The Abdus Salam International Centre for Theoretical Physics

SMR.1663- 17

SUMMER SCHOOL ON PARTICLE PHYSICS

13 - 24 June 2005

QCD Phase Transitions and Heavy ion Collisions - Part 3

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xQCD: What has RHIC wrought? From CGC to QGP

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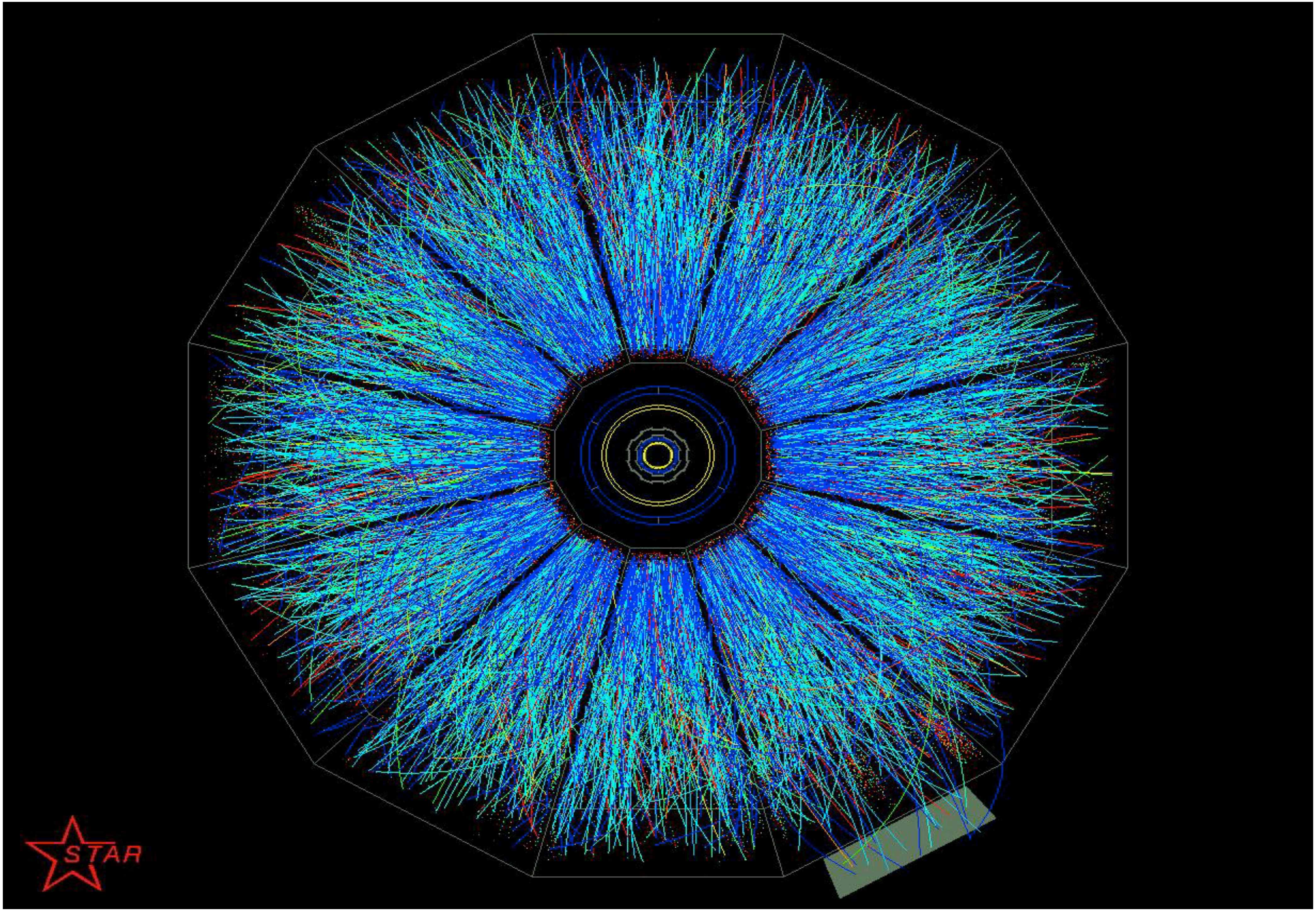
ICTP, Trieste, June 20th -24th, 2005

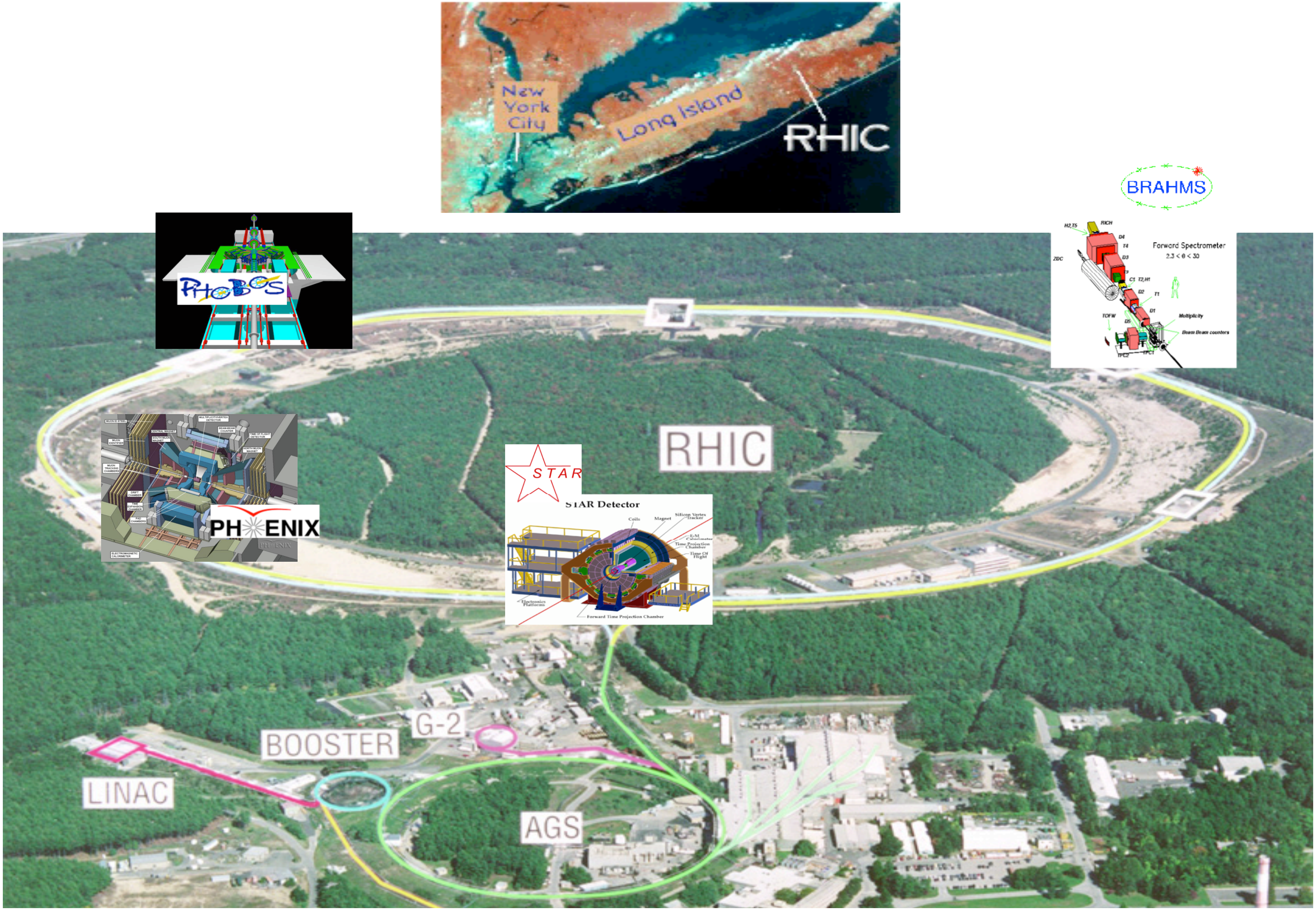
- **Lecture III**: What has RHIC wrought?
  From CGC to QGP

- **Lecture IV**: Exploring the QCD Phase diagram

Outline of lecture III

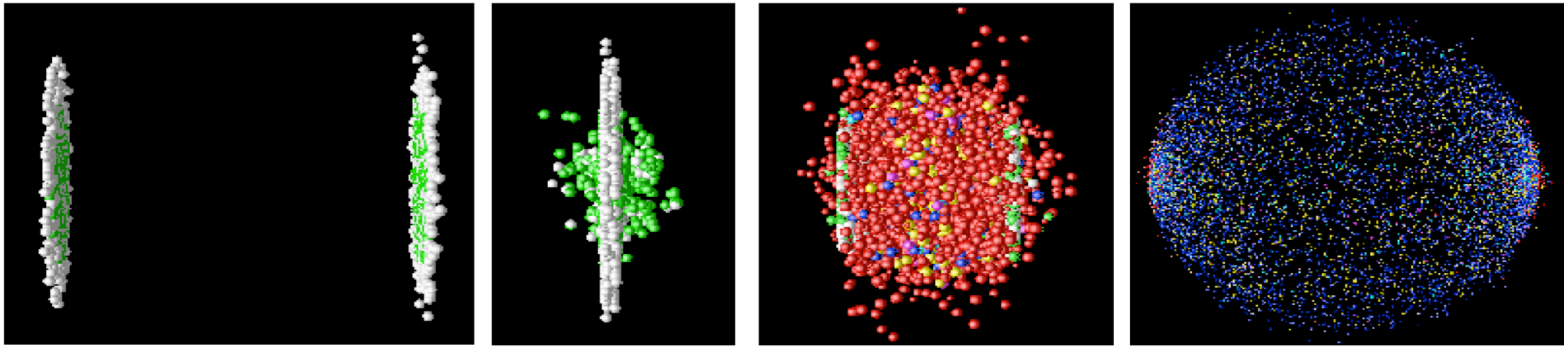
- **Heavy Ion Collisions at RHIC**
- **From CGC to QGP? Understanding thermalization in high energy heavy ion collisions.**


STAR


New York City
Long Island
RHIC
BRAHMS
Forward Spectrometer
PHOBOS
PHENIX
STAR
STAR Detector
Coils
Magnet
Silicon Vertex Tracker
Time Projection Chamber
Forward Time Projection Chamber
RHIC
G-2
BOOSTER
LINAC
AGS

RHIC Collisions

(VNI simulations)



- Gold-Gold collisions at $\sqrt{s} = 200\,\mathrm{GeV} \,/\, \mathrm{nucleon}$

- Polarized (and un-polarized) p-p collisions at $\sqrt{s} = 200\,\mathrm{GeV} \,/\, \mathrm{nucleon}$

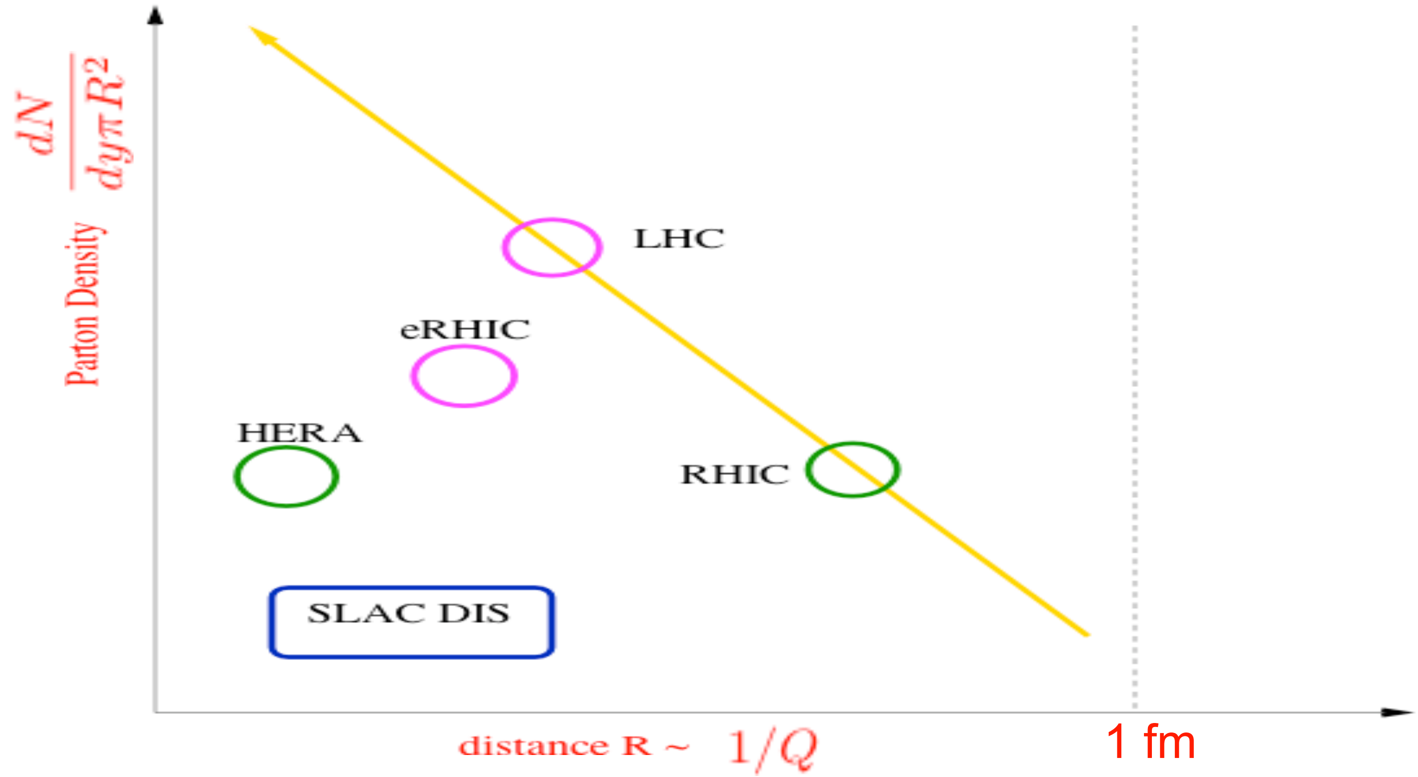
- Run 3- deuteron-Gold collisions at $\sqrt{s} = 200\,\mathrm{GeV} \,/\, \mathrm{nucleon}$

- Current run- Cu+Cu: polarized pp at 410 GeV, …

A “birds eye” view of RHIC

HEAVY-ION EXPERIMENTS

Facility	Location	System	Energy (CMS)
AGS	BNL, New York	Au+Au	2.6-4.3 GeV
SPS	CERN, Geneva	Pb+Pb	8.6-17.2 GeV
RHIC	**BNL, New York**	**Au+Au**	**200 GeV**
LHC	CERN, Geneva	Pb+Pb	5.5 TeV

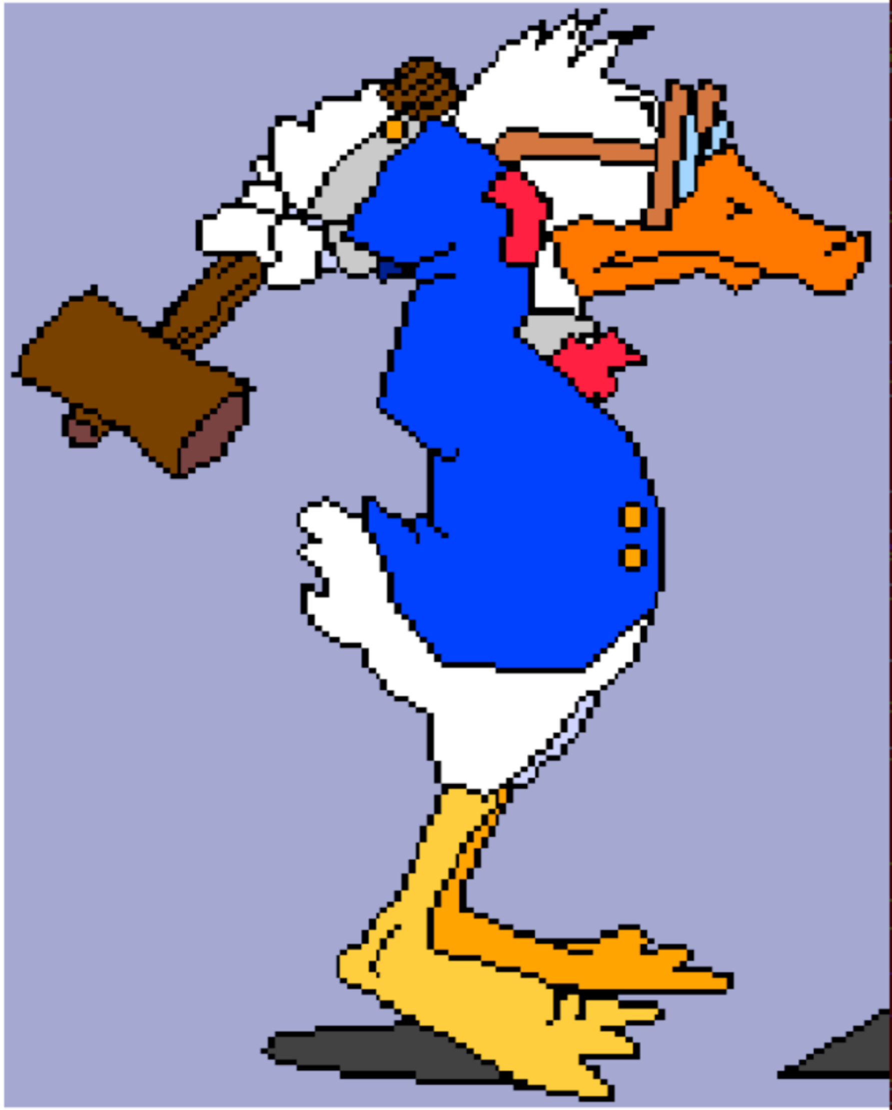


Results from the RHIC Au-Au experiments:

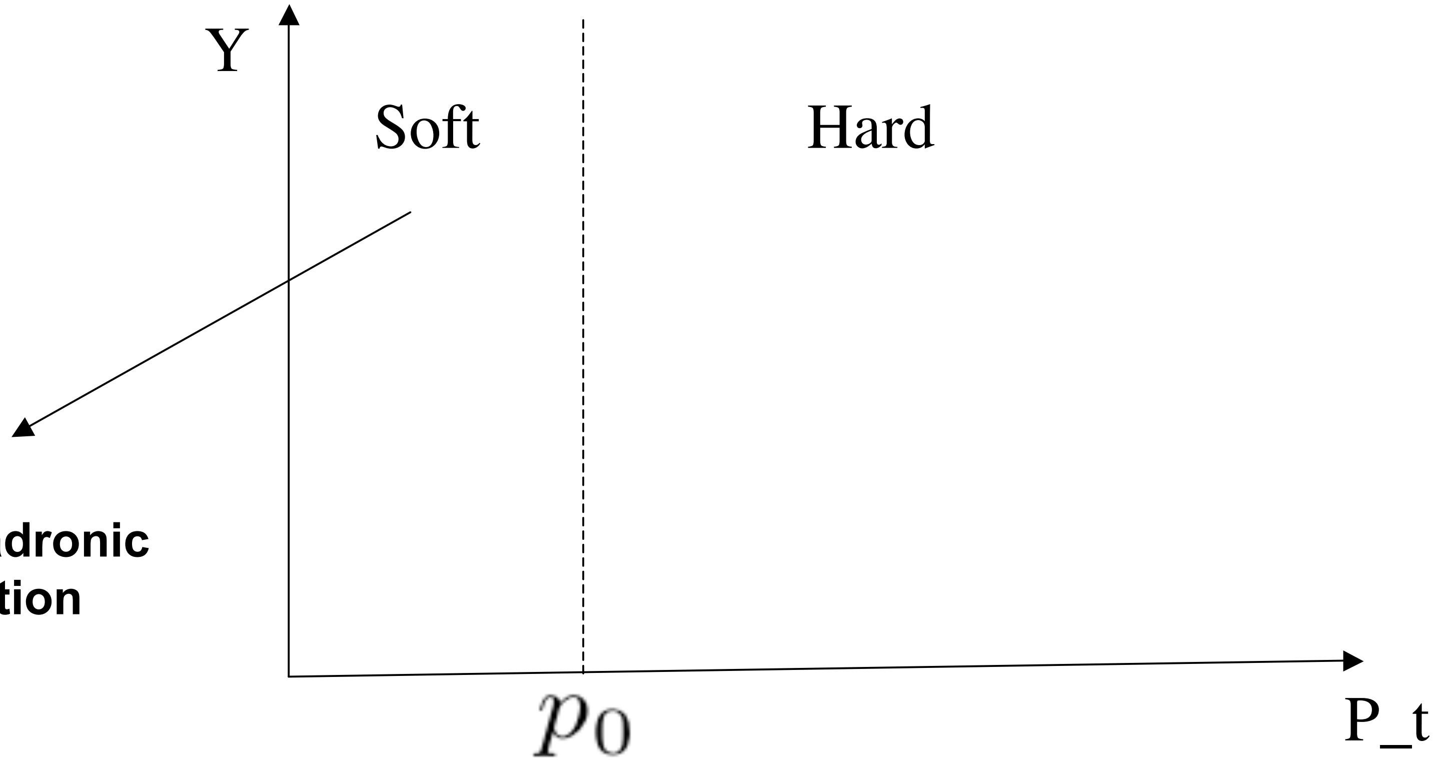
Bulk features: Energy, Centrality & Rapidity dependence of inclusive hadron distributions.
Flavor: Baryon #, Strangeness, Charm.
Flow: Radial & Elliptic flow.
Hanbury-Brown-Twiss: Two particle Bose-Einstein correlations.
"High" p_t physics:
a) High p_t inclusive hadron spectrum relative to p-p (central/peripheral)
b) p_t dependence of azimuthal anisotropy,
c) back-to-back jet correlations.
d) direct photons & di-leptons; J/psi's
Event-by-event physics:

p-p and d-Au ``control experiments" crucial to develop consistent framework

Melting Colored Glass in Heavy Ion Collisions

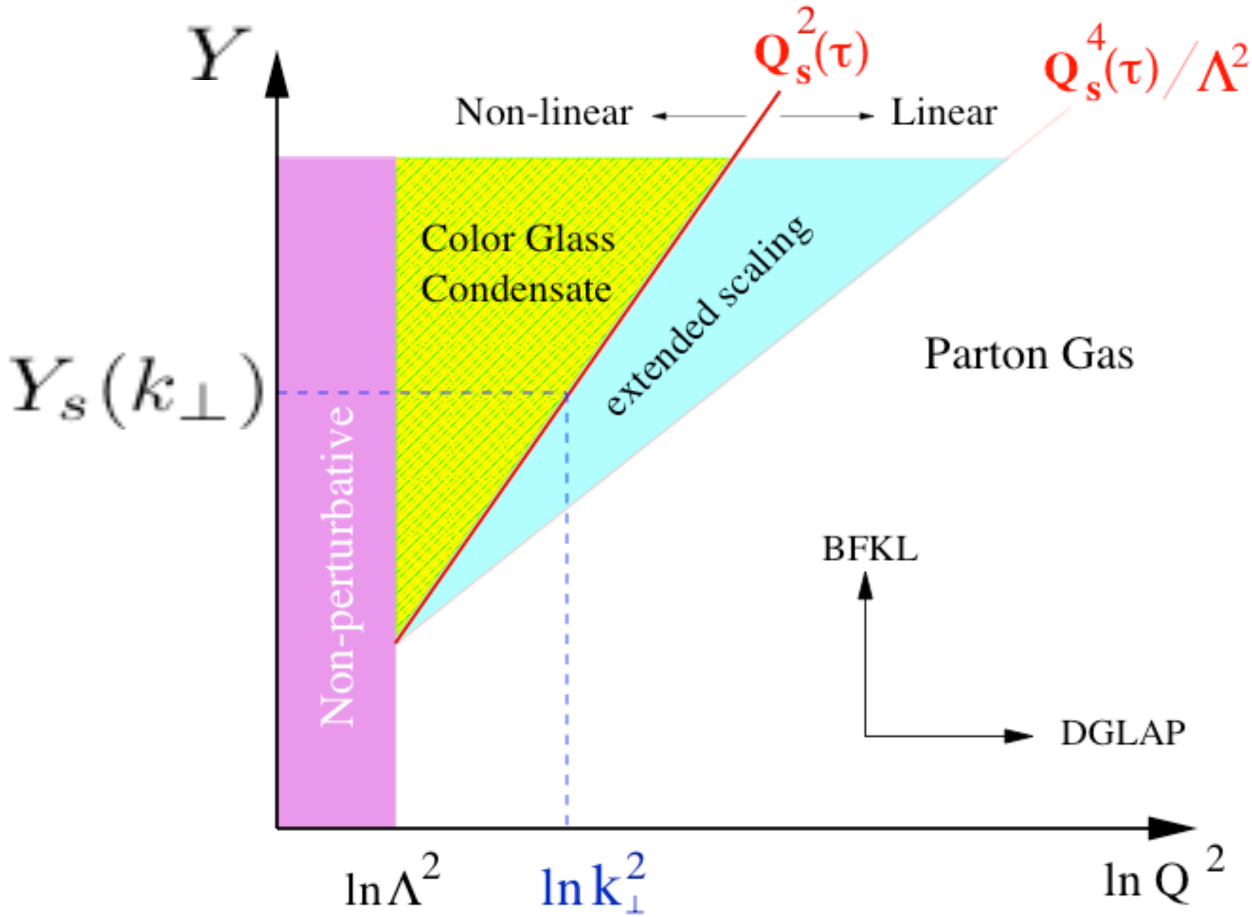


❖ Traditional view of heavy ion collisions



Bulk of hadronic cross-section

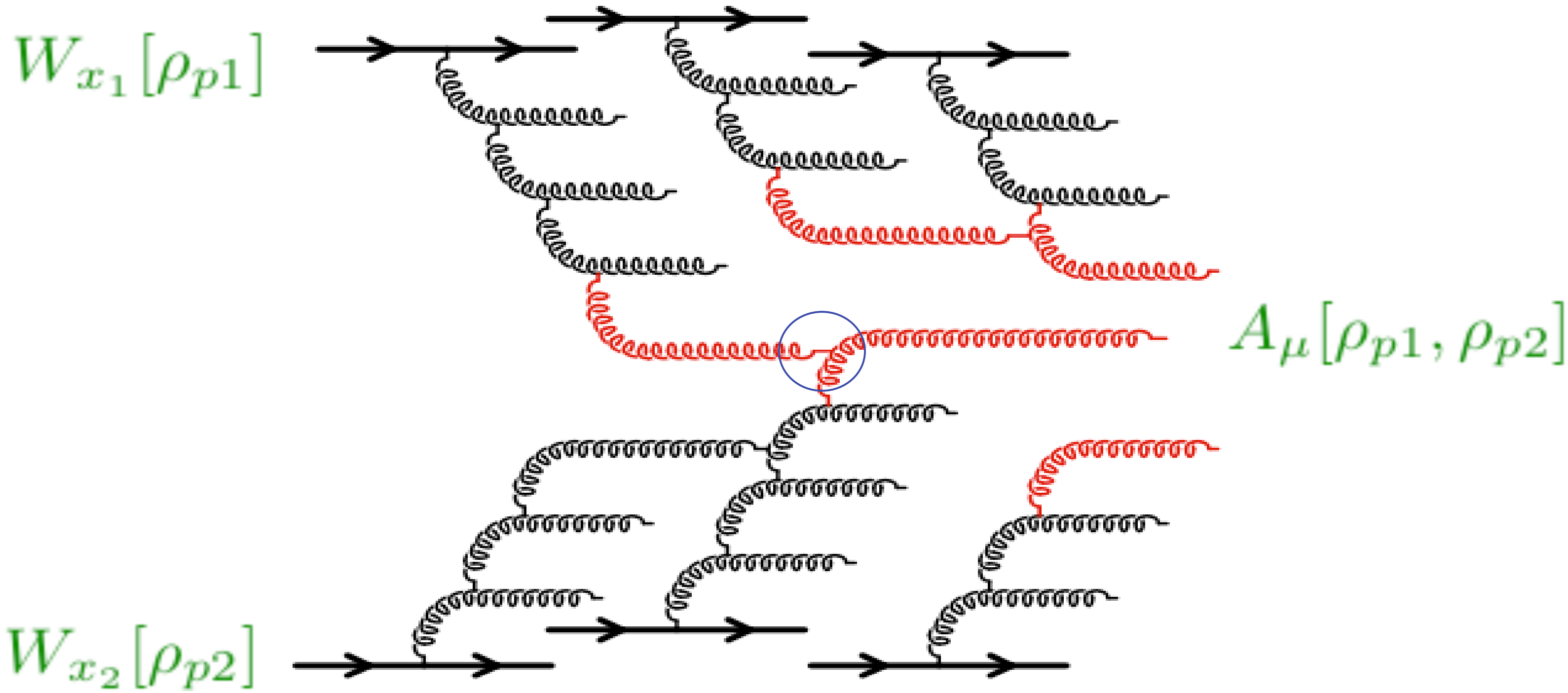
❖ An alternative perspective…



$$\alpha_S(Q_s^2) << 1 \text{ for } Q_s^2 >> \Lambda^2_{\rm QCD}$$

Weak coupling techniques may be applicable…

Hadronic collisions in the color glass framework



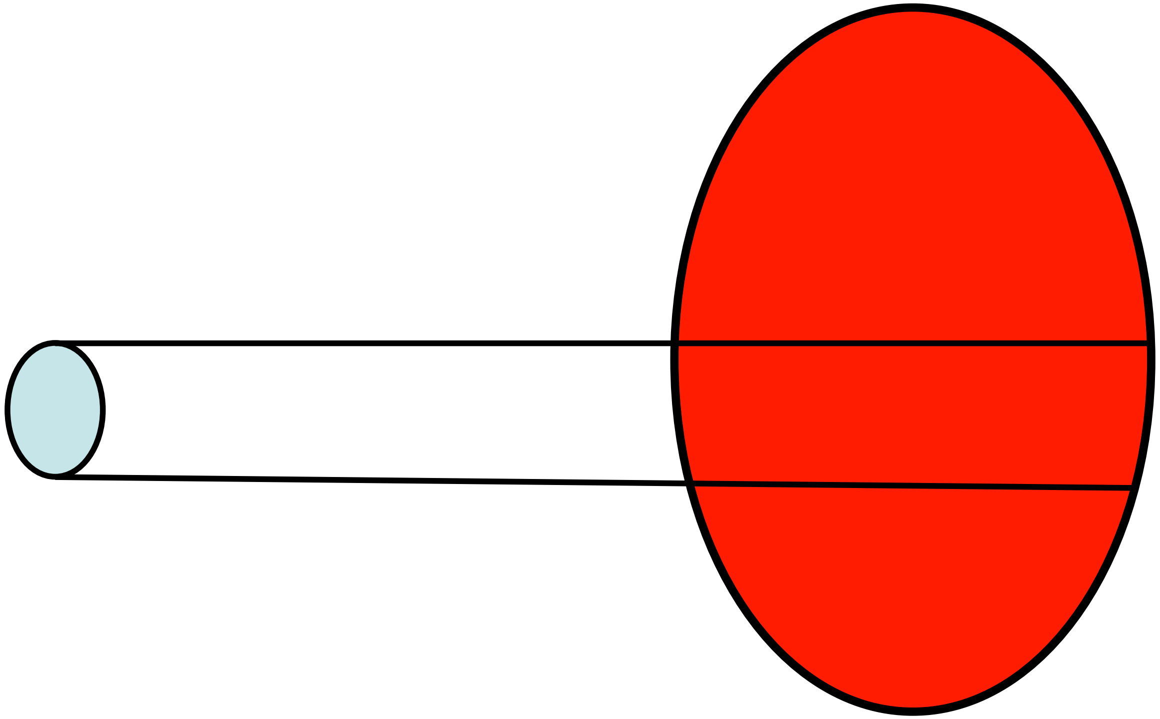
- **Solve Yang-Mills equations for two light cone sources:**

$$(\rho_1, \rho_2)$$

- **All quantum information on evolution of sources in**

$W[\rho_1]\ \&\ W[\rho_2]$ **- must be averaged over**

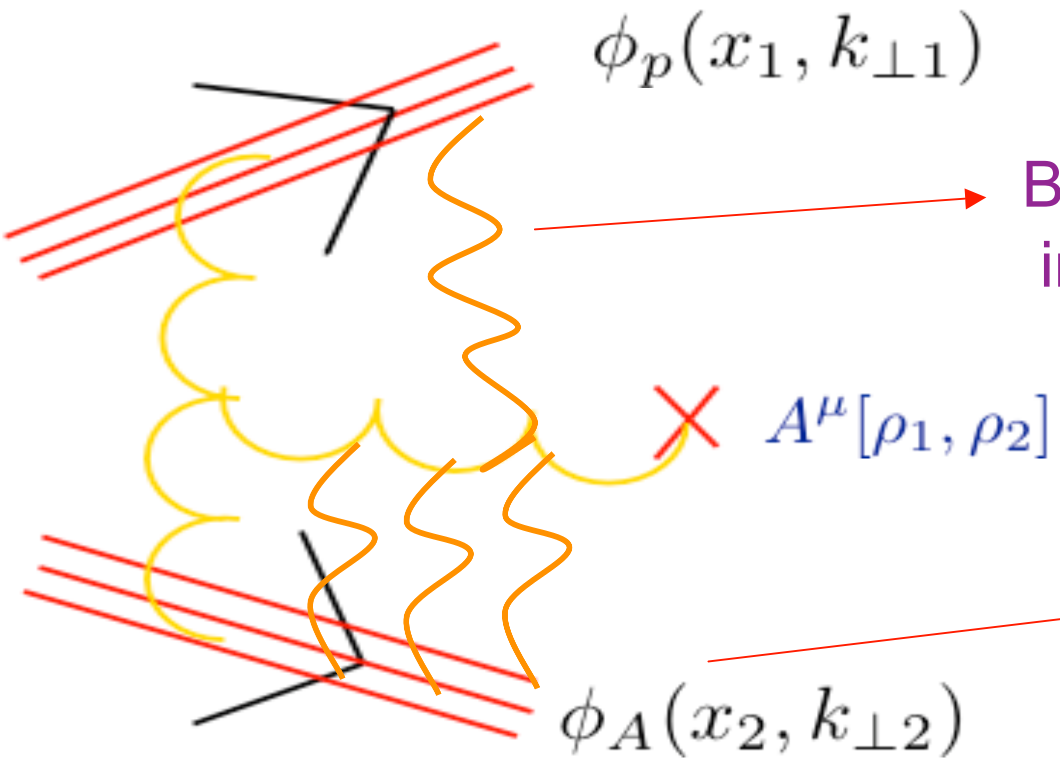
“Simpler” Cold Matter: proton/Deuteron - A scattering



RHIC data on Deuteron-Gold scattering.

Claim: Key features can be understood in CGC approach

gluon production in D-A: systematic power counting



Breaks down at next order in $\rho_p / k_{1\perp}^2$

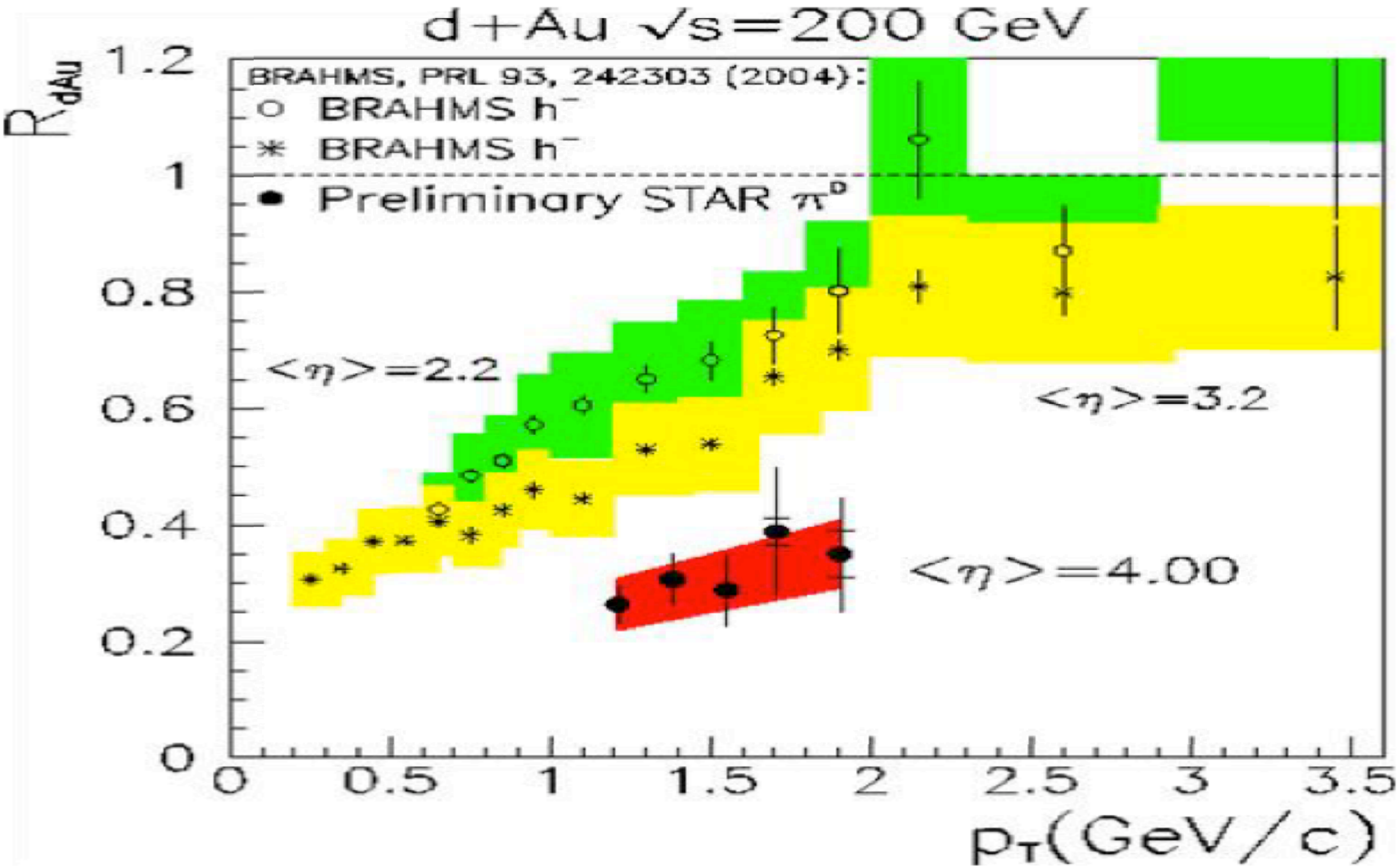
Krasnitz,RV;
Balitsky

Unintegrated "gluon" distribution-includes all twists

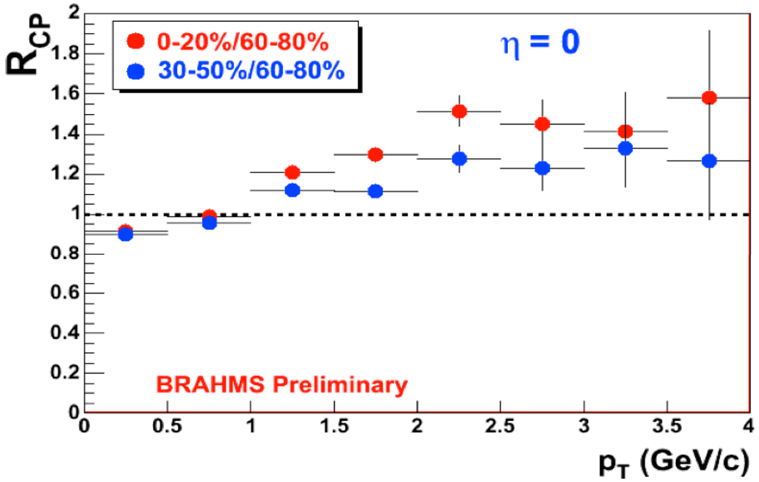
- K_t factorization holds for inclusive gluon production lowest order in $\rho_p / k_{\perp 1}^2$ but all orders in $\rho_A / k_{\perp 2}^2$

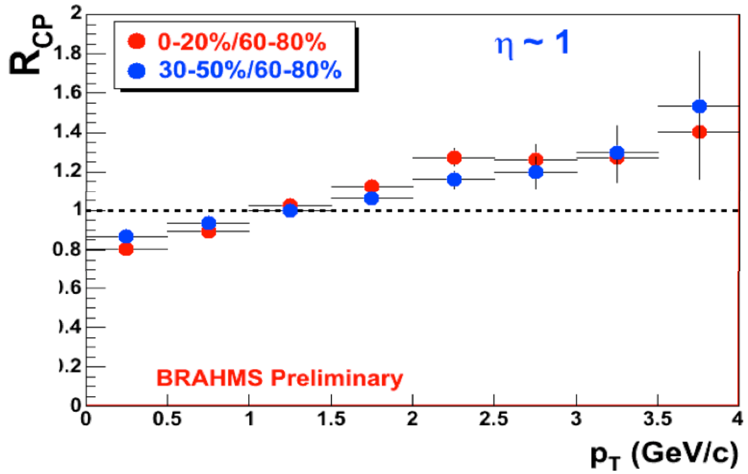
Kovchegov-Mueller

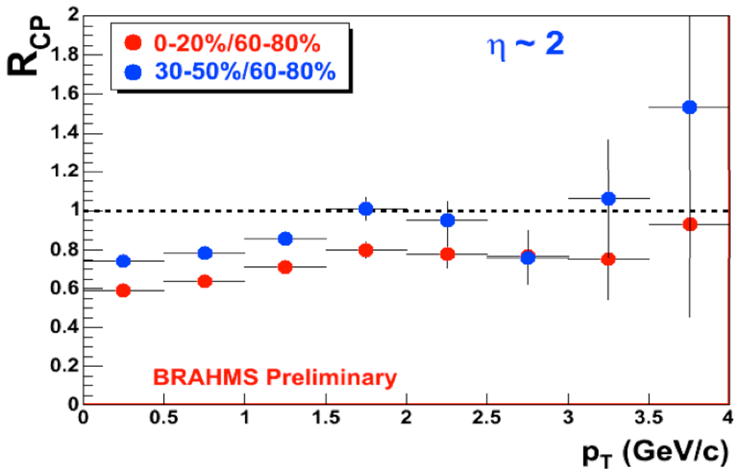
RHIC DATA ON THE CRONIN EFFECT in D-Au Collisions

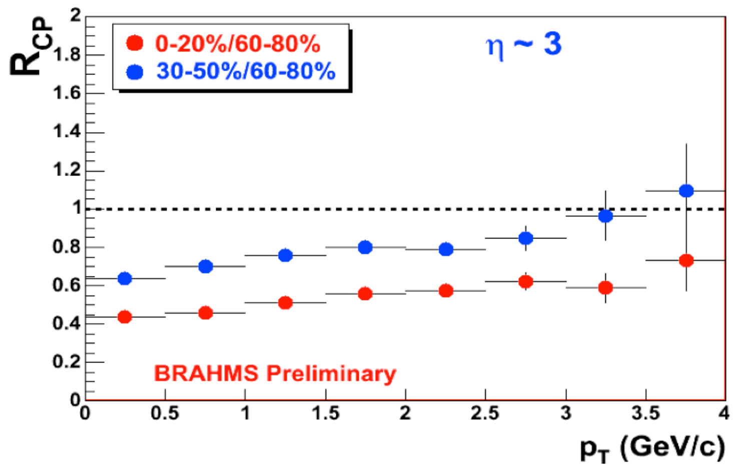


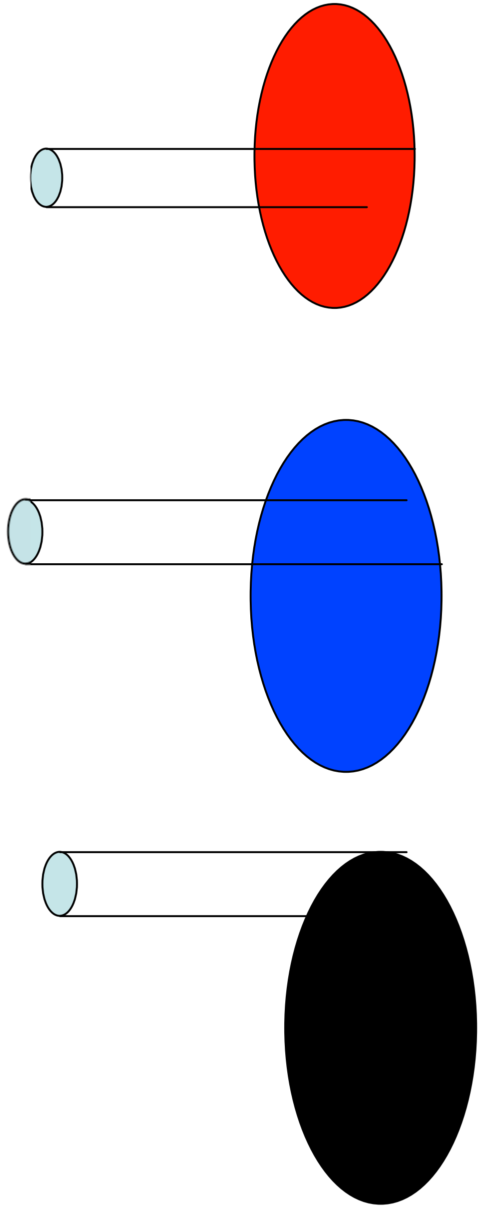
Centrality dependence



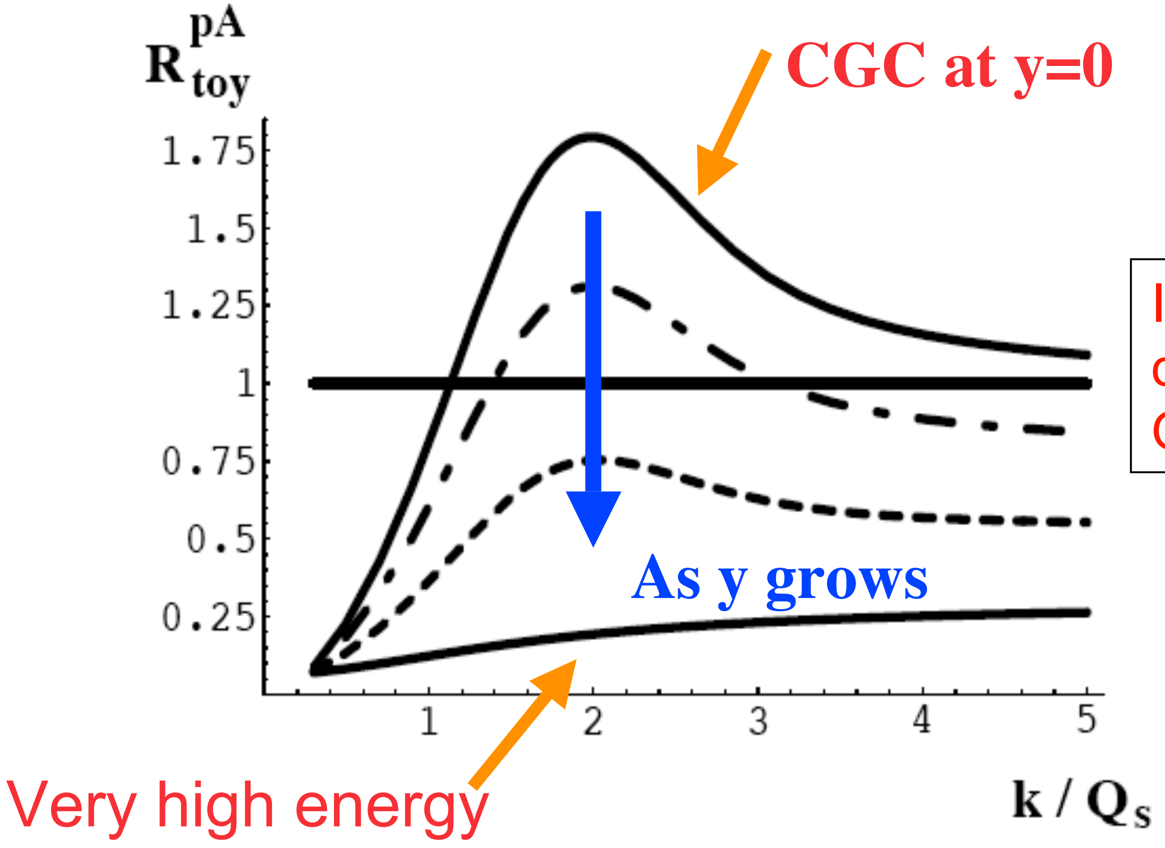








Compute R_pA



Dumitru,Jalilian-Marian
Jalilian-Marian, Gelis
Accardi

Inversion of centrality dependence due to softening Of the spectrum at small x

Kharzeev,Kovchegov,Tuchin
Baier,Kovner,Wiedemann;
Albacete,Armesto,Salgado,Kovner,Wiedemann
Blaizot,Gelis,RV
Iancu,Itakura,Triantafyllopolous

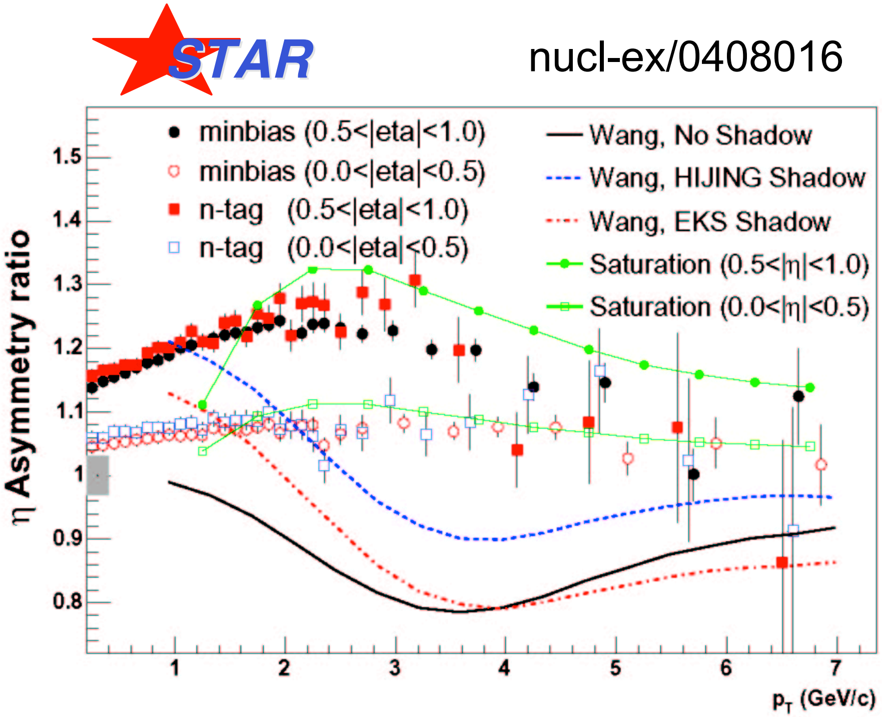
Broadening of azimuthal correlations due to CGC

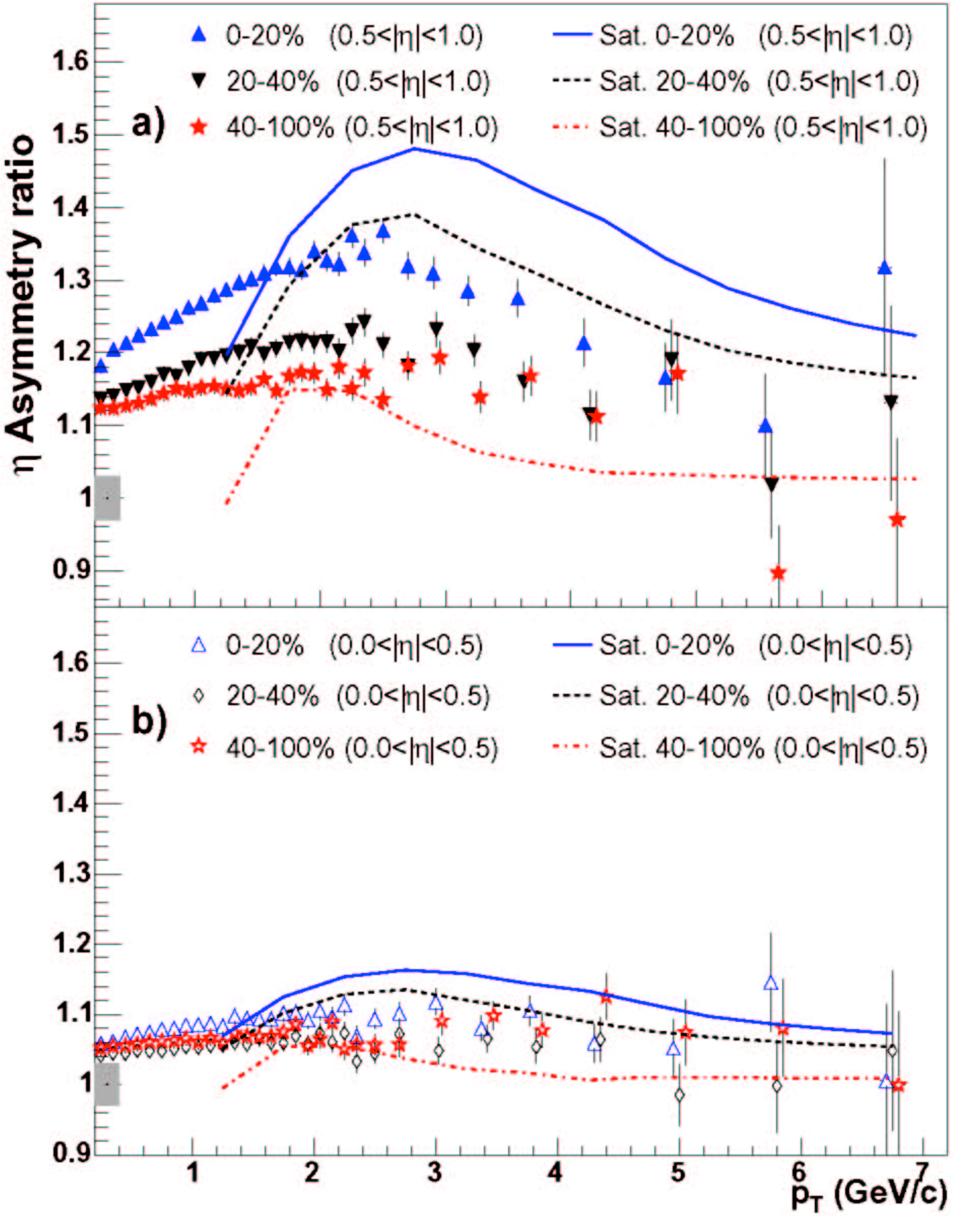
Kharzeev,Levin,McLerran

- Other tests-photons and di-leptons in forward region

Au direction / d direction

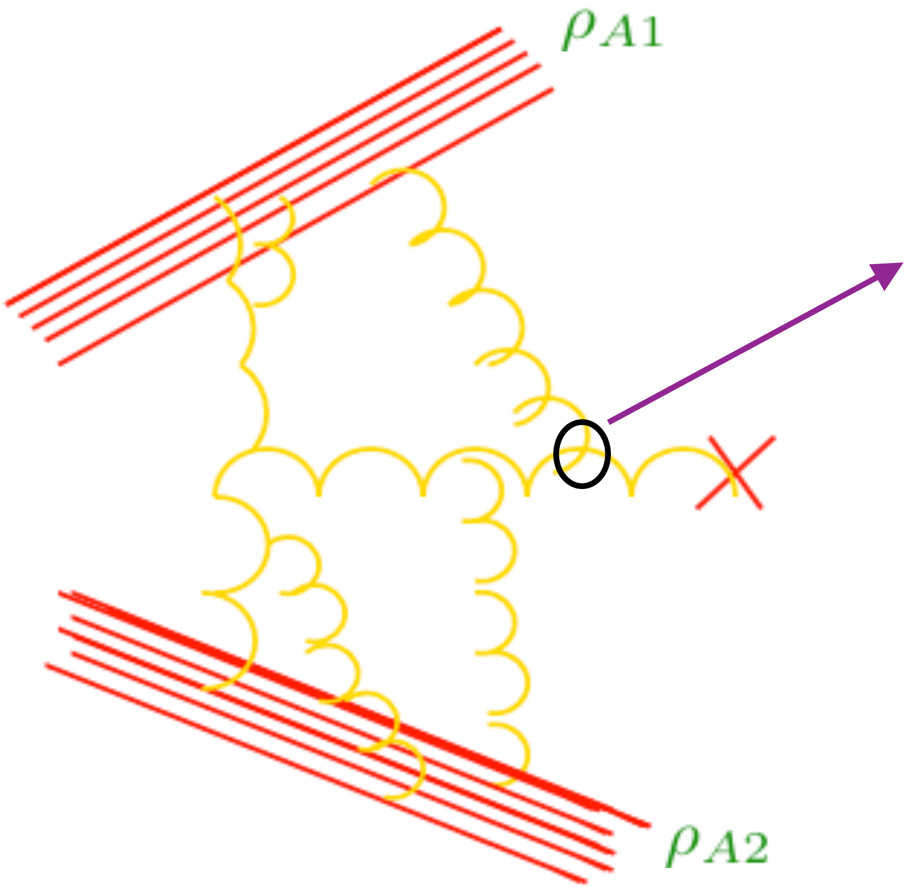
nucl-ex/0408016





Back to Nucleus-Nucleus Collisions…

$$(\rho_{A1}/k_\perp^2,\ \rho_{A2}/k_\perp^2 \sim 1)$$

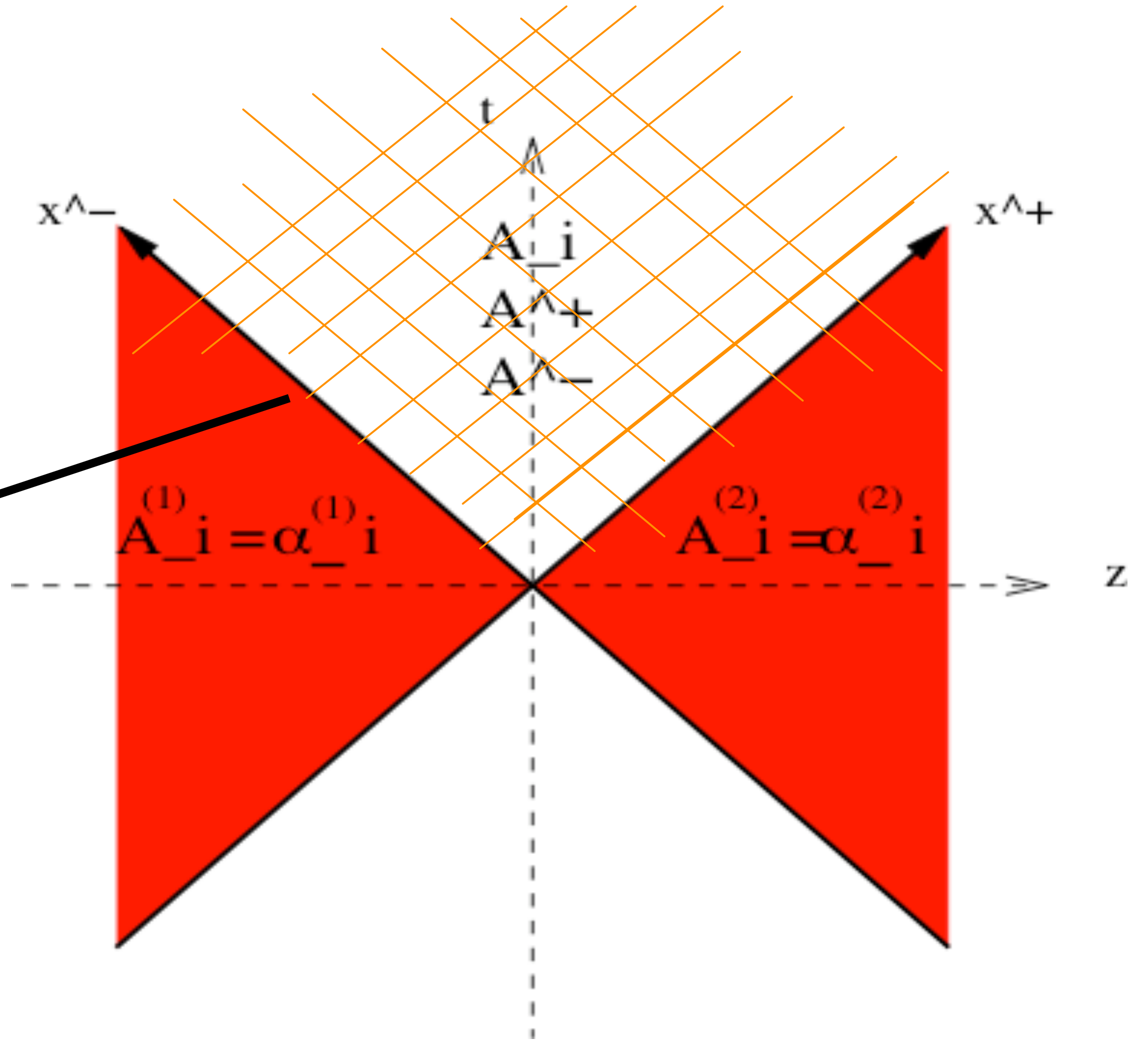


All such diagrams of Order O(1)

Yang-Mills Equations for two nuclei

$$D_\mu F^{\mu\nu,a} = \delta^{\nu+}\rho_1^a(x_\perp)\delta(x^-) + \delta^{\nu-}\rho_2^a(x_\perp)\delta(x^+)$$

Initial conditions from matching eqns. of motion on light cone



$$\tau = \sqrt{2x^+x^-}\,;\ \eta = \frac{1}{2}\ln\left(\frac{x^+}{x^-}\right)$$

Lattice Formulation

Krasnitz, RV

- Hamiltonian in $A^\tau = 0$ gauge; per unit rapidity,

$$H = \frac{\tau}{2}\int d^2 r_\perp \left[p^\eta p^\eta + \frac{1}{\tau^2}E_r E_r + \frac{1}{\tau^2}(D_r\Phi)(D_r\Phi) + F_{xy}F_{xy}\right]$$

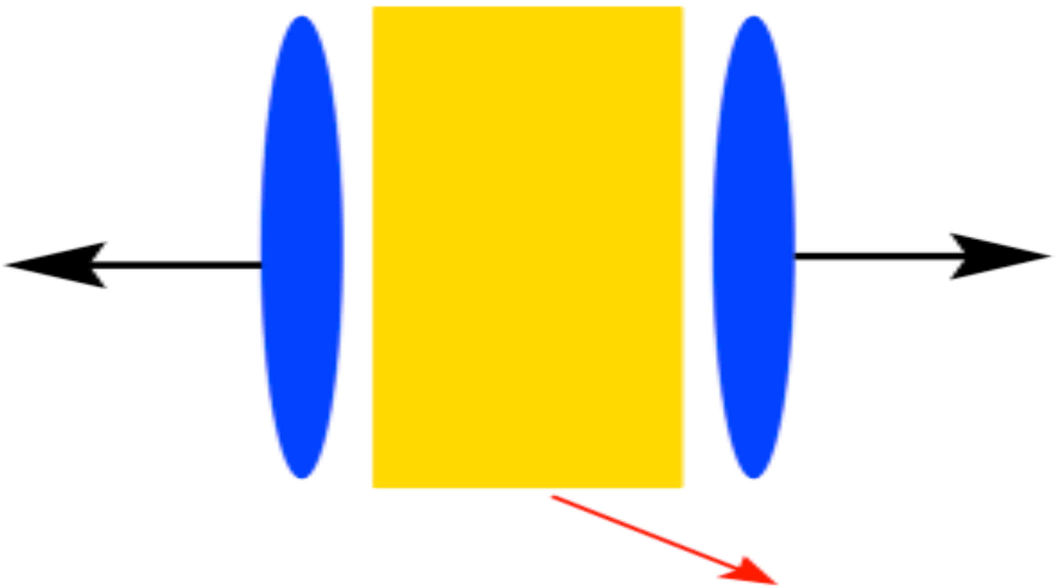
For ``perfect'' pancake nuclei, boost invariant configurations

$$A_r(\tau,\eta,r_\perp) = A_r(\tau,r_\perp)\ ;\ A_\eta(\tau,\eta,r_\perp) = \Phi(\tau,r_\perp)$$

- Solve Hamilton's equations in **real time** for space-time evolution of glue in Heavy Ion collisions

Krasnitz,Nara,RV;

Lappi



Classical Fields with occupation # f= $\frac{1}{\alpha_S}$

Initial energy & multiplicity of <u>produced</u> gluons depends on Q_s

$$\frac{1}{\pi R^2}\frac{dE}{d\eta} = \frac{0.25}{g^2} Q_s^3 \qquad \frac{1}{\pi R^2}\frac{dN}{d\eta} = \frac{0.3}{g^2} Q_s^2$$

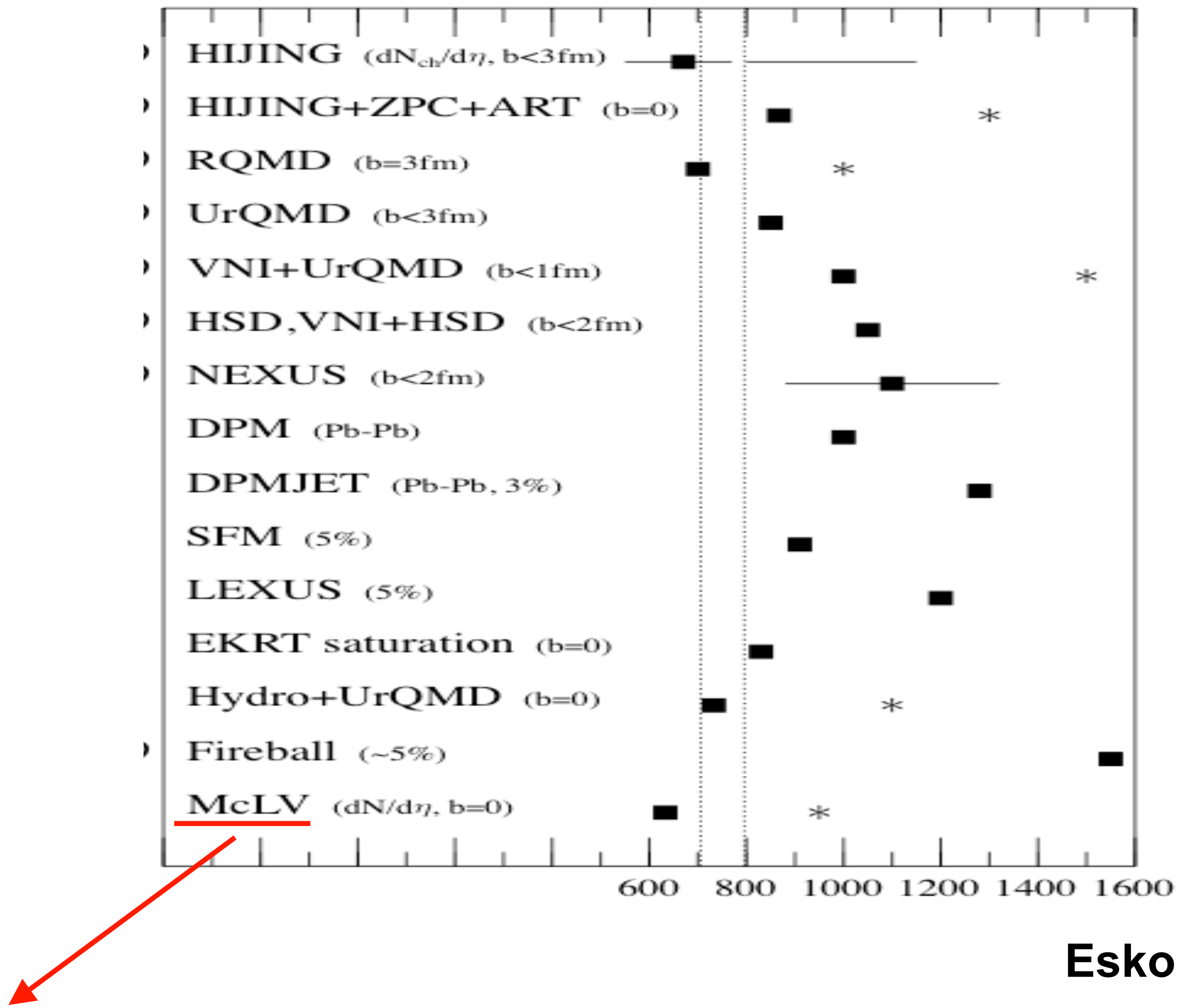
Straight forward extrapolation from fits of saturation models to HERA data

$$(Q_s^2)^{\text{RHIC}} = A^{1/3} \left(\frac{x_0}{x_{\text{RHIC}}} \right)^{0.3} \text{GeV}^2$$

RHIC : $Q_s \approx 1.4 \text{ GeV}$

LHC : $Q_s \approx 2.2 \text{ GeV}$

Predictions for Au+Au multiplicity at RHIC

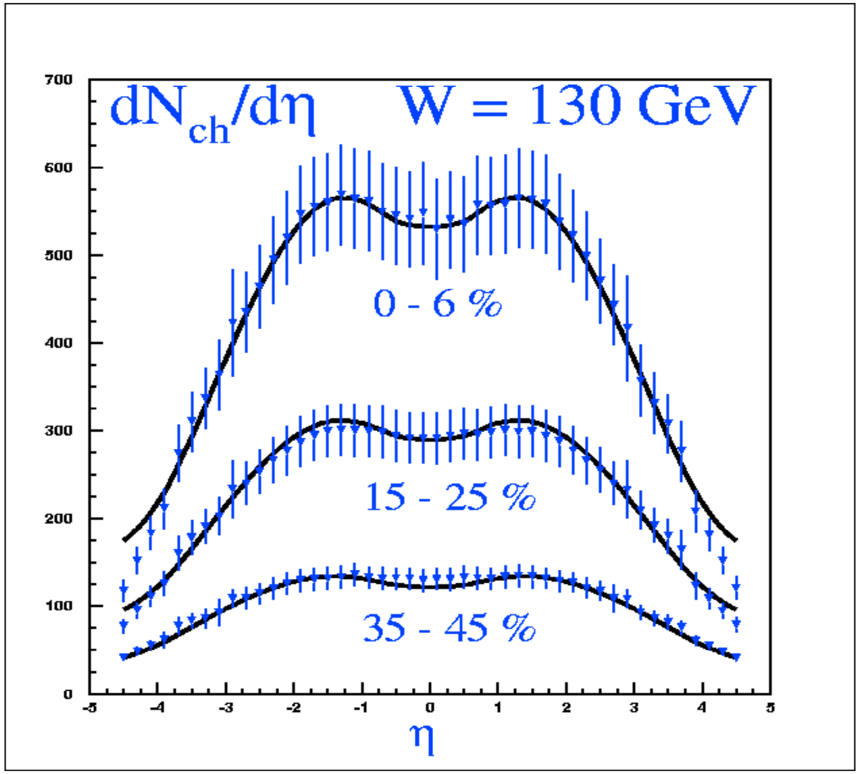


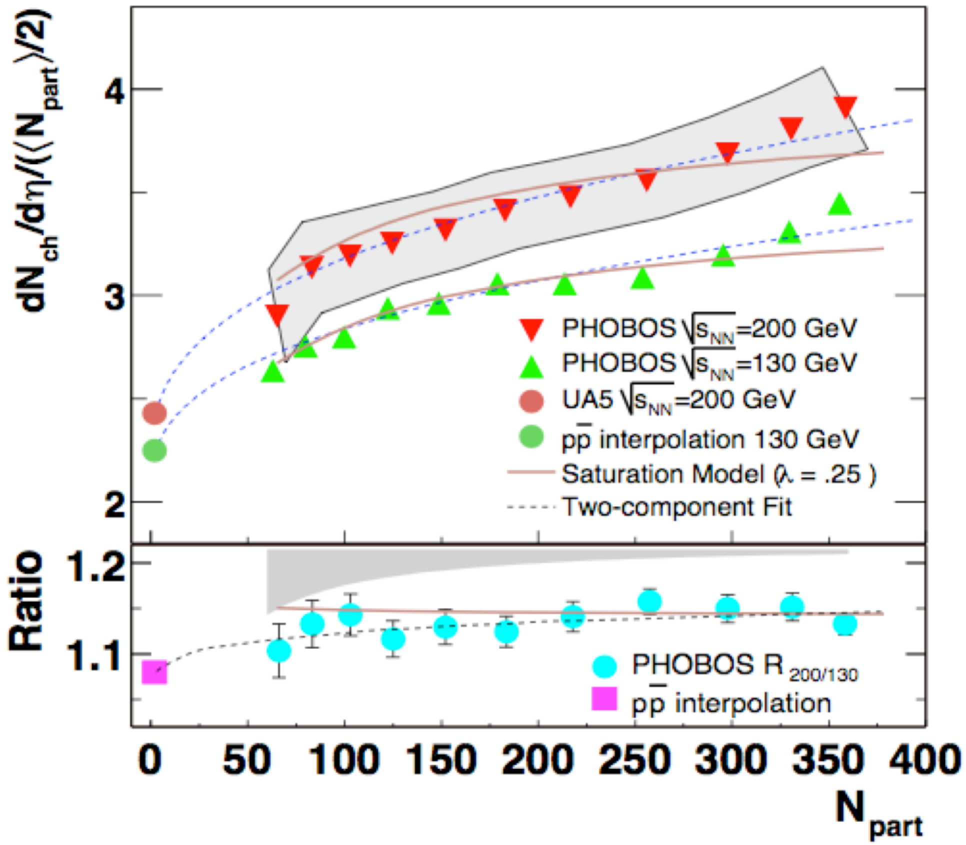
Eskola, QM 2001

Krasnitz, RV

Successful KLN phenomenology for multiplicities at RHIC

Kharzeev,Levin,N
ardi





- **Parton/Hadron duality assumed**

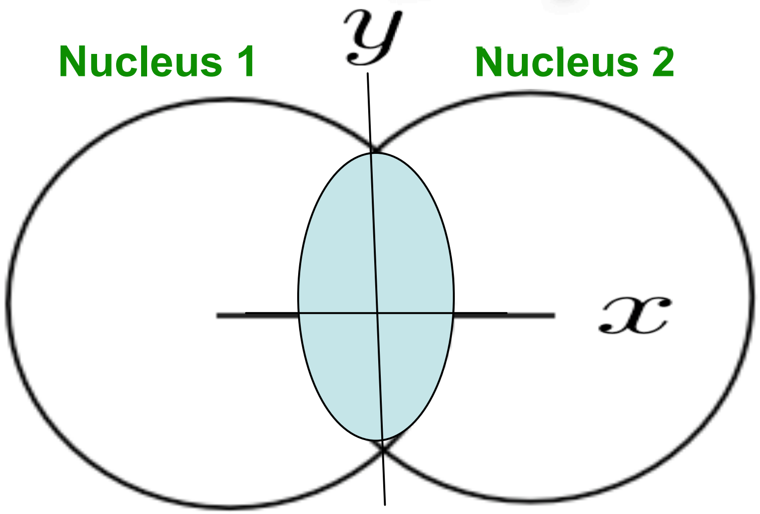
But…

$$(E_\perp/N)^{\mathrm{CGC}} \approx Q_s$$

$$(E_\perp/N)^{\mathrm{RHIC}} \approx Q_s/3$$

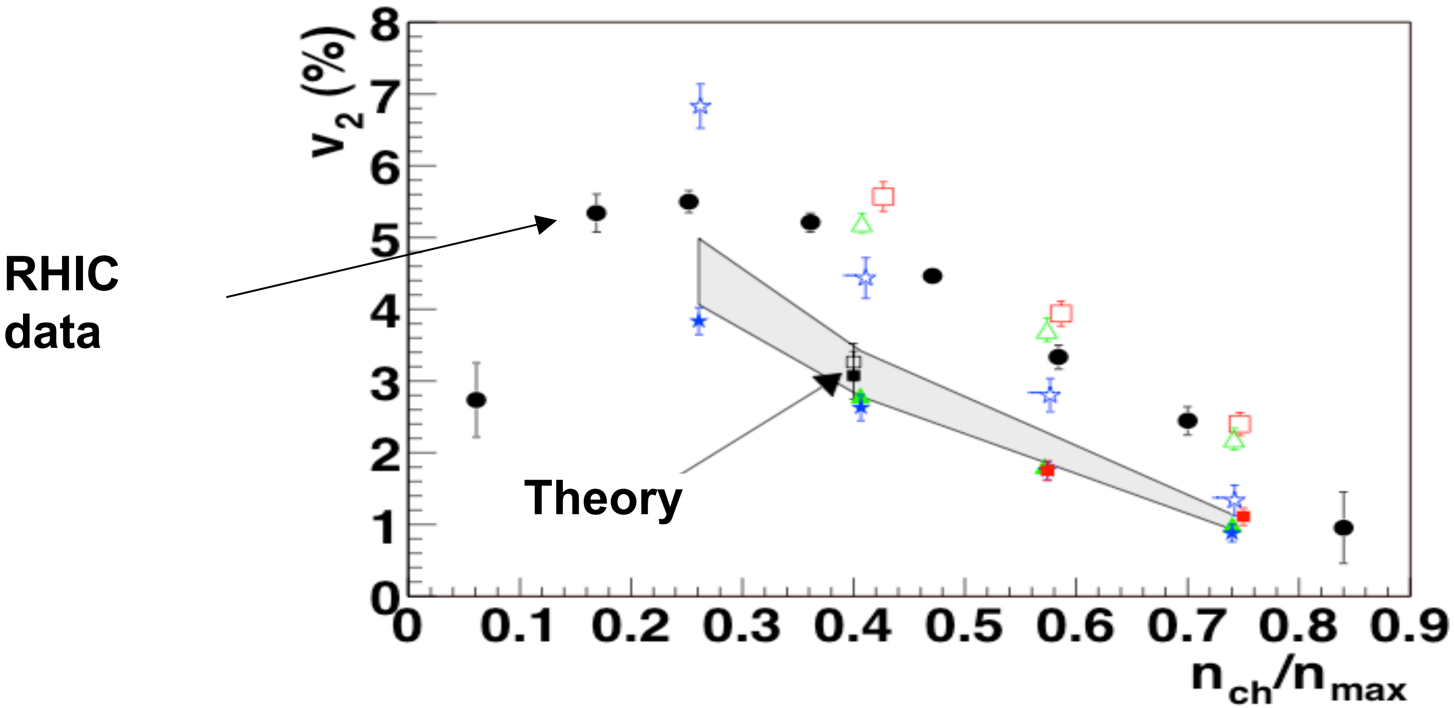
OK, if system does P dV work - hydrodynamics…

Elliptic flow of colored glass



$$v_2 N = \sqrt{\frac{2}{\pi}} \int_0^\infty \frac{dt}{\sqrt{t}} \left(T^{xx}(t) - T^{yy}(t)\right)$$

Transverse pressure in x (y) direction



Classical description breaks down when

occupation # f << 1: $\left(\tau \approx 1/Q_s\right)$

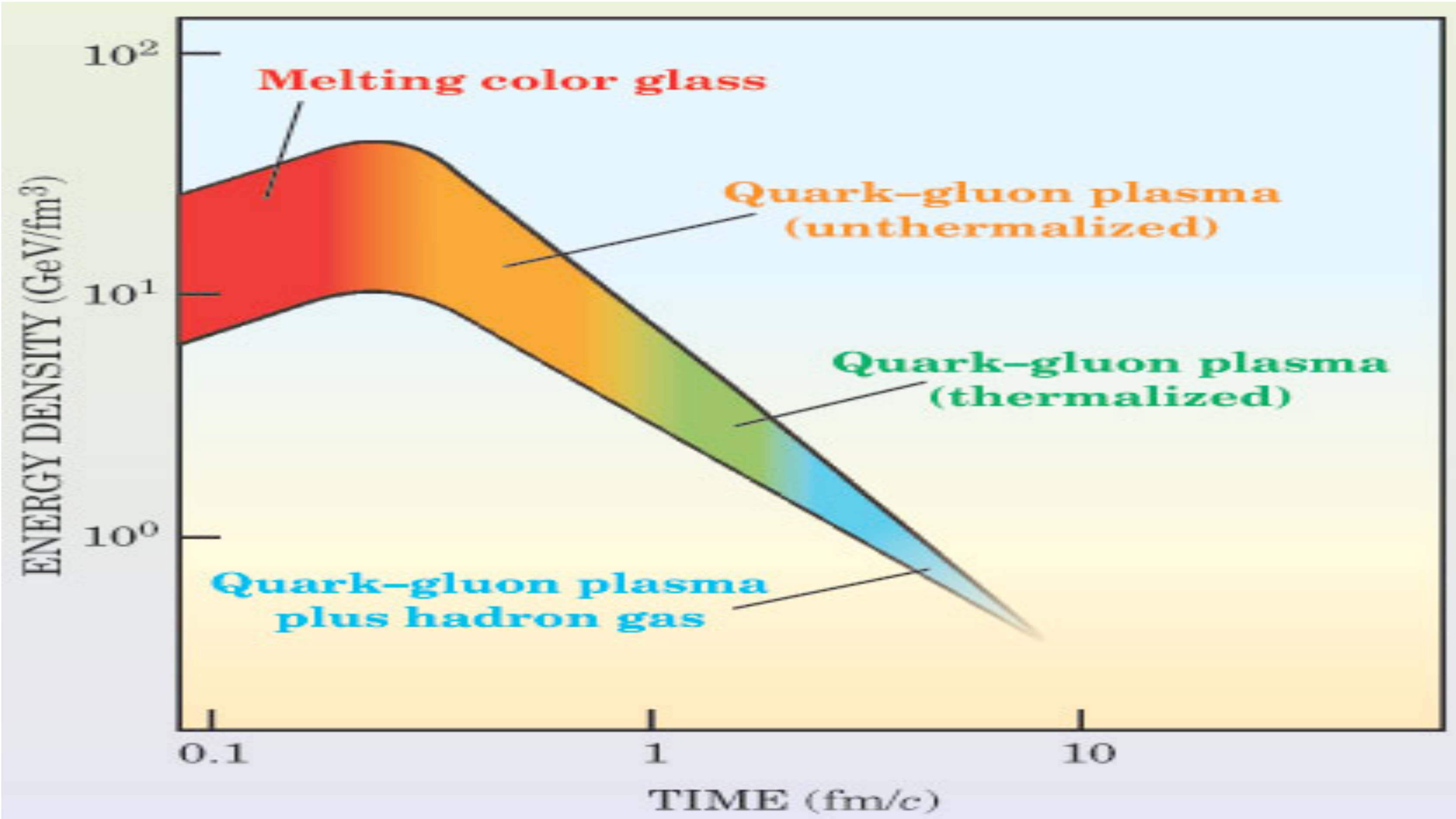
v_2 & E_t/N data suggest strong “final state”
re-scattering after classical phase -

fields -> particles

Can thermalization be understood in weak coupling ?

Melting CGC to QGP

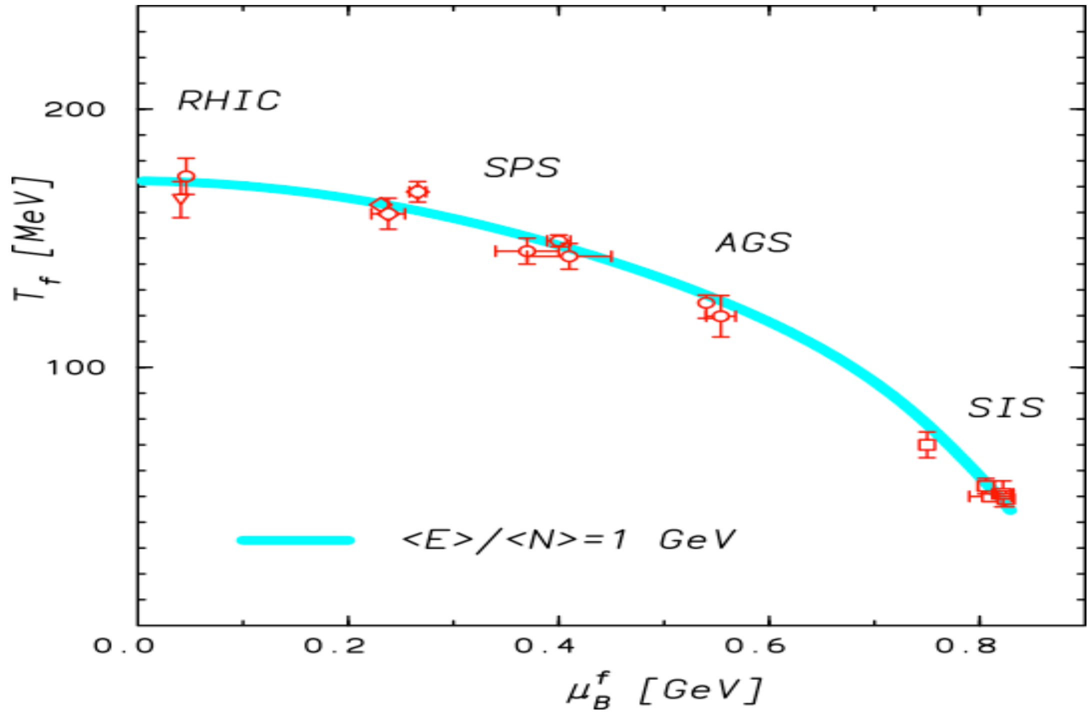
L. McLerran, T. Ludlam,
Physics Today

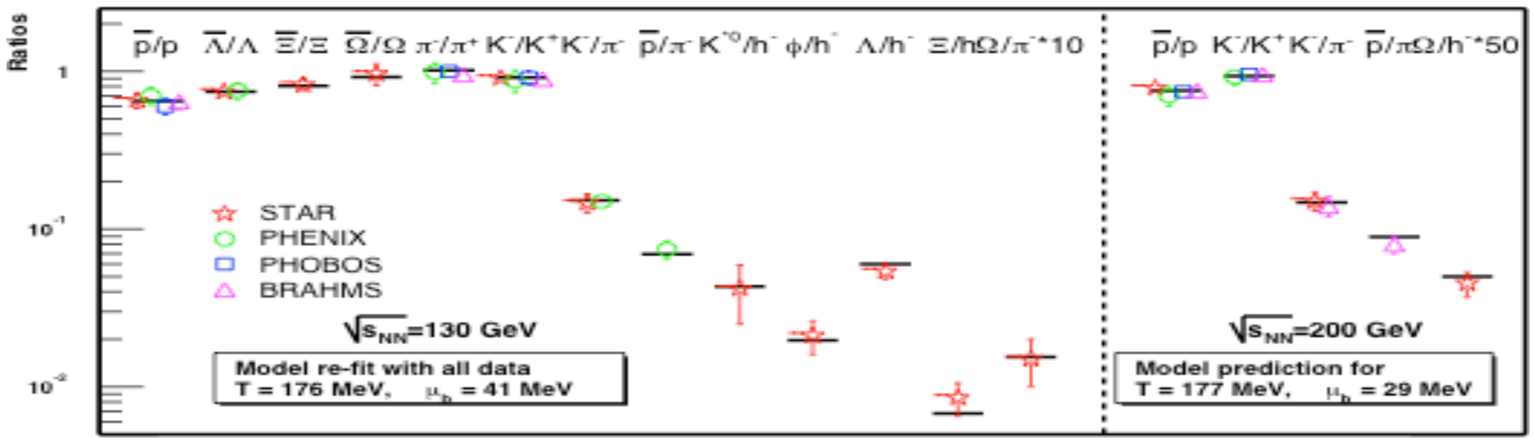


Emerging Consensus…final state interactions are essential.

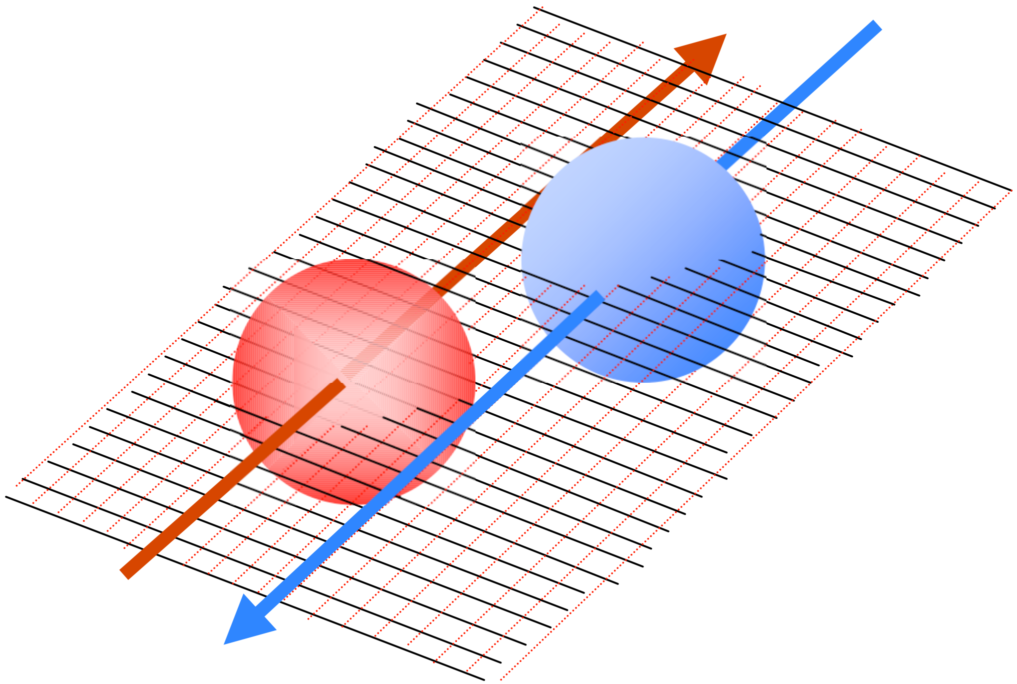
The evidence from low p_t physics

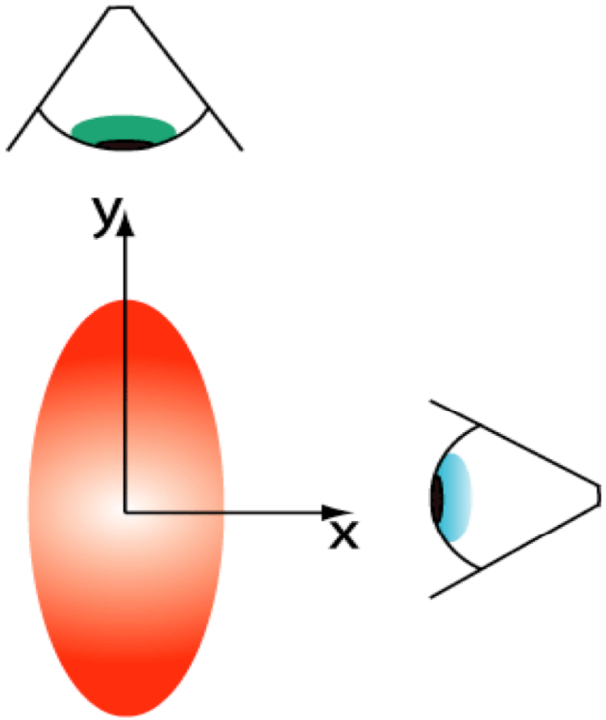
Thermal fits to
Particle ratios



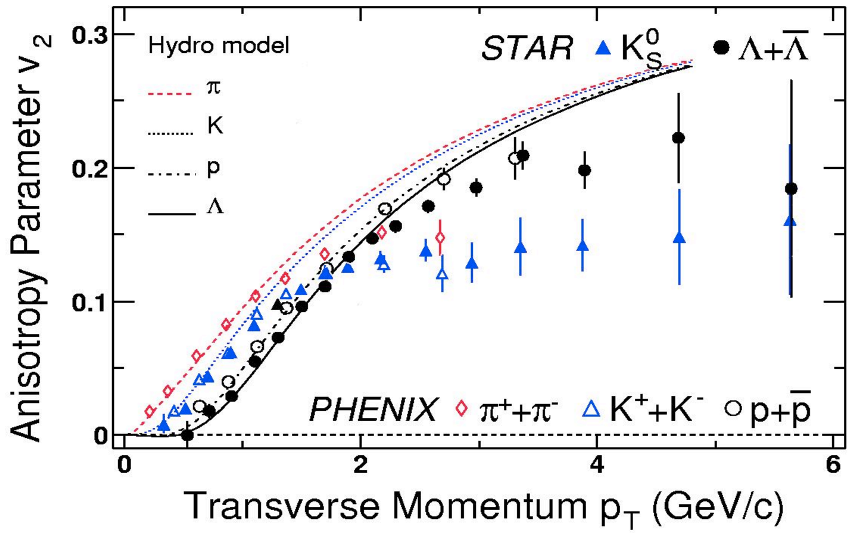


Azimuthal Anisotropy-Elliptic flow

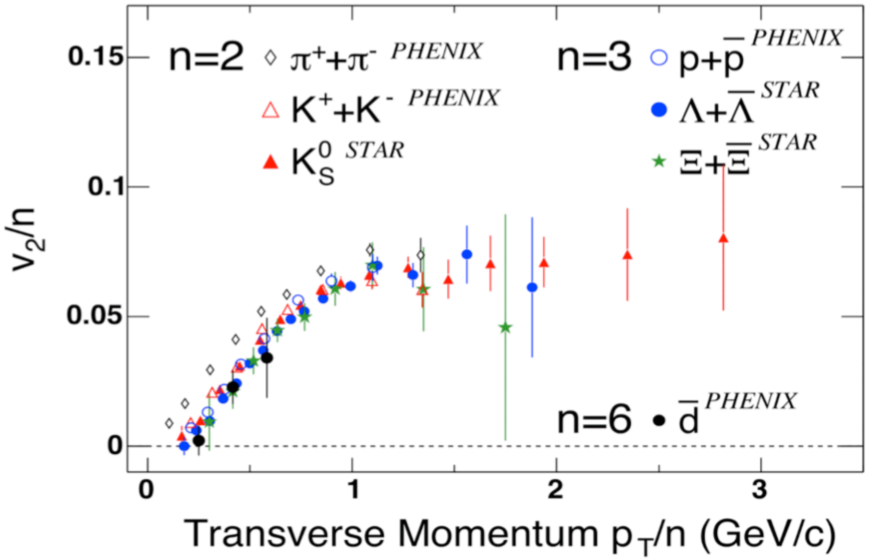




$$\frac{dN}{d\phi} \propto 1 + 2v_2(p_T)\cos[2(\phi - \Psi_R)]$$



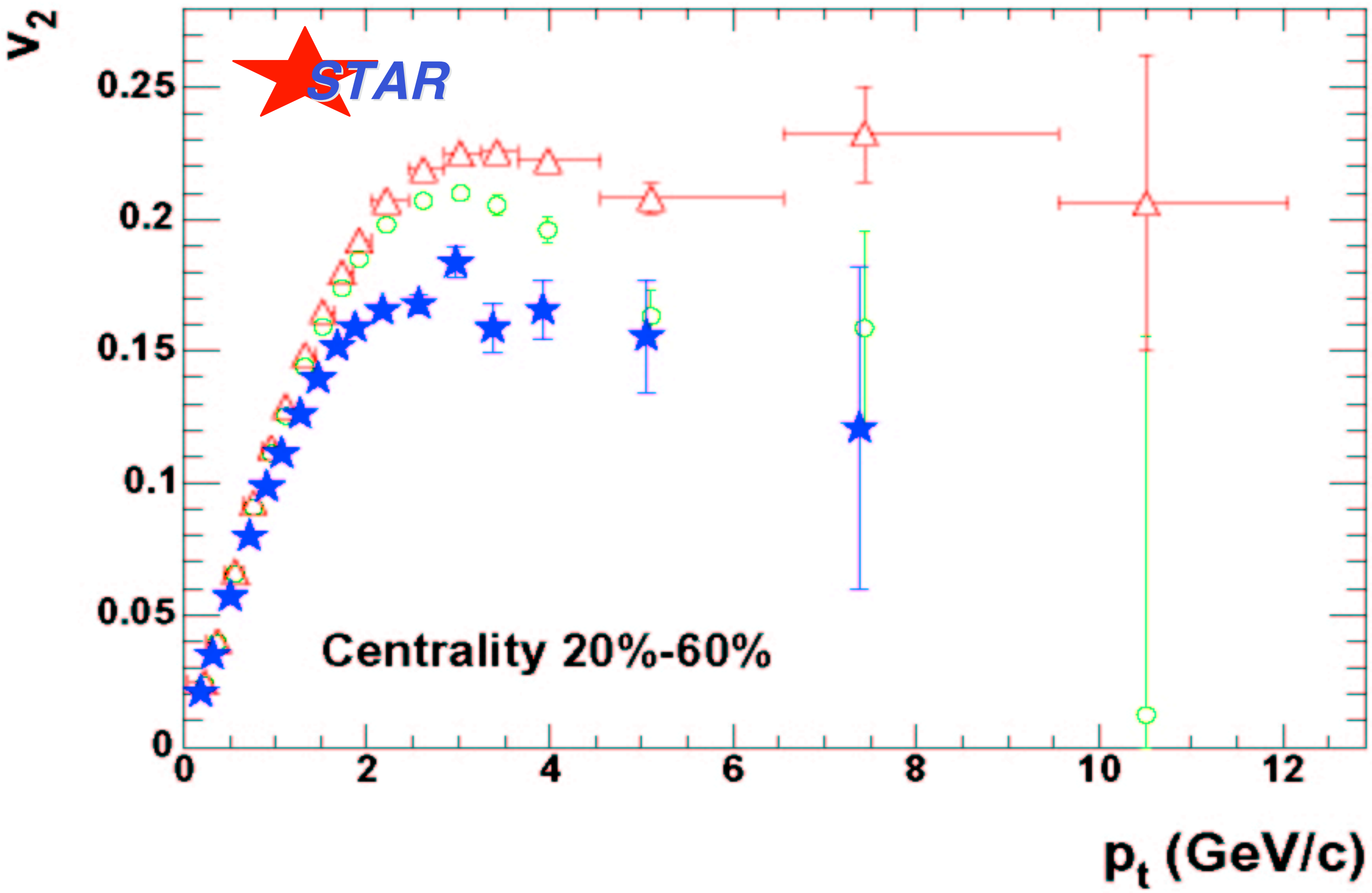
P. Huovinen
nucl-th/0305064



Flow of different particle species consistent with expectations from ideal relativistic hydrodynamics

Flow at High p_T in 200 GeV Au+Au

nucl-ex/0407007



v_2 {2-particle}

v_2 {AuAu – pp}

v_2 {4-particle}

Flow reaches a maximum ~3 GeV/c, then decreases slowly

Sizable real flow to ~8 GeV/c in mid-central collisions

Carl Gagliardi, Hard probes 04

Strong conclusions from comparing data with hydro calculations:

early thermalisation time (v_2)

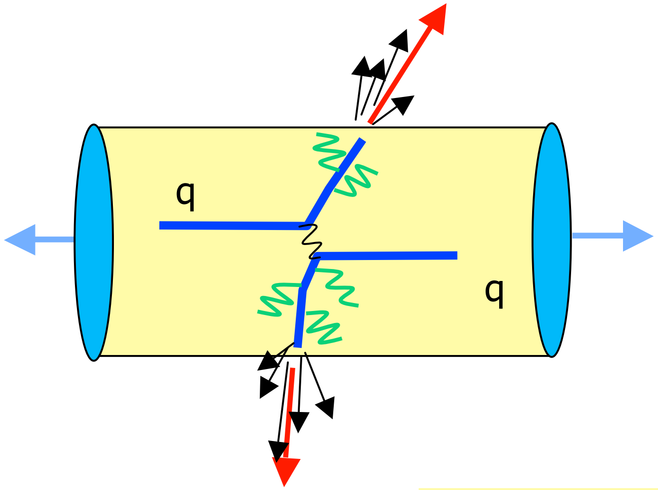
sensitivity to equation of state (particle spectra, v_2)

low viscosity (v_2)

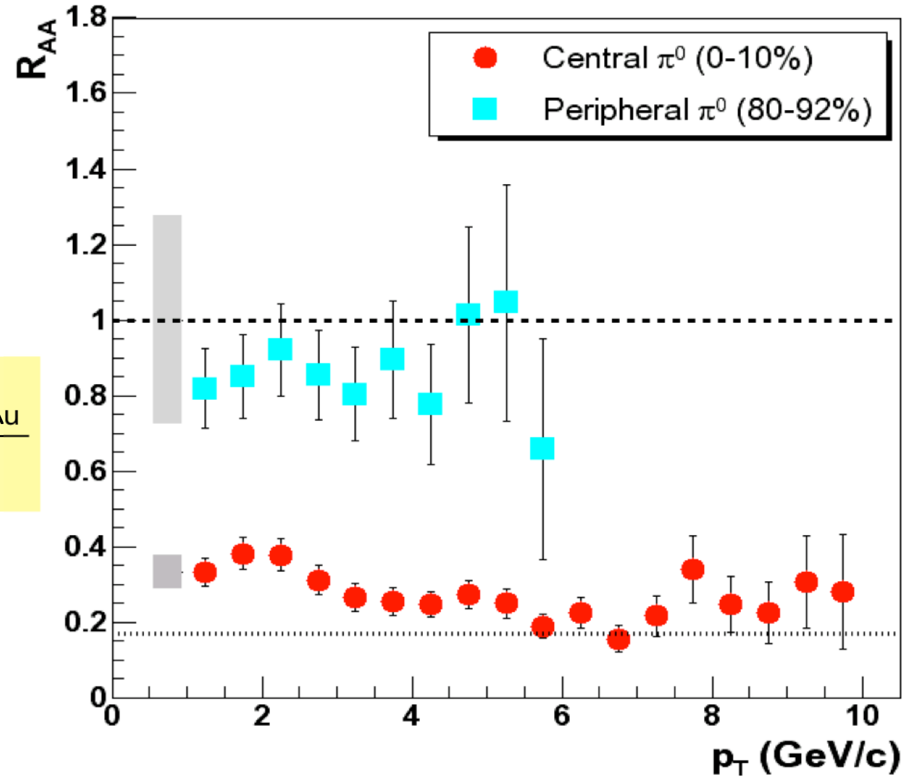
Next few runs and LHC will be decisive

What is the evidence from high p_t?

Jet quenching

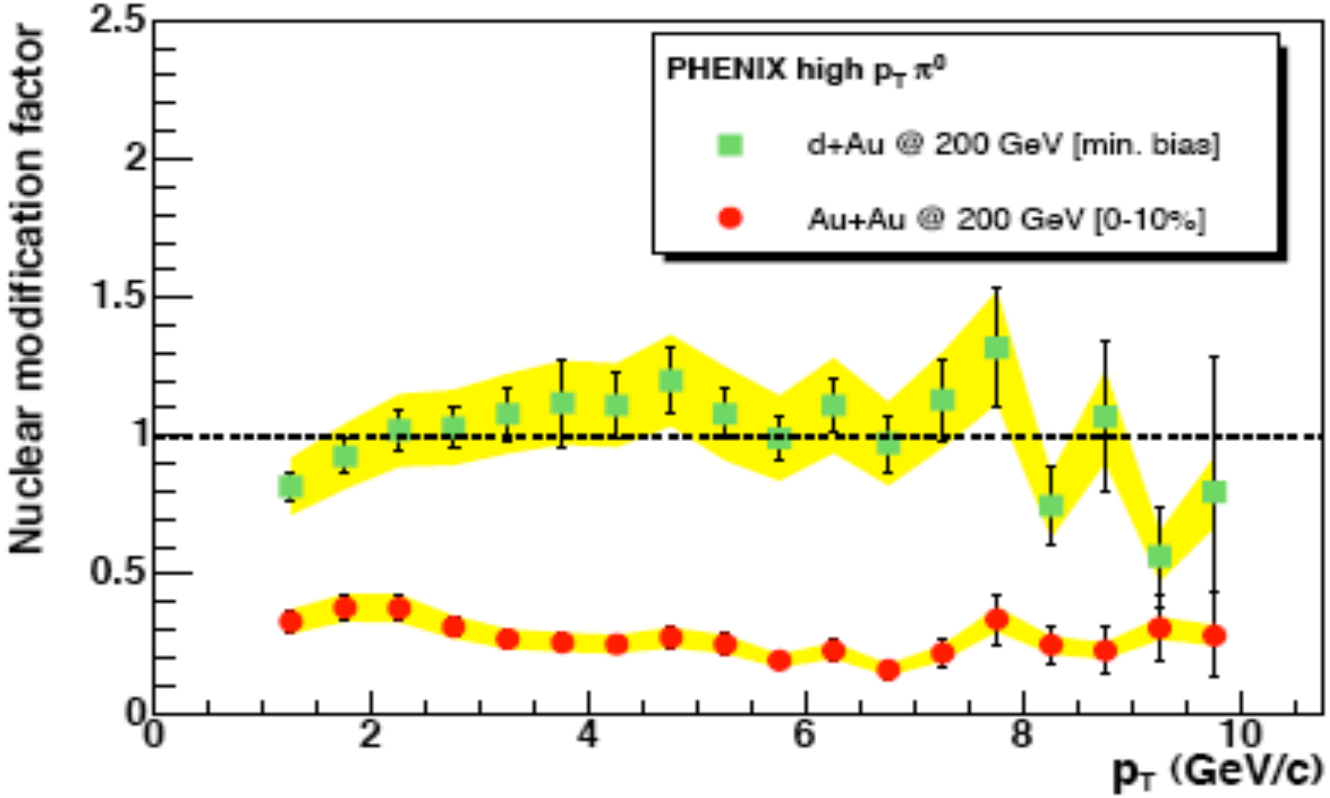


$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$



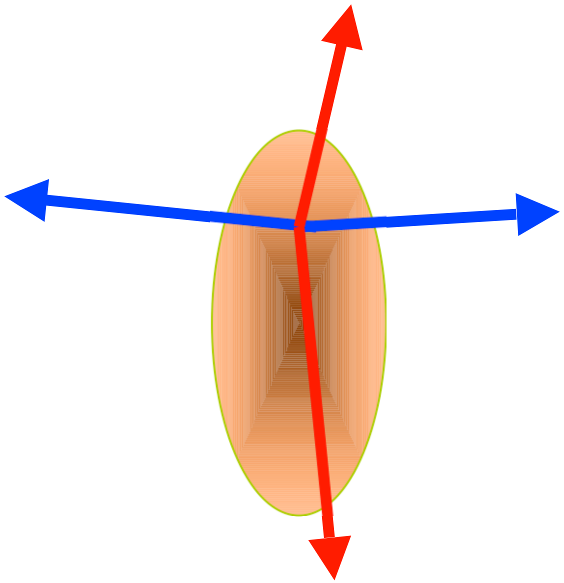
Consistent with models that compute energy loss of partons through hot matter

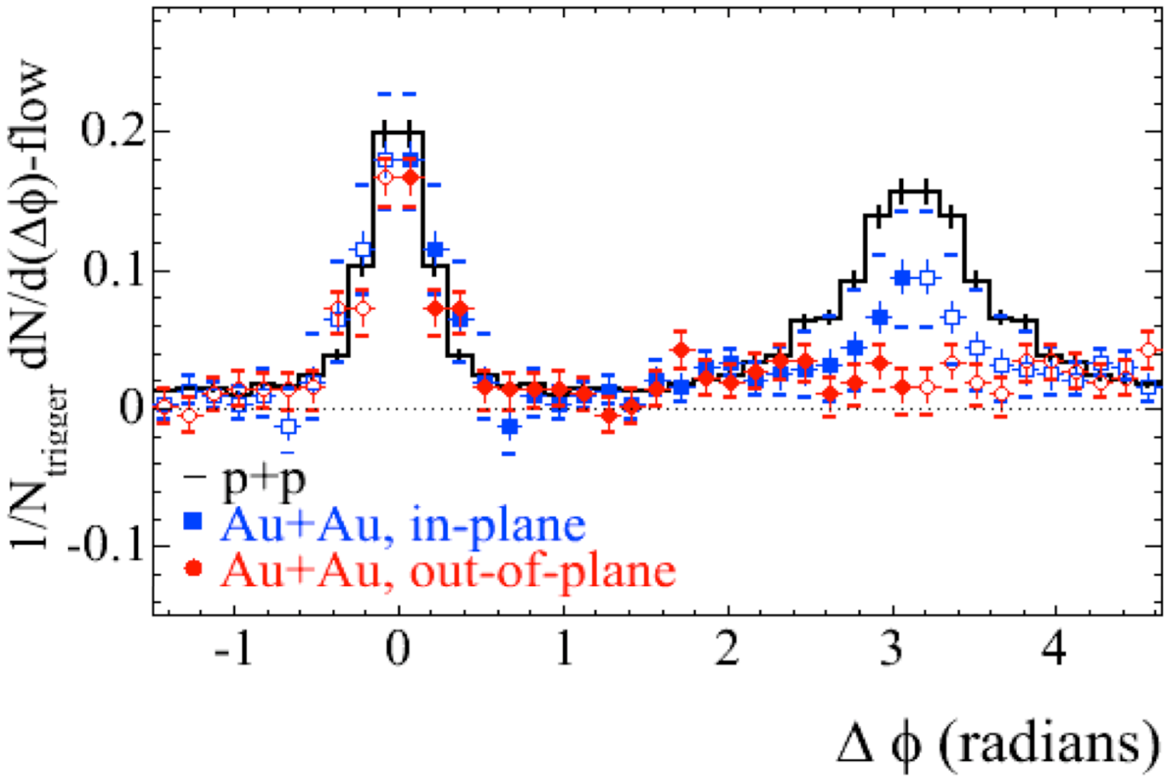
Control Experiment



(PHENIX, nucl-ex/0401001)

Reconstructing Jets from Azimuthal correlations

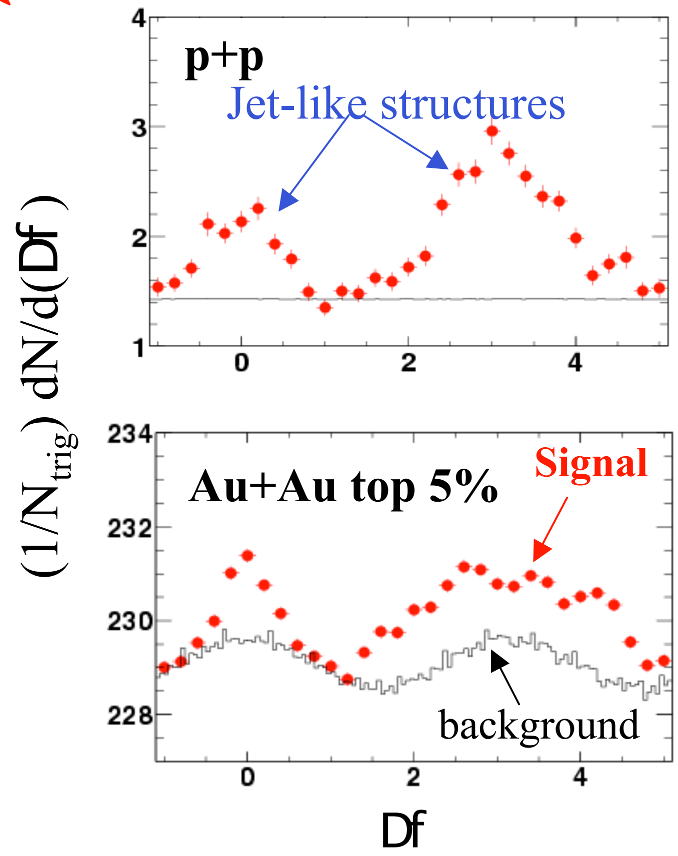


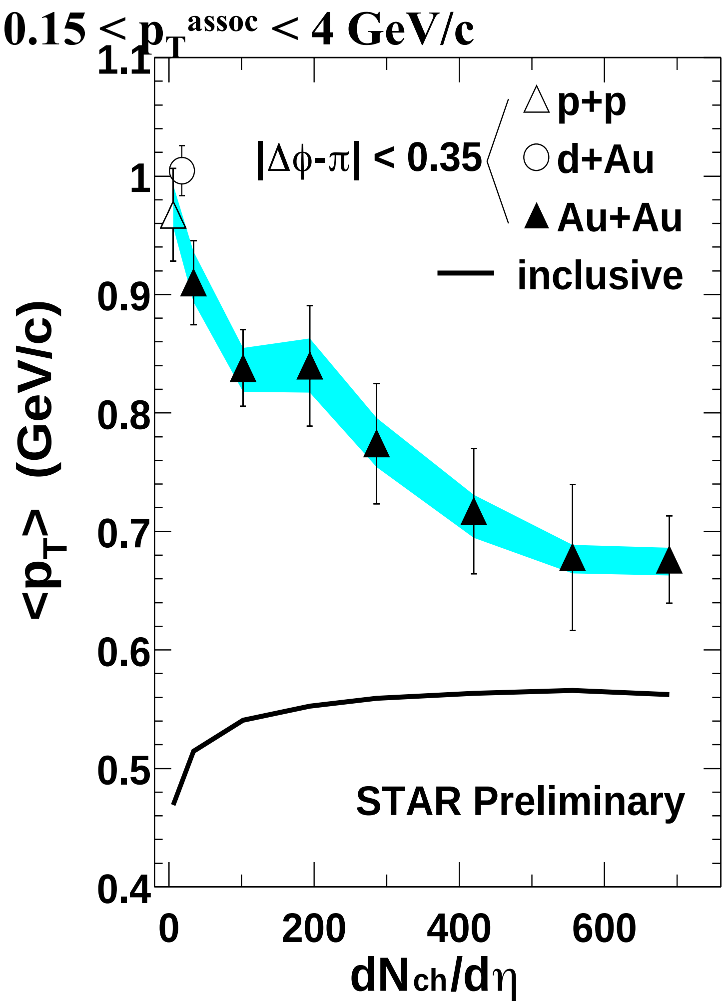


STAR data show clear dependence of correlations on path length in medium

Finding the Associated Hadrons

STAR Preliminary





Explores the interaction of an energetic parton with the dense medium

Evidence of novel final state effects

- Flow at low p_t
- high p_t suppression
- systematics of azimuthal correlations
- Clearly distinct from cold matter probed in d-Au

All models that explain these distinct features have to assume very dense, strongly interacting matter: consistent with the QGP …many open questions remain for RHIC to explore! **- RHIC II**