Creating a Quark Gluon Plasma With Heavy Ion Collisions

David Hofman

UIC

Special thanks to my Collaborators in PHOBOS, STAR, & CMS

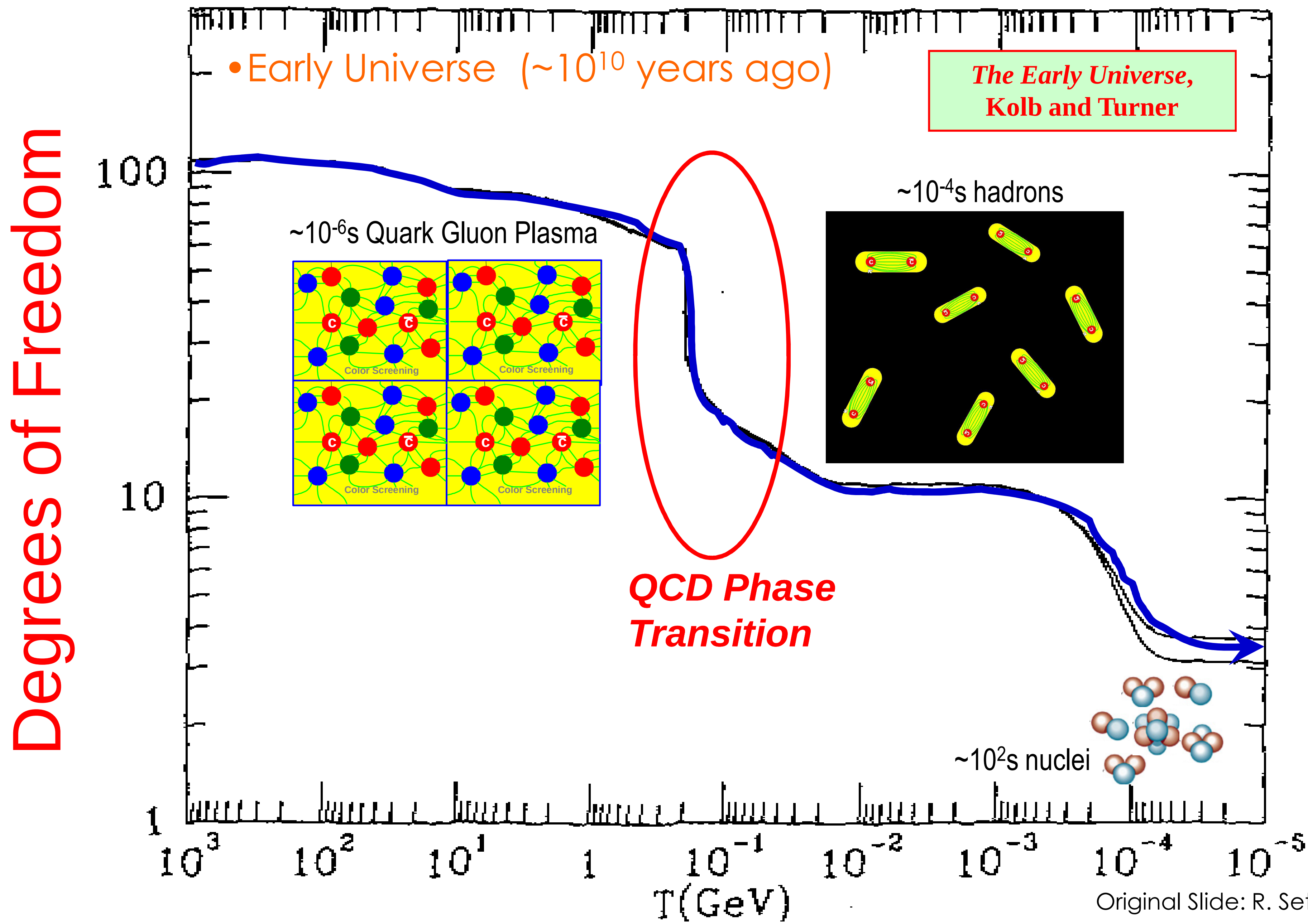
and

B. Back, M. Baker, R. Hollis, K. Rajagopal, R. Seto, and P. Steinberg

(whose thoughts/talks/papers have inspired and from whom some slides were “borrowed”)

Setting the Stage

A "big bang" view of our beginning…

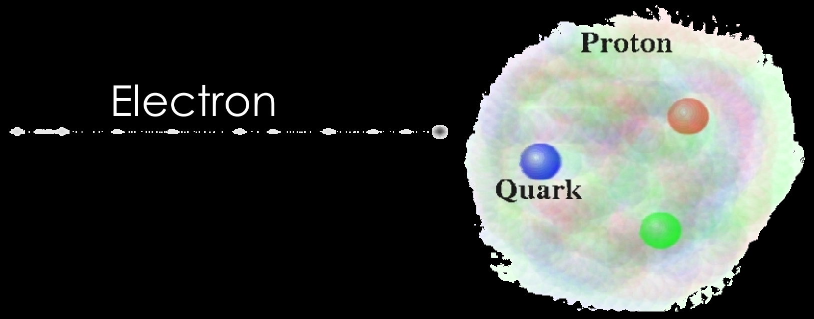


Original Slide: R. Seto

So Quarks "=" a Relevant DoF of the Early Universe… → Lets Study Them

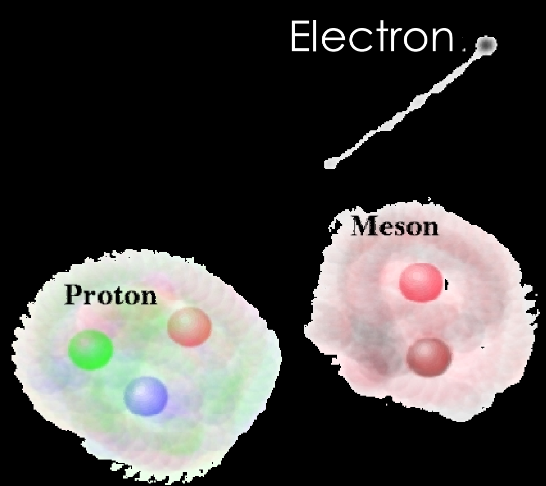
We can find the quarks inside the nucleus.
Lets free them!

e-p graphics: http://www.theorie.physik.uni-wuppertal.de/~wwwkroll/frames/main.eng.html



Two immediate problems:

1. If you try to break a proton apart, you just get a second particle made up of 2 quarks!
   → Quarks are not Free.

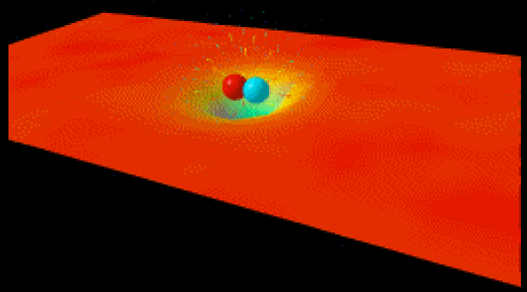


2. If you measure the mass of the quarks inside the proton, you only account for a fraction of the nucleon mass.
   → Something Strange with Mass

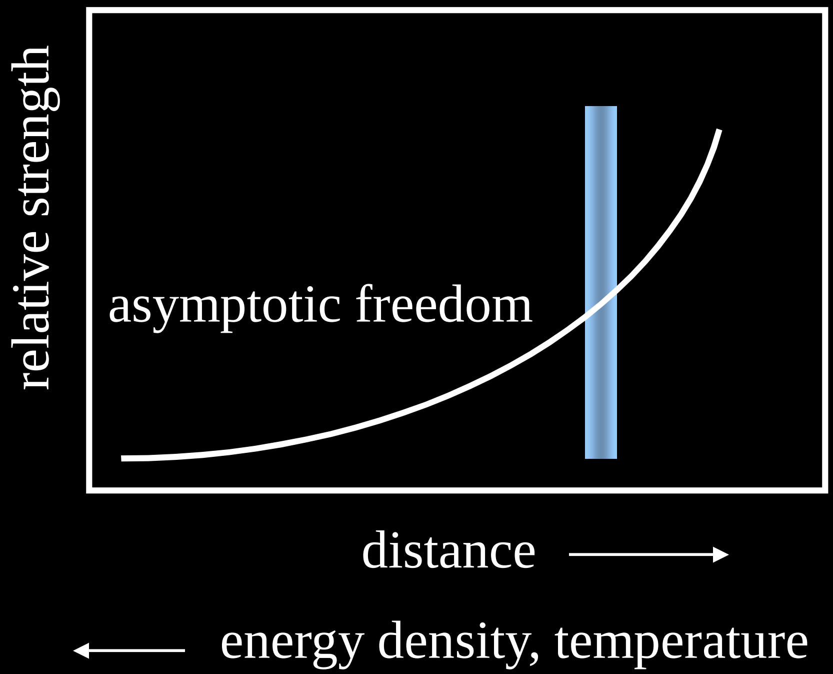
1. Why No Free Quarks Today?
QCD: Confinement (& asymptotic freedom)

Visualization of QCD
by Derek Leinweber

Centre for the Subatomic Structure of Matter (CSSM) and Department of Physics, University of Adelaide, 5005 Australia



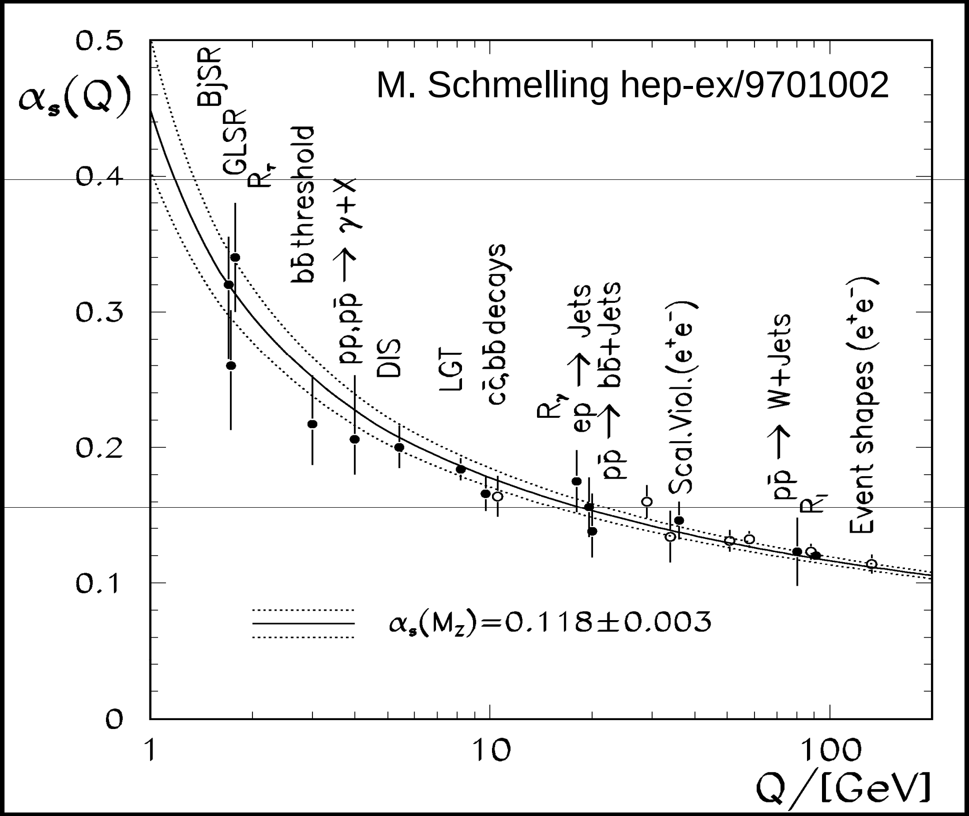
Separation of quarks varies from 0.125 fm to 2.25 fm (~1.3x diameter of proton)



http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/ImprovedOperators/index.html

Running Coupling Constant

experimental data and perturbative QCD (pQCD) calculation



Energy Density, Temperature →

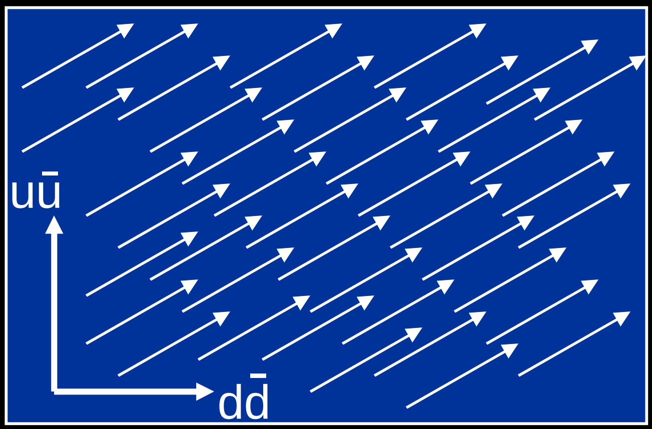
← Distance

2. What is Going on with Quark Masses?
QCD: The Properties of our "cold" Vacuum

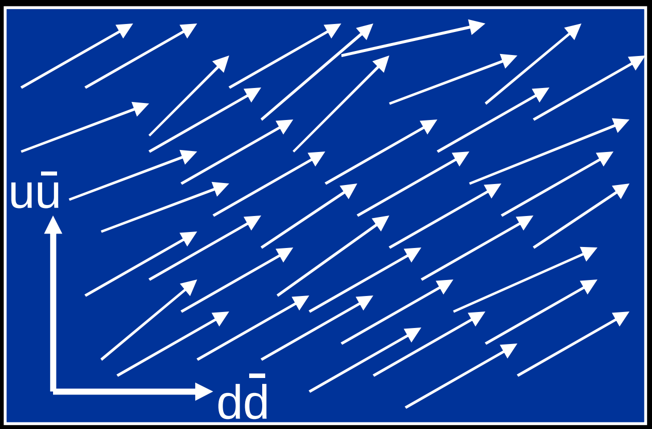
QCD Vacuum is a Condensate!

→ The reason why hadrons are so heavy.

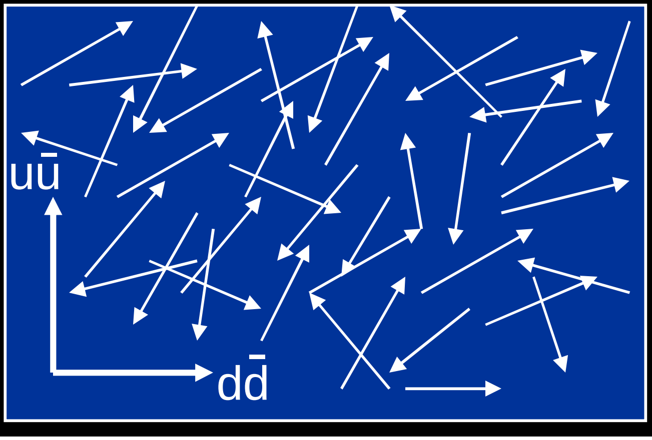
T = 0



T > 0 (but < T_c)



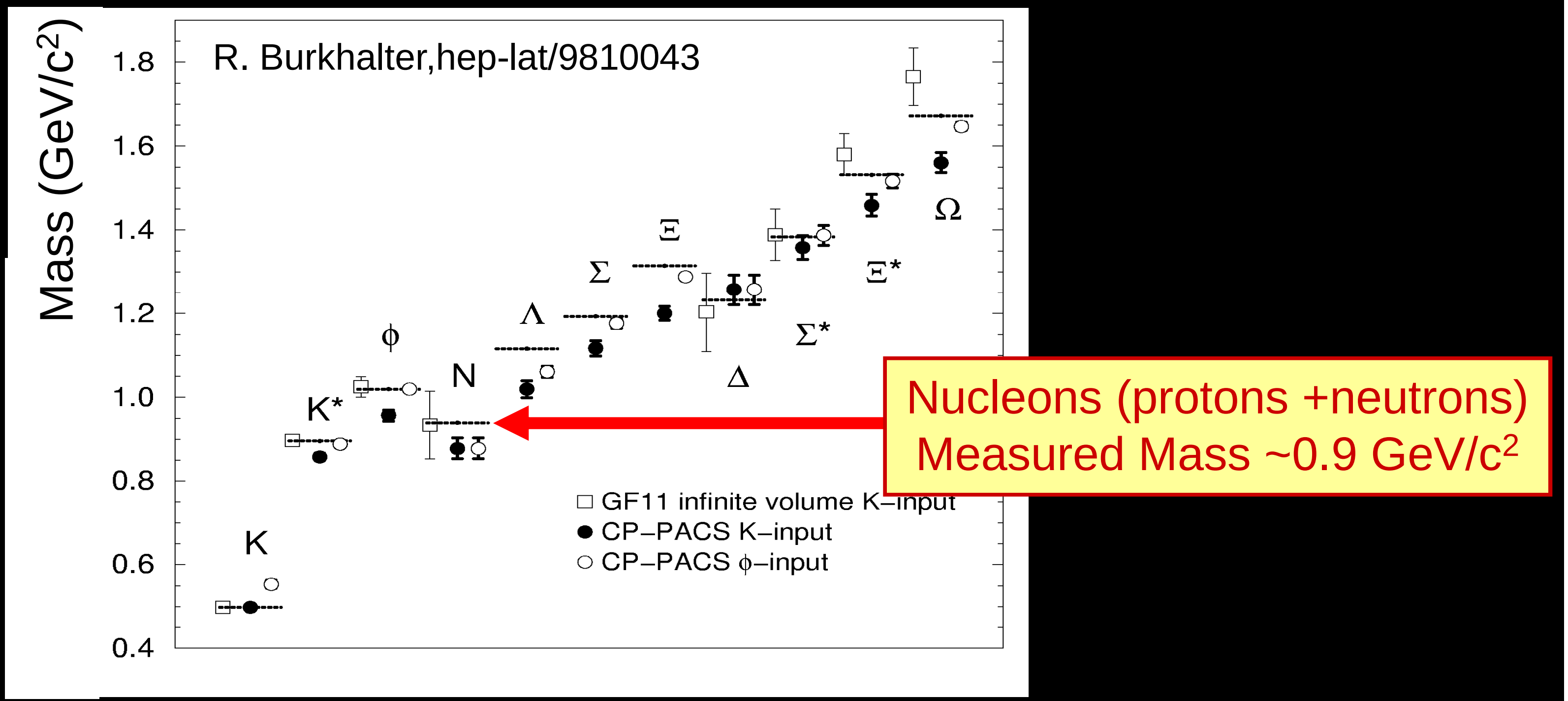
T > T_c



Inspiration/ideas from
Krishna Rajagopal

QCD and The Masses of Particles

Comparison of the “hadronic spectrum” with first-principles calculations from QCD, using techniques of lattice guage theory.



“…confinement and chiral symmetry breaking [i.e. the QCD condensate] are simply true facts about the solution of QCD, that emerge by direct calculation” – F. Wilczek

Back to Einstein…

Idea From: F. Wilczek's
Nobel Prize Lecture

$$\cancel{E = mc^2}$$

"Does the Inertia of a Body Depend Upon its Energy Content?"

By A. Einstein

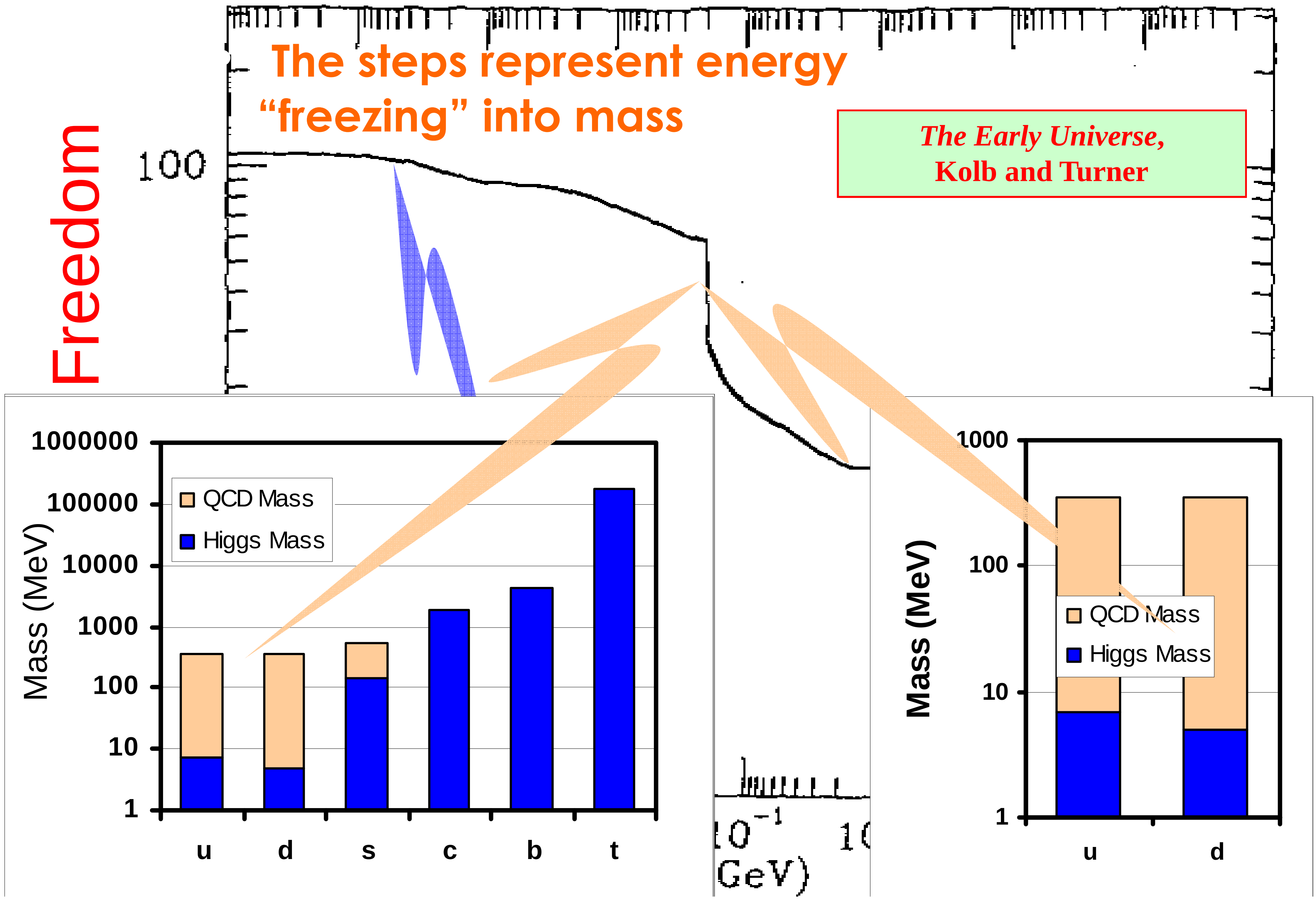
September 27, 1905

$$m = \frac{E}{c^2}$$

"The mass of a body is a measure of its energy-content;… It is not impossible that with bodies whose energy-content is variable to a high degree … the theory may be successfully put to the test." – A. Einstein (translated from the German of his 1905 paper).

Origin of (Our) Mass

Original Slide: R. Seto

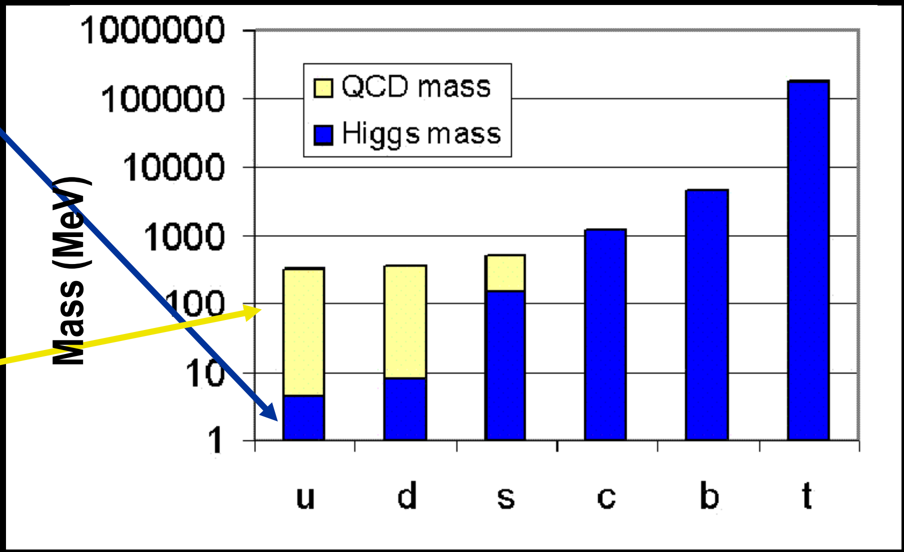


Forward to Today…

Figure and quote
From B. Muller; nucl-th/0404015

Current (or 'naked') Quarks

→ Mass u,d = 5-10 MeV generated by Higgs condensate.

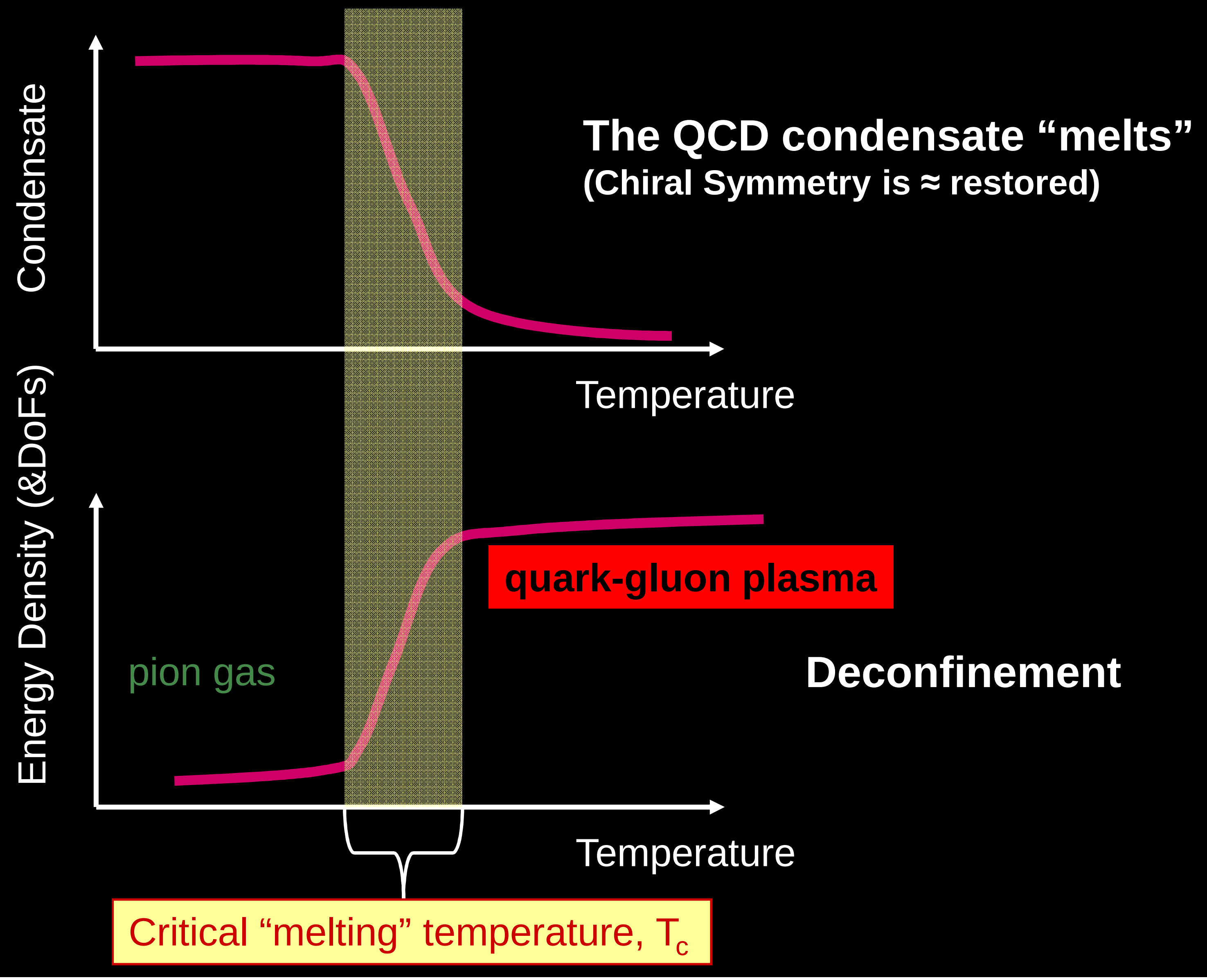


Constituent Quarks

→ Mass u,d ~ 300 MeV generated by QCD condensate.

→ "Because of the energy scales involved, only the QCD Vacuum is amenable to modification at energies accessible with present technologies."

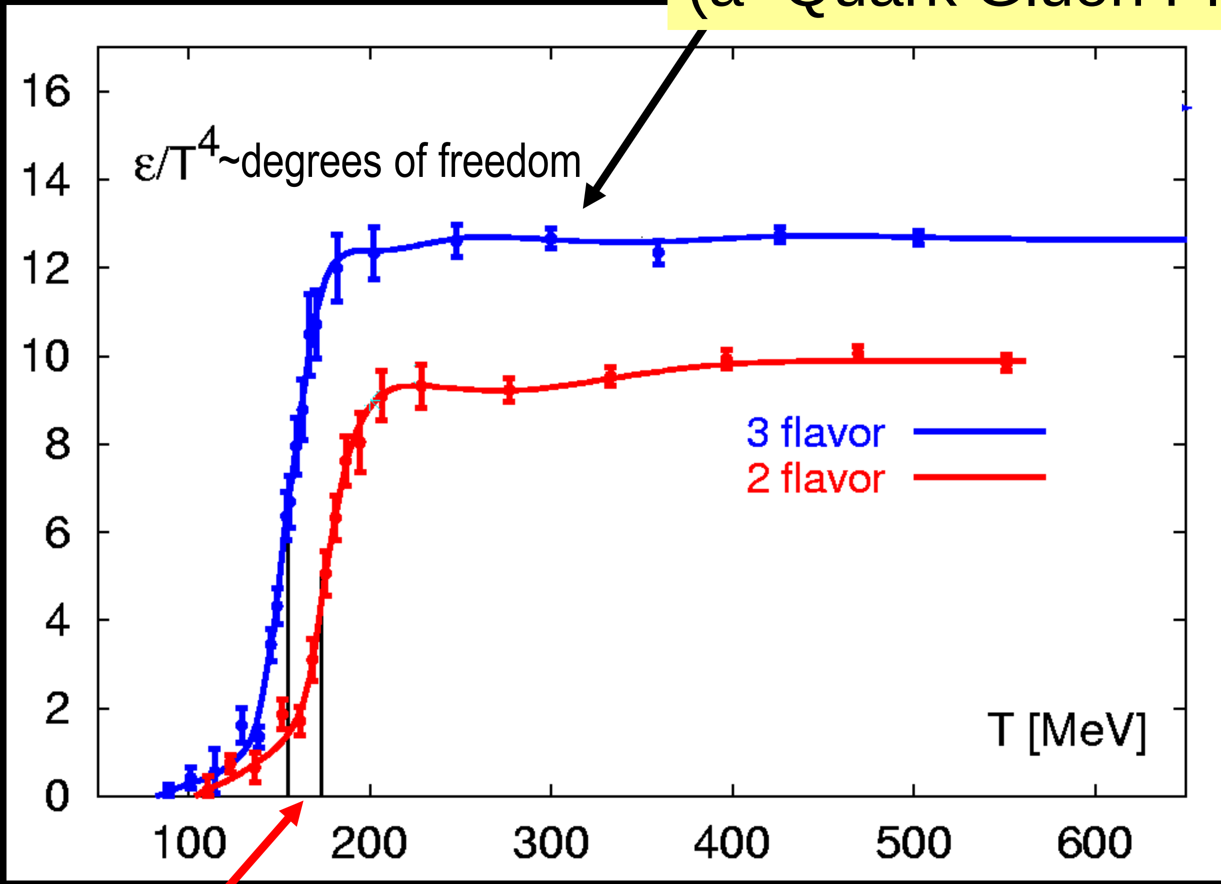
Melting the QCD Vacuum



Lattice QCD at Finite Temperature

F. Karsch, hep-ph/010314

A new form of matter
(a “Quark Gluon Plasma”)



(μ_B=0)

Critical Temperature, $T_C \sim 170$ MeV
Critical Energy Density, $\varepsilon_C \sim 1$ GeV/fm^3

Normal “cold” matter
energy density ~0.16 GeV/fm^3

How Much “Heat” is Needed?

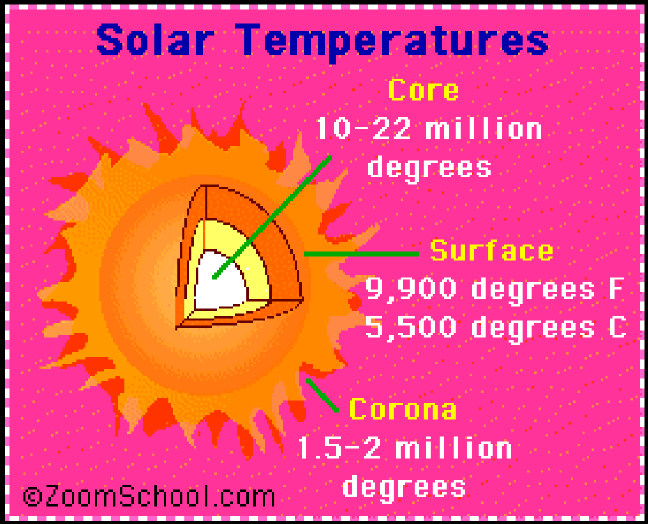
$T_C \sim 170$ MeV

1eV corresponds to an energy kT (where T~11,600 K) .
Assume transition at about 170 MeV (~1.2 x pion mass),
170E6*11600 = 1.7E8*1.16E4 ~2E12

Quark-Gluon plasma:

Need ~2 trillion degrees K

2 x 10^{12} K (or ^{o}C)

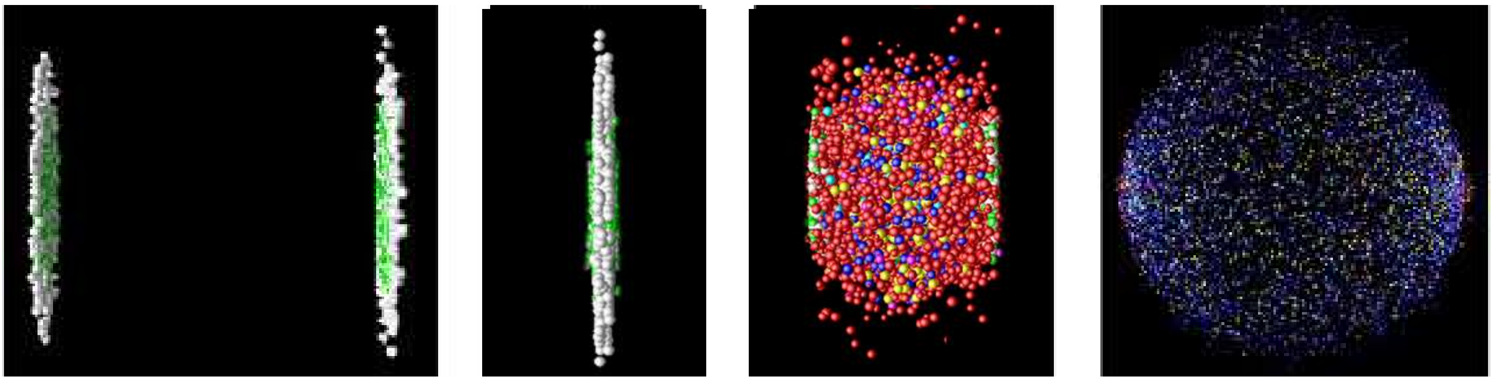


→ Too much “heat” to think about creating in a “traditional” sense.

How to Get this Much "Heat"?

Collide heavy nuclei at relativistic speeds

(e.g. 0.99996c at $\sqrt{s_{NN}}$ = 200 GeV)



→ We believe these conditions will reach the necessary temperature and pressures (energy-density) to create conditions in which the QGP could exist.

Laying the foundations: Relativistic Heavy-Ion Collisions

What do “we” think we know?

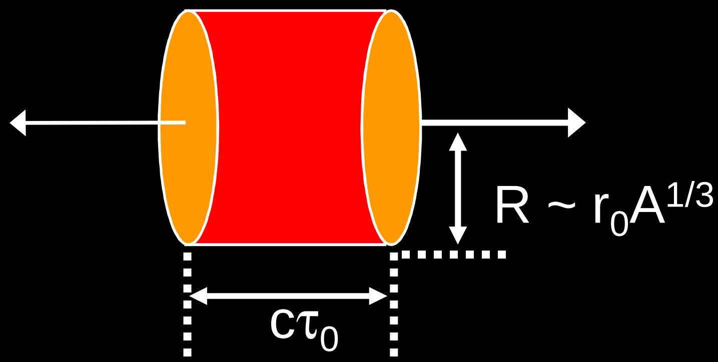
→ Focus on $\sqrt{s_{NN}}$=200 GeV Au+Au

The “relevant” energy density is above the critical value ($\varepsilon_c \sim 1$ GeV/fm^3)

From: B.B. Back – Lake Lousie 2006

Central (head-on) Collision

(for 200 GeV Au+Au)



PHOBOS: PRL **91**, 052303 (2003)

Create 5000 Charged Particles

Yield perpendicular to collision axis: $\left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0} \approx 700$

Bjorken

$$\varepsilon_0^{Bj} = \frac{\text{Energy}}{\text{Volume}}$$

$$\text{Energy} = \langle m_T \rangle \frac{dN}{dy}$$

$$\text{Volume} = \Delta z \times \text{Area}$$

$$= \langle m_T \rangle \frac{1}{\tau_0 \pi R^2} \frac{dN}{dy}$$

$$\langle m_T \rangle = 0.6 \text{ GeV/c}^2$$

$$\tau_0 = 1 \text{ fm/c}$$

$$\pi R^2 = 145 \text{ fm}^2$$

$$\frac{dN}{dy} = 1.1 \times \frac{dN_{ch}}{d\eta} \times \frac{N_{tot}}{N_{ch}}$$

$$= 1.1 \times 700 \times \frac{3}{2} = 1155$$

$$\varepsilon_0^{Bj} \approx 4.8 \text{ GeV/fm}^3$$

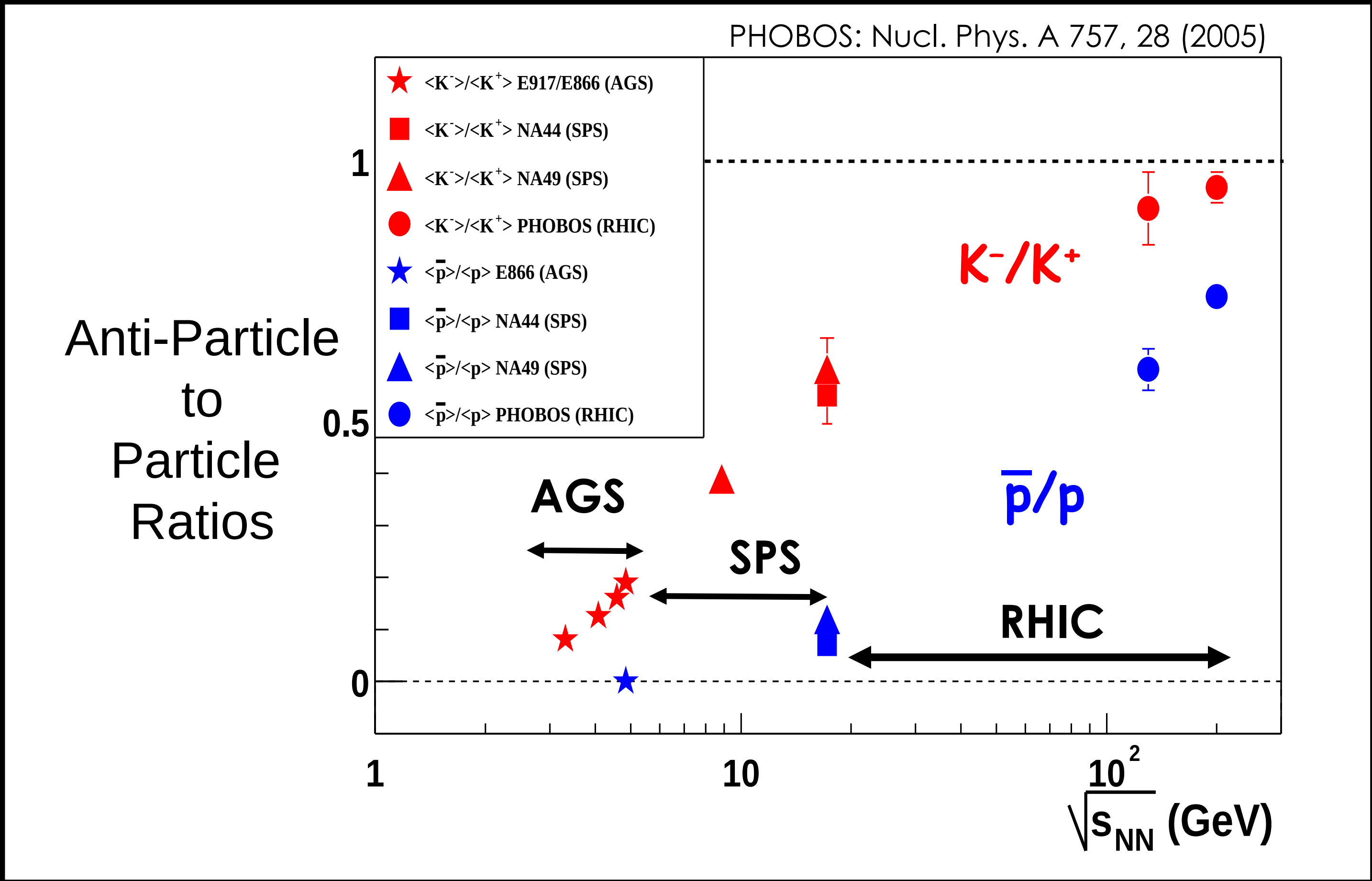
→“Equilibrated” energy density ε_0 > 4 GeV/fm^3

We are creating a state of matter that is approaching "baryon-freedom"

(Similar to the early Universe)

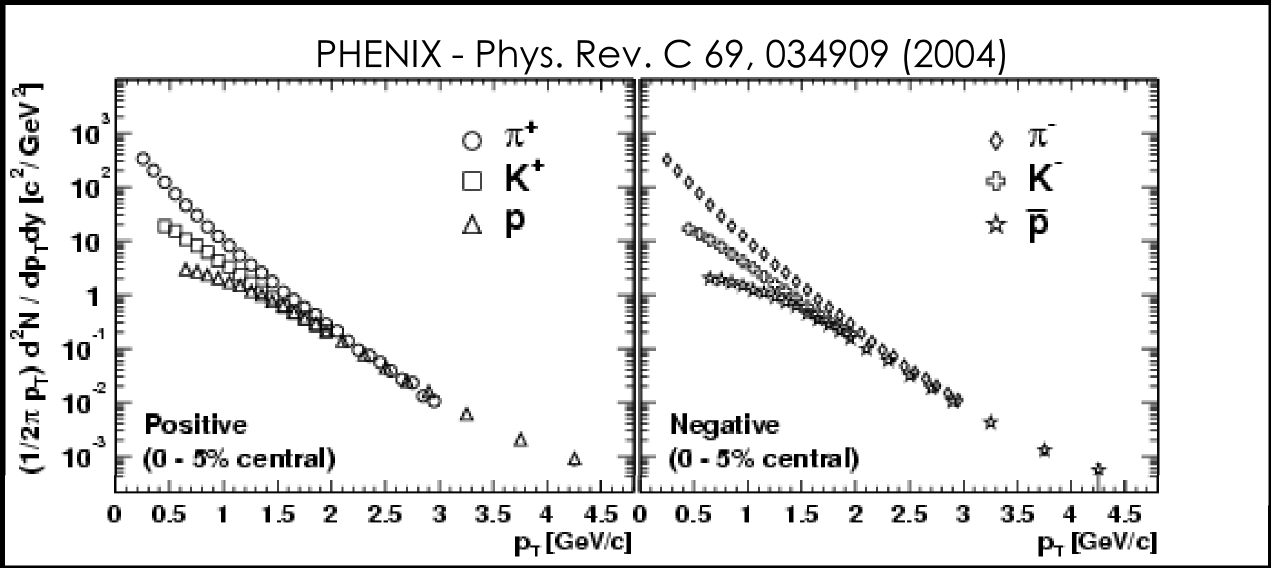
A+A central collisions

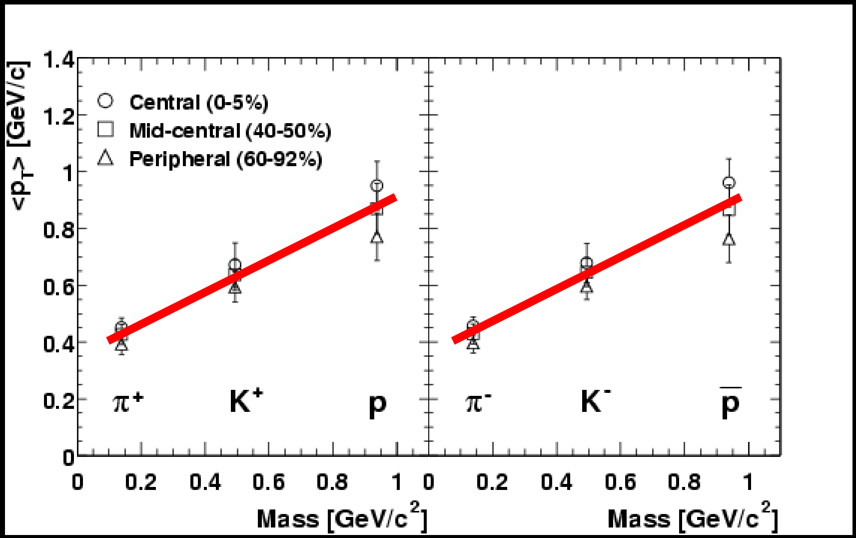
(measured near midrapidity)



→ Approaching equal production of matter and anti-matter as the collision energy increases. (i.e. "Baryon-Free")

The State of Matter appears to exhibit strong collective expansion characteristics





Observation only to motivate next slide

$p = mv$

Common Expansion Velocity?

Rapid "hydrodynamic" expansion…

Fit spectra with hydrodynamically motivated "blast waves" to gain insight into the dynamics of the collision.

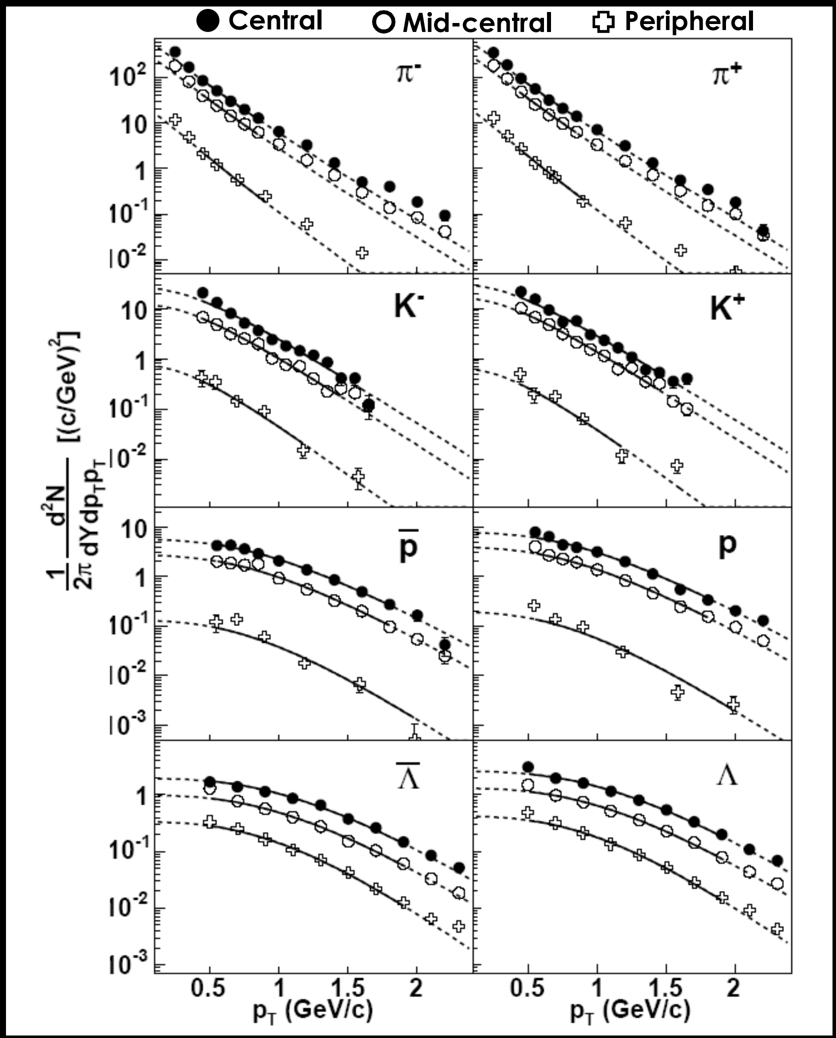
** Assumptions include particle freeze-out at a common temperature.*

** Seven fit parameters.*

→ Can describe the data with a common transverse "flow" velocity.

→ This velocity is large $\langle B_T \rangle \sim 0.5c$

Retiere and Lisa – nucl-th/0312024



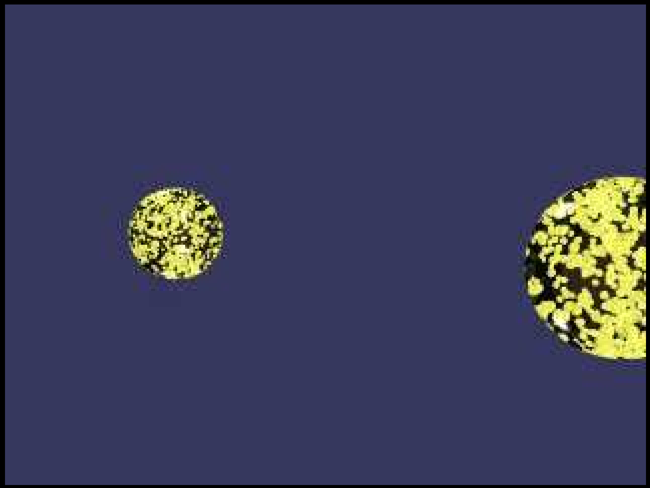
Note: Other analyses show a centrality dependence of $\langle B_T \rangle$

State of Matter appears strongly interacting

(Similar to a "fluid")

Animation of HI Collision:

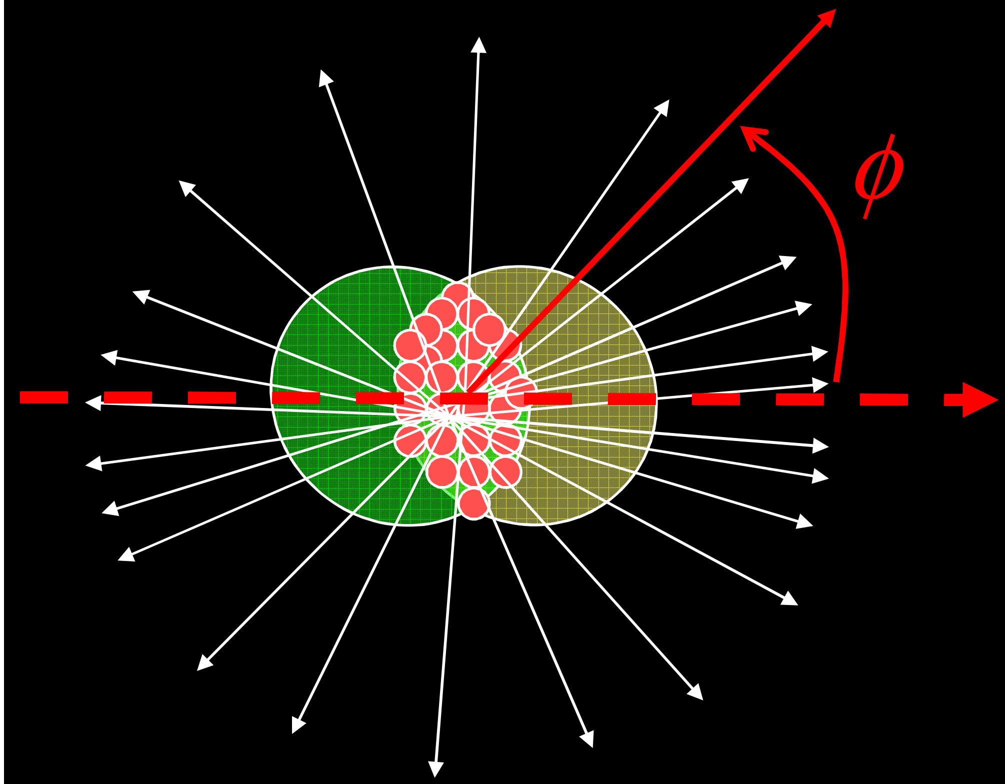
Note: is not relativistic – i.e no Lorentz contraction



Animation by Jeffrey Mitchell (Brookhaven National Laboratory)

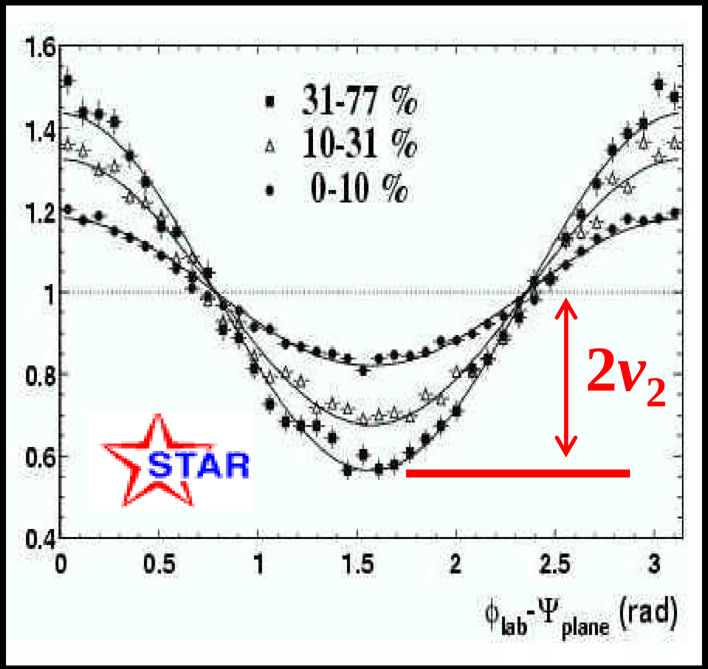
State of Matter appears strongly interacting

(Similar to a "fluid")



$$\frac{dN}{d\phi} \propto 1 + 2v_2(p_T)\cos(2\phi) + \ldots$$

"elliptic flow"



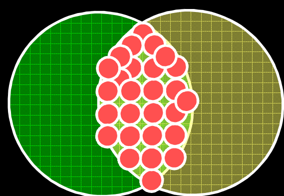
→ **Experiment finds a clear v_2 signal**

→ **If system was freely streaming the spatial anisotropy would be lost**

We call the measurement of v_2 "Elliptic Flow"

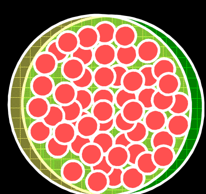
"elliptic flow"

Increasingly peripheral

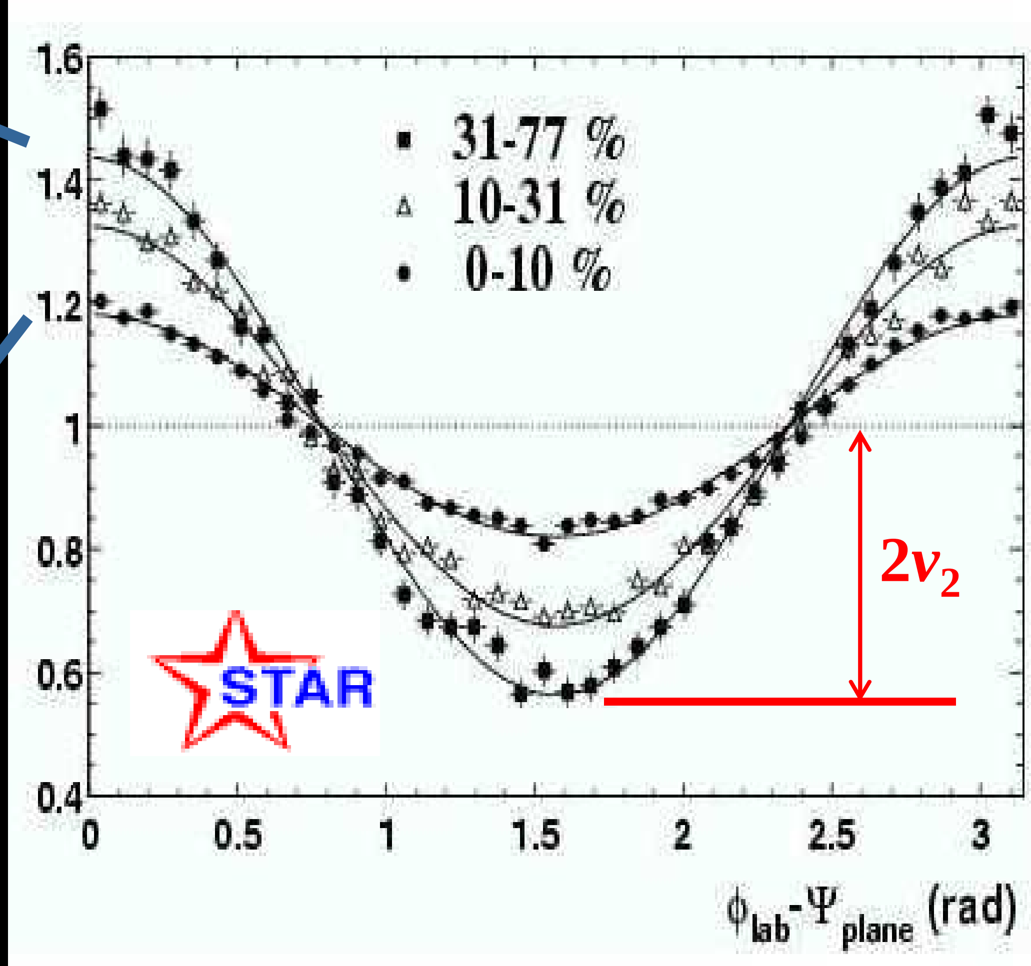


Larger eccentricity (and v_2)

0-10% = central collisions



Smaller eccentricity (and v_2)

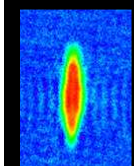


→ Magnitude of v_2 signal correlates with "overlap" eccentricity

State of Matter appears strongly interacting

(Similar to a "fluid")

Once again, in Pictures, what we see in experiment…



→ **Initial spatial anisotropy converted into momentum anisotropy (think of pressure gradients…)**

→ **Efficiency of conversion depends on the properties of the medium**

→ **In particular, the conversion efficiency depends on viscosity**

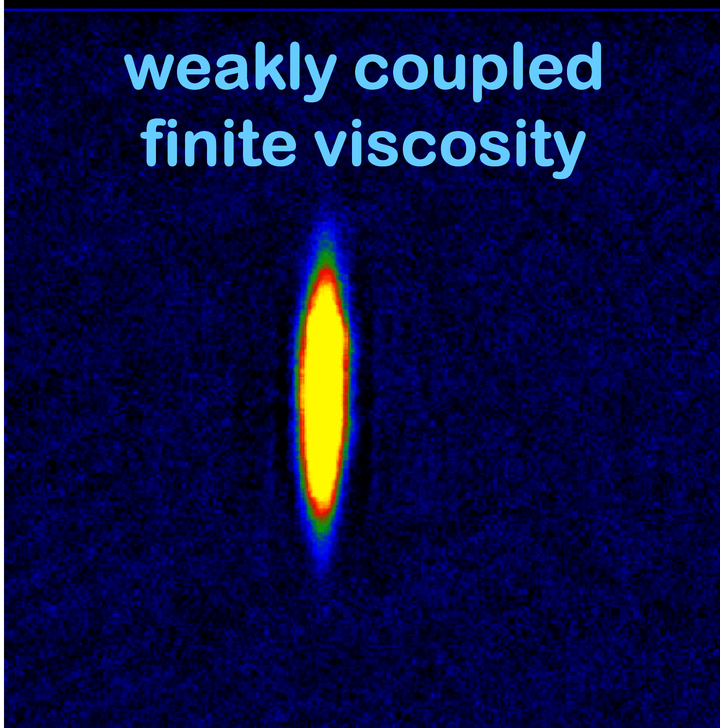
Pictures from: **M. Gehm, et al.,** Science **298** 2179 (2002)

The medium ("fluid") appears to have low viscosity

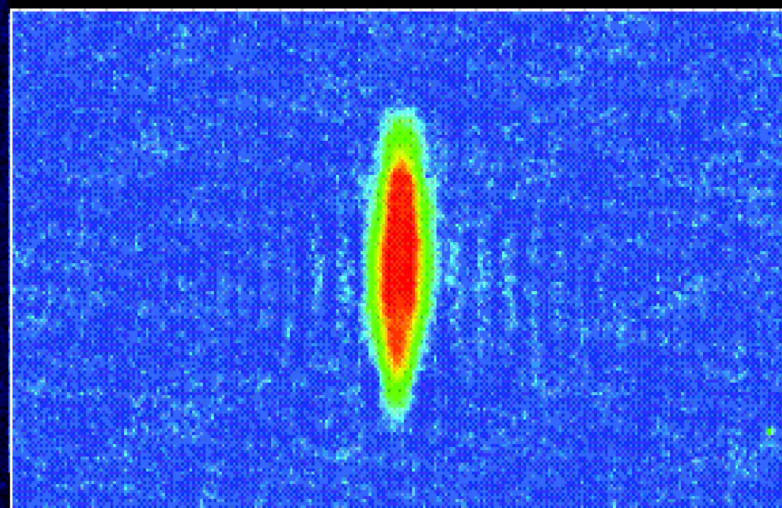
From R. Seto

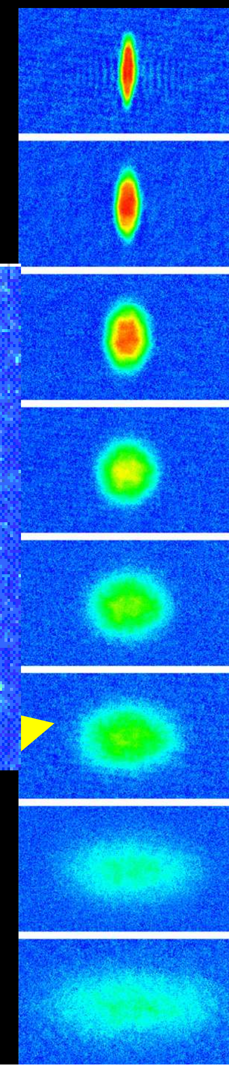
M. Gehm, et al
Science **298** 2179 (2002)

- Same phenomena observed in gases of strongly interacting atoms (Li6)



strongly coupled
viscosity=0

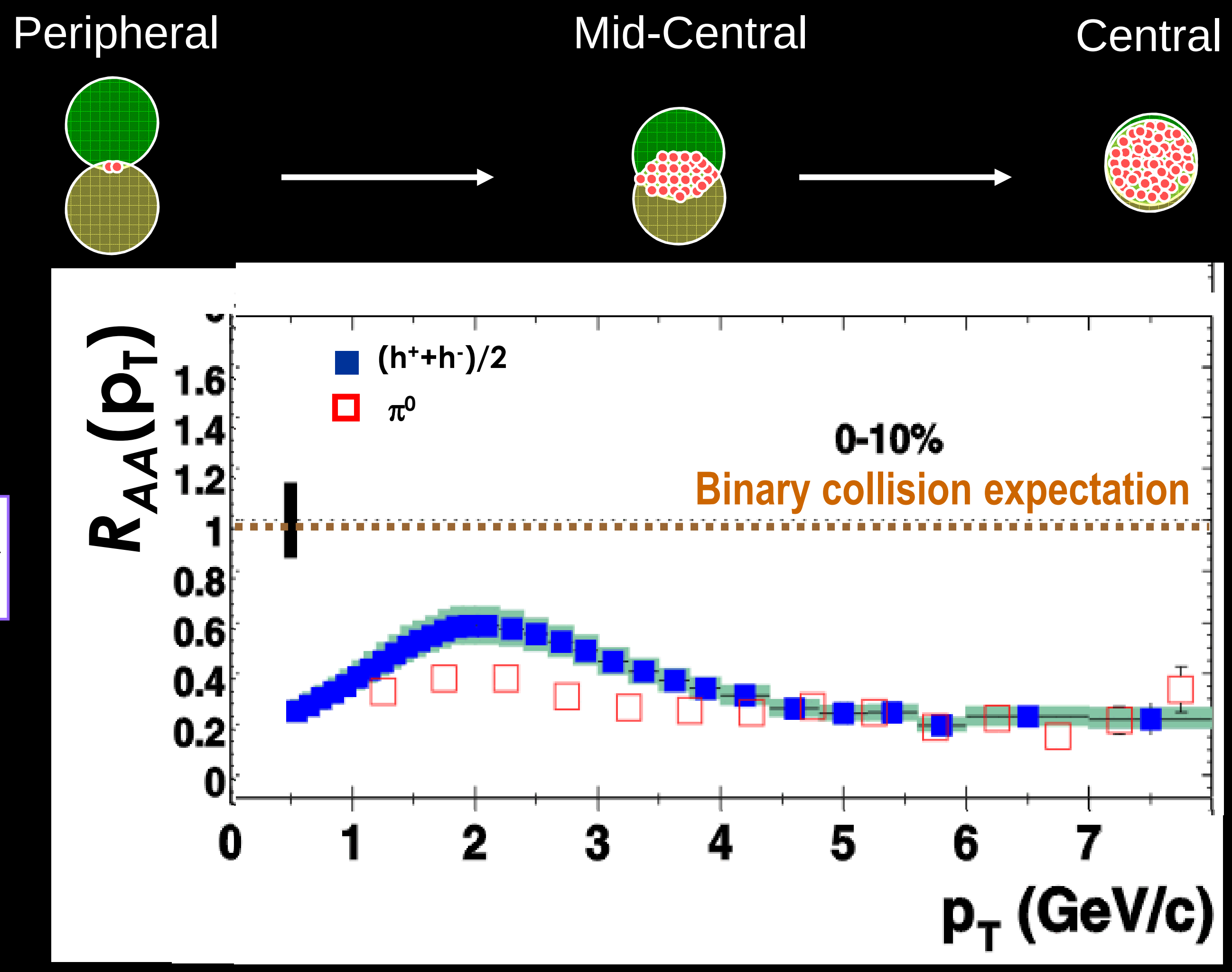




The RHIC fluid behaves like this,

that is, viscocity~0

Strongly interacting medium also appears to affect yields of high momentum particles

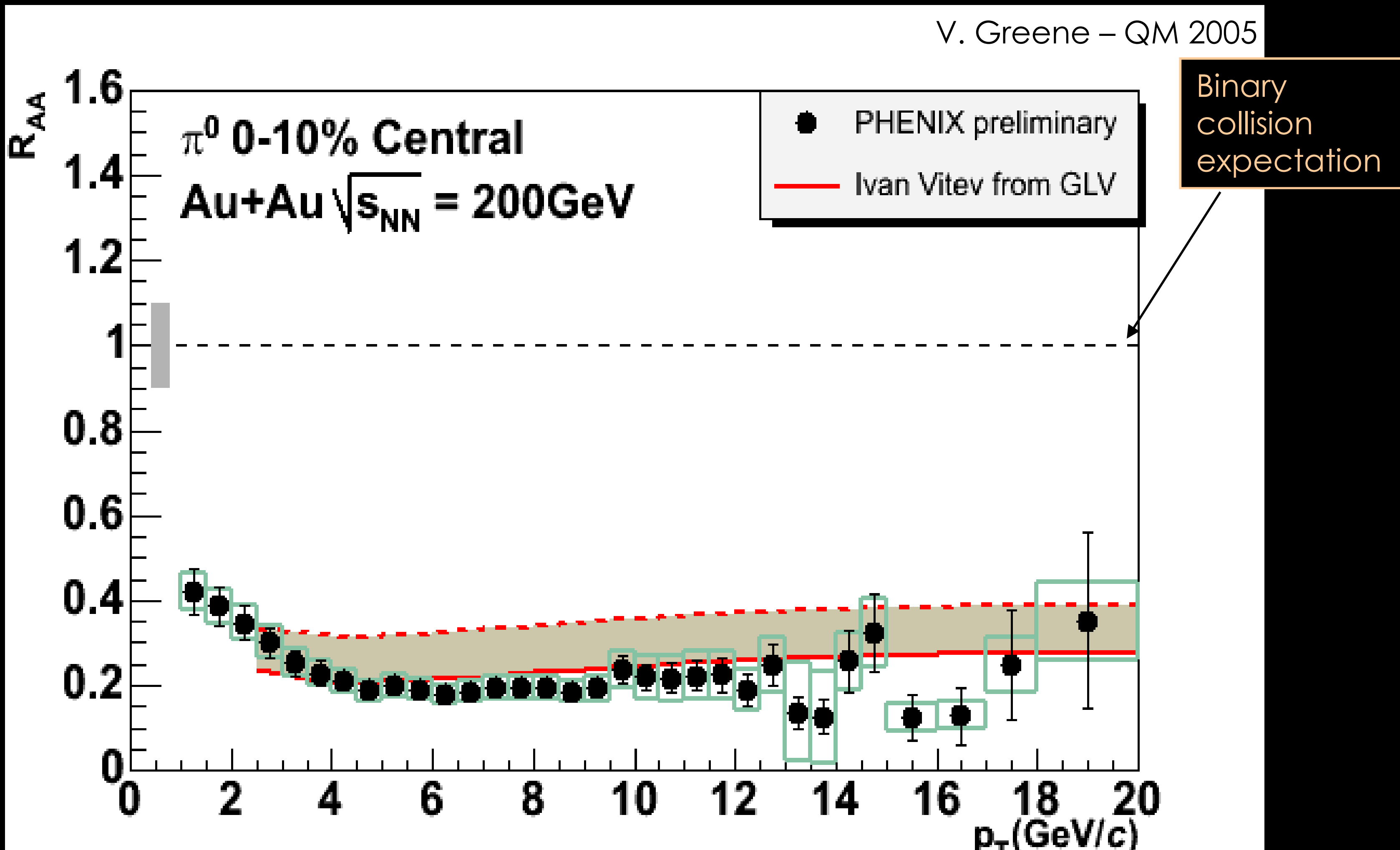


$$R_{AA} = \frac{\text{Yield}_{AuAu}}{\langle N_{binary}\rangle_{AuAu}\,\text{Yield}_{pp}}$$

Phenix: Phys.Rev. C69 (2004) 034910

→ See a strong suppression of high p_T yields in AuAu Central Collisions

Energy Loss in a Strongly Interacting Medium.



→ Energy loss models can account for suppression at p_T>3 GeV/c

So…what we think we know is:

- Relativistic heavy ion collisions at RHIC create a medium that:
  - has an energy density above critical value needed to "melt" the normal QCD vacuum
  - equilibrates very quickly
  - is close to being "baryon-free"
  - is fluid-like: strongly interacting, collective in behavior, posses low viscosity (also called a "perfect fluid")
  - Large energy loss for high momentum particles

The popular name is the sQGP:

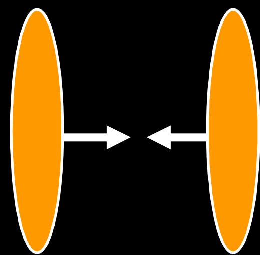
Strongly interacting Quark Gluon Plasma

Now to more recent results…

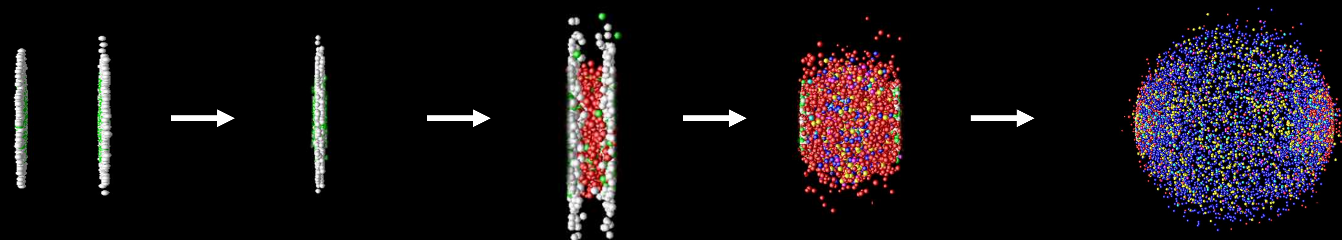
Relevant degrees-of-freedom

Look again at a single heavy ion collision

nuclei crossing times extremely fast

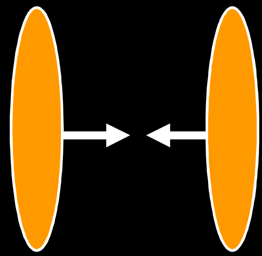


RHIC: ~0.13 fm/c
SPS: ~1.6 fm/c
AGS: ~5.3 fm/c



Two "snapshots" of colliding nuclei at RHIC

nuclei crossing times extremely fast



RHIC: ~0.13 fm/c
SPS: ~1.6 fm/c
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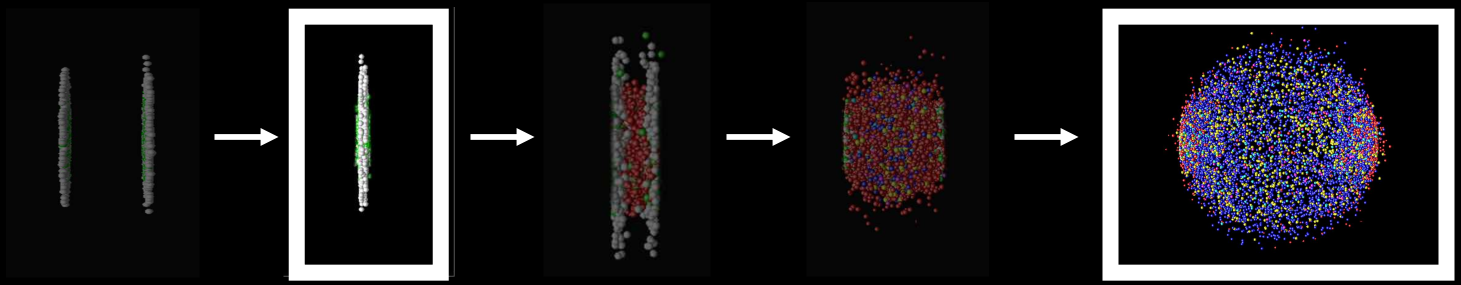
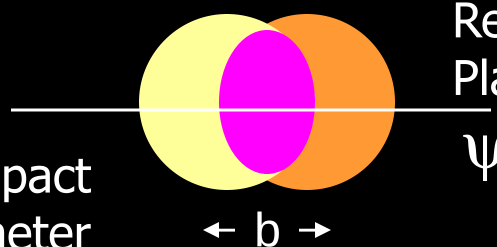


Of course, this one
is our actual measurement

We saw before: initial collision geometry matters

Elliptic Flow

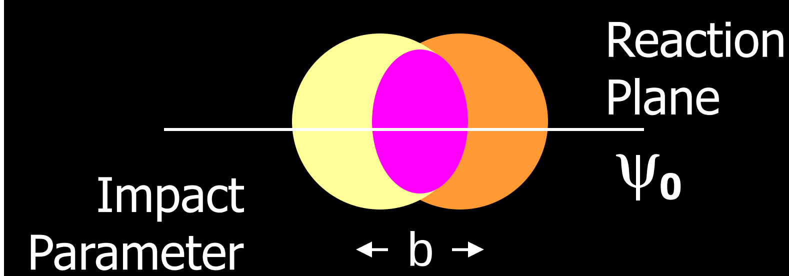
Initial overlap eccentricity

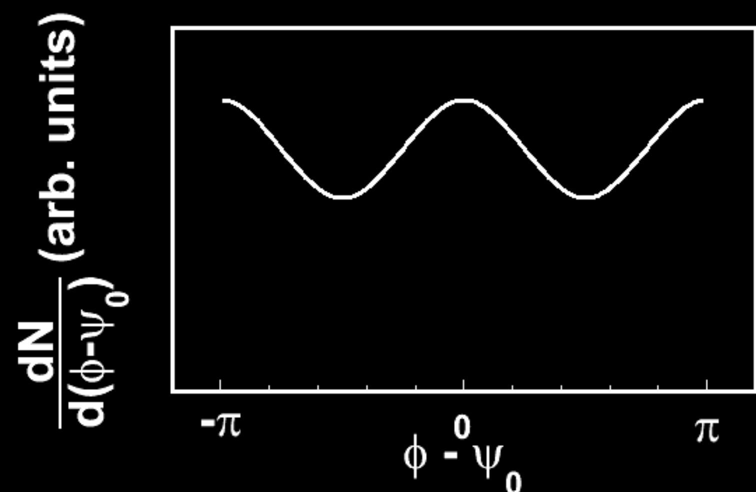


We saw before: initial collision geometry matters

Elliptic Flow

Initial overlap eccentricity → Visible in final measured particle azimuthal angular distributions





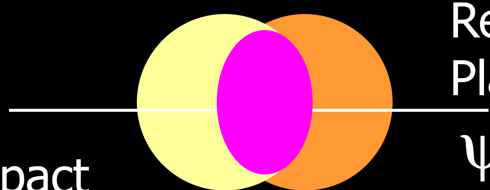
Well known: initial collision geometry matters

Elliptic Flow

Initial overlap eccentricity → Visible in final measured particle azimuthal angular distributions

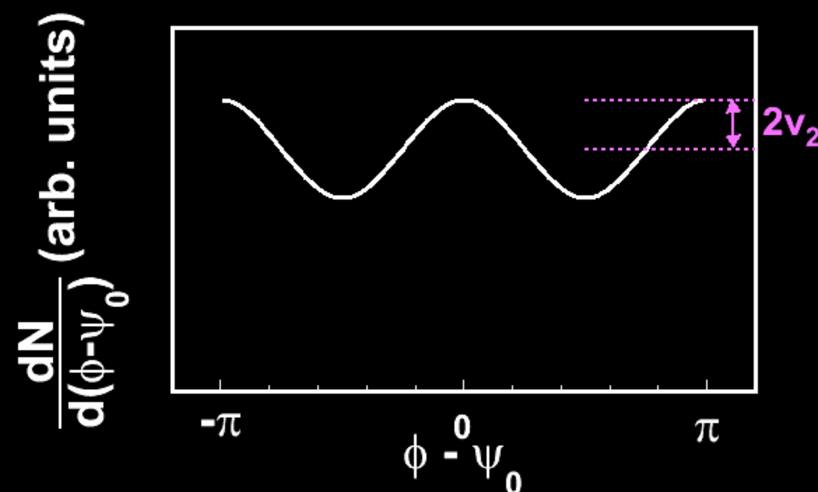
Reaction Plane

ψ_0



Impact Parameter

← b →



Initial Eccentricity $\boxed{\mathcal{E}}$ ⟶ $\boxed{v_2}$ Final Particle Distributions

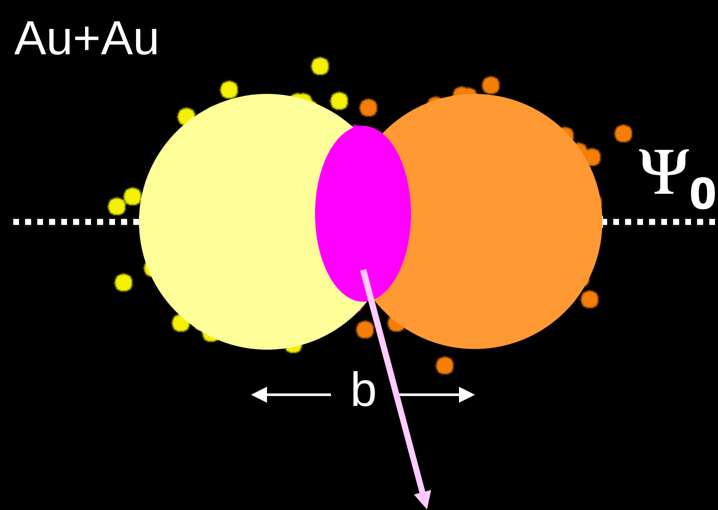
→ To first order: initial collision geometry drives magnitude of v_2

(of course, the density also matters)

Is our first RHIC snapshot "in focus"?

Our understanding of flow as a "hydrodynamical" expansion of a "perfect fluid" implies smooth surfaces…right?

BUT, what if we focus on the spatial distribution of the interaction points of participating nucleons?



Thus the eccentricity of the overlap region (which drives flow) is fixed relative to the impact vector "b"…

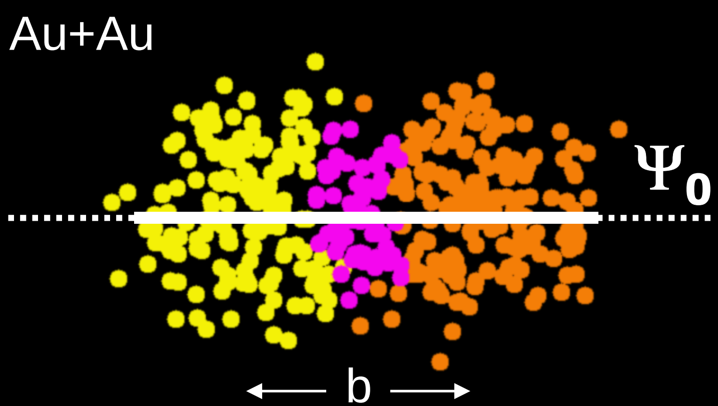
$\langle \varepsilon_{std} \rangle$
"standard" eccentricity

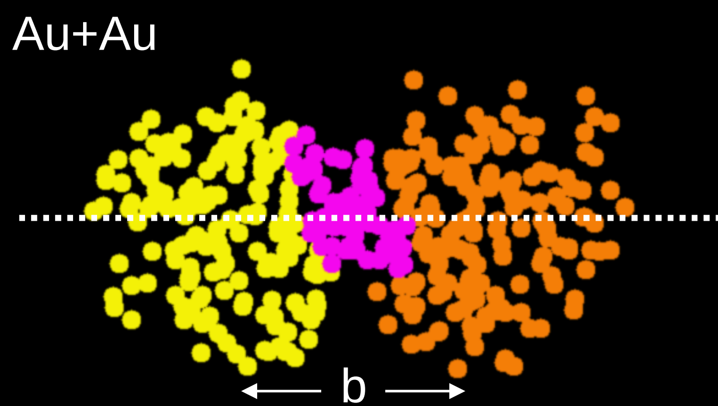
Is our first RHIC snapshot "in focus"?

<u>If we focus on:</u>
the spatial distribution of
the interaction points of participating nucleons

→

for the same b, these interaction points will vary from event-to-event





Is our first RHIC snapshot "in focus"?

<u>If we focus on:</u>
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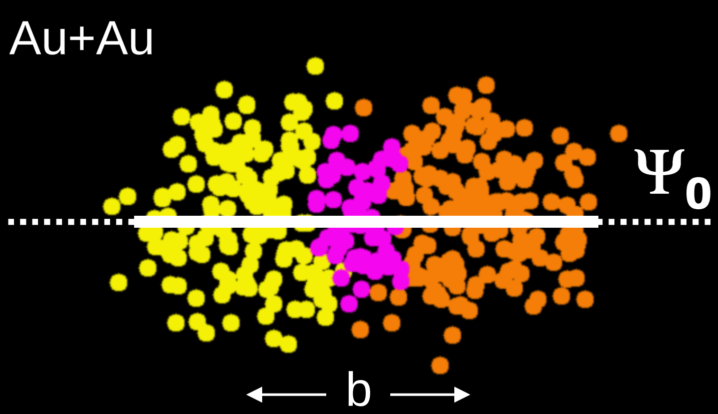
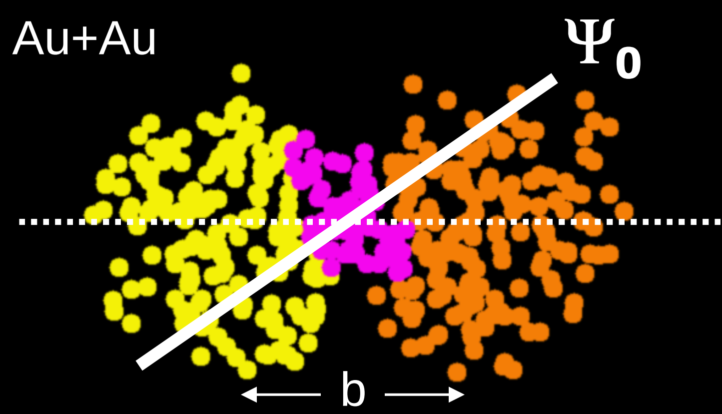




→ If these are relevant "DoF's", then the relevant eccentricity for elliptic flow also varies event-by-event for the same b

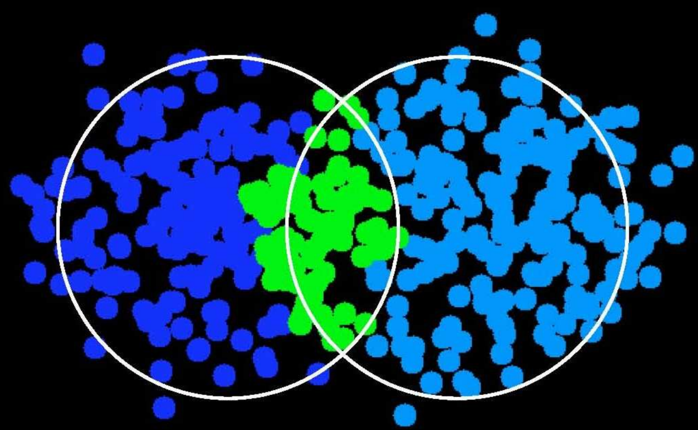
$$\langle \epsilon_{\text{part}} \rangle = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{(\sigma_y^2 + \sigma_x^2)}$$

→ $<\varepsilon_{part}>$
"participant" eccentricity

To summarize…

If interaction points of participating nucleons are relevant "DoF's"

Au+Au



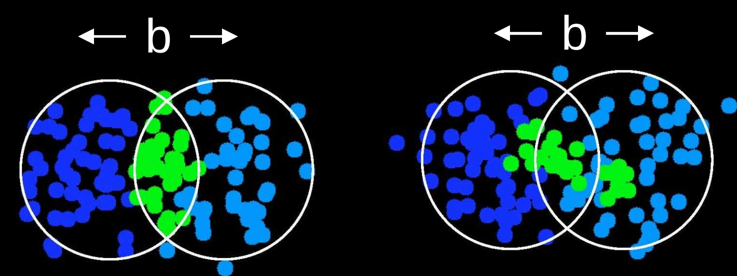
Interaction points trace out overlap eccentricity, but also include:

- Finite number fluctuations
  i.e. $\langle \epsilon_{part} \rangle \neq \langle \epsilon_{std} \rangle$
- Correlations ('takes two to tango'™)

Can study with smaller systems…

Cu+Cu

Same impact parameter, b

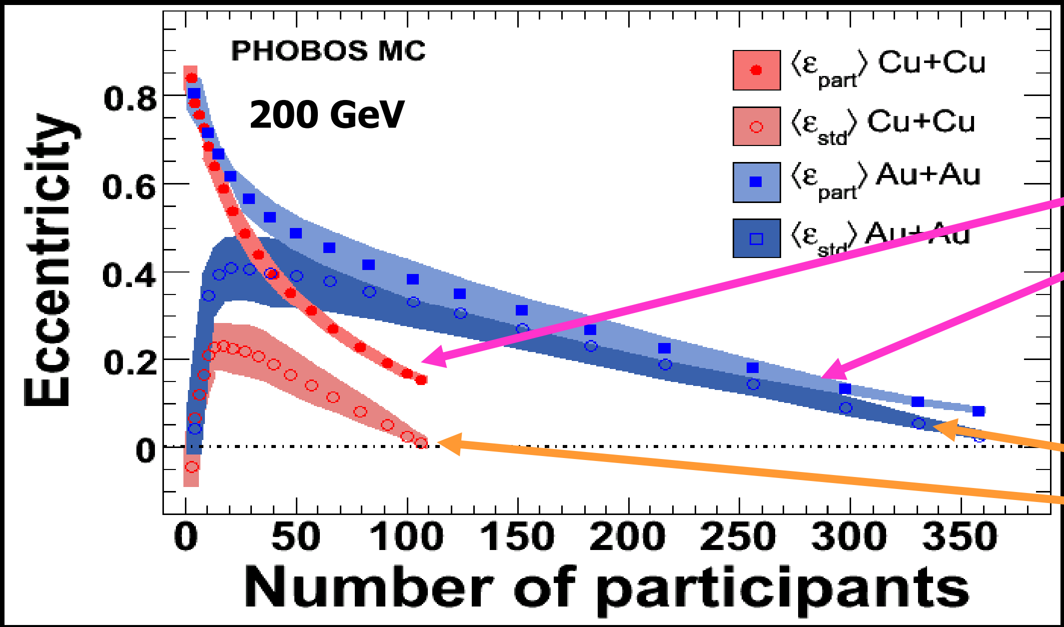


VERY different eccentricity for "standard" versus "participants" on an event-by-event basis.

™ P. Steinberg, RHIC/AGS Users Meeting 2007

Quantify the difference between "standard" and "participant" calculations of eccentricity

PHOBOS Monte Carlo Glauber Calculation

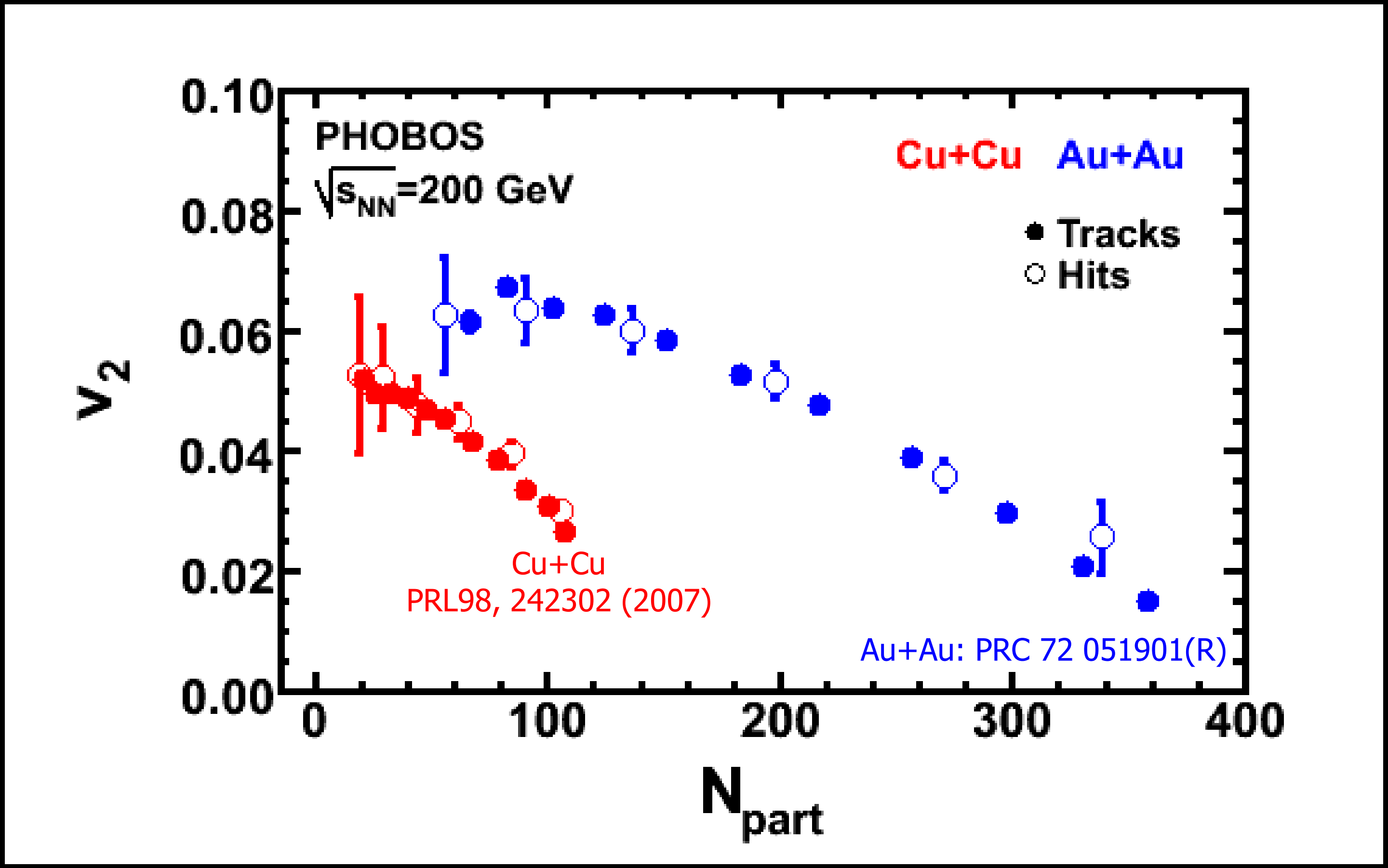


$<\varepsilon_{part}>$
"participant" nucleons
event-by-event calculation

$<\varepsilon_{std}>$
"standard" calculation

Effect is increasingly important for smaller systems

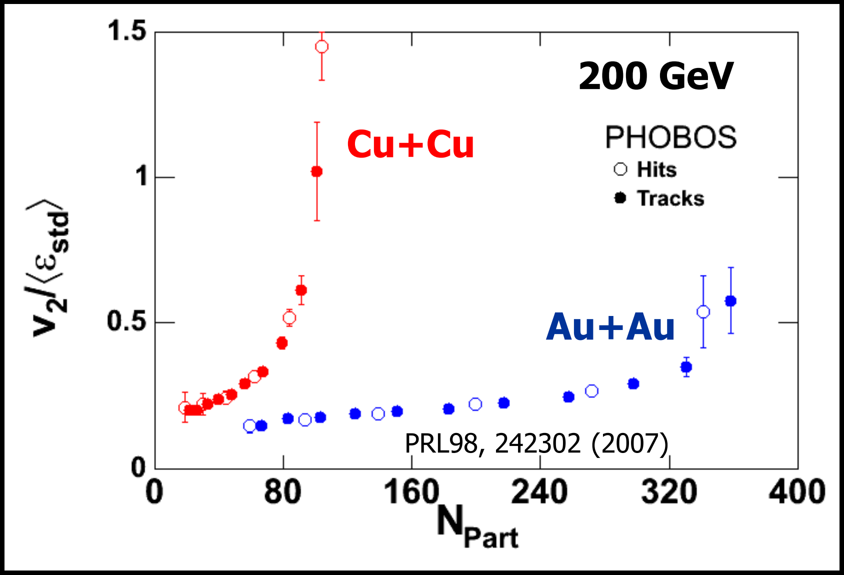
Data: average v_2 in Cu+Cu and Au+Au



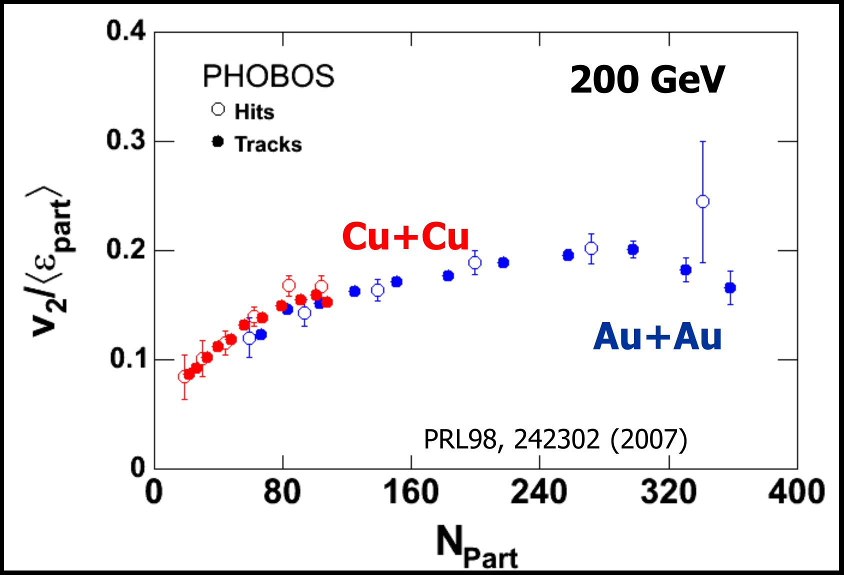
If eccentricity "determines" magnitude of v_2
then v_2/ε should be independent of size of colliding system…

Average v_2/ε in Cu+Cu and Au+Au

Standard Eccentricity



Participant Eccentricity

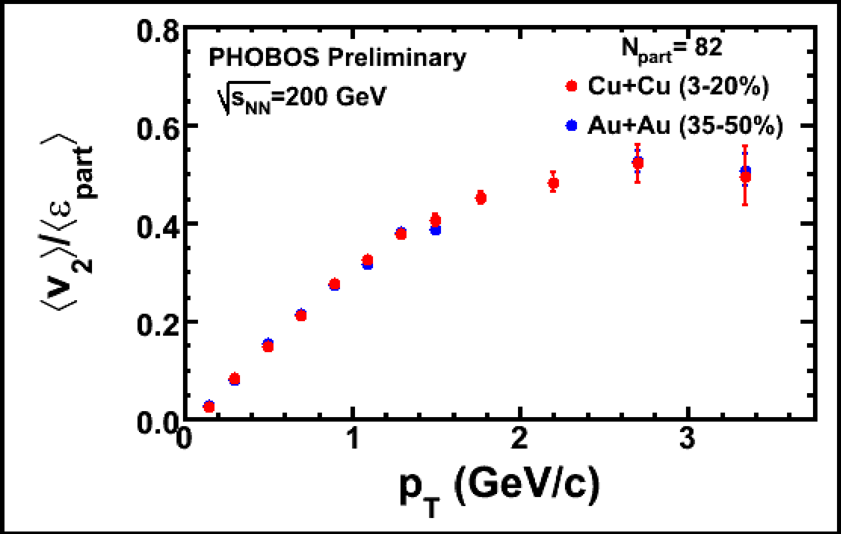


$\langle\epsilon_{part}\rangle$ unifies average v_2 in Cu+Cu and Au+Au

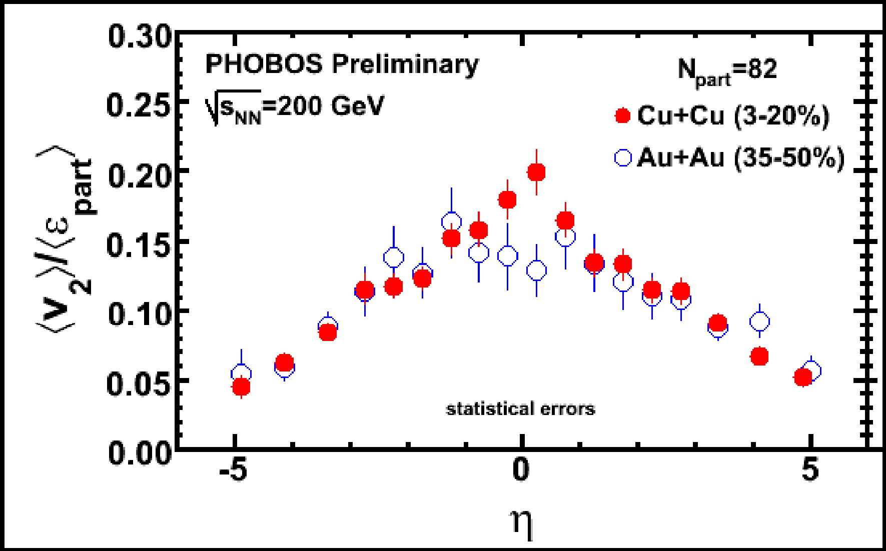
$\langle\epsilon_{part}\rangle$ Scaling holds for p_T and η

Au+Au and Cu+Cu at matched N_{part}

Transverse momentum, p_T



Pseudorapidity, η



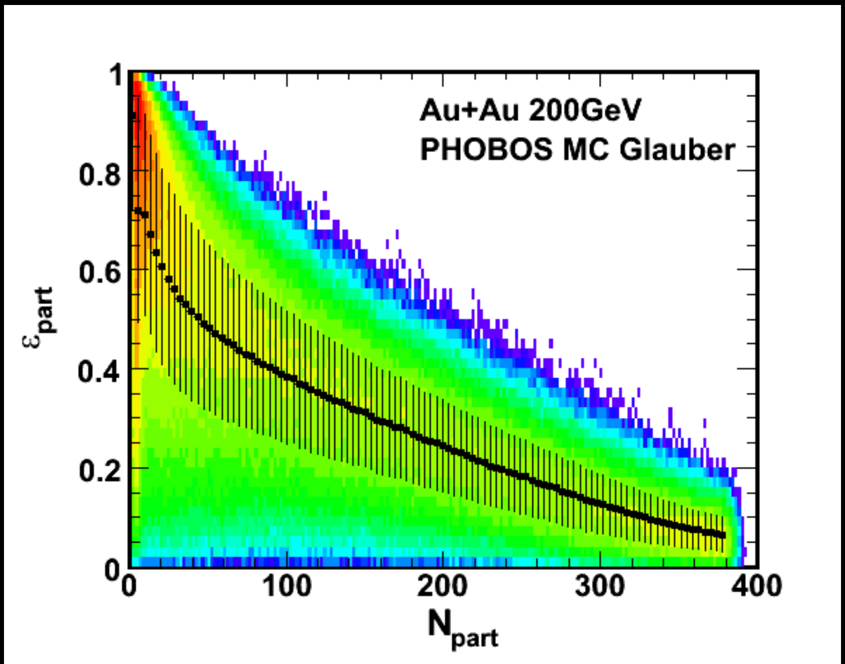
Consequence: this implies that the initial **event-by-event participant** collision geometry appears relevant.

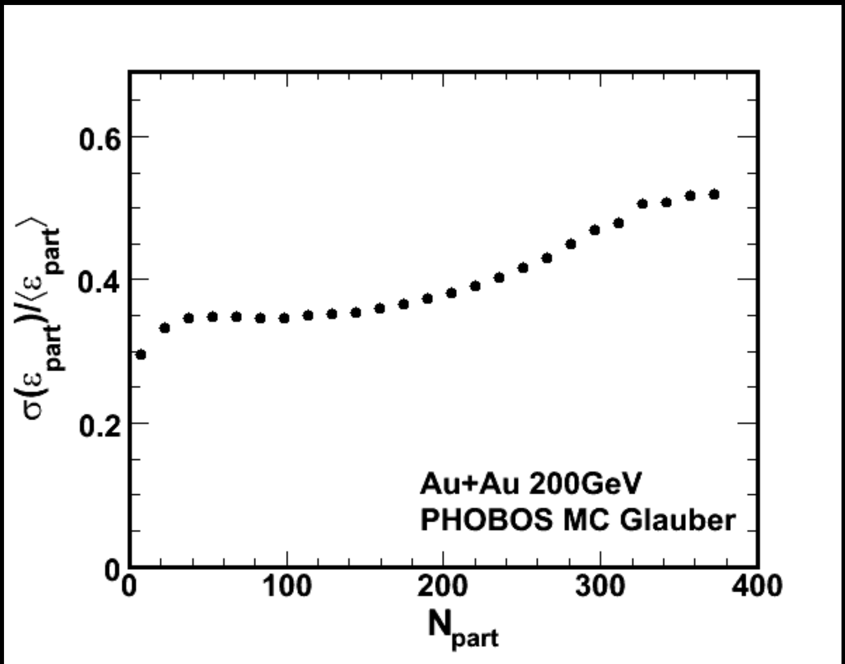
AND the participant collision geometry fluctuates event-by-event

Fluctuations in participant eccentricity

What magnitude of fluctuations are expected?

Quantify with $\sigma(\varepsilon_{part})/<\varepsilon_{part}>$





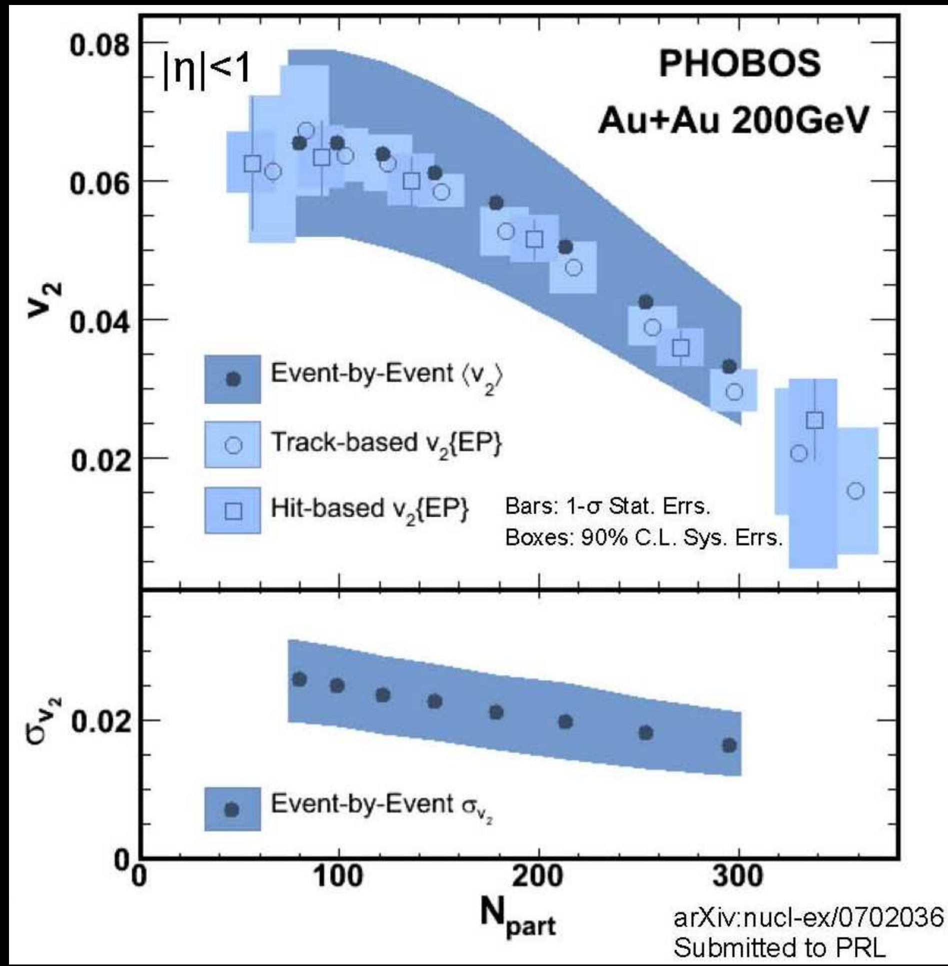
Expect large dynamical fluctuation in the participant eccentricity

Current Analysis: event-by-event v_2 measurement

200 GeV Au+Au

Analysis of: B. Alver

- Utilize Full Phase space coverage of PHOBOS ($|\eta|<5.4$, $\Delta\phi\sim2\pi$).
- Detailed modeling of detector response, statistical fluctuations and multiplicity dependence.
  - Method is described in arXiv:nucl-ex/0608025
- Measure v_2 on an event-by-event basis.
- Take e-by-e result and average to compare to our other results.

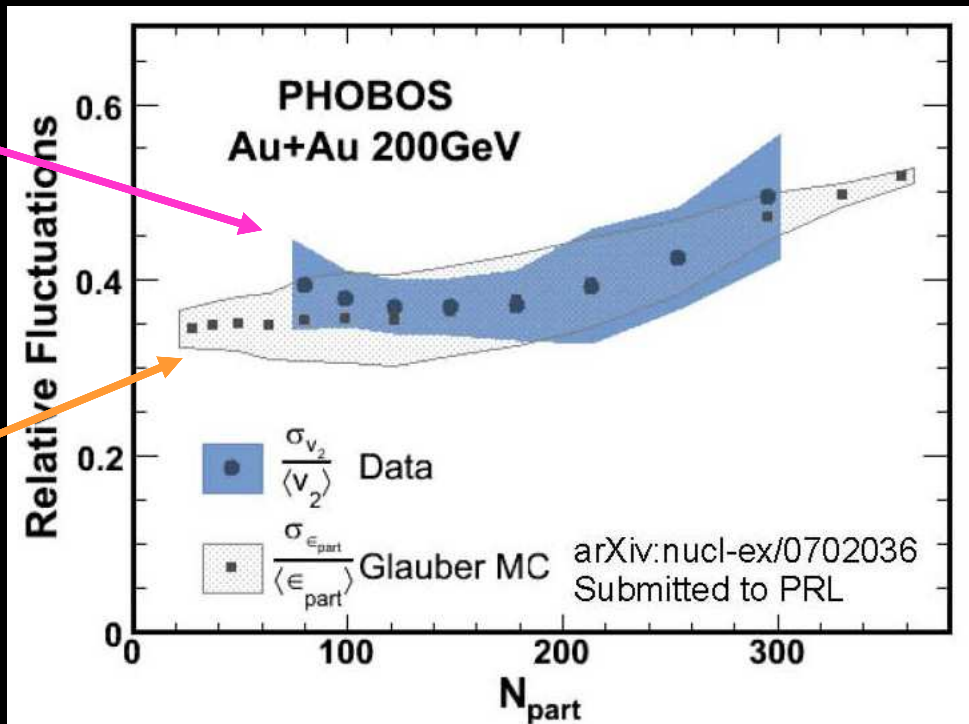


$\langle v_2 \rangle$ measured event-by-event is in agreement with both hit and track based PHOBOS results.

New Result: v_2 and ε_{part} Fluctuations

PHOBOS v_2 result

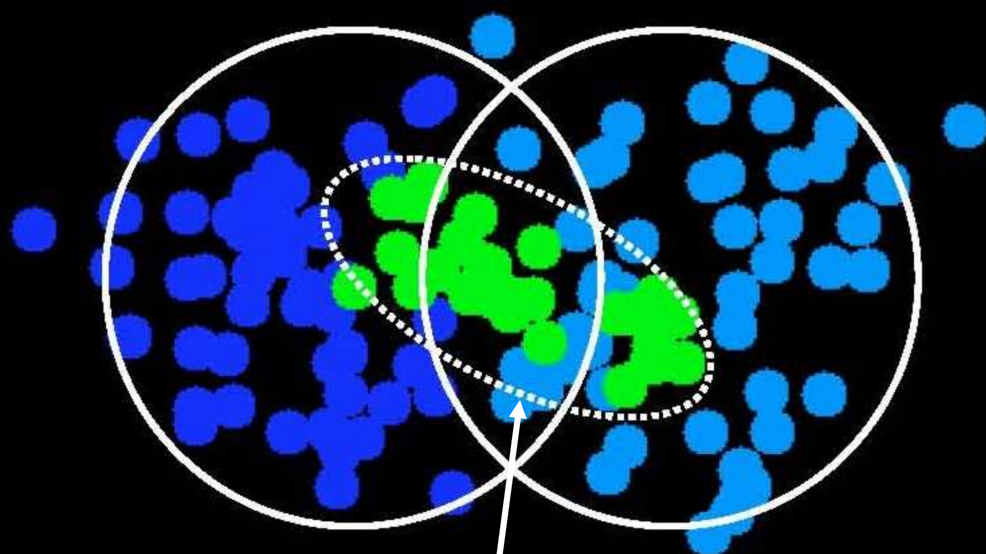
PHOBOS ε_{part} prediction



Magnitude of v_2 fluctuations is in agreement with ε_{part} fluctuations

To Summarize…

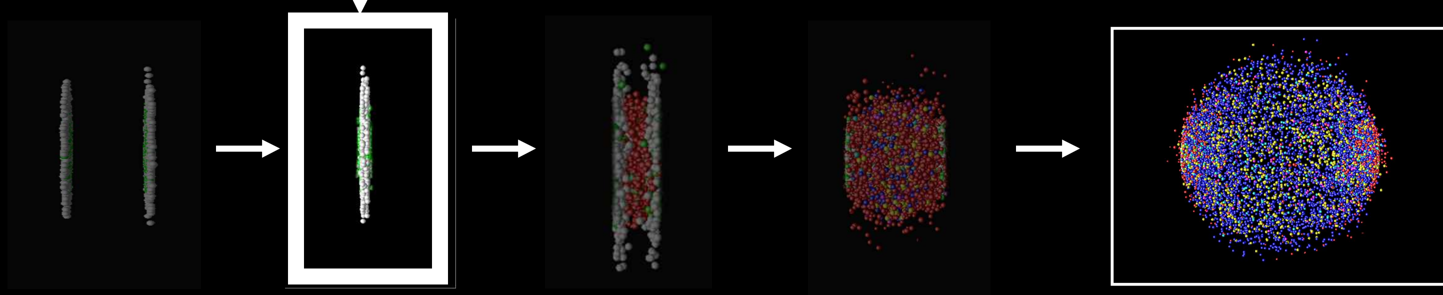
Flow fluctuations measurement appears to directly confirm the relevance of the initial participant nucleon configuration.



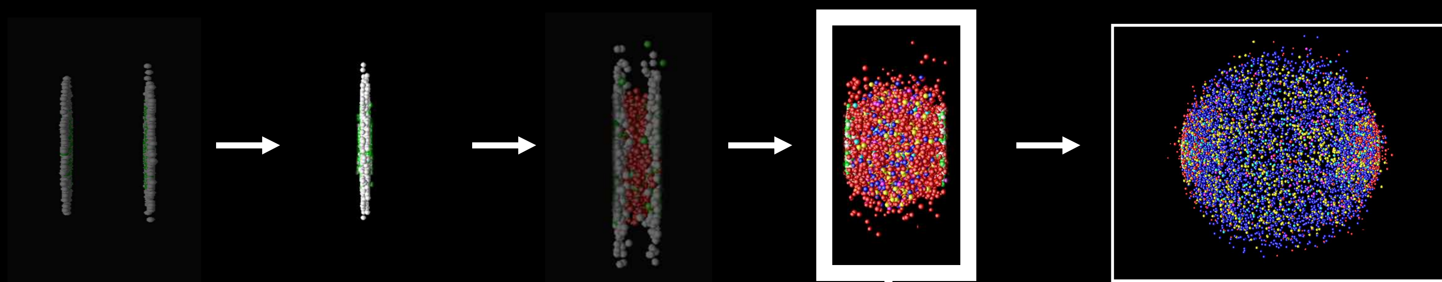
It is believed this initial configuration determines the detailed relevant geometry of the initial quark gluon plasma – which then evolves hydrodynamically.

What we learned

Initial participating nucleon interaction points act to define the detailed initial geometry.



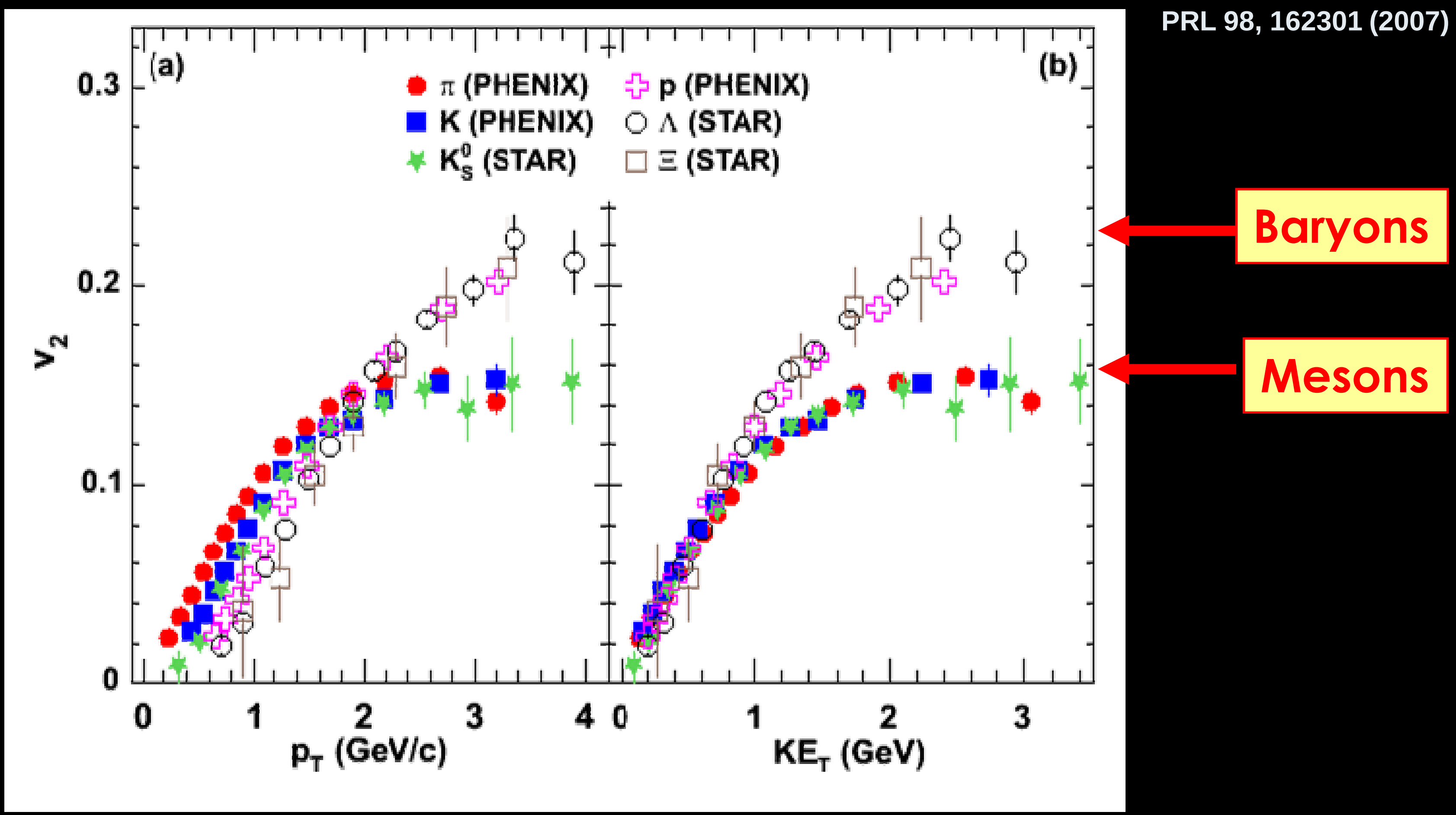
Of course, this one is our actual measurement



What about the state of matter undergoing "hydrodynamic" behavior?
What is the thermalized hot "plasma" made of?

What is the thermalized medium made of?

Look at v_2 in more detail.

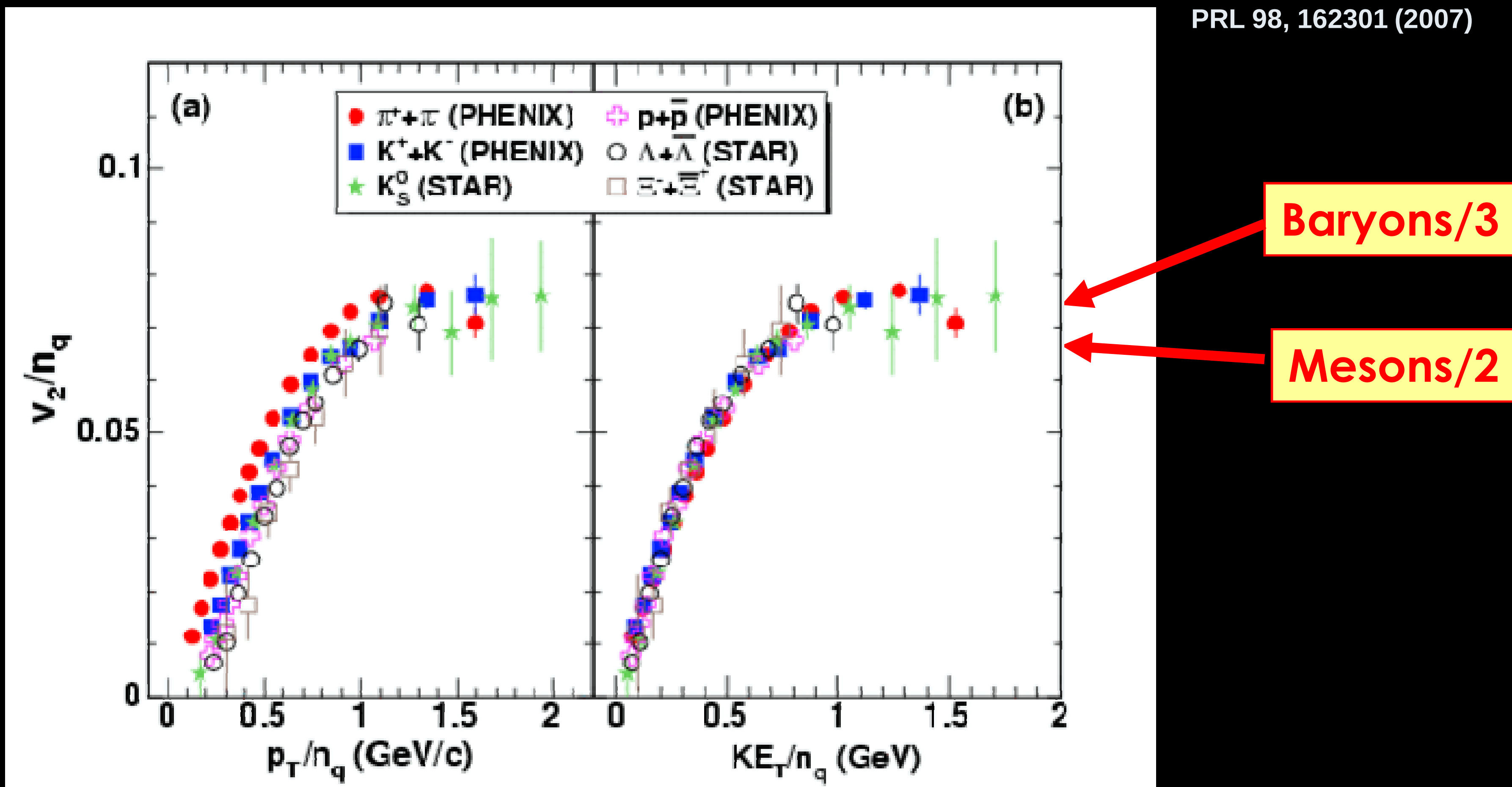


We again turn to elliptic flow (v_2) measurements.
Look in detail at the different mass and energy dependencies.

What is the thermalized medium made of?

Look at v_2 in more detail.

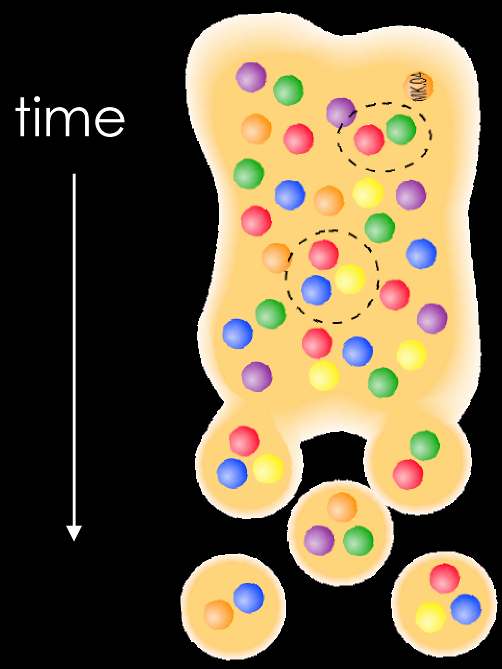
PRL 98, 162301 (2007)



Elliptic flow is "unified" across species when results divided by number of constituent quarks! Are these the relevant degrees of freedom?

A Possible Scenario

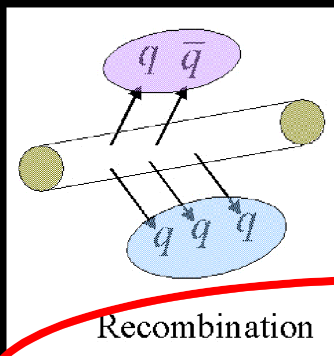
Start with a thermalized "liquid" QGP with quark degrees of freedom

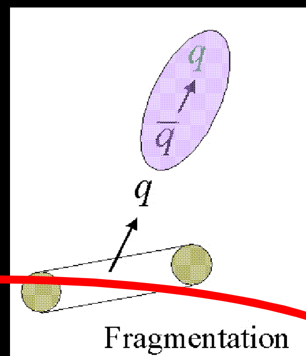


At particle "freeze out" these quarks recombine to form hadrons directly out of the QGP

Recombination vs. Fragmentation

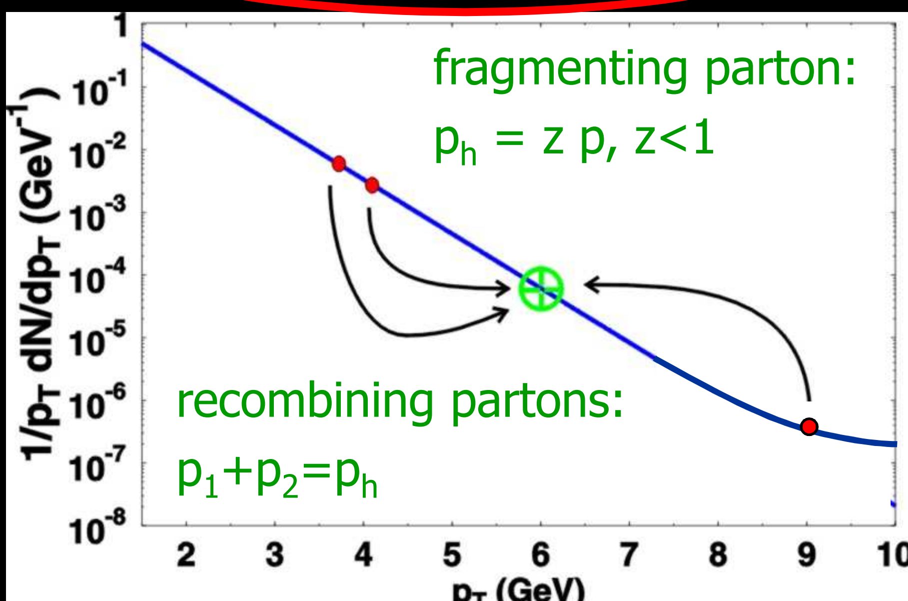
Figs from B. Muller: nucl-th/0404015, R. Fries: QM 2004, PRL 90 202303 (2003)



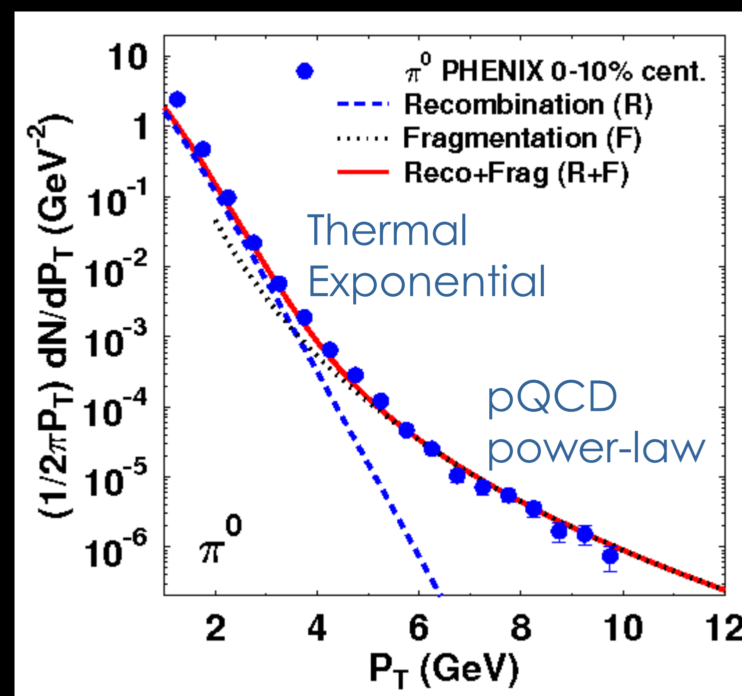


Should have a strong effect on Baryon to Meson ratios

THE IDEA

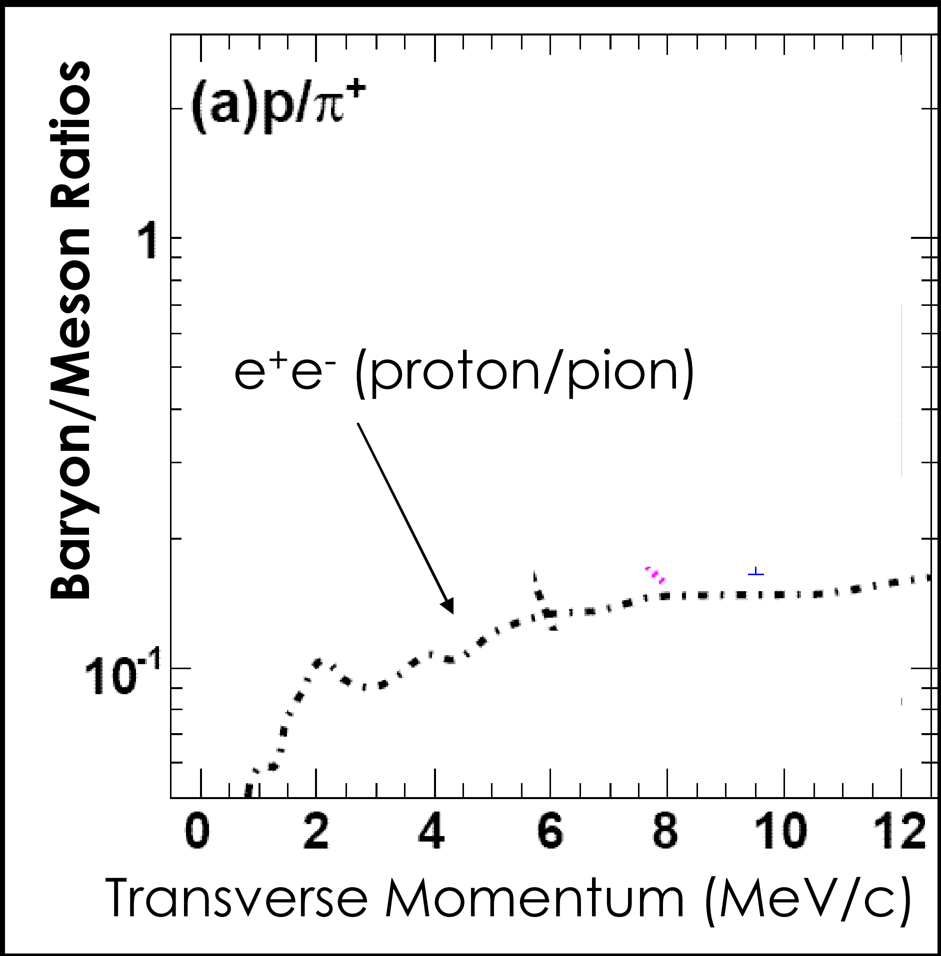


DATA and FITS

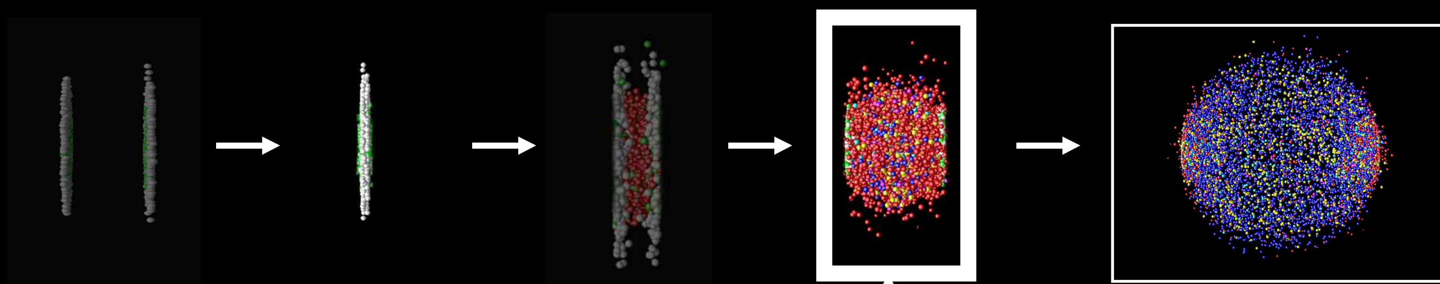


Quark Recombination (or Coalescence)

STAR; nucl-ex/0606003



→ Experiment sees ratios ~ 1 at lower p_T for central AuAu!



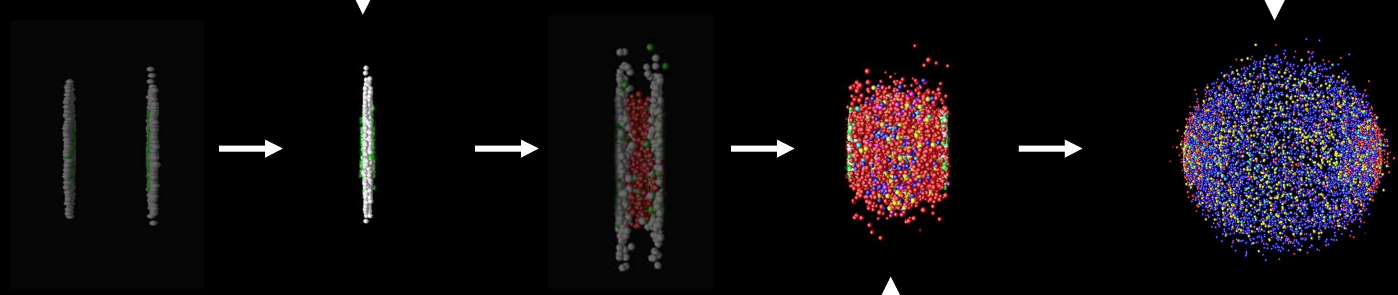
What we learned

Strong evidence that constituent quarks are relevant Degrees of Freedom and they recombine to form hadrons (at least at low momentum).

Found Relevant Degrees of Freedom…

Participating nucleon interaction points

Clusters
(can ask about if want)



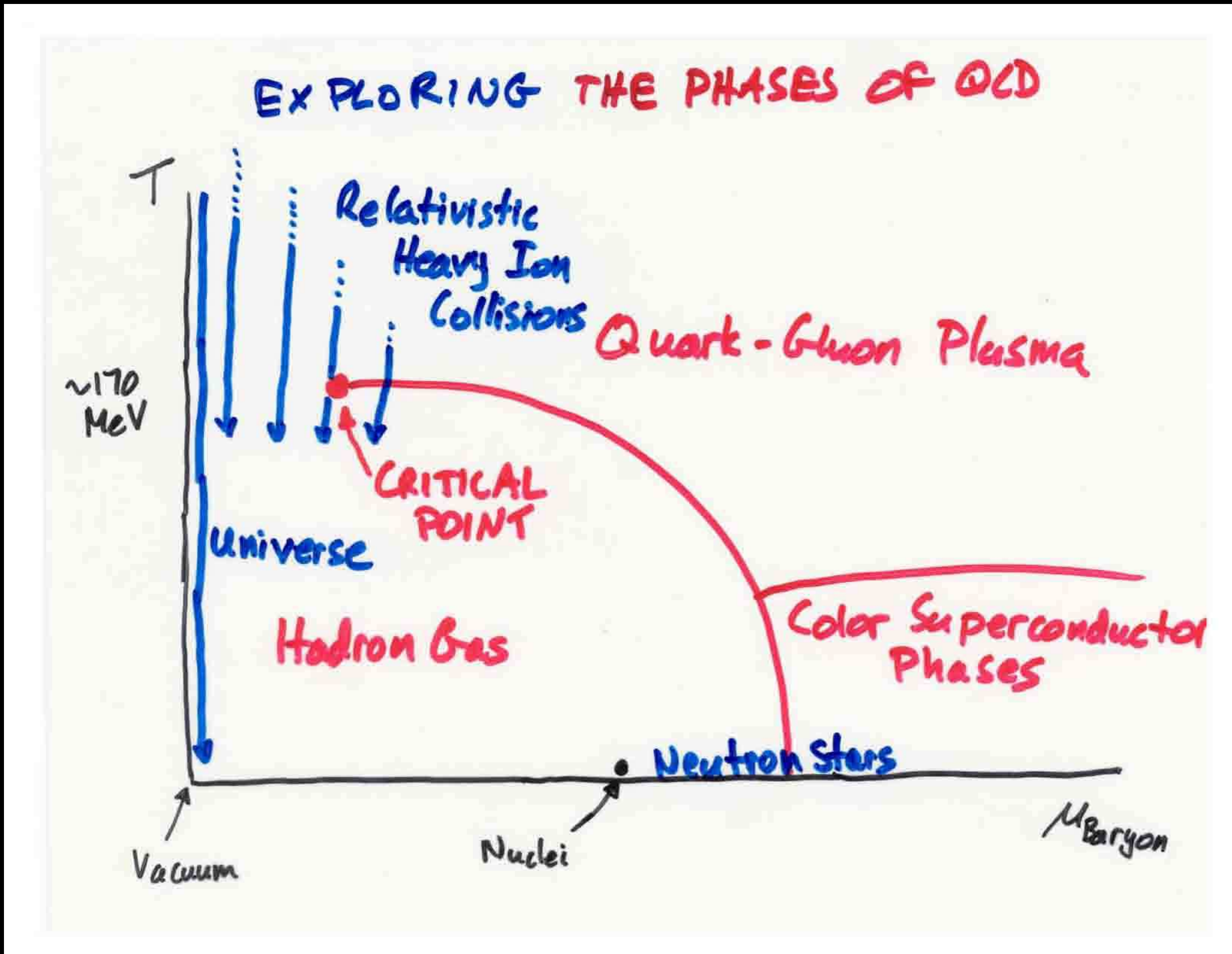
Constituent quarks

The Future

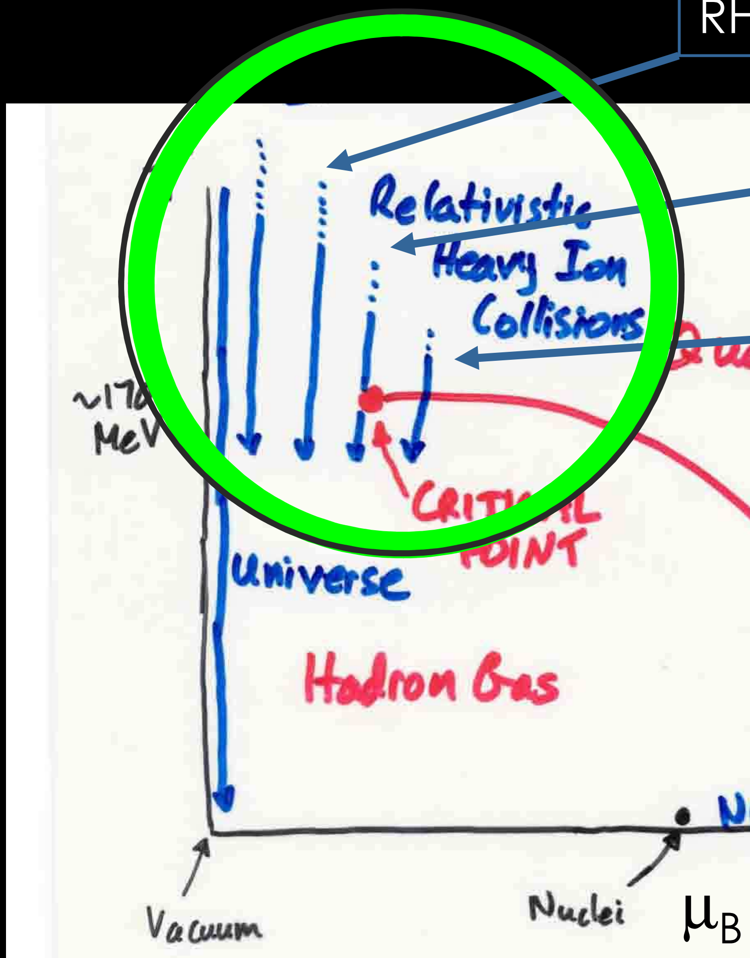
The Future of Heavy Ion Physics

(in a phase diagram)

K. Rajagopal, MIT – BNL Workshop 2006



The Future of Heavy Ion Physics



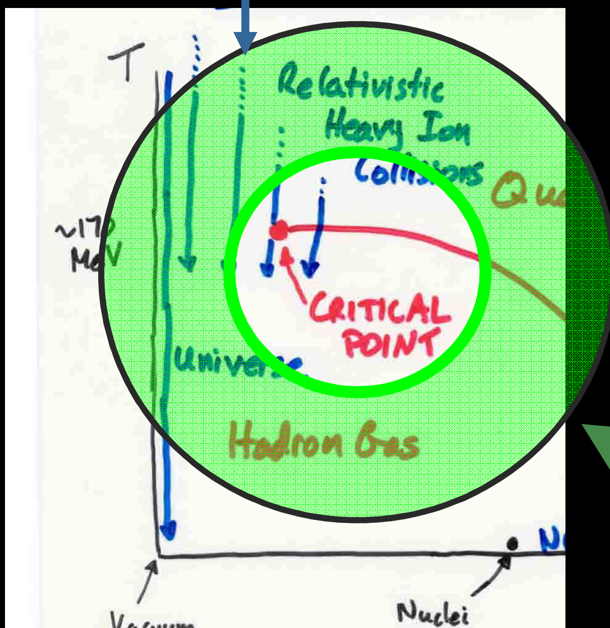
RHIC (μ_B = 30-40 MeV , $\sqrt{s_{NN}}$~ 130-200 GeV)

SPS (μ_B = 255-400 MeV , $\sqrt{s_{NN}}$~ 9-18 GeV)

AGS (μ_B = 540 MeV , $\sqrt{s_{NN}}$~ 4 GeV)

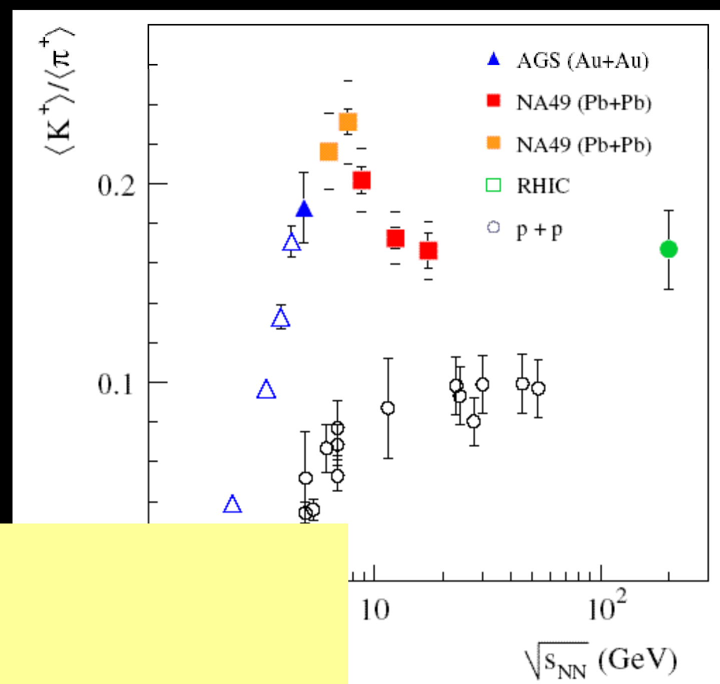
The Future I: Search for the Critical Point

RHIC → LOWER ENERGY



Possible connections with dramatic non-monotonic behavior seen at the lower-energy CERN-SPS experiments.

M. Gazdzicki- NA49 – QM 2004



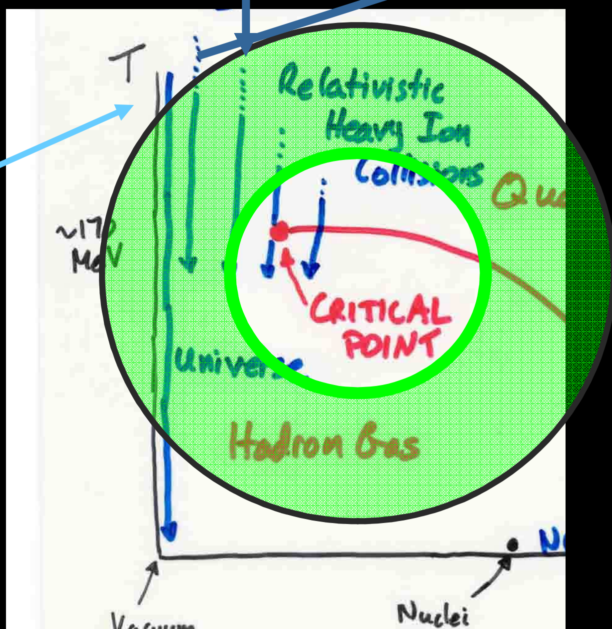
EXPLORE FURTHER WITH:
→ Low-energy Running at RHIC
→ New Accelerator: FAIR @ GSI, Darmstadt

The Future II: Heavy-Ions at the LHC

HIGHER ENERGY ← **RHIC**

LHC (μ_B =??, $\sqrt{s_{NN}}$= 5.5 TeV)

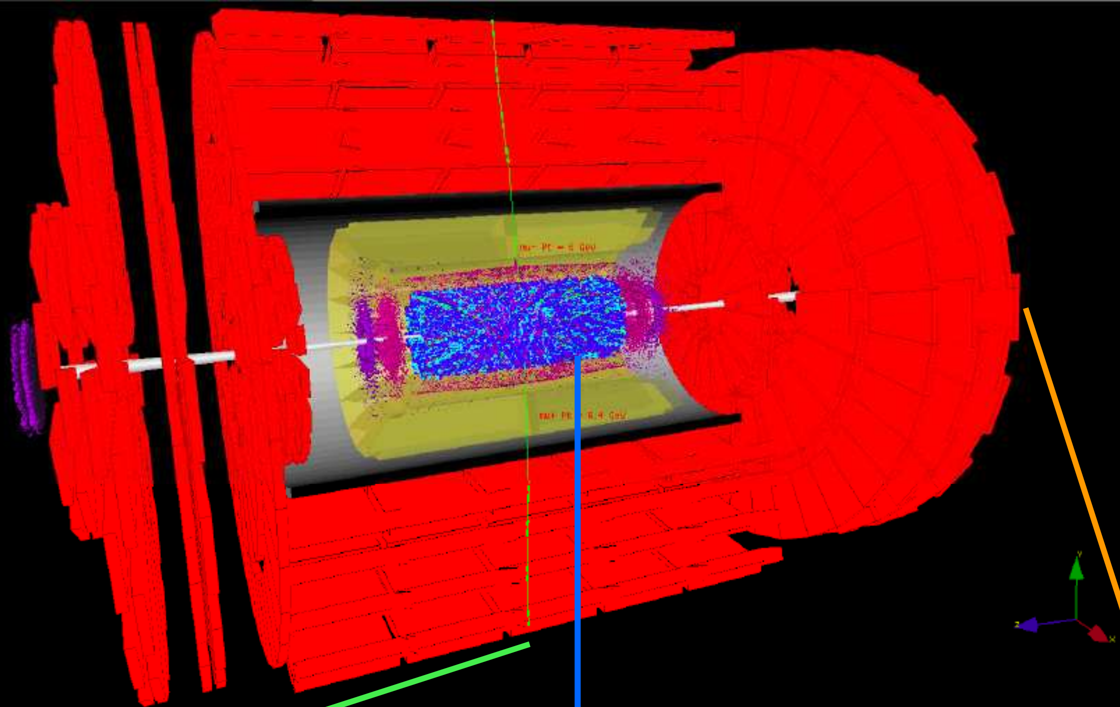
Closer to our universe path.



EXPLORE FOR FIRST TIME WITH:
→ Heavy-Ion Running at the LHC

Heavy Ions in CMS

Pb+Pb event ($dN/dy|_{y=0}$ = 3500) with $\Upsilon \rightarrow \mu^+\mu^-$



World-class capabilities in hard probes.

Complementary (& surprising) abilities for soft physics and global observables.

Unique opportunities and capabilities in forward region.

+

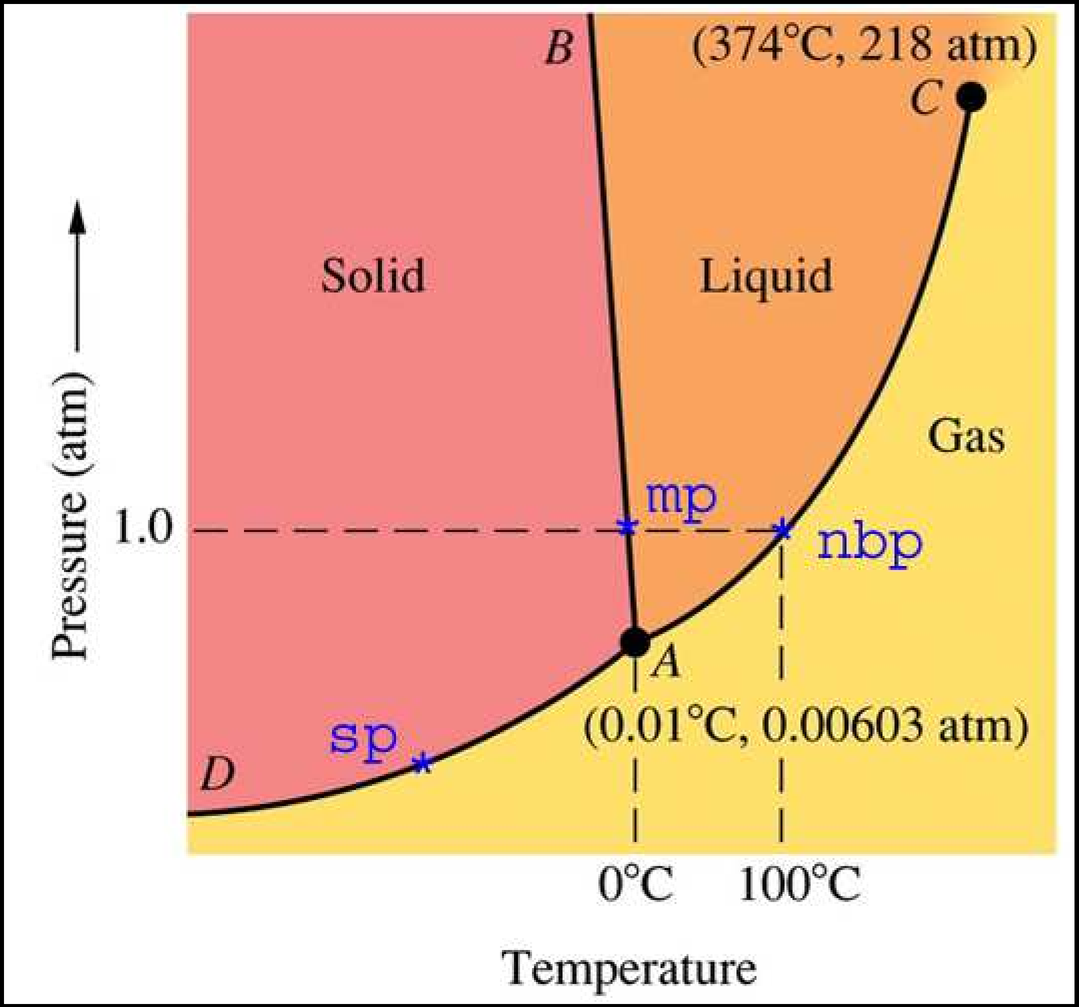
Sophisticated high-rate triggering to exploit and maximize physics output.

Final Thoughts

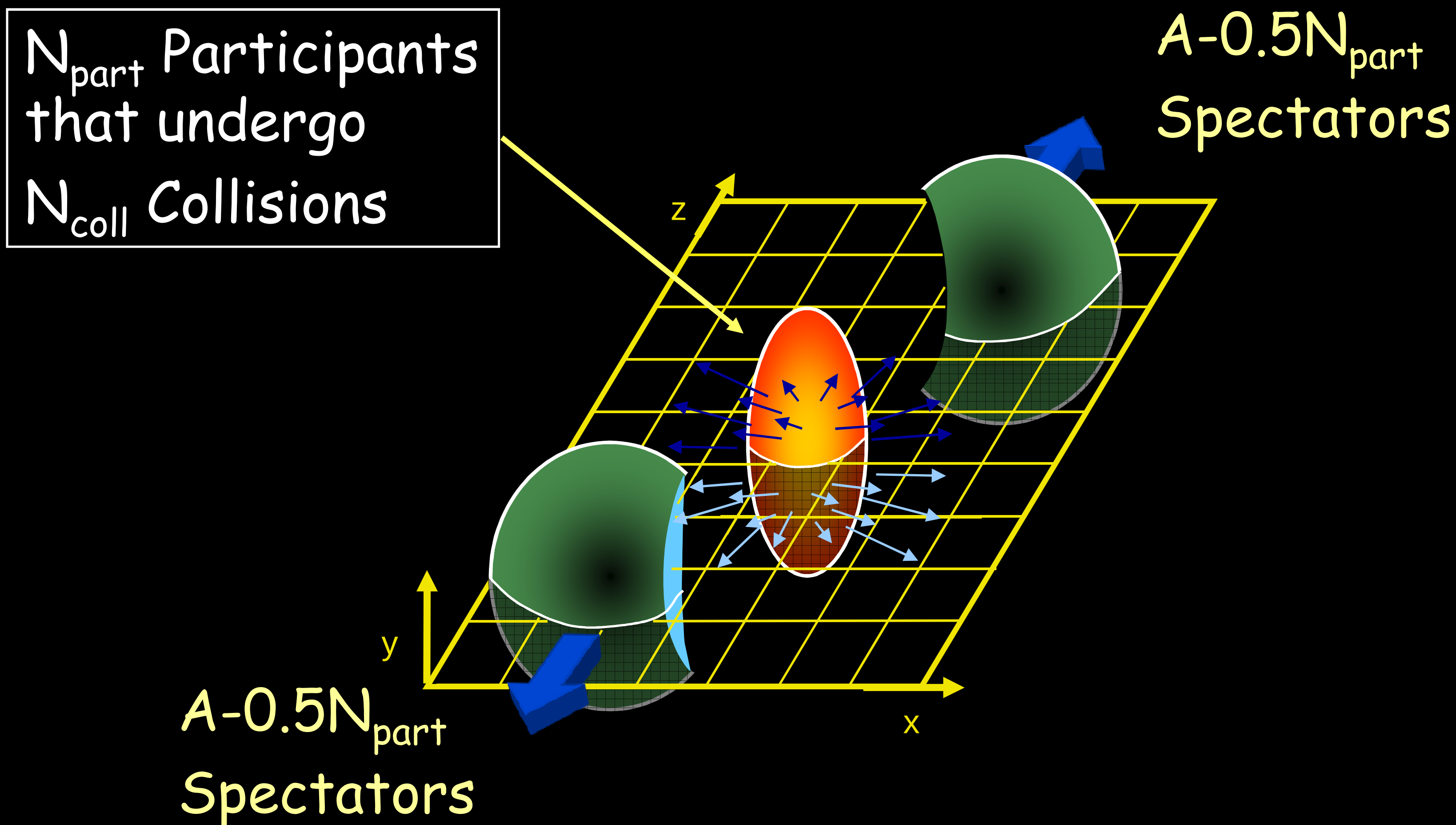
- In the brief moment of a relativistic heavy-ion collision, we have created a new state of matter.
  - We believe: At RHIC (& likely the SPS) → sQGP
  - We wonder: What will the LHC reveal?
- Work continues to understand exactly what the new state of matter is, quantify its properties, and discover what it will teach us about the strong interaction and QCD.
- **Thanks for inviting me!**

backups

Phase Diagrams… (start with water)

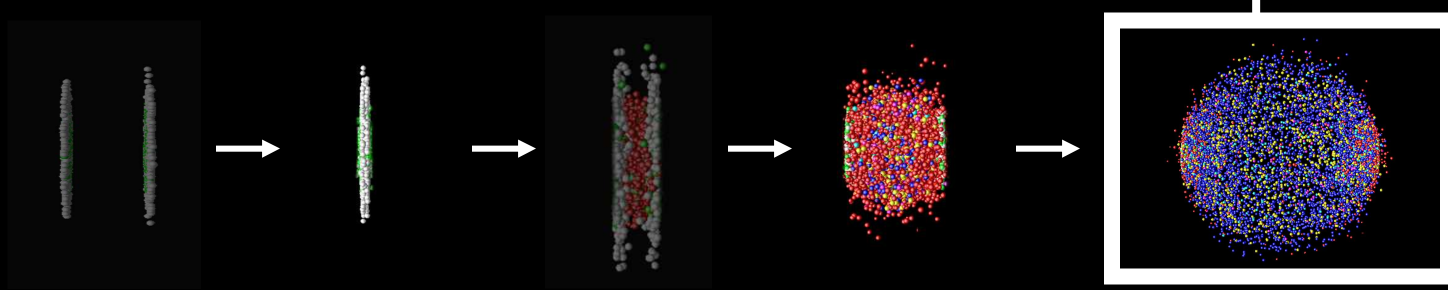


Important Features of a Heavy Ion Collision



→ Detailed Collision Geometry of Heavy Ion Collisions is extremely important!

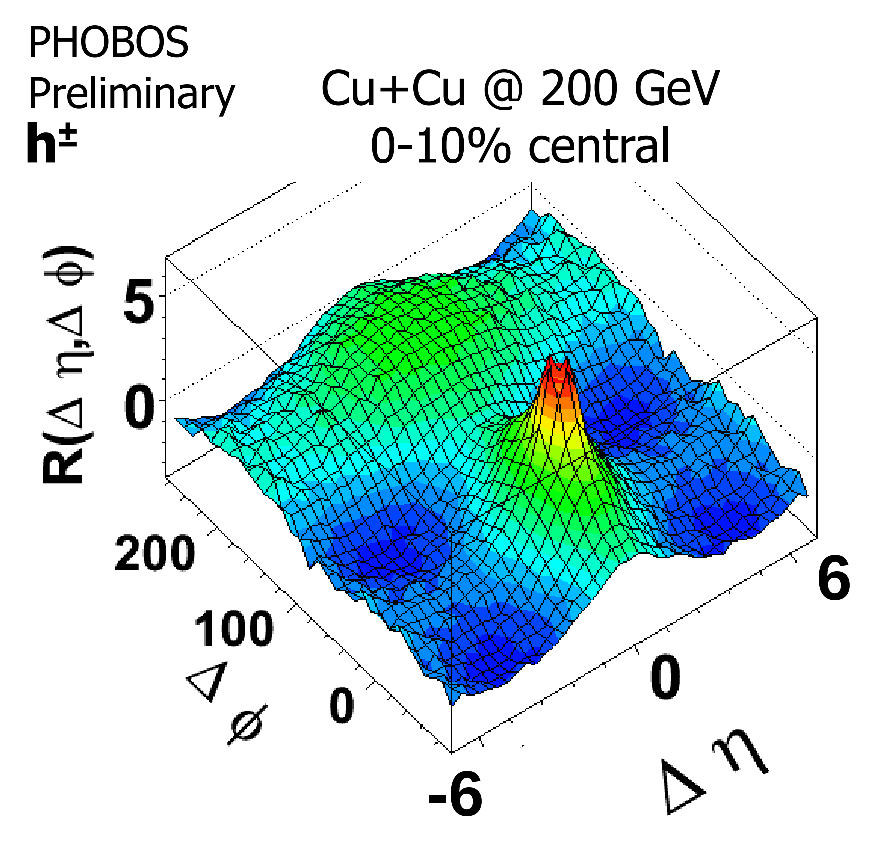
How are particles emitted when they "freeze out"?

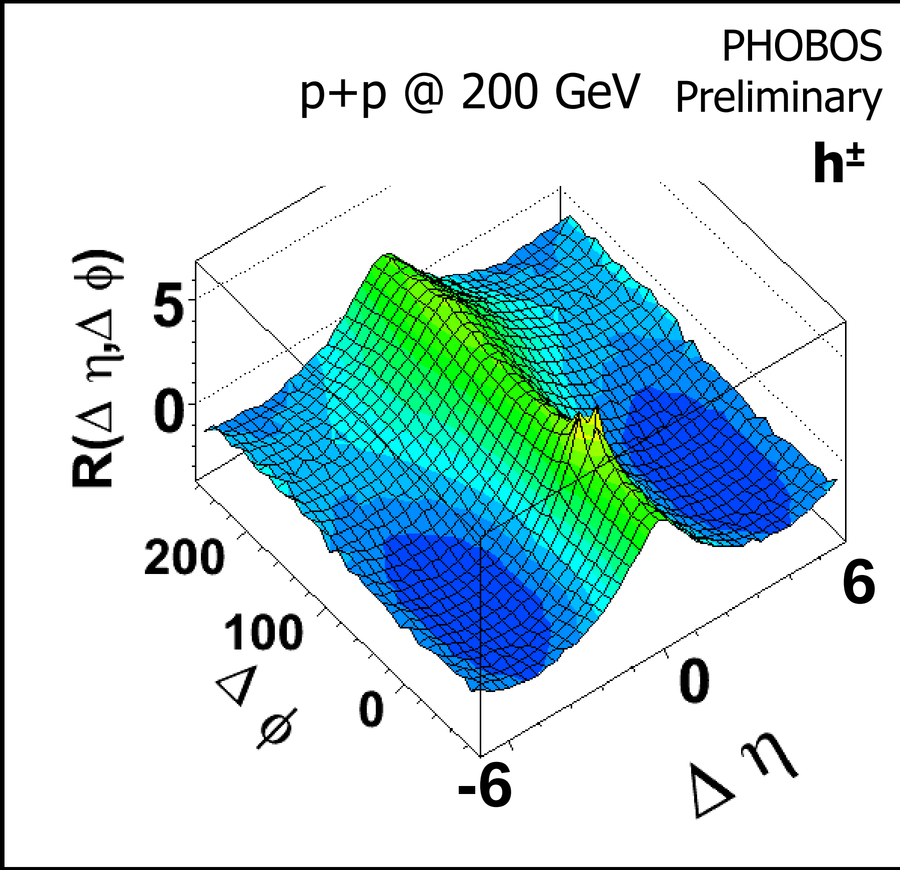


New Analysis: two particle correlations

$$R(\Delta\eta,\Delta\phi) = <(n-1)\left(\frac{F_n(\Delta\eta,\Delta\phi)}{B_n(\Delta\eta,\Delta\phi)}-1\right)>$$

Analysis of: W. Li





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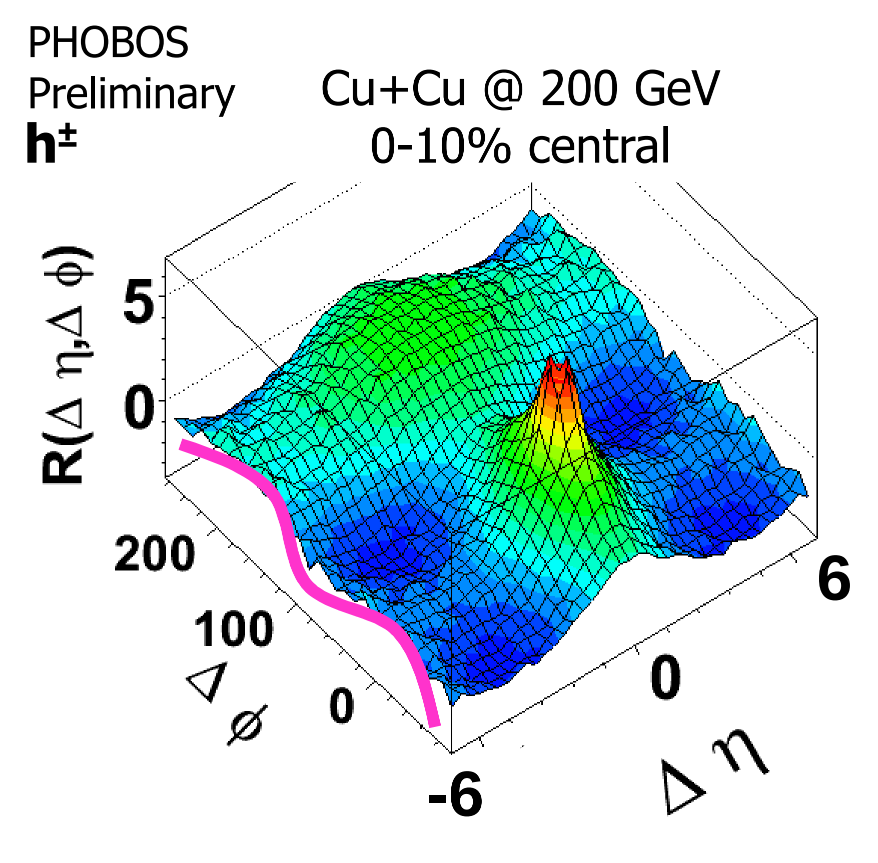

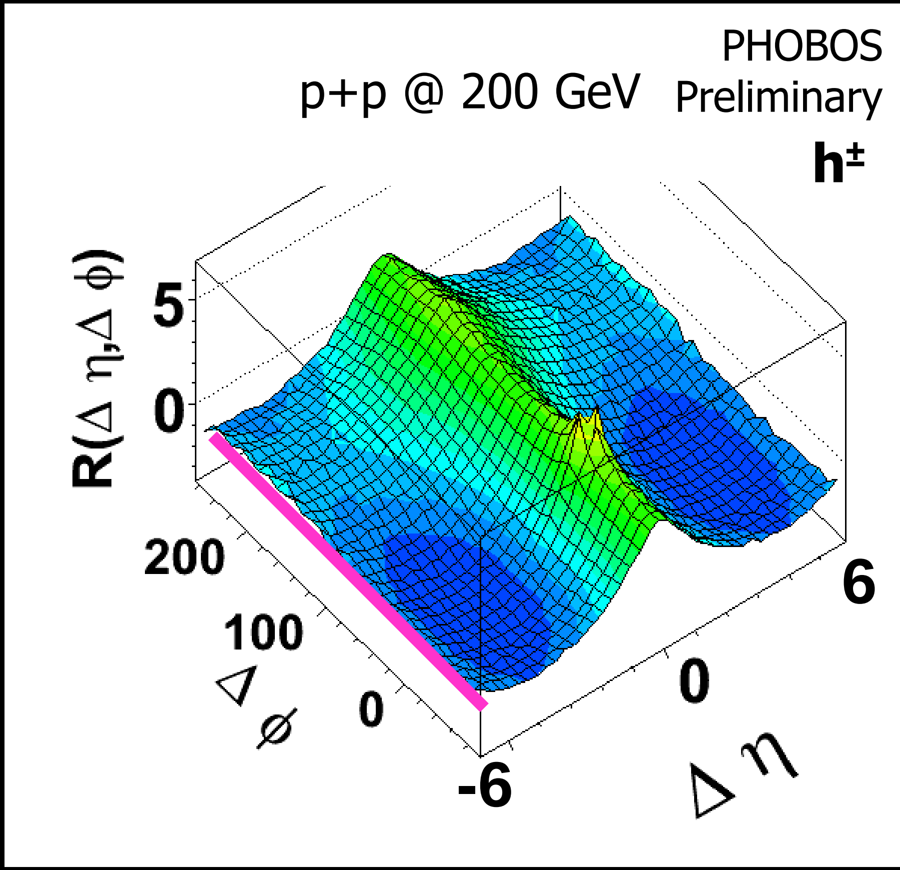

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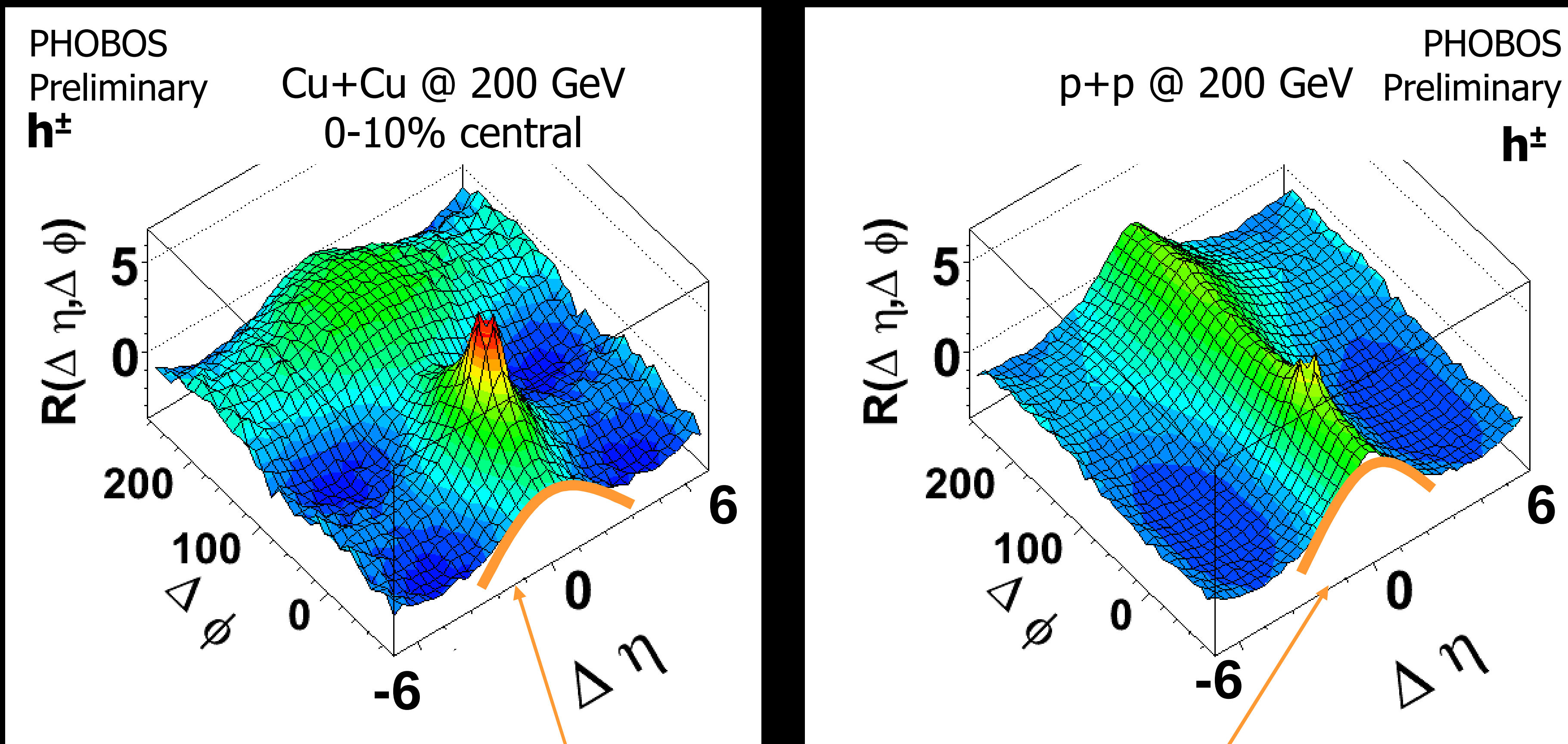
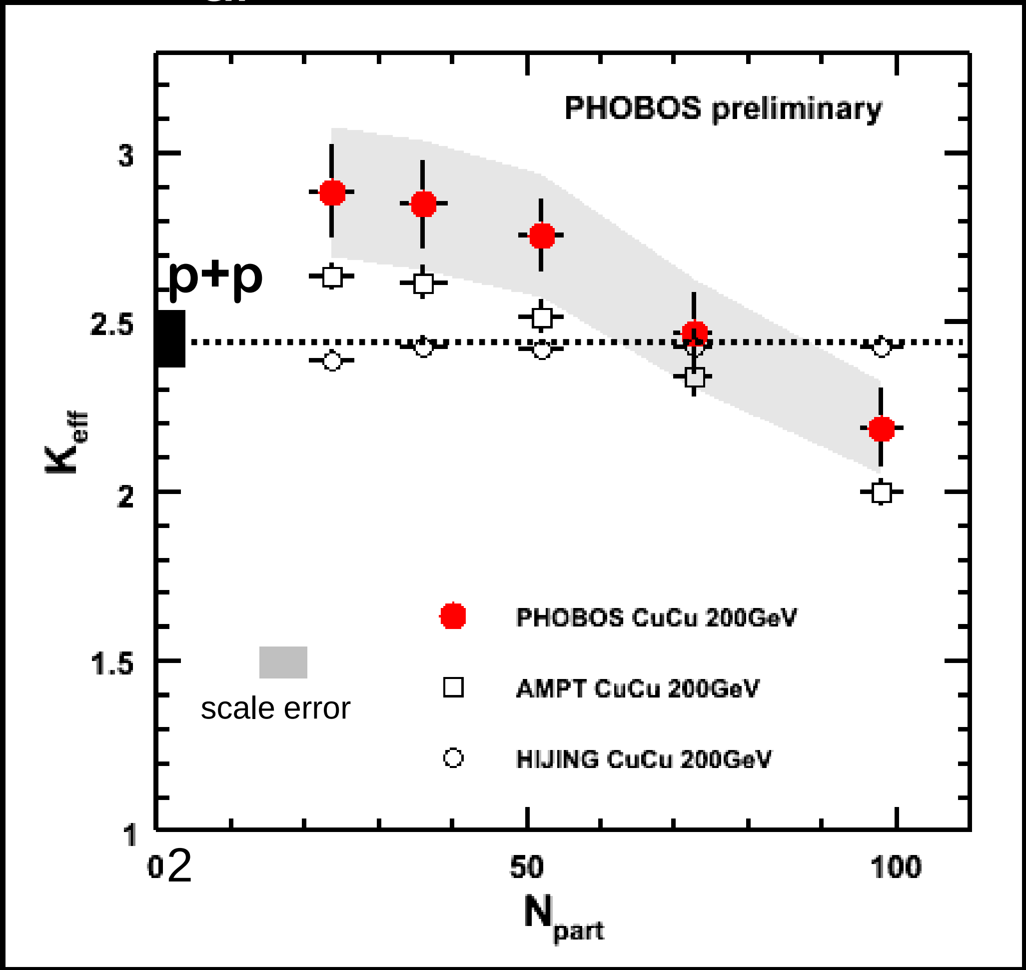
Analysis of: W. Li



Study the short-range rapidity correlations

New Result: effective cluster size

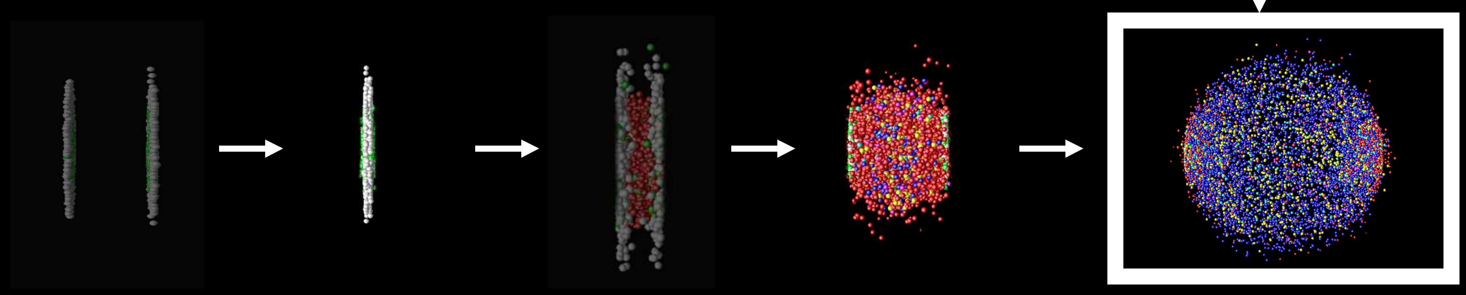
K_{eff} = effective cluster size



On average, particles tend to be produced in clusters with a size of 2-3.
Interesting centrality dependence for heavy-ions…

What we learned

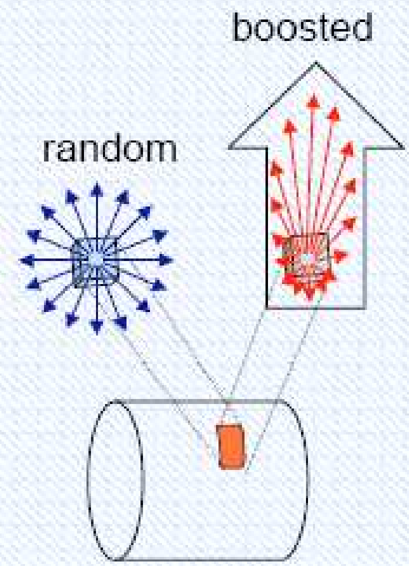
Particles are emitted as clusters (or resonances) which decay.



Blast-wave expansion model

Combining hydrodynamic expansion and thermal emission to fit particle spectra.

E.Schnedermann, J.Sollfrank, and U.Heinz, Phys. Rev. **C48**, 2462(1993)



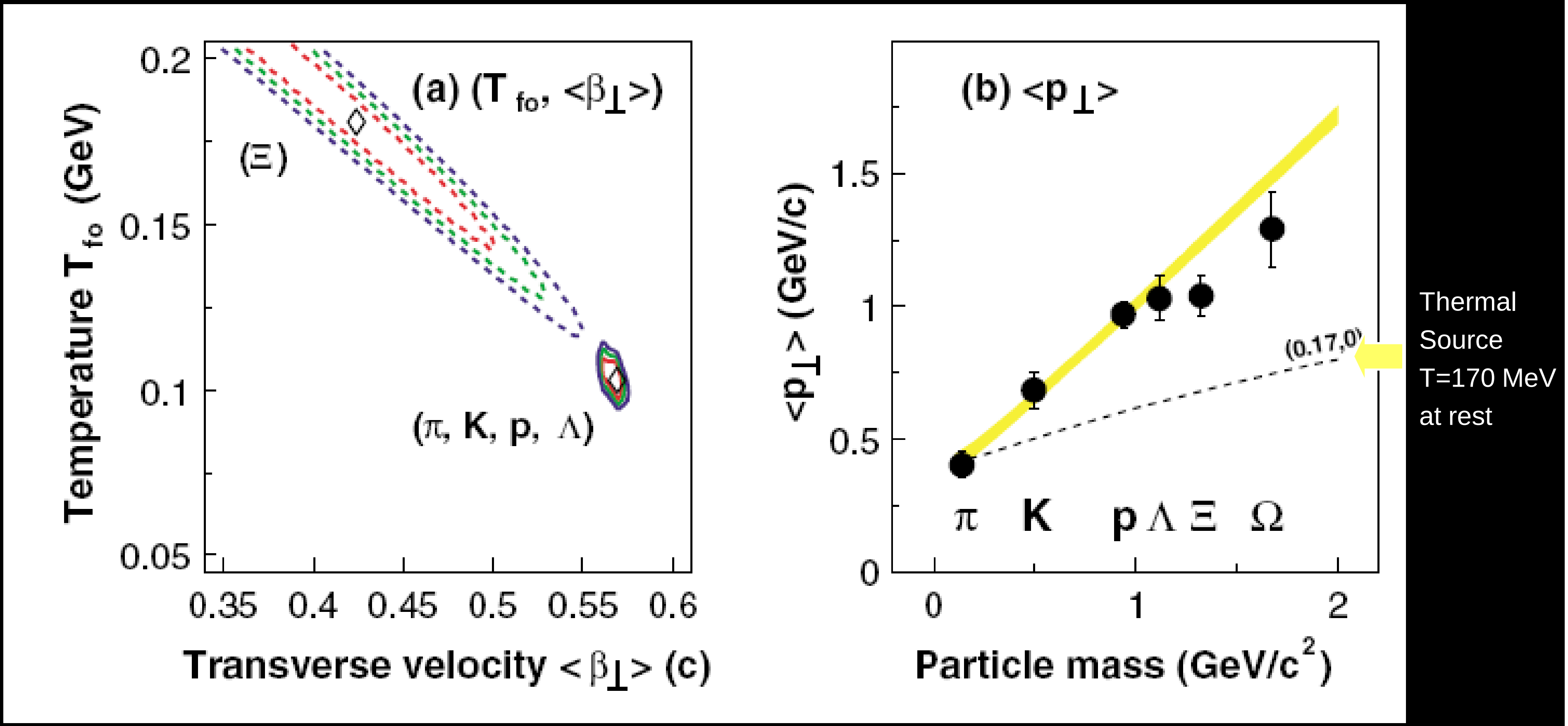
$$E\frac{d^3N}{dp^3} \propto \int_\sigma e^{-(u^\mu p_\mu)/T_{fo}} p\, d\sigma_\mu \Rightarrow$$

$$\frac{dN}{m_T dm_T} \propto \int_0^R r\,dr\, m_T K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)$$

$$\rho = \tanh^{-1}\beta_T \qquad \beta_T = \beta_S\left(\frac{r}{R}\right)^\alpha \qquad \alpha = 0.5,\ 1,\ 2$$

Extract thermal temperature T_{fo} and velocity parameter $\langle\beta_T\rangle$

200 GeV Au+Au



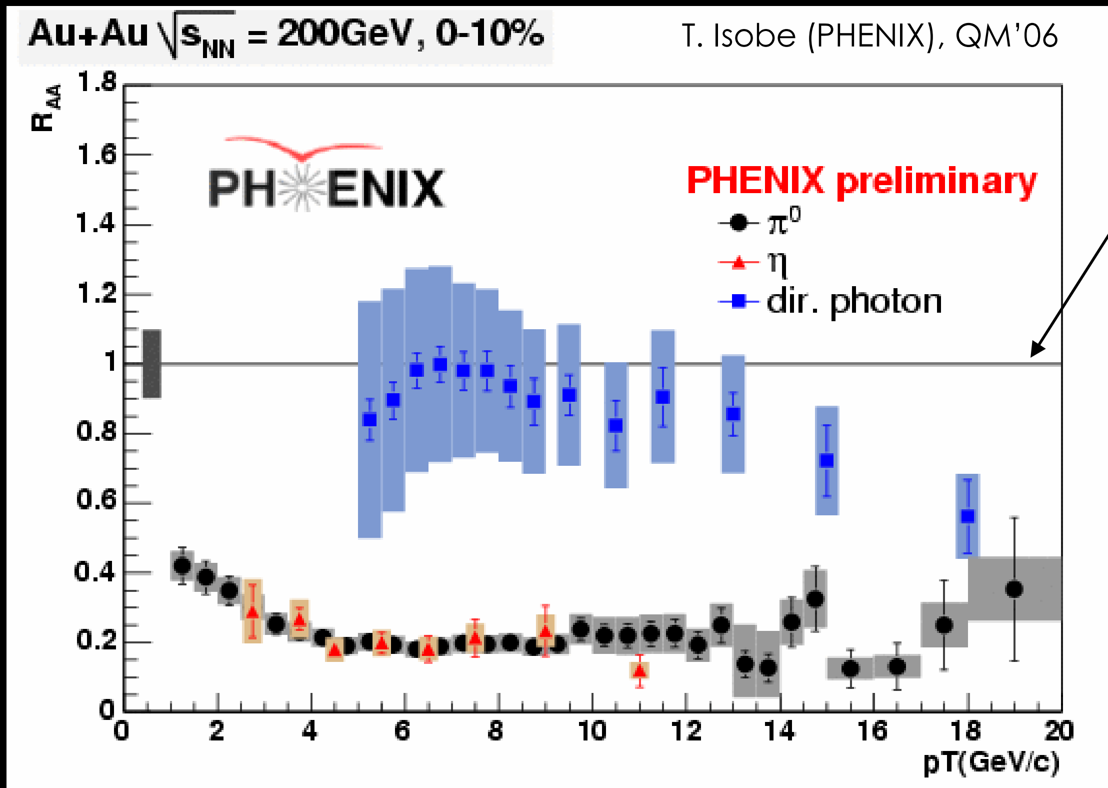
STAR, Phys. Rev. Lett. 92, 182301 (2004)

π, K, p,Λ: Kinetic freeze-out at T_{kin}~100 MeV, $<\beta_T>$=0.56

Direct photons to check $\langle N_{binary} \rangle$ scaling

$$R_{AA} = \frac{\text{Yield}_{AuAu}}{\langle N_{binary} \rangle_{AuAu} \text{Yield}_{pp}}$$

PHOTONS do not interact via the strong force and thus the created medium should be transparent to them.

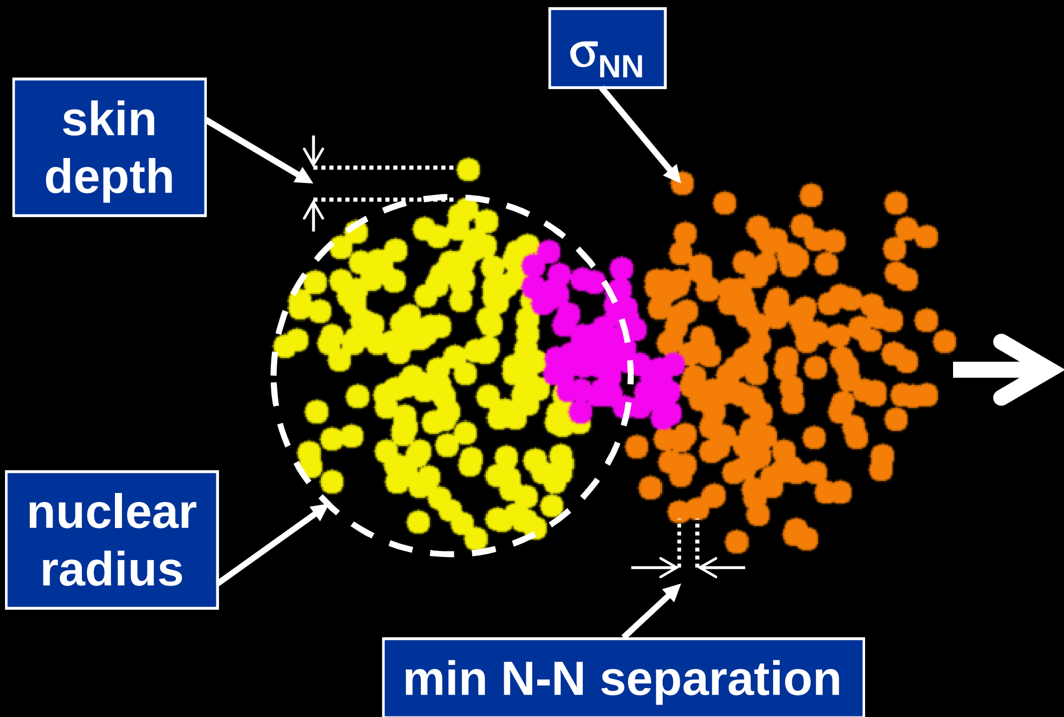


Binary collision expectation

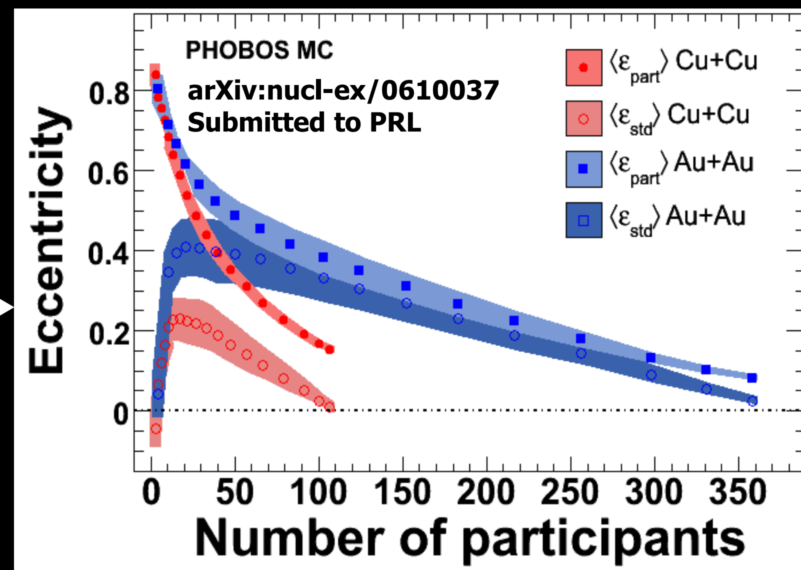
→ The effect does not appear to be an artifact of normalization.

How robust is Glauber MC + $\langle \epsilon_{\mathrm{part}} \rangle$ calculation?

Studied variations in:



90% CL bands on calculation



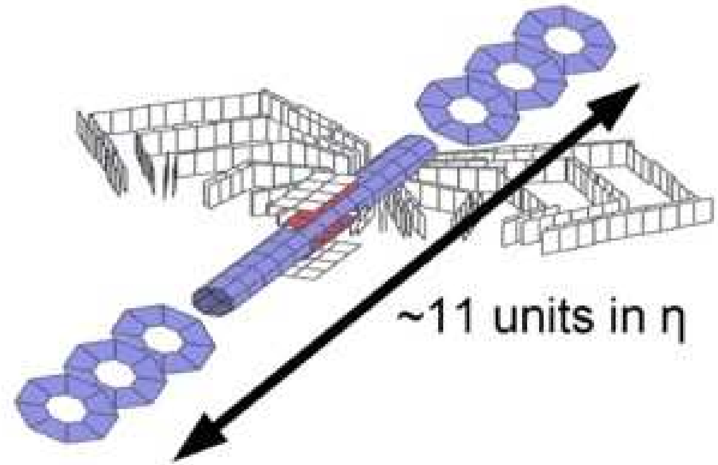
In collaboration with Ulrich Heinz

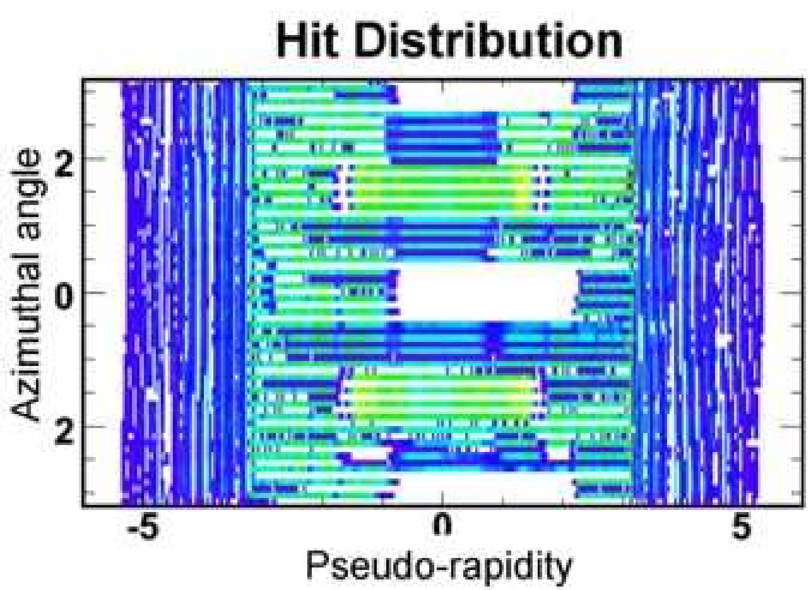
More recent studies have included variations in individual nucleon density profiles and different N_{part} and N_{coll} weighting.

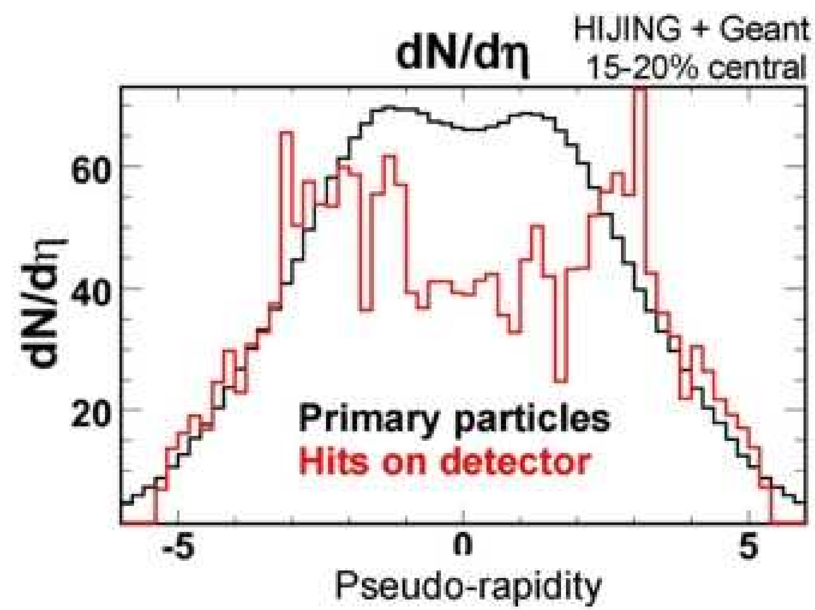
$\langle \epsilon_{\mathrm{part}} \rangle$ calculation from Glauber MC is robust

Event-by-event measurement of v_2^{obs}

- PHOBOS Multiplicity Array
  - $-5.4<\eta<5.4$ coverage
  - Holes and granularity differences
- Usage of all available information in event to determine event-by-event a single value for v_2^{obs}

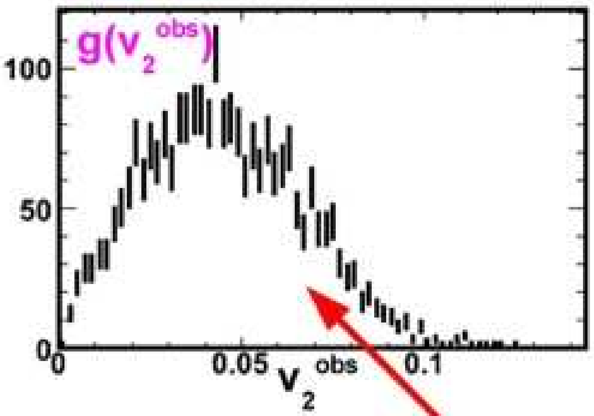




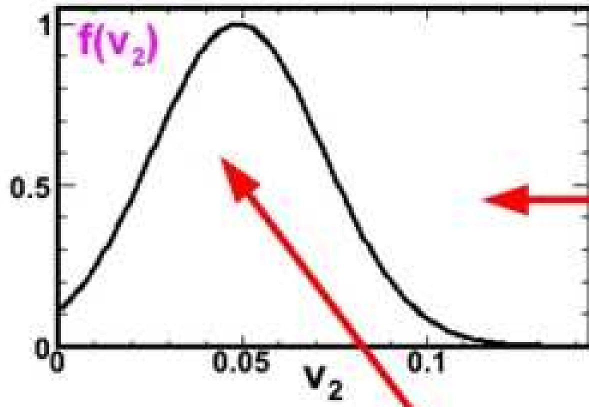


Measuring elliptic flow fluctuations

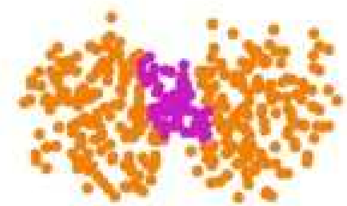
Observed v_2 distribution



True v_2 distribution

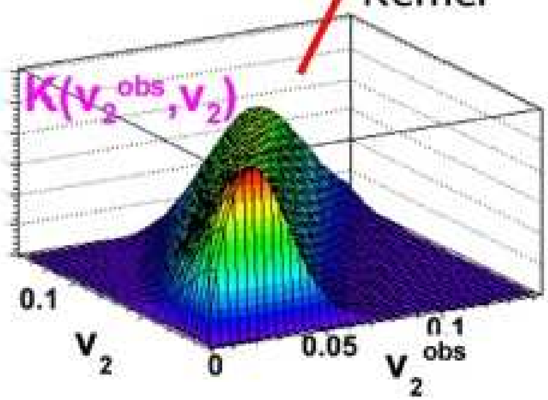


Source of v_2 fluctuation



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

Kernel



Detector response

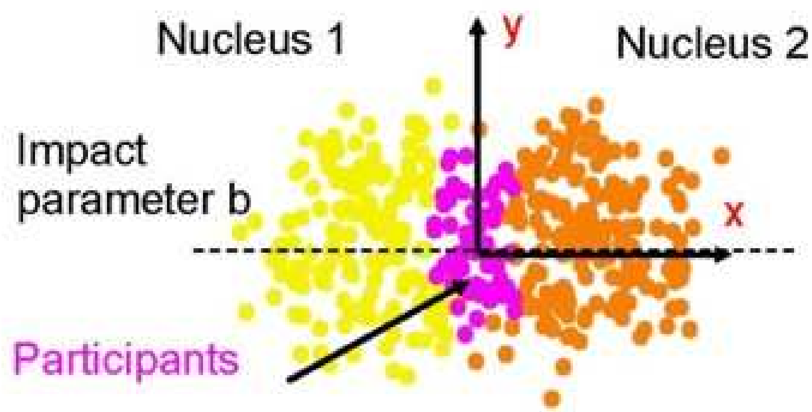
Kernel

- Detector and acceptance effects
- Finite-number fluctuations
- Multiplicity fluctuations

Glauber MC

- Glauber Monte Carlo
  - Radial distribution of nucleons (in nucleus) drawn from Wood-Saxon distribution
  - Isotropic angular distribution
  - Separate by impact parameter
  - Nucleons travel on straight-line paths and interact inelastically when

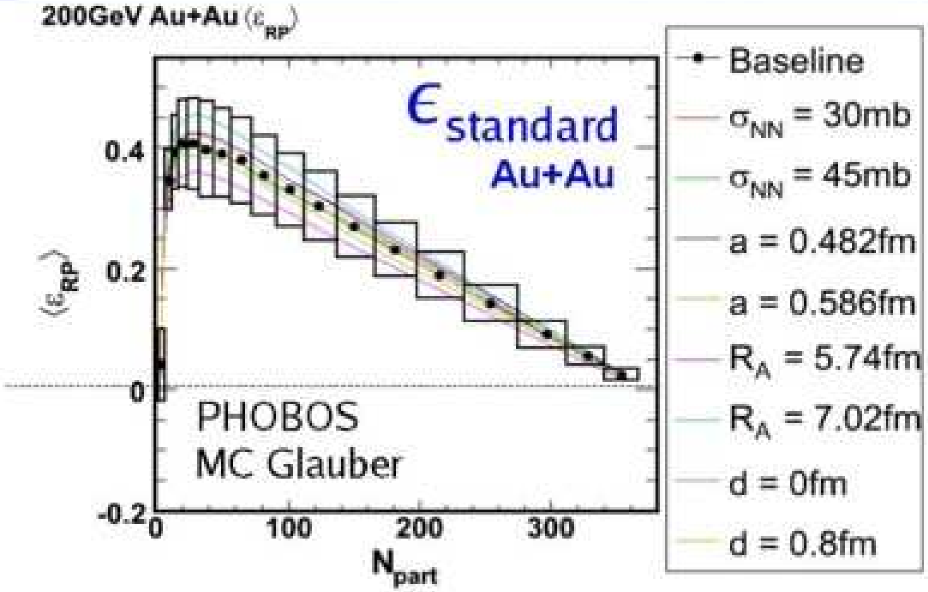
$$d=\sqrt{(x_1-x_2)^2+(y_1-y_2)^2}<\sqrt{\sigma_{NN}/\pi}$$

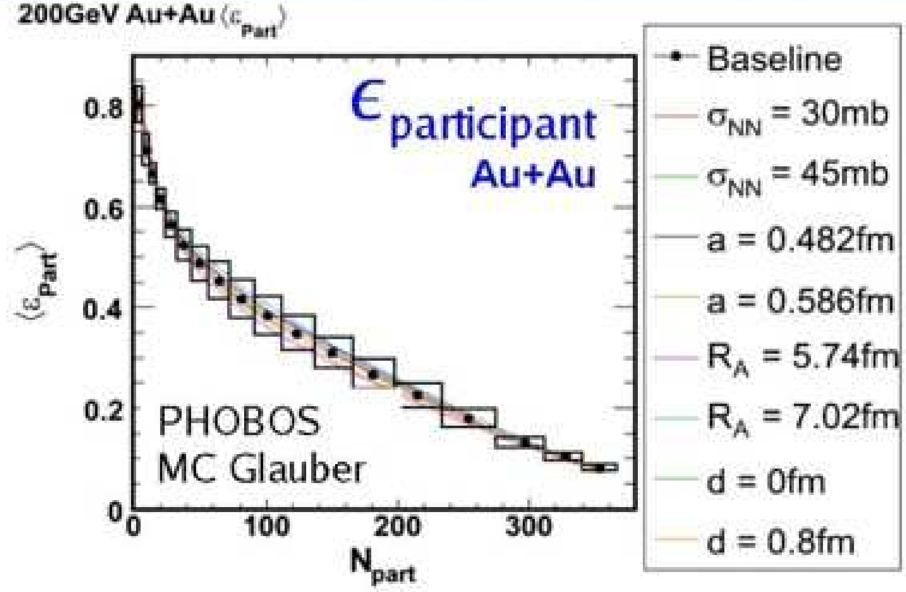


- Centrality of collision
  - #Participants
    - Nucleons that interact at least once
  - Related to cross section and impact parameter range
- Eccentricity of collision zone
  - Given by participants position distributions

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

Robustness with geometry variables





- Variation of
  - Nucleon-nucleon cross section (30-45mb)
  - Nuclear radius (±10% from the nominal value)
  - Skin depth (0.482-0.586fm)
  - Minimum separation distance between nucleons (d=0-0.8fm)

$$\rho(r) = \frac{\rho_0}{1+\exp((r-R)/a)}$$

$\epsilon_{\text{participant}}$ even slightly more robust than $\epsilon_{\text{standard}}$

Methodology of 2-particle correlations measurement

Two-particle correlation function:

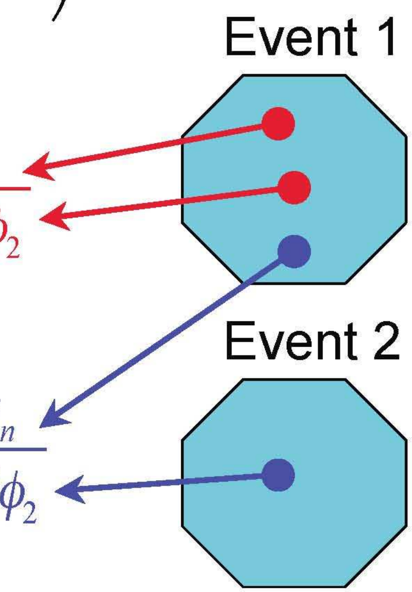
$$R(\Delta\eta,\Delta\phi) = < (n-1)\left(\frac{F_n(\Delta\eta,\Delta\phi)}{B_n(\Delta\eta,\Delta\phi)} - 1\right) >$$

Foreground:

$$F_n(\Delta\eta,\Delta\phi) \sim \rho_n^{II}(\eta_1,\eta_2,\phi_1,\phi_2) = \frac{1}{n(n-1)\sigma_n}\frac{d^4\sigma_n}{d\eta_1 d\eta_2 d\phi_1 d\phi_2}$$

Background:

$$B_n(\Delta\eta,\Delta\phi) \sim \rho_n^{I}(\eta_1,\phi_1)\rho_n^{I}(\eta_2,\phi_2) = \frac{1}{n\sigma_n}\frac{d^2\sigma_n}{d\eta_1 d\phi_1} \bullet \frac{1}{n\sigma_n}\frac{d^2\sigma_n}{d\eta_2 d\phi_2}$$



Parameterize cluster size (multiplicity)

Quantitatively understand cluster phenomena

correlations between particles from one cluster

Two-particle rapidity correlation function:

$$\Gamma(\Delta\eta) \propto \exp\left(-\frac{(\Delta\eta)^2}{4\delta^2}\right)$$

Decay width: $\sqrt{2}\,\delta$

$$R(\Delta\eta) = \alpha\left[\frac{\Gamma(\Delta\eta)}{B(\Delta\eta)} - 1\right]$$

K. Eggert et al.,
Nucl. Phys. B 86:201, 1975

k: cluster size

$$K_{eff} = \alpha + 1 = \frac{<k(k-1)>}{<k>} + 1 = <k> + \frac{\sigma_k^2}{<k>}$$

K_{eff} : effective cluster size

$B(\Delta\eta)$: **background distribution**

QM2006, Shanghai

Wei Li, MIT

PHOBOS

A New Viewpoint for QCD Matter at LHC

- Factor 28 Higher $\sqrt{s_{NN}}$ than RHIC
- Initial state dominated by low-x components (Gluons).
- Abundant production of variety of perturbatively produced high p_T particles for detailed studies
- Higher initial energy density state with longer time in QGP phase
- Access to new regions of x