Highlights of RHIC Results

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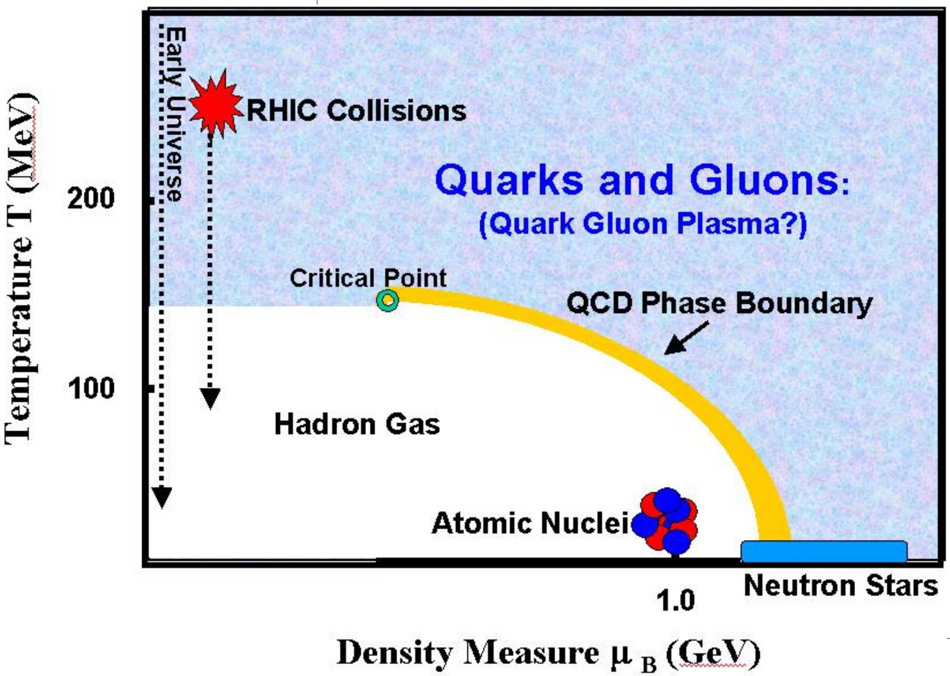
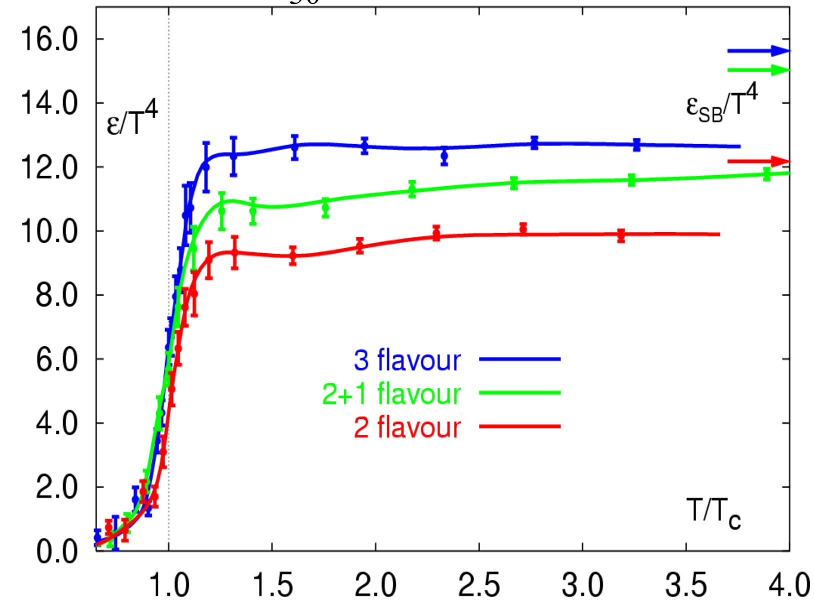
2008 APCTP Workshop on
"Nuclear Physics in Science Business Belt:
Future Heavy Ion Accelerator in Korea"

QCD Phase Transition

- The colliding nuclei at RHIC energies would melt from protons and neutrons into a collection of quarks and gluons
- A QCD phase transition that the universe last went through ~1μs after the Big Bang



$$\varepsilon_{SB}(T) = \frac{\pi^2}{30}(N_{bosons} + 7/8\, N_{fermions})T^4$$

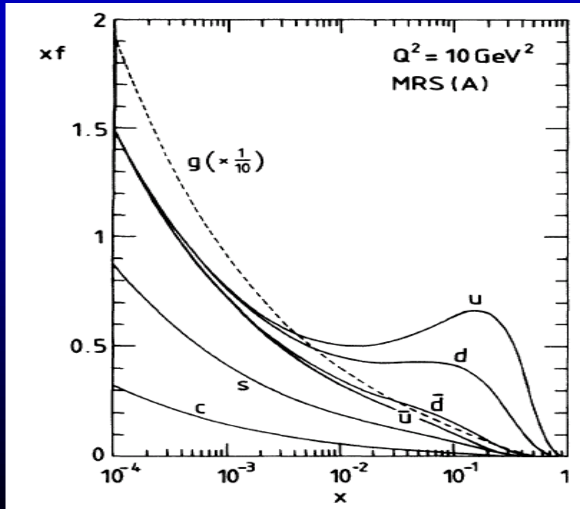


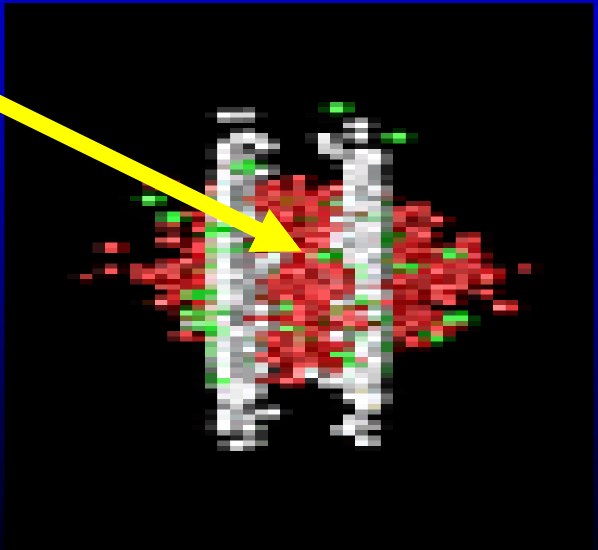
T_c ~ 170 MeV; ε ~ 1 GeV/fm^3

How to make such a condition and show that such a transition is occurred?

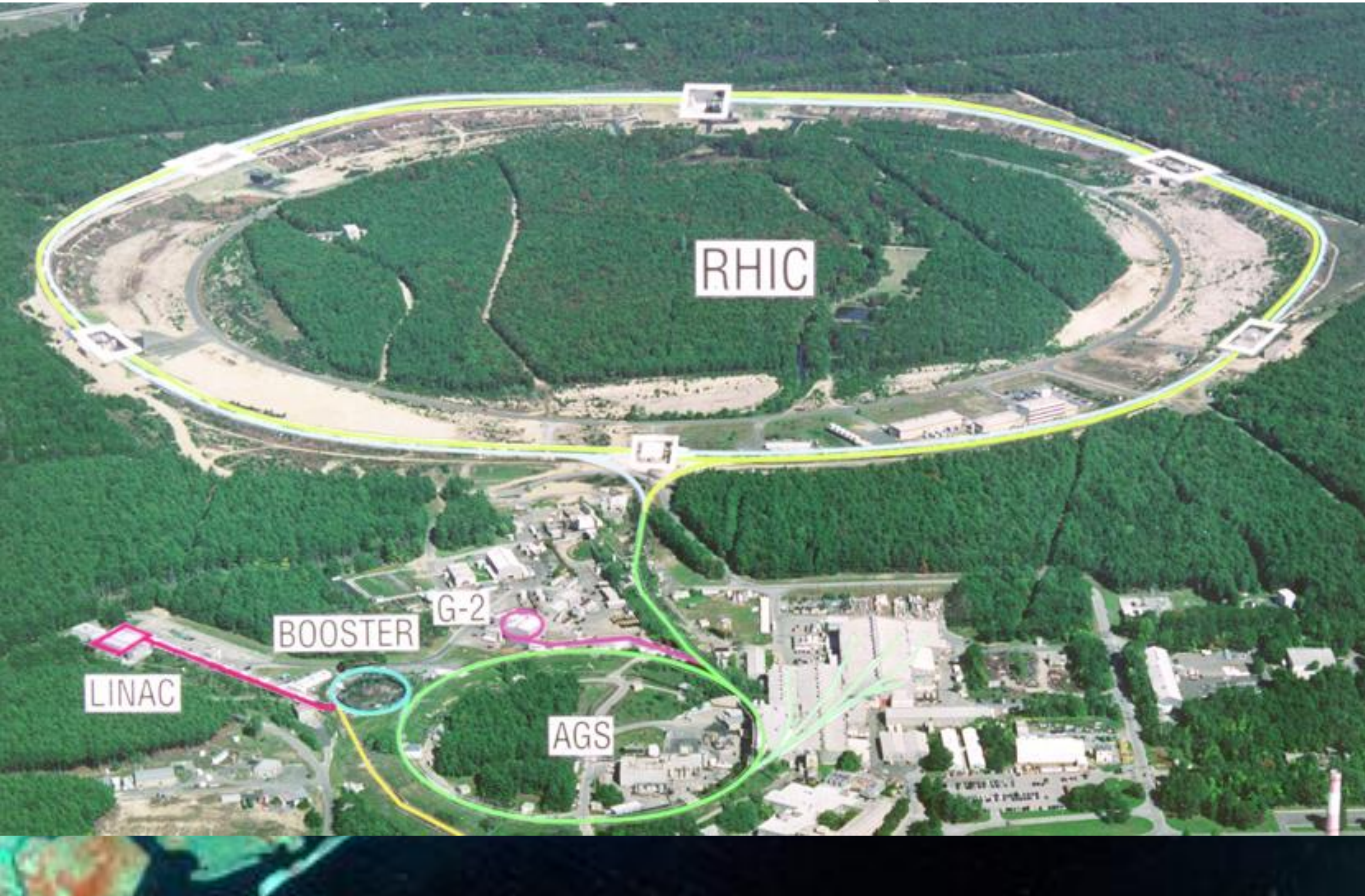
RHIC FAQ's

- What is RHIC?
  - Relativistic Heavy Ion Collider
- What does it do?
  - Collides Heavy Ions, Light Ions, protons, polarized protons
- To what energy?
  - 200 GeV x 200 GeV (pp to 500x500)
- How does it make heat?
  - By colliding Heavy ions which leave behind a hot vacuum i.e Baryon number =0



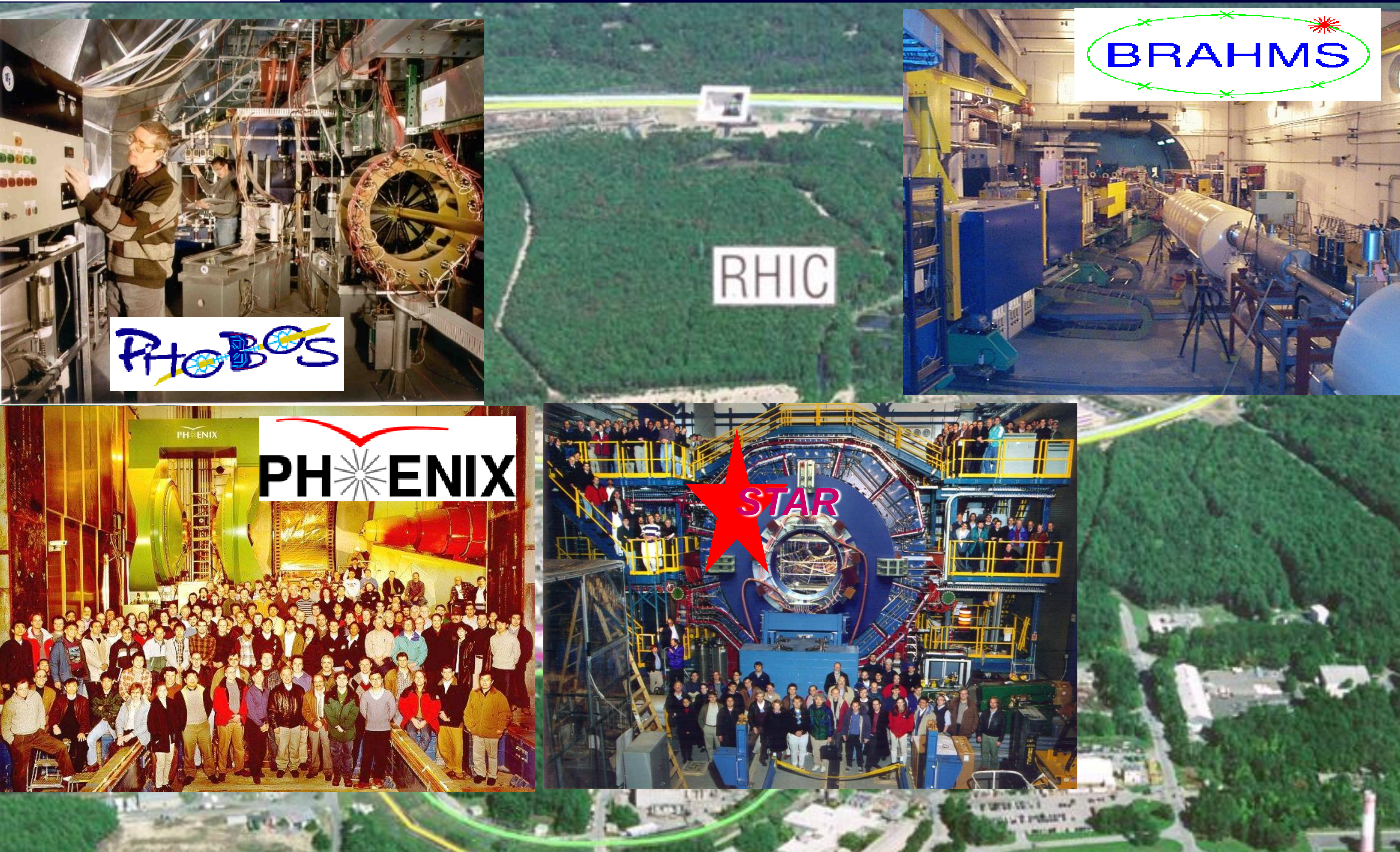


RHIC



RHIC

RHIC's Experiments

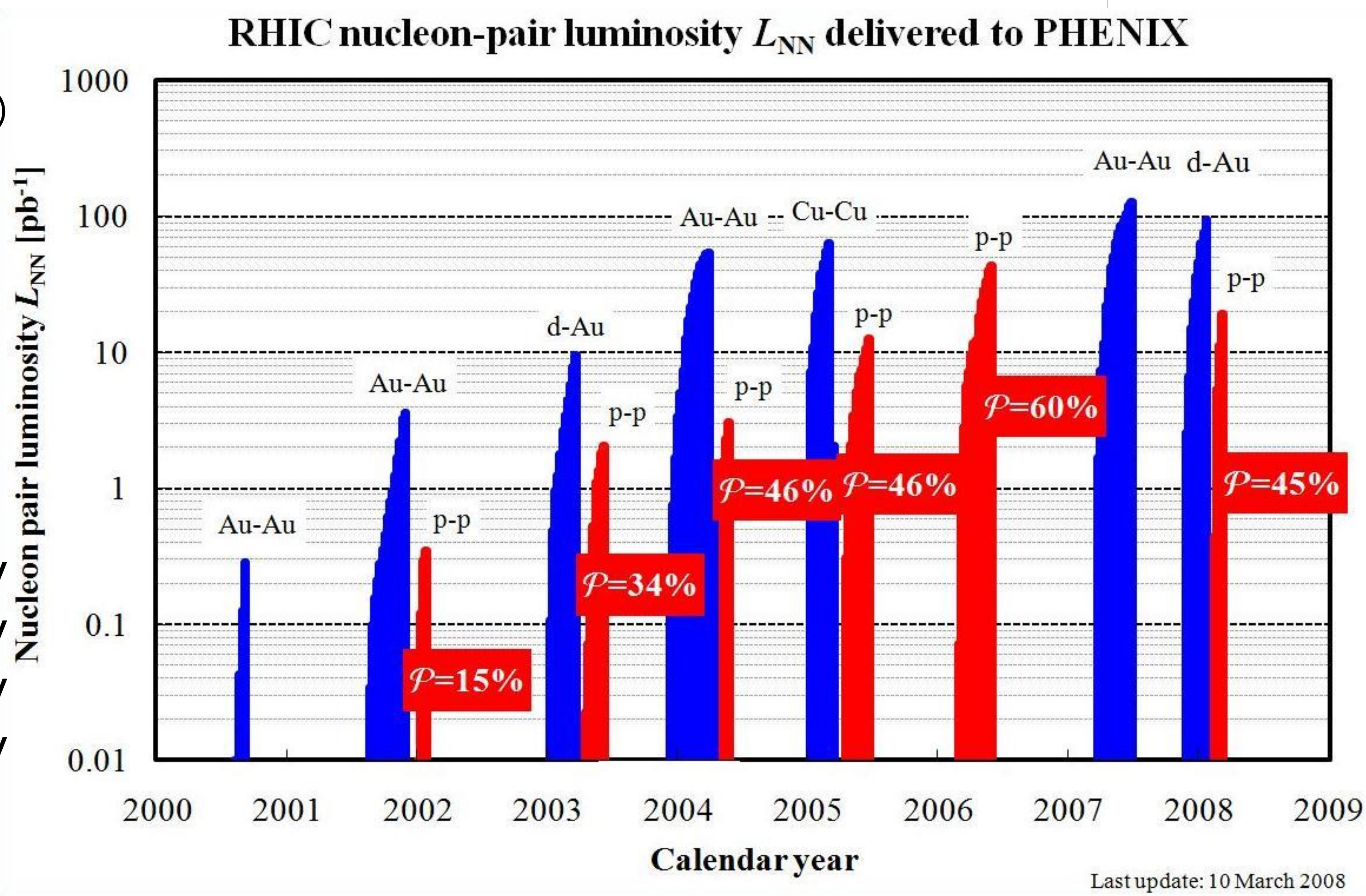


RHIC runs (2001-2008)

Beam species:
p+p (polaized)
d+Au
Cu+Cu
Au+Au

Energy:
$s_{NN}^{1/2}$=200 GeV

Also @ 130 GeV
62 GeV
56 GeV
22 GeV
(10 GeV)



130 GeV ⟵ 200 GeV ⟶

RHIC Results

- Huge amount of data are accumulated from RHIC in the past 8 years
- Many interesting phenomena are observed
  - Strong elliptic flow of hadrons
  - Strong suppression of high pT jets
  - Modification of jet correlation
  - Strong suppression of J/ψ
  - Energy loss and flow of heavy quarks
  - Enhanced production of lepton pairs and photons
- These observations are consistent with formation of high temperature, high density partonic matter

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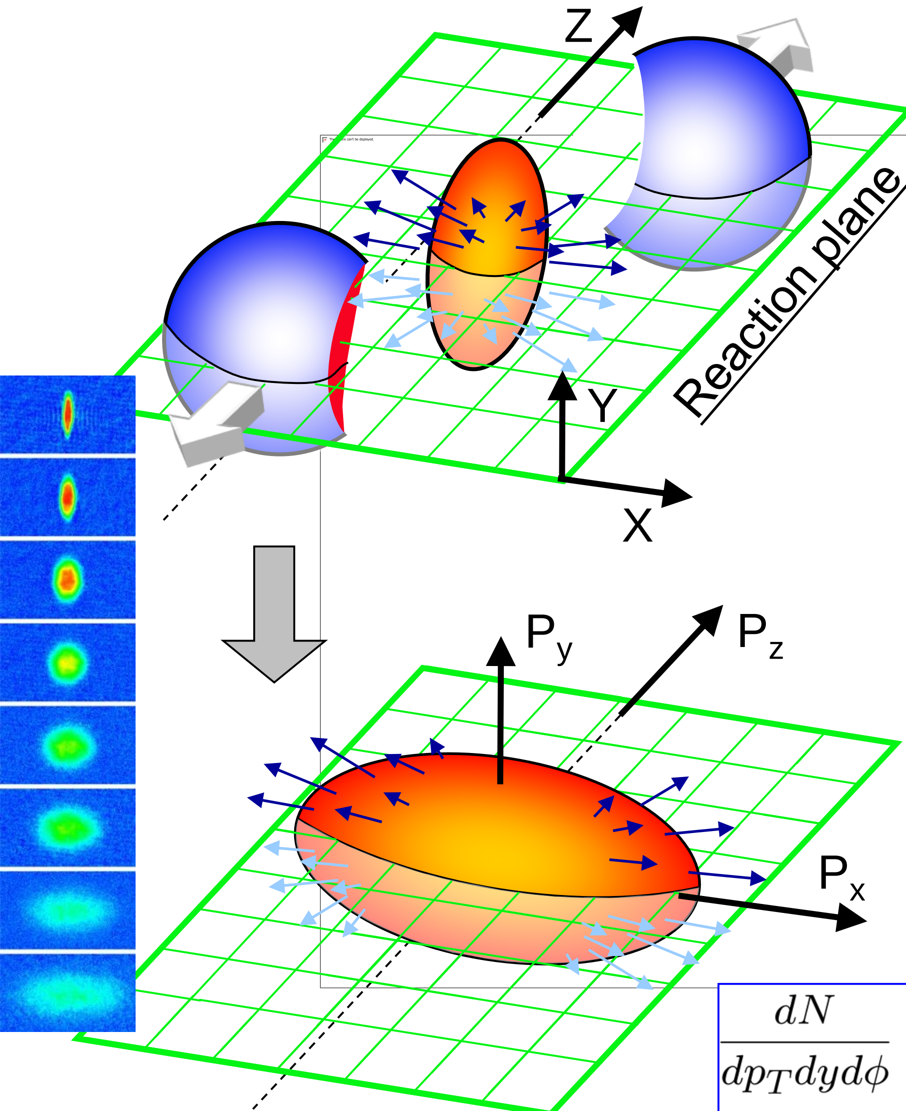
Elliptic flow

v_2

Why Elliptic Flow ?



$$\phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

- Elliptic flow is generated early when the system is asymmetric: sensitive to early dynamics
- Pressure gradient is largest in the shortest direction of the ellipsoid
- Spatial anisotropy is transformed into momentum anisotropy as the system expands
- Maximum (Minimum) number of particles at Φ=0,π (Φ=π/2,3π/2)
- Elliptic flow (v_2) is defined by the 2nd coefficient of Fourier expansion, having the period of π

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

$$v_2 = \langle \cos(2\phi) \rangle$$

Azimuthal Anisotropy and Flow

For measured particles, azimuthal distribution w.r.t. the reaction plane (i.e. ϕ) can be expressed as Fourier series:

$$dN/d\phi = (1/2\pi)\,(1 + \Sigma\, 2v_n \cos(n\phi))$$

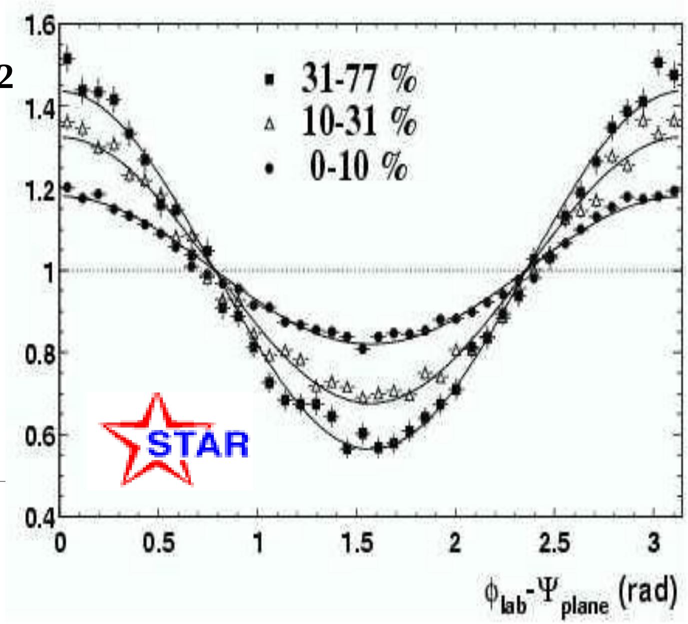
1) "Directed" flow if n=1 :

Shows the anisotropy having the period of 2π (only one maximum)

2) "Elliptic" flow if n=2 :

Shows the anisotropy having the period of π (two maximums)

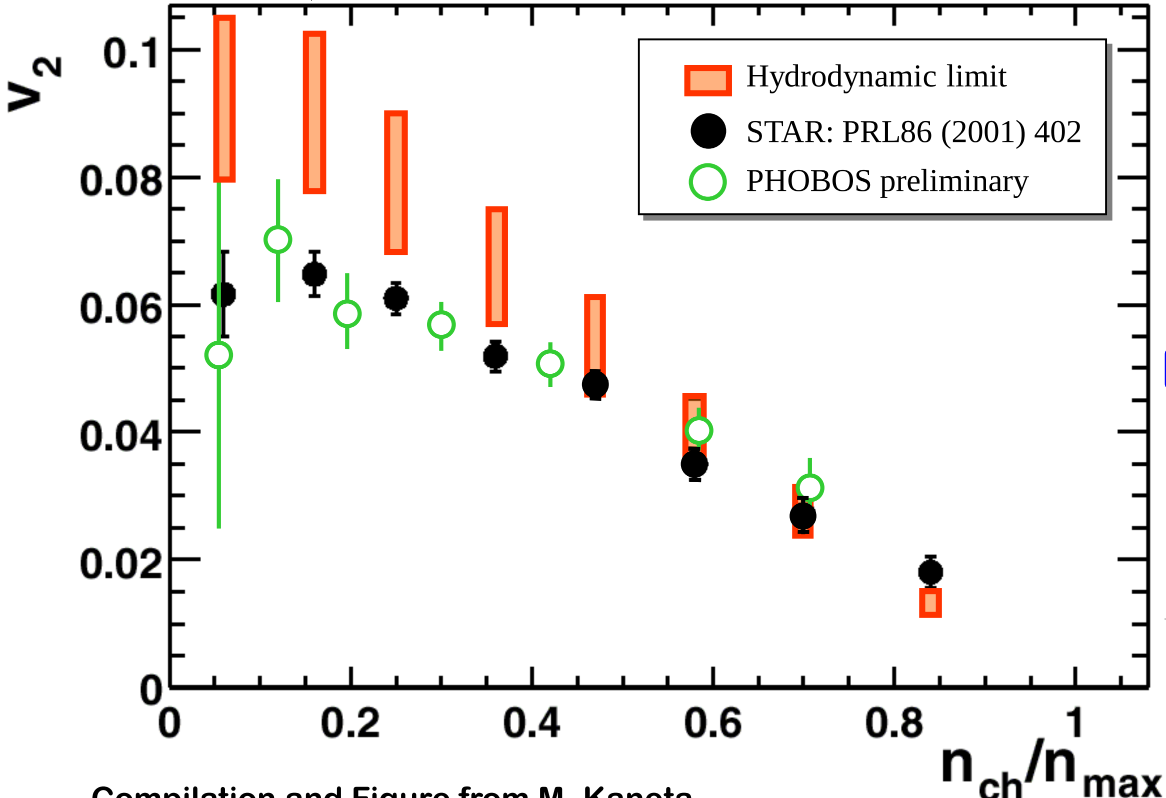
v_2

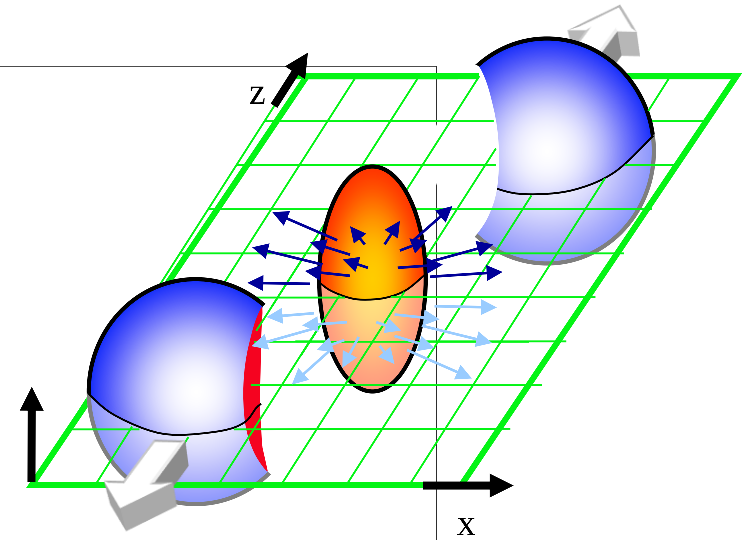


Centrality Dependence of Elliptic Flow

Parameterize *azimuthal anisotropy* of charged particles as

$$1 + 2\, v_2 \cos(2\,\phi)$$





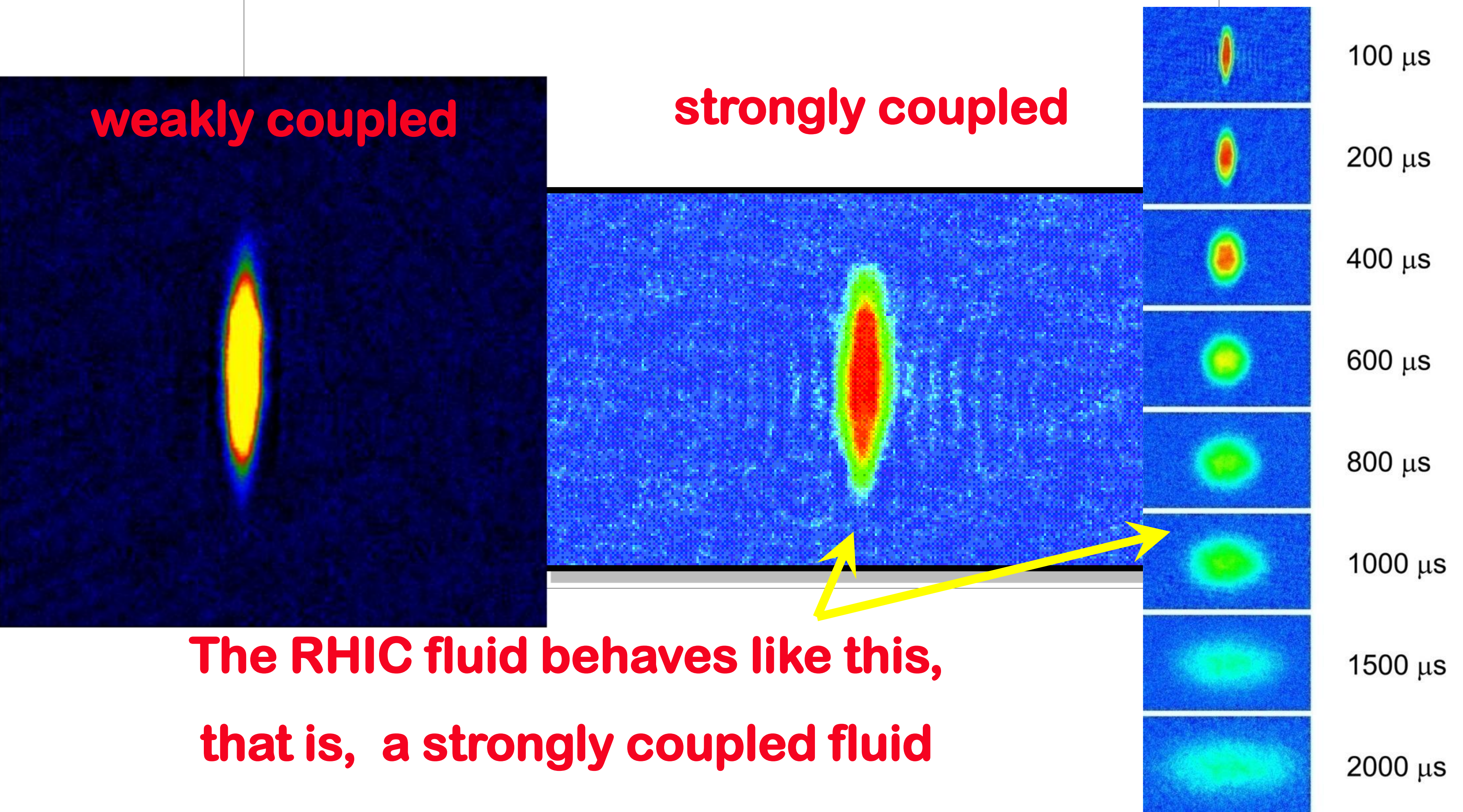
Evidence that initial spatial asymmetry is efficiently translated to momentum space (as shown by a hydrodynamic description)

Compilation and Figure from M. Kaneta

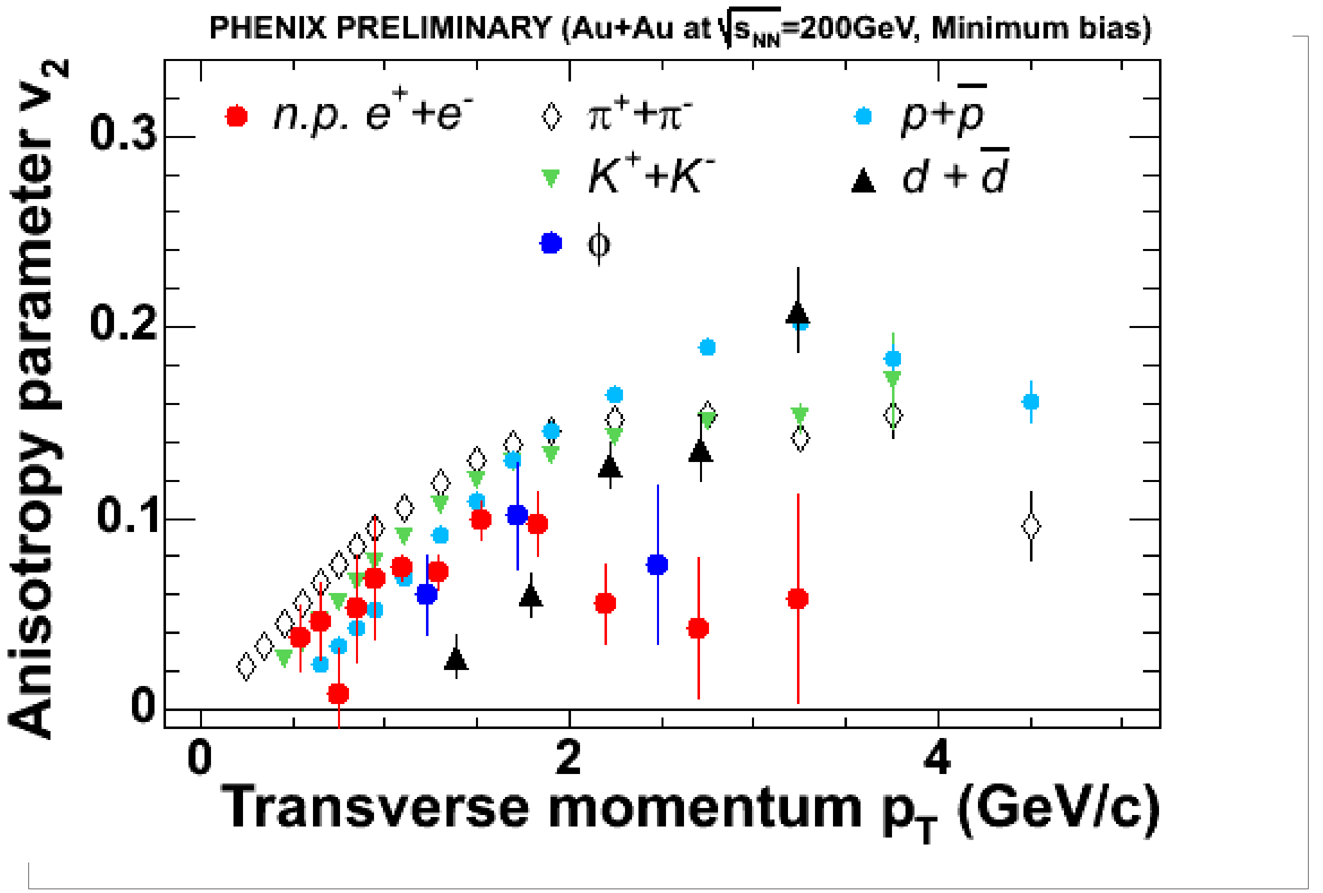
(PHOBOS : Normalized Paddle Signal)

Anisotropic Flow

- **Same phenomena observed in gases of strongly interacting atoms**
  - **M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas**
    Science **298** 2179 (2002)

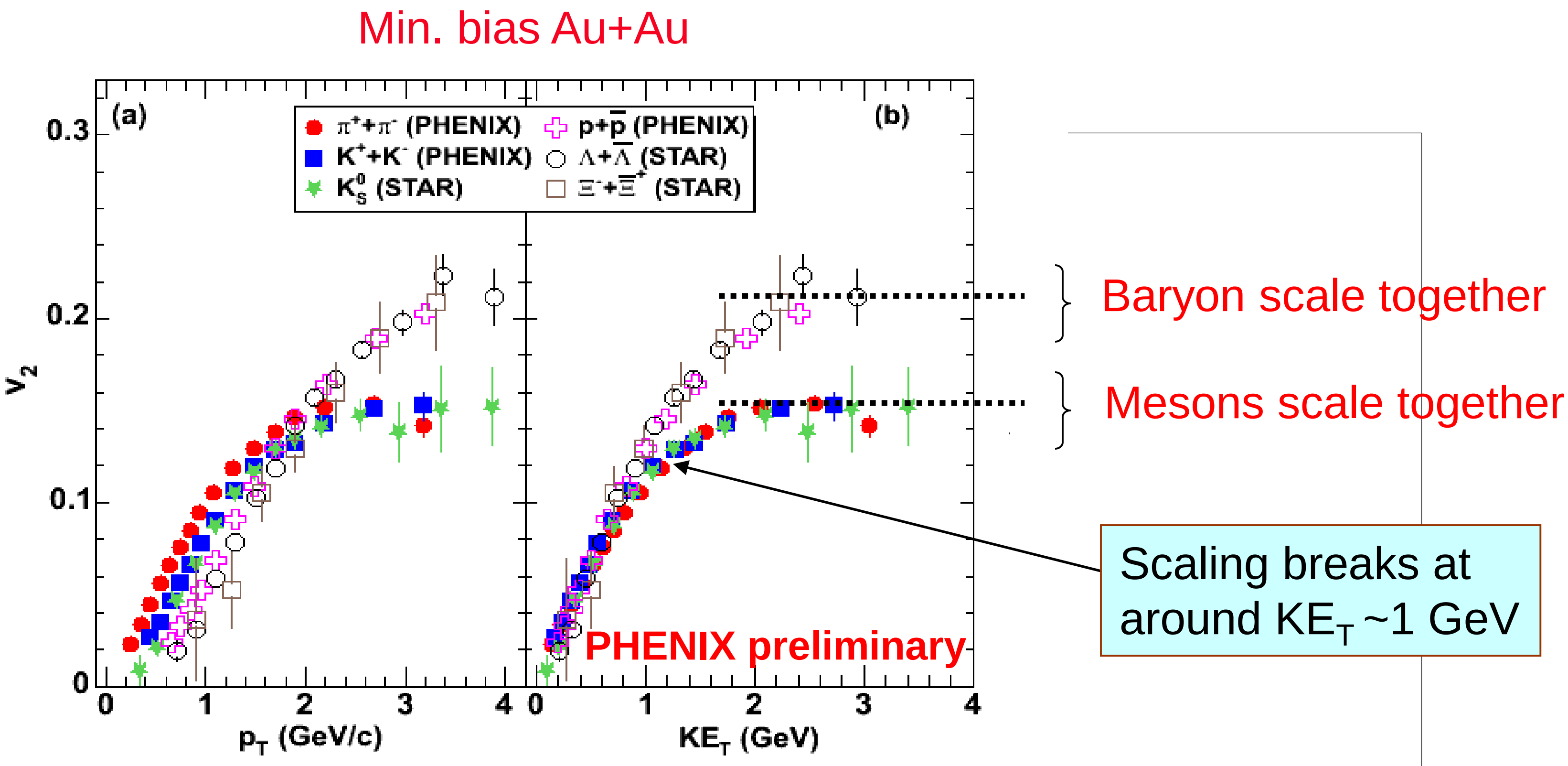


v2 of identified particles in PHENIX



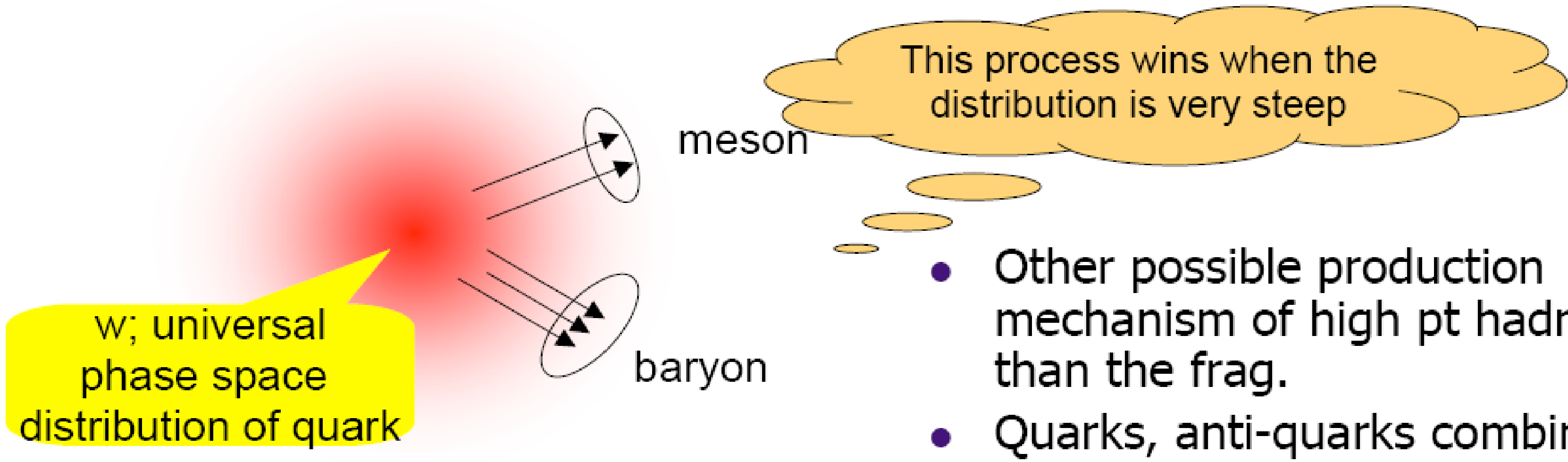
Significant elliptic flow observed for all identified particles

Transverse kinetic energy as a scaling variable



- Pressure gradients convert some work into kinetic energy
- Hence, KE_T is a natural variable to use for testing hydrodynamic behavior
- Very good scaling of v_2 with KE_T seen for $KE_T \leq 1$ GeV
- Two separate branches appear for mesons and baryons at $KE_T > 1$ GeV
- Hint of quark degrees of freedom due to partonic flow

Quark Recombination Model



$$E\frac{d^3N_M}{d^3p} \approx C_M \cdot w^2(p_t/2), \quad E\frac{d^3N_B}{d^3p} \approx C_B \cdot w^3(p_t/3)$$

$$\frac{dN_M}{d\phi} \propto (1+2v_{2,q}\cos 2\phi)^2 \approx (1+4v_{2,q}\cos 2\phi) \qquad \frac{dN_B}{d\phi} \propto (1+2v_{2,q}\cos 2\phi)^3 \approx (1+6v_{2,q}\cos 2\phi)$$

$$v_{2,M} \approx 2v_{2,q}(p_t/2), \quad v_{2,B} \approx 3v_{2,q}(p_t/3)$$

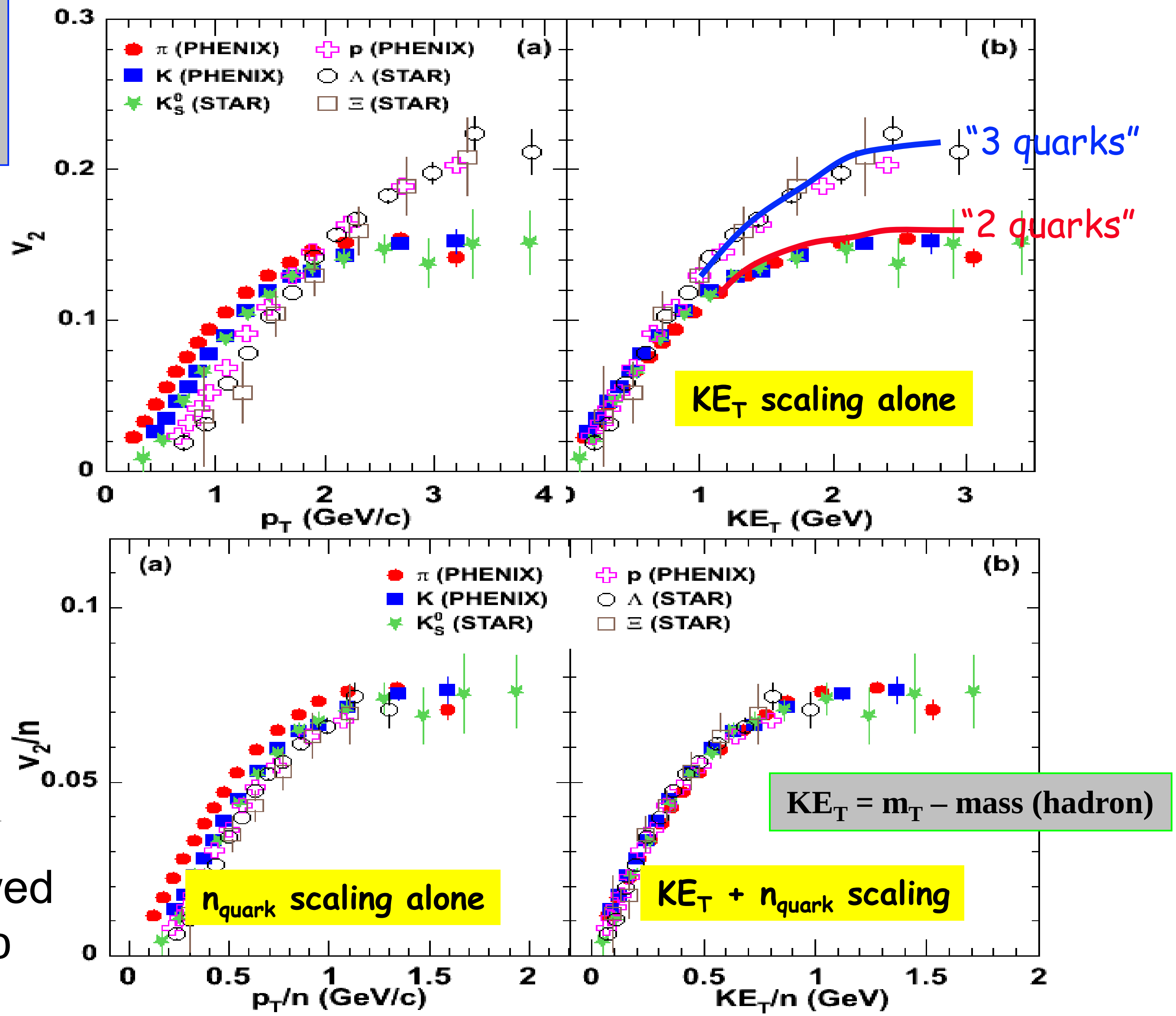
- Other possible production mechanism of high pt hadrons than the frag.
- Quarks, anti-quarks combine to form mesons and baryons from universal quark distribution, *w*.
  - Mesons from 2 q with 1/2 of p_T, baryons from 3 q with 1/3 of p_T.
  - Bacause of the steep distr. of w, this process wins at mid-pt.
  - Characteristic scaling features expected.
  - →*Quark number scaling*

KE_T & n_{quark} scaling of v_2

Quark coalescence:
$v_2^{hadron}(p_T) \approx n\, v_2^{quark}(p_T/n)$

"partonic flow followed by coalescence to form hadrons"

Min. bias Au+Au



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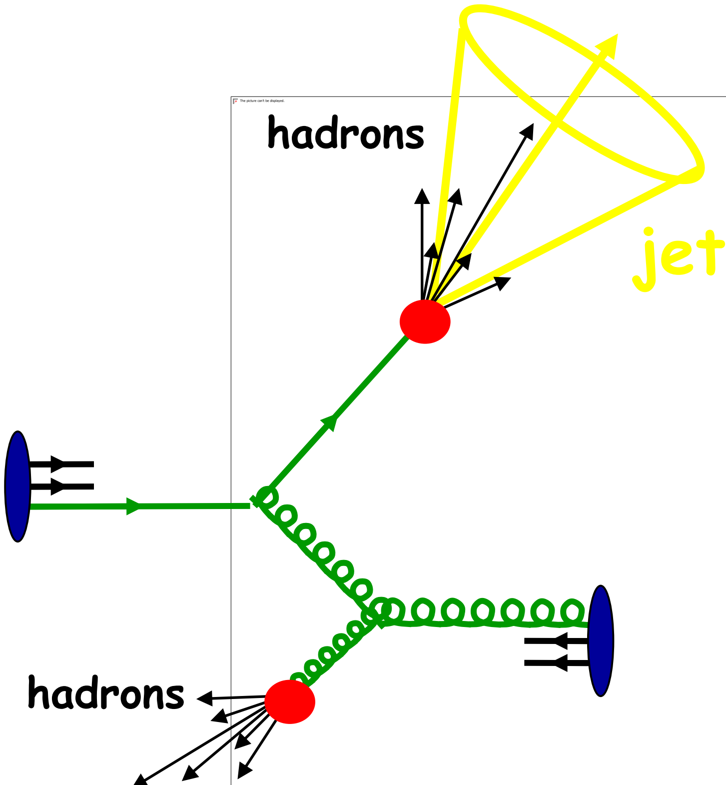
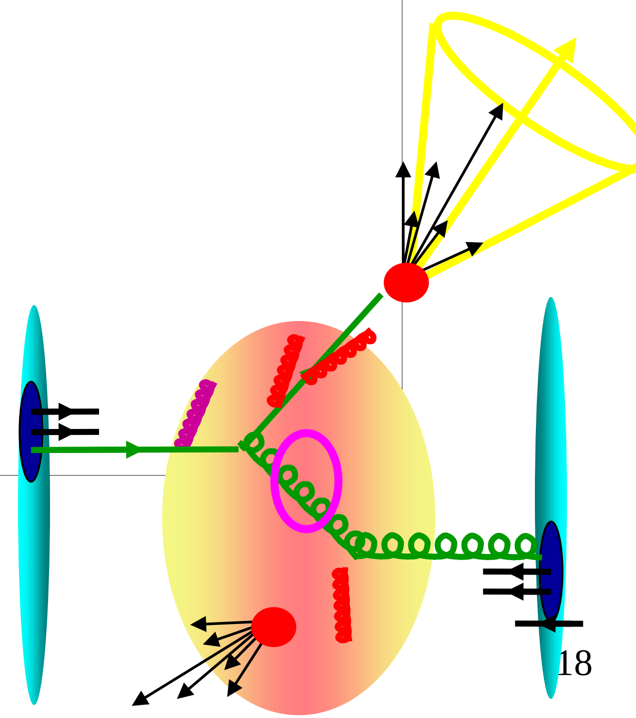
High p_T suppression

R_{AA}

High p_T particle production



- **nucleon-nucleon collision :**
  hard scattered partons fragment into jets of hadrons

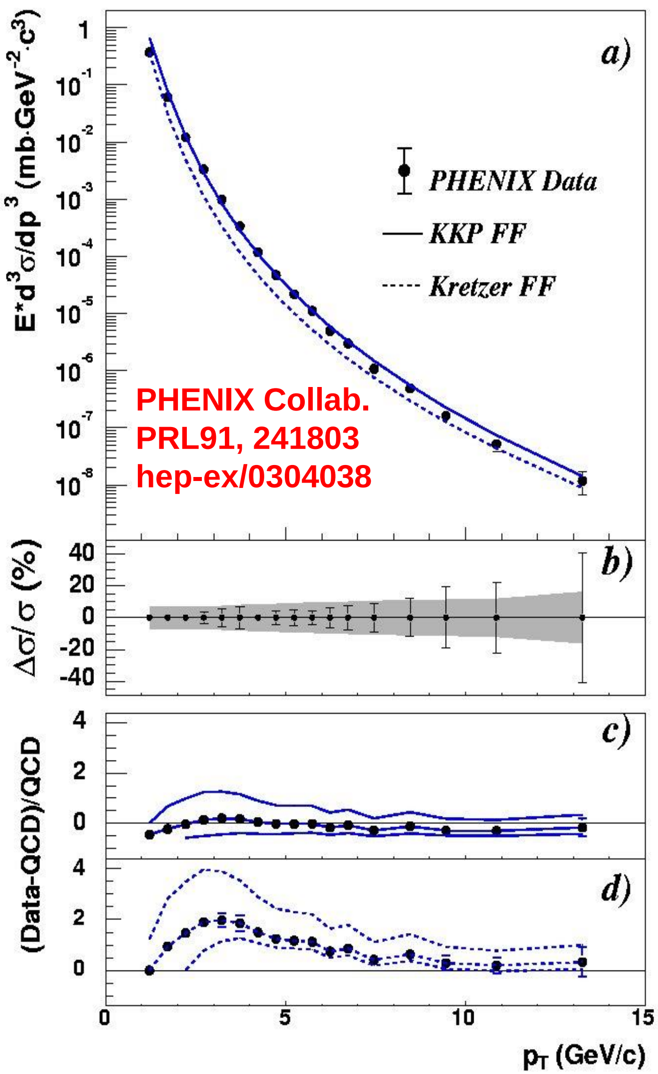


- **nucleus-nucleus collisions :**
  partonic **energy loss** in dense matter
  ⇒ **Jet quenching**

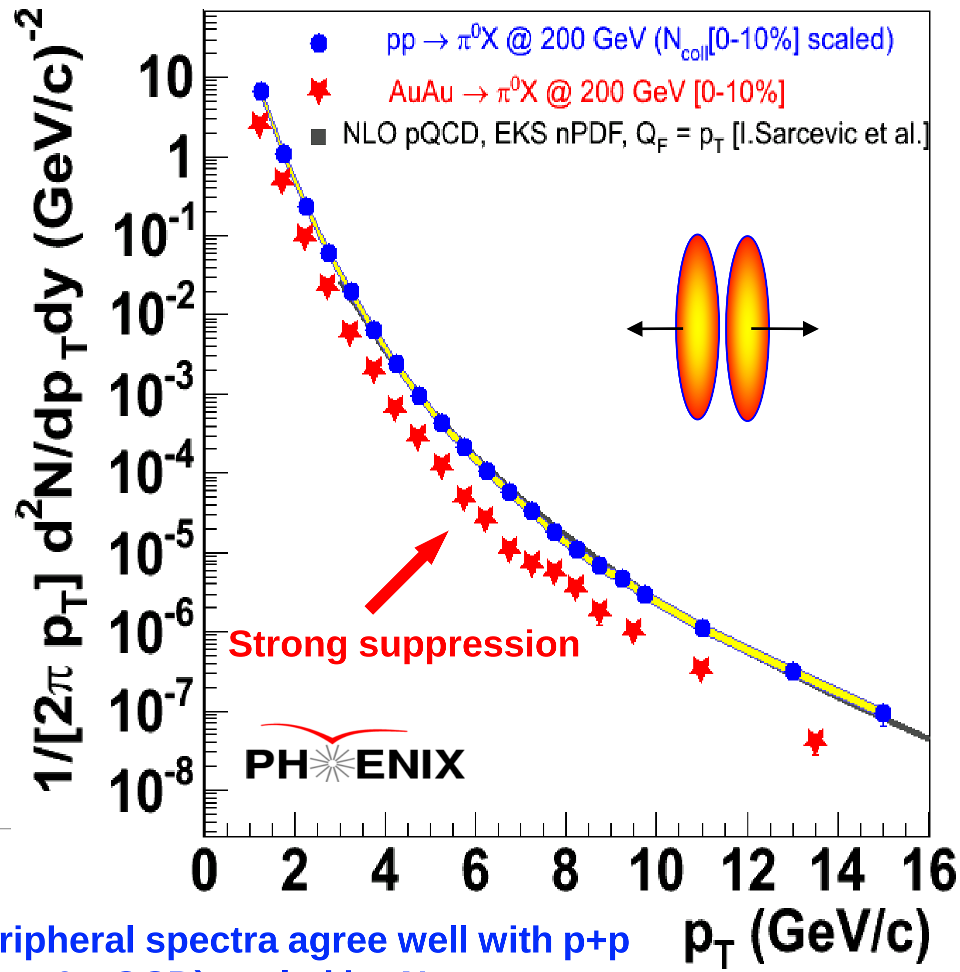
Hard-scattering & Parton energy loss

Single-particle spectrum and QCD predictions

$p+p \to \pi^0+X$



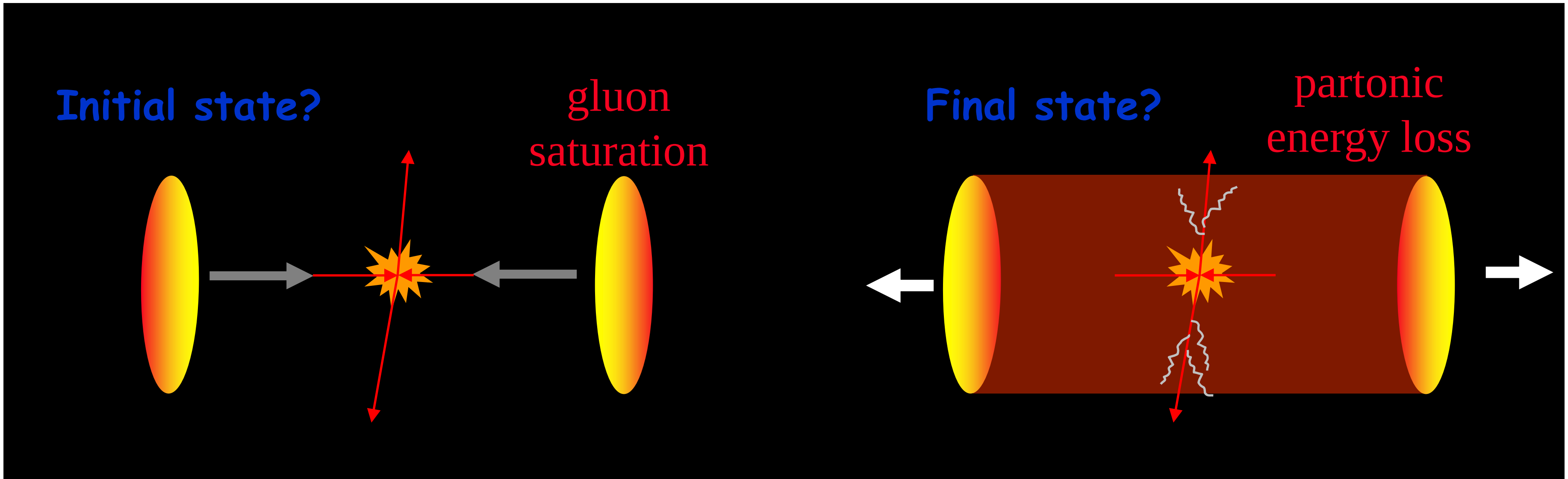
Au+Au $\to \pi^0$ + X (central)



Peripheral spectra agree well with p+p (data & pQCD) scaled by N_{coll}

Central data exhibits suppression: R_{AA}= red/blue < 1

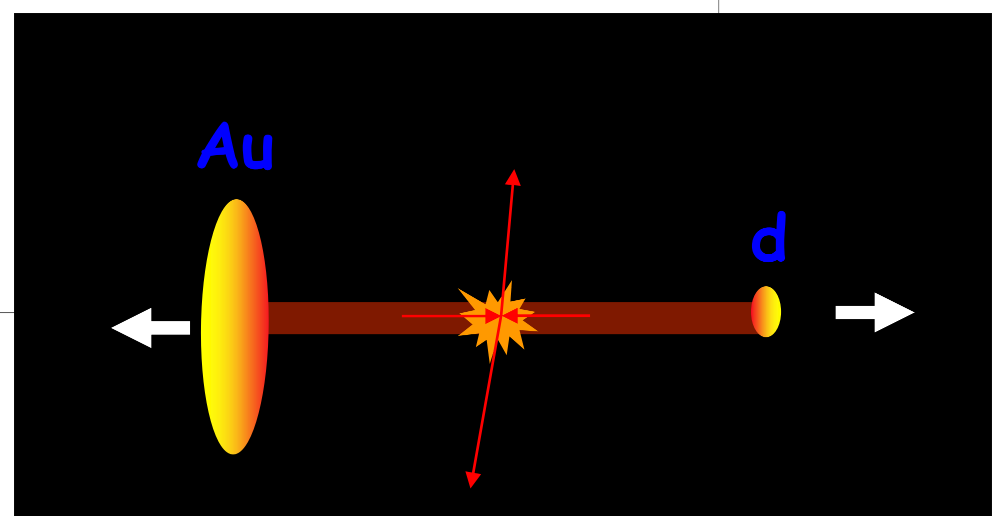
Is suppression an initial or final state effect?



How to discriminate?
- Turn off final state
- only initial state effect

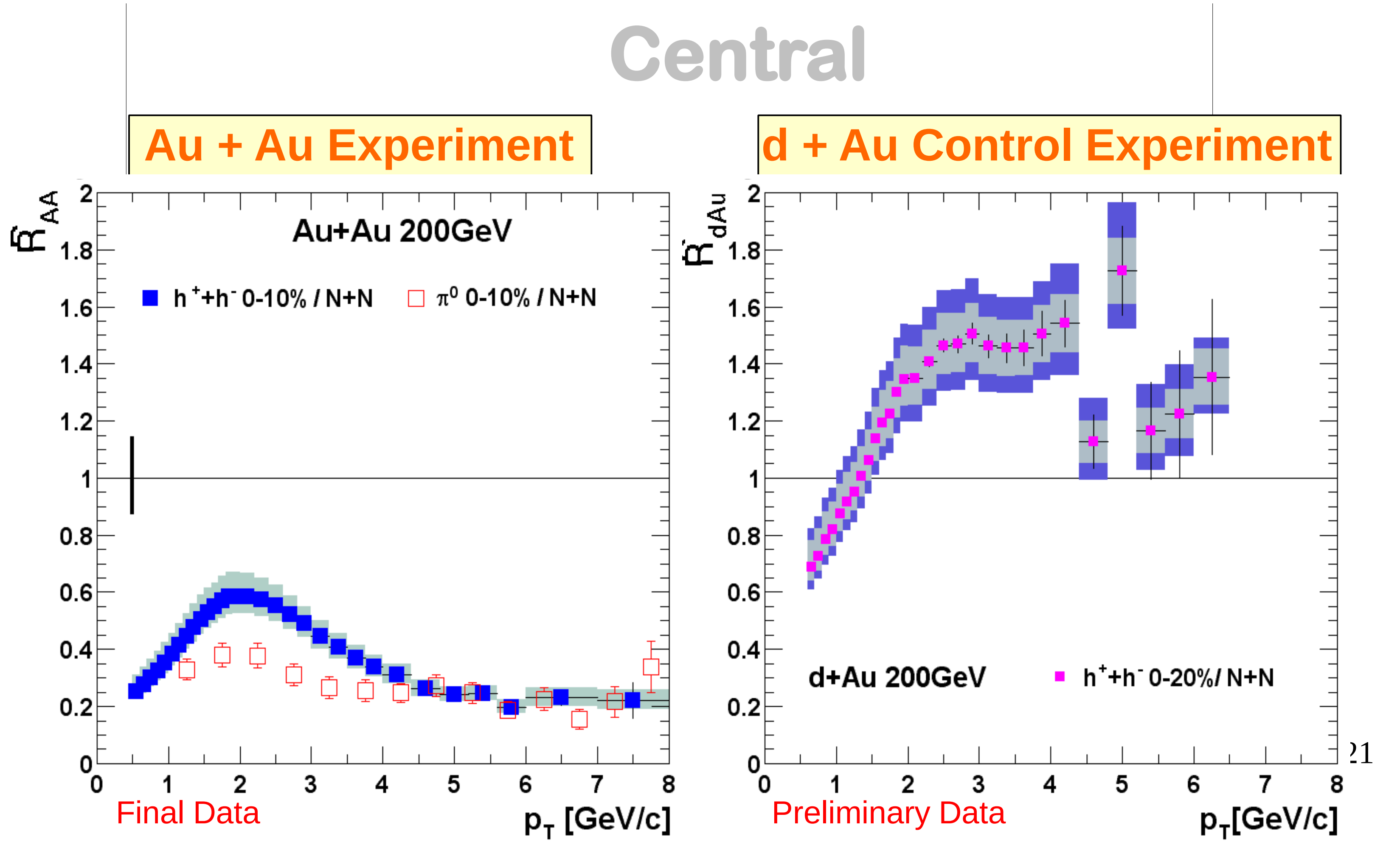
⇒ d+Au collisions

“Control” Experiment

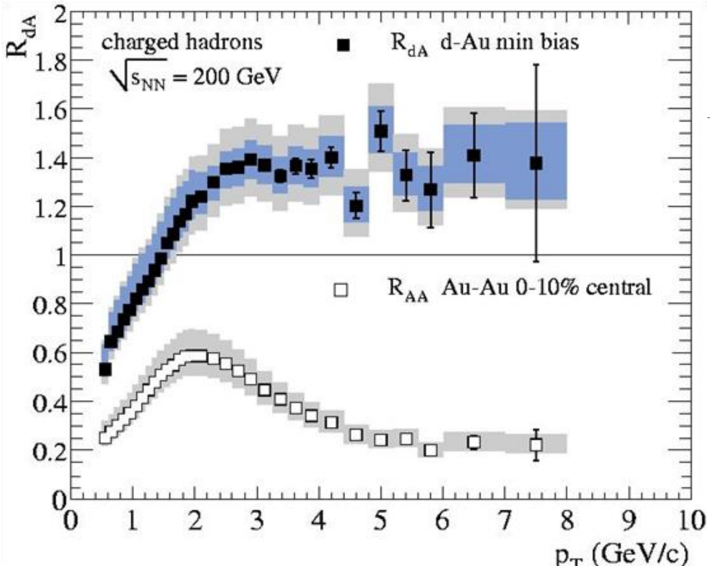


D+A – the "control" experiment

- Its a final state thing!

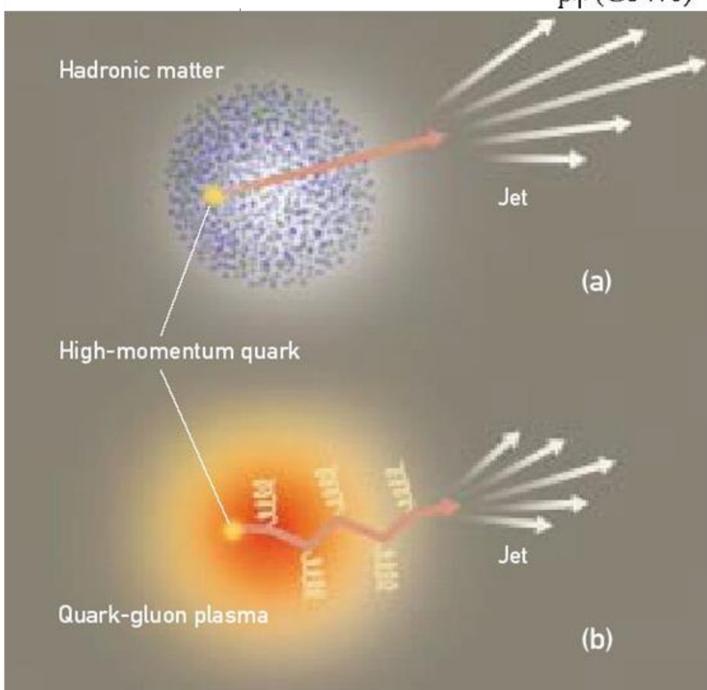


The Suppression is Final State Effect

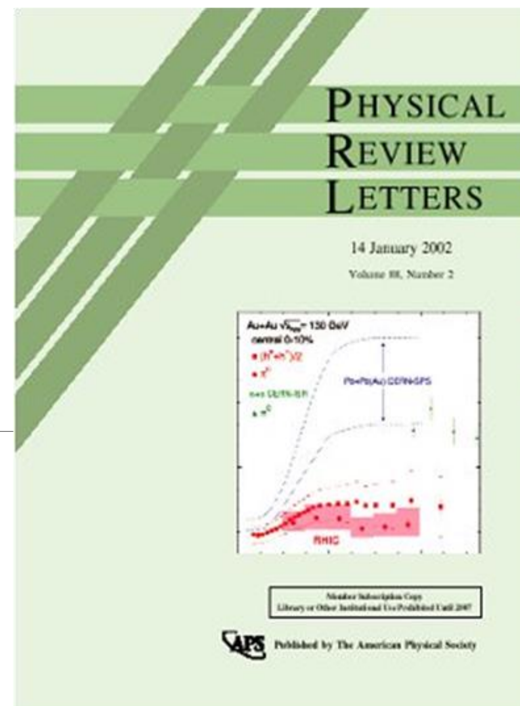


$$R_{AA}(p_T) = \frac{\text{Measured yield A + A}}{\text{Expectation for indep. N + N scatterings}}$$

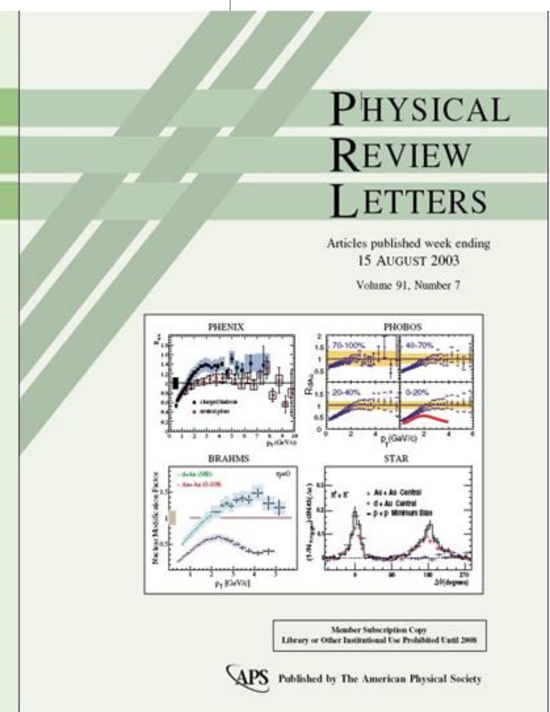
Strong suppression of high p_T in Au + Au, indicating large energy loss of an initial parton in partonic matter(QGP)



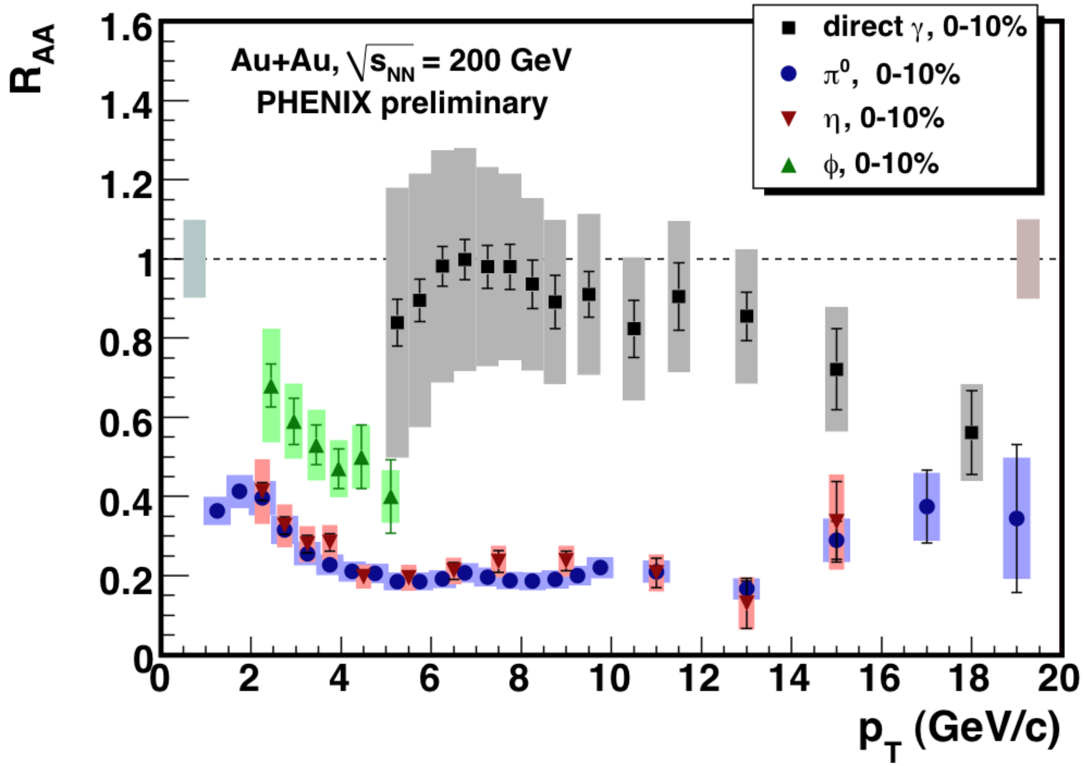
130: Au+Au(465)



200: d+Au(298), Au+Au(374)



R_{AA} of hadrons and direct photon (AuAu 200GeV)

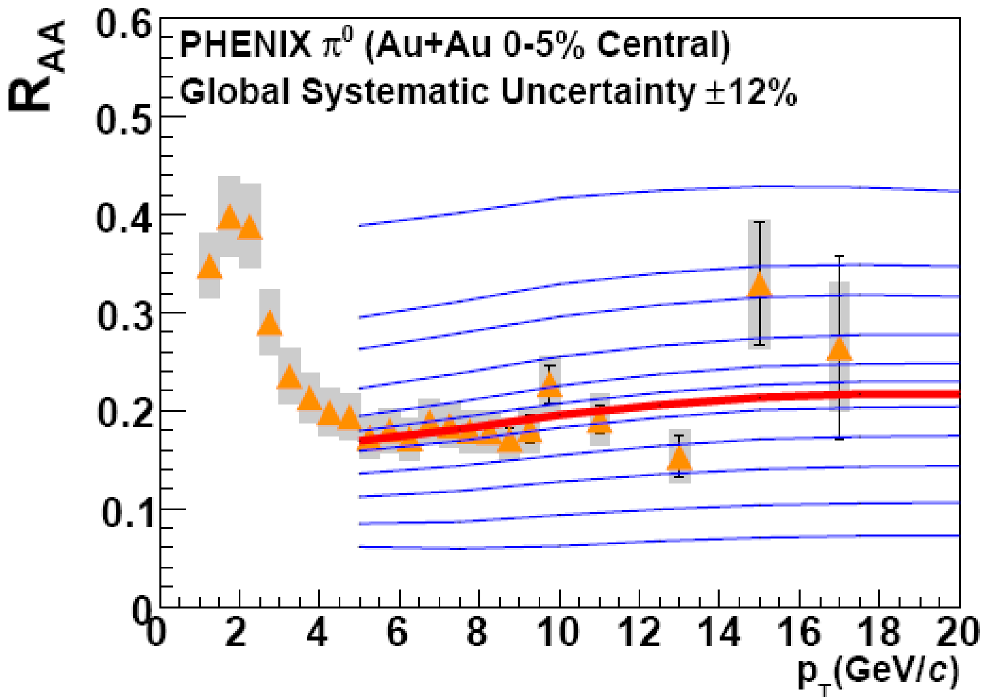


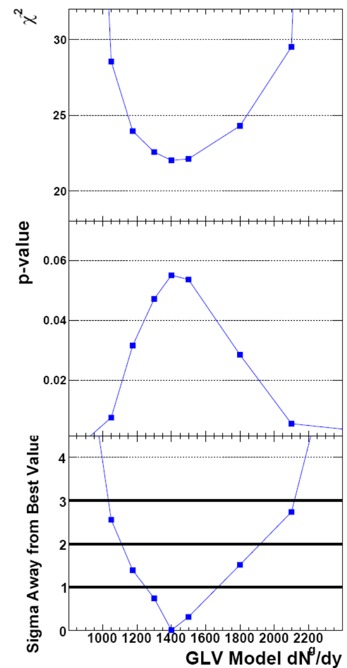
A factor of ~5 suppression to ~20 GeV !

- A factor of ~5 suppression of π^0 to ~20 GeV/c
- Ncoll scaling for direct γ
- Same suppression pattern for π^0 and η:
  Consistent with parton energy loss and fragmentation in the vacuum
- Smaller suppression for the ϕ meson for $2<p_T<5$ GeV/c

Quantitative analysis: contrain density parameters

Comparison with GRV model: dNg/dy=1400 PRC77,064907





Model Name	Opacity Parameter	One Standard Deviation Uncertainty	
PQM	$\langle\hat{q}\rangle = 13.2$ GeV^2/fm	+2.1	−3.2
GLV	$dN^g/dy = 1400$	+270	−150
WHDG	$dN^g/dy = 1400$	+200	−375
Linear	b (intercept) = 0.168	+0.033	−0.032
	m (slope) = 0.0017 (c/GeV)	+0.0035	−0.0039

Di-jet correlations

Jet on the "other" side?

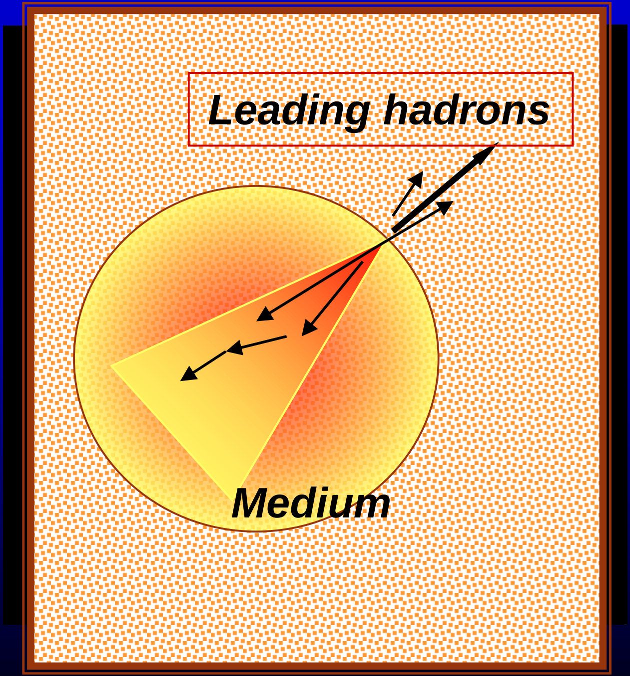
Jet correlations in central Gold-Gold.

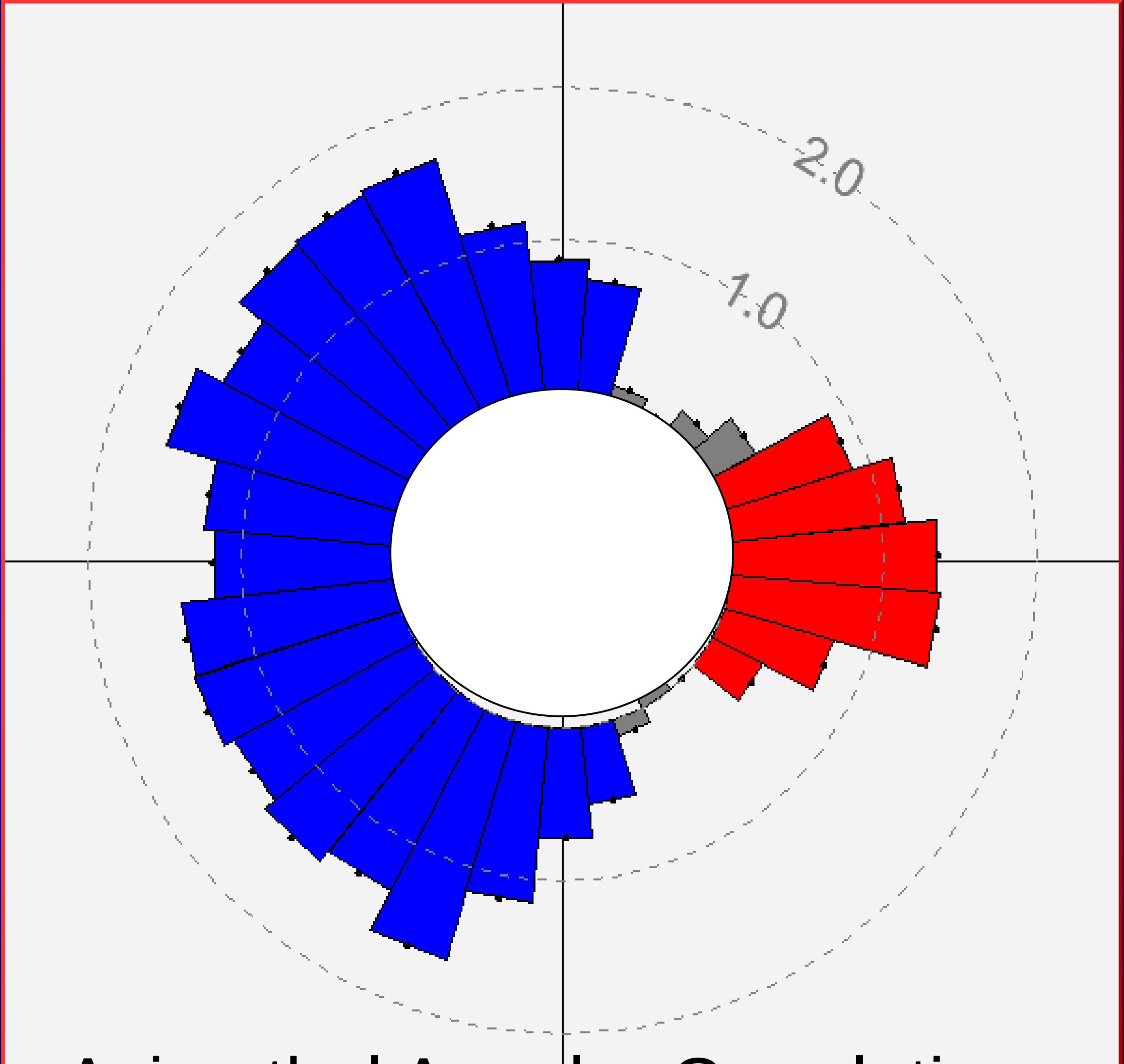
Away side jet reappears for particles $p_T > 200$ MeV

Jet correlations in proton-proton reactions.

Strong back-to-back peaks.

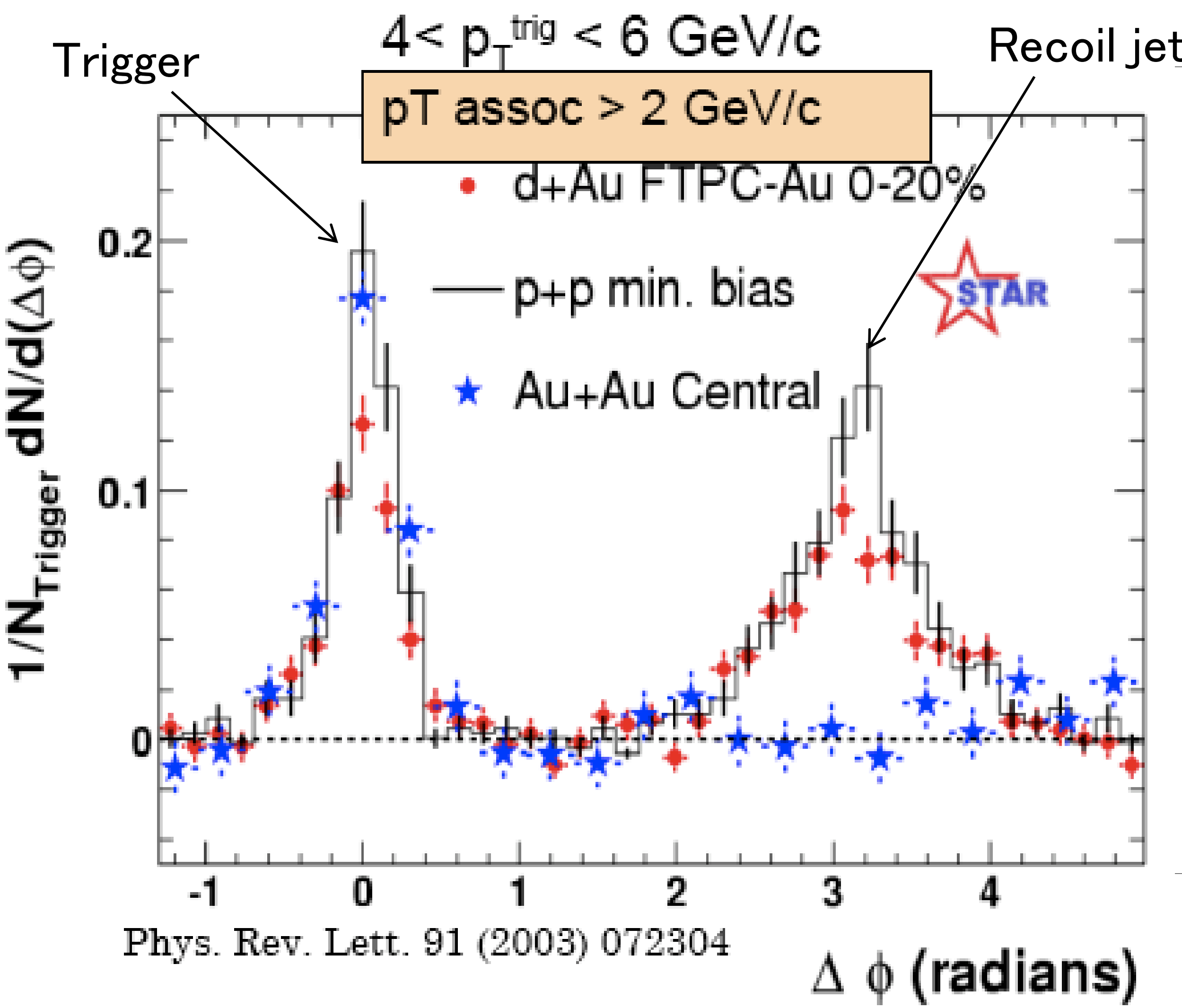
Away side jet disappears for particles $p_T > 2$ GeV





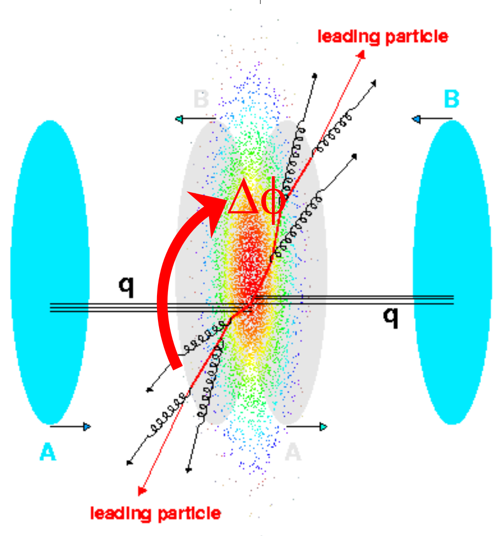
Azimuthal Angular Correlations

Dijet correlation

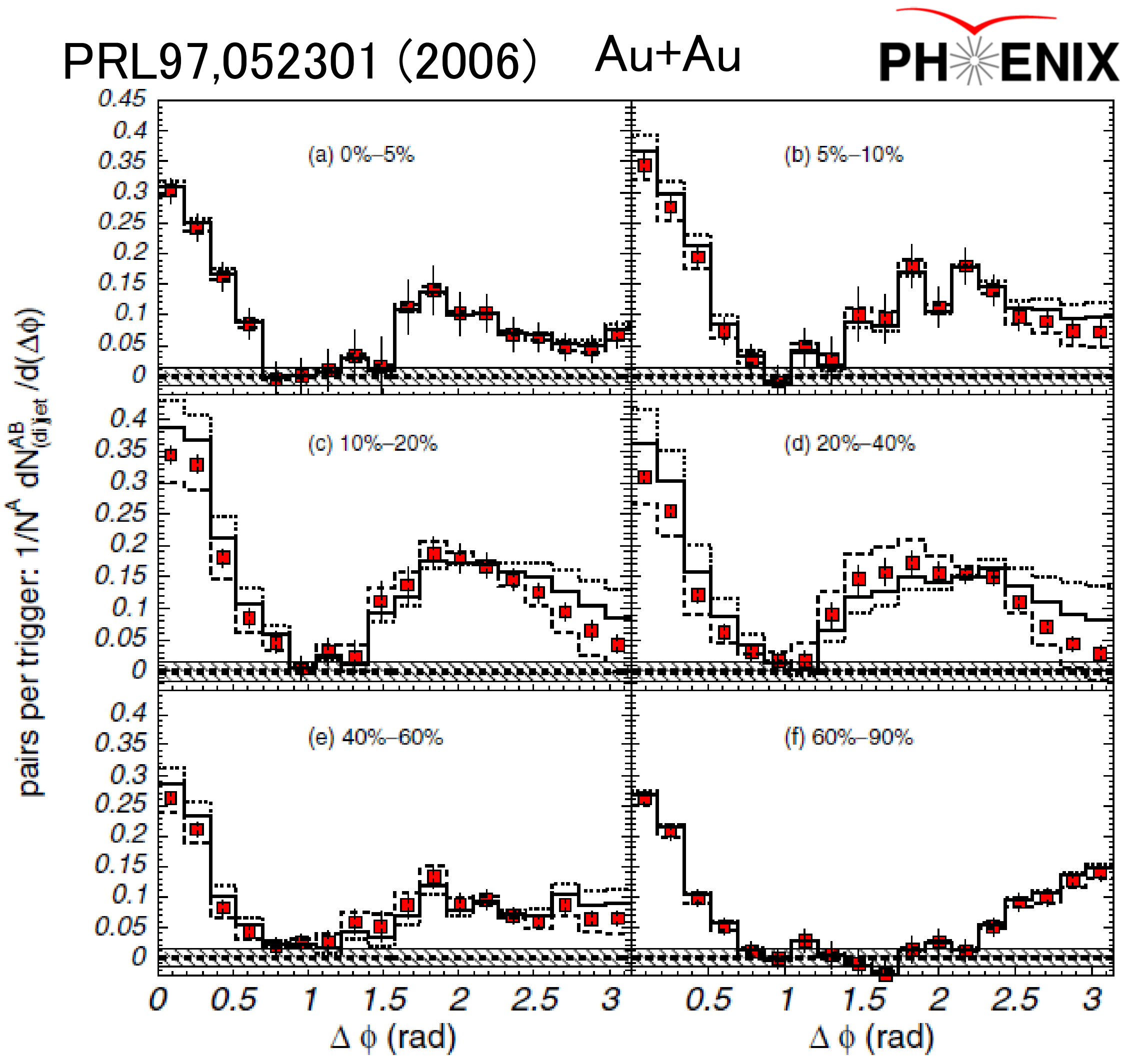


Back-to-back peak due to di-jets is seen in two particle correlation

In central Au+Au collisions, the peak in the far side ($\Delta\phi \sim \pi$) is suppressed, consistent with energy loss of the recoil jet.



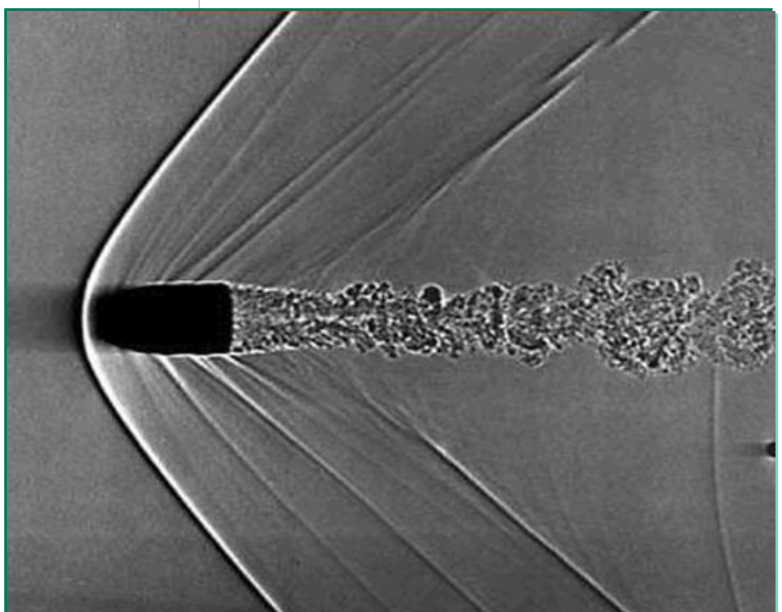
Modification of jet correlation

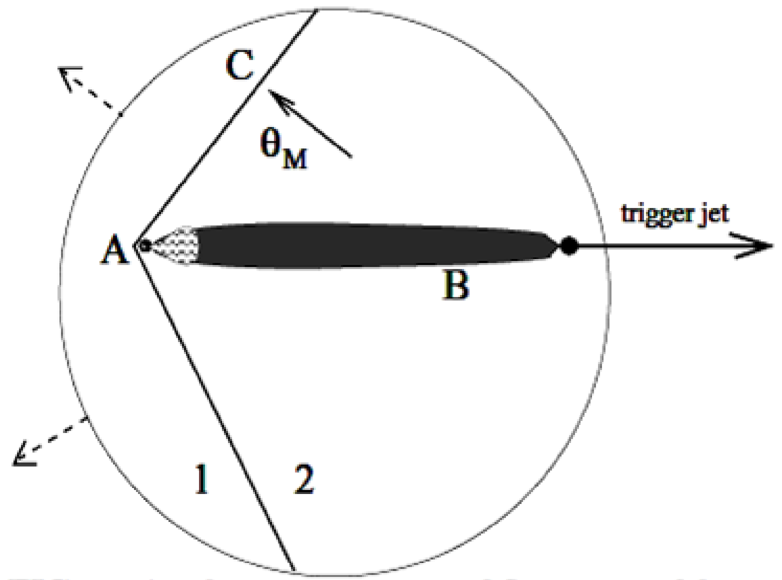


- **This is another big surprise: two particle of two high pT track (jet correlation) is modified in central Au+Au collisions.**
- **Many theory attempts to explain this effect**

A: 2.5GeV<pT<4.0GeV
B:1.0GeV<pT<2.5GeV

Origin of the modification of jets?





- An interesting interpretation of the modification is that it is Mach cone in the medium
- Scattered parton travels faster than the speed of sound in the medium, causing a shock-wave
- If this is the case, the opening angle can be related to the speed of sound in the medium…

Summary

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- These observations are consistent with formation of high temperature, high density partonic matter

PHENIX & RHIC Upgrade Plans

Near term: Base line | **Medium term: first upgrades** | **Long term: full detector and RHIC upgrades**

2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

Analysis of data on tape

Near term detector upgrades of PHENIX TOF-W, HBD, VTX , μTrig

Long term upgrades FVTX, TPC/GEM, NCC

PHENIX upgrades

Commissioning

40x design luminosity for Au-Au via electron cooling

RHIC luminosity upgrade

RHIC baseline program

Au-Au ~ 250 μb^{-1} at 200 GeV
Species scan at 200 GeV
Au-Au energy scan
Polarized protons $\geq$ 150 nb^{-1}

Extended program with 1st detector upgrades:

Au-Au ~ 1.5 nb^{-1} at 200 GeV
Polarized p at 500 GeV
(start p-A program)

Full utilization of RHIC opportunities:

Studies of QGP with rare probes:
jet tomography, open flavor,
J/ψ, ψ', χc, $\Upsilon(1s)$, $\Upsilon(2s)$, $\Upsilon(3s)$
Complete spin physics program
p-A physics

Backups