the Grand-Canonical Ensemble

Temperature   Chemical Potential

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

Yield   Mass   Quantum Numbers

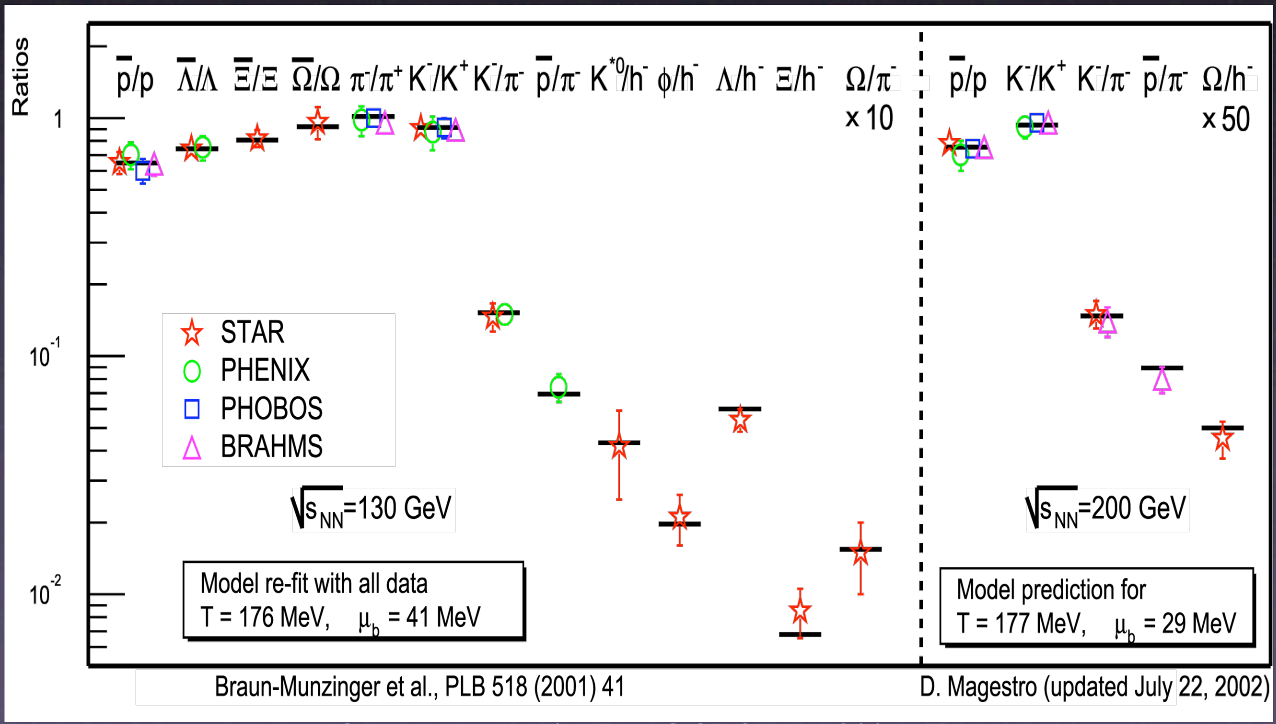
c.f. Hagedorn, Becattini, Braun-Munzinger, Cleymans, Heinz, Letessier, Mekijan, Rafelski, Redlich, Satz, Sollfrank,Stachel,Tounsi + many others

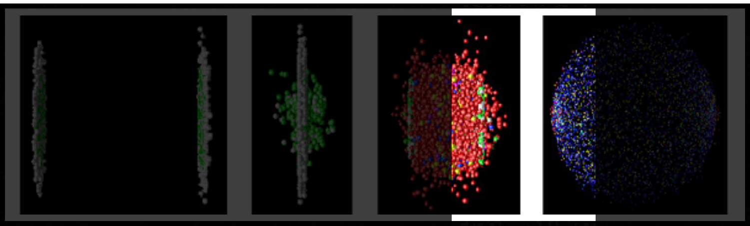


Hadronization

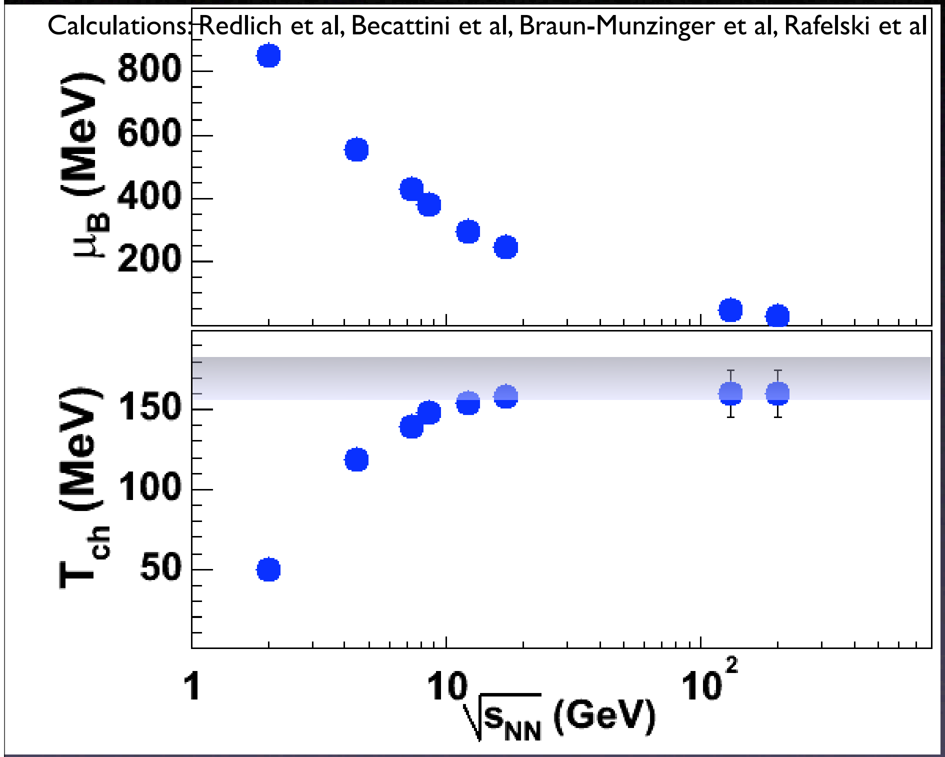
Statistical Hadronization in the Grand-Canonical Ensemble

Relative Abundances: Two Parameters !



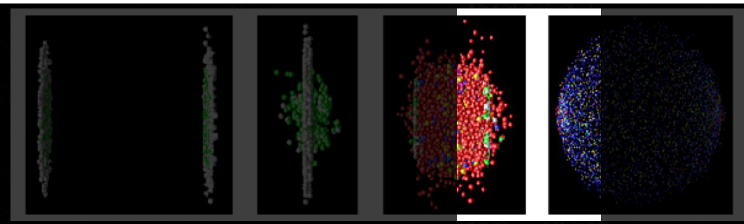


Hadronization



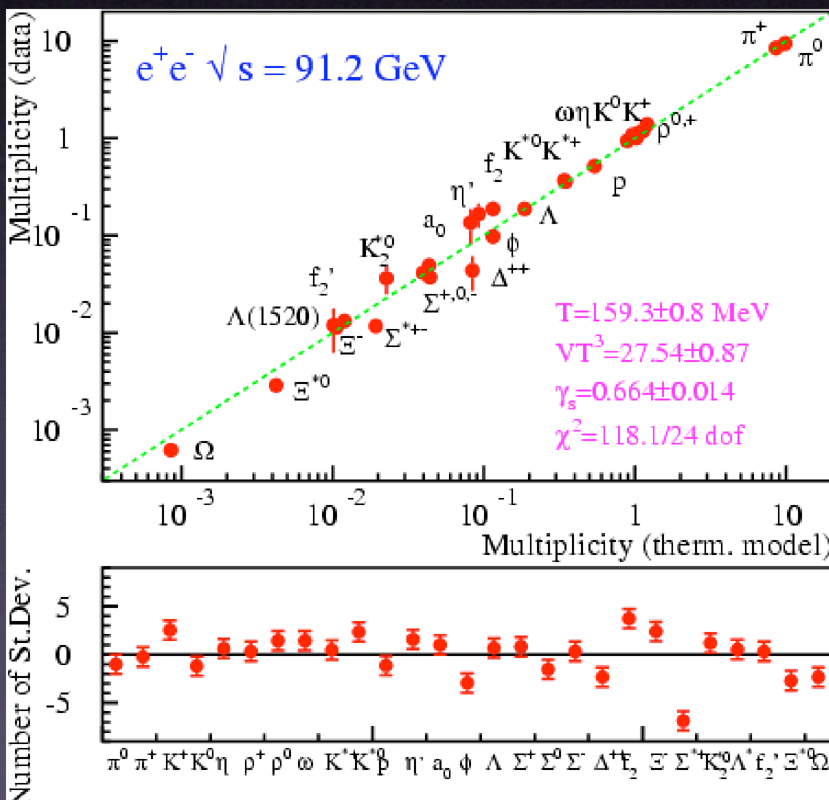
μ_B drops with collision energy

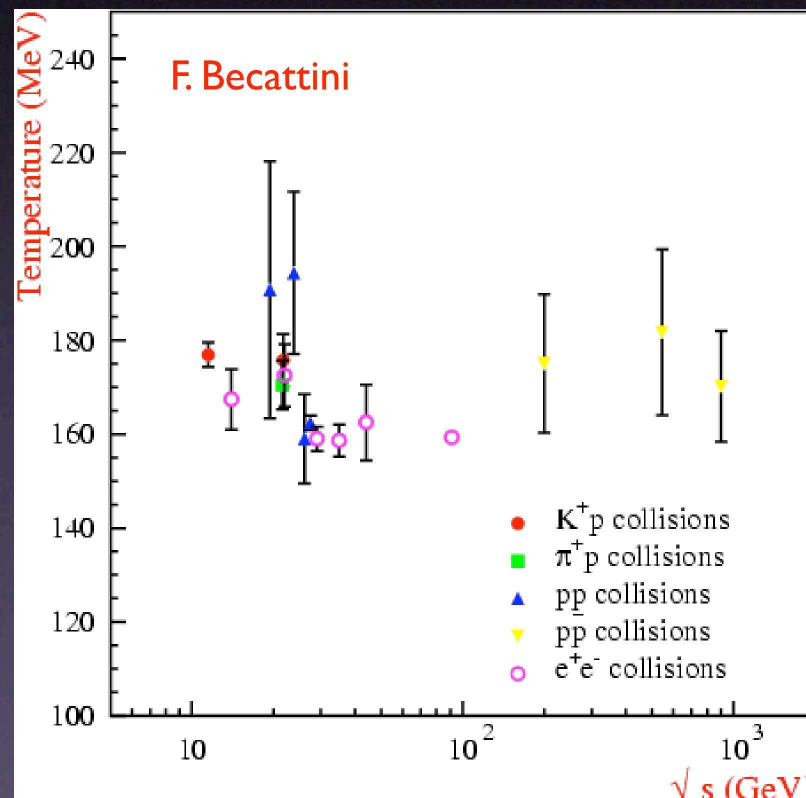
T_{ch} approaches limiting value

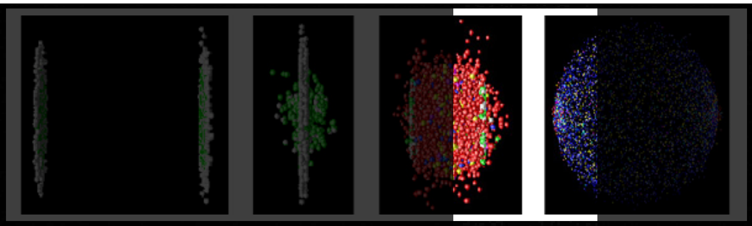


Hadronization

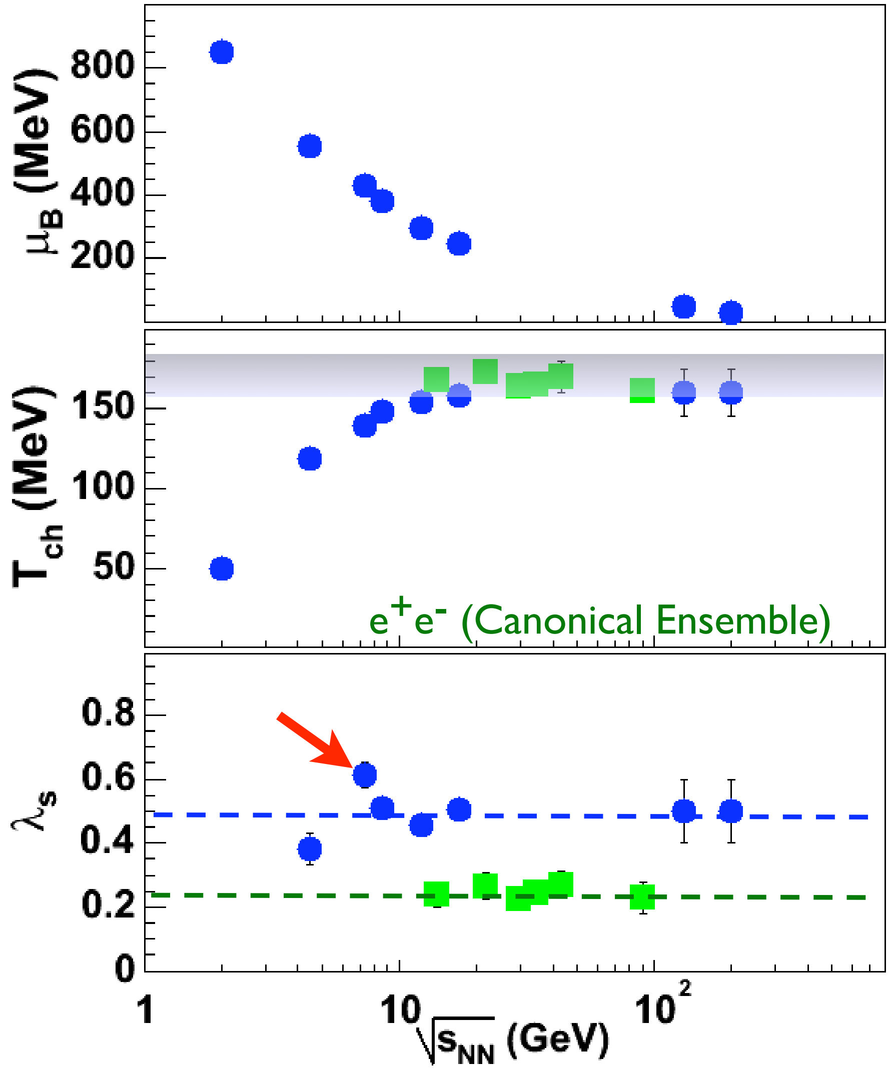
Statistical Model for Elementary Collisions







Hadronization

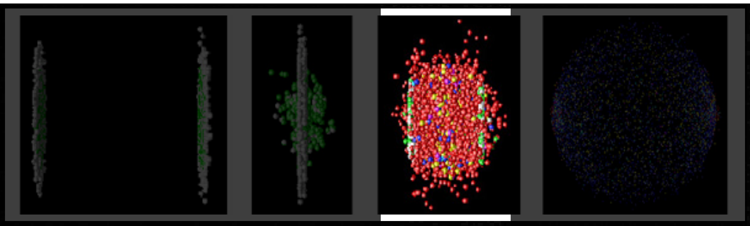


e^+e^- hadronizes at same T_{ch}

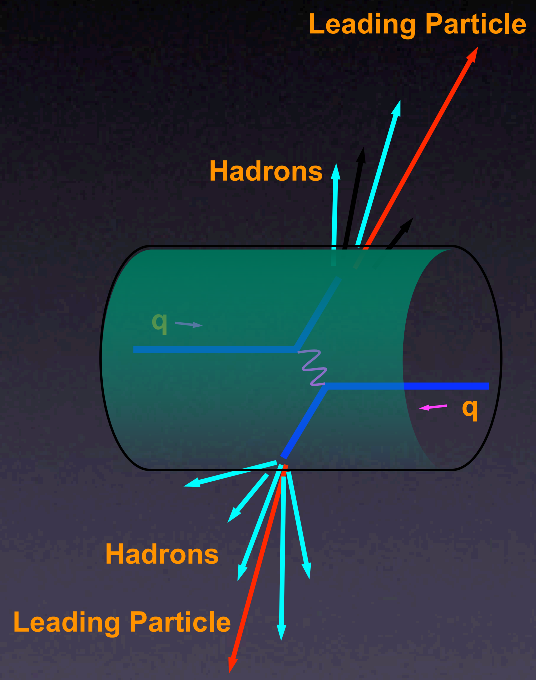
Are we looking at a *local* or *global* property?

Strangeness enhancement unique to AA

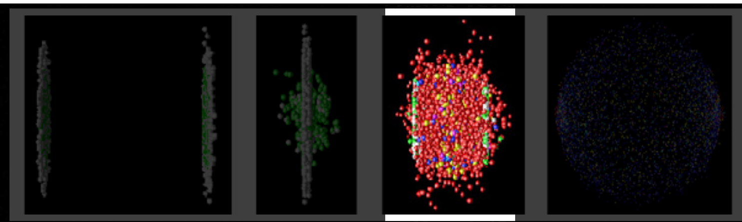
Global (or at least large) correlation volume in AA



Properties of the Medium

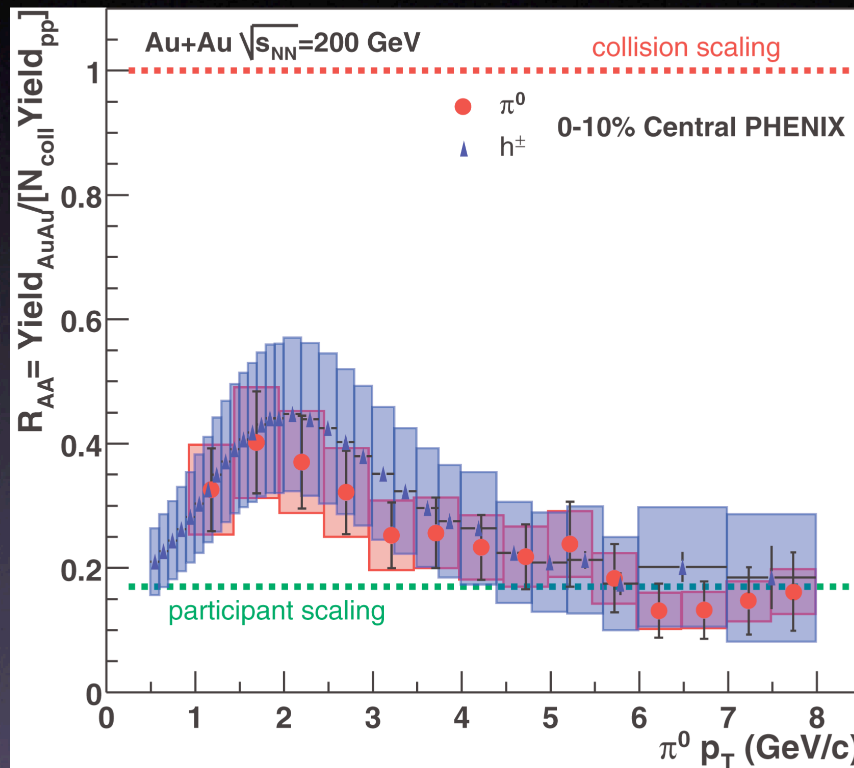


Use high p_T hadron yield as “calibrated” probe



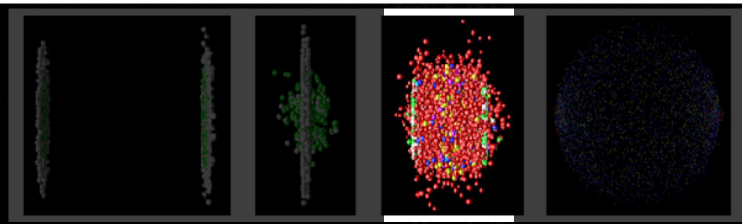
Properties of the Medium

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta}$$



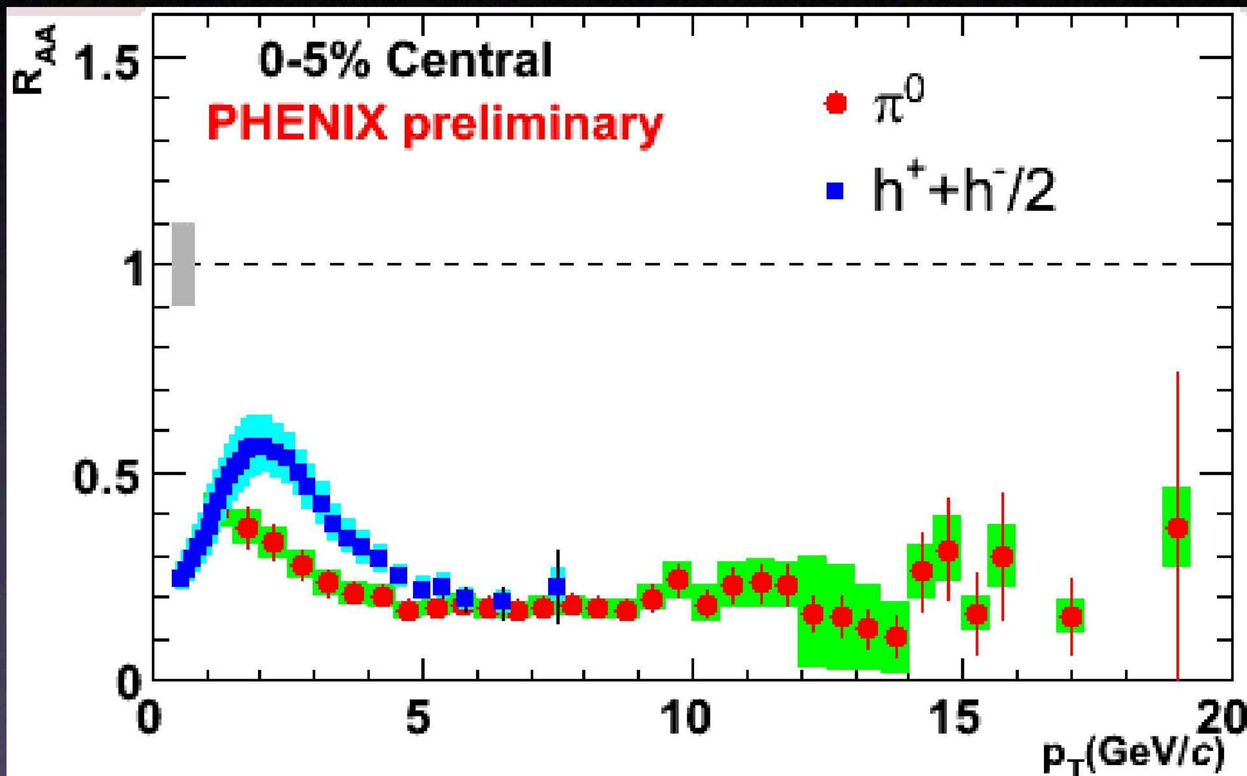
Use high p_T hadron yield as "calibrated" probe

Strong (factor 5) suppression observed

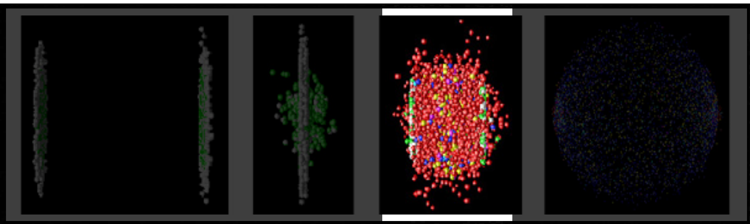


Properties of the Medium

QM '05

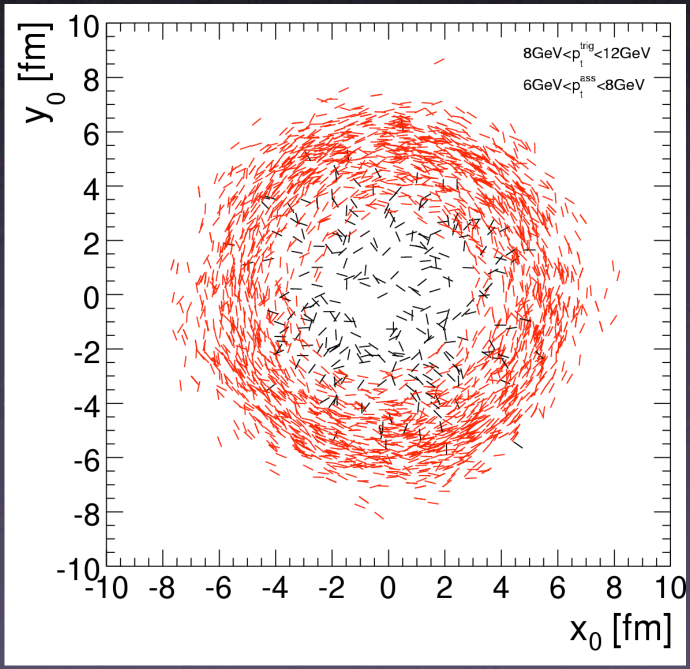


Suppression persists out to > 15 GeV/c

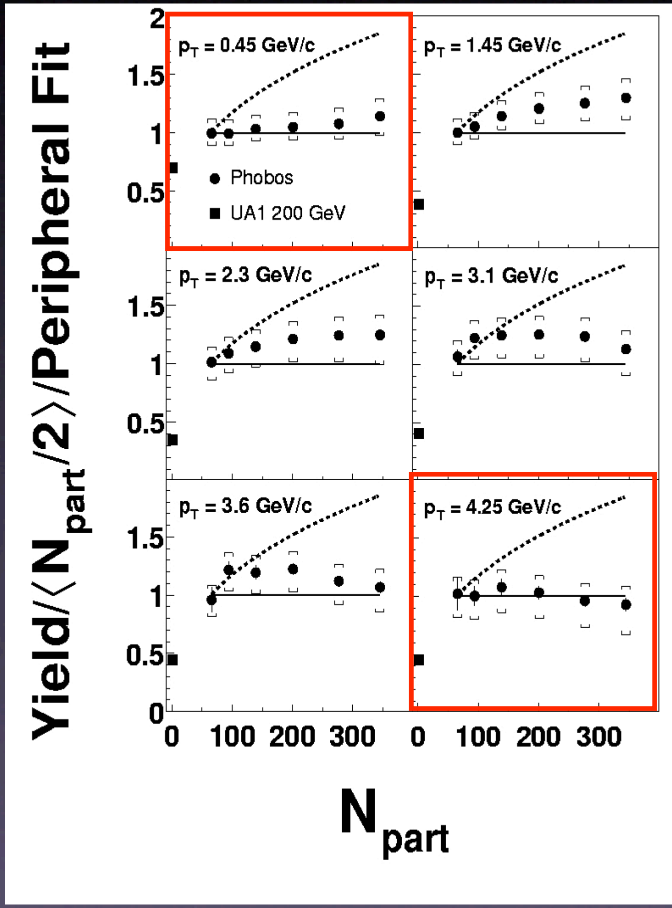


Properties of the Medium

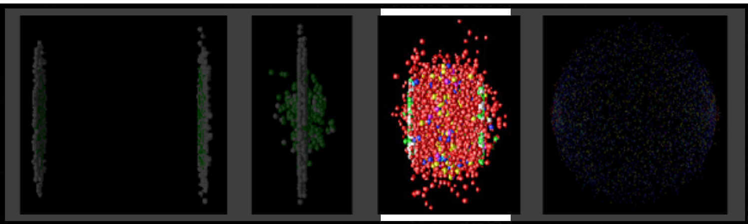
Poster by Dainese, Loizides and Paic
(best poster award at QM 2005)



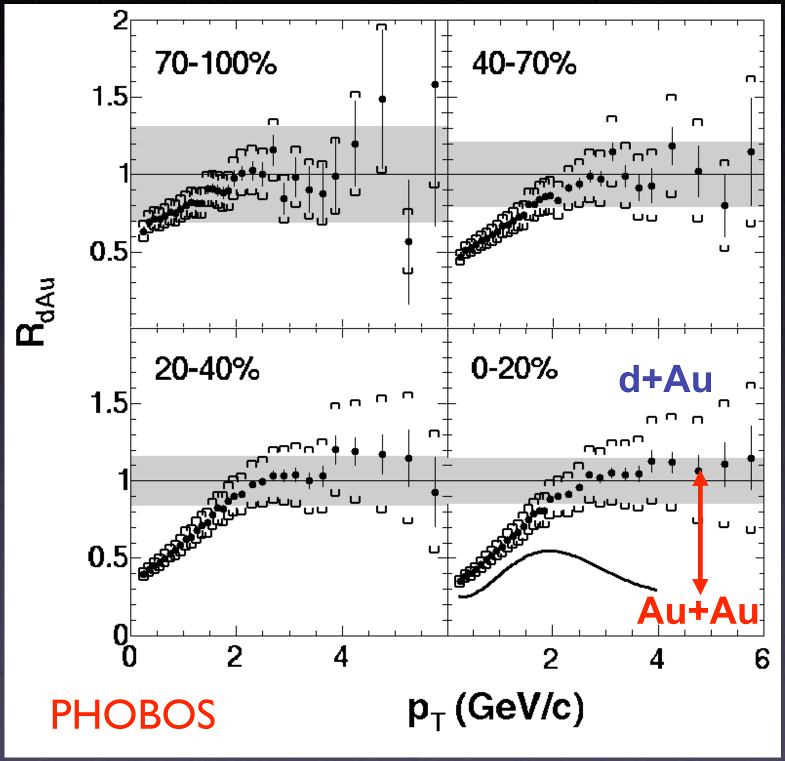
PHOBOS, nucl-ex/0302015

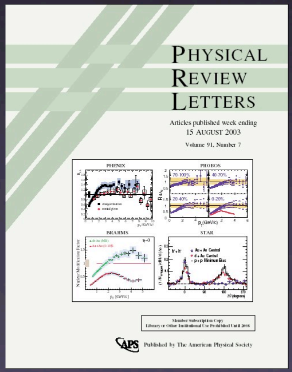


Dominance of surface emission?



Properties of the Medium





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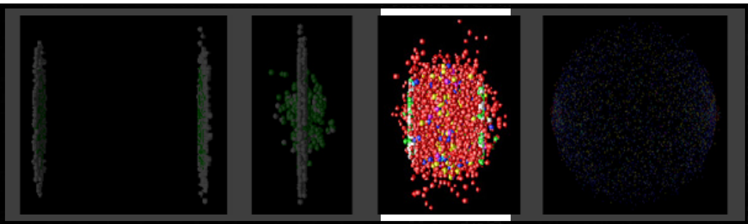
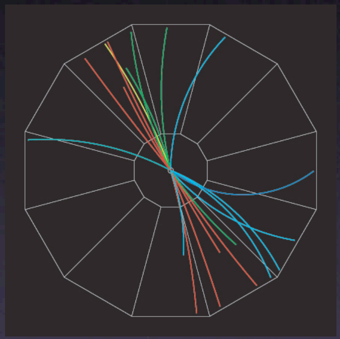
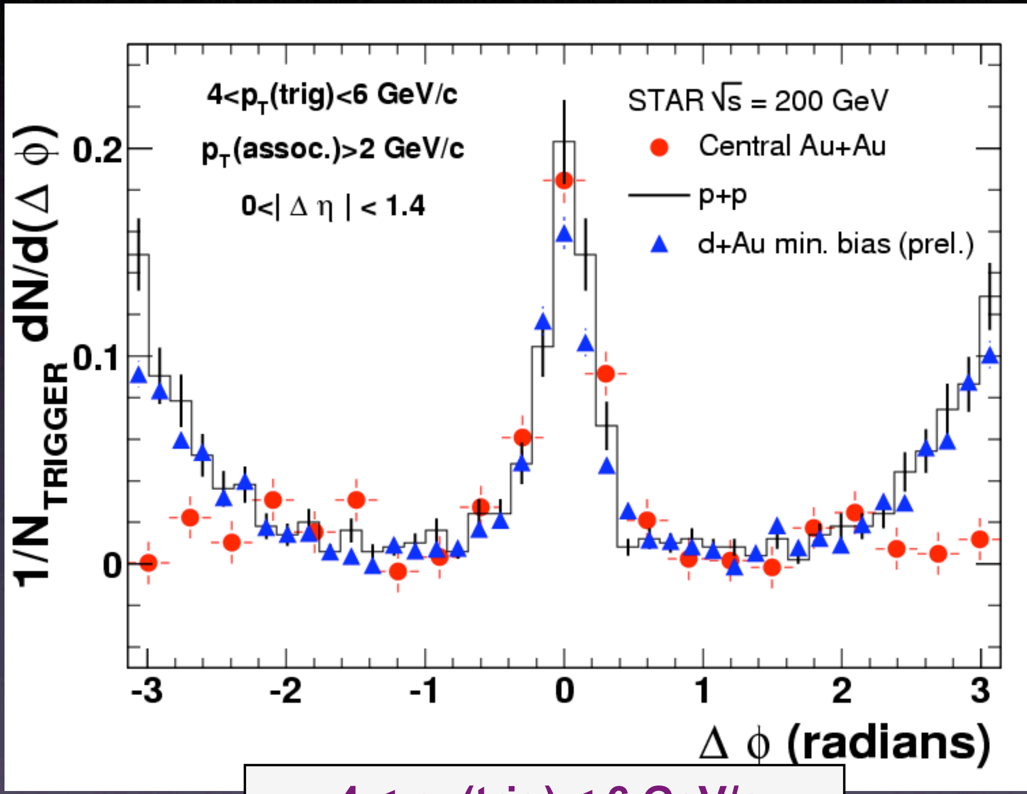


Properties of the Medium

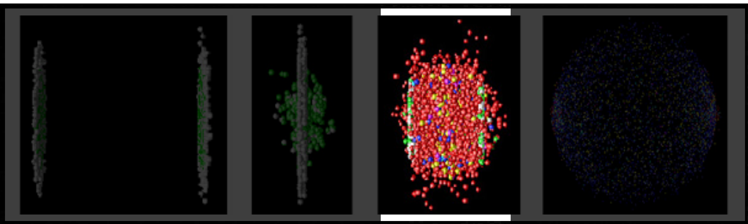




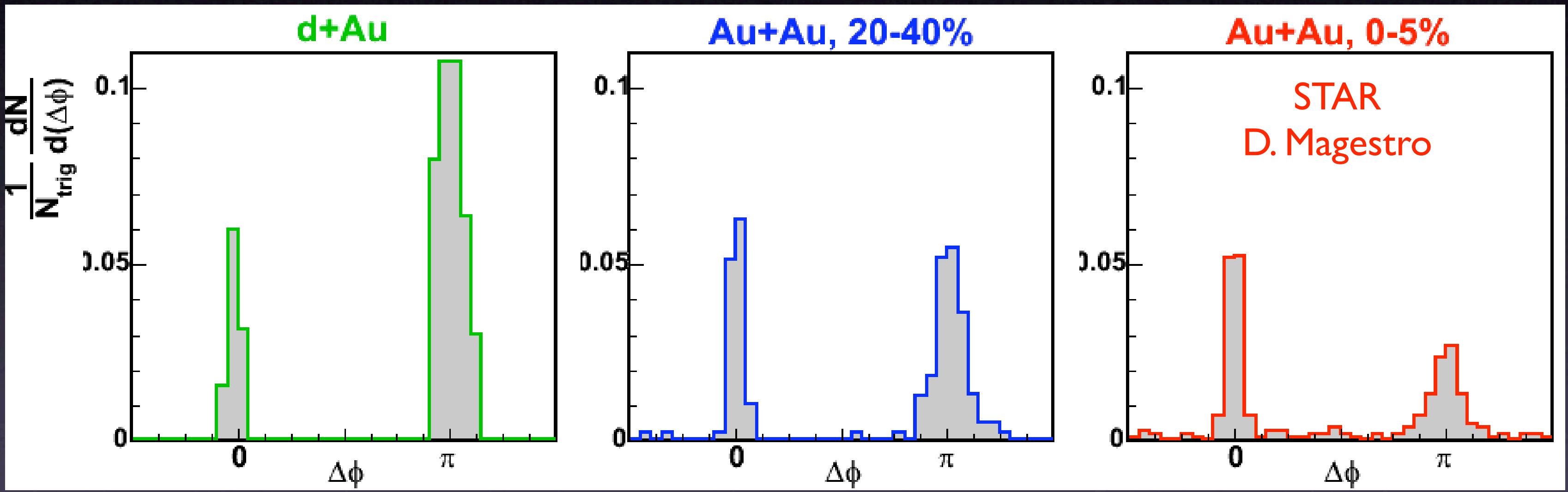
4 < p_T(trig) < 6 GeV/c

p_T(assoc) > 2 GeV/c

Disappearence of back-to-back correlations in Au+Au

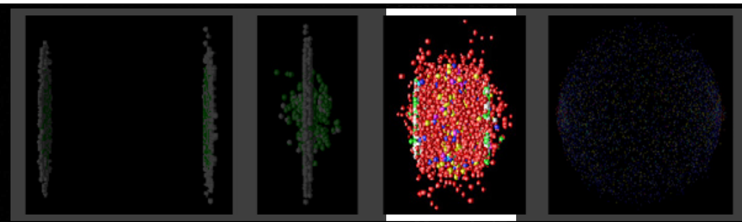


Properties of the Medium



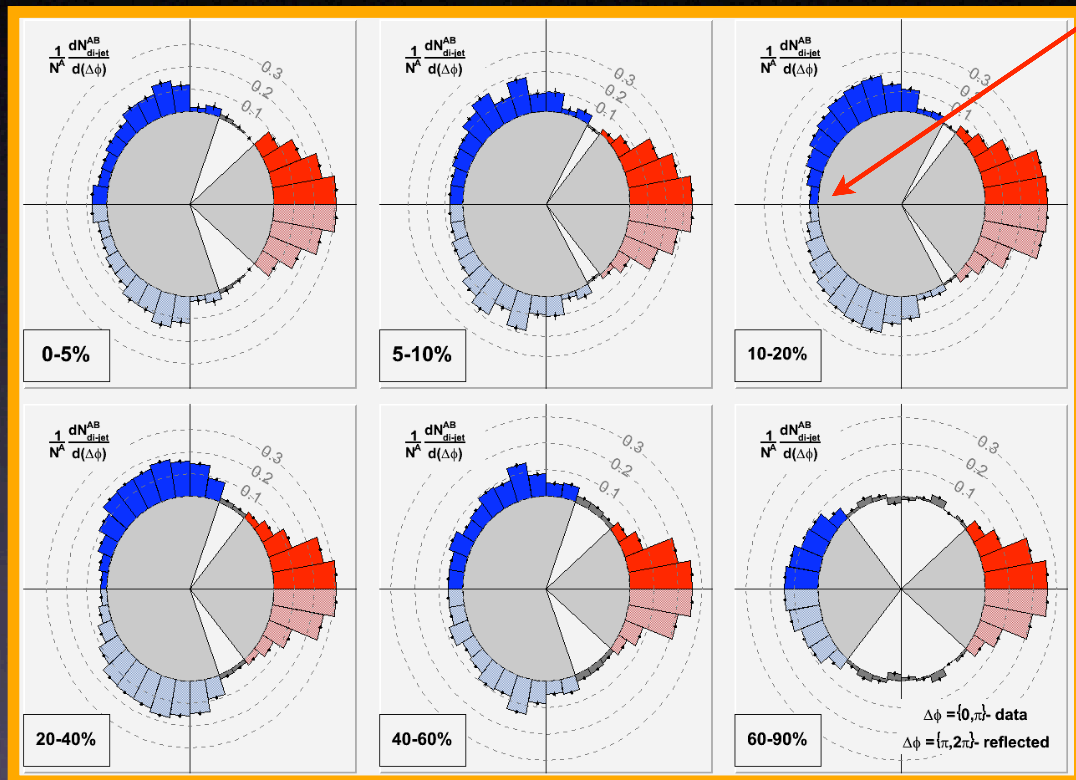
8 < p_T(trig) < 15 GeV/c
p_T(assoc) > 8 GeV/c

Back-to-back jets re-appear at sufficiently high pT

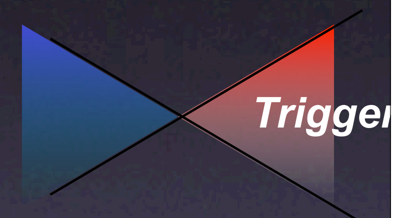


Properties of the Medium

Cone?!?



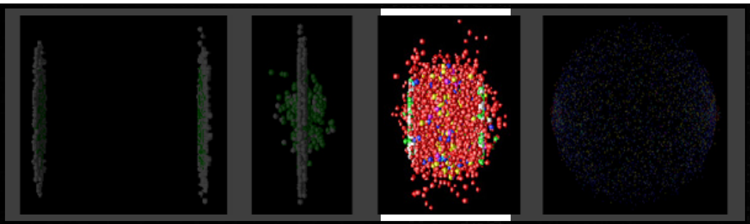
Trigger particle
$p_T > 2.5$ GeV



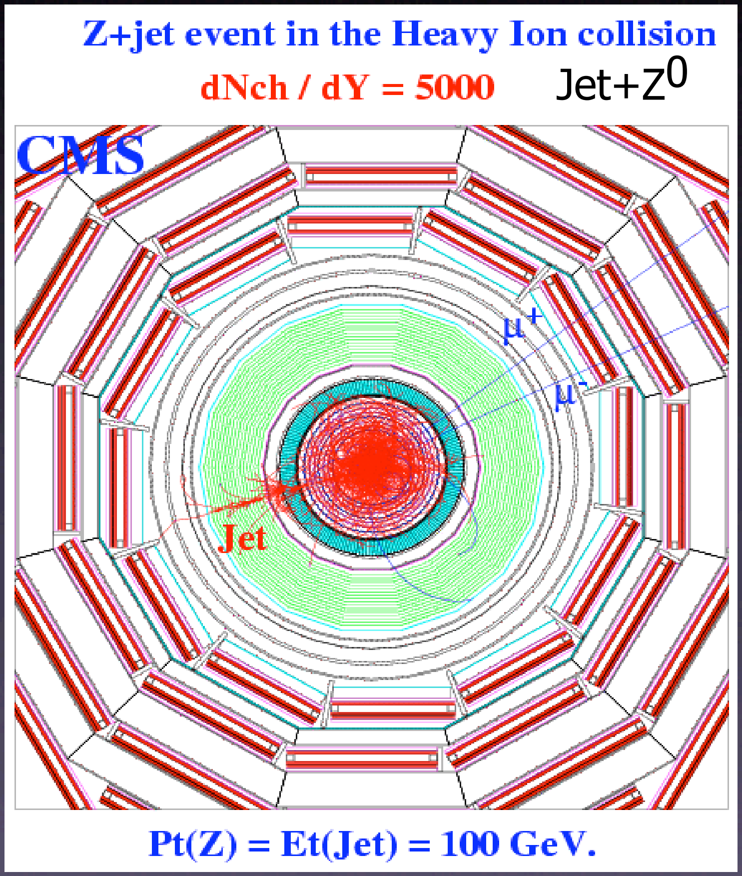
jet-pair partners
$p_T > 1.0$ GeV

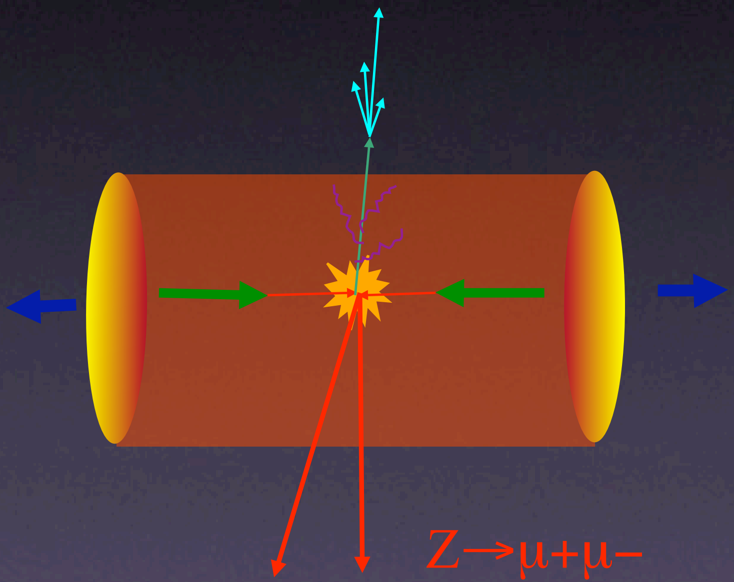
PHENIX
H. Buesching

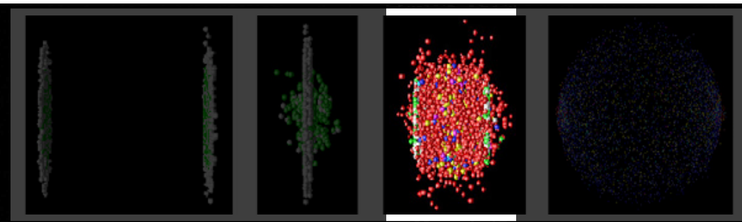
Rich phenomenology at intermediate p_T



Properties of the Medium

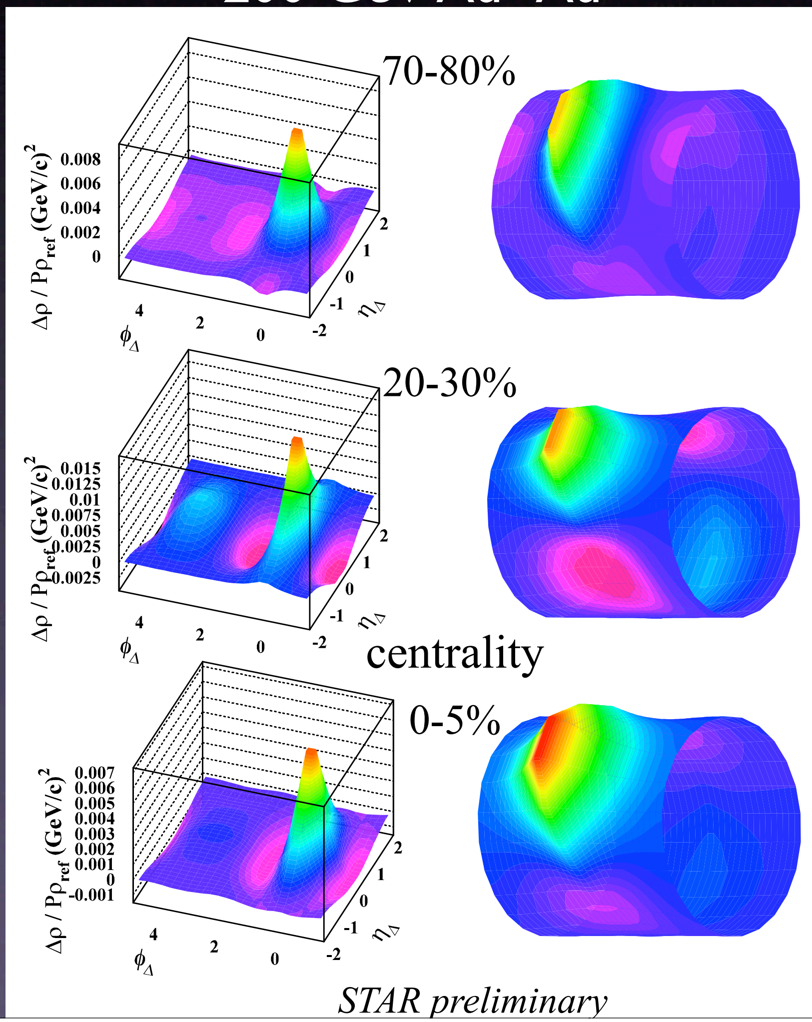




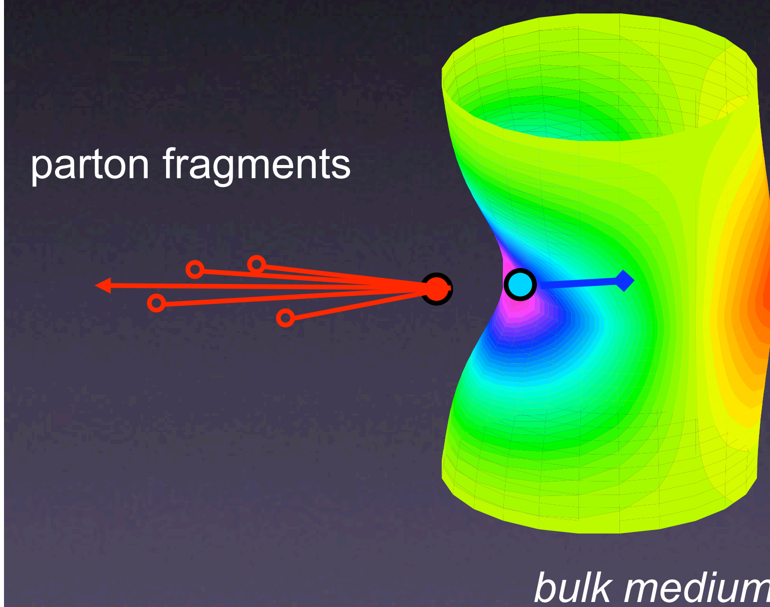


Properties of the Medium

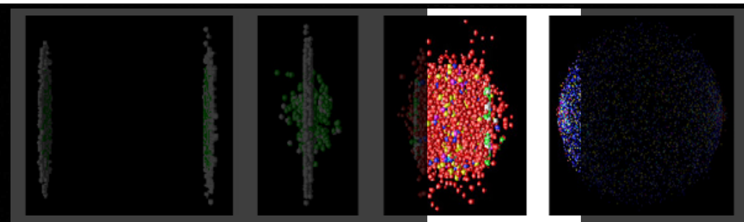
200 GeV Au+Au



Subtract fragmentation peak to look at medium



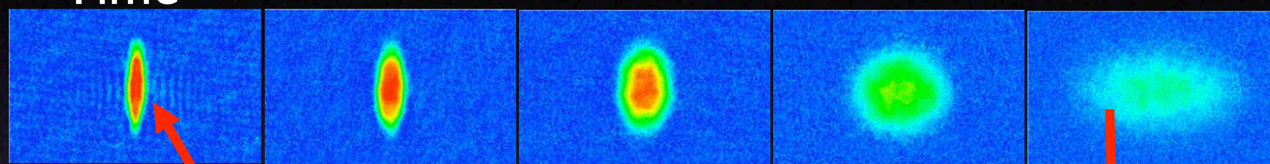
Tom Trainor

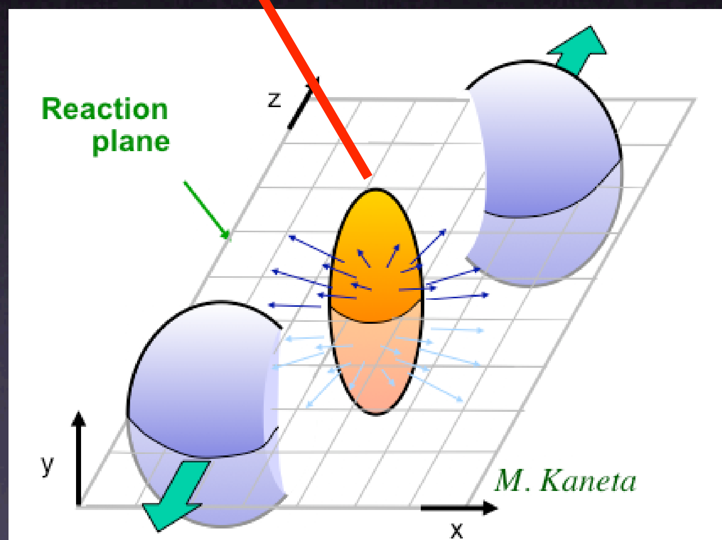


Hydrodynamic Evolution

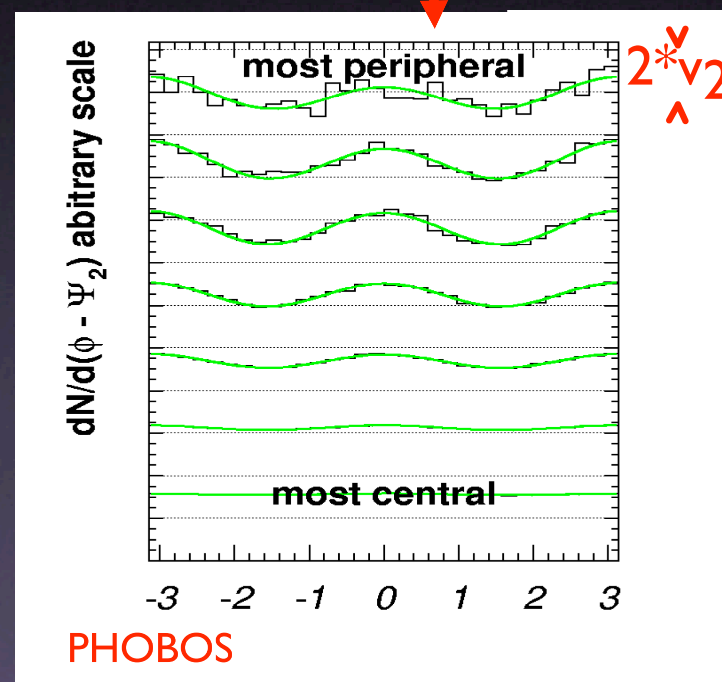
Time →

Transverse Plane

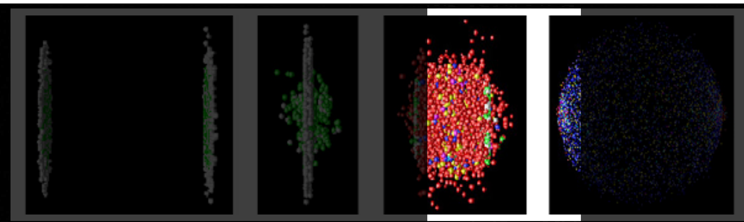




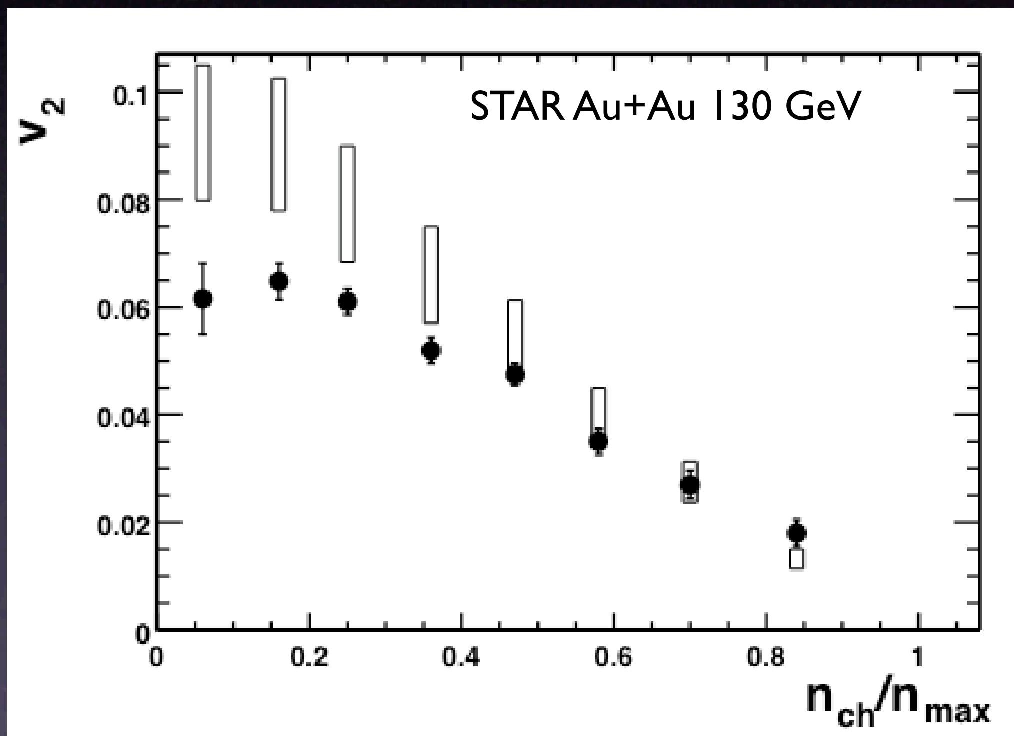
Non-central collision:
Initial state eccentricity

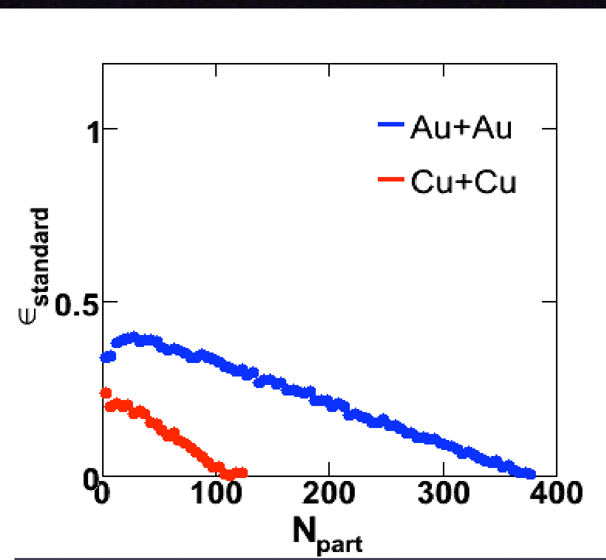


Momentum space anisotropy



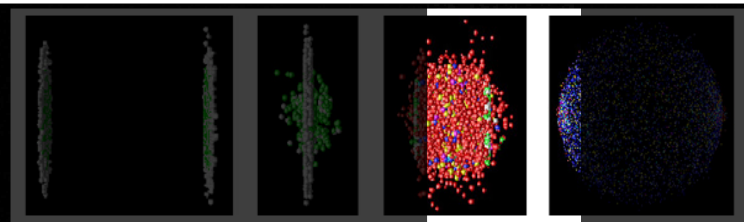
Hydrodynamic Evolution





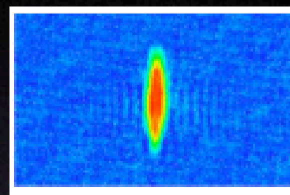
Geometrical initial state eccentricity from Glauber model

Elliptic Flow signal exhausts "hydro limit" for mid-central to central collisions



Hydrodynamic Evolution

Initial State



+

Energy/Momentum Conservation

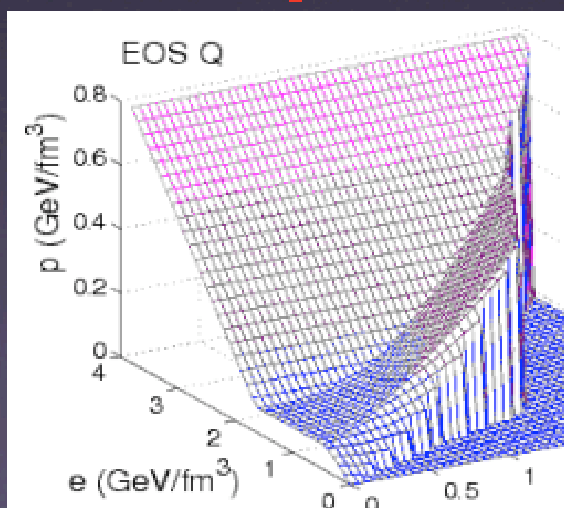
$$\partial_\mu T^{\mu\nu} = 0$$

Baryon number Conservation

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

+

Equ. of State



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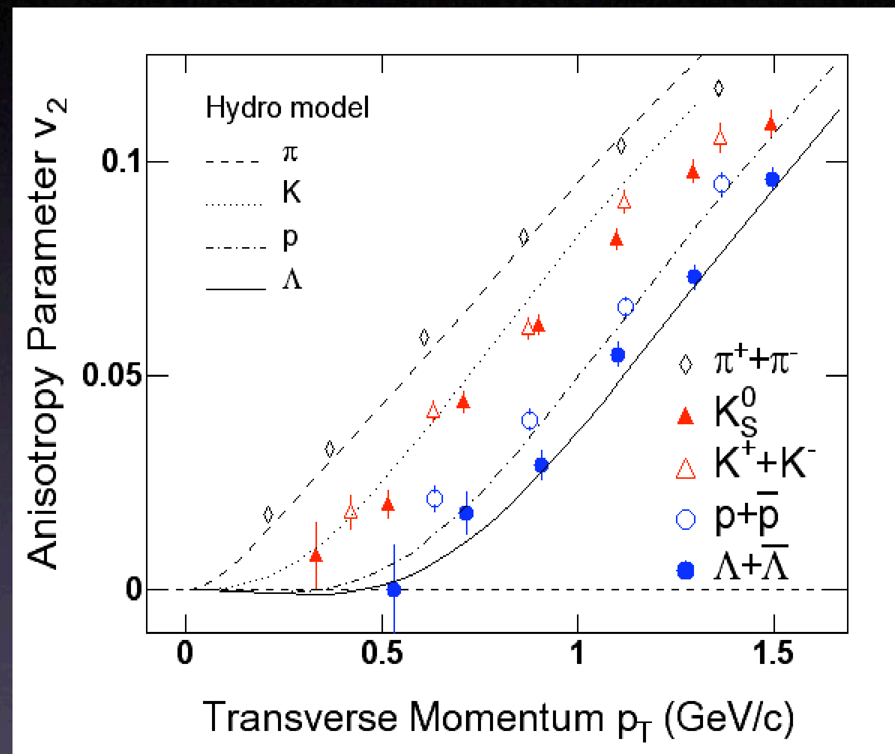
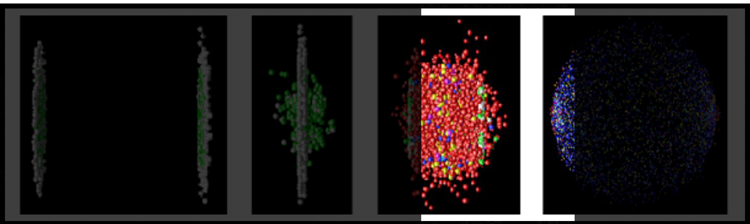
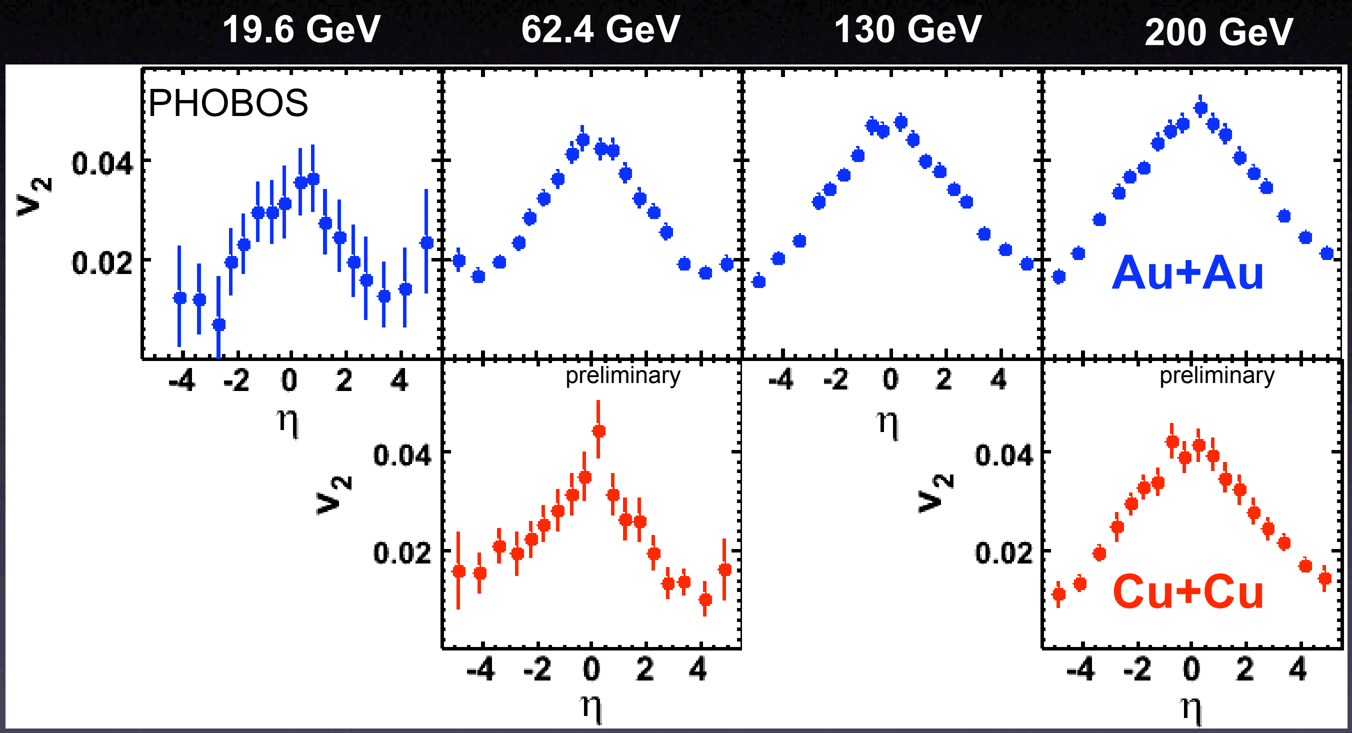


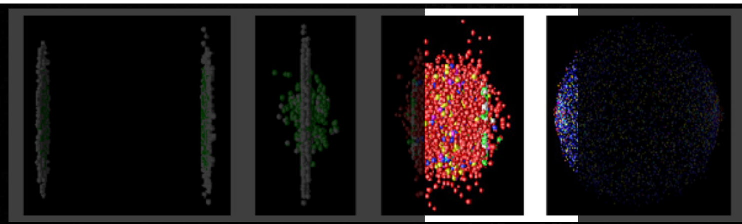


Hydrodynamic Evolution



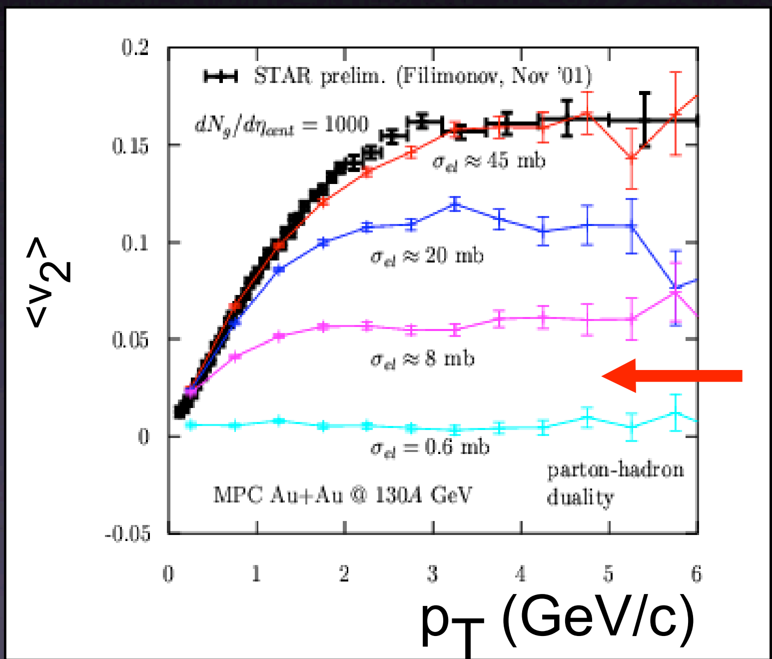
First observation of rapidity dependence of elliptic flow
Challenge to hydrodynamic calculations
Connection between flow and dN/dη

Au+Au: PRL 94 122303 (2005)
[centrality dependence near y=0 - Carla Vale]
Cu+Cu: PHOBOS QM 2005



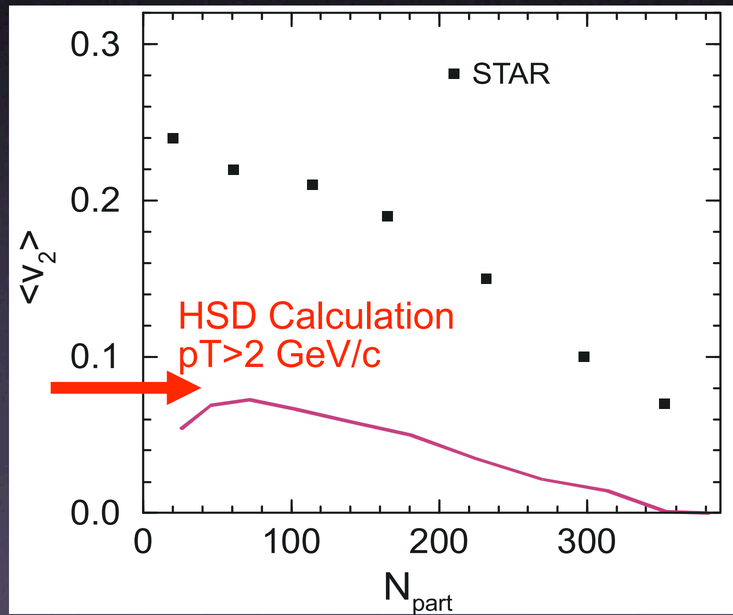
Hydrodynamic Evolution

Parton Cascade



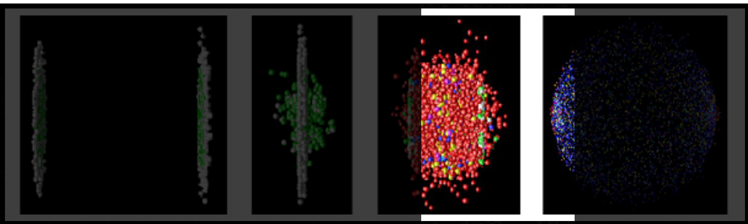
Molnar et al

Hadron Cascade

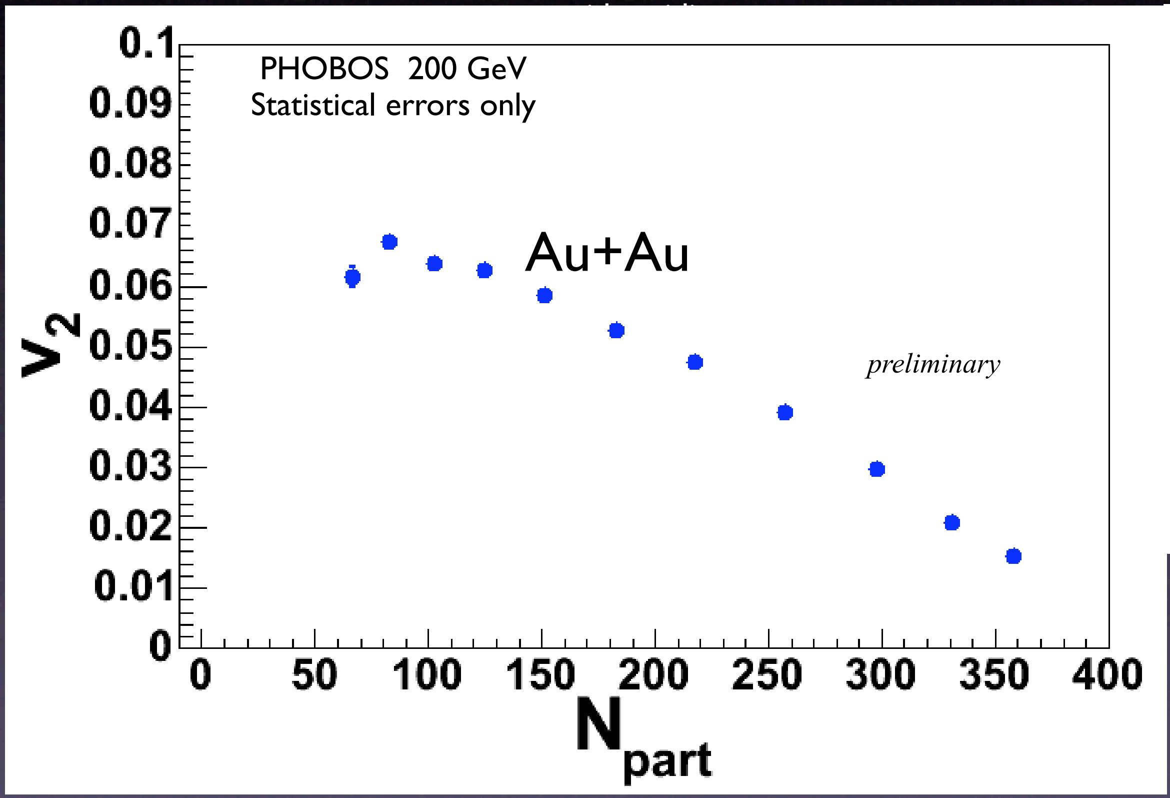


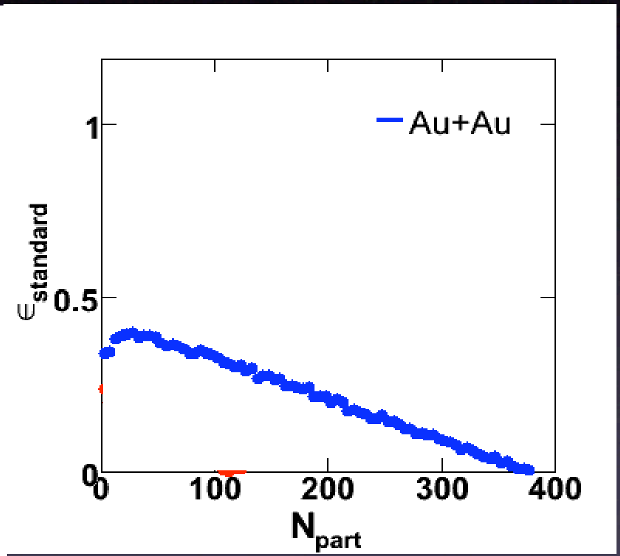
Cassing et al

Neither partonic nor hadronic cascade reproduces flow

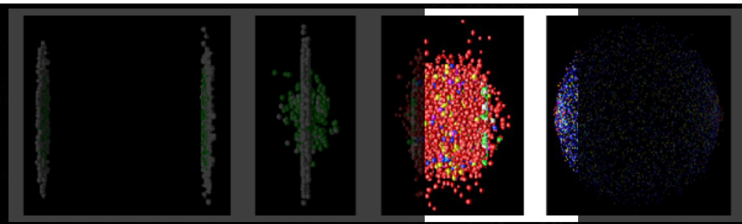


Hydrodynamic Evolution

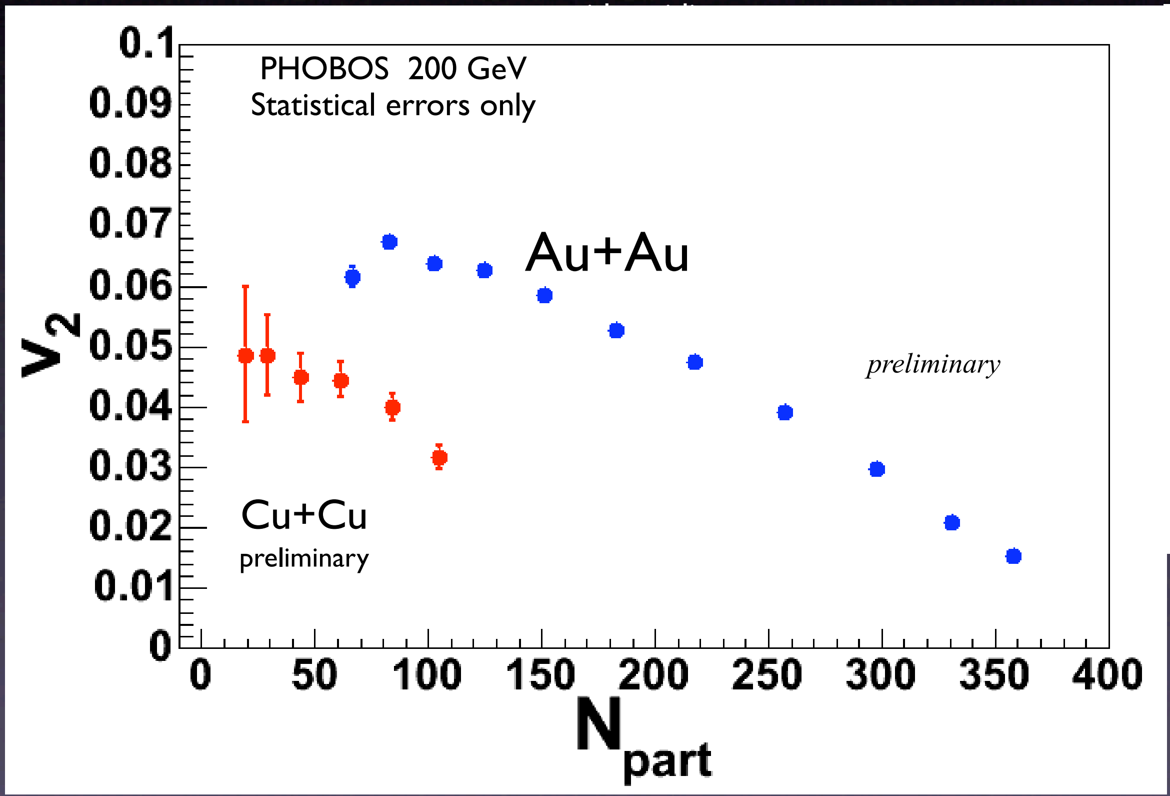


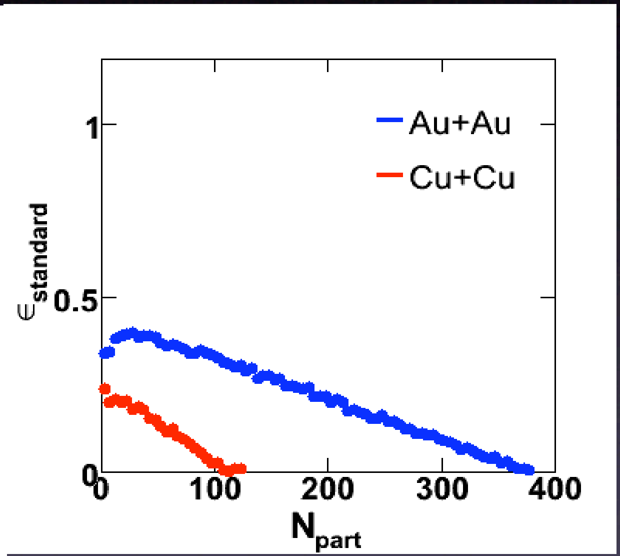


Geometrical initial state eccentricity from Glauber model



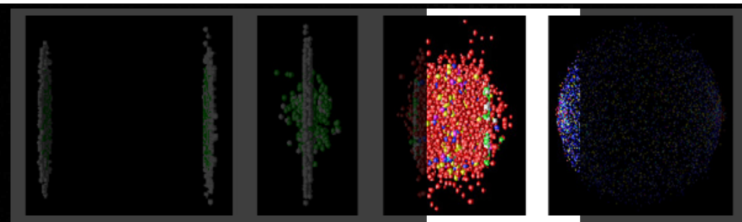
Hydrodynamic Evolution



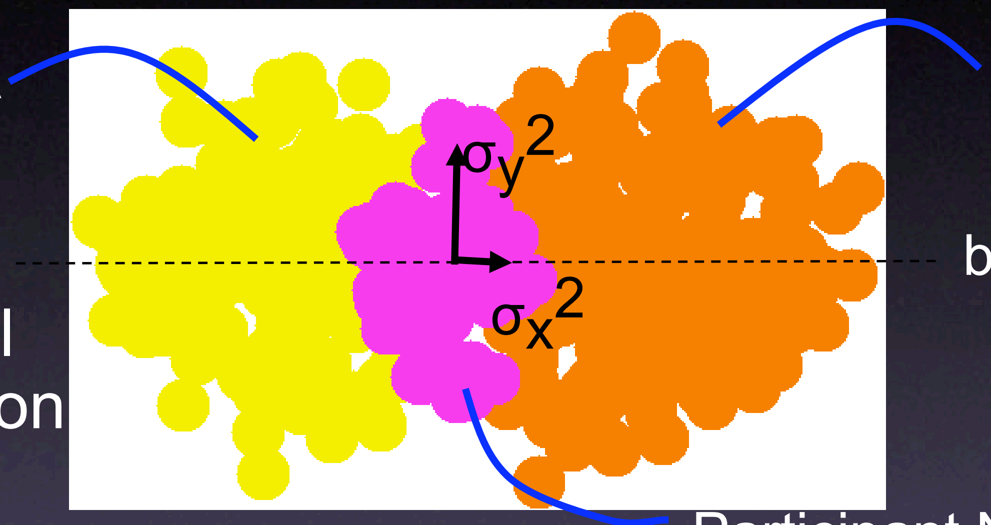


Geometrical initial state eccentricity from Glauber model

Surprisingly large flow signal in Cu+Cu!



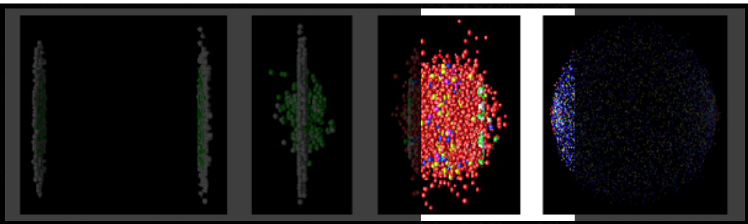
Hydrodynamic Evolution



Glauber model of AuAu collision

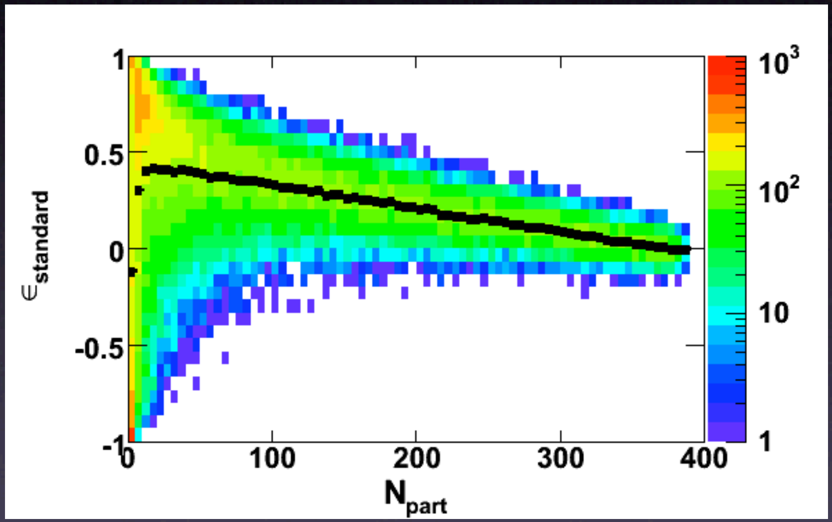
Using the impact parameter as the x-axis, we define the standard eccentricity using the widths of the distribution in x and y

$$\varepsilon = \frac{\sigma_y^{\,2} - \sigma_x^{\,2}}{\sigma_y^{\,2} + \sigma_x^{\,2}}$$



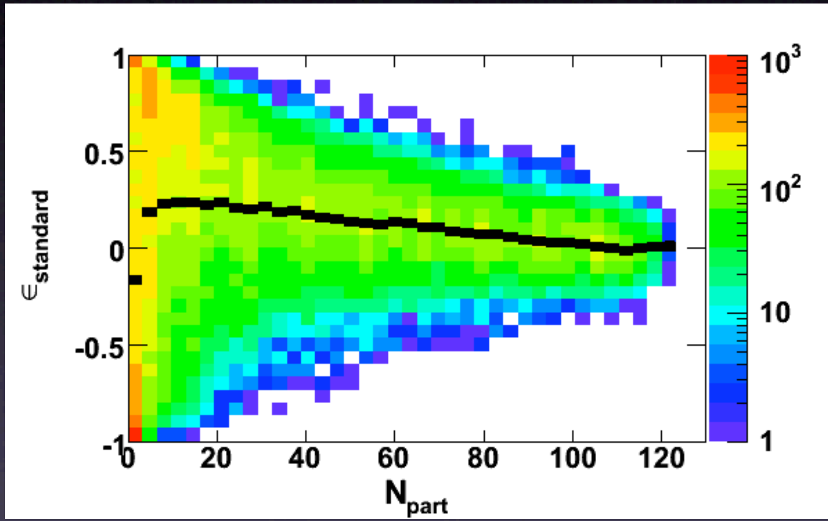
Hydrodynamic Evolution

Au+Au



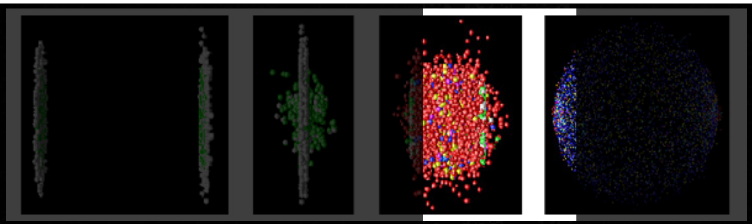
Large fluctuations in eccentricity

Cu+Cu



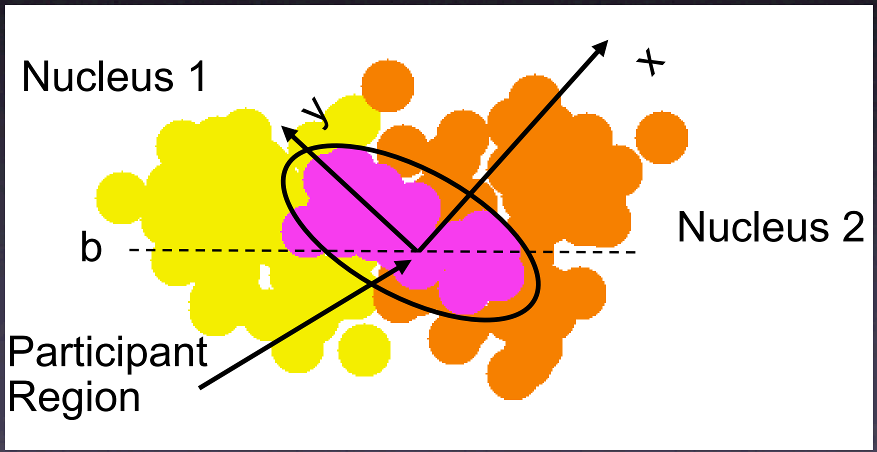
Even bigger fluctuations in Cu+Cu

Many peripheral events with negative eccentricity



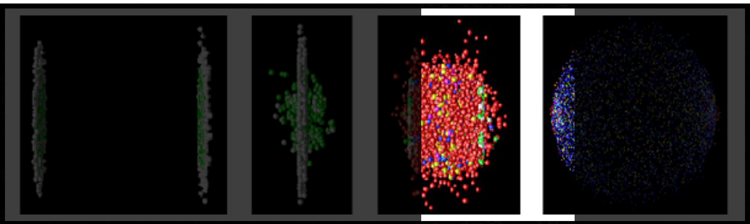
Hydrodynamic Evolution

One reasonable method is to realign the coordinate system
to maximize the ellipsoidal shape (a principal axis transformation)

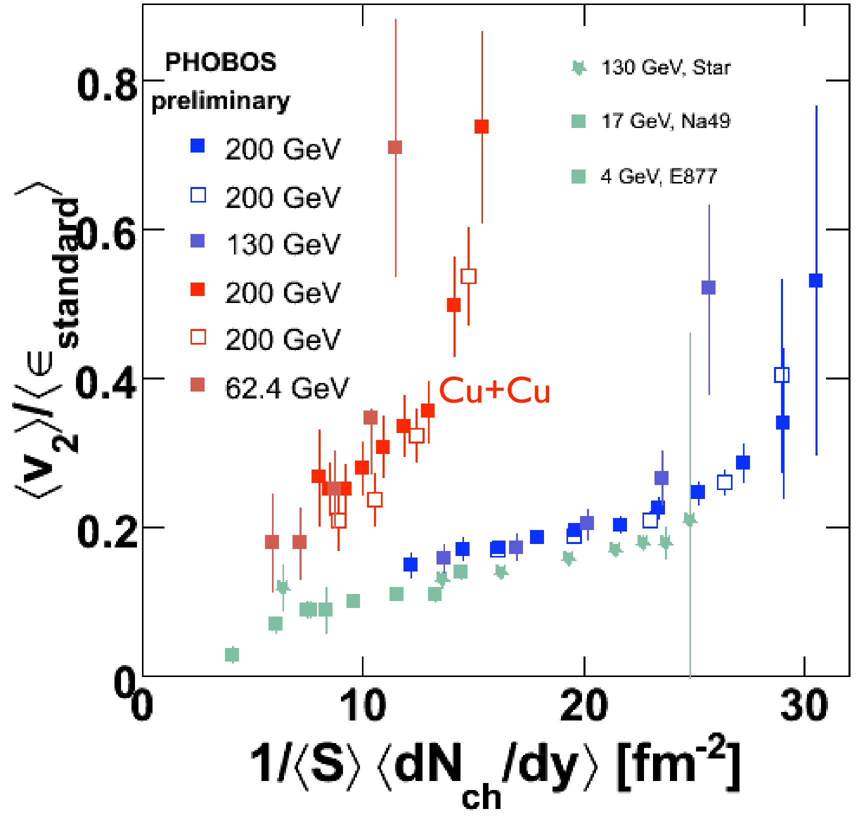


“Participant” eccentricity

Opposed to “standard” eccentricity



Hydrodynamic Evolution

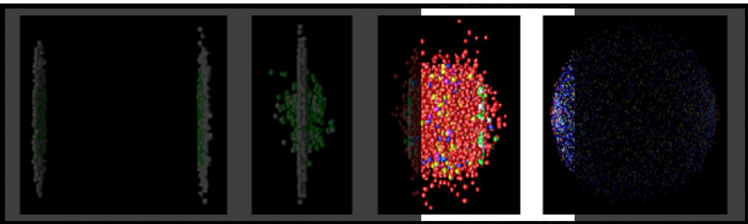


Low Density Limit:
STAR, PRC 66 034904 (2002)
Voloshin, Poskanzer, PLB 474 27 (2000)
Heiselberg, Levy, PRC 59 2716, (1999)

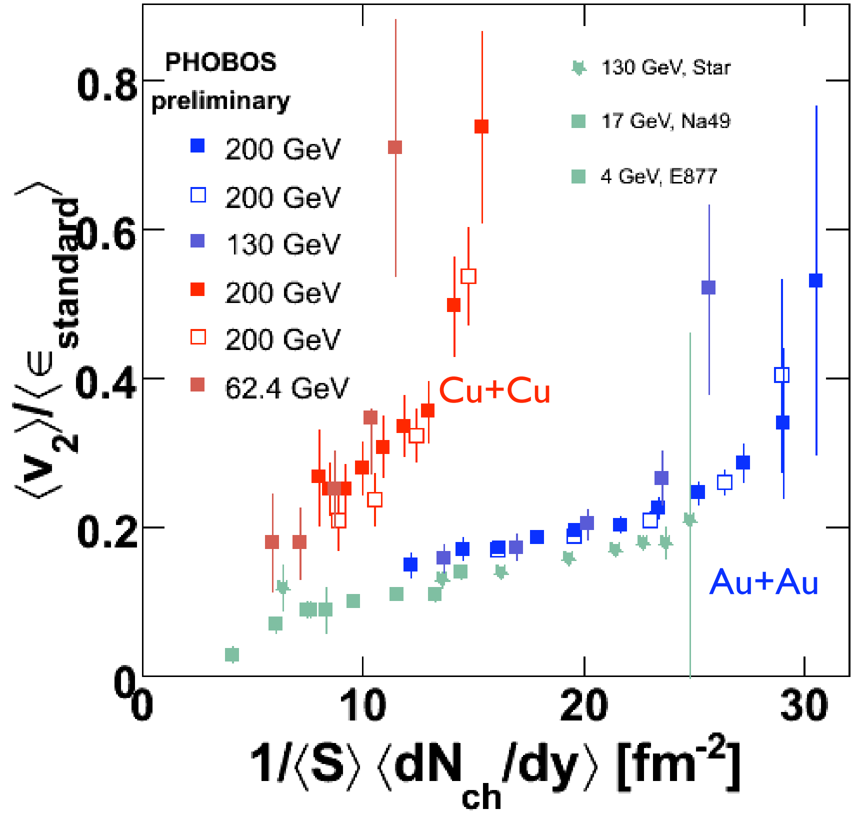
Au+Au

Surprisingly strong elliptic flow in Cu+Cu
Challenge to hydrodynamic picture

Cu+Cu: PHOBOS QM 2005
Compilation, Glauber calculations: Constantin Loizides



Hydrodynamic Evolution



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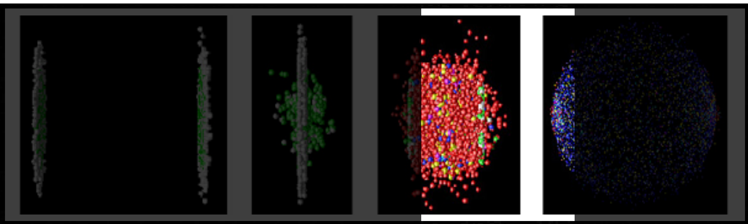
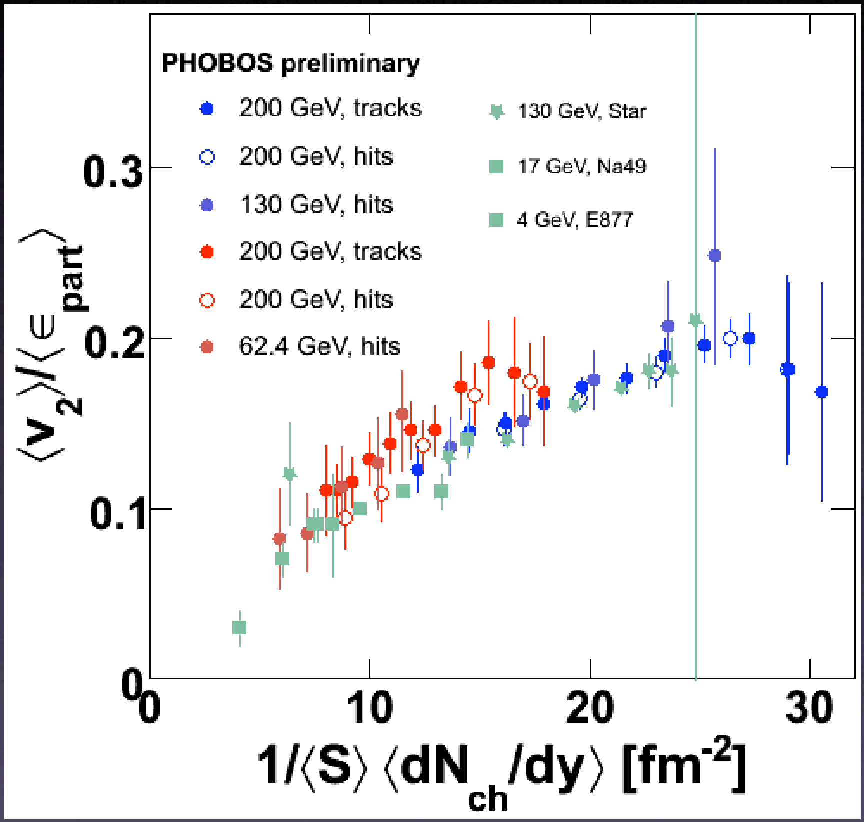


Hydrodynamic Evolution



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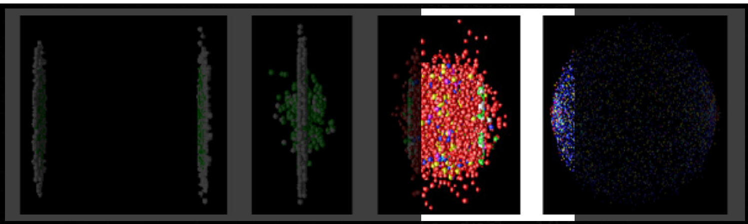
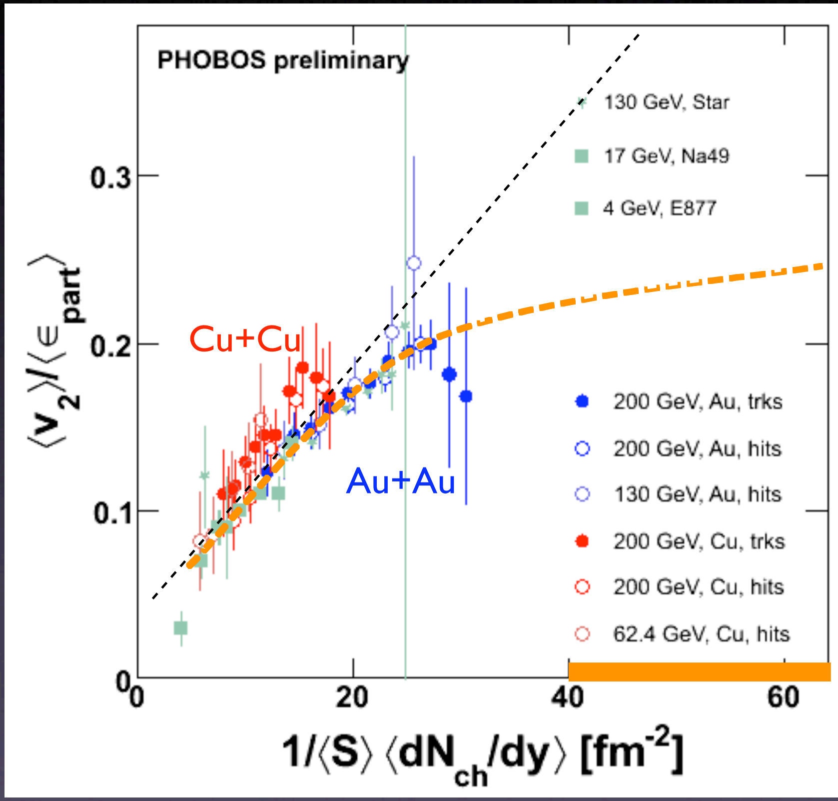


Hydrodynamic Evolution

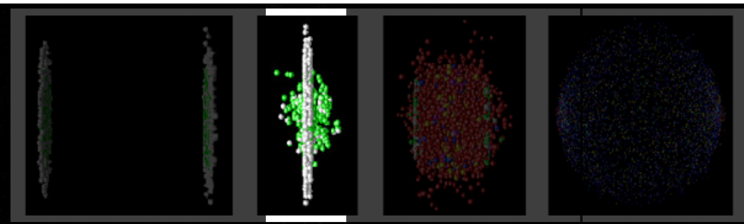


Low Density Limit:
STAR, PRC 66 034904 (2002)
Voloshin, Poskanzer, PLB 474 27 (2000)
Heiselberg, Levy, PRC 59 2716, (1999)

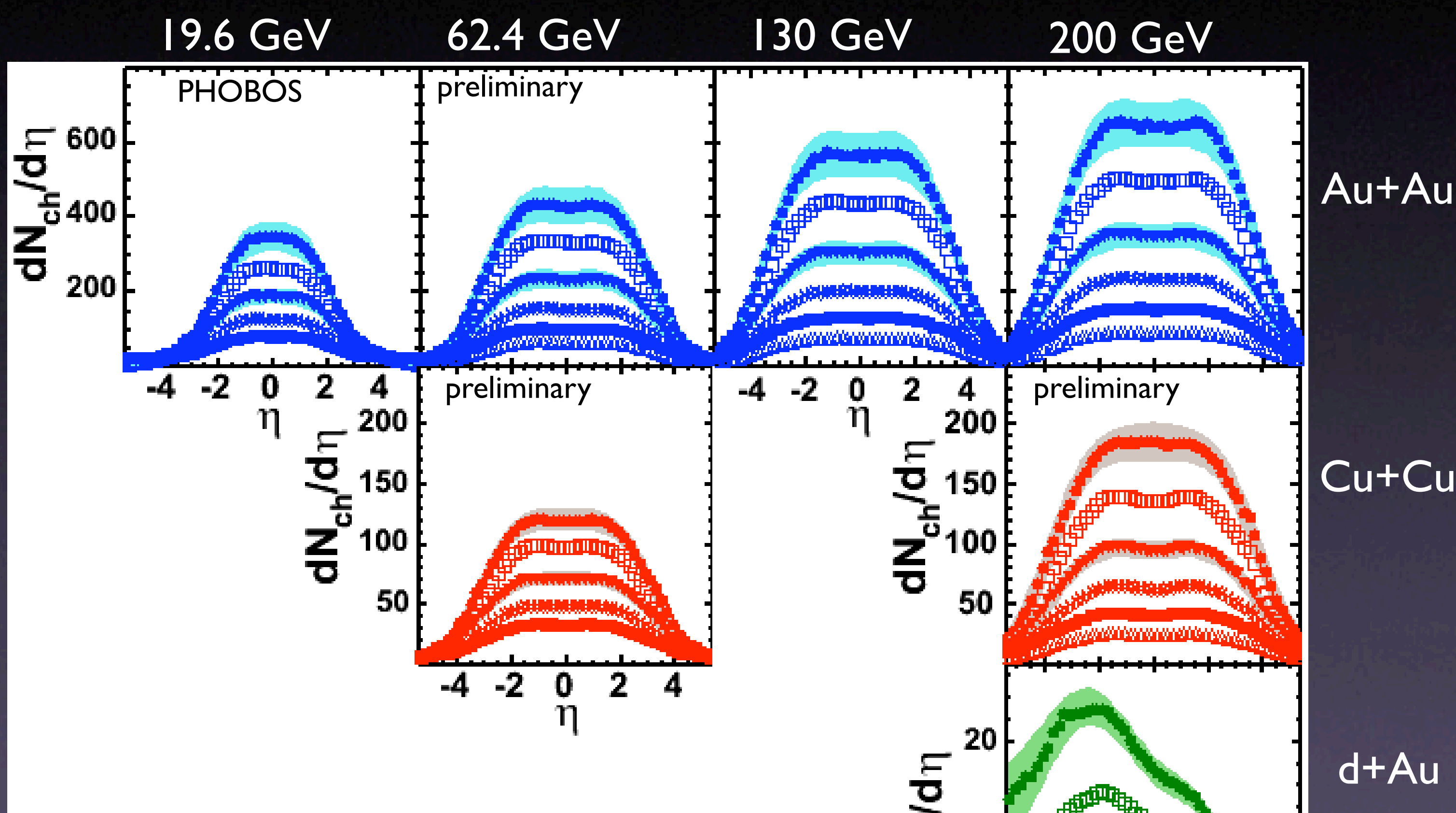
LHC

Will flow saturate at LHC
as themeralization is achieved?

Cu+Cu: PHOBOS QM 2005
Compilation, Glauber calculations: Constantin Loizides

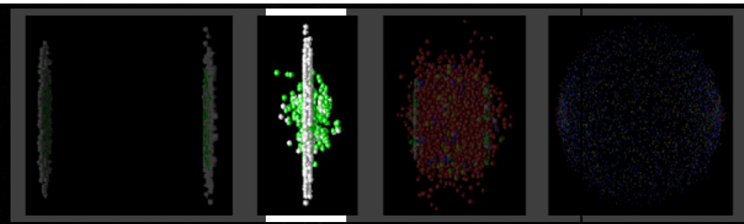


Hadron Multiplicities

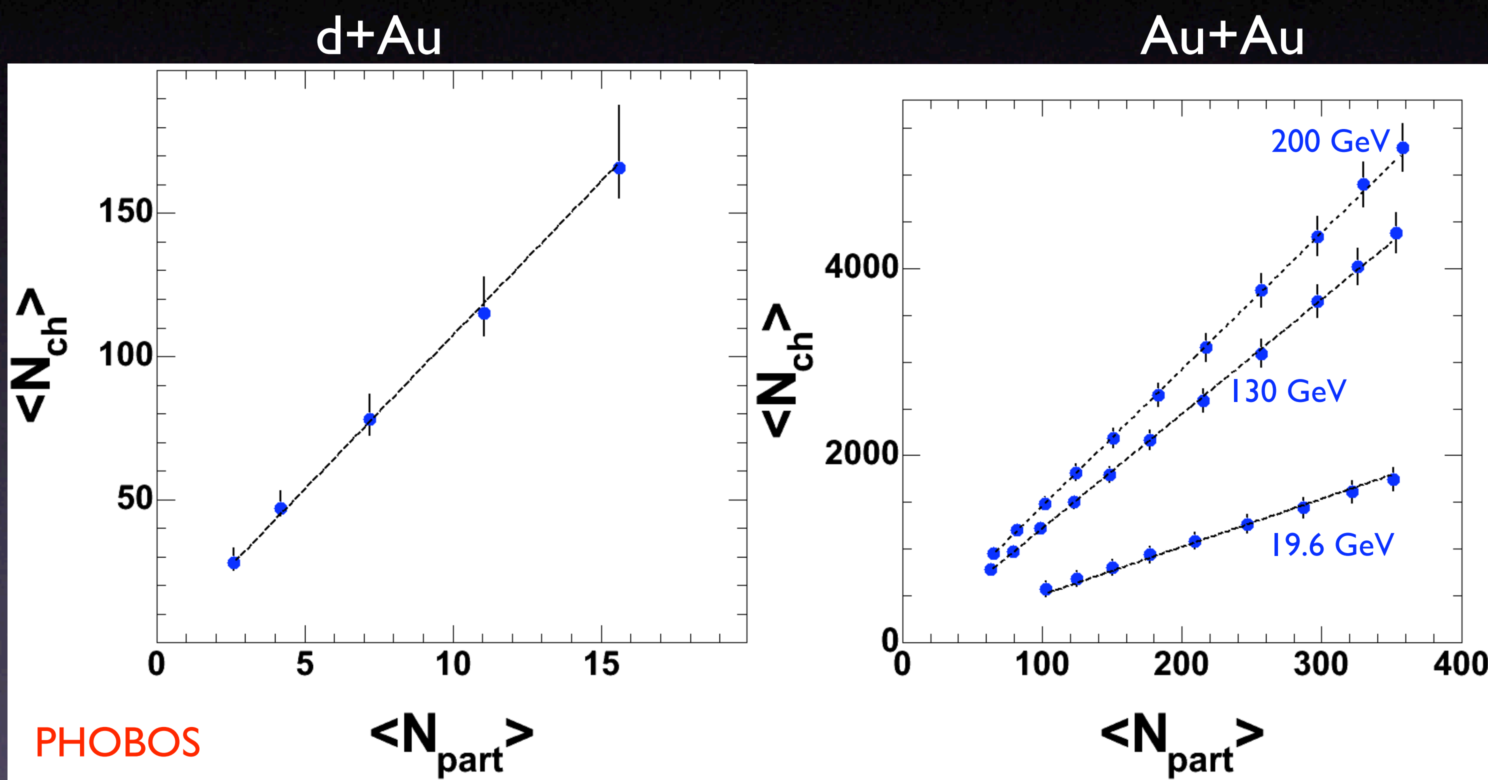


PHOBOS

Au+Au : PRL 91, 052303 (2003)
d+Au : PRL 93, 082301 (2004)
Cu+Cu: QM 2005
[Analog analysis: Robin Verdier]



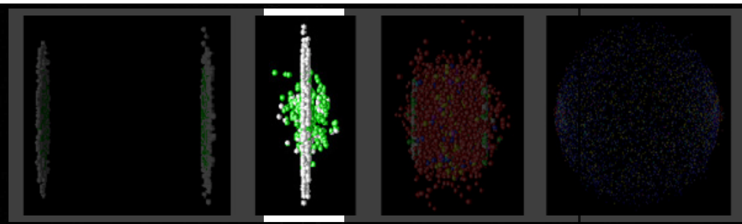
Hadron Multiplicities



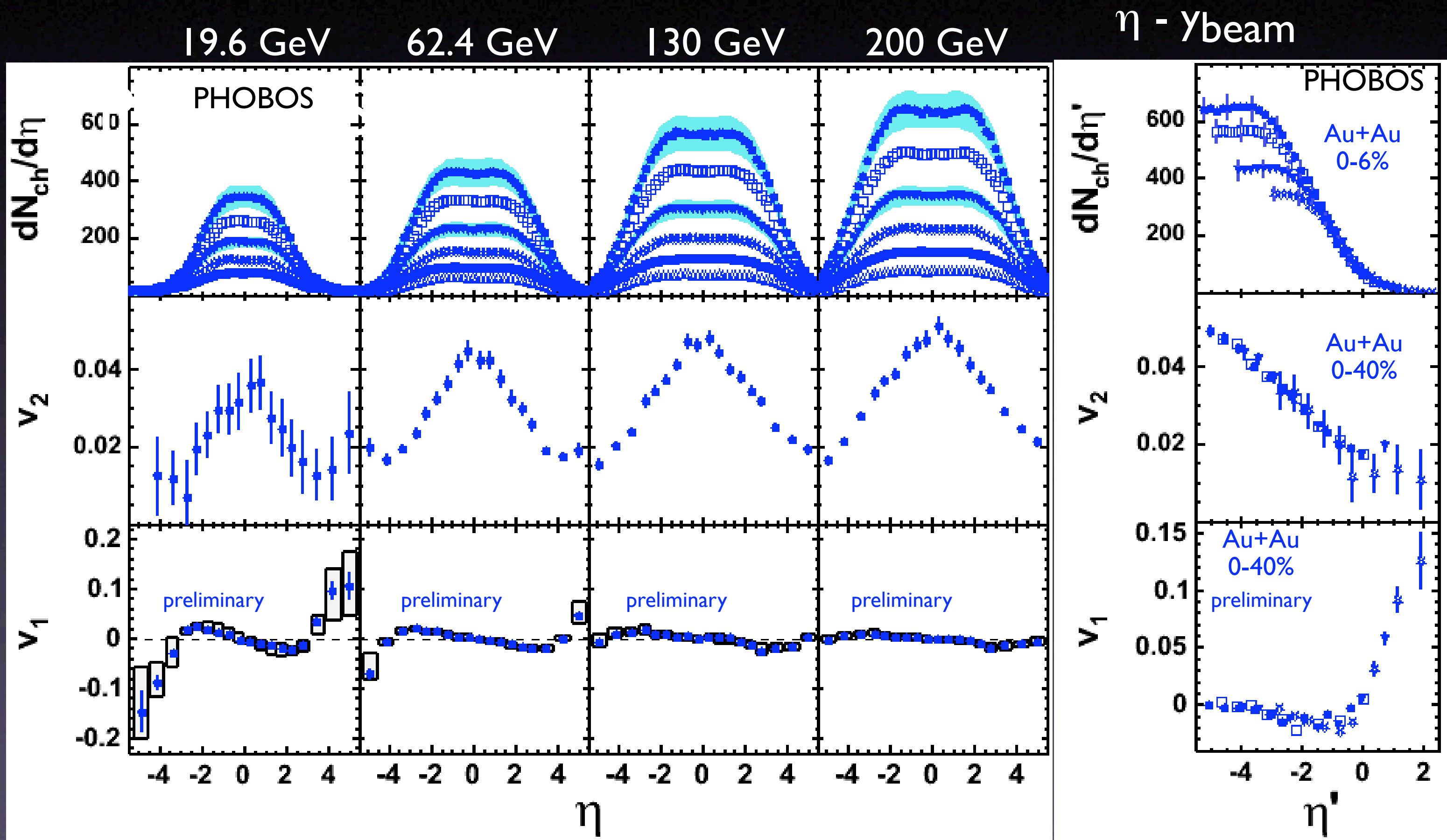
N_{part} scaling of particle production in Au+Au

Connection to p+p and e^+e^- collisions

Au+Au : nucl-ex/0301017
d+Au : PRL 93, 082301 (2004)



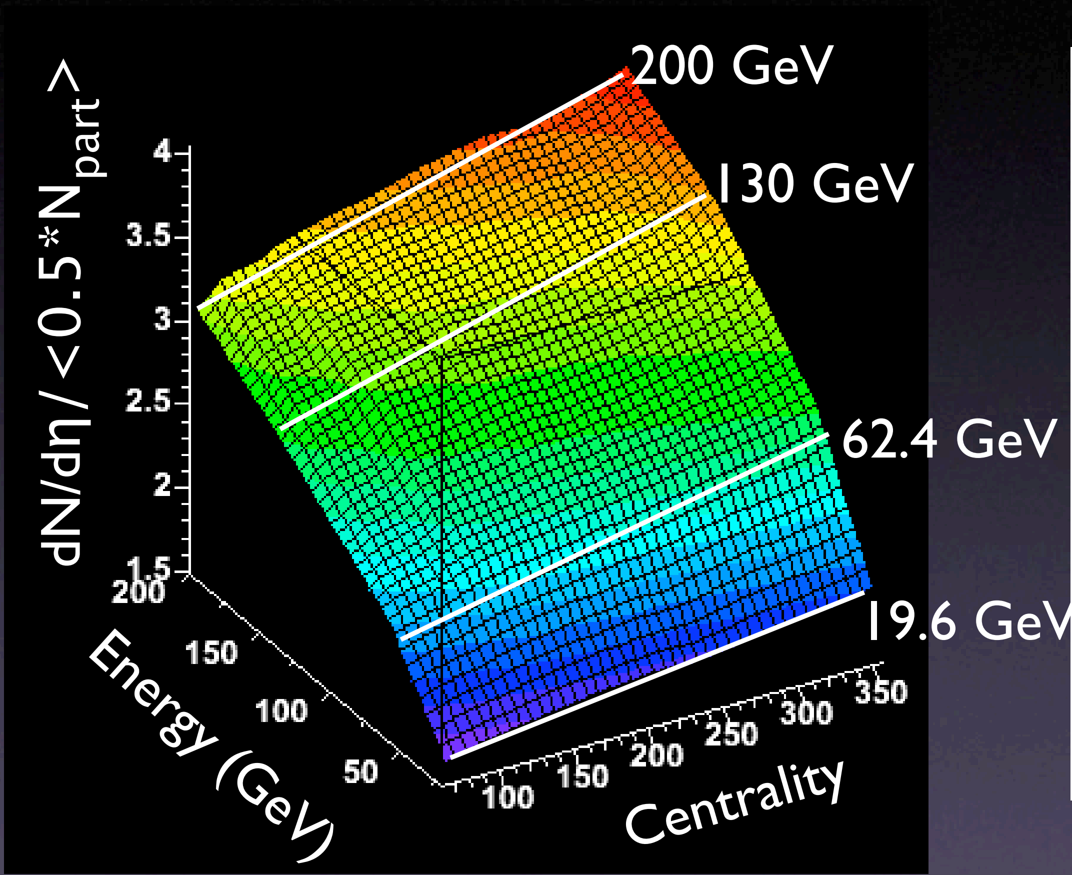
Hadron Multiplicities

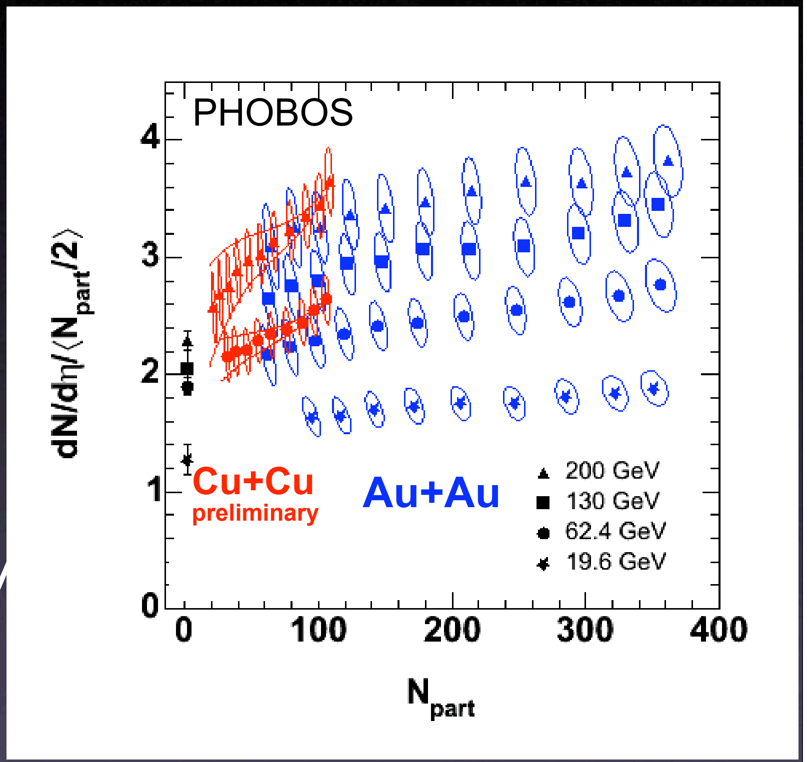


"Extended longitudinal scaling" (aka limiting fragmentation) of all longitudinal distributions

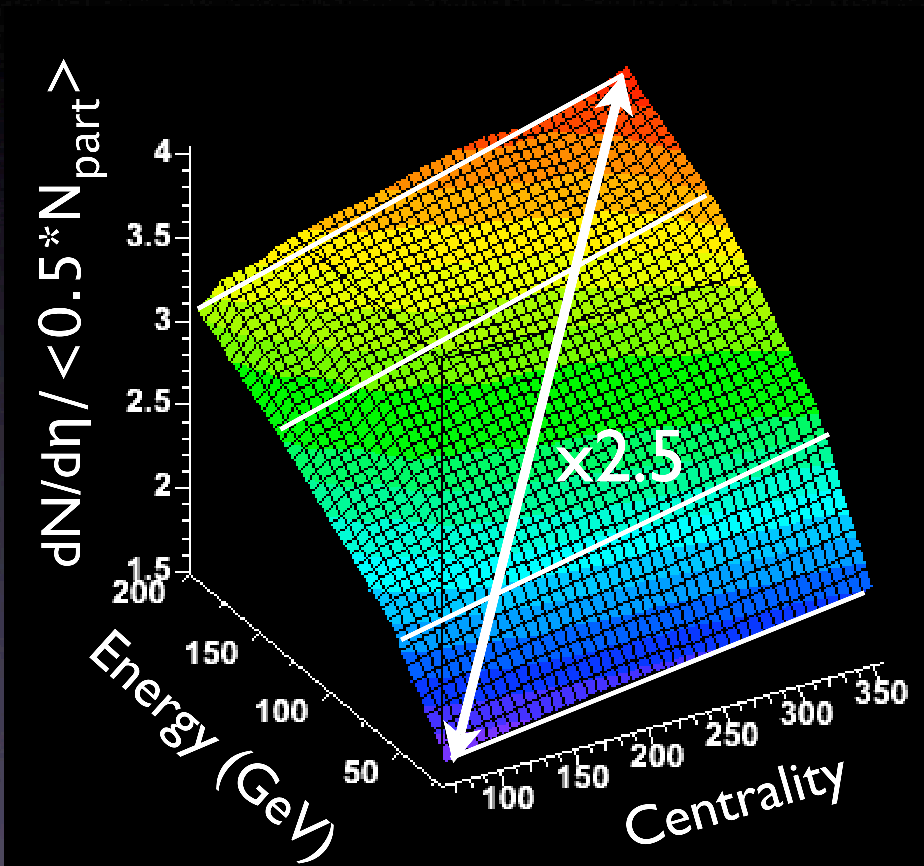
Mid-rapidity dN/dη vs √s and N_{part}

Au+Au : nucl-ex/0509034, submitted to PRC
Cu+Cu: QM 2005





dN/dη vs √s and N_{part}



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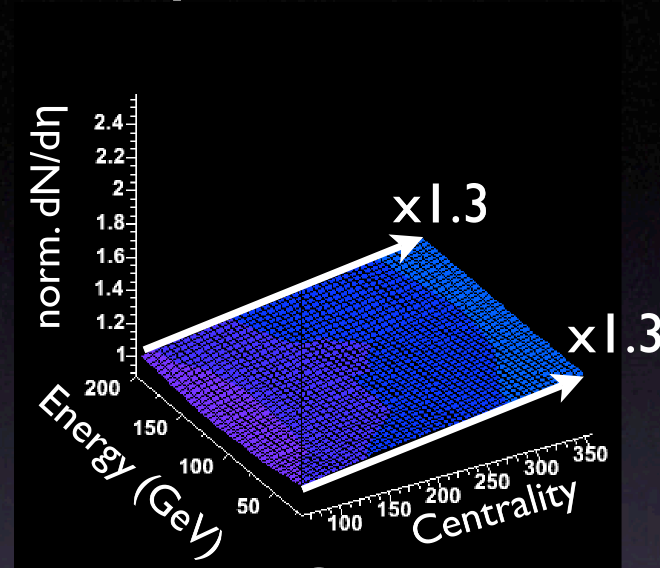

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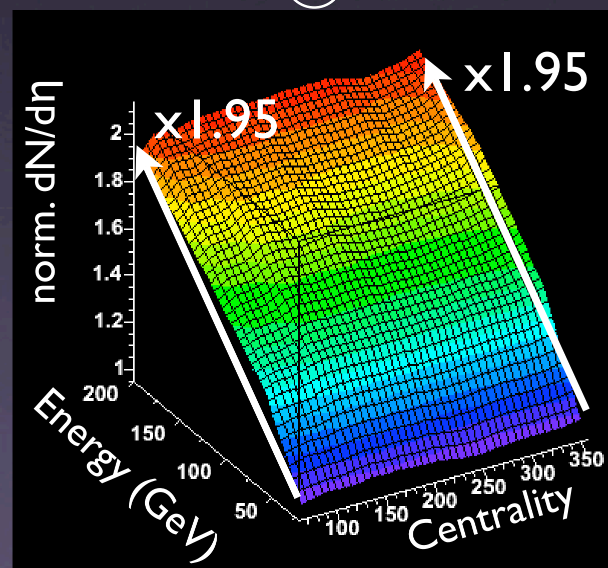
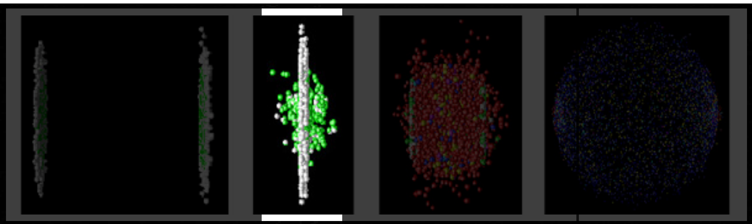


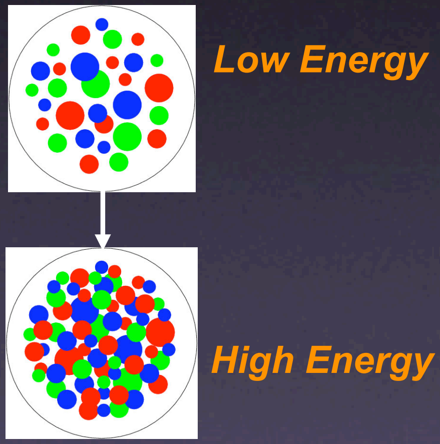
$$\frac{1}{N_{\rm part}} \frac{dN^{AA}}{d\eta}\bigg|_{\eta\sim 0} = N_0 \sqrt{s}^{\lambda} N_{\rm part}^{\frac{1-\delta}{3\delta}}$$

Armesto, Salgado, Wiedemann hep-ph/0407018



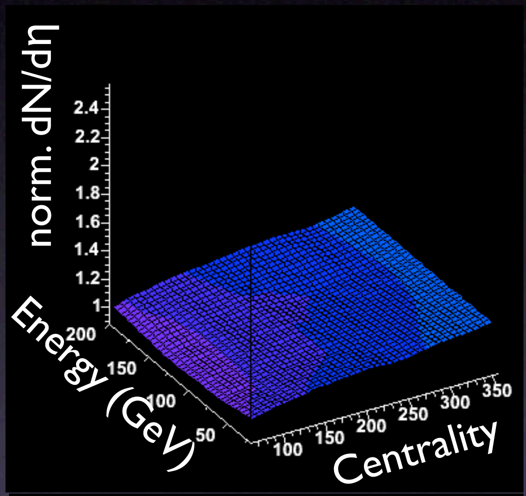
Hadron Multiplicities

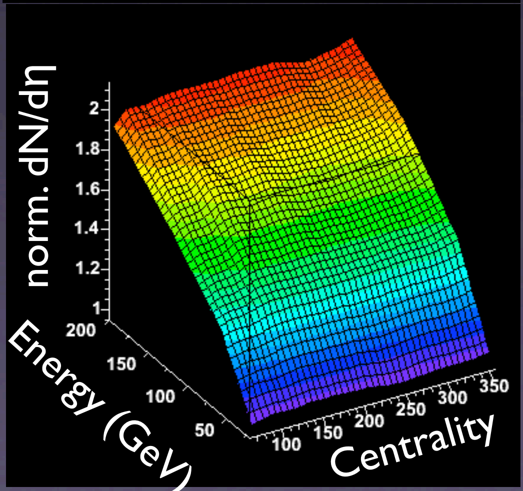
Initial State
Parton Saturation

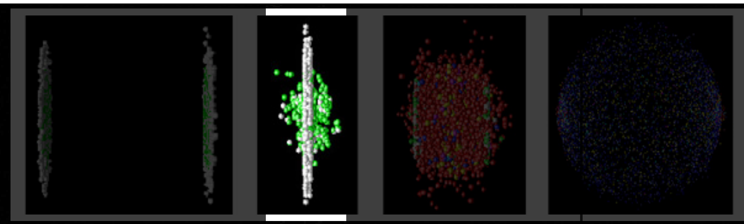


$$\left.\frac{1}{N_{\rm part}}\frac{dN^{AA}}{d\eta}\right|_{\eta\sim 0} = N_0\sqrt{s}^{\lambda} N_{\rm part}^{\frac{1-\delta}{3\delta}}$$

Armesto, Salgado, Wiedemann hep-ph/0407018



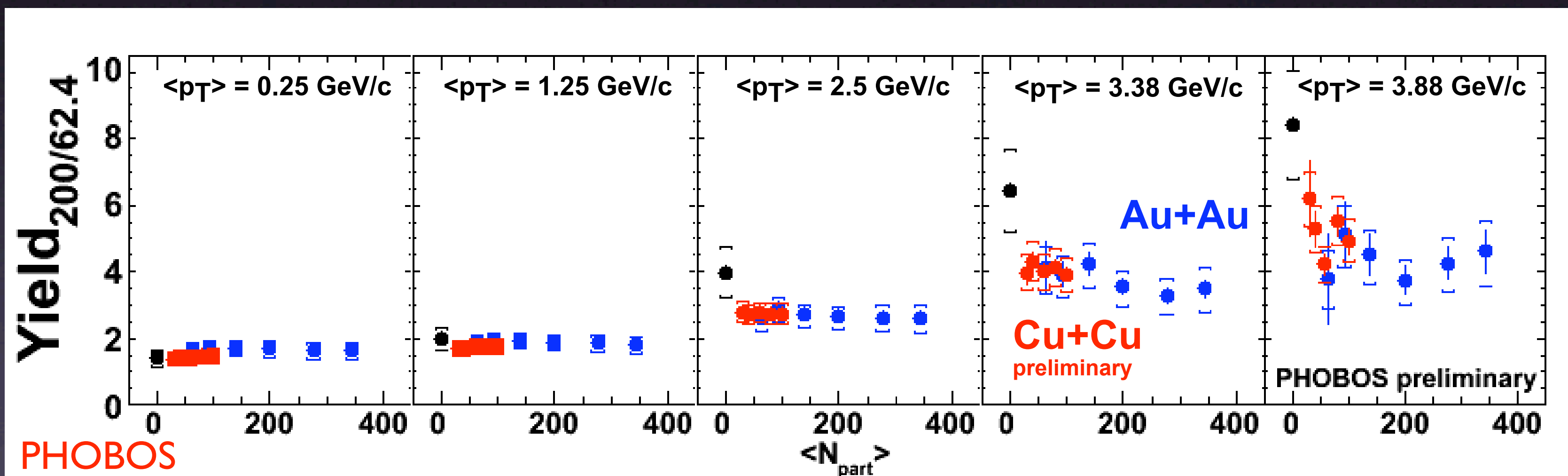




Energy/Centrality Factorization

Ratio of yields in bins of p_T

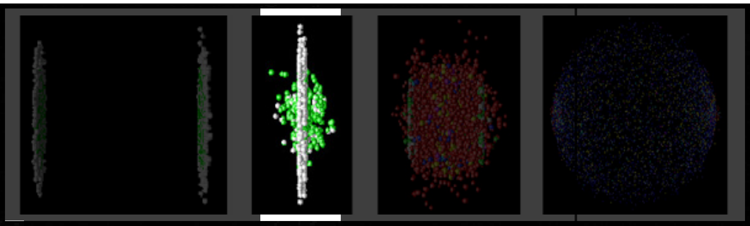
between 200 and 62 GeV



Au+Au: Phys Rev Lett 94, 082304 (2005)
Cu+Cu: PHOBOS QM 2005, to be submitted to PRL
Ed Wenger, PhD thesis

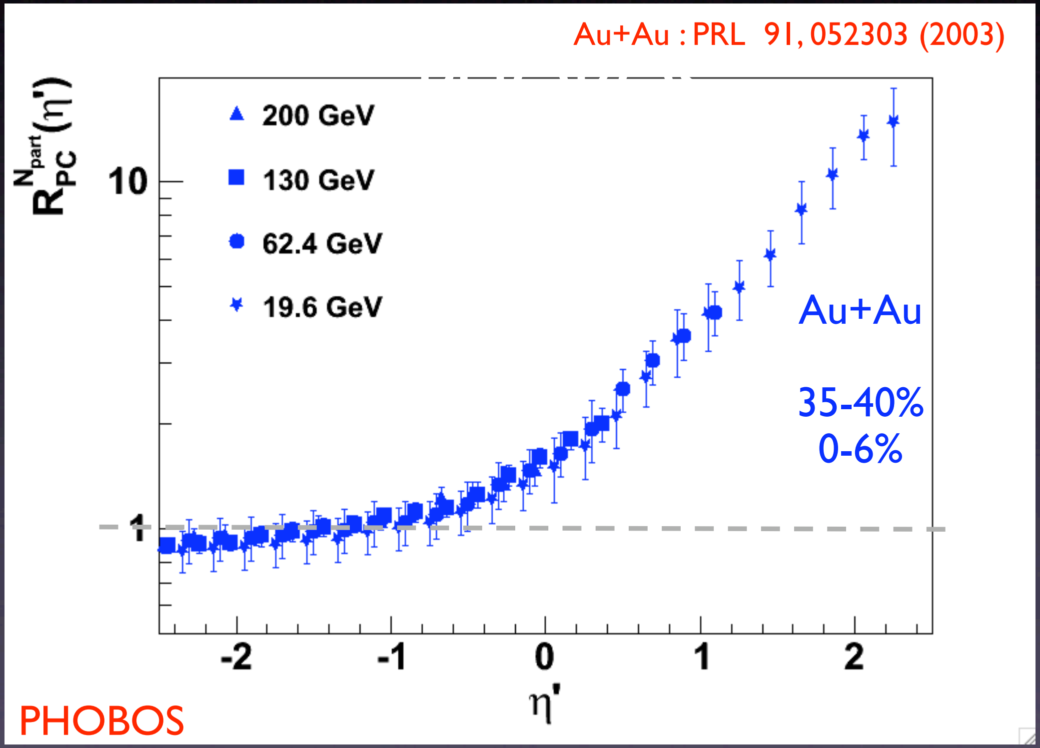
Energy/centrality factorization vs p_T

Dominance of Collision Geometry?



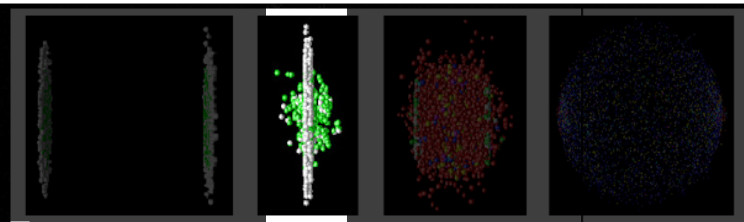
Energy/Centrality Factorization

Ratio of 0-6% and 35-40% centrality bins, each normalized by N_{part}

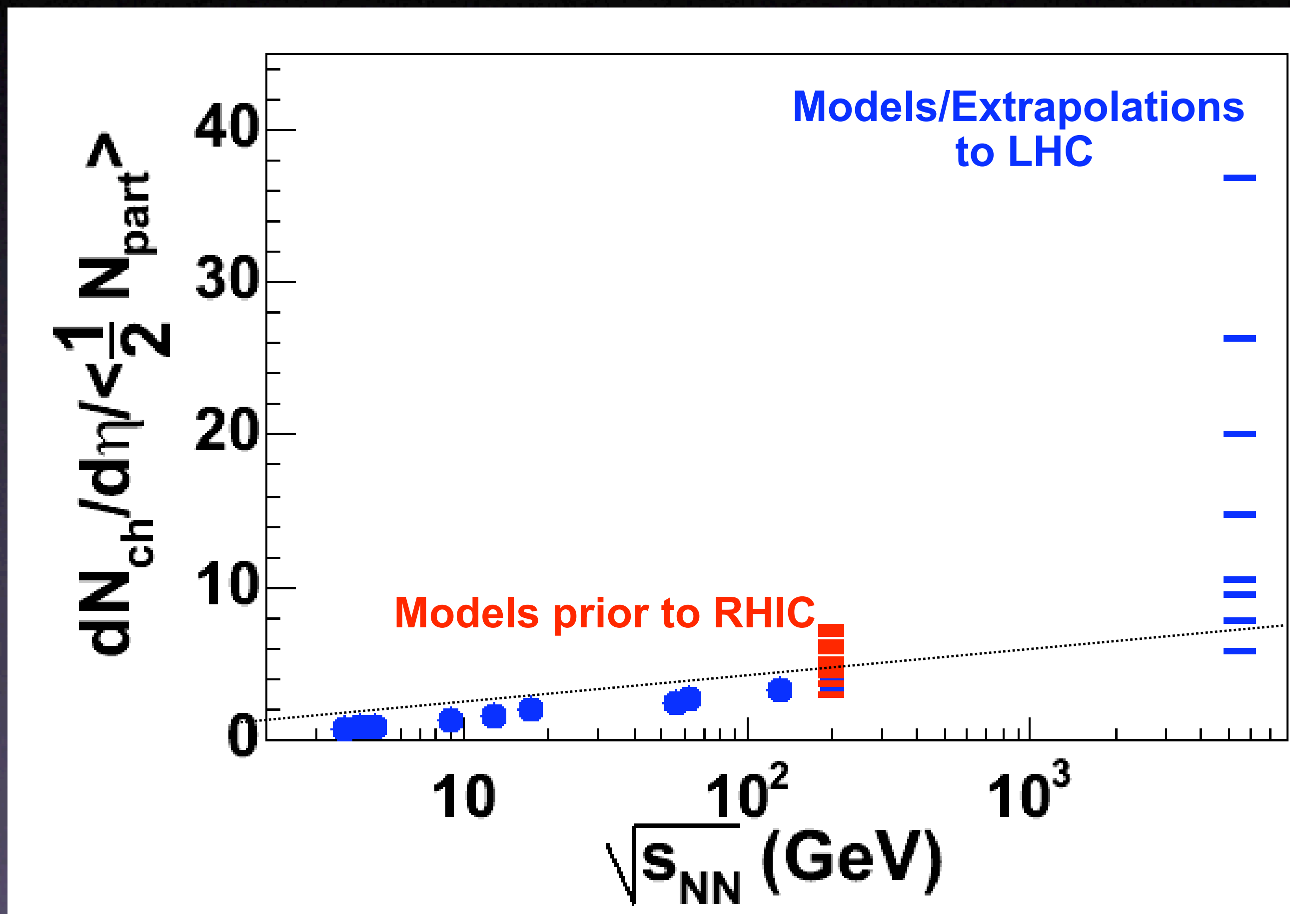


Energy/centrality factorization vs η

Dominance of Collision Geometry?



Hadron Multiplicities at LHC



Detectors planned for dN/dy > 5000!

$dN/d\eta \sim 1800$

$dN/d\eta \sim 1100$

Will saturation dominate? What about high p_T, p+p?

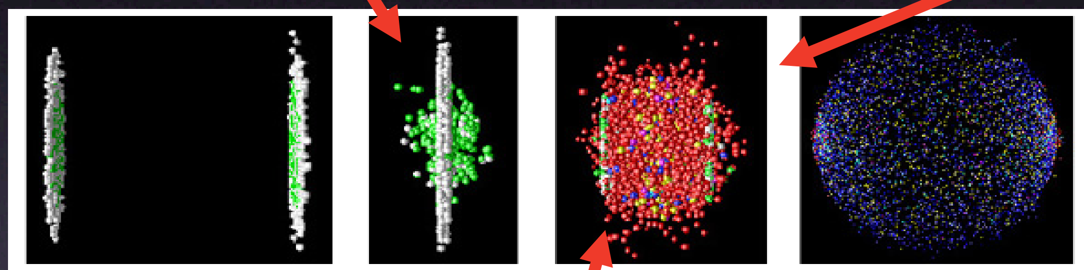
The Big Picture

Initial Collisions

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

Hadronization

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



Early Stage (~ few fm/c)

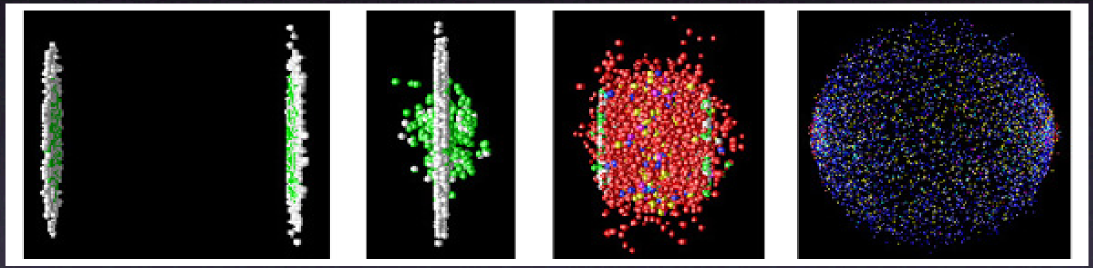
- High Density (~ 5 GeV/fm^3) [$dN/d\eta$, high p_T suppression]
- Local thermal equilibration[Elliptic Flow v_2]
- Pressure driven expansion [Elliptic Flow v_2, HBT]
- Low viscosity [Elliptic Flow v_2]
- Opaque for fast partons [Back-to-Back jets]

"The Liquid Vacuum"

Big Questions

What is the
initial temperature?

What is the nature
of the medium?

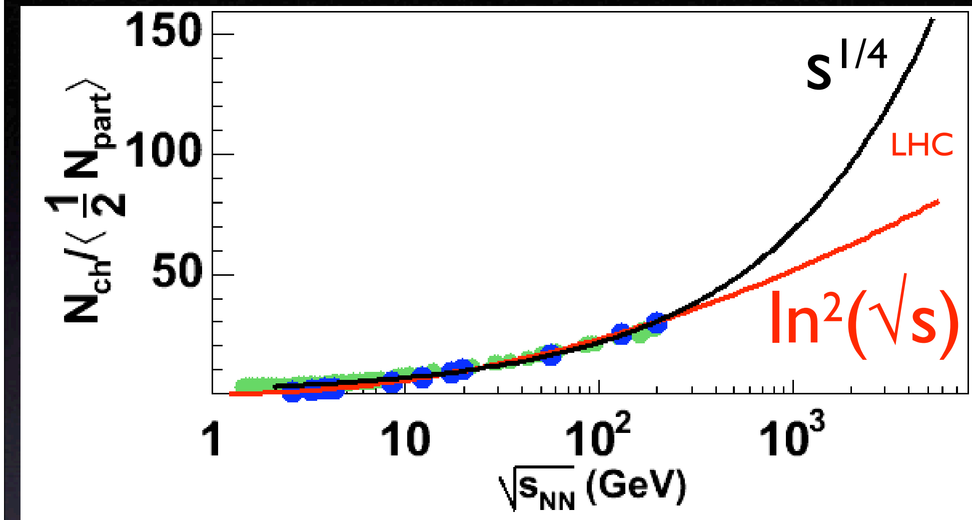


What is the origin
of scaling rules?

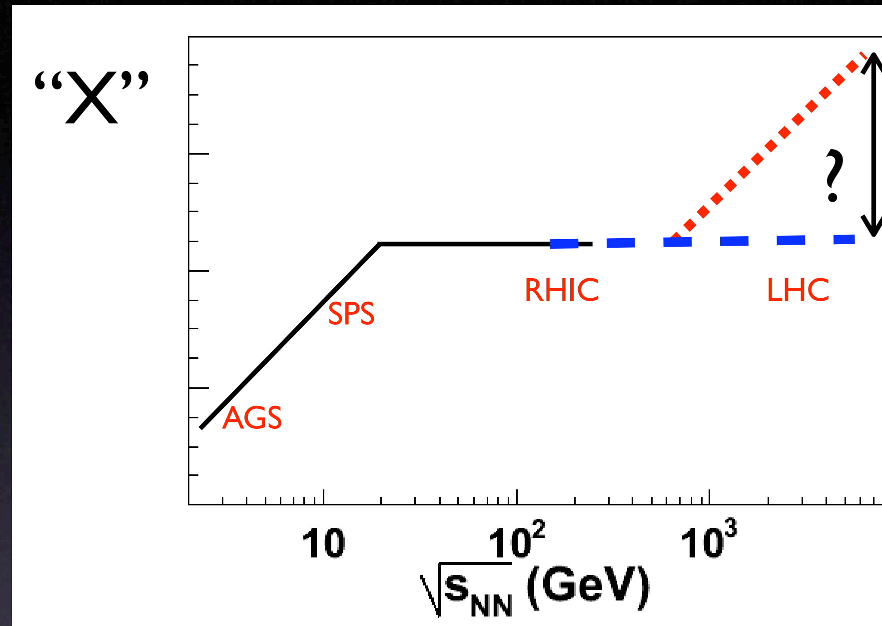
What is the location of
the phase transition?

☛ LHC

Physics goals at LHC, I



Extrapolation to LHC?

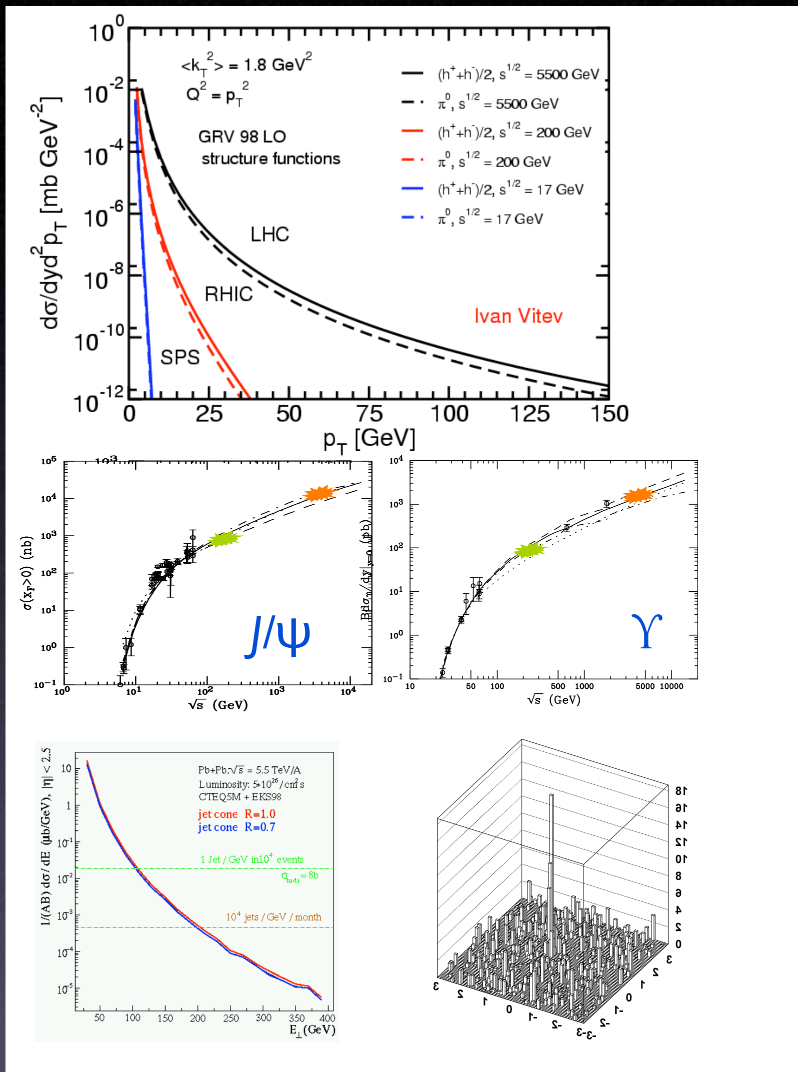


'Soft' physics at RHIC: Scaling regime?

First exciting LHC results will be on "soft physics"

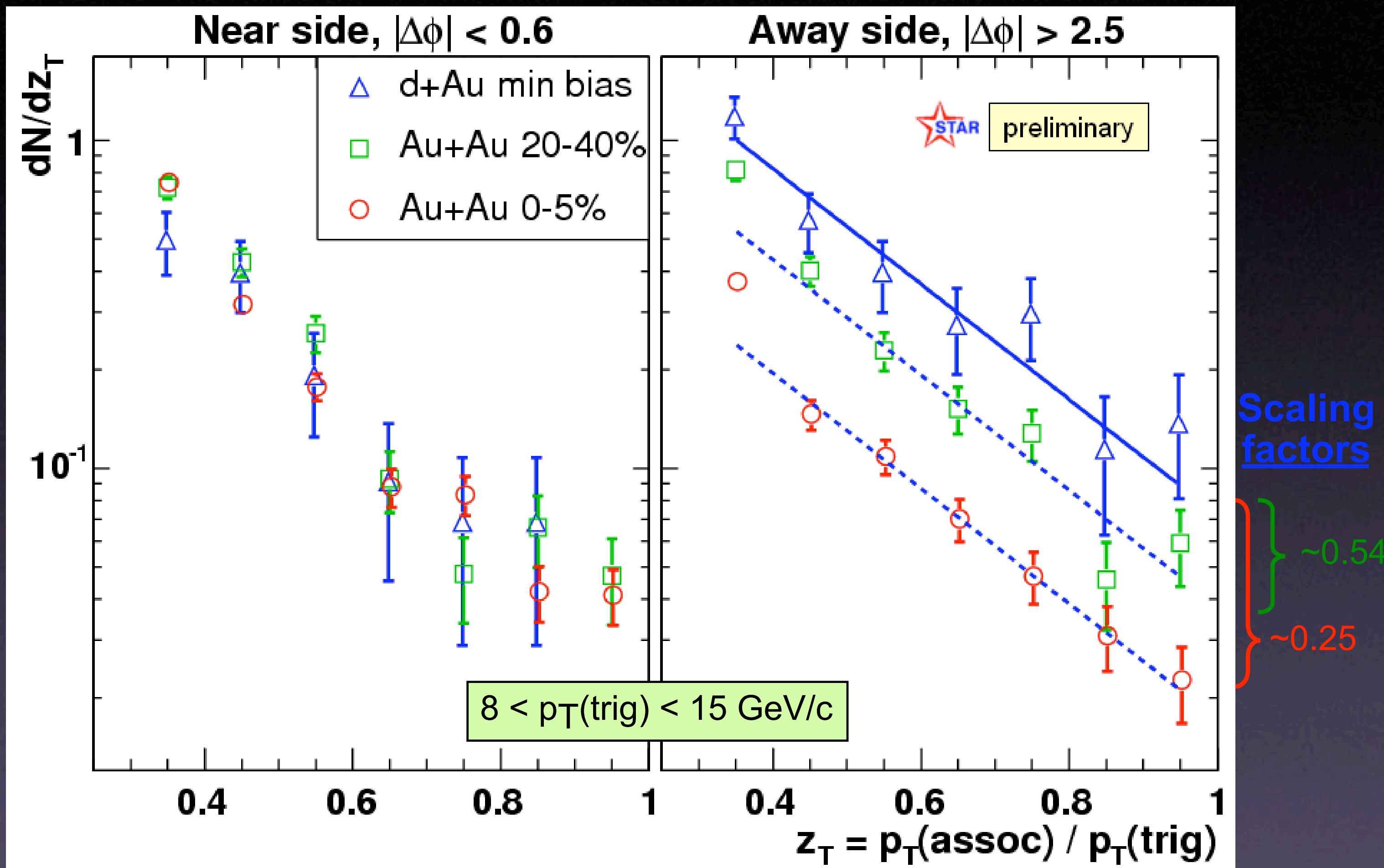
Dynamical connection between soft observables?

Physics goals at LHC, II



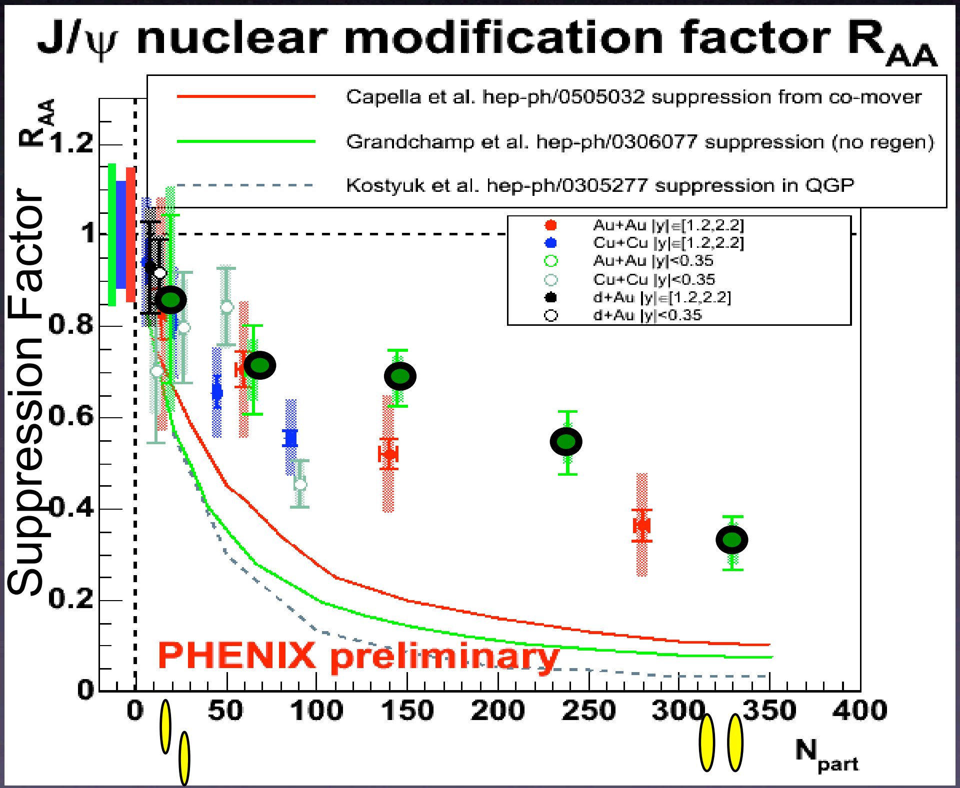
- Medium modification at high p_T
  - Copious production of high p_T particles
  - Large jet cross section,
- Different "melting" for members of ϒ family depending on binding energy
  - Large cross section for J/ψ and ϒ family production
- Correlations, scattering in medium
  - jets directly identifiable

MIT responsibilities: Jet Physics (Christof Roland, Gabor Veres)
High Level Trigger: G. Roland, Loizides, Ballintijn



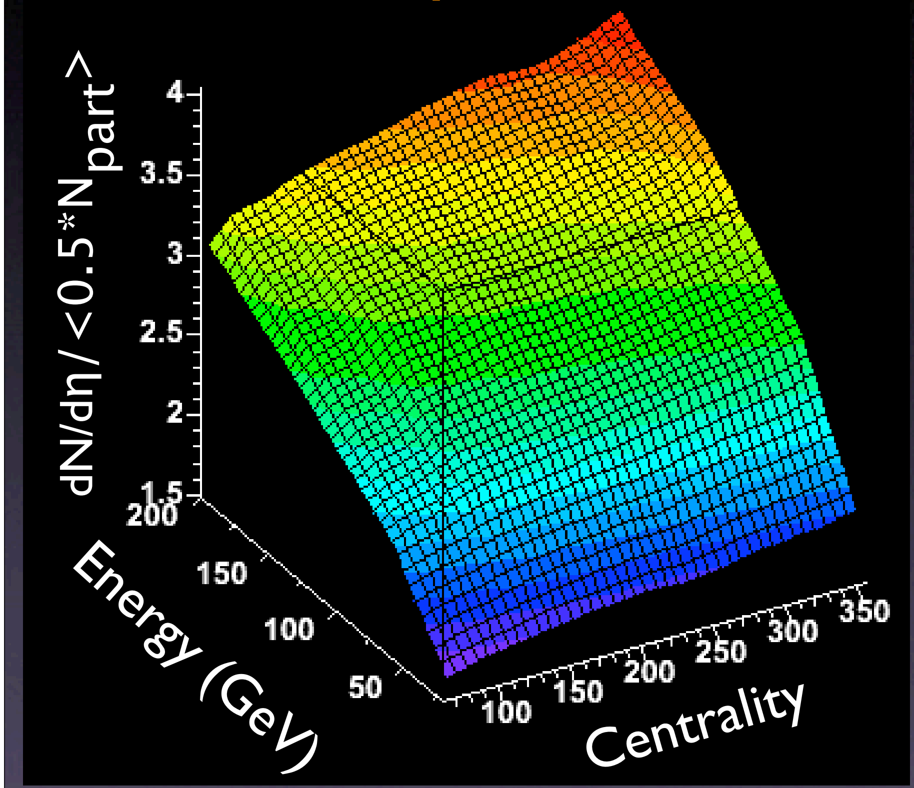
Away-side $D(z_T)$ suppressed, but shape unchanged

J/psi suppression

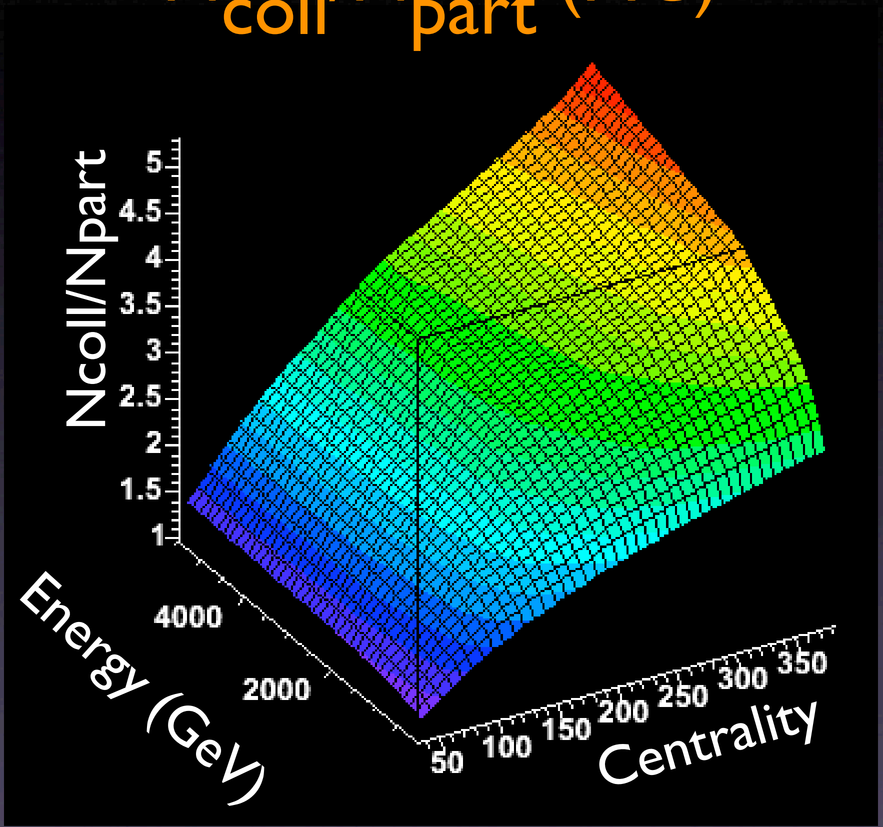


Ncoll/Npart vs √s and N_{part}

dN/dη (Data)



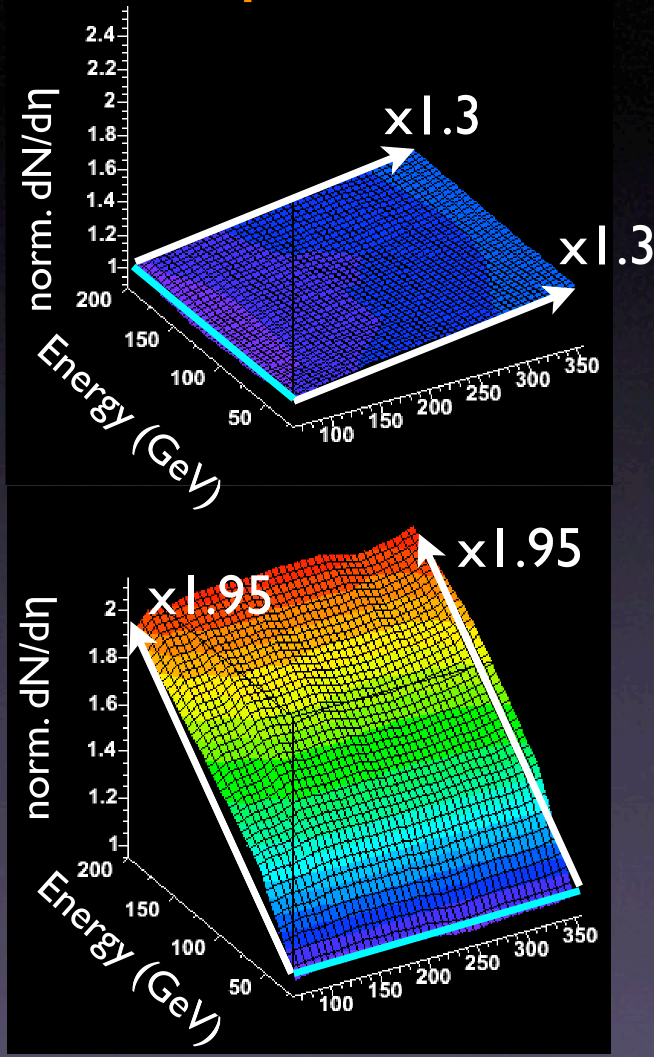
N_{coll}/N_{part} (MC)

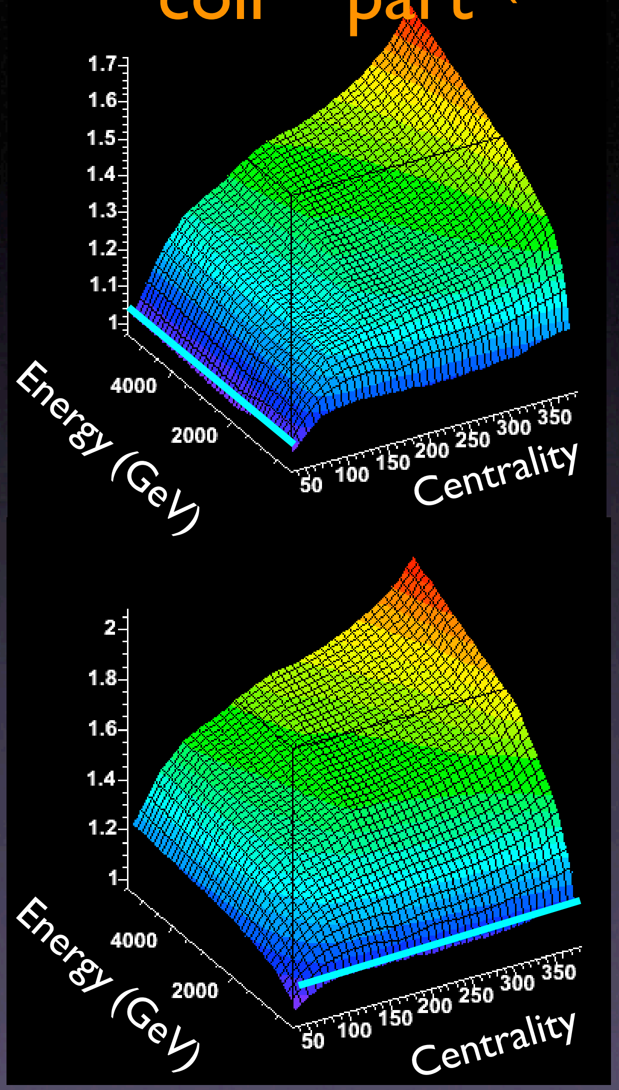


Factorization in a hard/soft picture?

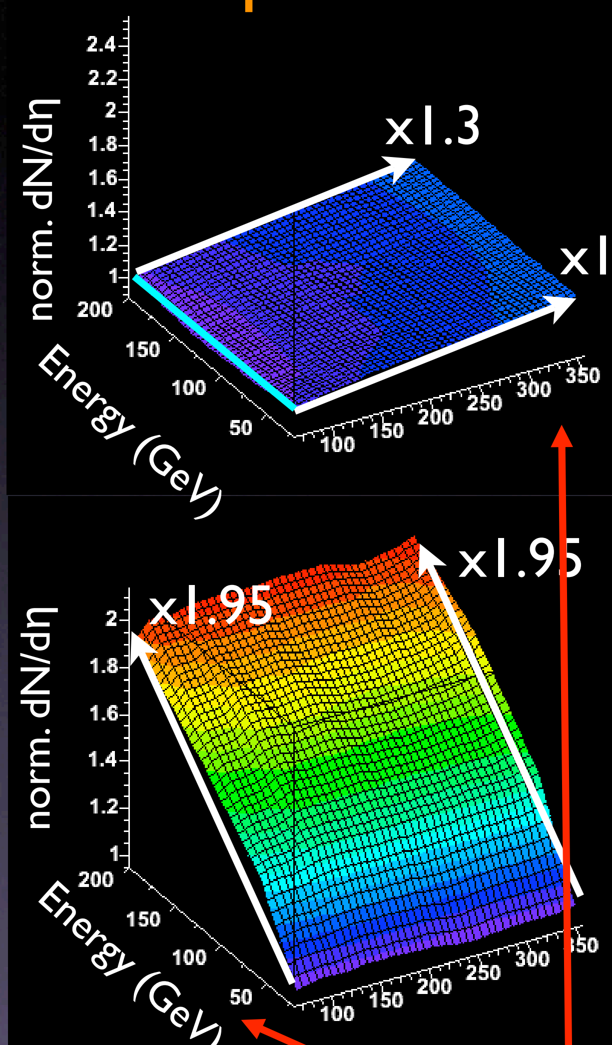
$dN/d\eta/N_{part}$ (Data)

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

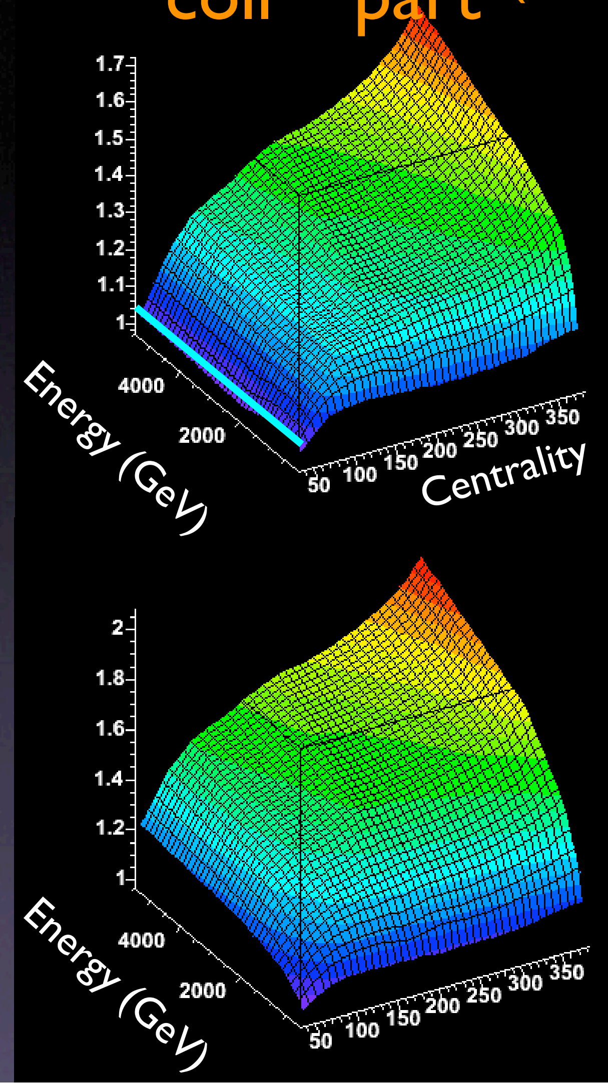




$dN/d\eta/N_{part}$ (Data)



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



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

Armesto, Salgado, Wiedemann hep-ph/0407018