QCD at RHIC:

Moving forward

D. Kharzeev

1. QCD of dense partonic systems
2. What have we learned from RHIC so far?
    - Lessons from AA
    - First lessons from dA
    - Open problems
3. The importance of moving forward at RHIC
    - High $p_\perp$ suppression
    - Identified hadrons, flow, baryon number
    - Charm
4. Summary

Quarks

$$q(x) = \begin{pmatrix} q^{\text{red}}(x) \\ q^{\text{green}}(x) \\ q^{\text{blue}}(x) \end{pmatrix}$$

+ Local Gauge Invariance

$$q(x) \to \exp\left(i\omega_a(x)T^a\right)\; q(x),$$

$$\left[T^a, T^b\right] = i f^{abc} T_c$$

= Quantum Chromo-Dynamics

$$L_{\text{free}} = \sum_{q=u,d,s\ldots} \sum_{colors} \bar{q}(x) \left(i\gamma_\mu \frac{\partial}{\partial x_\mu} - m_q \right) q(x)$$

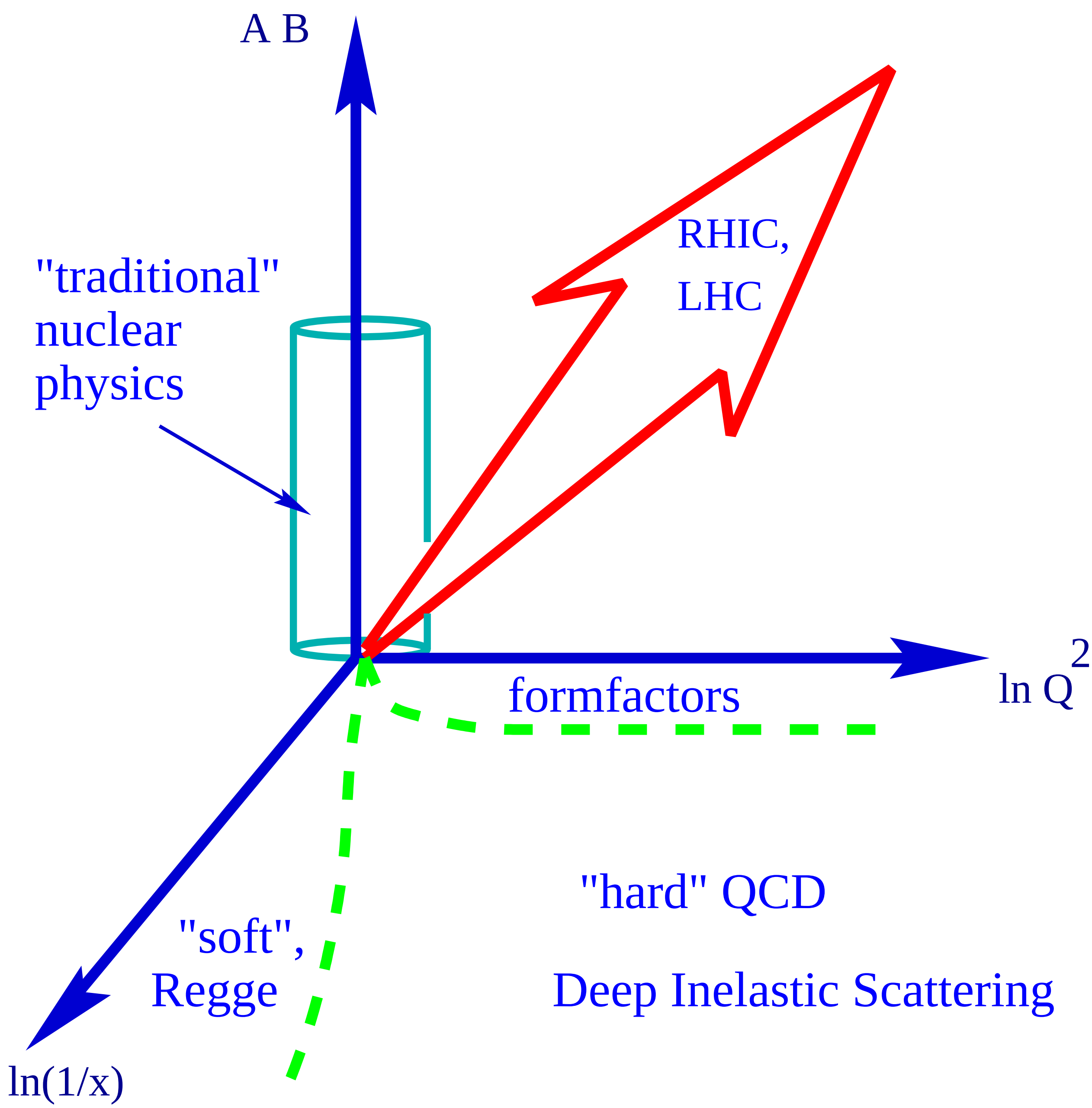
$$\Downarrow$$

$$\mathsf{L}_{\text{QCD}} = \textstyle\sum_q \bar{q}(x)\left(i\gamma_\mu D^\mu - m_q\right) q(x) - \frac{1}{4g^2} \text{tr}\; G^{\mu\nu}(x) G_{\mu\nu}(x);$$

$$G^a_{\mu\nu}(x) = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + f^{abc} A_{\mu b} A_{\nu c} \;\; \Rightarrow \text{GLUONS!}$$

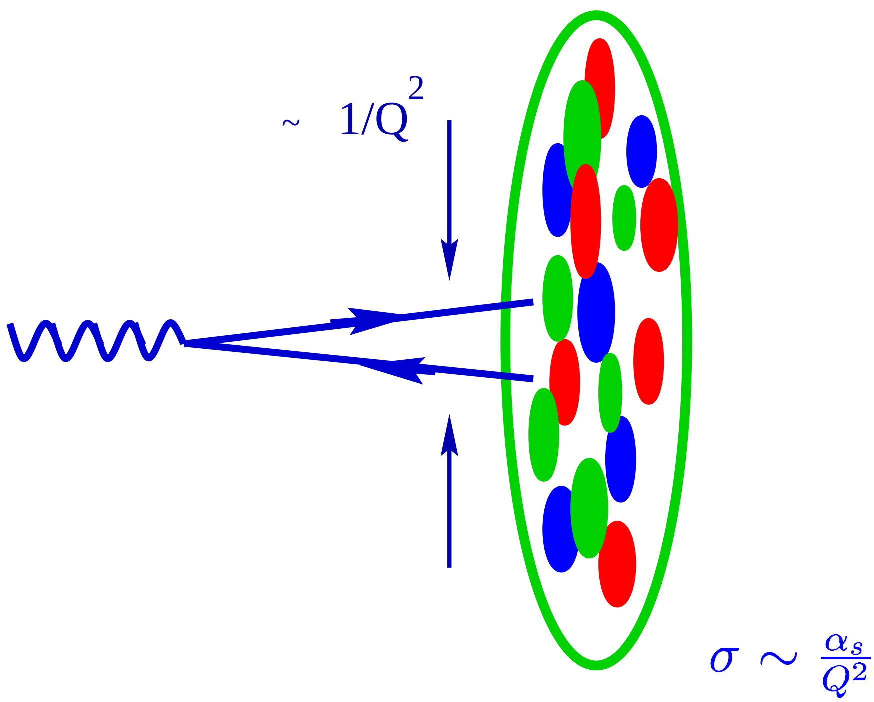
- Asymptotic freedom: perturbation theory justified at short distances
  (Bjorken scaling, parton model, ...)
- Classical solutions: non–trivial topological properties of the Vacuum
  ($U_A(1)$ breaking, η' mass, ...)
- Lattice QCD: a first–principle numerical approach (hadron masses, matrix elements, phase transitions at high temperature, ...)

- What is the mechanism of confinement?
  (Why isolated quarks have been never observed?)
- How are the hadron masses generated from (almost) massless quarks?
- What is the mechanism of chiral symmetry breaking?
  (the absence of parity doublets, light Goldstone bosons
  $\Rightarrow$ effective chiral theories)
- The strong CP problem
  (why is parity conserved in QCD?)


A B
RHIC,
LHC
"traditional"
nuclear
physics
formfactors
ln Q
2
"hard" QCD
"soft",
Regge
Deep Inelastic Scattering
ln(1/x)

High parton density regime of QCD

$$\rho_A = \frac{\text{Number of partons}}{\text{area}} \simeq \frac{xG_A(x,Q^2)}{\pi R_A^2} \sim A^{1/3}$$



- $\sigma\ \rho_A << 1$ – dilute regime, incoherent interactions
- $\sigma\ \rho_A >> 1$ – dense parton system

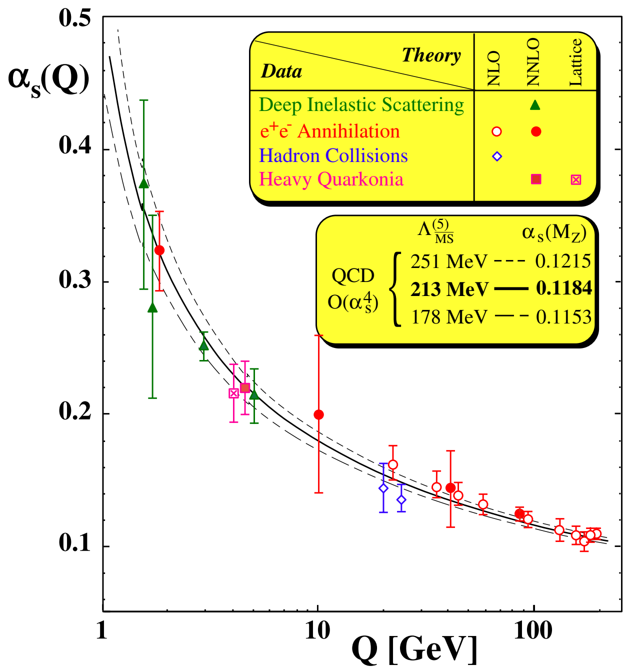
Qualitatively new regime in QCD

"saturation"; "colored glass"; classical theory?

High parton density $\Rightarrow$ weak coupling

At high parton density $Q_s^2 \gg \Lambda_{QCD}^2$ the coupling is weak:

Asymptotic freedom

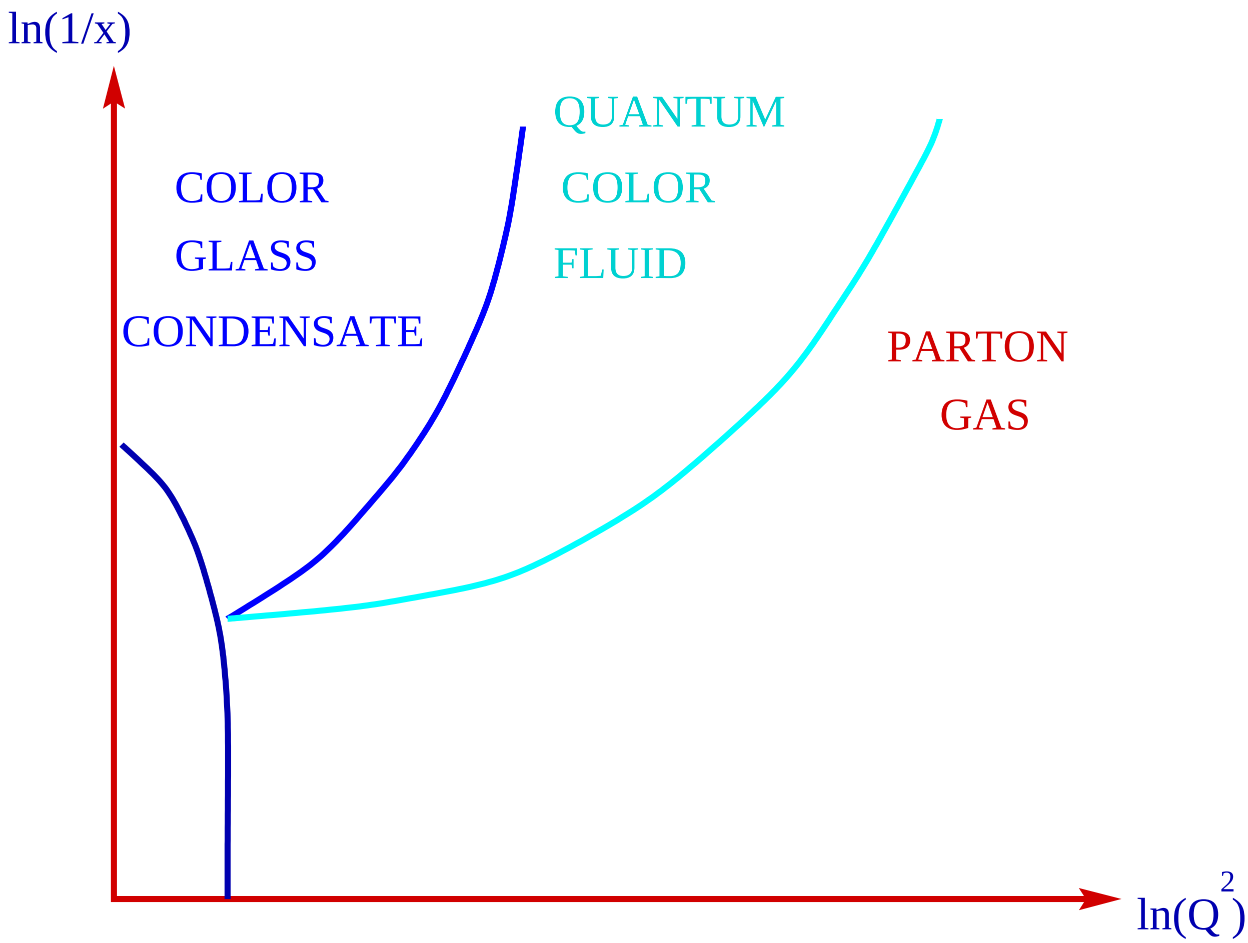


S. Bethke, J.Phys.G26:R27,2000

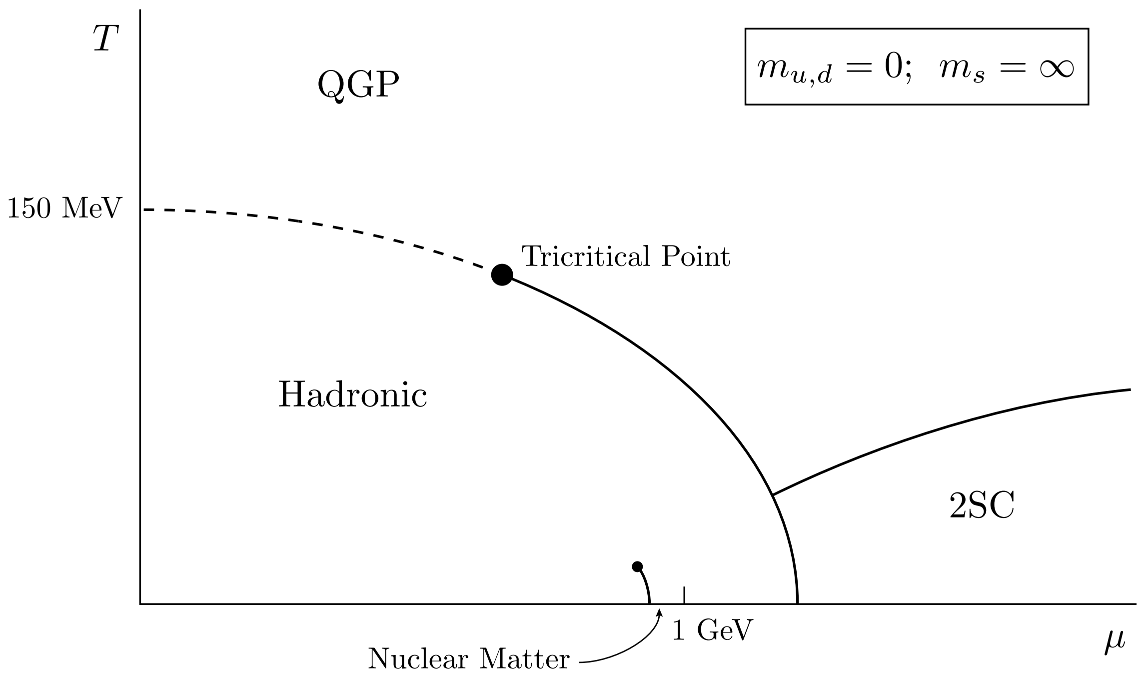
Weak coupling, high density $\Rightarrow$ classical theory

$\Rightarrow$ Simple predictions; e.g. multiplicity $N \sim \frac{Q_s^2 S}{\alpha_s(Q_s^2)}$

At small x and/or large A, new phases of QCD are formed:



Phase diagram of statistical QCD



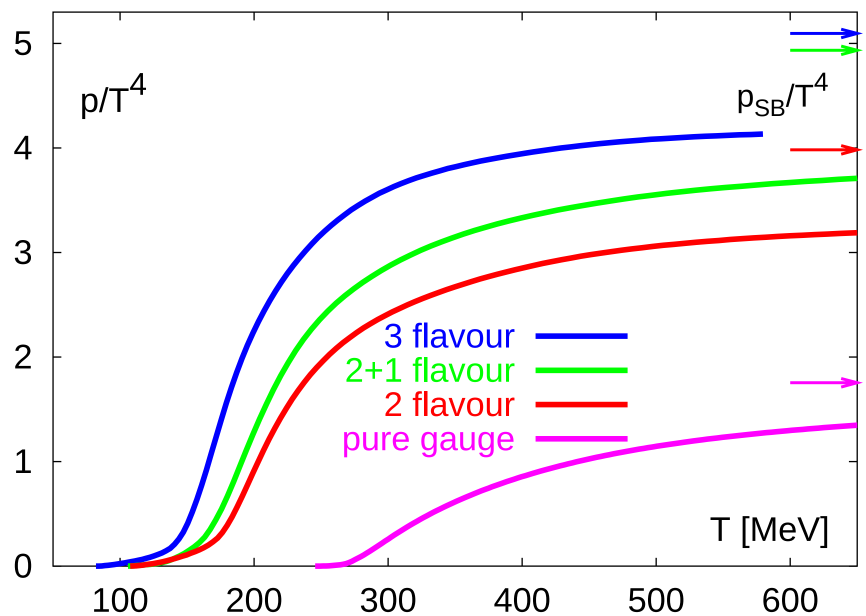
K. Rajagopal and F. Wilczek, hep-ph/0011333

Novel physics at high baryon density $\Rightarrow$ manifestations in astrophysics?

Phase transitions

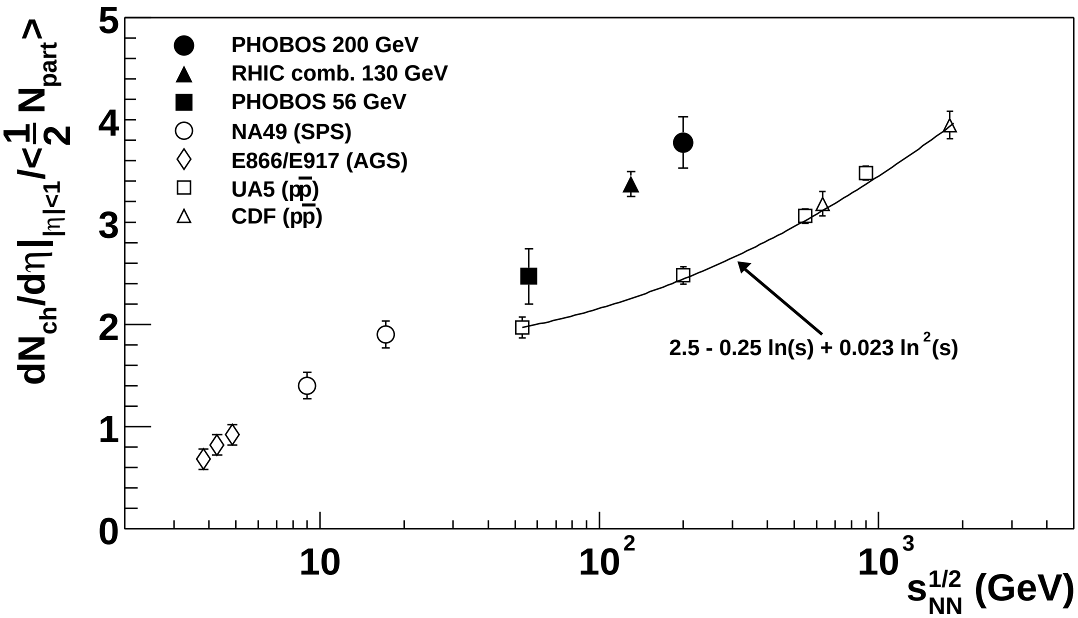
High initial parton density ⇒ statistical description, approach to thermalization

Quark–gluon plasma



F. Karsch, hep-lat/0106019

Energy dependence of multiplicity in Au-Au



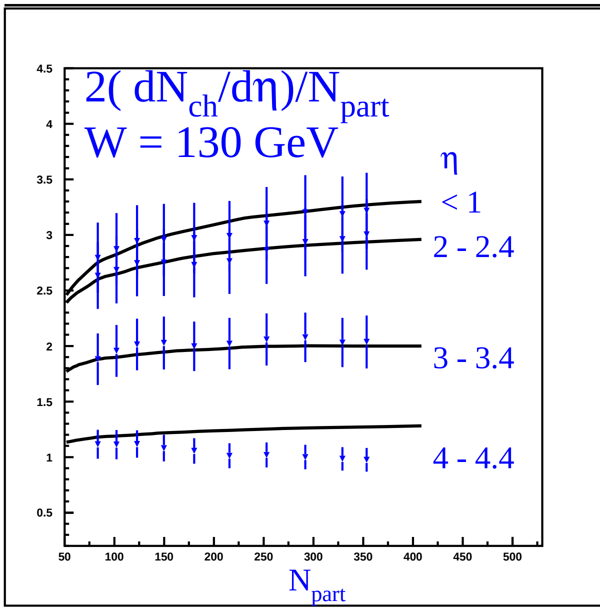
B.B. Back et al (PHOBOS Coll.), Phys.Rev.Lett.88:022302,2002

Is this multiplicity "large" or "small"?

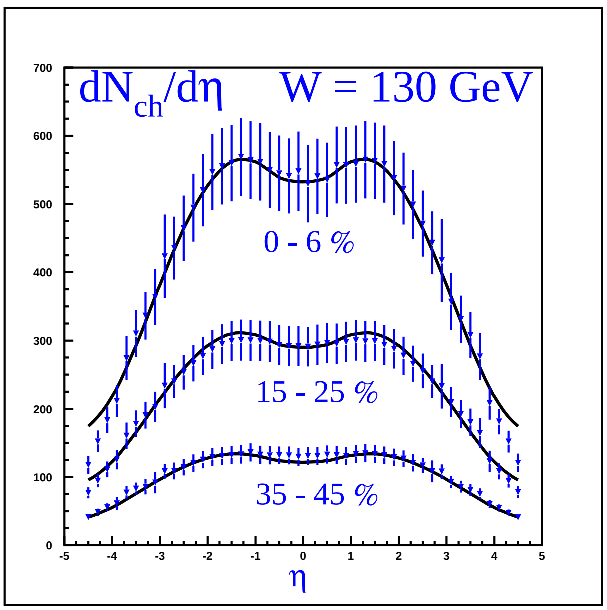
Independent NN collisions would yield $N \sim N_{coll} \sim N_{part}^{4/3}$

This is not observed; instead, interactions are coherent

Centrality and rapidity dependences of N_{ch}



Predictions of the Color Glass Condensate model for multi-particle production are shown to describe well RHIC data on centrality dependence of hadron multiplicity;

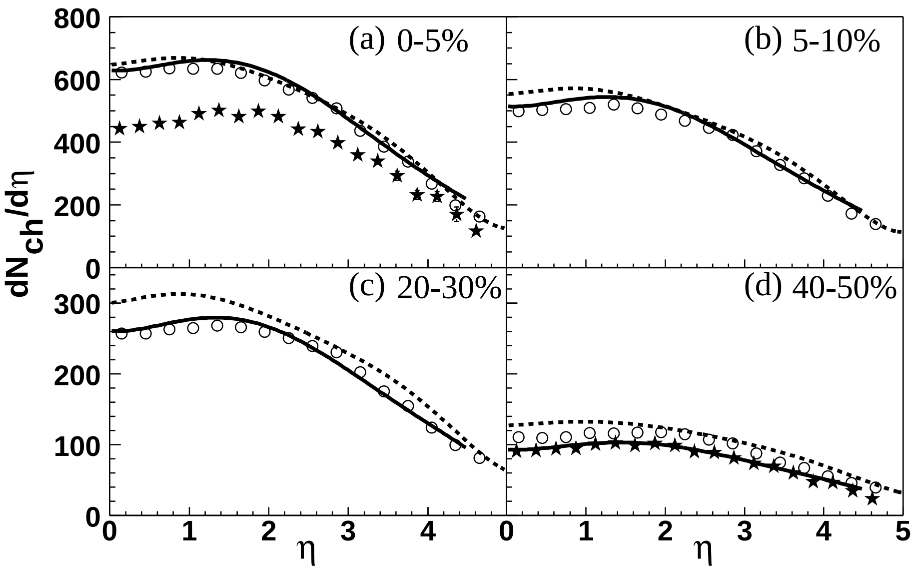


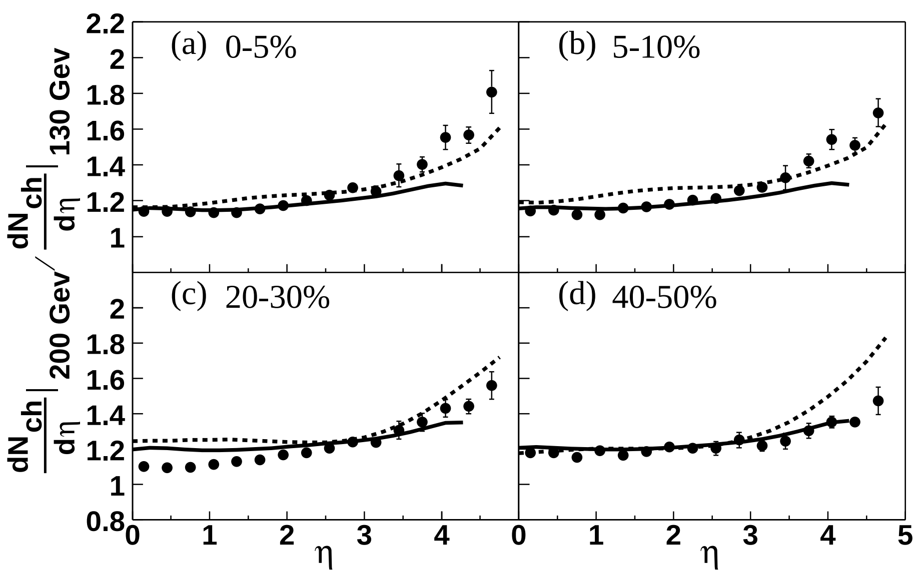
Rapidity and energy dependences have been found to follow the predictions of high density QCD as well.

B.B. Back et al (PHOBOS Coll.), Phys.Rev.Lett.87:102303,2001;

Saturation model: D. Kharzeev and M. Nardi, Phys.Lett.B507:121-128,2001; D.Kharzeev and E. Levin, Phys.Lett.B523:79-87,2001

Rapidity dependence of multiplicity: $\sqrt{s} = 200$ GeV



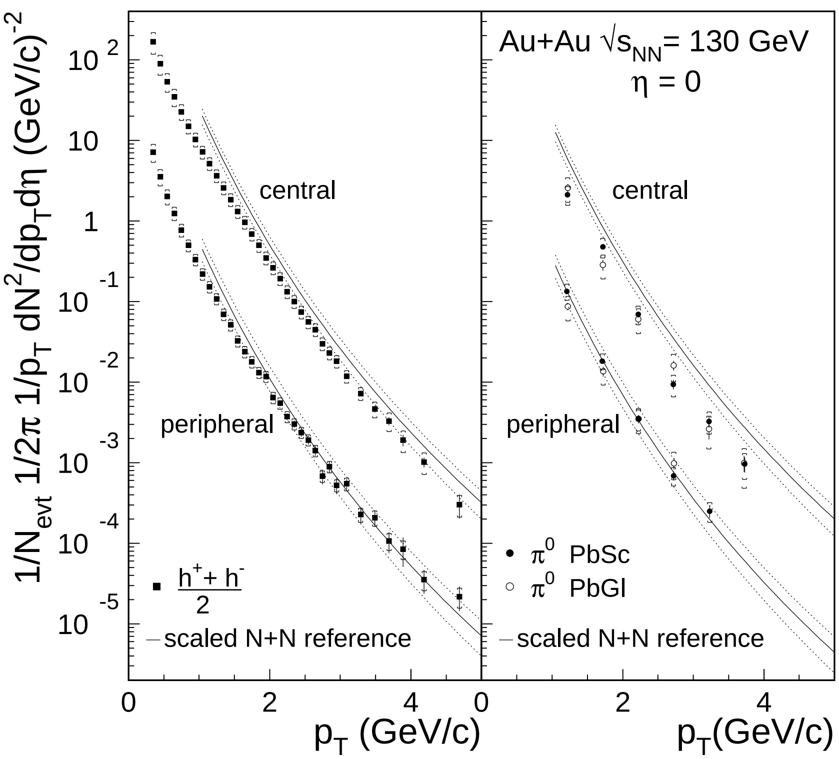


I.G. Bearden et al (BRAHMS Coll.), Phys.Rev.Lett.88:202301,2002

Solid line: KL saturation; dashed line: AMTP model

Suppression of hadrons at high p_t

Hadron production at high p_t allows to study propagation of fast partons in dense matter

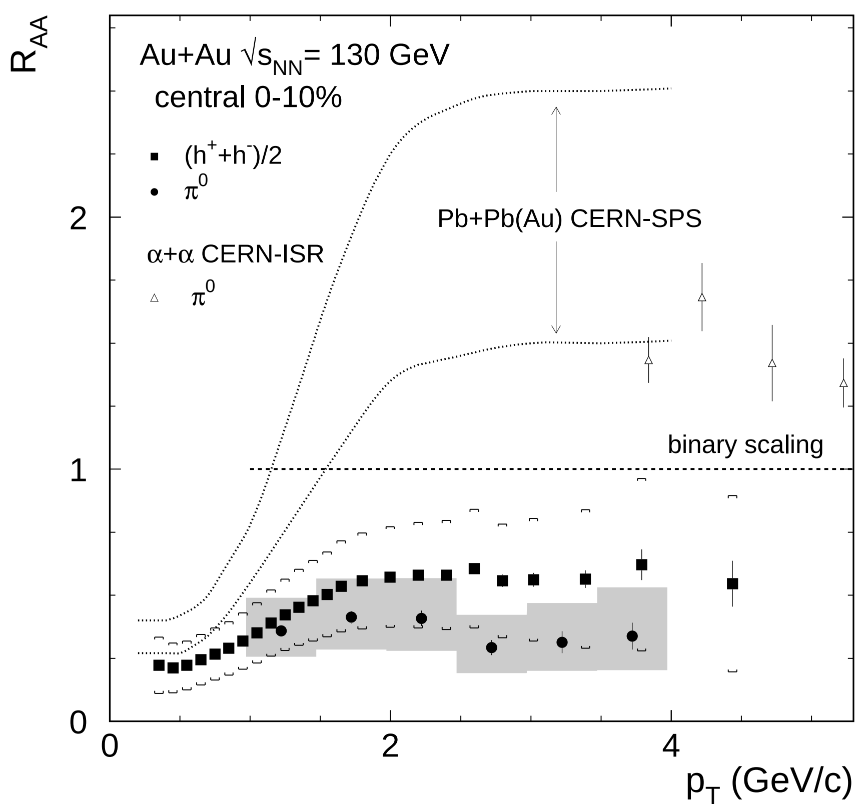


K. Adcox et al (PHENIX Coll.), Phys.Rev.Lett.88:022301,2002

N-N reference has been rescaled by the number of collisions; note also a suppression below $p_t \sim 2$ GeV

Suppression of hadrons at high p_t

While there was no suppression at lower energies,

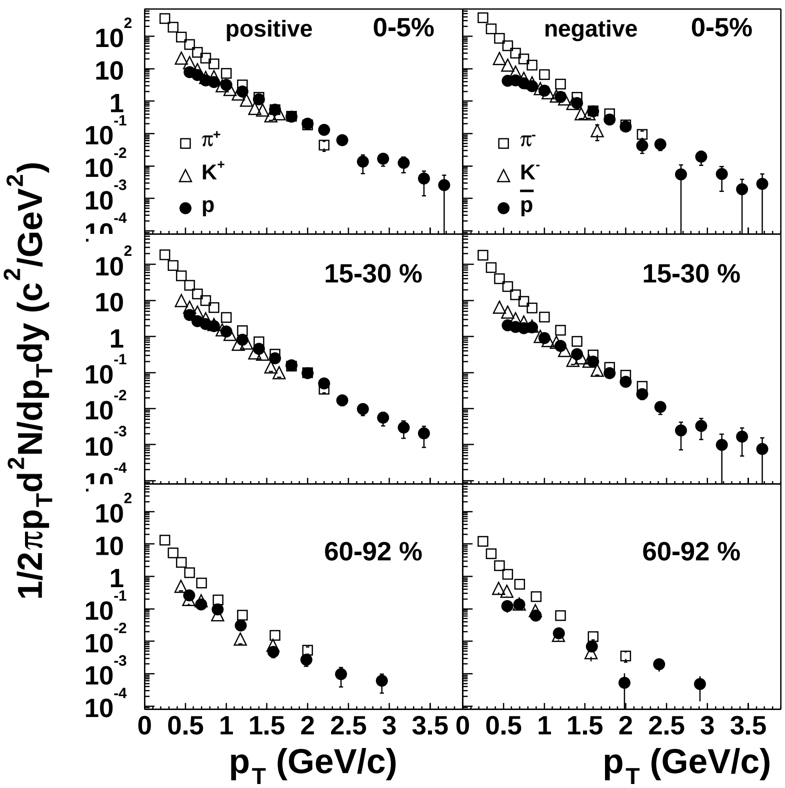


K. Adcox et al (PHENIX Coll.), Phys.Rev.Lett.88:022301,2002

a strong effect has been observed at RHIC !

Particle composition at high p_t

Does the particle composition vary with p_t?



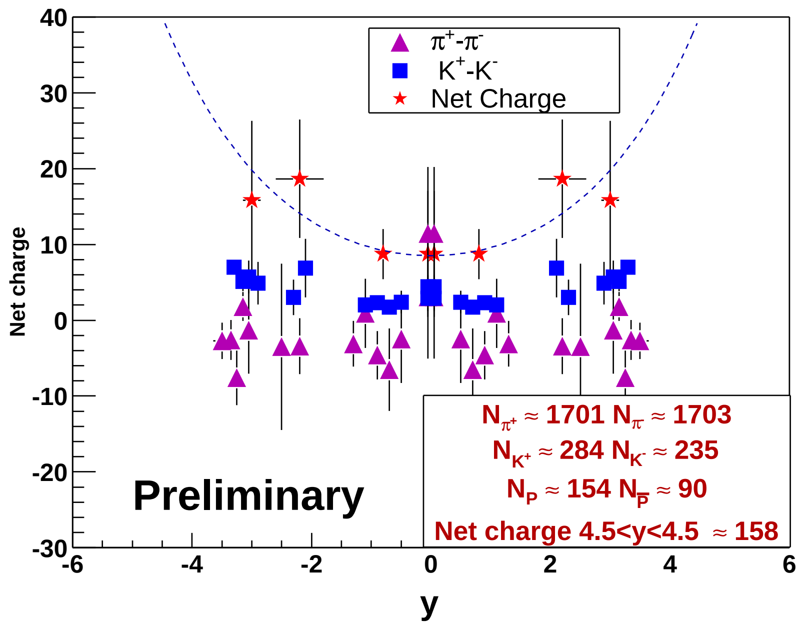
K. Adcox et al (PHENIX Coll.), Phys.Rev.Lett.88:242301,2002

Yes, in a very strange way – B/π ratio at high p_t exceeds 1 !

Flow? Baryon junctions? Dependence of energy loss on virtuality?

Baryon number transport

What is the mechanism of baryon number transport in QCD?



R. Debbe (BRAHMS Coll.), nucl-ex/0308004

Soft quark exchange? Large angle quark scattering?
Baryon junctions (non-Abelian vortices)?

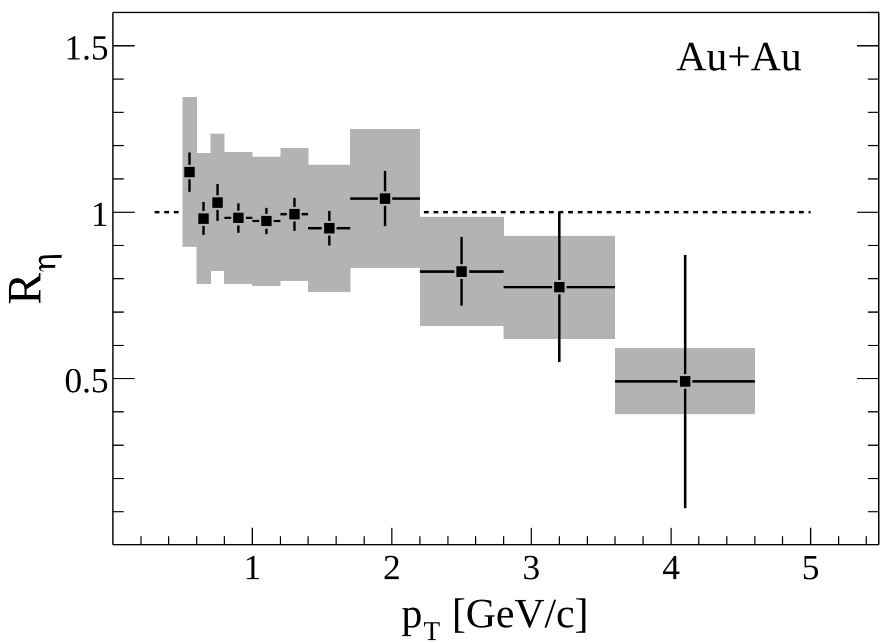
Does the distribution of baryon number follow the distribution of electric charge?

Rapidity dependence of high $p_\perp$ suppression

What are the origins of high $p_\perp$ suppression in $AuAu$ collisions at RHIC?

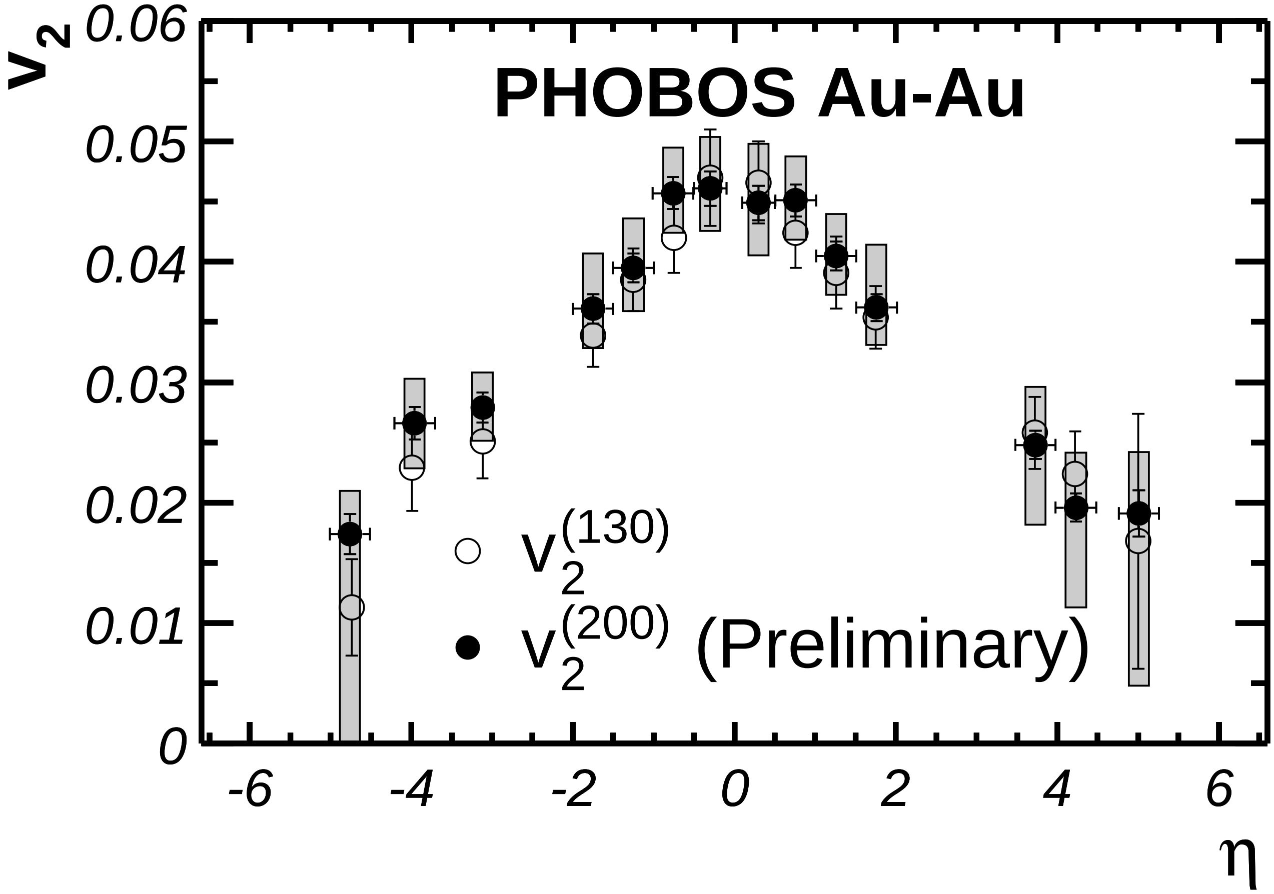
Initial- and final-state effects have different dependence on rapidity; final-state effects are maximal at mid-rapidity whereas initial-state effects are enhanced in the forward region

$\rightarrow$ study the rapidity dependence of high $p_\perp$ suppression to understand its origin!



I. Arsene et al (BRAHMS Coll.), Phys.Rev.Lett.91:072305,2003

Rapidity dependence of v_2



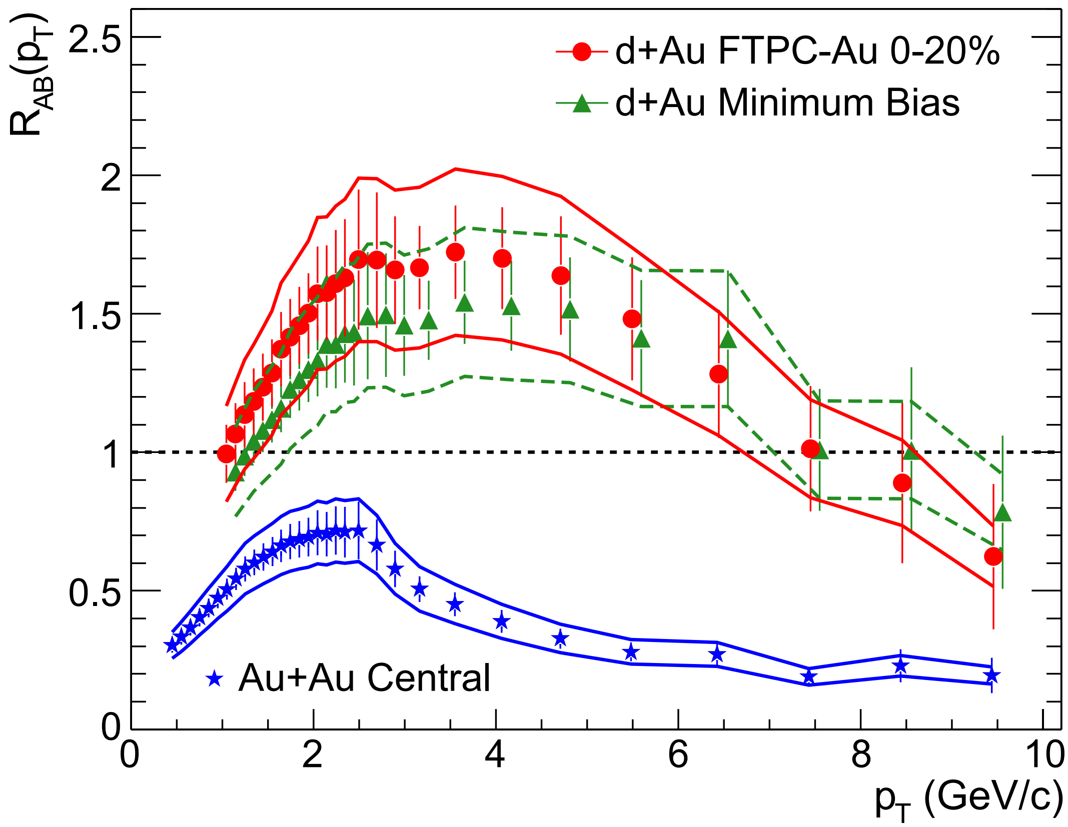
R. Pak (PHOBOS Coll.), Nucl.Phys. A721 (2003) 227

The effects of final-state interaction as seen through the elliptic flow seem to diminish at larger rapidities

Why does the high p_t suppression increase at larger rapidity?

$d - Au$ results

Cronin enhancement is seen in the charged hadron spectra: coherent parton scattering



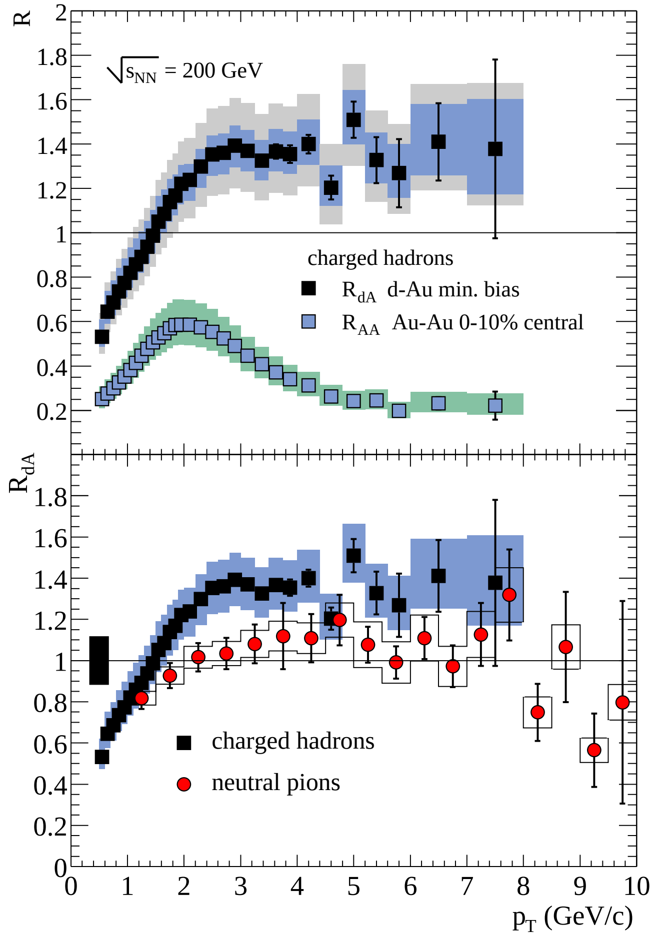
STAR Coll., nucl-ex/0306024

Suppression in $Au - Au$ in the Cronin region is a final state effect – parton thermalization/energy loss?

What happens at high p_t? Centrality dependence?

$d - Au$ results

Cronin enhancement is seen in the charged hadron spectra: a smaller effect for neutral pions?

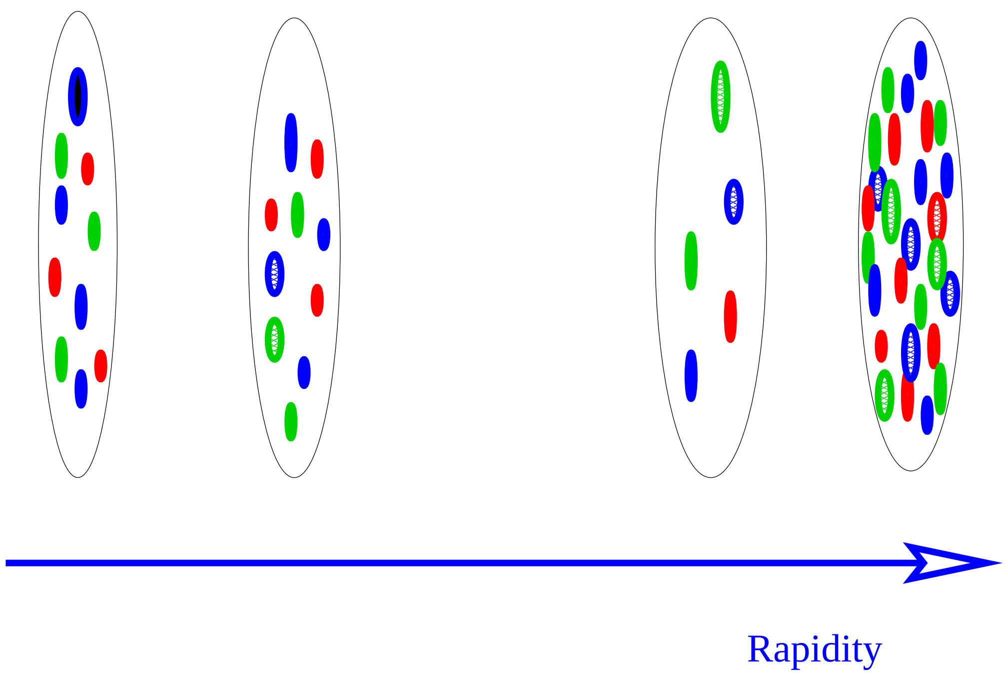


PHENIX Coll., nucl-ex/0306021

The effect is not universal for baryons and pions in $d - Au$? Initial–state physics?

The importance of moving forward at RHIC

Going forward in rapidity, we probe small x region in the wave function of one of the colliding nuclei:

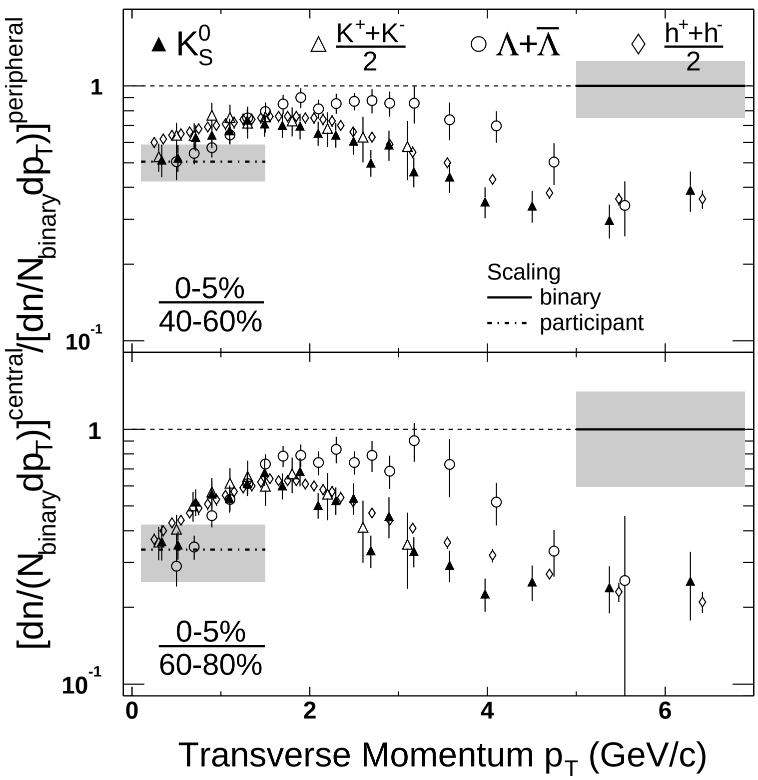


the density of partons in the transverse plane (saturation scale) grows as $Q_s^2(s;y) = Q_s^2(s;0)\ exp(\lambda y)$ with $\lambda \simeq 0.25 \div 0.3$ and $Q_s^2(s;0) \simeq 2\ GeV^2$, one gets

$$Q_s^2(s; y = +4) \simeq \underline{7}\ GeV^2$$

$d - Au$ results

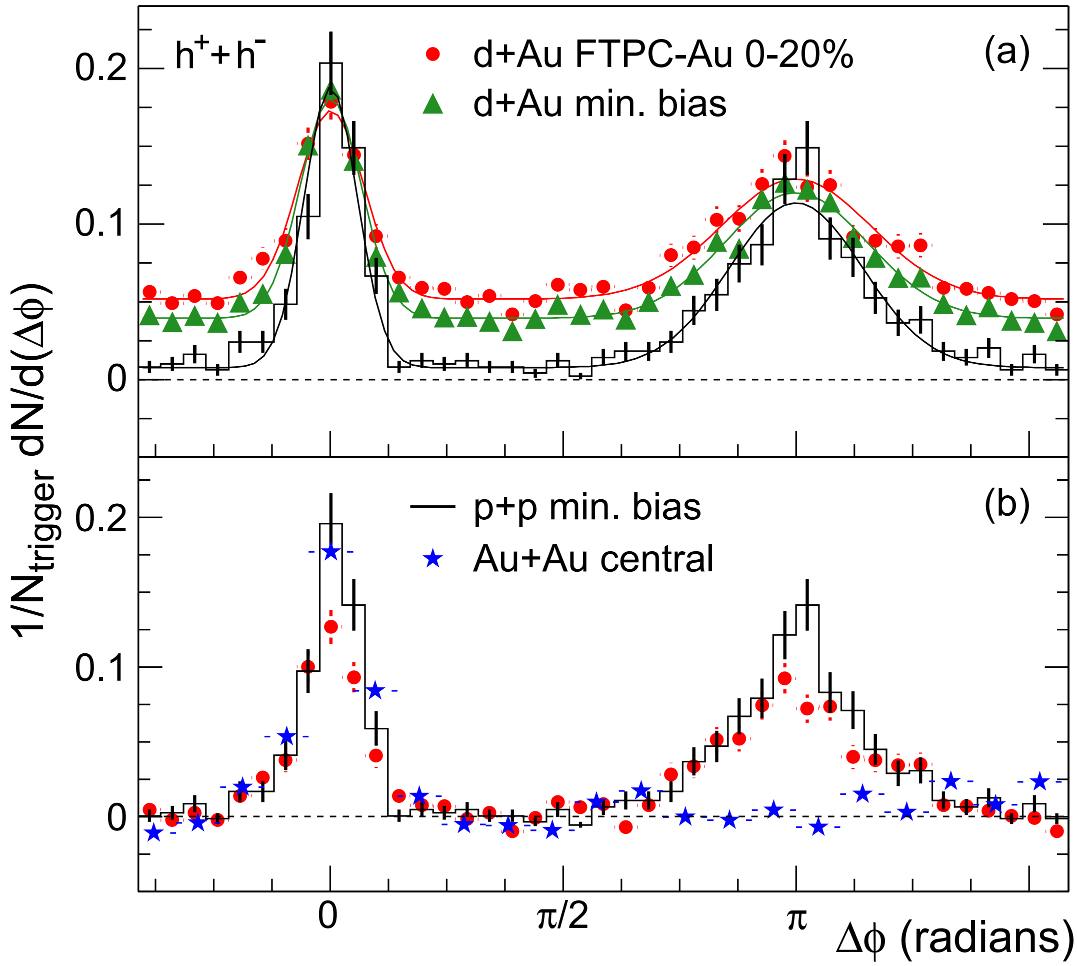
The difference in the suppression of baryons and mesons in $Au - Au$ exists up to $p_t \simeq 6$ GeV; at higher p_t universal attenuation (independent jet fragmentation?) sets in



STAR Coll., nucl-ex/0306007

An effect which is common for $d - Au$ and $Au - Au$? Why are the baryons suppressed less?

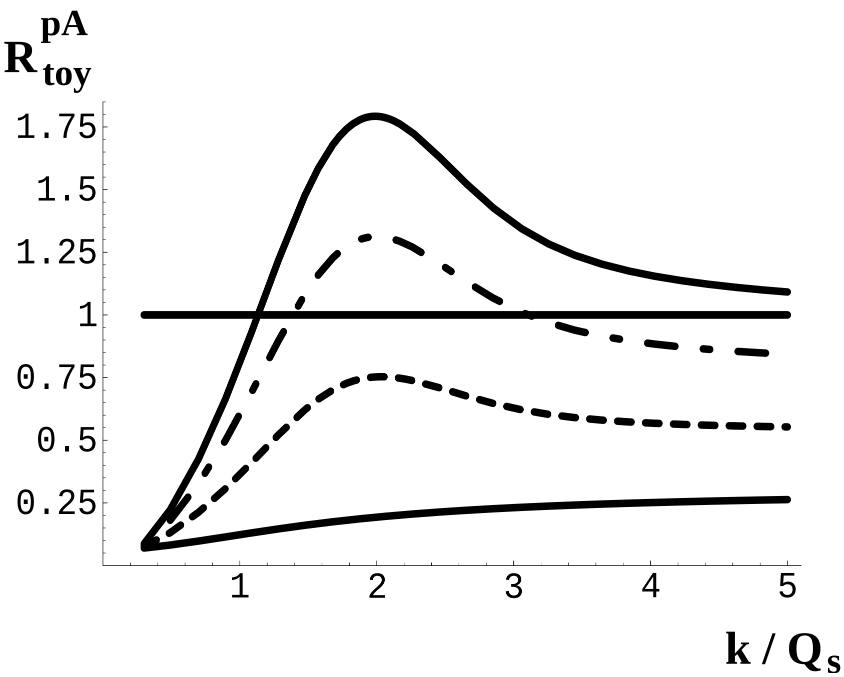
Back–to–back correlations survive in $d - Au$, but not in $Au - Au$:



STAR Coll., nucl-ex/0306024

the shape of the correlation function gets modified in $d - Au$ as well

Is there a high p_t suppression in forward $d - Au$?



D.K., Yu. Kovchegov and K. Tuchin, hep-ph/0307037 (Phys. Rev. D, in press)

Recent theoretical studies agree that quantum evolution effects should induce high p_t suppression at sufficiently small x

D.K., E. Levin, L. McLerran, Phys.Lett.B561:93-101,2003;
J. Jalilian-Marian, Y. Nara, R. Venugopalan, nucl-th/0307022;
R. Baier, A. Kovner, U. Wiedemann, Phys.Rev.D68:054009,2003;
J. Albacete, N. Armesto, A. Kovner, C. Salgado, U. Wiedemann, hep-ph/0307179

Summary

1. A coherent picture is beginning to emerge from RHIC:

   - Strong coherence effects in the initial state are necessary to explain the measured hadron multiplicities.The physics of initial stage of the collision is adequately described by hard processes at high p_t and, at smaller transverse momenta, by parton saturation in the Color Glass Condensate. Large energy densities $\epsilon \simeq 20\ \mathrm{GeV/fm^3}$ are produced.
   - The produced super–dense quark–gluon matter then undergoes final–state interactions driving it towards equilibrium; this is supported by flow, high p_t suppression, particle composition and other observables.

2. Two reasons for moving forward at RHIC:

   - To understand better the contributions of initial– and final–state effects to the observed phenomena
   - To study the physics of coherent strong color fields in its own right