Energy Loss and Flow in Heavy Ion Collisions at RHIC

Neils Bohr was almost right about the liquid drop model

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XIth Mexican Workshop on Particles and Fields

Tuxtla Gutierrez, Mexico

November 7th, 2007

Who is RHIC and What Does He Do?

RHIC

- Two independent rings
- 3.83 km in circumference
- Accelerates everything, from p to Au

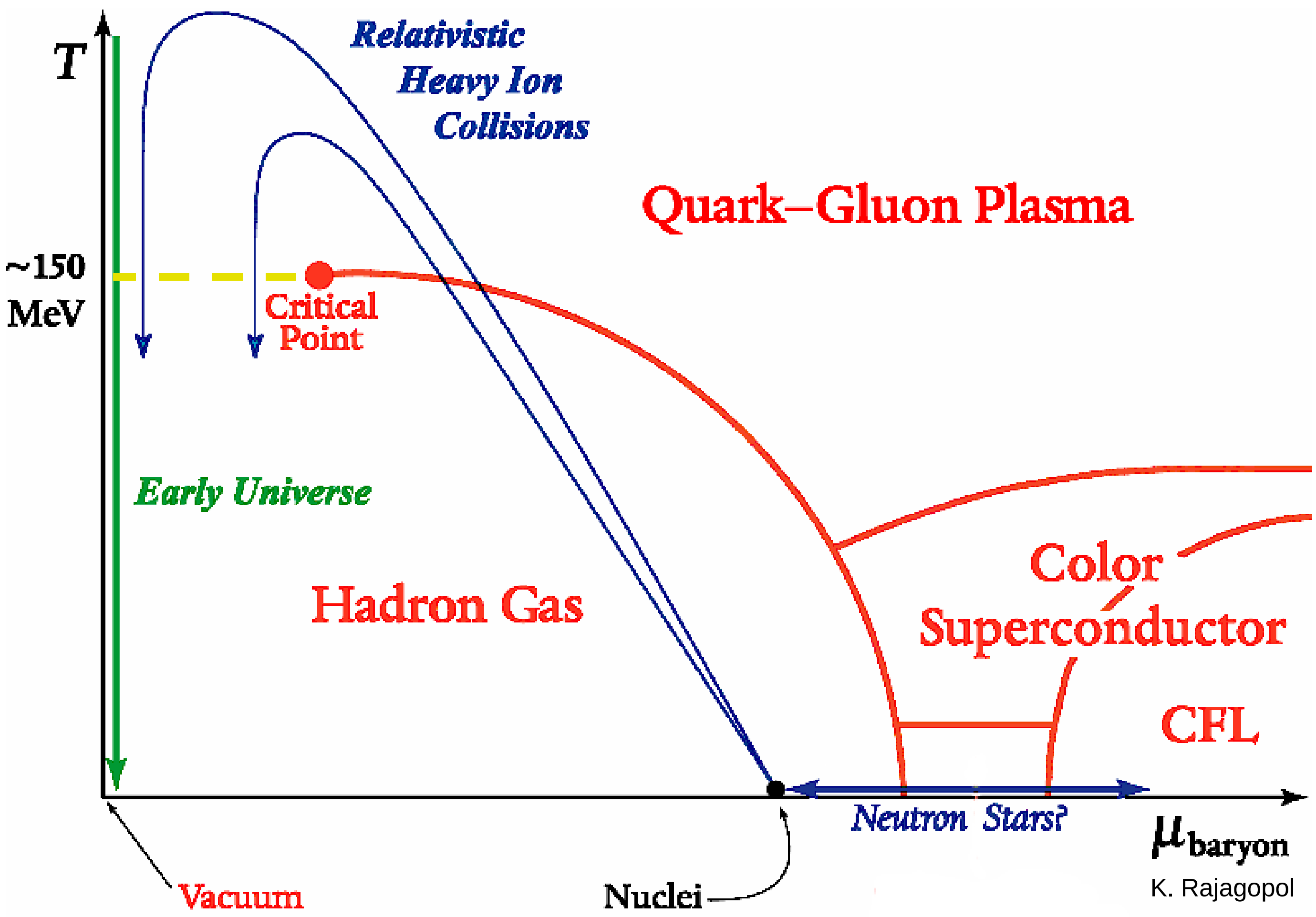
	√s	L
p-p	500	10^{32}
Au-Au	200	10^{27}

(GeV and $cm^{-2}\ s^{-1}$)

- Polarized protons
- Two Large and two small detectors were built

And for a little while longer, it is the highest energy heavy ion collider in the world

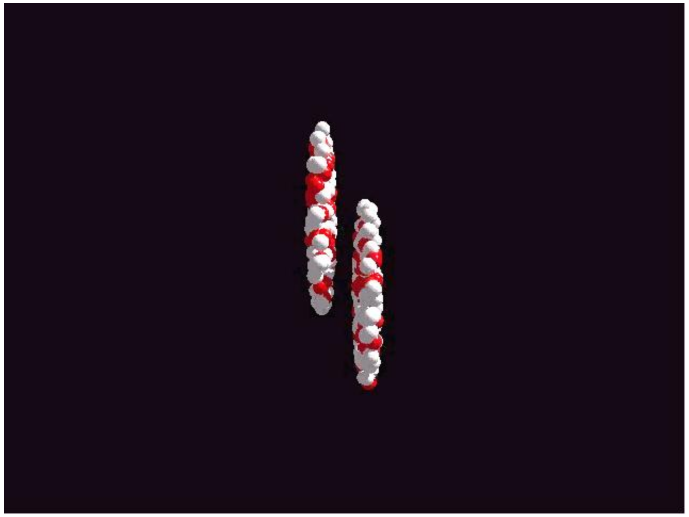
The Phase Diagram for Nuclear Matter

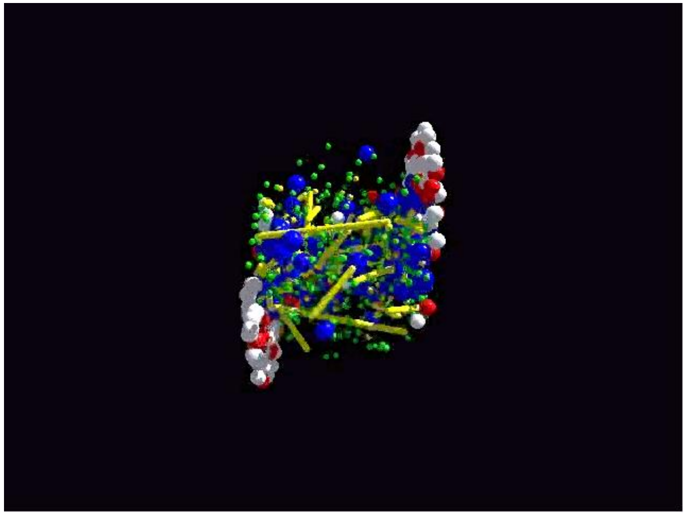


The goal is to explore nuclear matter under extreme conditions – T > $m_\pi c^2$ and ρ > 10 * ρ_0

- **One of the goals of RHIC is to understand the QCD in the context of the many body problem**
- **Another goal is to discover and characterize the Quark Gluon Plasma**
- **RHIC is a place where fundamental theory and experiment can meet after many years of being apart**

Unlike Particle Physics, the initial state is important

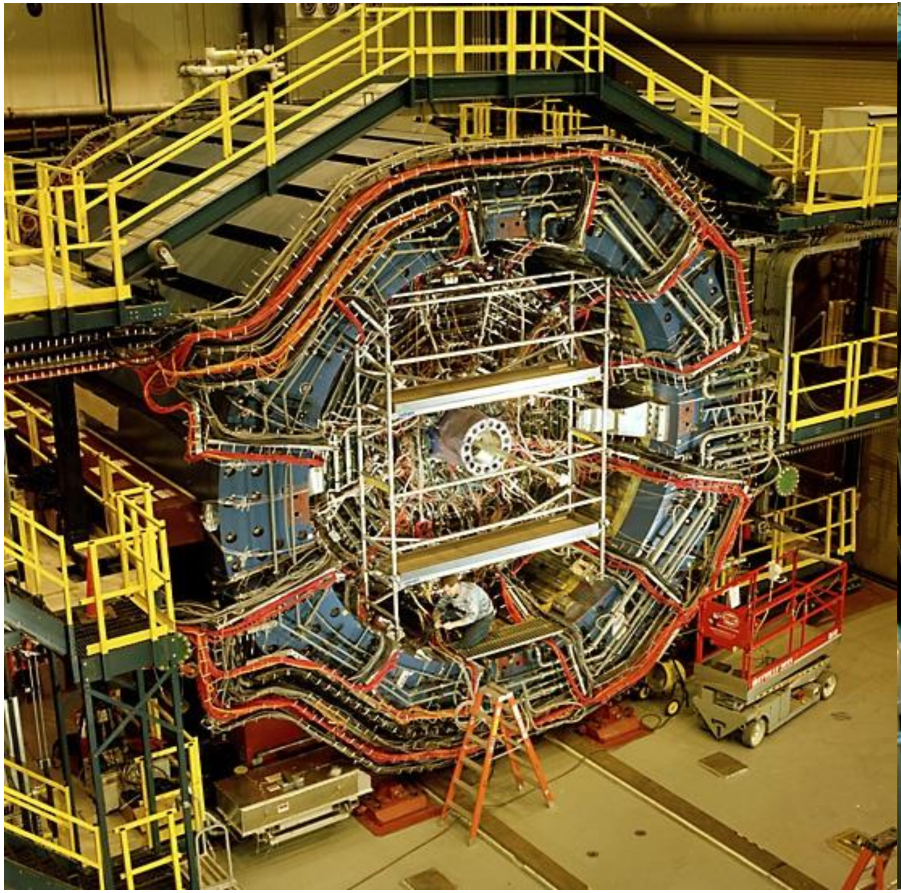


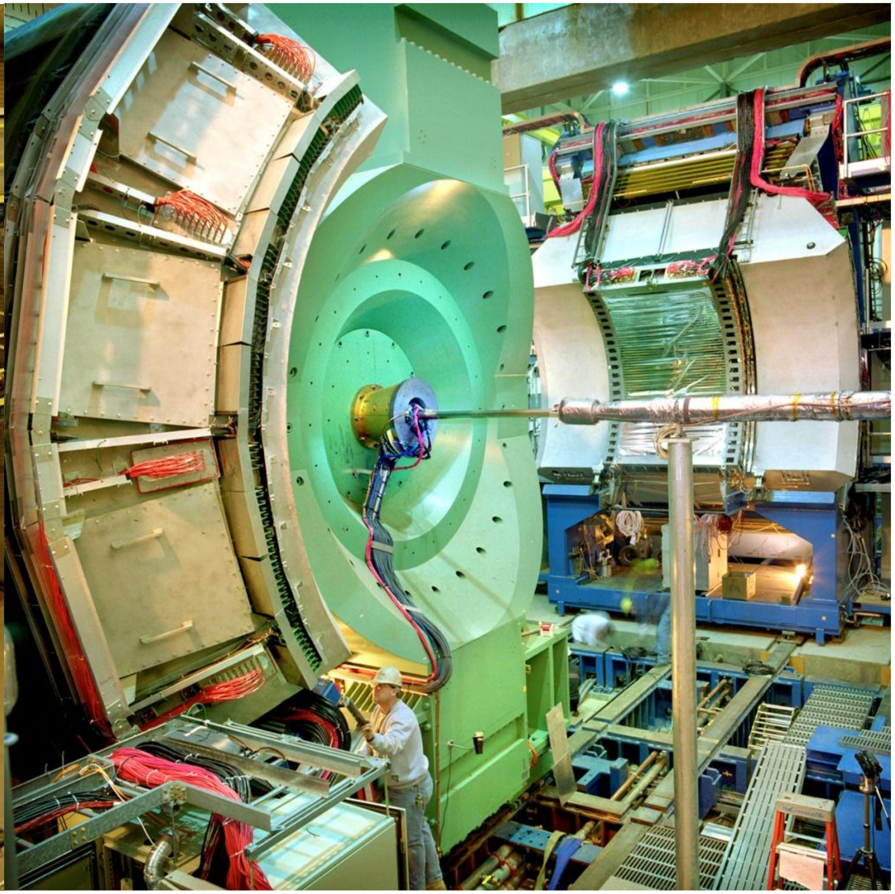


- Only a few of the nucleons participate in the collision as determined by the impact parameter
- There is multiple scattering in the initial state before the hard collisions take place
  - Cronin effect
- The initial state is Lorentz contracted
- Cross-sections become coherent.
  - The uncertainty principle allows wee partons to interact with the front and back of the nucleus
  - The interaction rate for wee partons saturates ($\rho\sigma = 1$)
- The intial state is even time dilated
  - A color glass condensate

proton neutron delta pion string

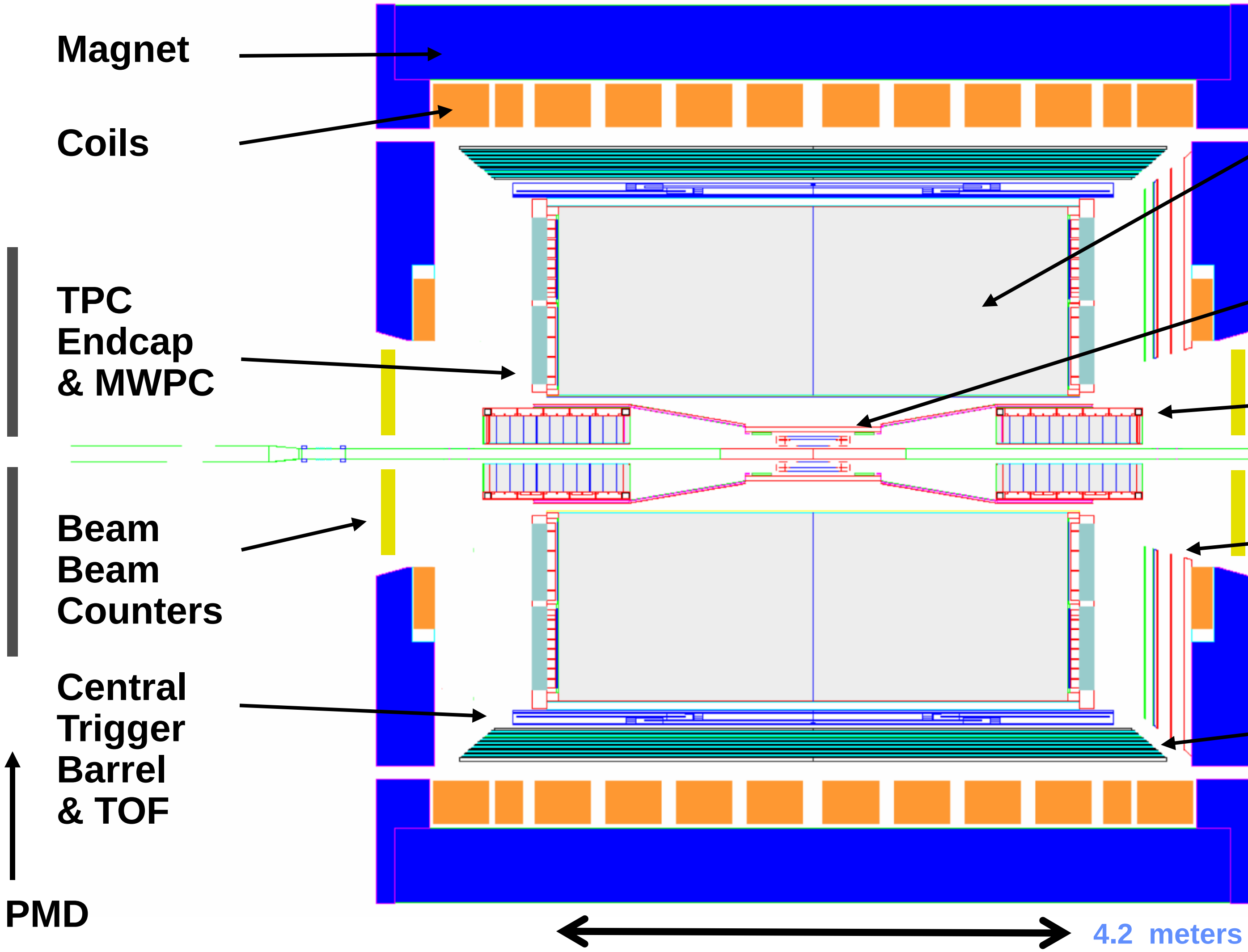
The Large Detectors – PHENIX and STAR





STAR **PHENIX**

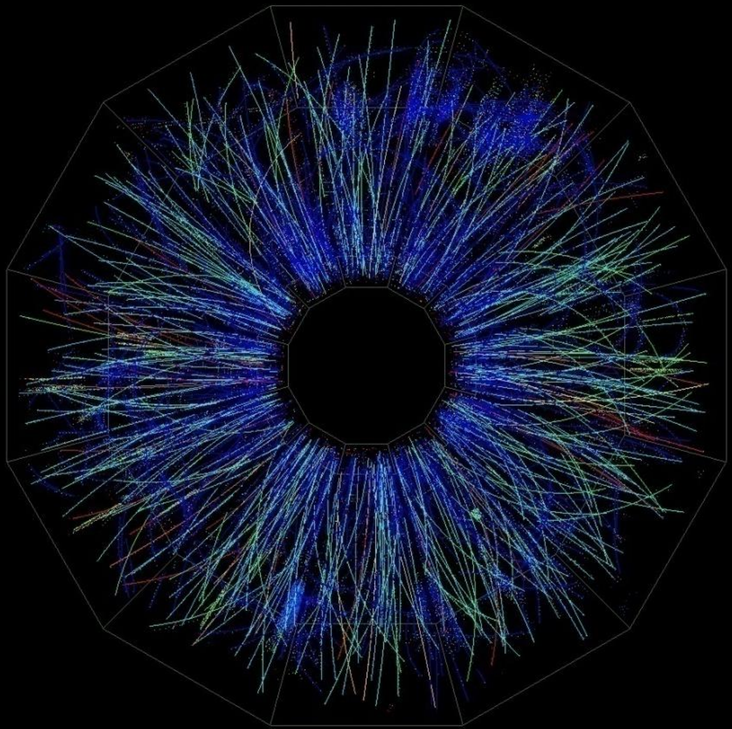
STAR is a Suite of Detectors



Not Shown: pVPDs, ZDCs, and FPDs

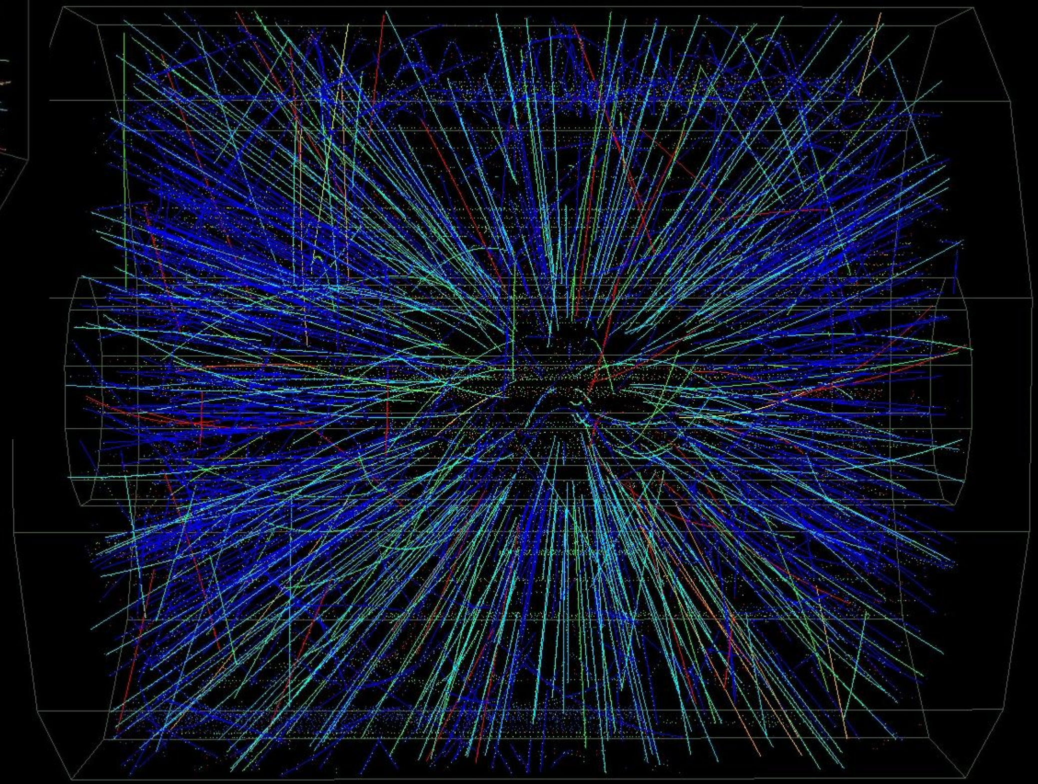
A TPC lies at the heart of STAR

Au on Au Event at CM Energy ~ 130 GeV*A



Data taken June 25, 2000.

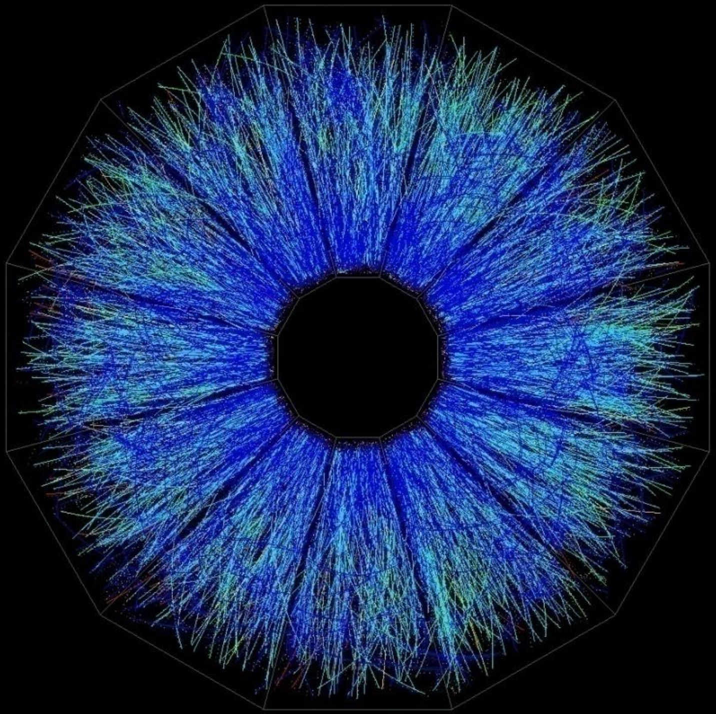
The first 12 events were captured on tape!



Real-time track reconstruction

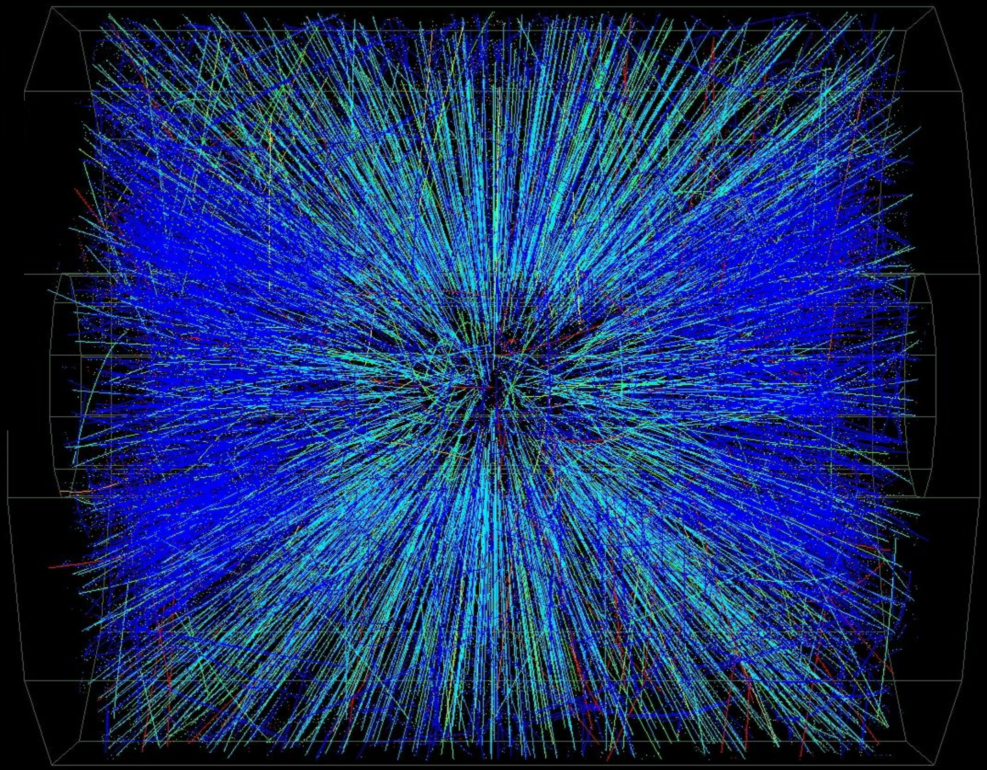
Pictures from Level 3 online display.   (< 70 mSec)

Au on Au Event at CM Energy ~ 130 GeV*A



A Central Event

Typically 1000 to 2000 tracks
per event into the TPC



Two-track separation 2.5 cm

Momentum Resolution < 2%

Space point resolution ~ 500 μm

Rapidity coverage –1.8 < η < 1.8

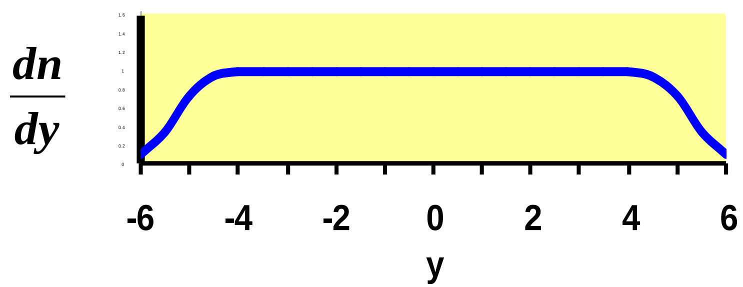
Nomenclature: Rapidity vs x_f

- $x_f = p_z / p_{max}$
  - A natural variable to describe physics at forward scattering angles

- Rapidity is different. It is a measure of velocity but it stretches the region around v = c to avoid the relativistic scrunch

$$y \equiv \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \qquad \textit{or} \qquad y \equiv \tanh^{-1}(\underbrace{p_z / E}_{\beta})$$

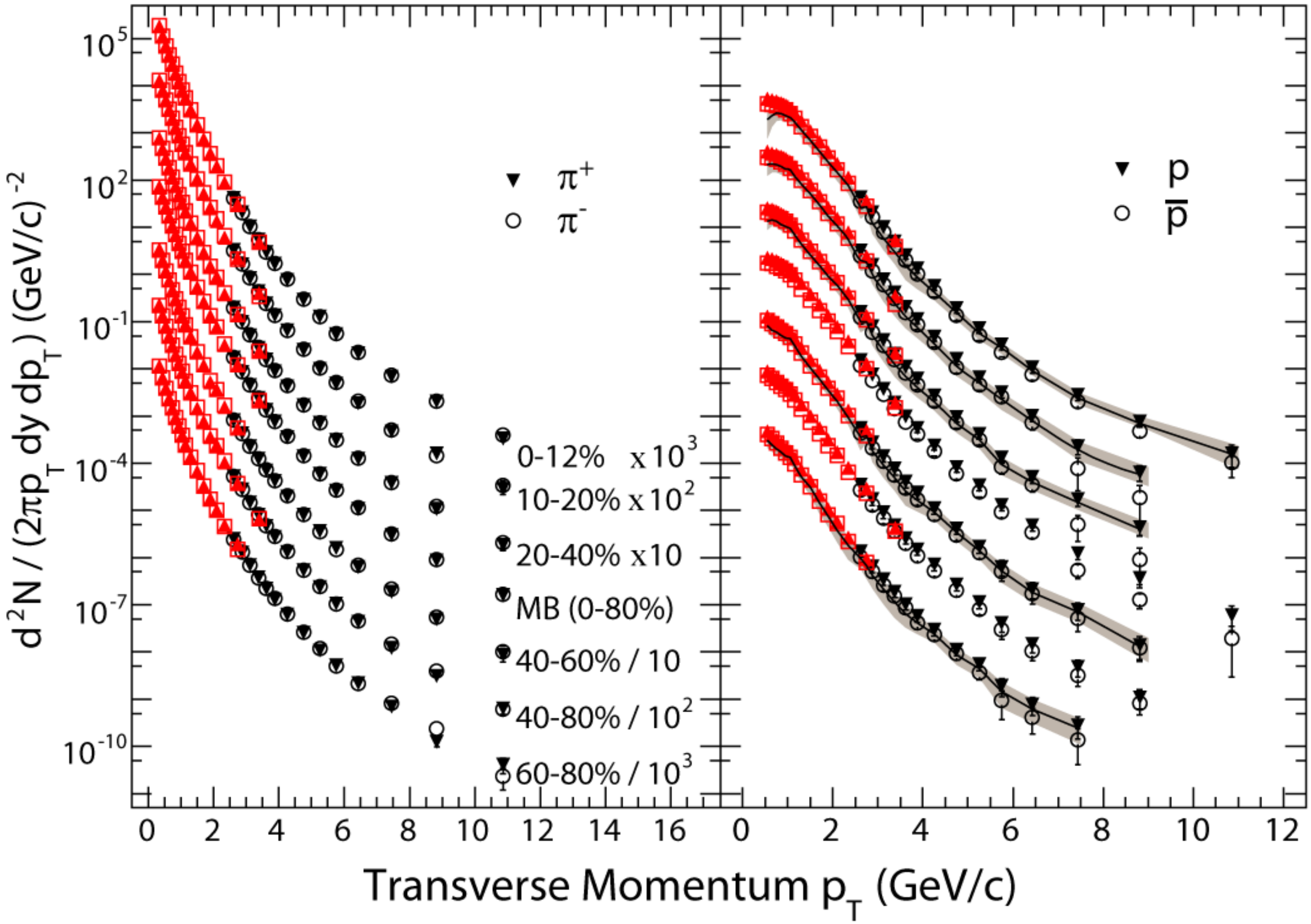
  - Rapidity is relativistically invariant and cross-sections are invariant



$$y \Rightarrow y + \tanh^{-1}\beta$$

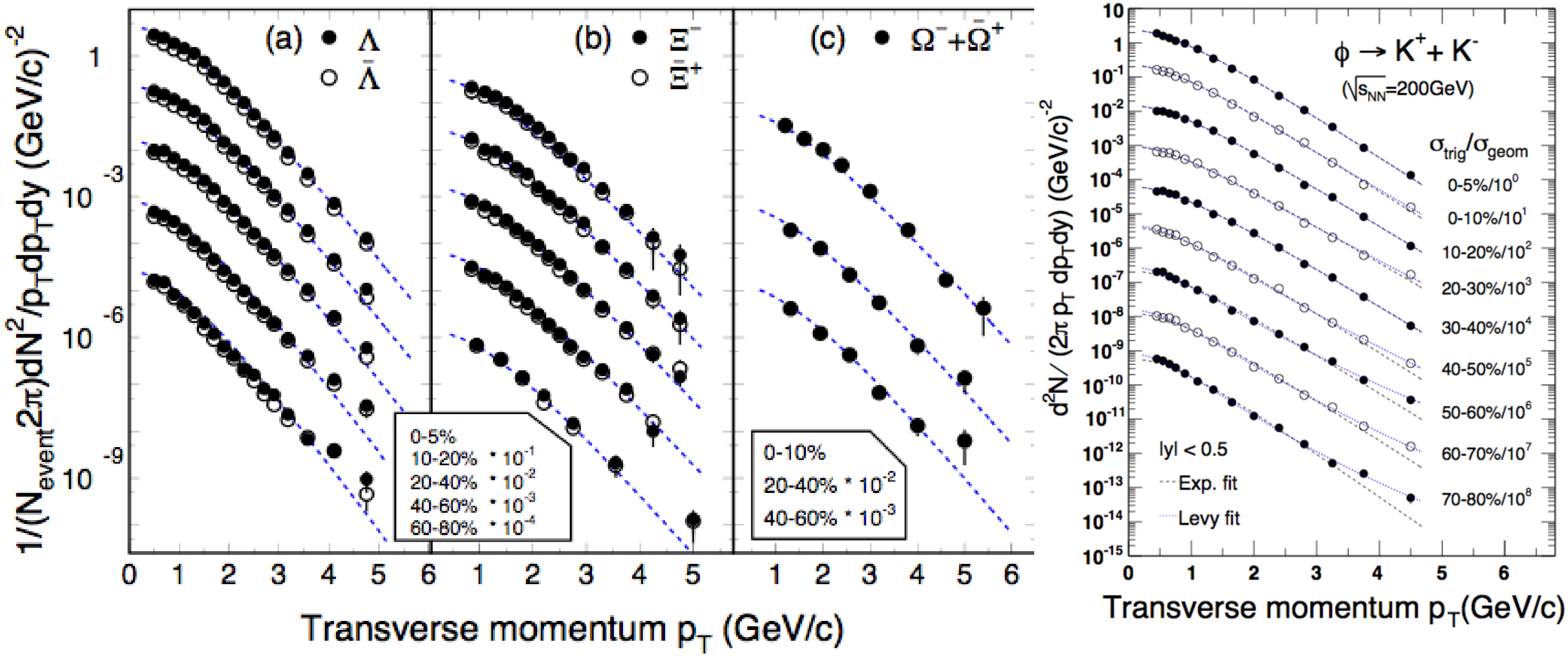
Rapidity and p_T are the natural kinematic variable for HI collisions
(y is approximately the lab angle … where y = 0 at 90 degrees)
When the mass of the particle is unknown, then y ⇒ η

Identified Mesons and Baryons: Au+Au @ 200 GeV



π and p yields .vs. p_T
Phys. Rev. Lett. 97 (2006) 152301

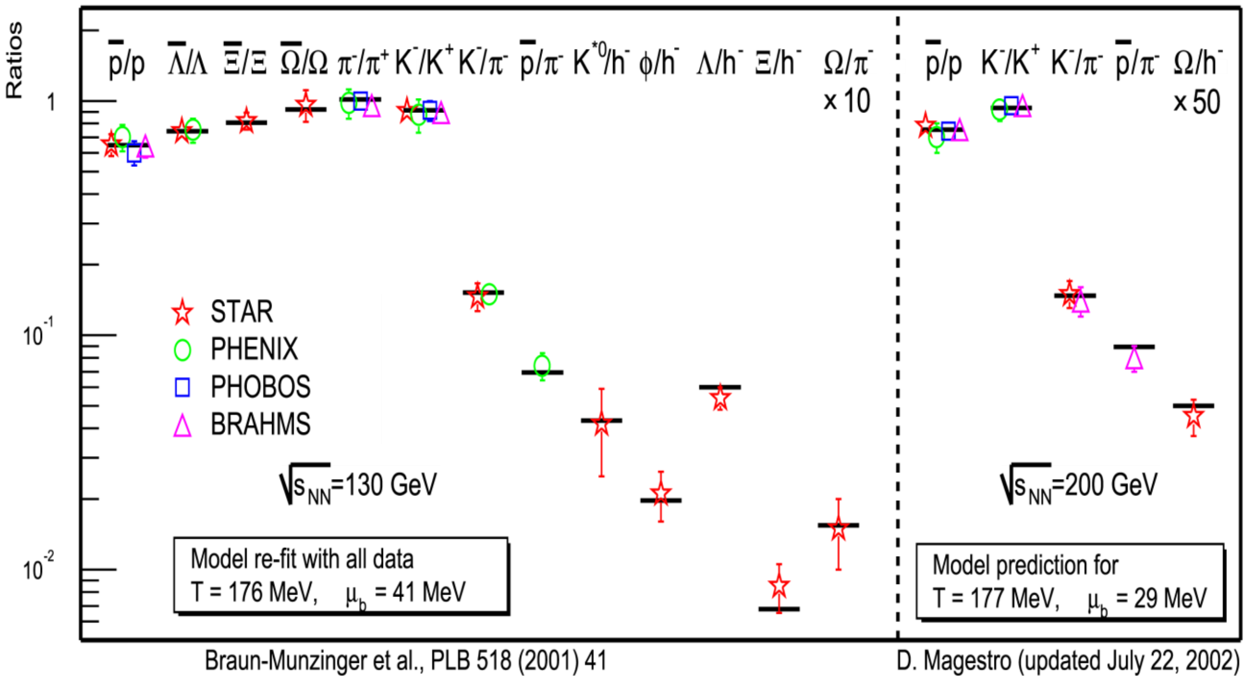
Strange Baryons and Mesons: Au+Au @ 200 GeV



Λ, Ξ, Ω and ϕ yields .vs. p_T

Phys. Rev. Lett. 98 (2007) 060301

Chemical Freeze-out – from a thermal model



Thermal model fits

$T_{ch}(\mathrm{RHIC}) = 177 \pm 7\,\mathrm{MeV}$

$\mu_B(\mathrm{RHIC}) = 29 \pm 6\,\mathrm{MeV}$

$T_{ch}(\mathrm{SPS}) = 160-170\,\mathrm{MeV}$

$\mu_B(\mathrm{SPS}) \cong 270\,\mathrm{MeV}$

Compare to QCD on the (old) Lattice:

$T_c = 154 \pm 8$ MeV (N_f=3)

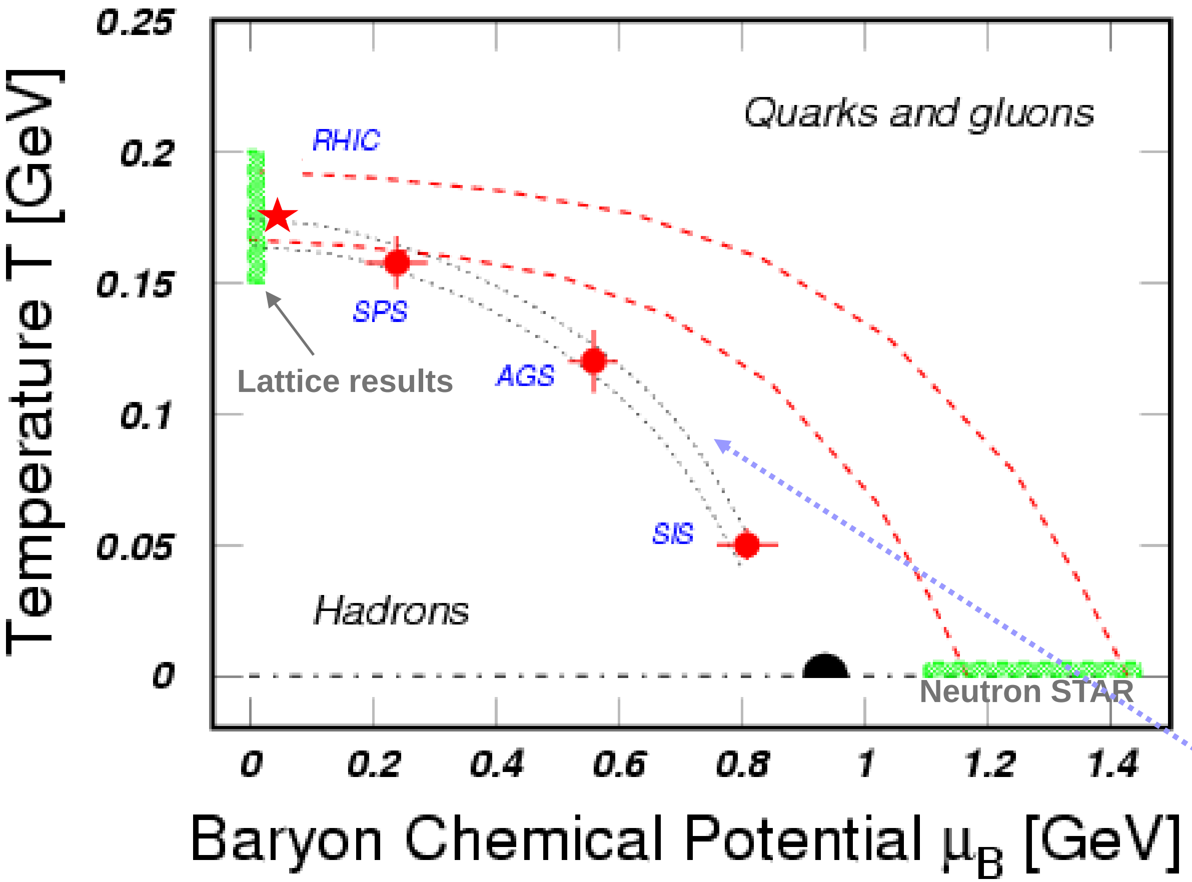
$T_c = 173 \pm 8$ MeV (N_f=2)

(ref. Karsch, various)

- **The model assumes a thermally and chemically equilibrated fireball at hadro-chemical freeze-out which is described by a temperature T and (baryon) chemical potential μ : dn ~ $e^{-(E-\mu)/T}$ d^3p**
- **Works great, but there is not a word of QCD in the analysis. Done entirely in a color neutral Hadronic basis!**

input: measured particle ratios output: temperature T and baryo-chemical potential μ_B

Putting RHIC on the Phase Diagram

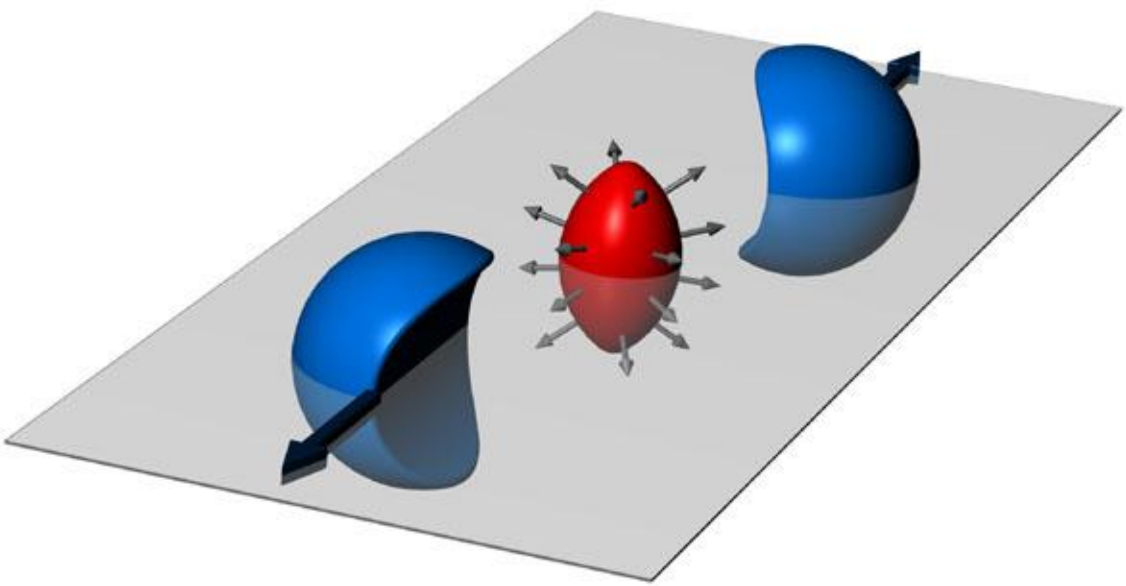


- **Final-state analysis suggests RHIC reaches the phase boundary**
- **Hadron spectra cannot probe higher temperatures**
- **Hadron resonance ideal gas** **(M. Kaneta and N. Xu, nucl-ex/0104021 & QM02)**
  - **T_{CH} = 175 ± 10 MeV**
  - **μ_B = 40 ± 10 MeV**
- **<E>/N ~ 1 GeV**

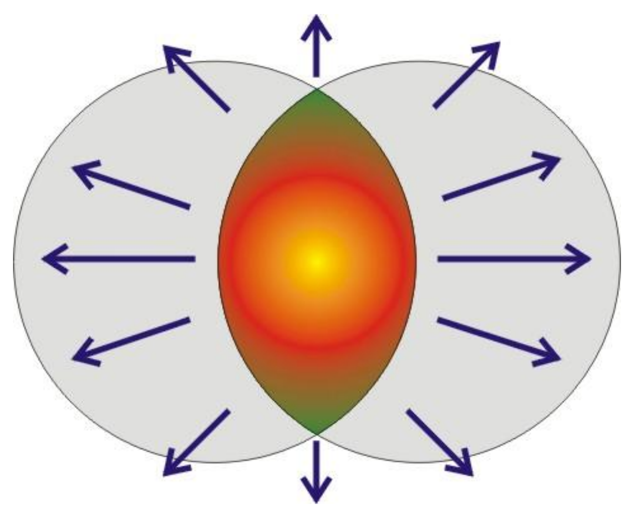
(J. Cleymans and K. Redlich, PRL 81, p. 5284, 1998)

We know where we are on the phase diagram but eventually we want to know what other features are on the diagram

ϕ Dependent Distributions – Flow



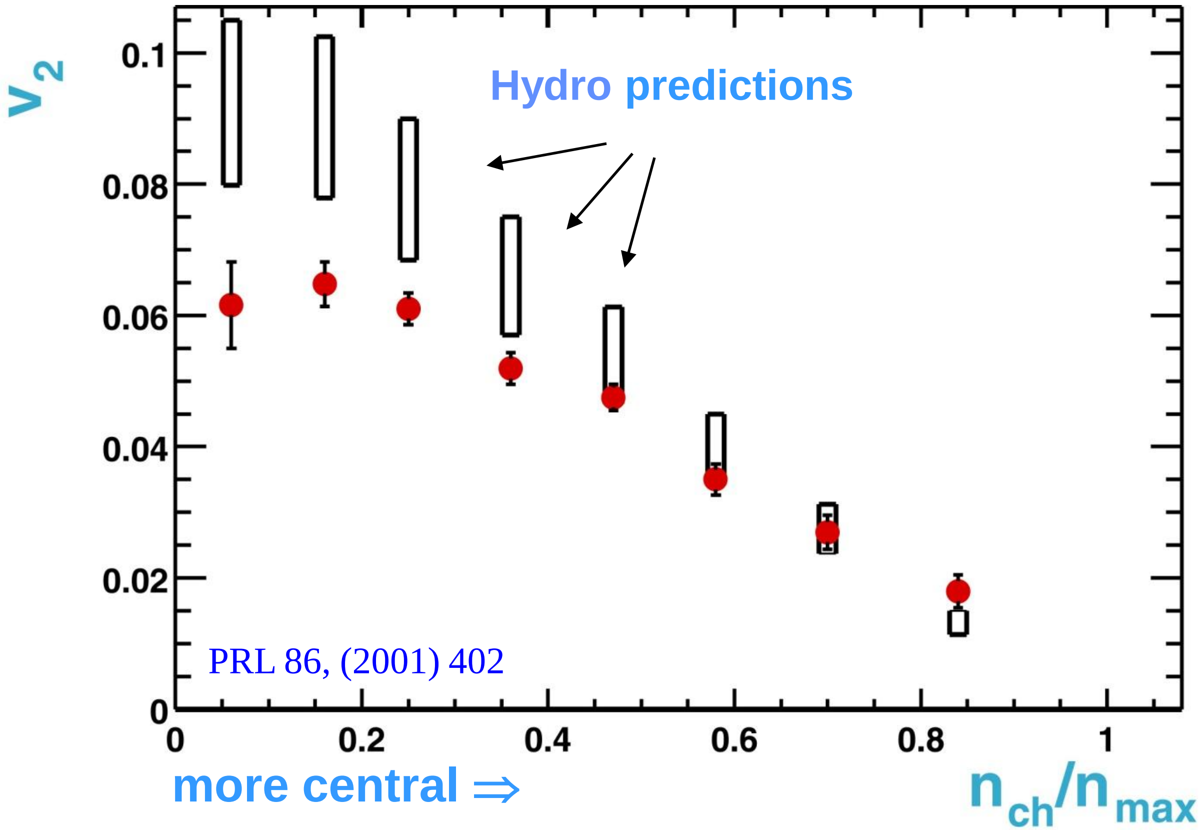
- **The overlap region in peripheral collisions is not symmetric in coordinate space**
- **Almond shaped overlap region**
  - **Larger pressure gradient in the x-z plane drives flow in that direction**
  - **Easier for high p_T particles to emerge in the direction of x-z plane**
- **Spatial anisotropy → Momentum anisotropy**



- **Perform a Fourier decomposition of the momentum-space particle distribution in the ⊥ plane**
  - **For example, v_2 is the 2nd harmonic Fourier coefficient of the distribution of particles with respect to the reaction plane**

$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(\underbrace{1}_{\text{isotropic}} + \underbrace{2v_1}_{\text{directed}}\cos(\phi) + \underbrace{2v_2}_{\text{elliptic}}\cos(2\phi) + \ldots \right)$$

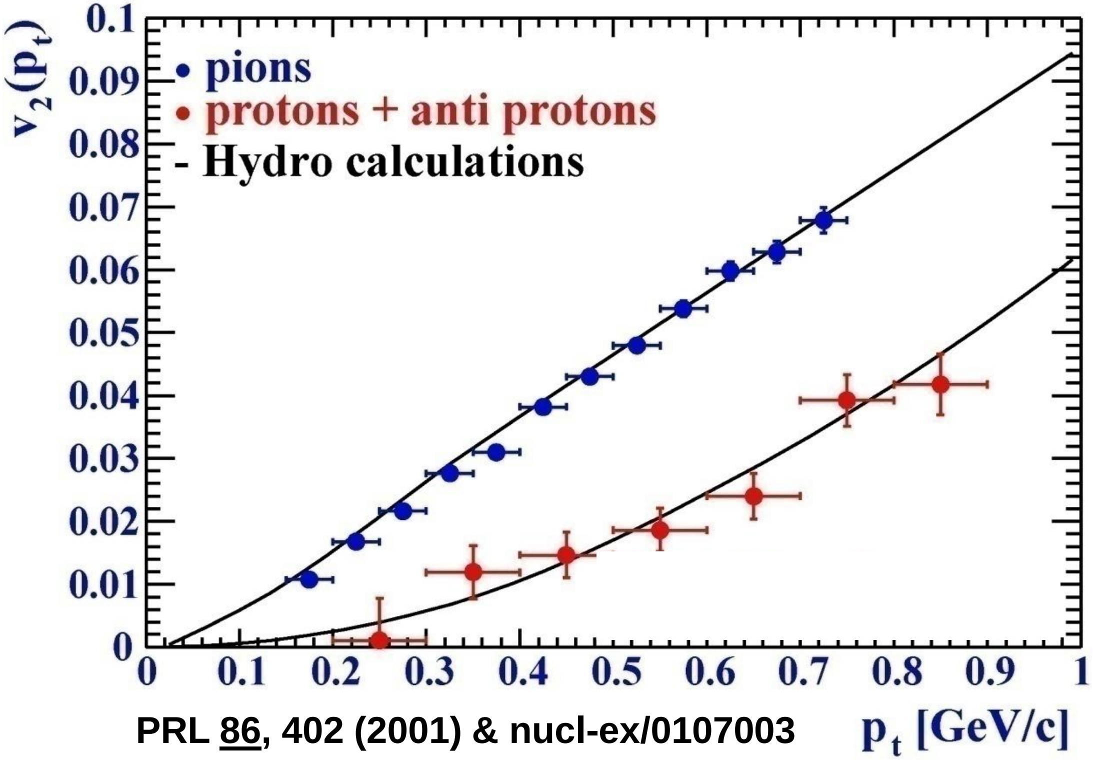
v_2 vs. Centrality



Anisotropic transverse flow is large at RHIC

- **v_2 is large**
  - **6% in peripheral collisions**
  - **Smaller for central collisions**
- **Hydro calculations are in reasonable agreement with the data**
  - **In contrast to lower collision energies where hydro over-predicts anisotropic flow**
- **Anisotropic flow is developed by rescattering**
  - **Data suggests early time history**
  - **Quenched at later times**

v_2 vs. p_T and Particle Mass



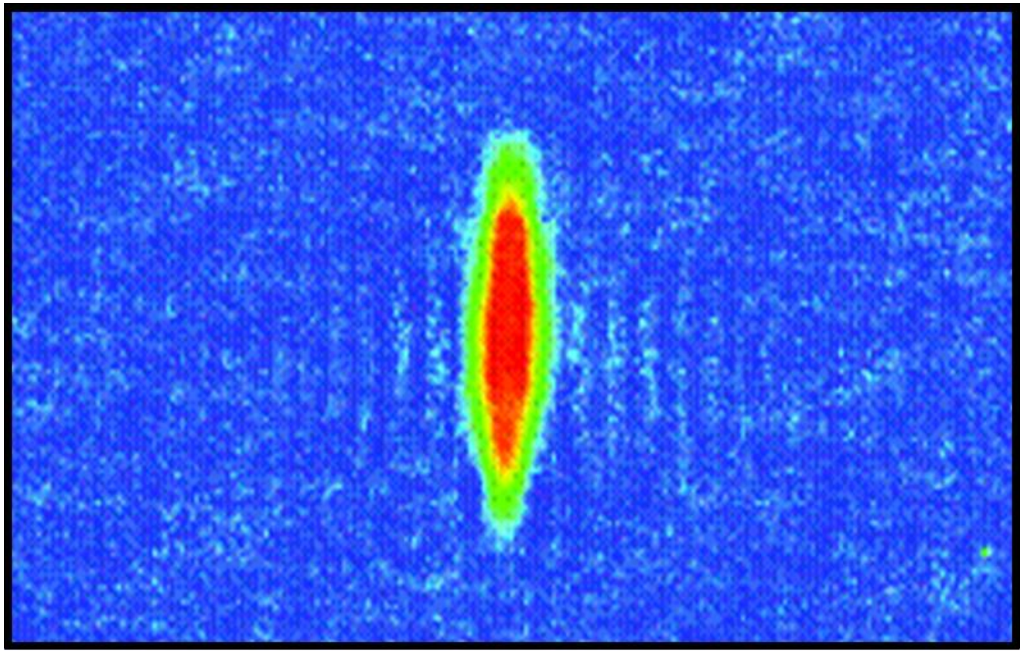
PRL 86, 402 (2001) & nucl-ex/0107003

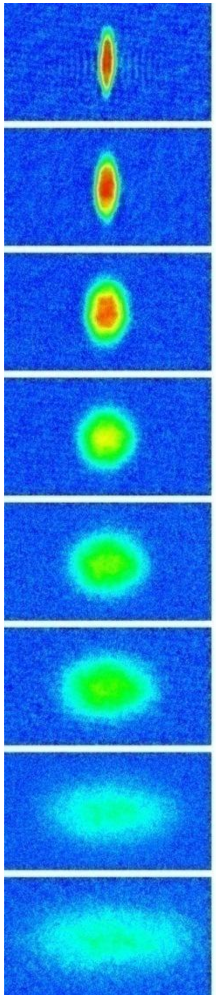
- **The mass dependence is reproduced by hydrodynamic models**
  - **Hydro assumes local thermal equilibrium**
  - **At early times**
  - **Followed by hydrodynamic expansion**

Hydro is a theme that will return again

D. Teaney et al., QM2001 Proc.
P. Huovinen et al., nucl-th/0104020

Elliptic Flow in an Ultra-Cold Fermi-Gas
A Simulation of Elliptic Flow

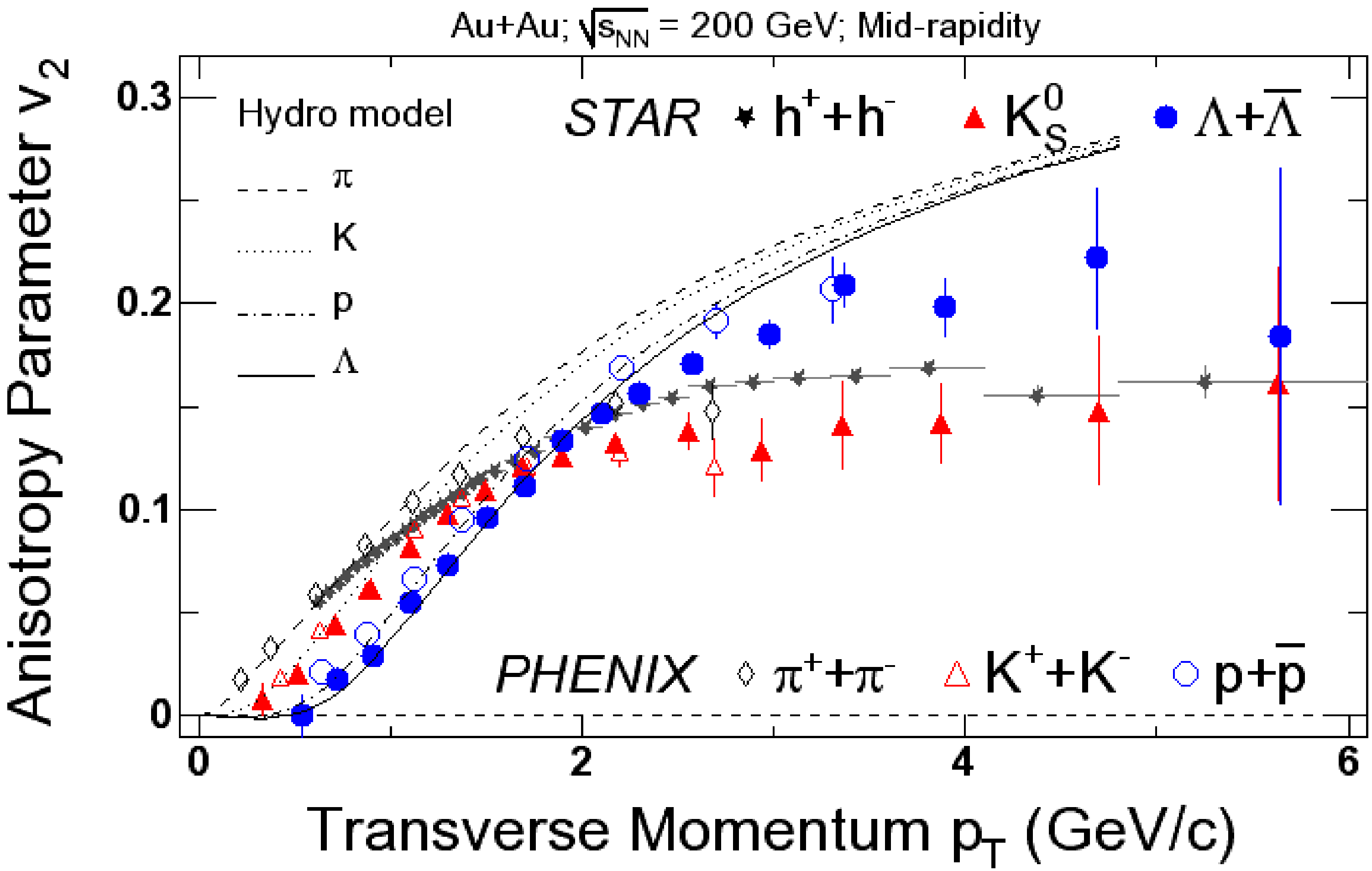




Li-atoms released from an optical trap exhibit elliptic flow analogous to what is observed in ultra-relativistic heavy-ion collisions

- **Elliptic flow is a general feature of strongly interacting systems!**

v_2 at high p_T shows meson / baryon differences

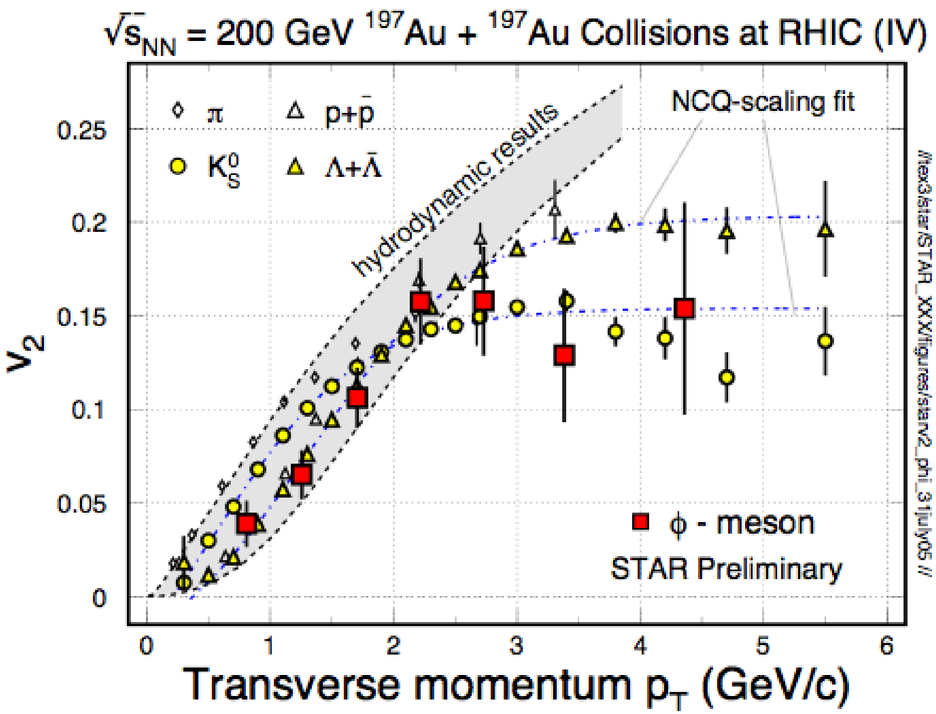


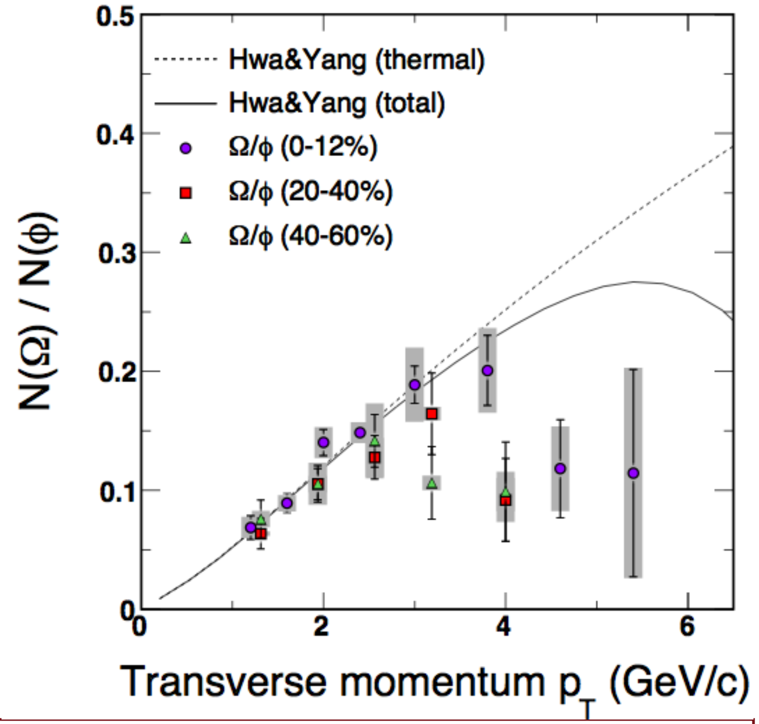
Bulk P_{QCD} Hydro

Asym. pQCD Jet Quenching

q^n Coalescence

ϕ-meson Flow: Partonic Flow





ϕ-mesons are special:

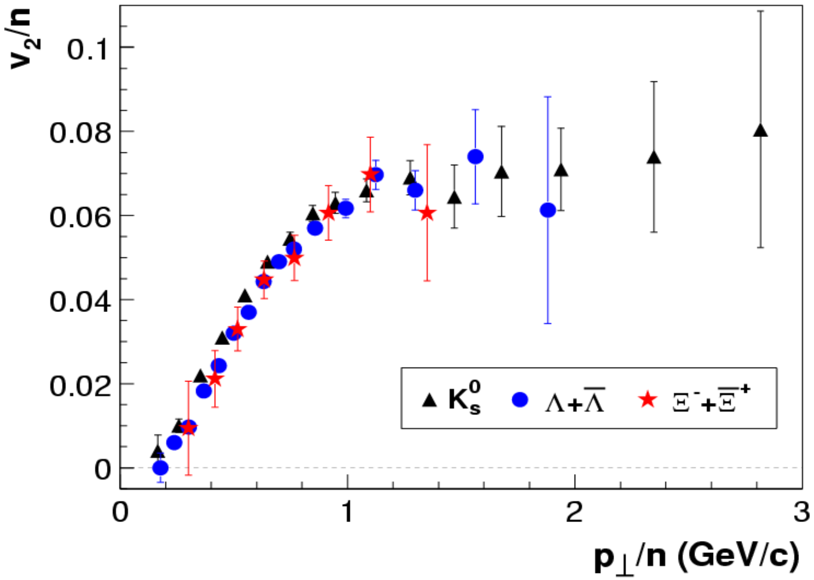
- they show strong collective flow and

- they are formed by coalescence of thermalized s-quarks

'They are made via coalescence of seemingly thermalized quarks in central Au+Au collisions, the observations imply *hot and dense matter with partonic collectivity* has been formed at RHIC'

Phys. Rev. Lett. 99 (2007) 112301 and Phys. Lett. B612 (2005) 81

The Recombination Model (Fries et al. PRL 90 (2003) 202303)

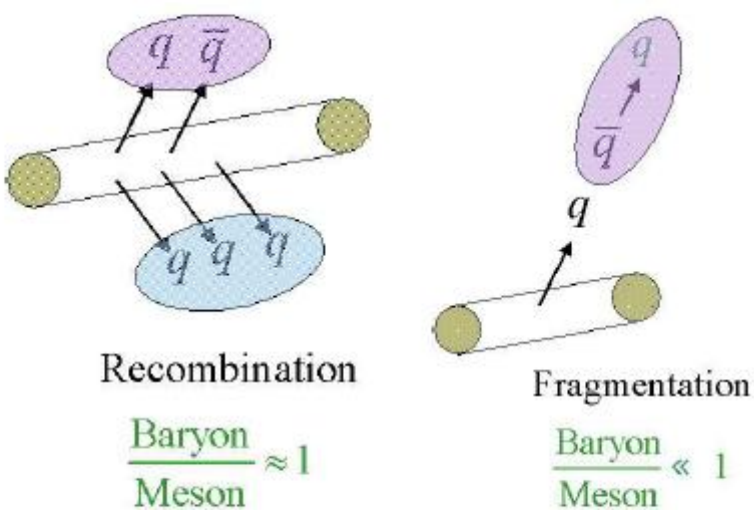


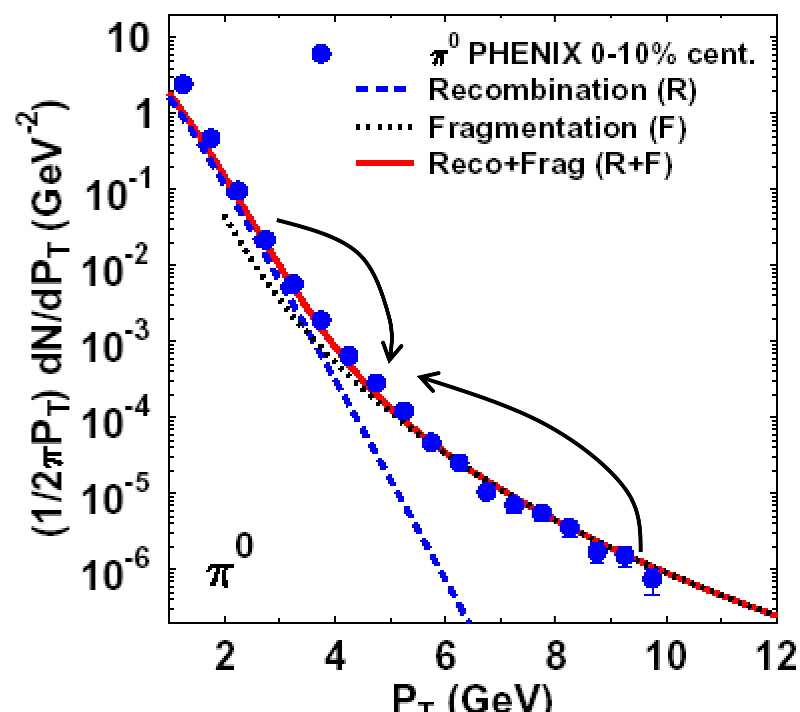
The flow pattern in $v_2(p_T)$ for hadrons is predicted to be simple if flow is developed at the quark level

$p_T \rightarrow p_T/n$

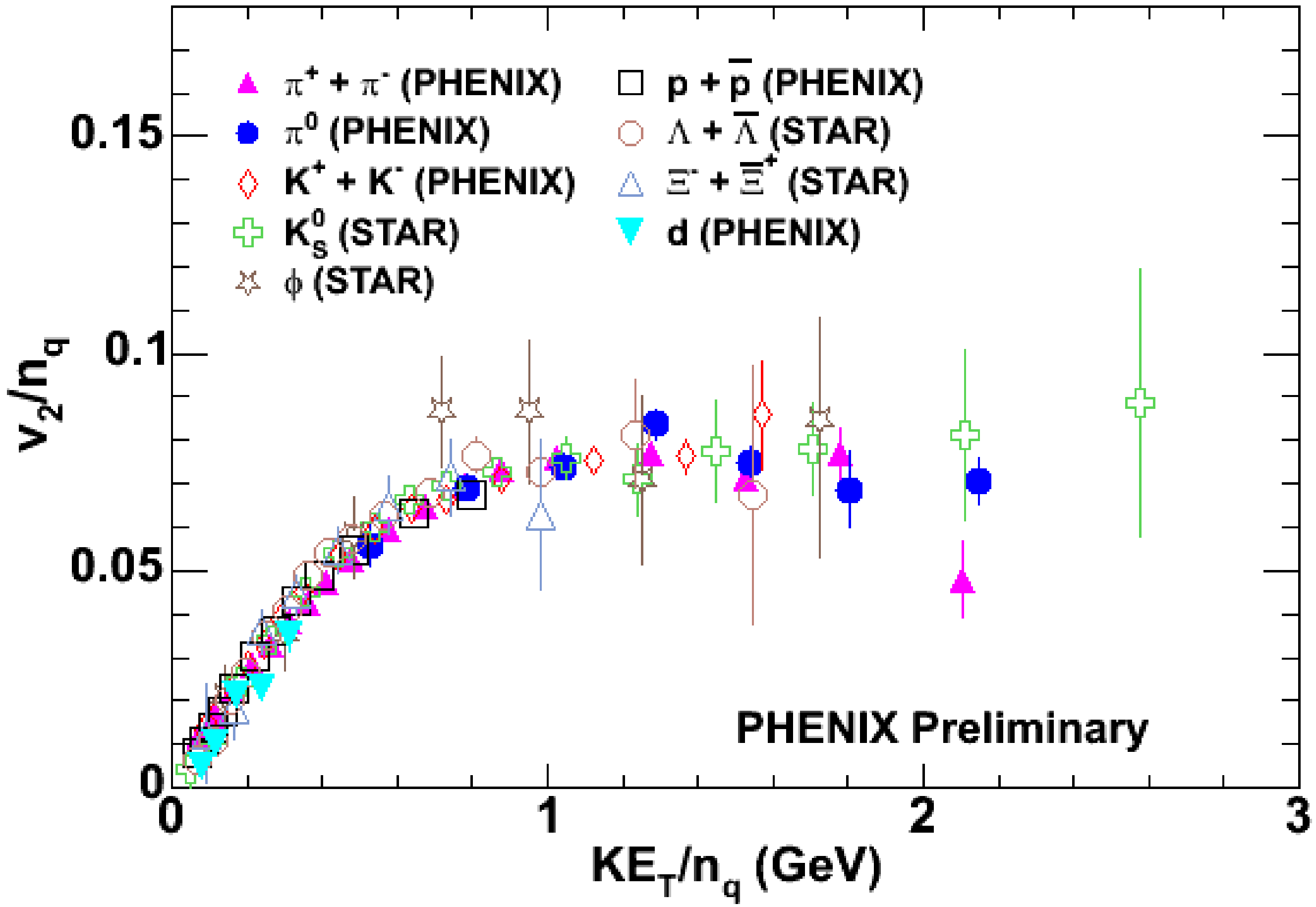
$v_2 \rightarrow v_2 / n$,

n = (2, 3) for (meson, baryon)



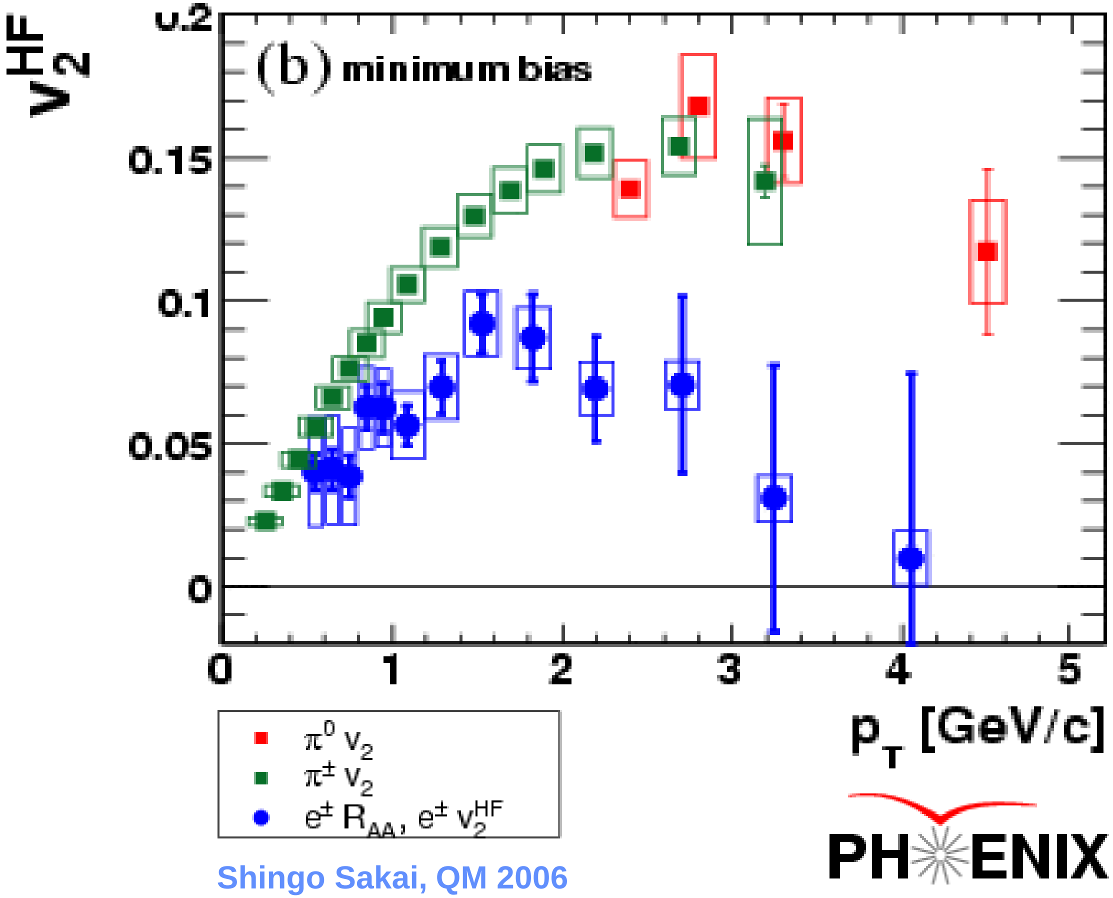


Elliptic flow scales with the number of quarks



Implication: quarks, not hadrons, are the relevant degrees of freedom at early times in the collision

Hints of Elliptic Flow with Charm



Shingo Sakai, QM 2006
PRL 98, 172301 (2007)

Better if we can do direct topological identification of Charm

- **D $\rightarrow$ e +X**

  Single electron spectra from PHENIX show hints of elliptic flow

  Is it charm or beauty?

- **The RHIC upgrades will cut out large photonic backgrounds:**

  $\gamma \rightarrow e^+e^-$

  and reduce other large stat. and systematic uncertainties

What does this mean?

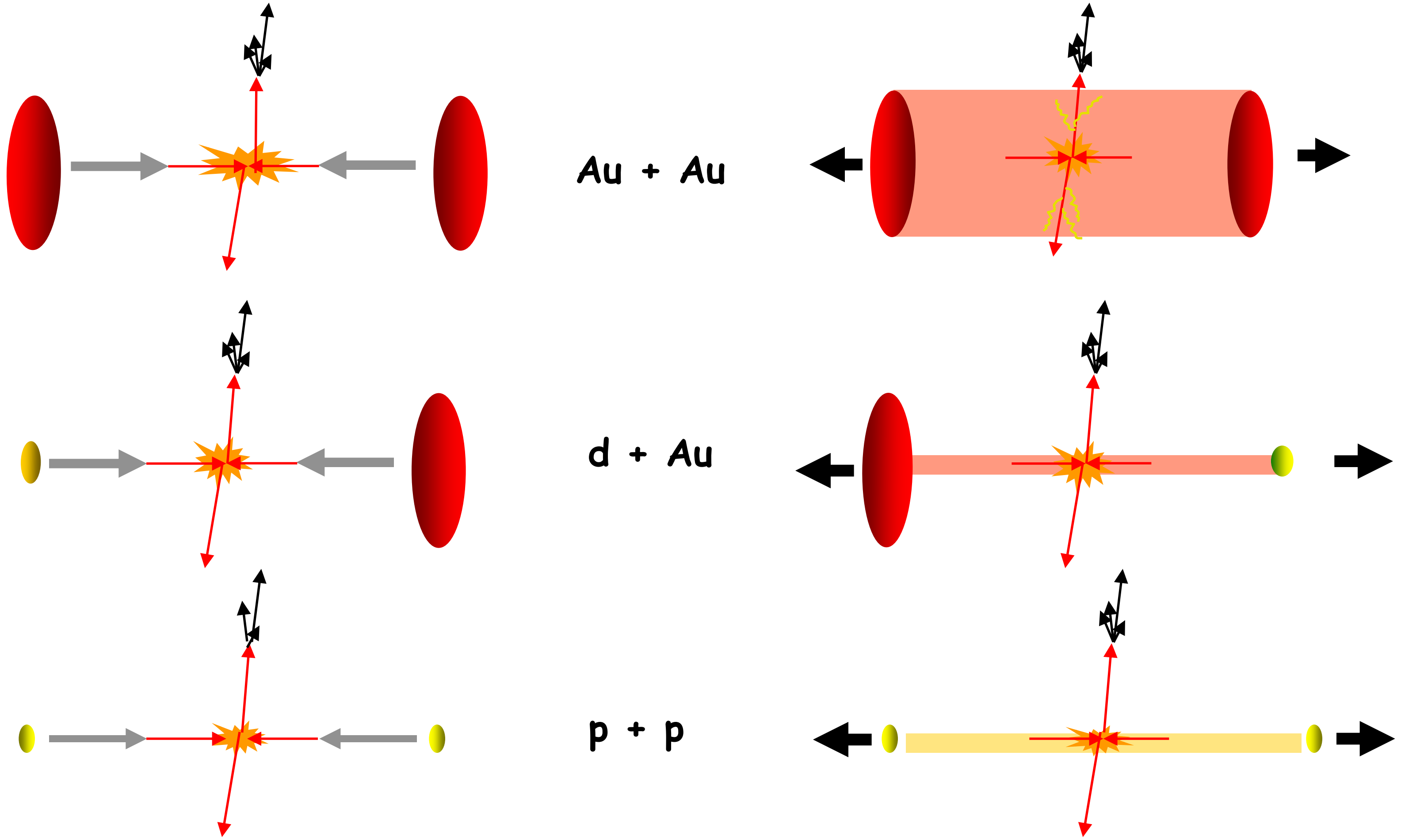
- **Hadrons are created by the recombination of quarks and this appears be the dominant mechanism for hadron formation at intermediate p_T**
- **Baryons and Mesons are produced with equal abundance at intermediate p_T**
- **The collective flow pattern of the hadrons appears to reflect the collective flow of the constituent quarks.**

Partonic Collectivity

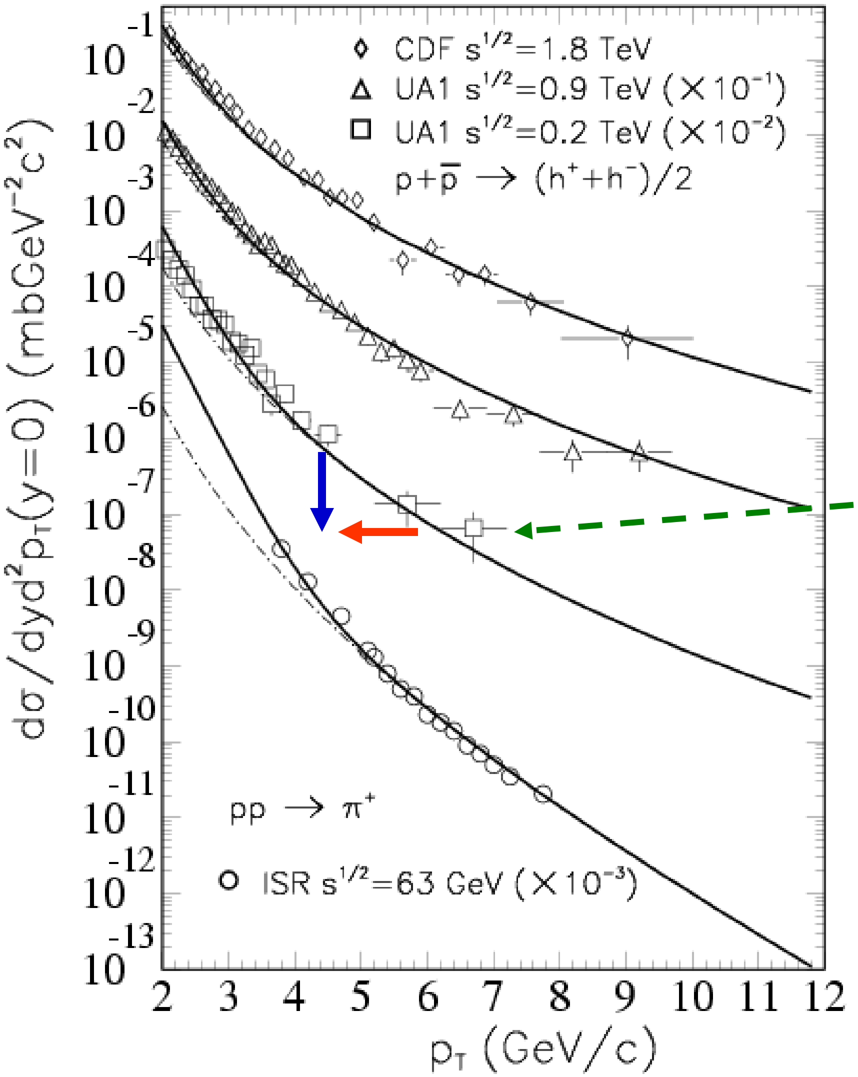
Lets look at some collision systems in detail …

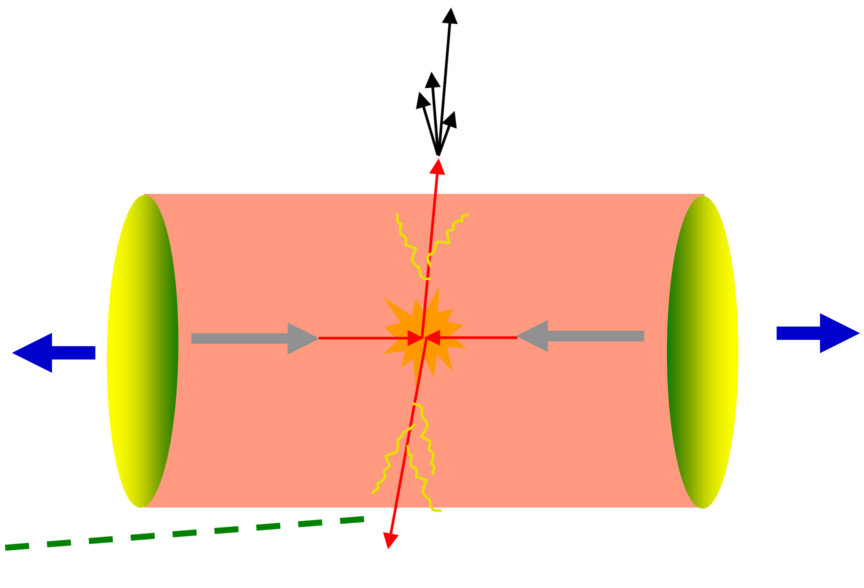
Initial state

Final state



Partonic energy loss via leading hadrons





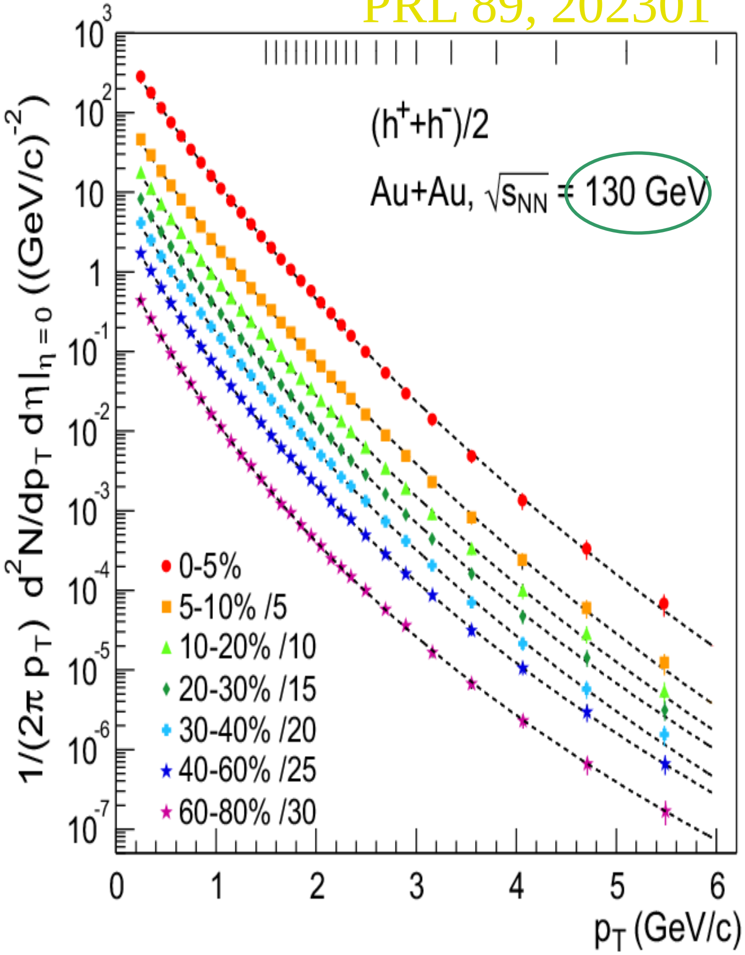
Energy loss ⇒
softening of fragmentation ⇒
suppression of leading hadron yield

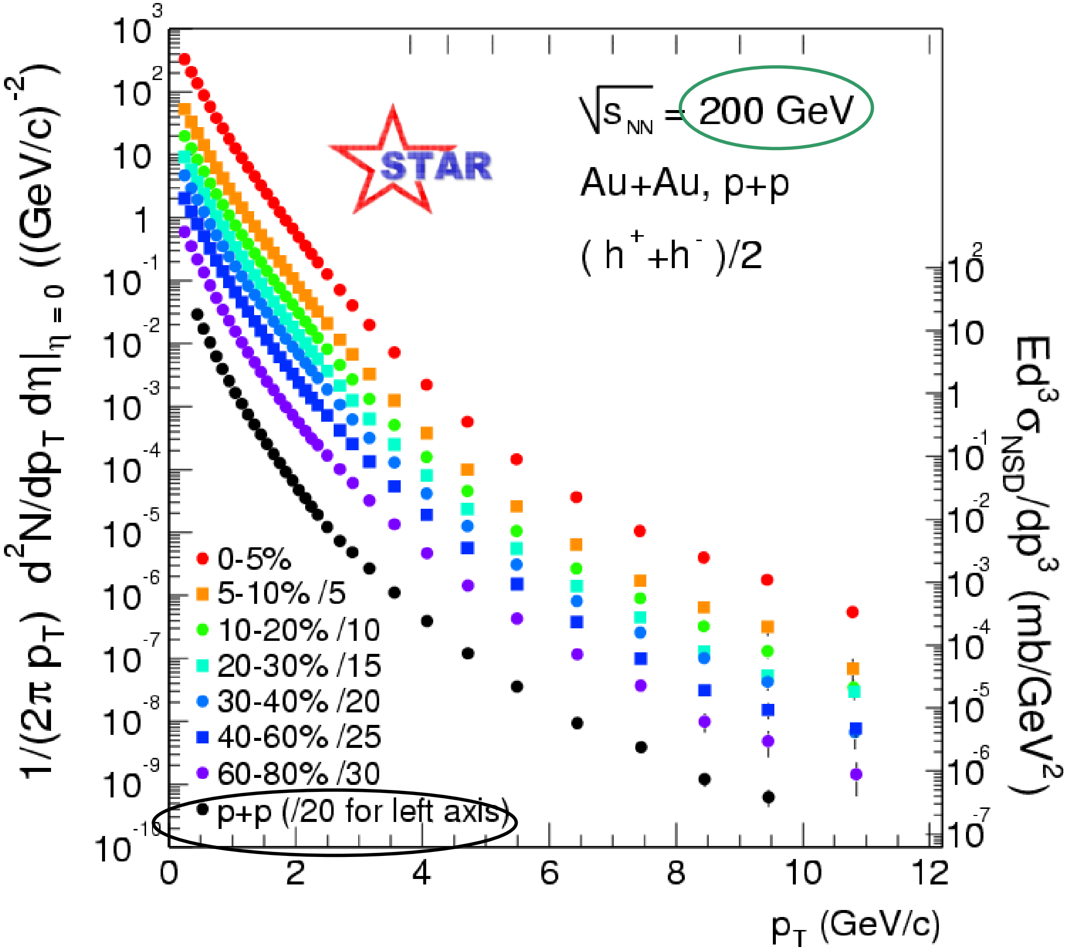
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

Binary collision scaling   p+p reference

Au+Au and p+p: inclusive charged hadrons

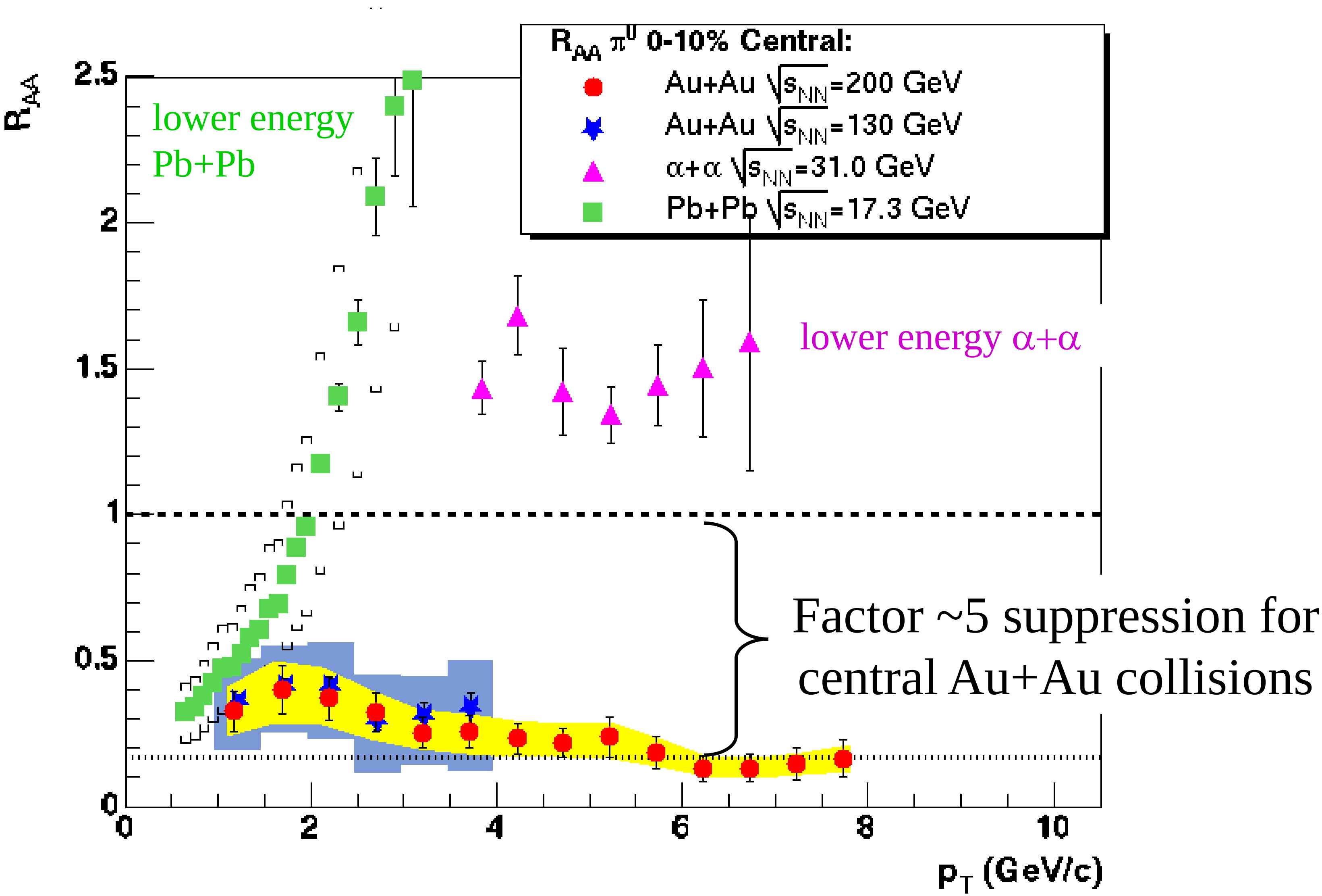
PRL 89, 202301





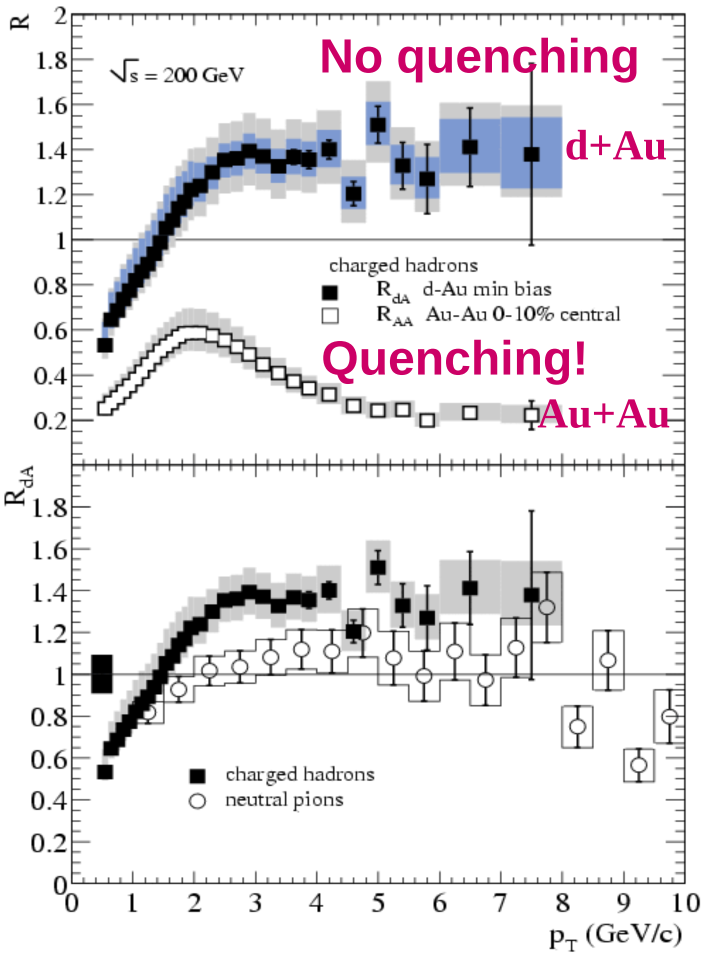
p+p reference spectrum measured at RHIC

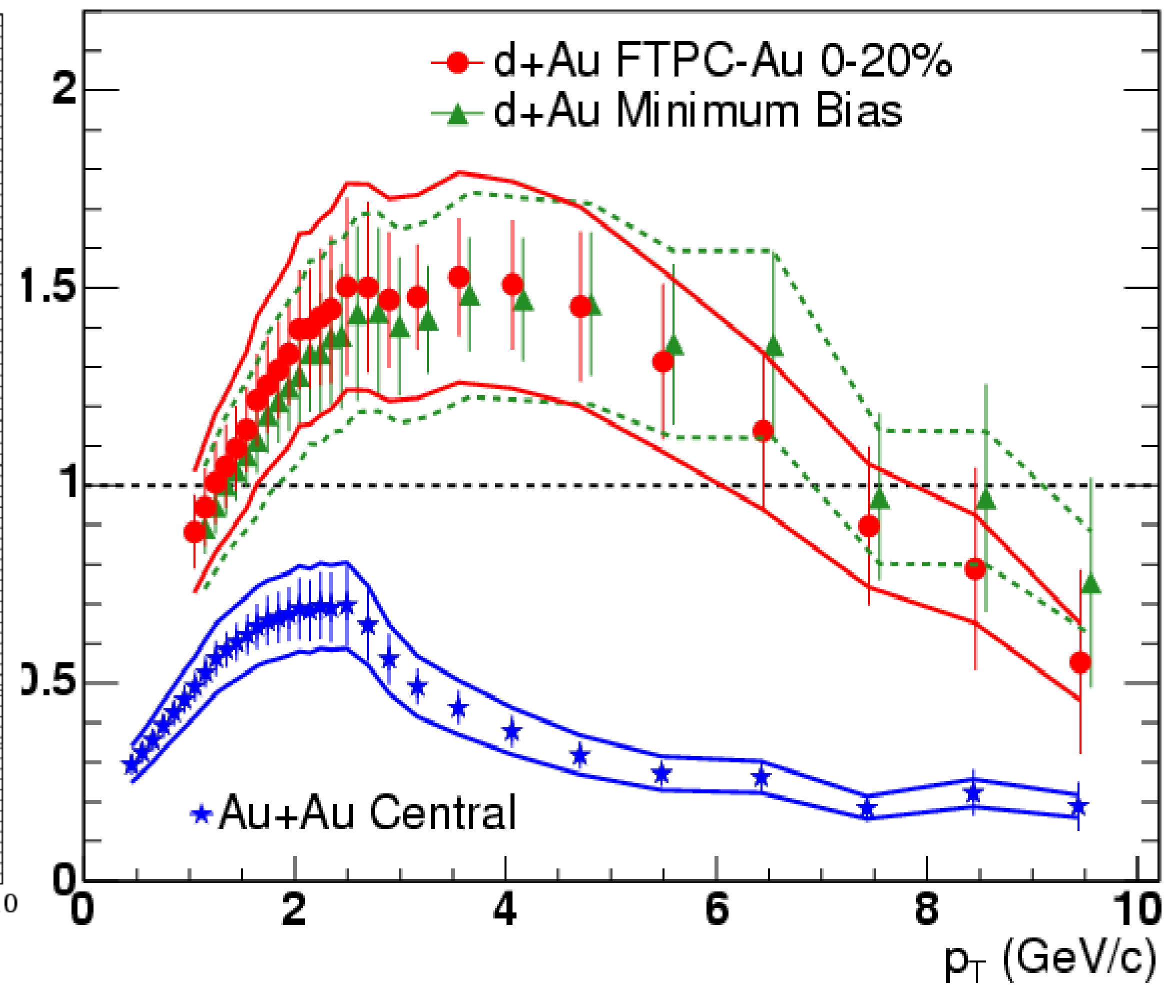
PHENIX data on the suppression of π^0s



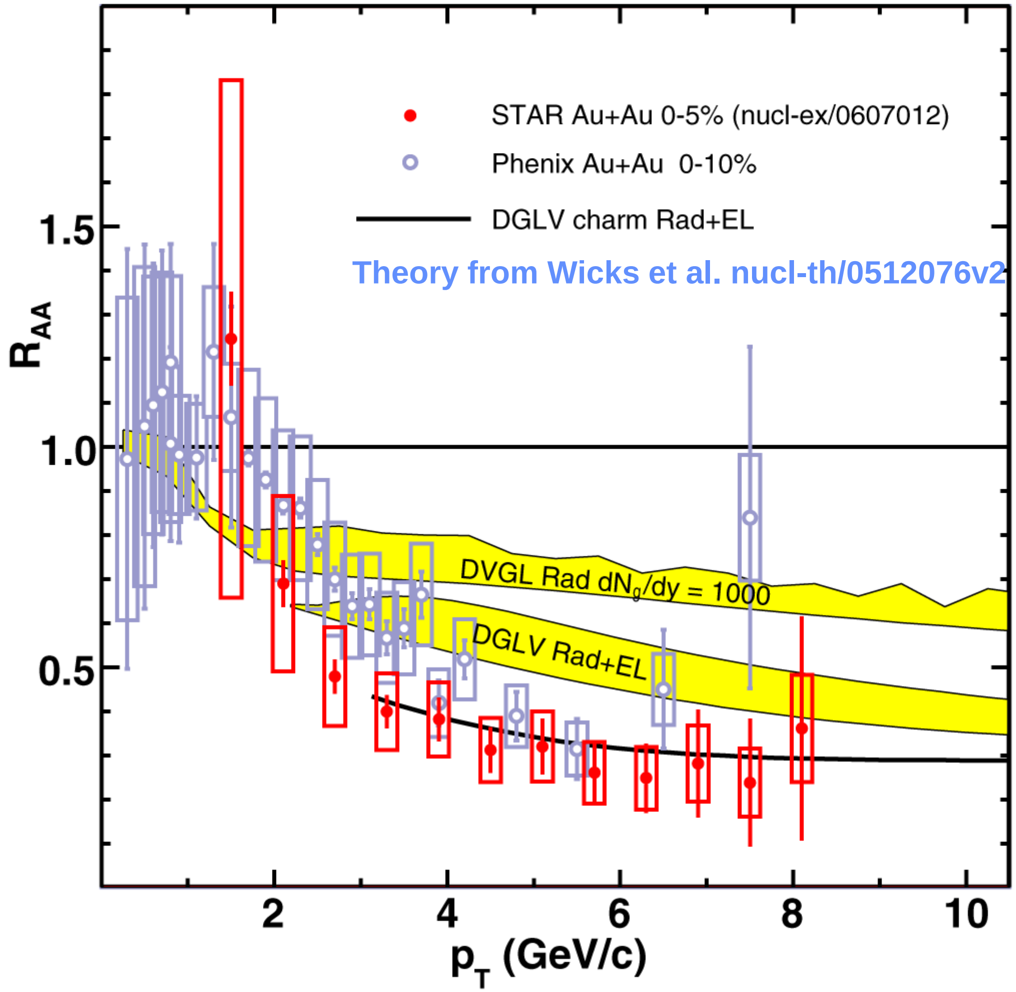
The Suppression occurs in Au-Au but not d-Au

STAR





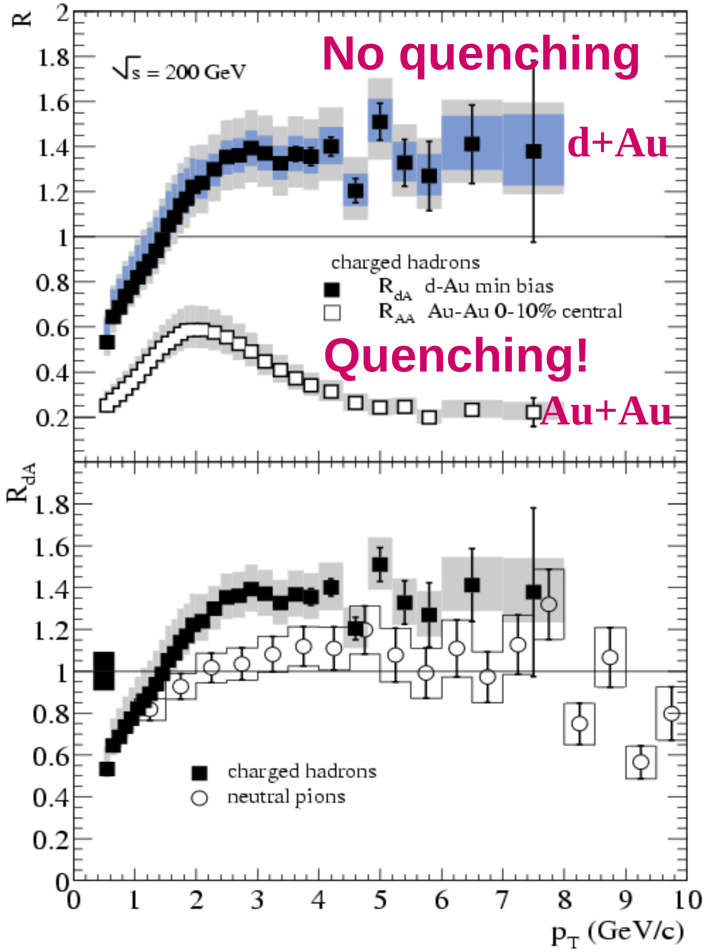
Heavy Flavor Energy Loss … R_{AA} for Charm

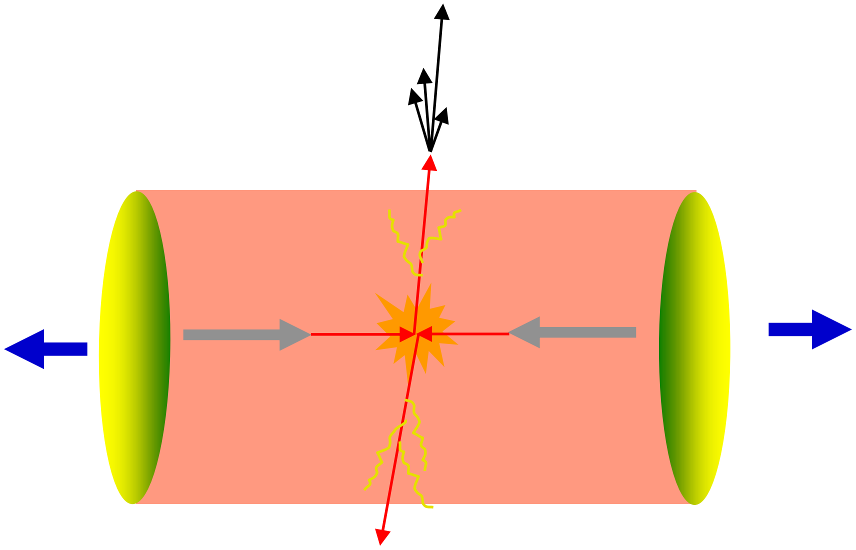


Where is the contribution from Beauty?

- **Heavy Flavor energy loss is an unsolved problem**
  - **Gluon density ~ 1000 expected from light quark data**
  - **Better agreement with the addition of inelastic E loss**
  - **Good agreement only if they ignore Beauty …**
- **Beauty dominates single electron spectra above 5 GeV**
- **RHIC upgrades will separate the Charm and Beauty contributions**

Partonic energy loss





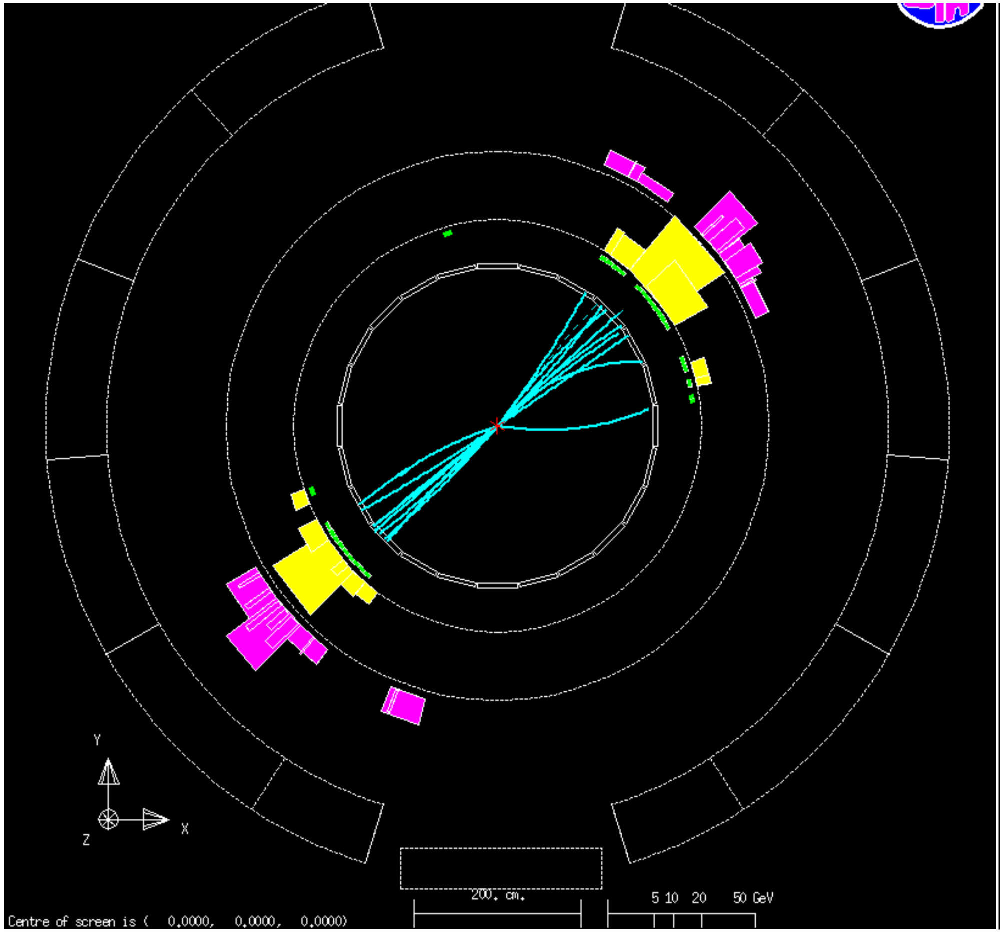
Energy loss $\Rightarrow$
suppression of leading hadron yield
The jet can't get out!

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

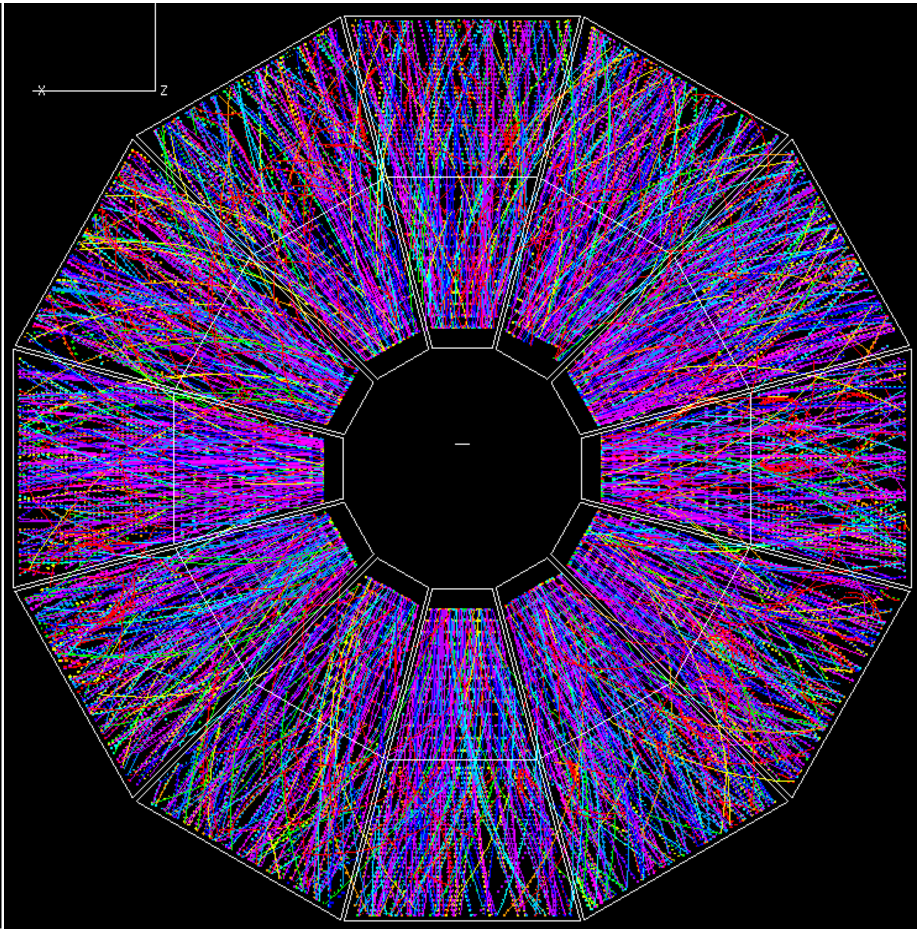
Binary collision scaling p+p reference

Jet Physics … it is easier to find one in e^+e^-

Jet event in e^+e^- collision

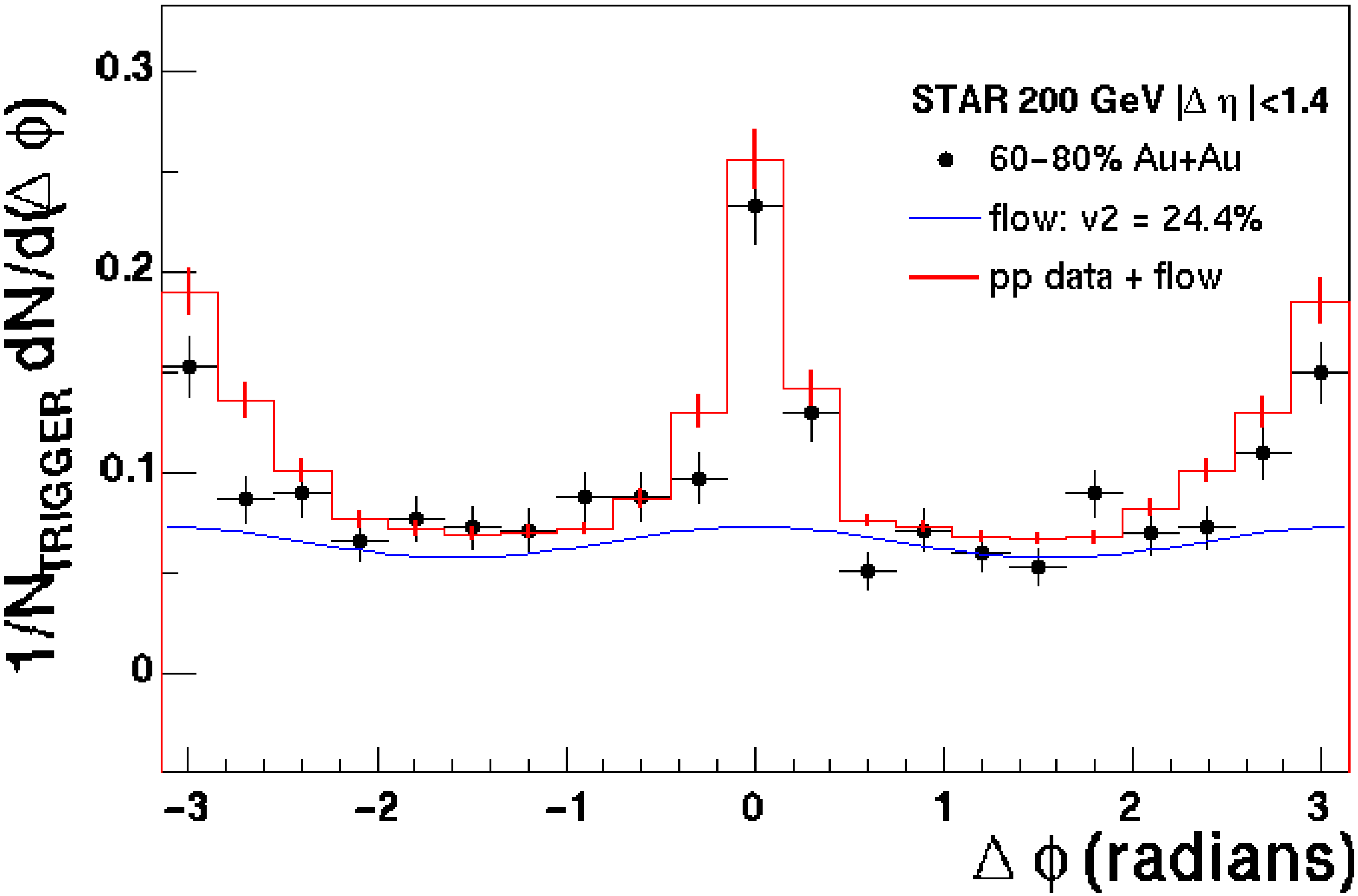


STAR Au+Au collision



Angular Distribution: Peripheral Au+Au data vs. pp+flow

$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$



Ansatz:

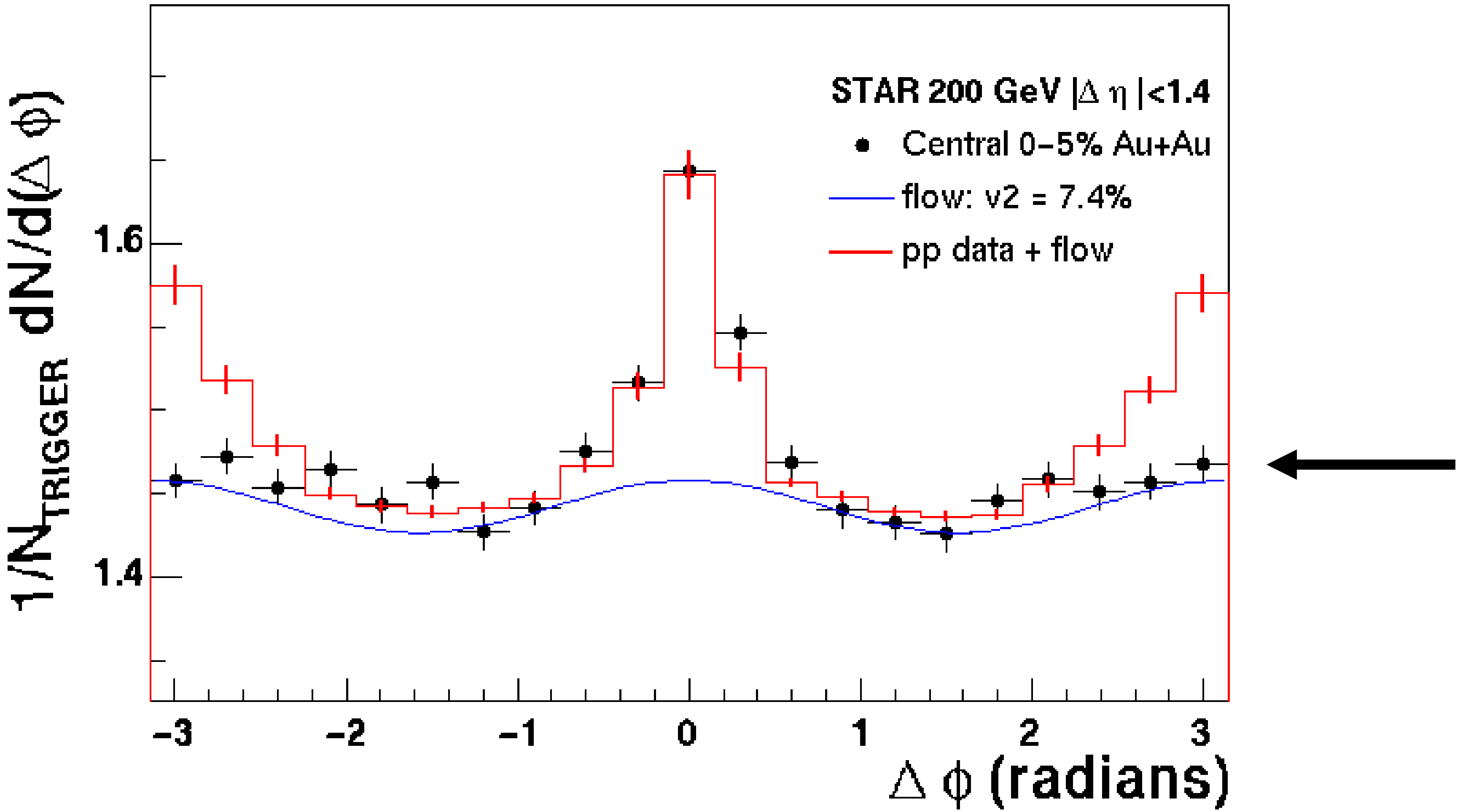
A high p_T triggered Au+Au event is a superposition of a high p_T triggered p+p event plus anisotropic transverse flow

v_2 from reaction plane analysis

"*A*" is fit in non-jet region (0.75<|Δϕ|<2.24)

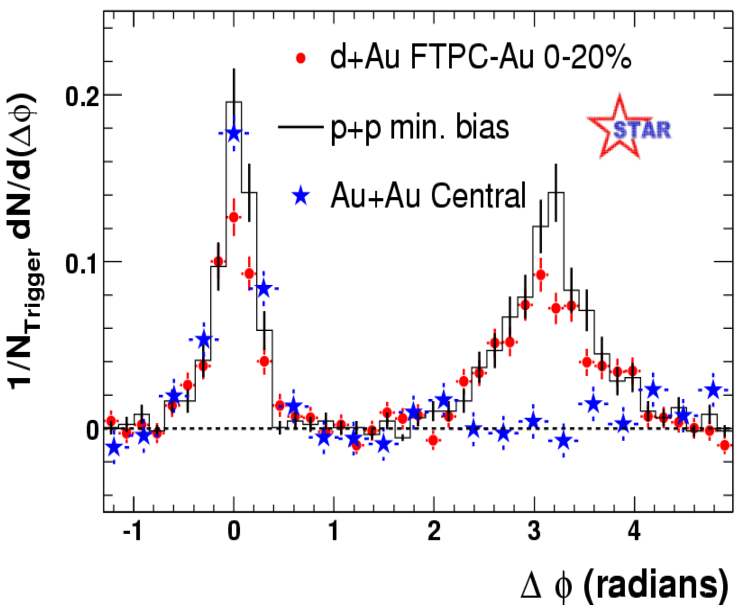
Angular Distribution: Central Au+Au data vs. pp+flow

$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$

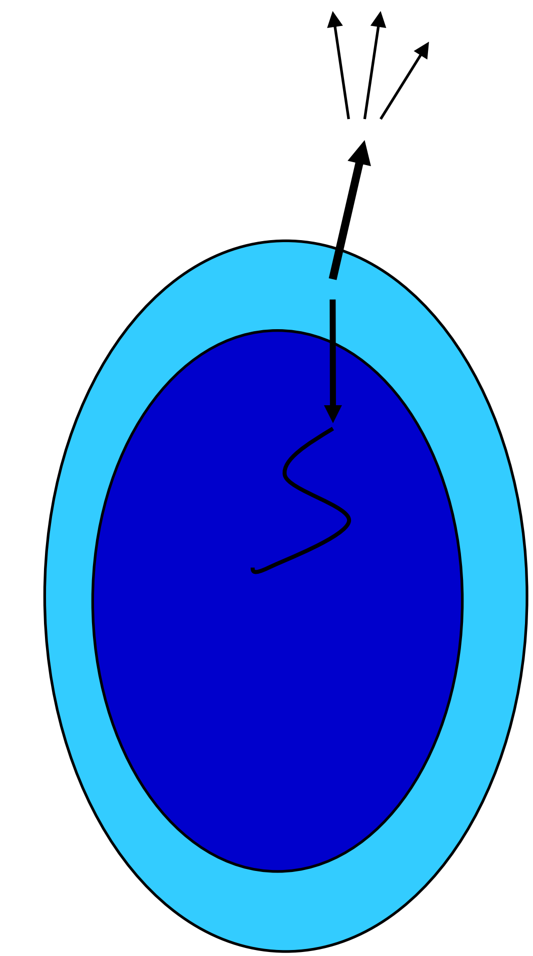


Lessons learned – Dark Matter … its opaque

- The backward going jet is missing in central Au-Au collisions when compared to p-p data + flow
- The backward going jet is not suppressed in d-Au collisions
- These data suggest opaque nuclear matter and surface emission of jets

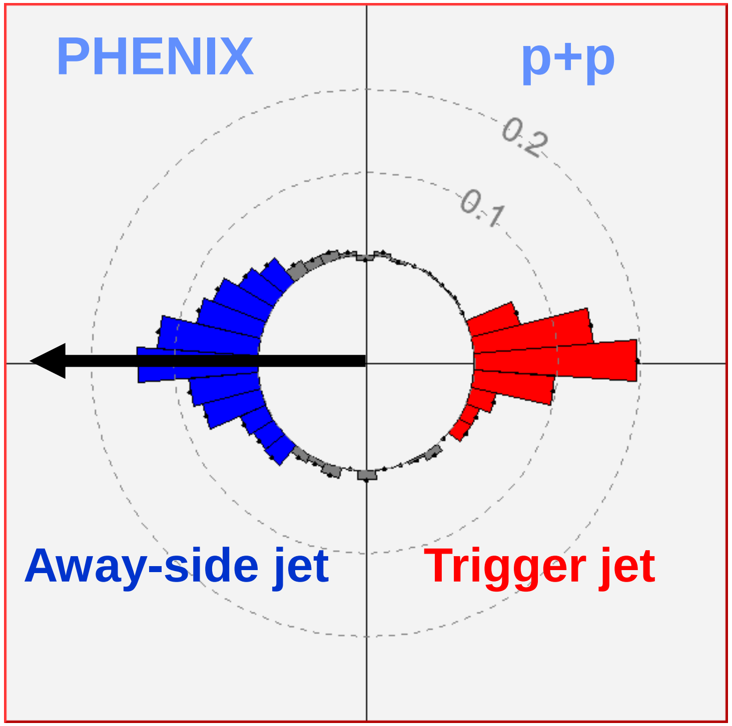


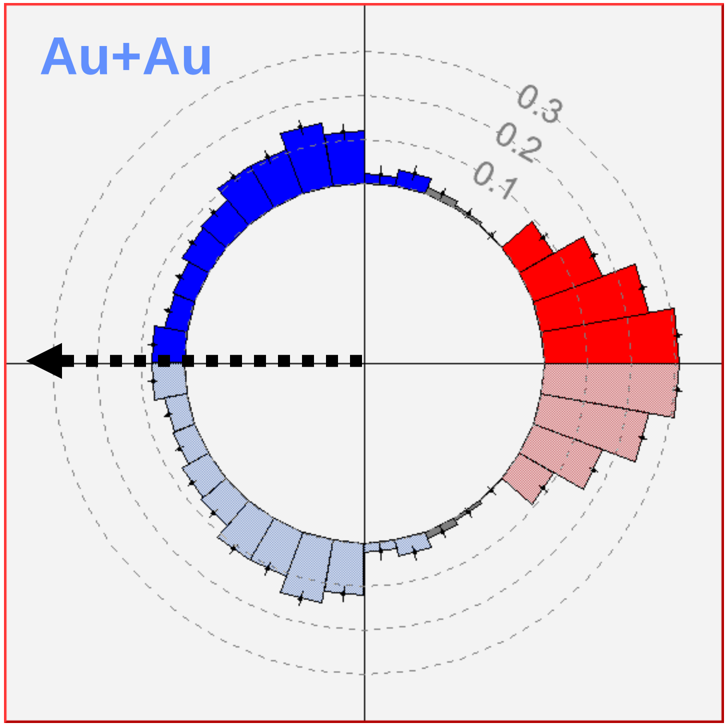
Surface emission



Suppression of back-to-back correlations in central Au+Au collisions

Where does the E_{loss} go?

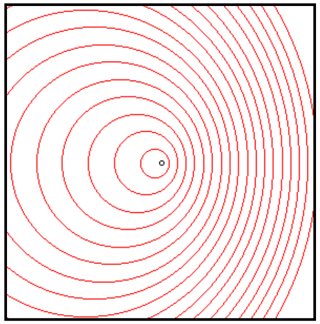




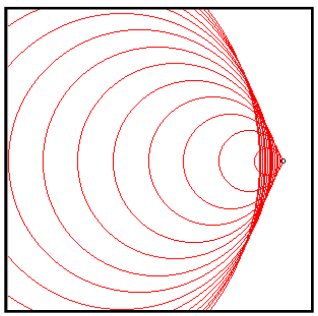
Lost energy of away-side jet is redistributed to rather large angles!

Mach Cone: Theory vs Experiment

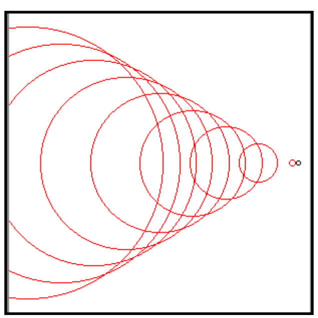
$v/u = 0.5$

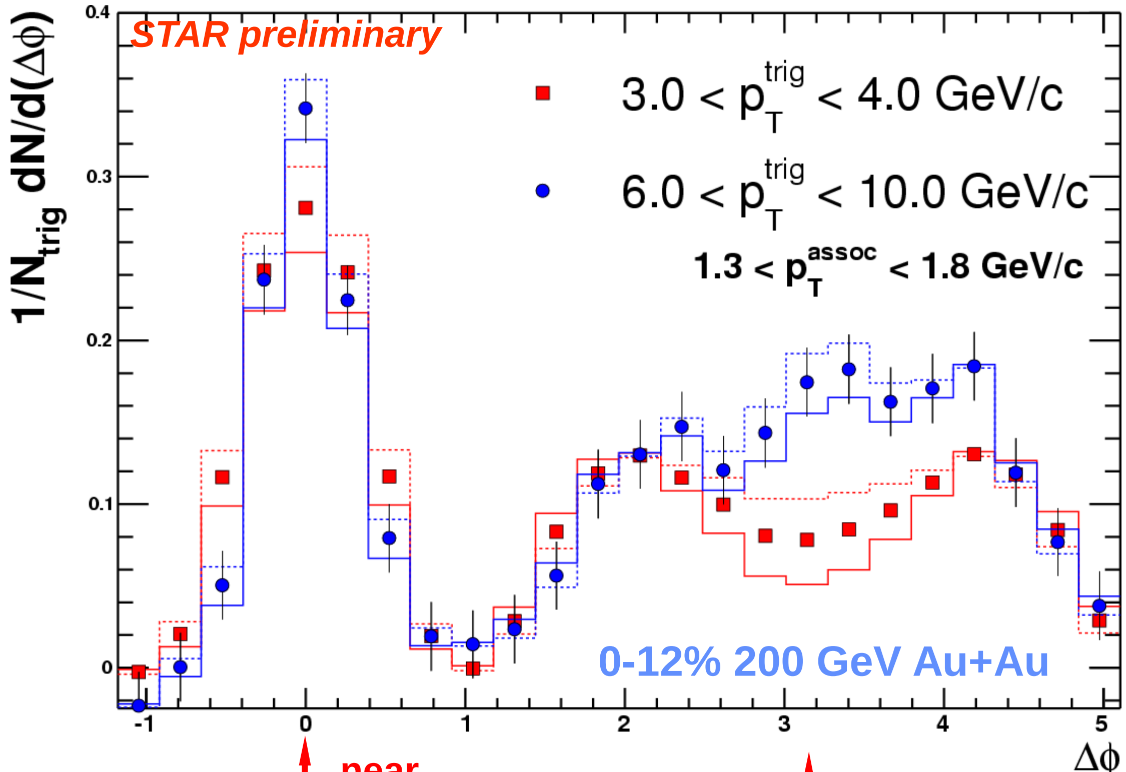


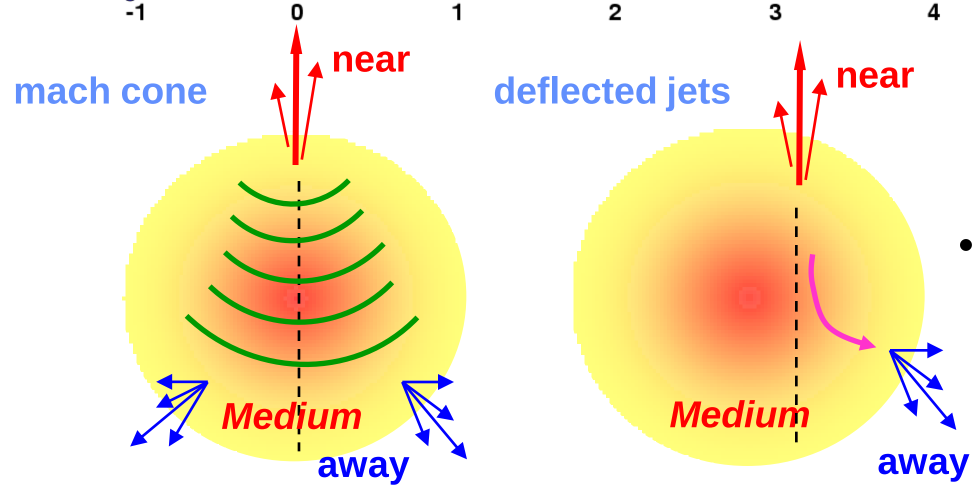
$v/u = 1.1$



$v/u = 2$







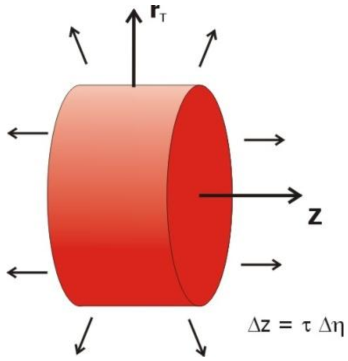
- **Hint of a Mach Cone?**

Nuclear Fluid Dynamics ... with friction

- **The energy momentum tensor for a viscous fluid**

$$T^{\mu\upsilon} = (\varepsilon + p)\, u^{\mu} u^{\upsilon} - p g^{\mu\nu} + \Pi^{\mu\nu}$$

- **Conservation laws:** $\partial_{\mu} T^{\mu\upsilon} = 0$ **and** $\partial_{\mu} j^{\mu} = 0$ **where** $j_i^{\mu} = \rho_i\, u^{\mu}$
- **The elements of the shear tensor, $\Pi^{\mu\nu}$, describe the viscosity of the fluid and can be thought of as velocity dependent 'friction'**
- **Simplest case: scaling hydrodynamics**
  - assume local thermal equilibrium
  - assume longitudinal boost-invariance
  - cylindrically symmetric transverse expansion
  - no pressure between rapidity slices
  - conserved charge in each slice



- **Initially expansion is along the Z axis, so viscosity resists it**
  - Conservation of $T^{\mu\nu}$ means that energy and momentum appear in the transverse plane … viscosity drives radial flow
- **Viscosity is velocity dependent friction so it dampens v_2**
  - Viscosity (η/z) must be near zero for elliptic flow to be observed

AdS/CFT correspondence   (from H. Liu)

Maldacena (1997) Gubser, Klebanov, Polyakov, Witten

N = 4 Super-Yang-Mills theory with SU(N) ⟺ **A string theory in 5-dimensional anti-de Sitter spacetime**

anti-de Sitter (AdS) spacetime: homogeneous spacetime with a negative cosmological constant.

***N* = 4 Super-Yang-Mills (SYM):**

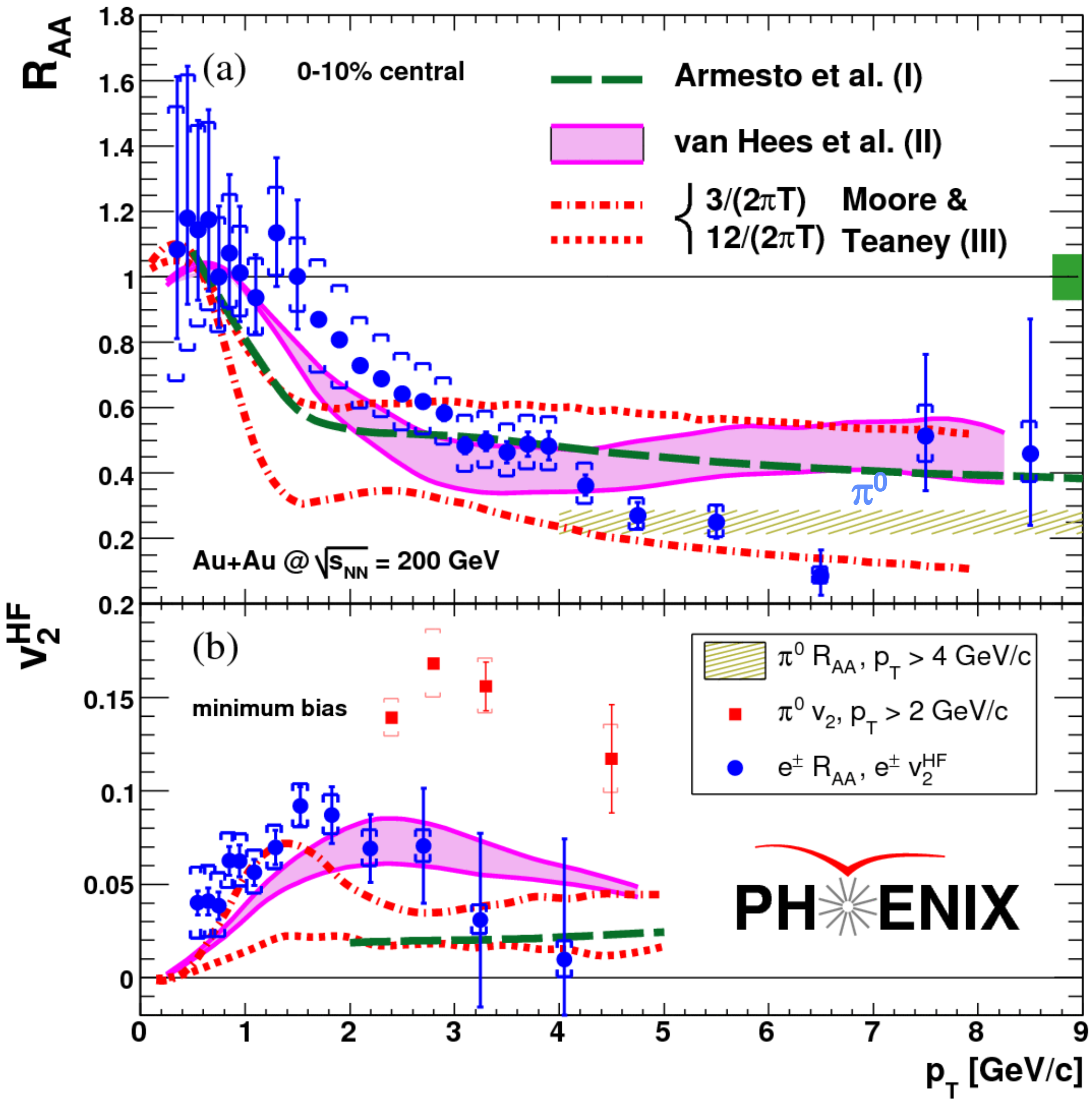
maximally supersymmetric gauge theory

scale invariant

A special relative of QCD

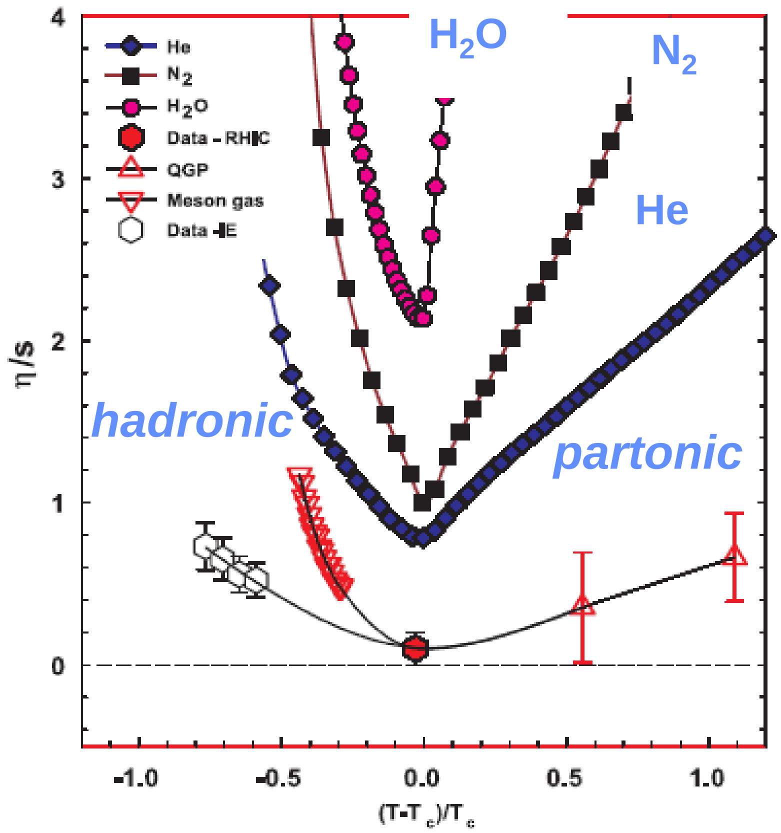
The value $\frac{\eta}{s} = \frac{1}{4\pi}$ turns out to be universal for all strongly coupled QGPs with a gravity description.   It is a universal lower bound.

PHENIX PRL 98, 172301 (2007)



- R_{AA} of heavy-flavor electrons in 0%–10% central collisions compared with π^0 data and model calculations
- V_2 of heavy-flavor electrons in minimum bias collisions compared with π^0 data and the same models.
- Conclusion is that heavy flavor flow corresponds to η/s at the conjectured QM lower bound

Viscosity and the Perfect Fluid



Caption: *The viscosity to entropy ratio versus a reduced temperature.*

Lacey et al. PRL 98:092301(07)
hep-lat/0406009; hep-ph/0604138
Csernai et al, PRL97, 152303(06)

The universal tendency of flow to be dissipated due to the fluid's *internal friction* results from a quantity known as the shear viscosity. All fluids have non-zero viscosity. The larger the viscosity, the more rapidly small disturbances are damped away.

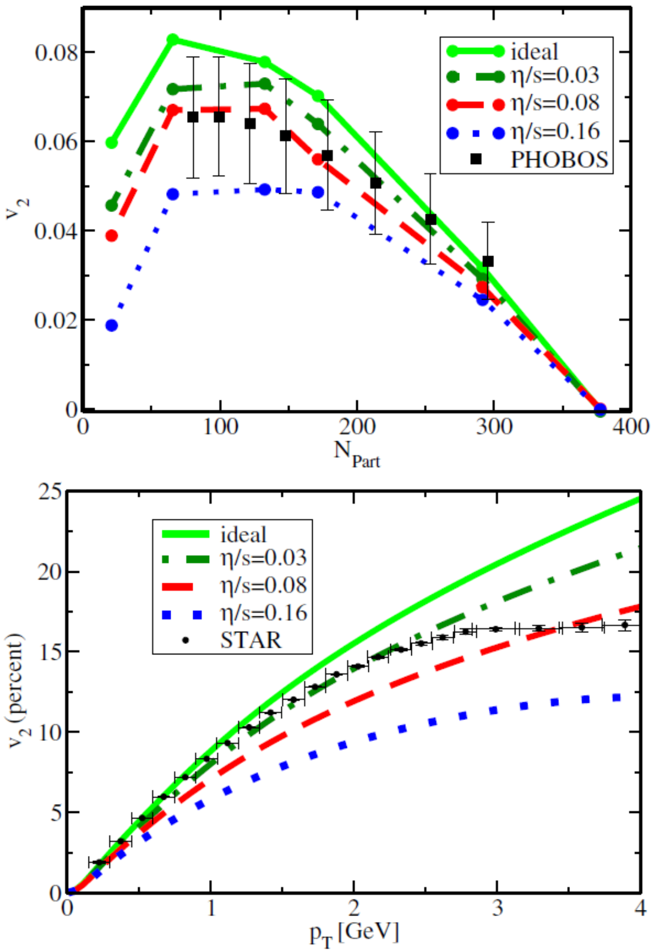
Quantum limit: $\eta/s_{AdS/CFT}$ ~ $1/4\pi$

pQCD limit: ~ 1

At RHIC: ideal ($\eta/s = 0$) hydrodynamic model calculations fit to data ⇒

Perfect Fluid at RHIC?

PRL 99, 172301 (2007) … new insights



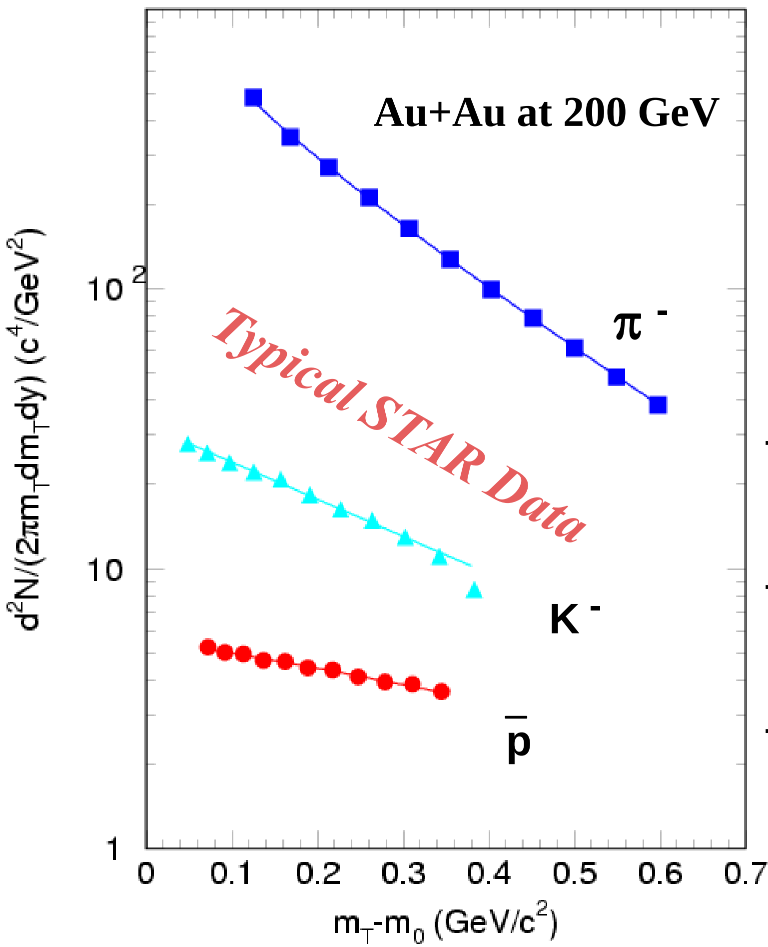
- **Romatschke[2] perform relativistic viscous hydrodynamics calculations**
- **Data on the integrated elliptic flow coefficient v_2 are consistent with a ratio of viscosity over entropy density up to $\eta/s \approx 0.16$**
- **But data on minimum bias v_2 seem to favor a much smaller viscosity over entropy ratio, below the bound from the anti–de Sitter conformal field theory conjecture**

Conclusions About Nuclear Matter at RHIC

- Its hot
  - Chemical freeze out at 175 MeV
  - Thermal freeze out at 100 MeV
- Its fast
  - Transverse expansion with an average velocity greater than 0.55 c
  - Large amounts of anisotropic flow (v_2) suggest hydrodynamic expansion and high pressure at early times in the collision history
- Its opaque
  - Saturation of v_2 at high p_T
  - Suppression of high p_T particle yields relative to p-p
  - Suppression of the away side jet
- There are hints that it is thermally equilibrated
  - Excellent fits to particle ratio data with equilibrium thermal models
  - Excellent fits to flow data with hydrodynamic models that assume equilibrated systems
  - Hints of heavy flavor flow
- And at has nearly zero viscosity and perhaps a Mach cone
  - Perhaps it is at or below the quantum bound from the AdS/CFT conjecture

Neils Bohr was almost right … he just didn't know about q and g

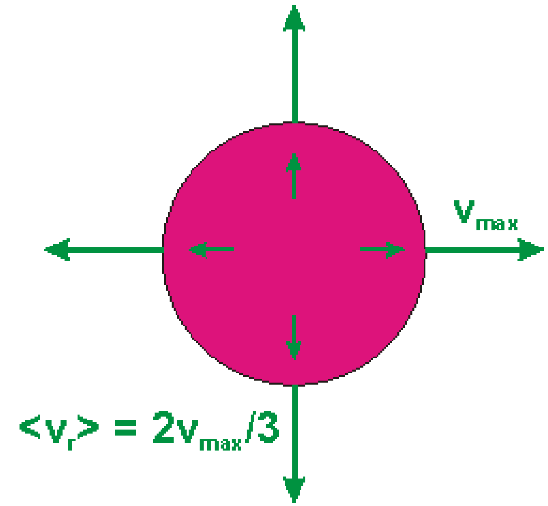
Transverse Radial Expansion: Isotropic Flow



T ≈ 215 MeV

T ≈ 310 MeV

T ≈ 575 MeV



Slopes decrease with mass. $\langle p_T \rangle$ and the effective temperature increase with mass.

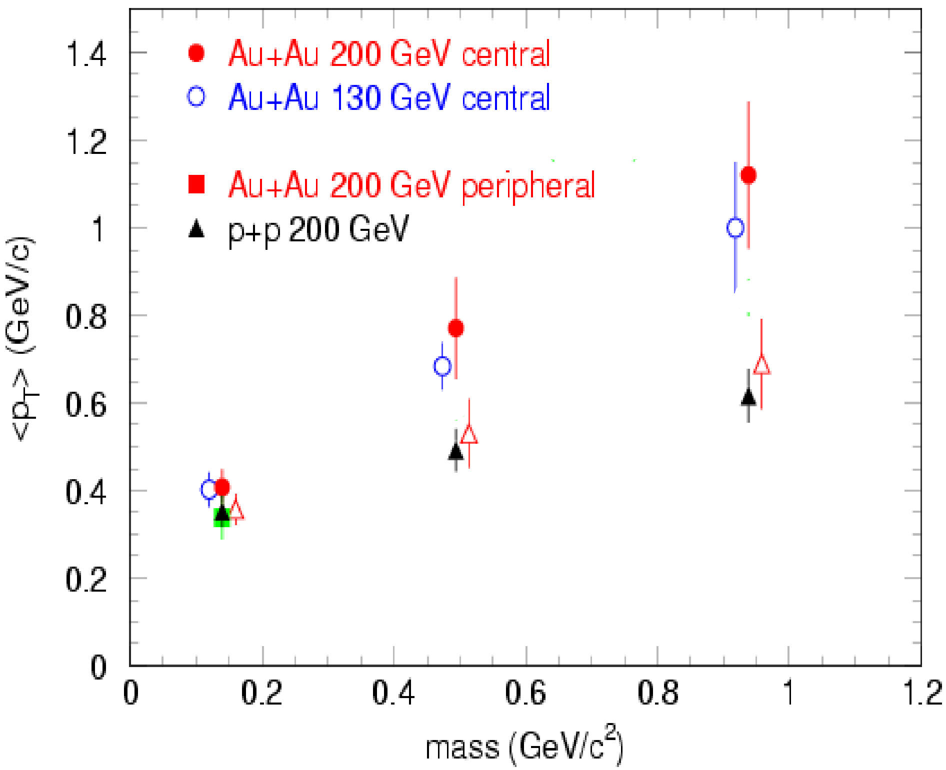
The transverse radial expansion of the source (flow) adds kinetic energy to the particle distribution. So the classical expression for E_{Tot}

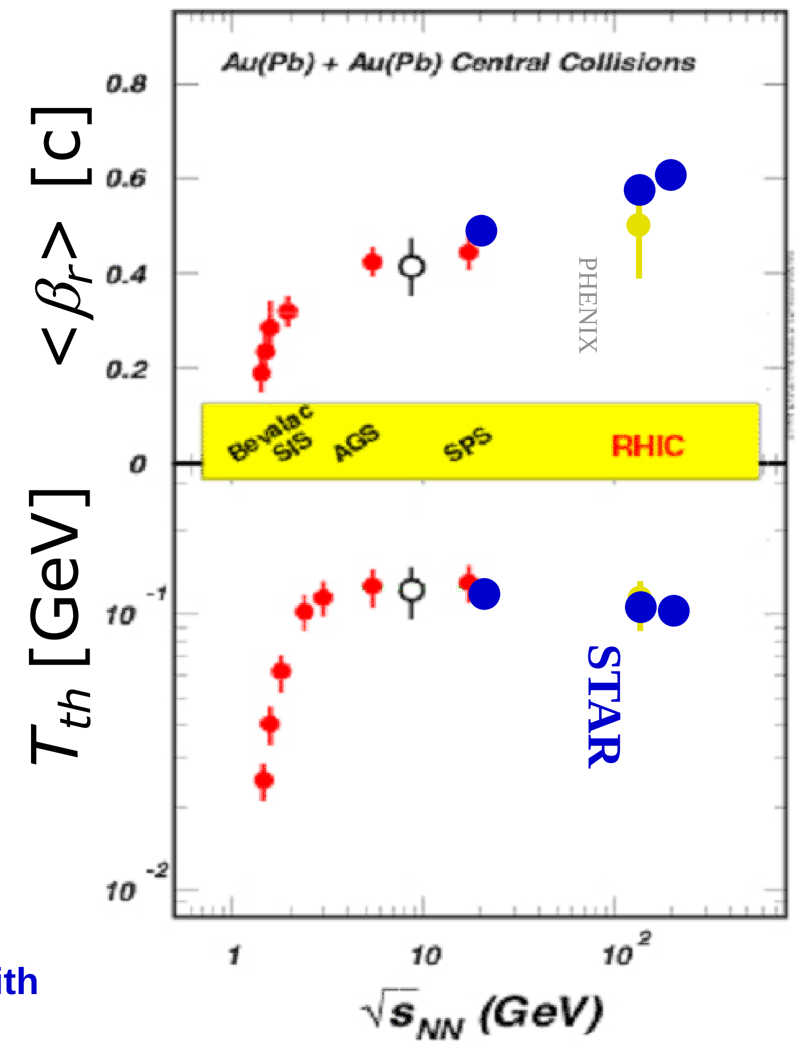
$$\bar{E} = \frac{3}{2}T + \frac{1}{2}mv^2$$

suggests a linear relationship

$$T_{Obs} = T_{KFO} + mass \times \bar{\beta}^2$$

Kinetic Freezeout from Transverse Flow





$\langle \beta_r \rangle$ (RHIC) = 0.55 ± 0.1 c

T_{KFO} (RHIC) = 100 ± 10 MeV

Thermal freeze-out determinations are done with the blast-wave model to find $\langle p_T \rangle$

Explosive Transverse Expansion at RHIC ⇒ High Pressure

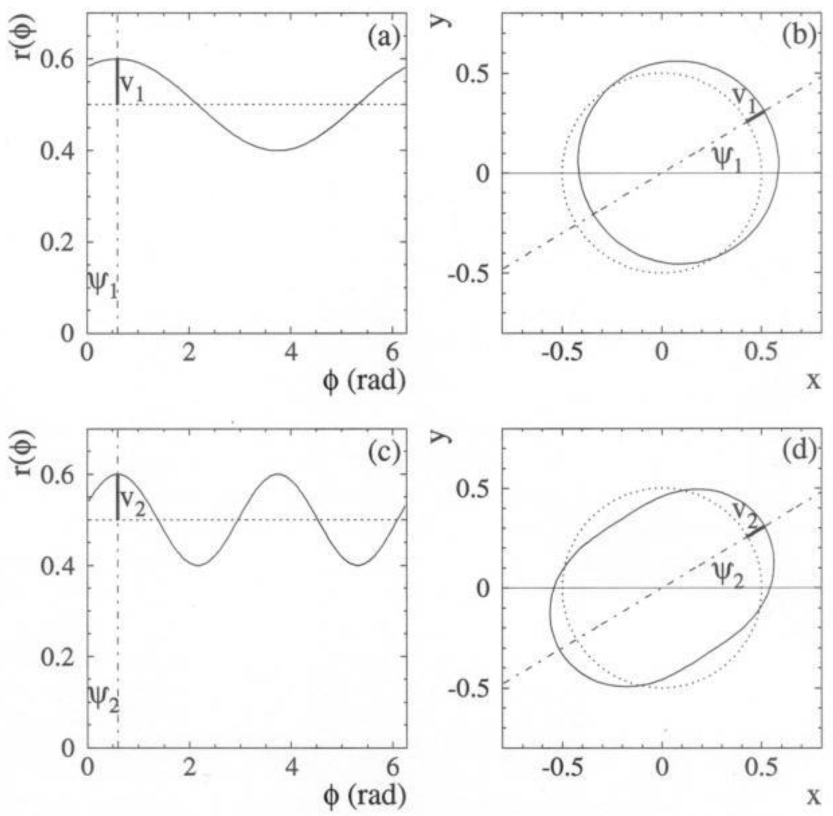
Interpreting Flow – order by order

If n=1: Directed Flow has a period of 2π (only one maximum)

- **v_1 measures whether the flow goes to the left or right – whether the momentum goes with or against a billiard ball like bounce off the collision zone**

If n=2: Elliptic flow has a period of π (two maximums)

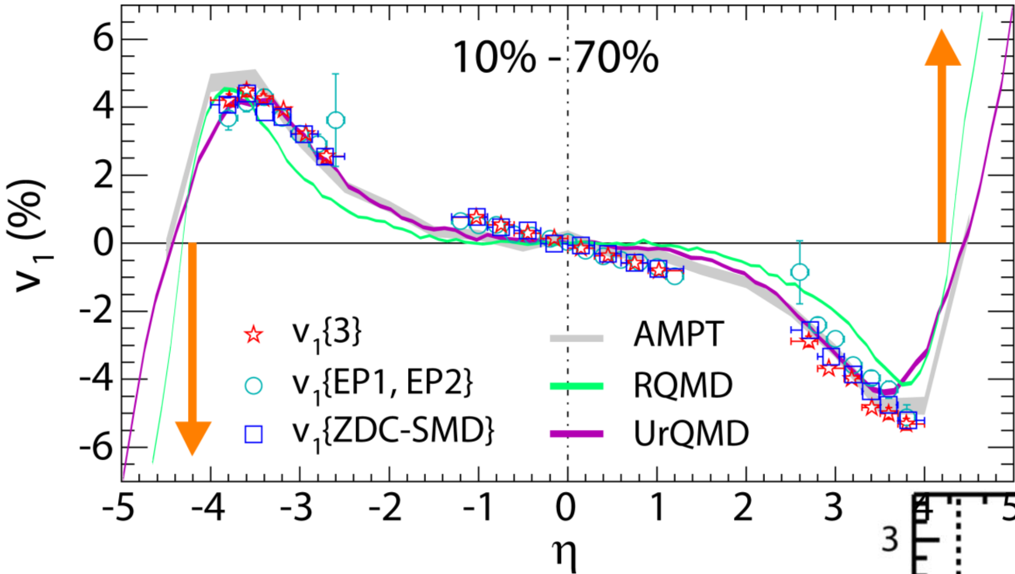
- **v_2 represents the elliptical shape of the momentum distribution**



$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots\right)$$

isotropic **directed** **elliptic**

V_1: Pions go opposite to Neutrons



62 GeV Data

At low energy, the pions go in the opposite direction to the 'classical' bounce of the spectator baryons

200 GeV Data

At the top RHIC energy, the pions don't flow (v_1 at η=0) but at ALICE, v1 may have a backward wiggle. Reveals the EOS