BNL Physics Department Symposium, October 2, 2007

Status of QCD studies at BNL: QGP and spin

D. Kharzeev

Nuclear Theory Group

The current status of QCD studies at BNL

RHIC heavy ion program:

- Discovery of sQGP
- Near-perfect liquid: shear viscosity low
- Opaque to jets and heavy quarks
- Evidence for parton saturation and CGC

RHIC spin program:

- Getting close to uncovering the spin composition of the proton

Next step: precision and luminosity, calibrated hard probes
= RHIC II and eRHIC

The physics program of BNL Nuclear Theory Group

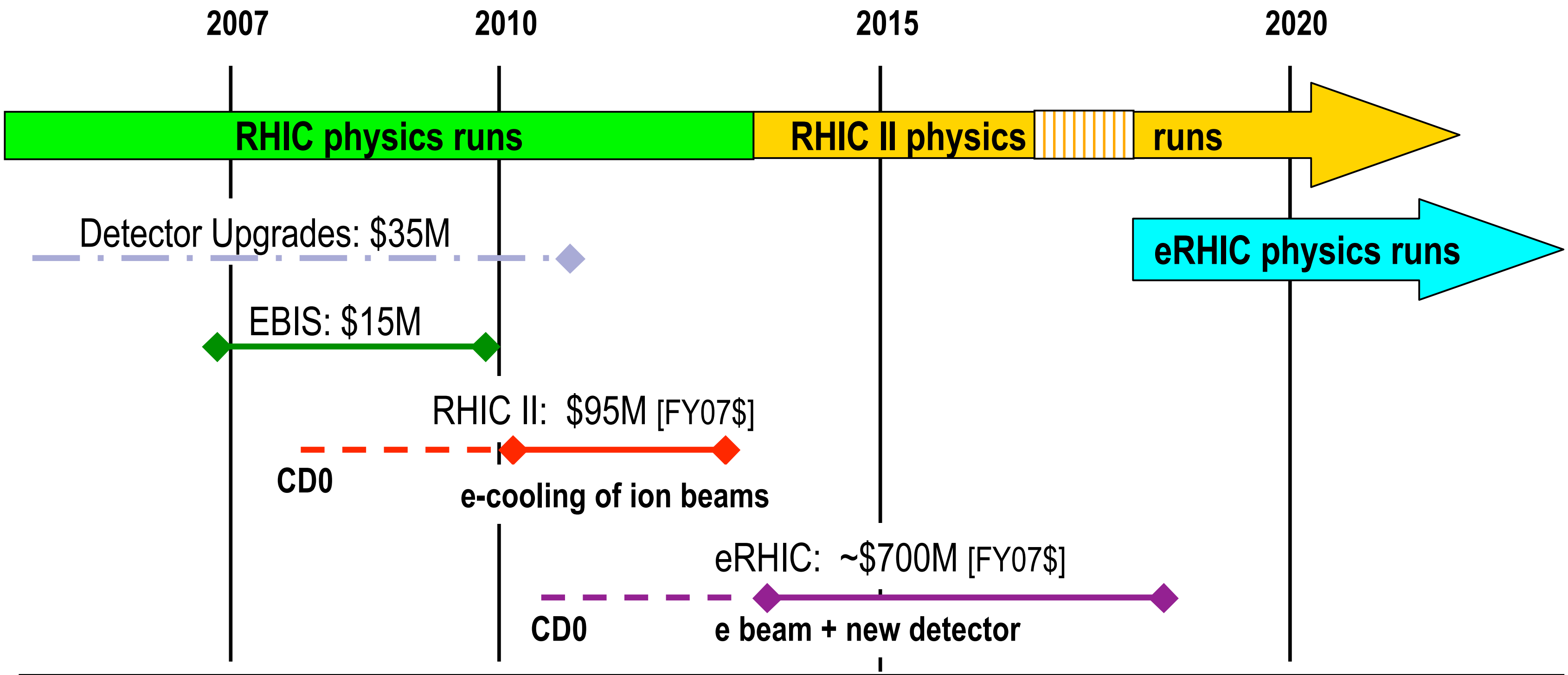
1. Quantum Chromo-Dynamics at finite temperature and density and the physics of Quark-Gluon Plasma

2. QCD at high energies and small x and the physics of the Color Glass Condensate

3. Perturbative QCD and the spin structure of the nucleon

4. Electromagnetic interactions of nuclei at high energies and nuclear structure

Nuclear Theory program in the context of BNL long-term plans



NT program is tightly connected to the existing and planned experimental programs at BNL and to the NSAC performance milestones for Nuclear Theory

The physics program of BNL Nuclear Theory Group and the NSAC performance milestones

Physics of High Temperature and High Density Hadronic Matter:

a) perform realistic 3D numerical simulations to describe the medium and the conditions required by the collective flow measured at RHIC

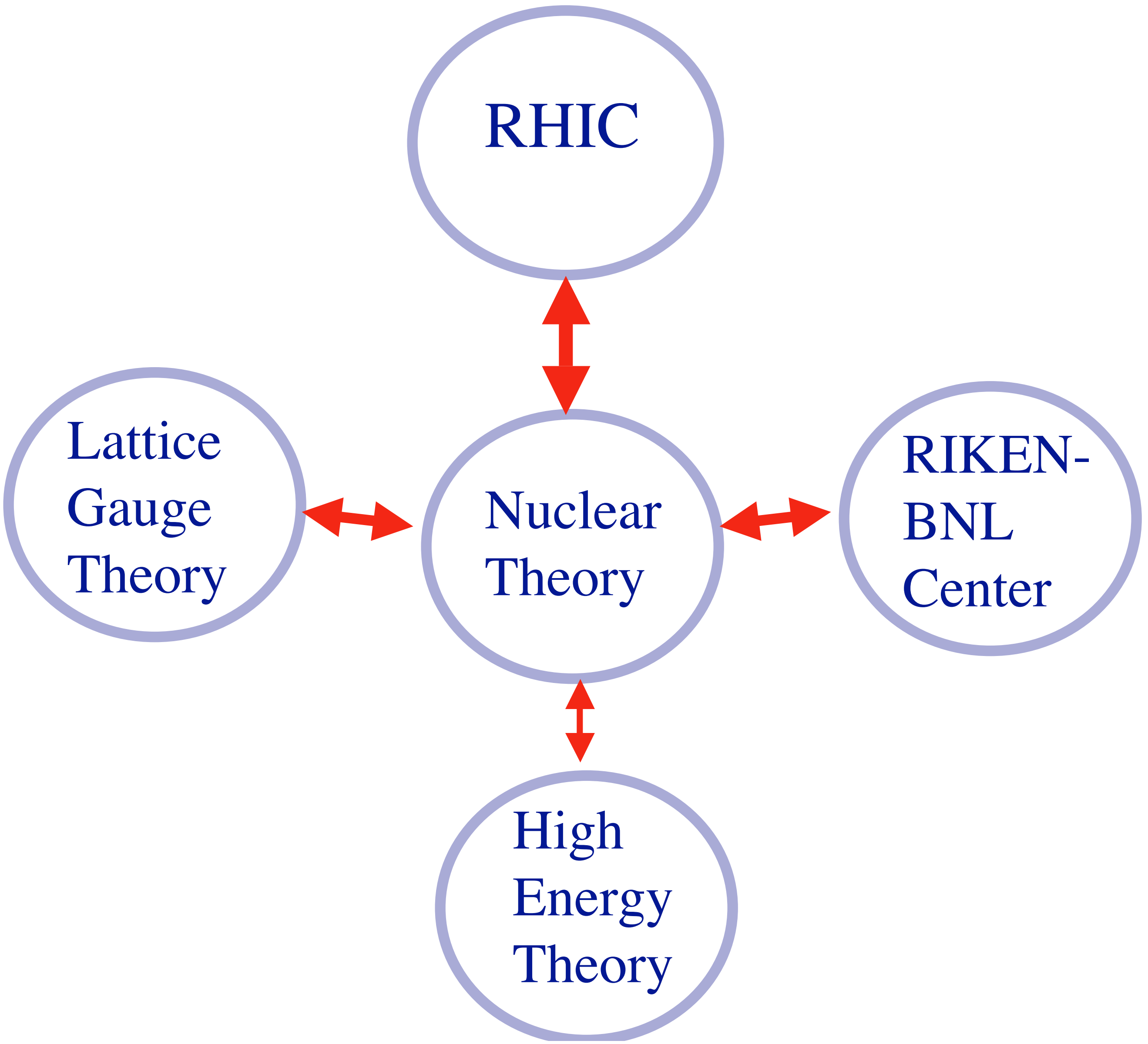
b) complete realistic calculations of jet production in a high density medium for comparison with experiment

c) Determine gluon densities at low x in cold nuclei

Hadronic physics: a) Make measurements of spin carried by the glue in the proton

b) Carry out ab-initio microscopic studies of the structure and dynamics of light nuclei + Nuclear Structure and Astrophysics

Nuclear Theory Group at BNL



RIKEN-BNL Center:

Founded by T. D. Lee

Director: N. Samios

Associate Director: H. Enyo

Theory Group Leader: L. McLerran

Experimental Group Leader: G. Bunce

Funded by RIKEN Institute in Japan

Physics Interests:

Experimental and Theoretical Aspects of Spin and Heavy Ion Collisions

Lattice Gauge Theory and QCDOC

Theory of Strong Interactions

Funds workshops, joint university fellows and postdocs

Recently renewed funding for 5 years

Slides from L.McLerran

RBRC University Fellows Program

University pays 1/2 of academic year salary

University selects candidates

Must be approved by Theory Advisory Committee

Current Theory Fellows:

T. Blum, Connecticut

R. Fries, Texas A&M

D. Molnar, Purdue

P. Petreczky, BNL

K. Tuchin, Iowa State

New Theory Fellows:

C. Lunardini, Arizona State

D. Teaney, Stony Brook

F. Yuan, LBL

18 Tenured Graduates:

S. Bass, Duke

D. Bodeker, Bielefeld

C. Dawson, Virginia

K. Iida, Kochi

T. Izubuchi, Kanazawa

S. Jeon, McGill

D. Kharzeev, BNL

A. Kusenko, UCLA

D. Rischke, Frankfurt

S. Sasaki, Tokyo

T. Schaefer, N. Carolina

M. Stephanov, Illinois

D. Son, Washington

R. Venugopalan, BNL

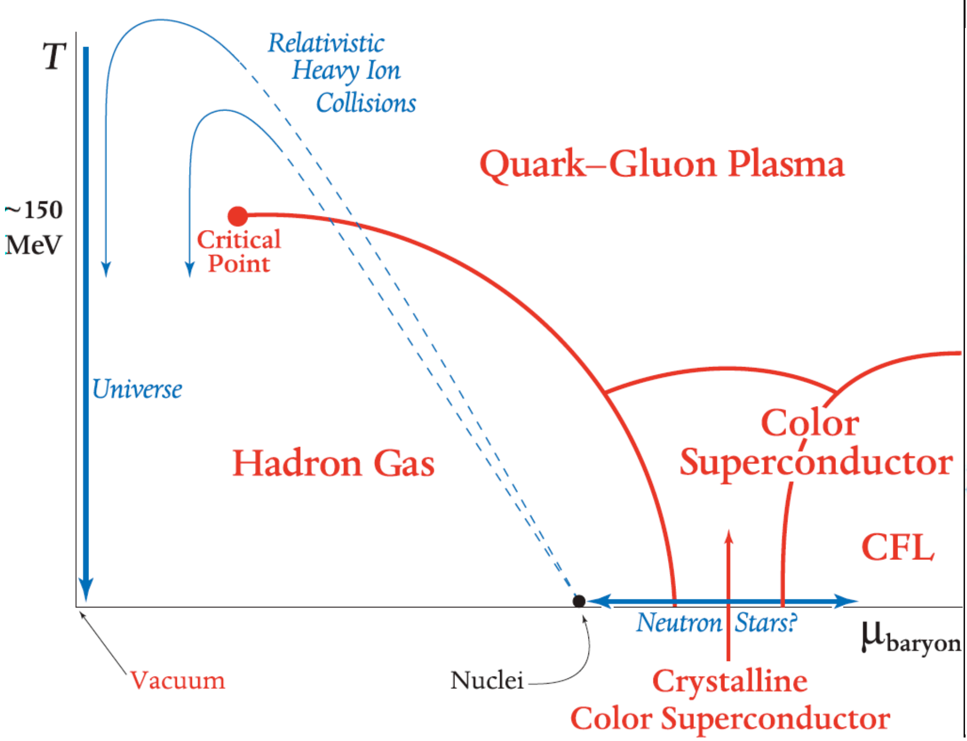
U. Van Kolck, Arizona

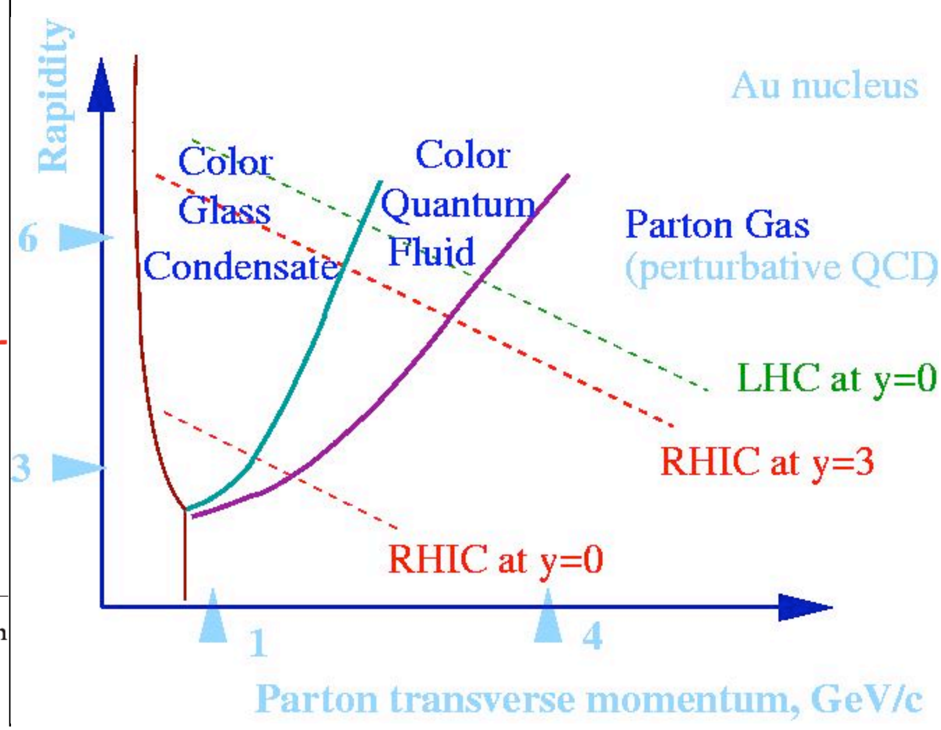
W. Vogelsang, BNL

U. Wiedemann, CERN

T. Wettig, Regensburg

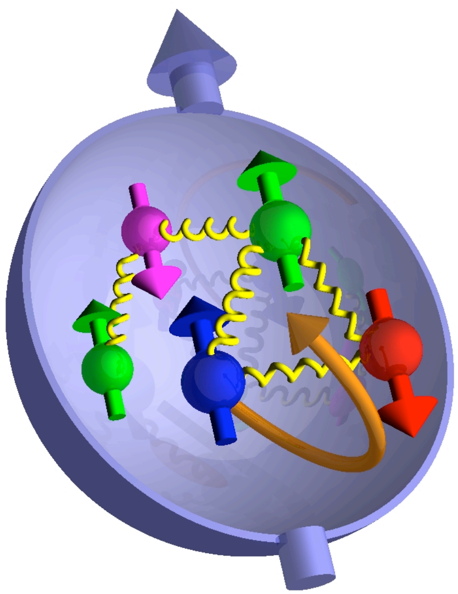
Research highlights:
QCD at high densities and energies





Exciting program with polarized protons underway at RHIC:

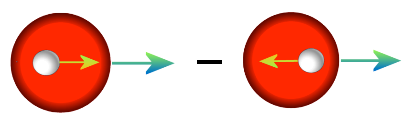
What carries the proton spin ?



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

Quark spins

only ≈ 20 %



Gluon spins

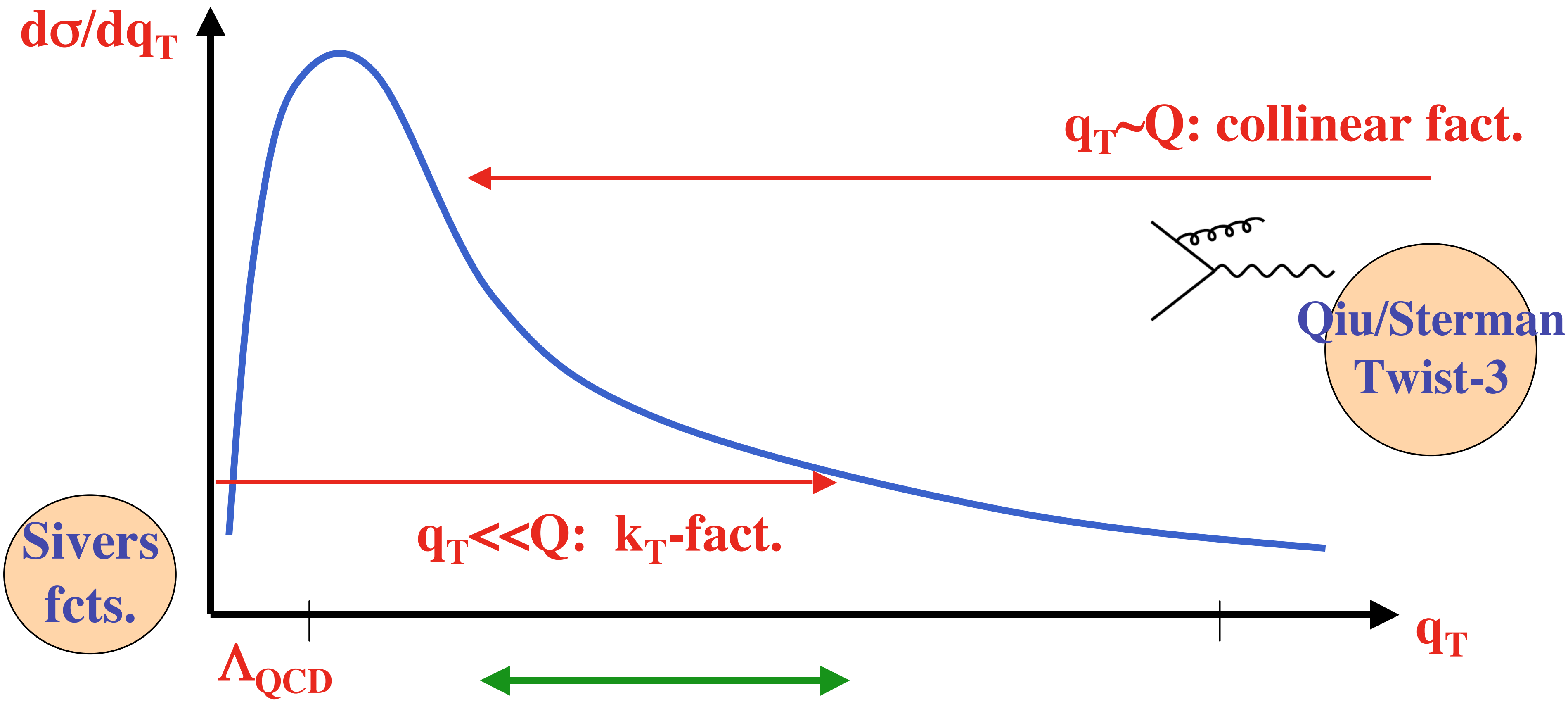
??

Quark and gluon orbital ang. mom.

??

- **BNL Nuclear Theory devotes a major effort to QCD spin physics, in particular for RHIC**

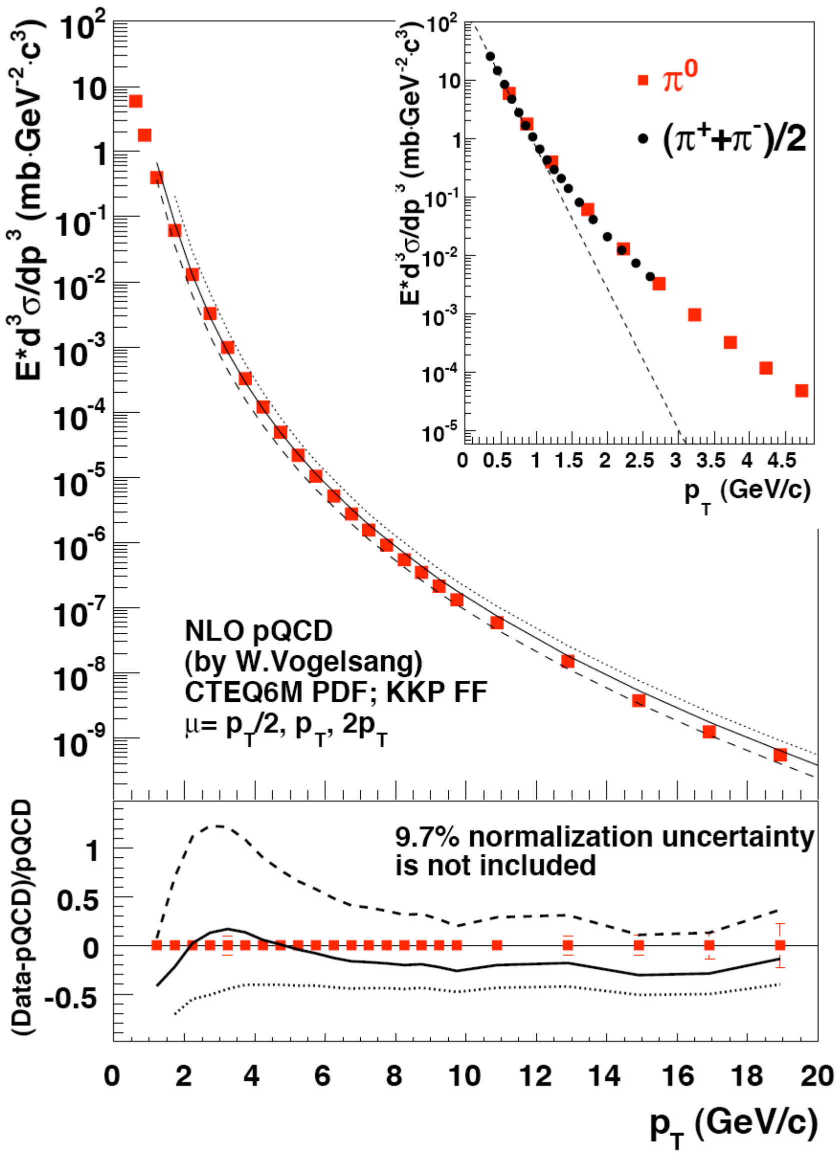
Connection between two mechanisms for single-spin asymmetries: for example, Drell-Yan



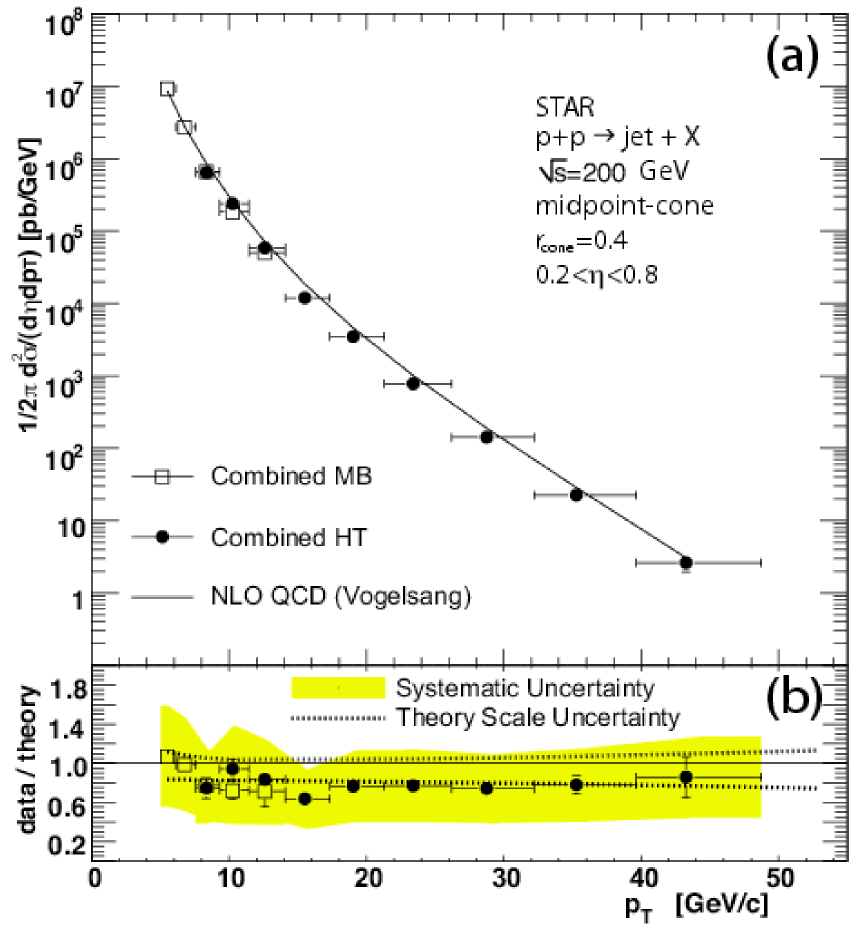
$\Lambda_{QCD} \ll q_T \ll Q$ same physics !

Ji, Qiu, Vogelsang, Yuan PRL97 (2006) 082002, PRD73 (2006) 094017, PLB638 (2006) 178
Qiu, Vogelsang, Yuan, to appear in PLB 2007, arXiv:0706.1196 [hep-ph]

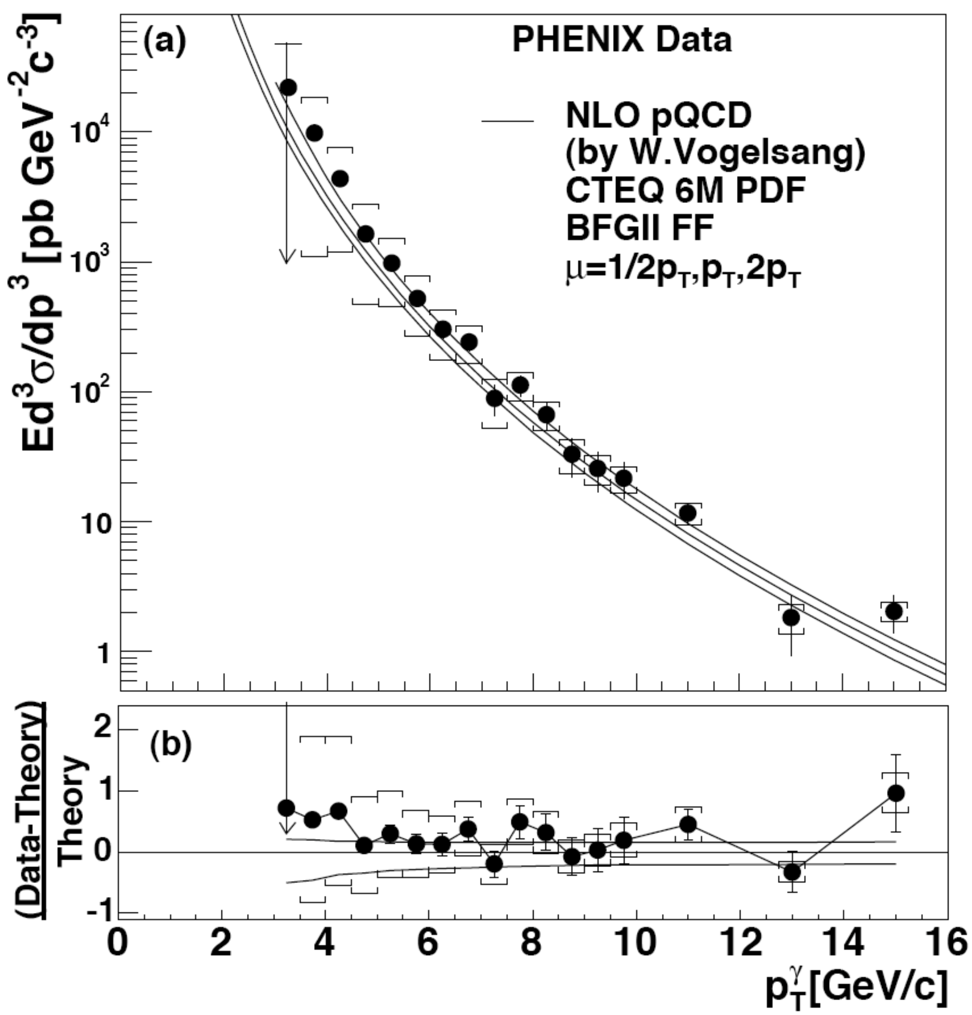
$pp \to \pi^0 X$ **PHENIX**



$pp \to \text{jet}\ X$ **STAR**



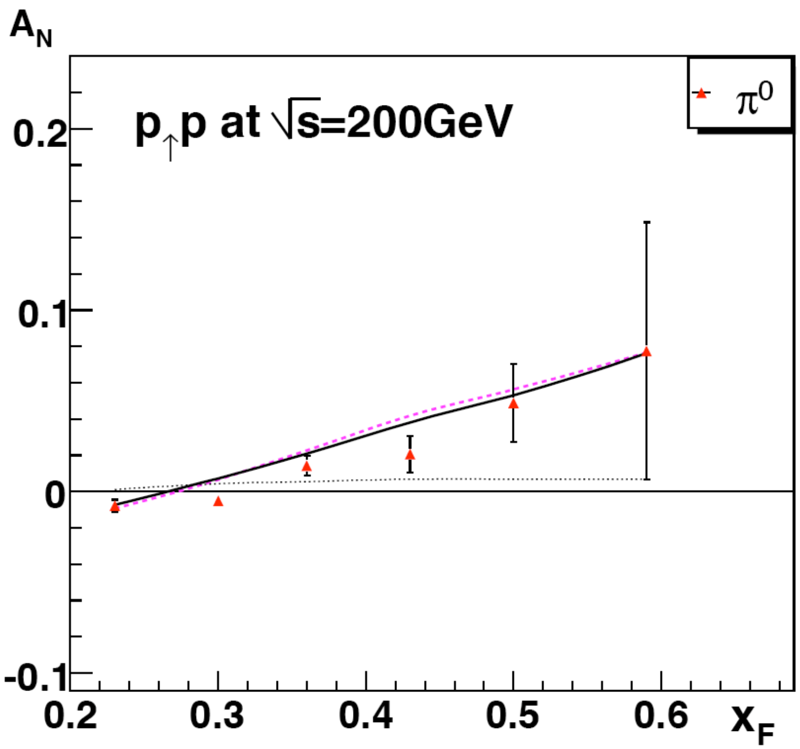
$$pp \to \gamma X$$ **PHENIX**



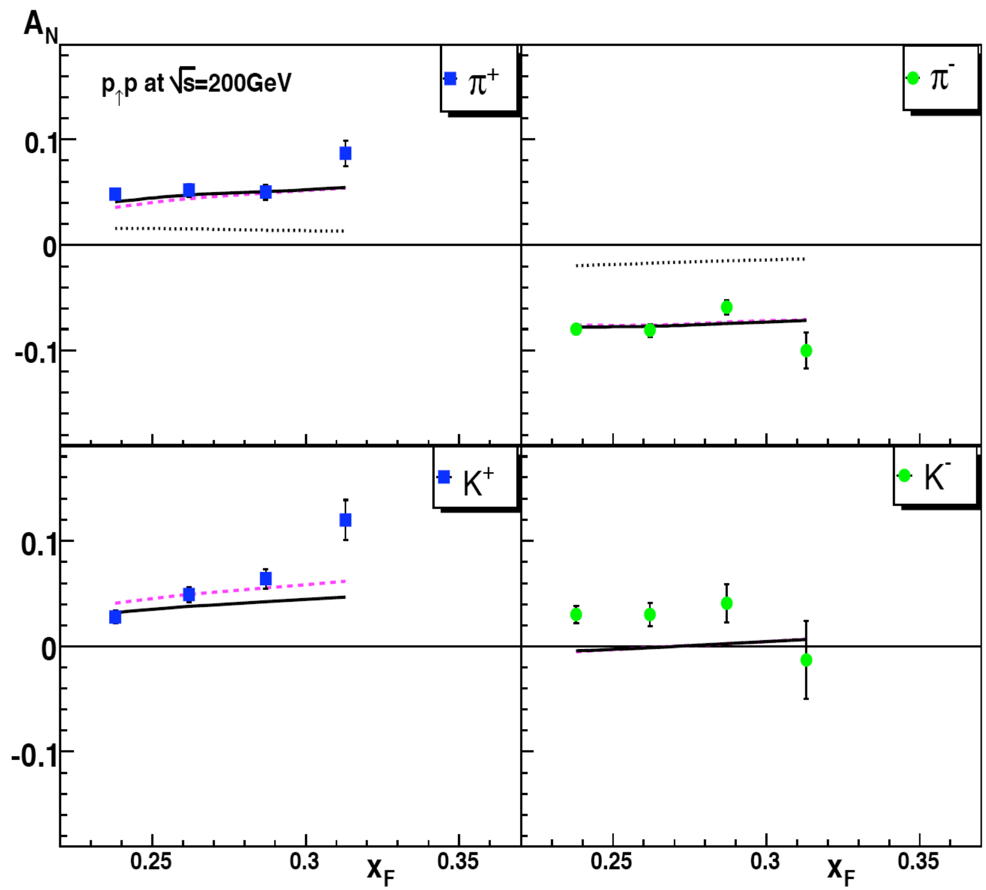
Reliable
“baseline”
pQCD calculations

New analysis of single-spin asymmetry in $pp \rightarrow \pi X$ at RHIC:

Kouvaris, Qiu, Vogelsang, Yuan
Phys. Rev. D74 (2006) 114013

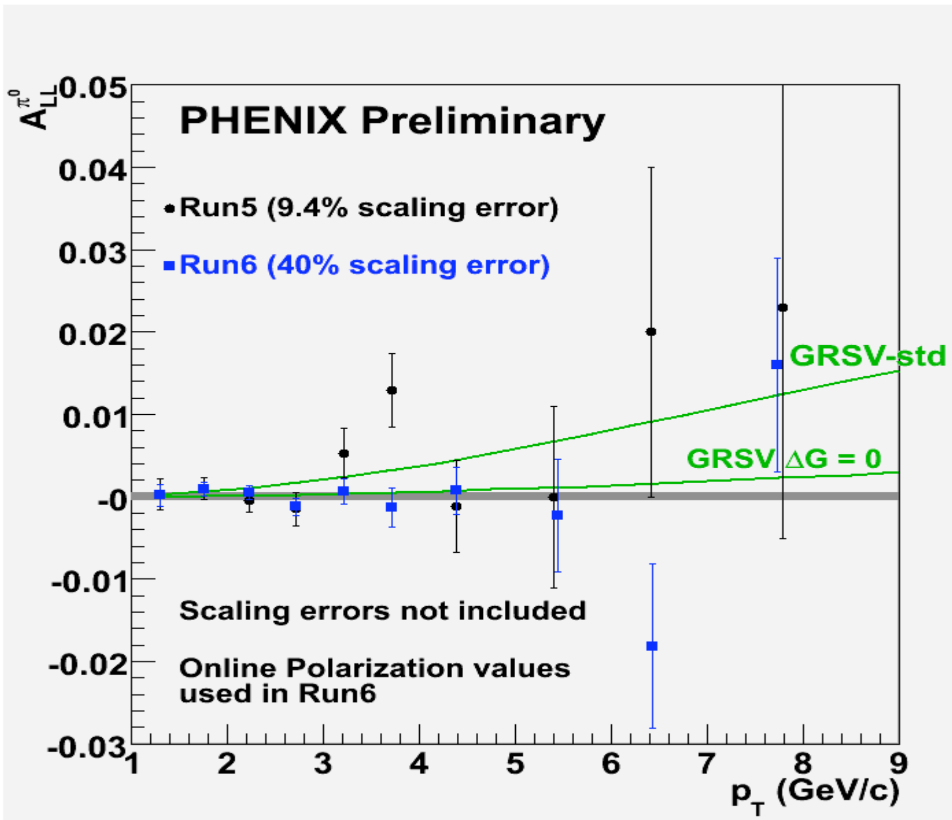


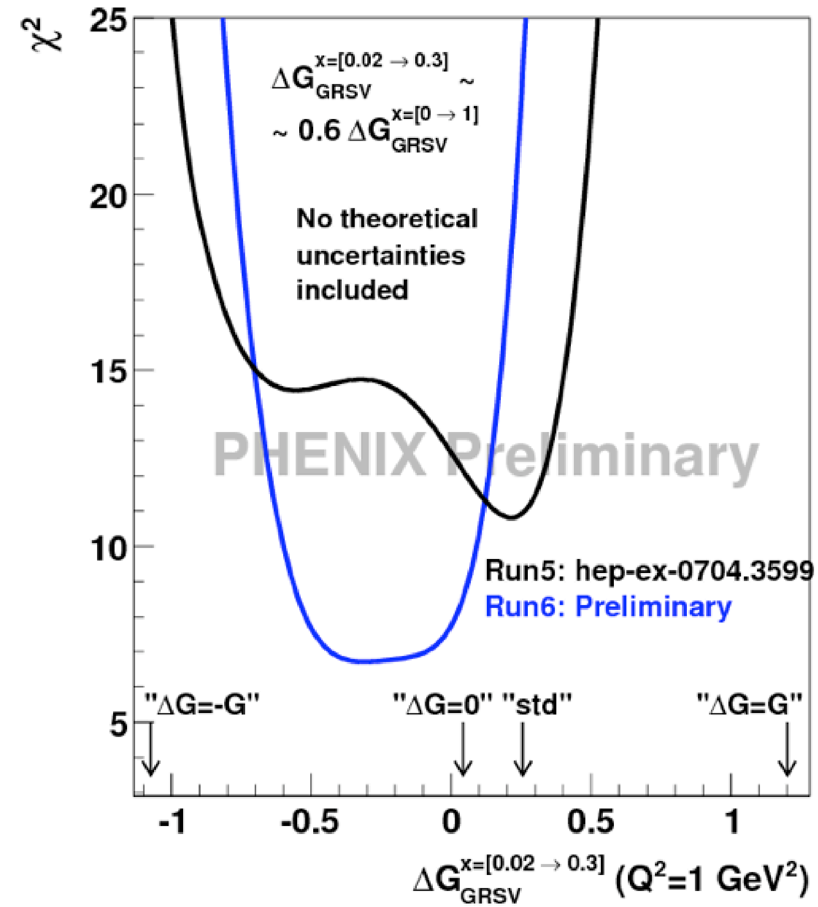
STAR



BRAHMS

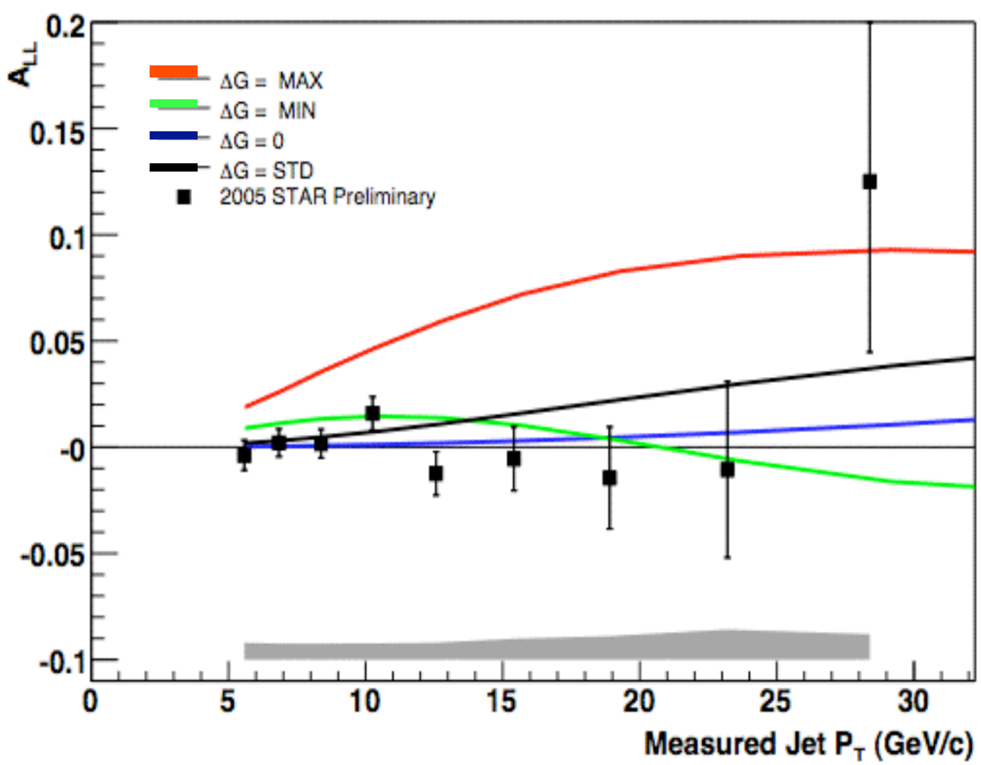
$pp \to \pi^0 X$ **PHENIX**

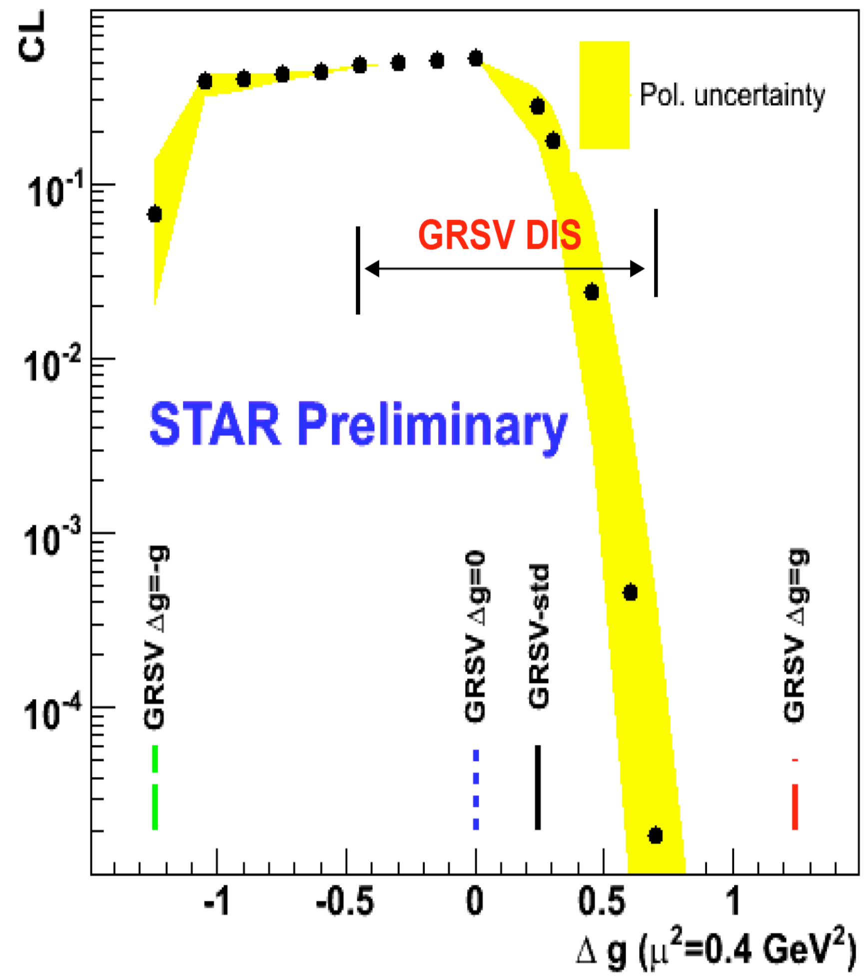




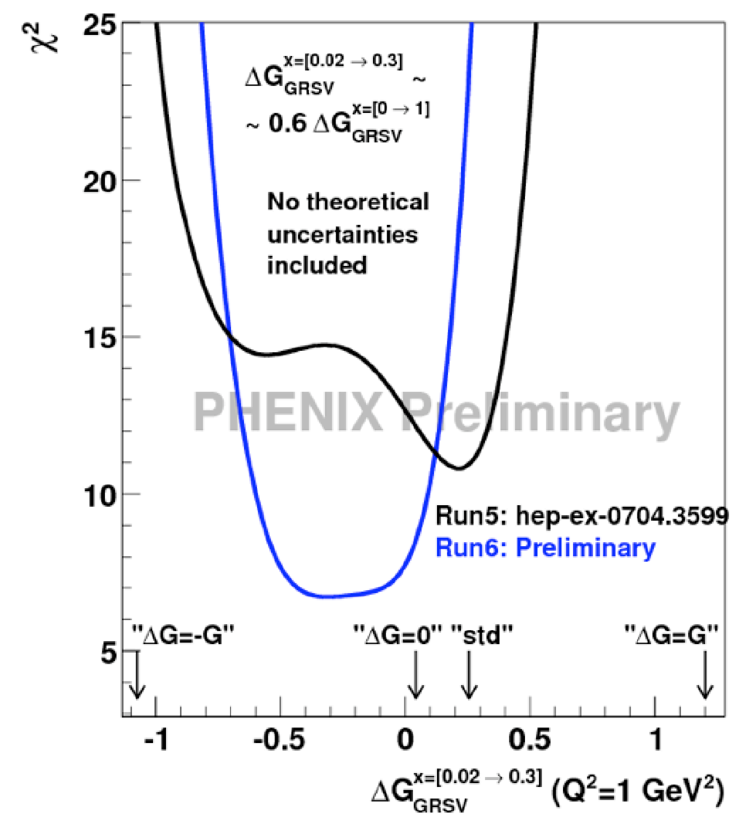
Towards extracting the gluons' contribution to the spin of the proton

$pp \rightarrow \text{jet}\ X$ **STAR**





What does “ΔG=0” mean?



Not that gluons carry no spin inside the proton:

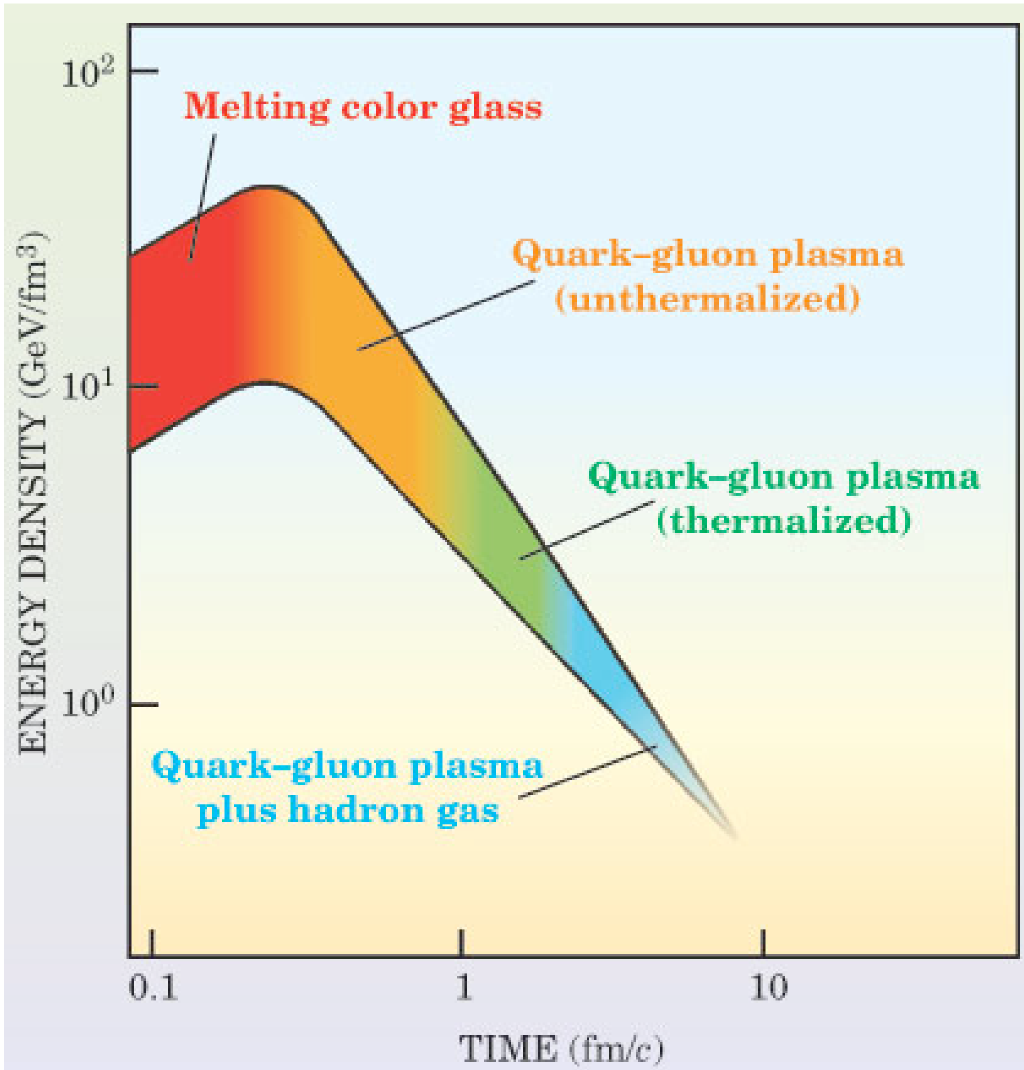
Perturbative evolution at large Q^2 necessarily implies that the produced gluons carry spin (gluons with helicities +1 and -1 are produced with different probabilities in DGLAP splitting process);

“ΔG=0” means that gluons do not carry spin at the initial scale $Q^2 \sim 1$ GeV^2

Either no gluons at all (hard to believe - what causes confinement then?)

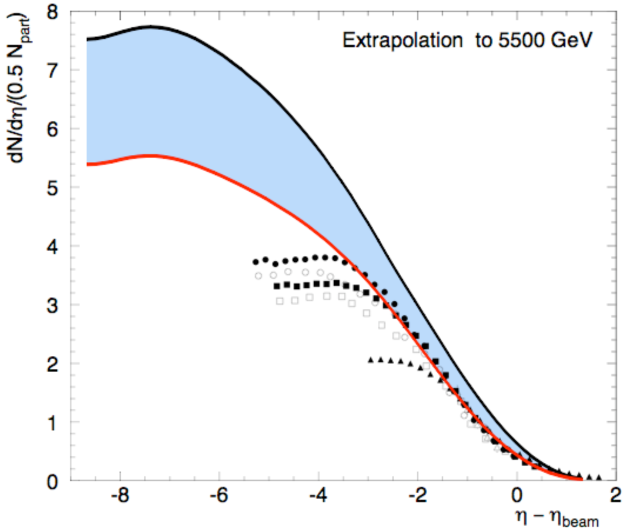
or perhaps gluons exist in scalar bound states with zero spin? (cf bulk viscosity

Time evolution in heavy ion collisions



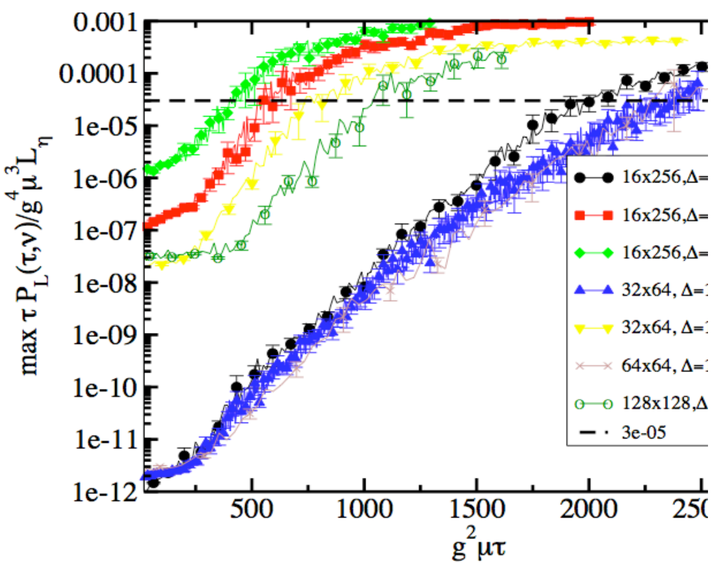
T. Ludlam,
L. McLerran,
Physics Today
October 2003

Initial conditions and approach to thermalization



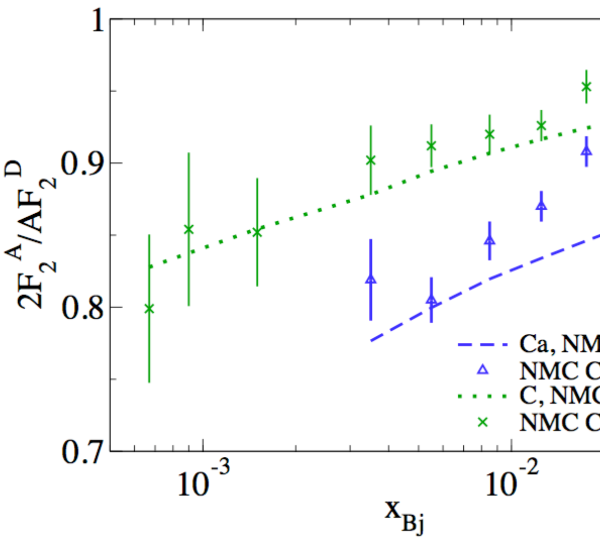
CGC prediction: limiting fragmentation fits to RHIC data give charged particle multiplicity of 1000-1400 at $y=0$ in Pb+Pb at the LHC

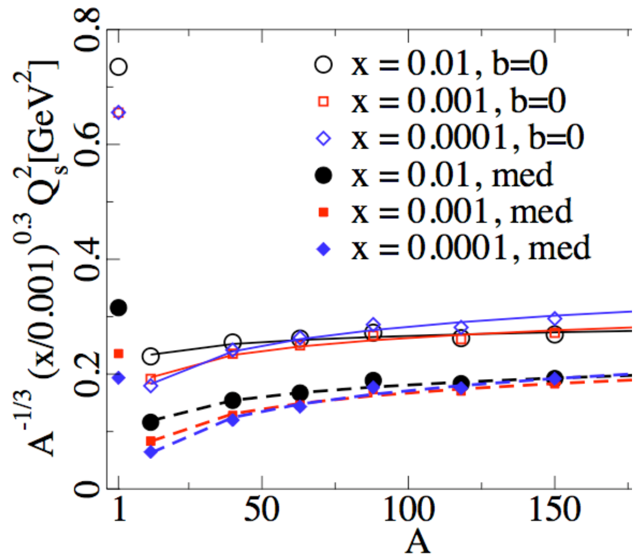
F. Gelis, A. Stasto and R. Venugopalan, Eur. Phys. J C48 (2006):489.



3+1-D numerical simulations of Yang-Mills equations: demonstrates explosive growth of "glasma" gluon fields in heavy ion collisions-may hold clue to early thermalization

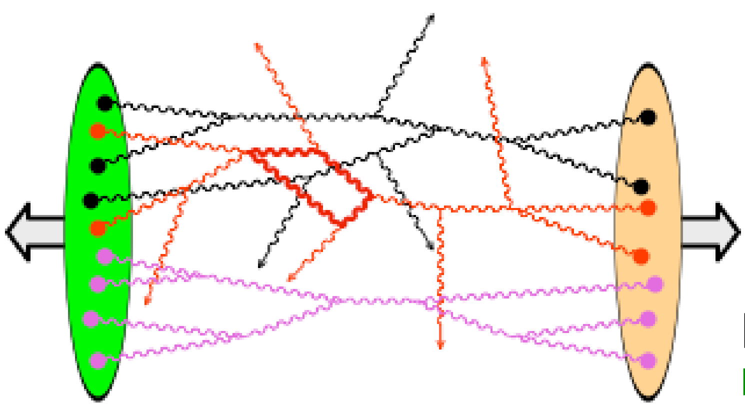
P. Romatschke and R. Venugopalan,
Phys. Rev. Lett. 96:062302 (2006)
Eur. Phys. J. A29: 71 (2006)
Phys. Rev. D74:045011 (2006)





H. Kowalski, T. Lappi and R. Venugopalan, arXiv:0705.3047[hep-ph], submitted to Phys. Rev. Lett.

Left: Fits of CGC models to HERA data give parameter free comparison (theory curves) to NMC shadowing data.
Right: Extracted saturation scale scales as $(A/x)^{0.3}$ -responsible for nuclear "oomph" that makes EIC attractive.



New theory of NLO particle production in HI collisions.

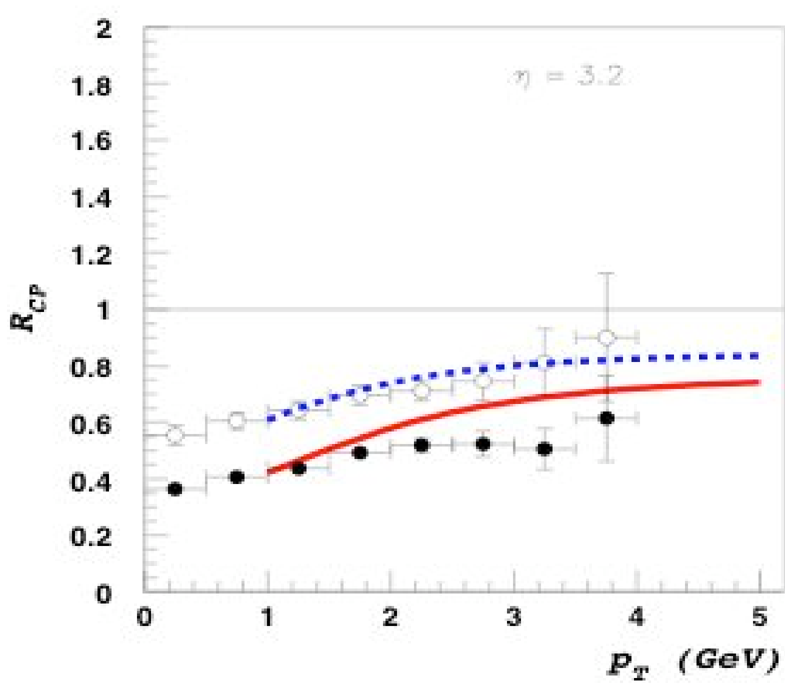
F. Gelis and R. Venugopalan,
Nucl. Phys. A776: 135 (2006)
Nucl. Phys. A779: 177 (2006)
Acta. Phys. Polon. B37:3253 (2006).

First derivation of Glasma kinetic equation

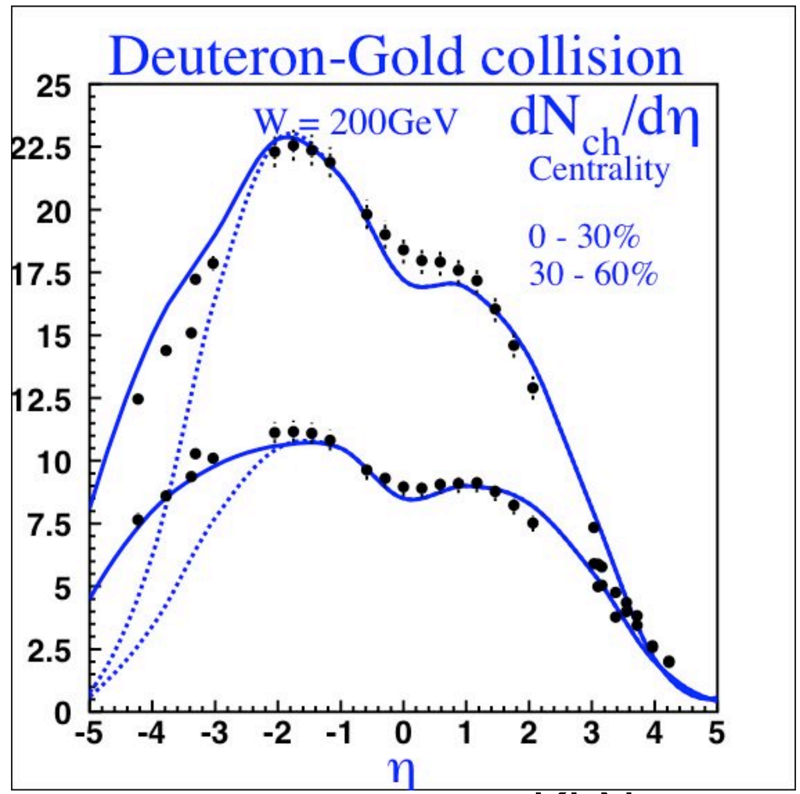
F. Gelis, S. Jeon and R. Venugopalan,
arXiv: 0706.3775 [hep-ph]

Color Glass Condensate at RHIC

Synergy between Nuclear Theory group and
RHIC experimentalists



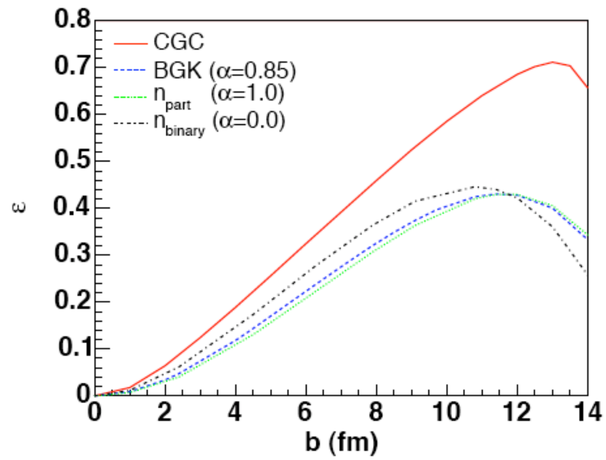
KKT



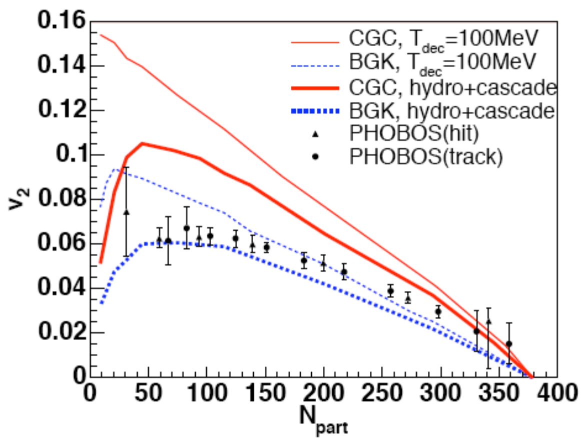
KLN

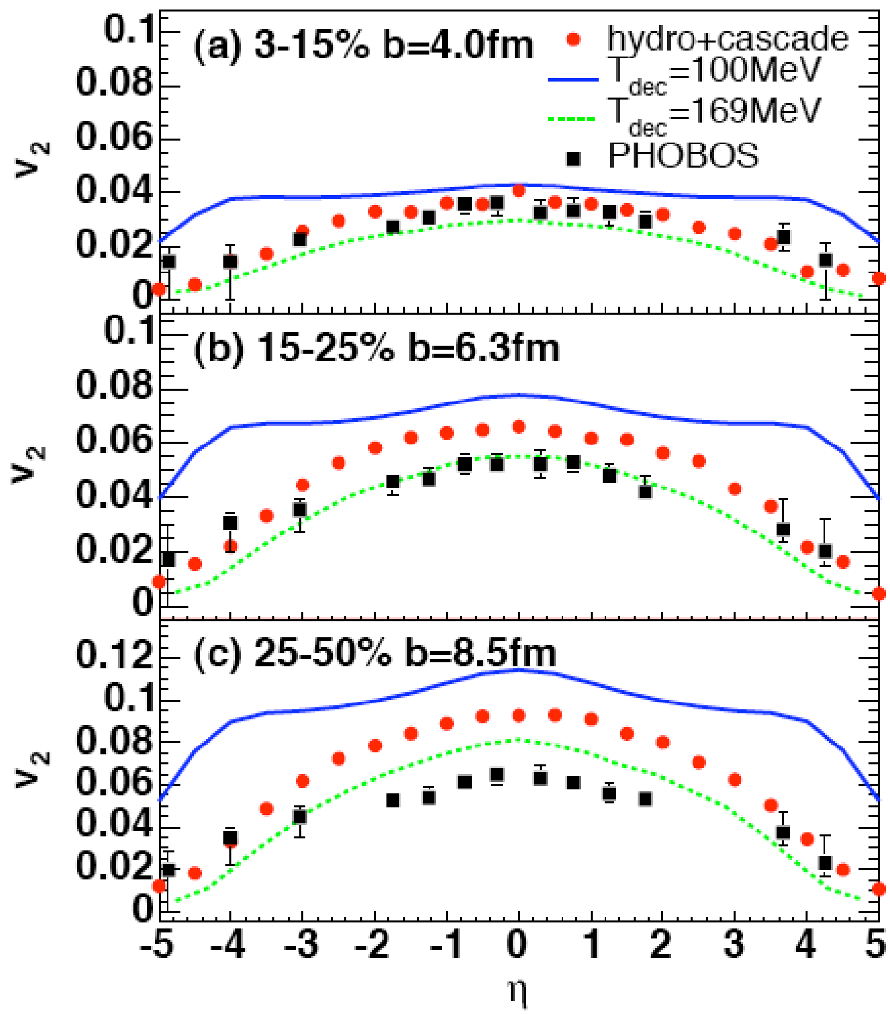
How small is the viscosity of sQGP?

CGC initial conditions lead to larger ellipticity,



require some viscous effects:





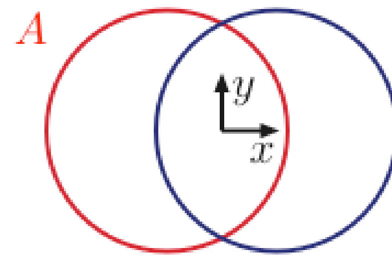
T.Hirano, U.Heinz, D.Kharzeev, R.Lacey, Y.Nara

Eccentricity and universality,

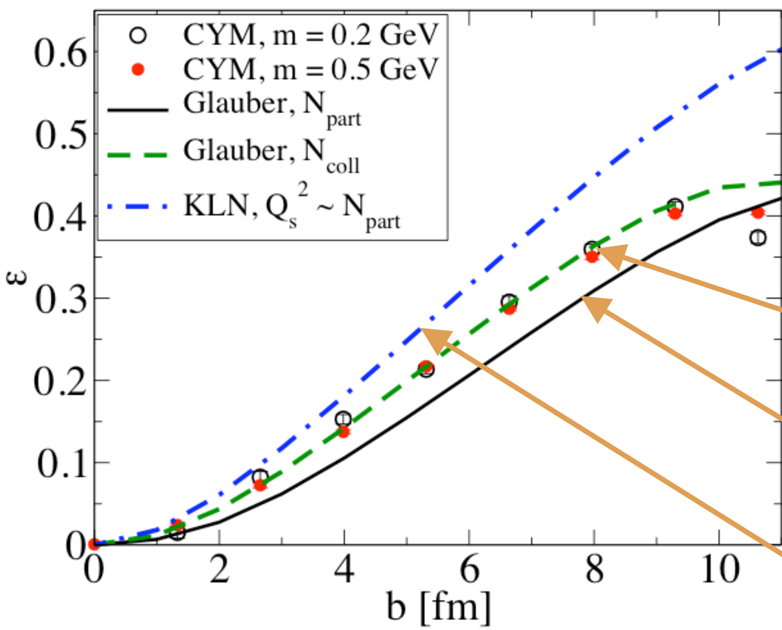
CGC initial conditions for viscous hydro

Lappi, Venugopalan,
Phys.Rev.C74:054905,2006.

Initial eccentricity from CGC initial stage of heavy ion collision



$$\epsilon = \frac{\int d^2\mathbf{x}_T\, \varepsilon(\mathbf{x}_T)\,(y^2 - x^2)}{\int d^2\mathbf{x}_T\, \varepsilon(\mathbf{x}_T)\,(y^2 + x^2)}$$

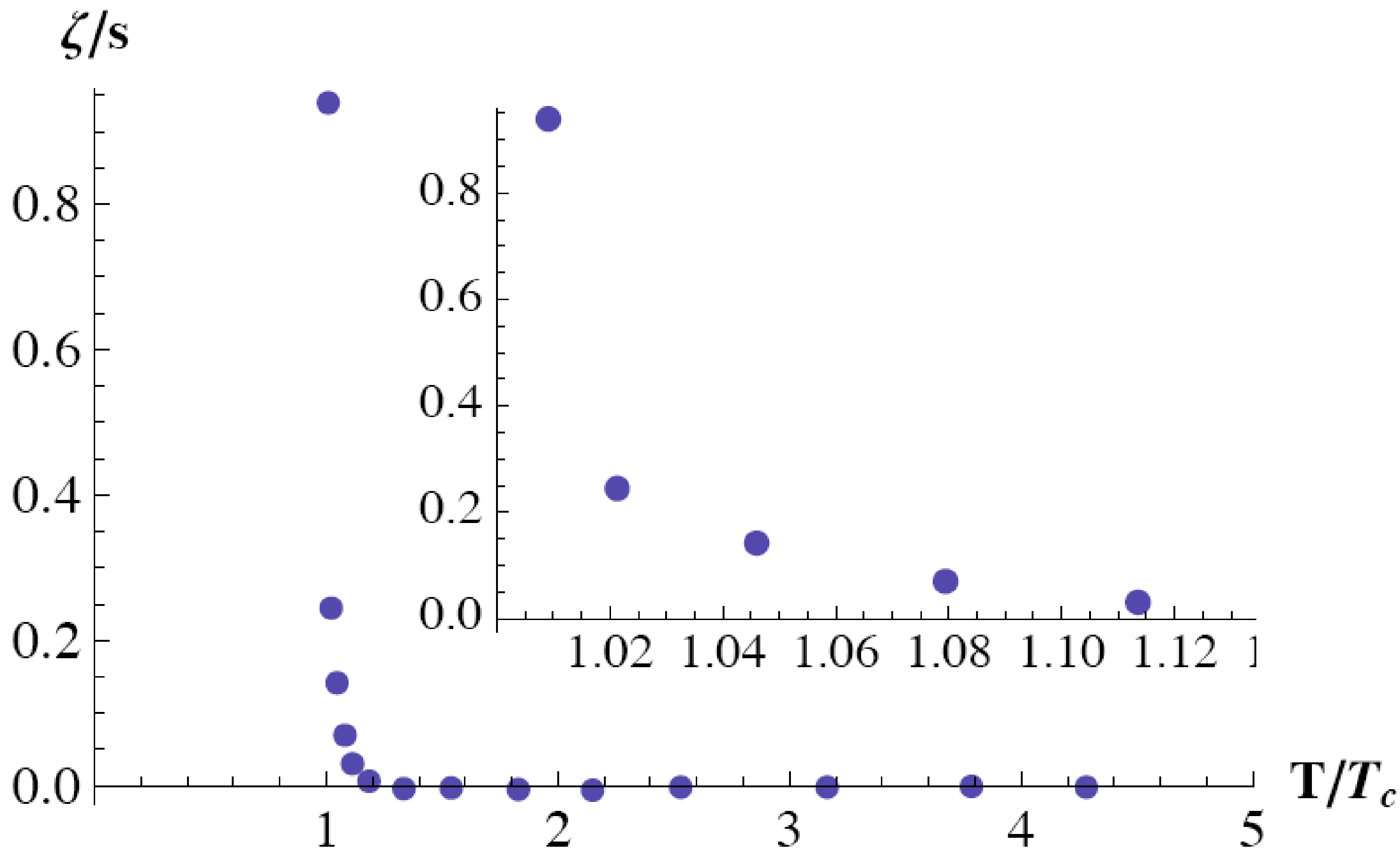


Universal Q_s gives larger eccentricity than traditional Glauber

But smaller than nonuniversal Q_s in KLN model

Essential for using hydro to extract viscosity

Bulk viscosity of sQGP

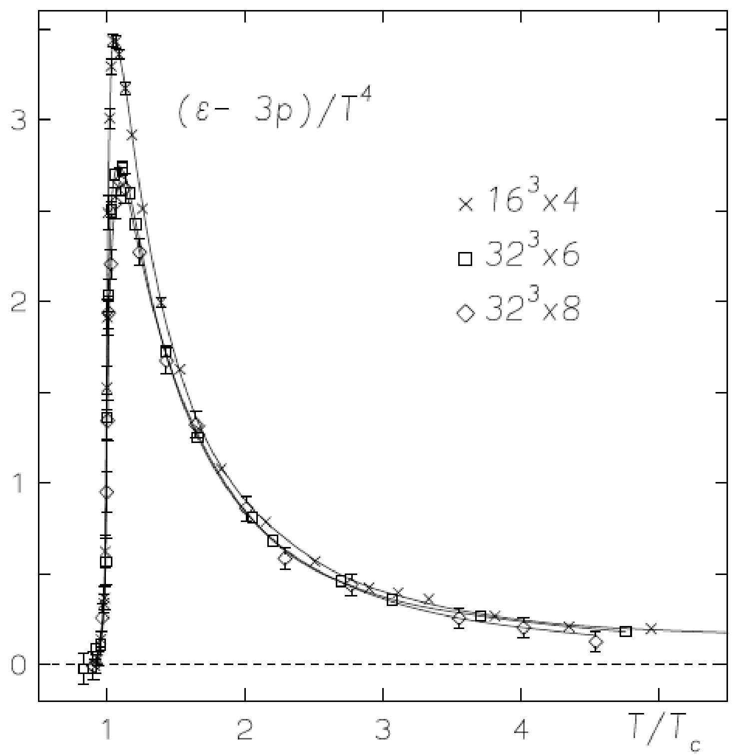


DK, K.Tuchin '07

Used the numerical data supplied by
the Lattice Gauge Theory Group (F. Karsch)

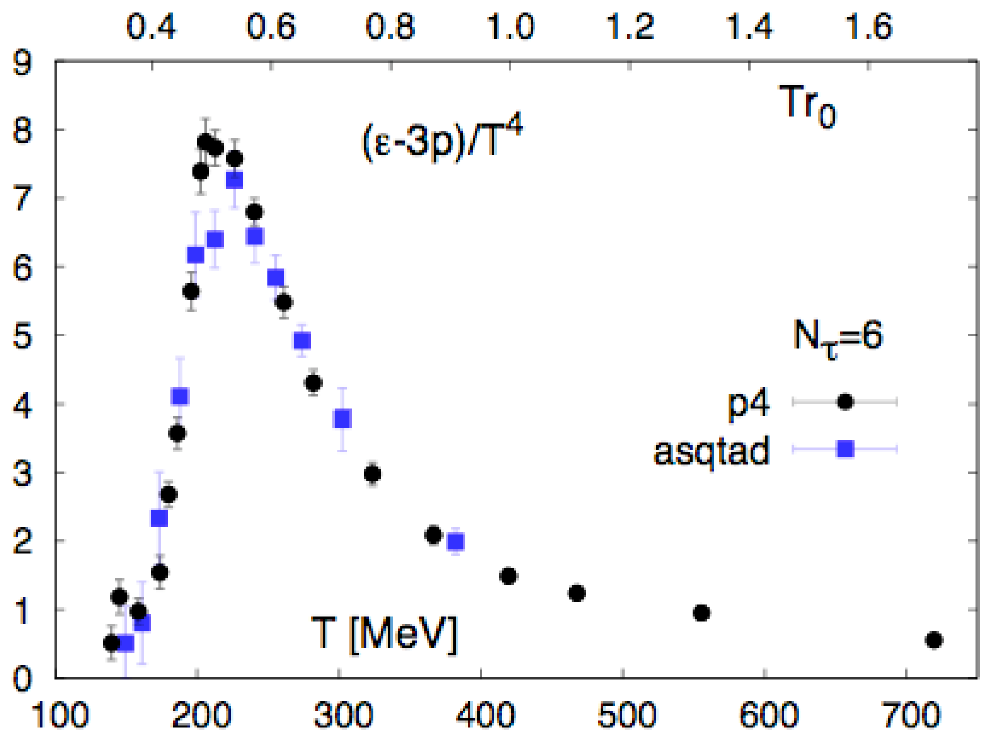
Bulk viscosity of sQGP

SU(3), pure gauge



G.Boyd, J.Engels, F.Karsch, E.Laermann, C.Legeland, M.Lutgeimer, B.Petersson, hep-lat/9602007

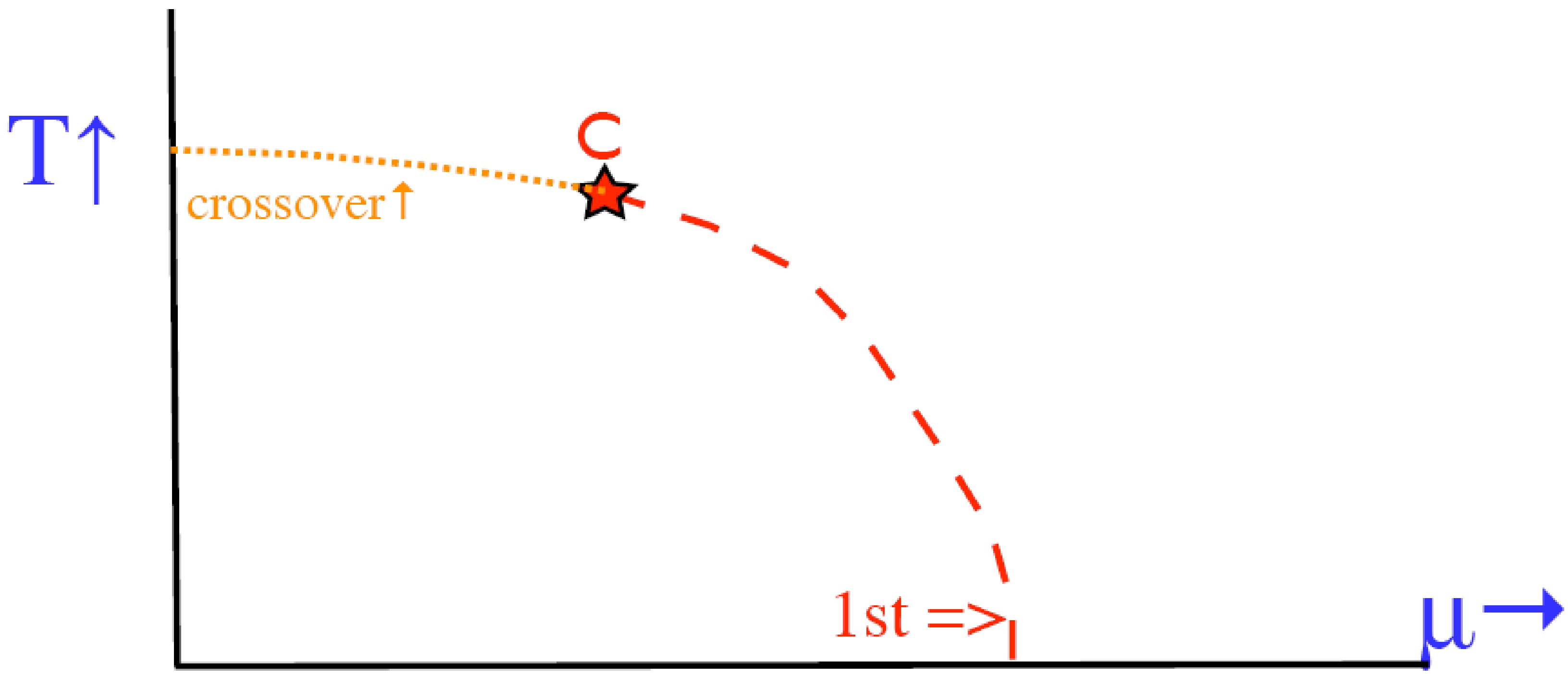
QCD, 2+1 quark flavors (pion mass 220 MeV)



BNL-RBRC-Bielefeld-Columbia-arXiv:0710.0354 (today!)

Phase diagram of QCD matter

Transitions versus temperature, T, and chemical potential, μ:
Crossover at RHIC. Maybe a chiral critical end point, C, at "critRHIC"?

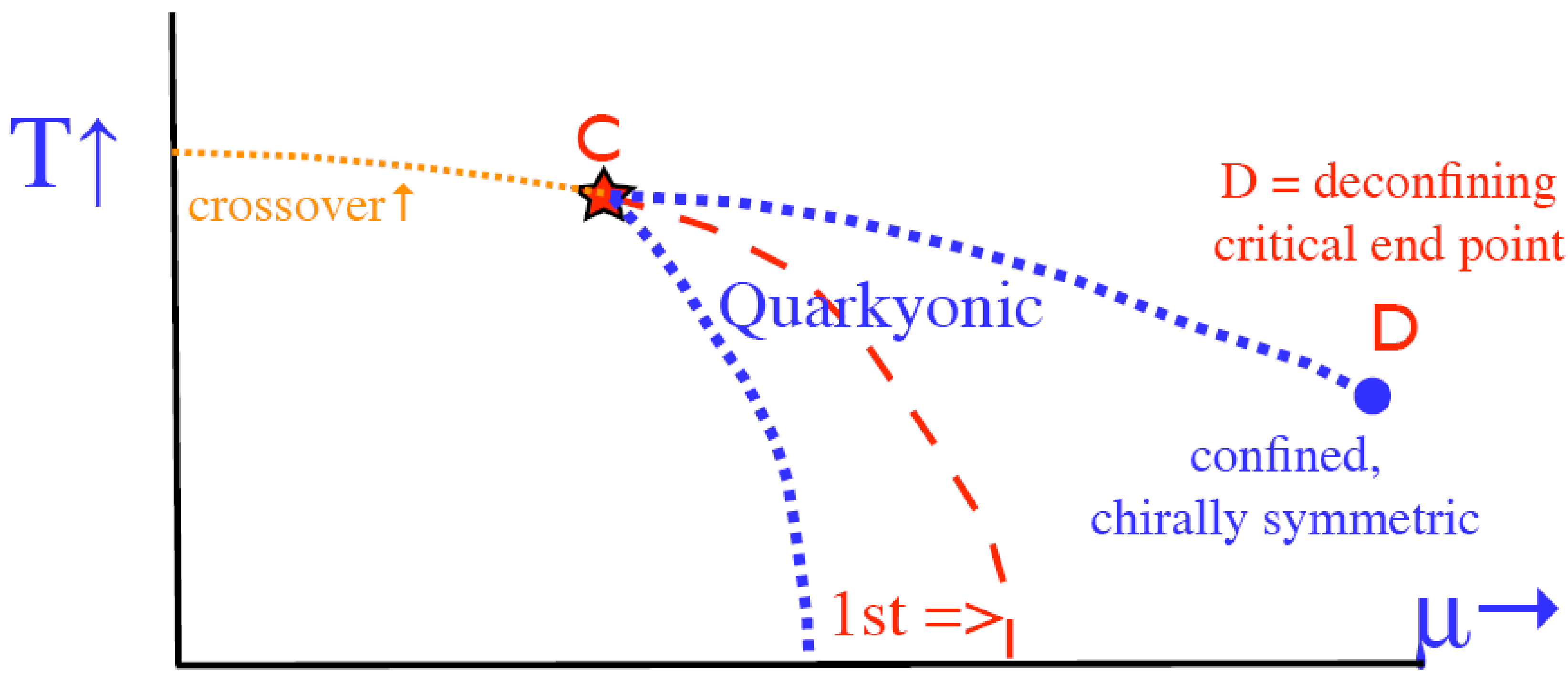


Phase diagram of QCD matter

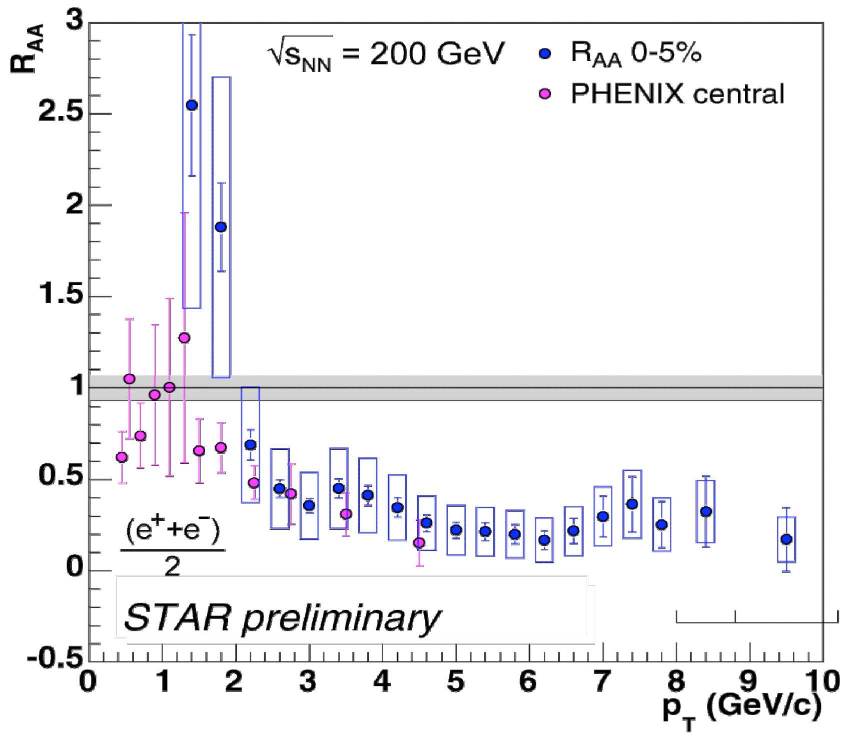
Transitions versus temperature, T, and chemical potential, μ:
Crossover at RHIC. Maybe a chiral critical end point, C, at "critRHIC"?

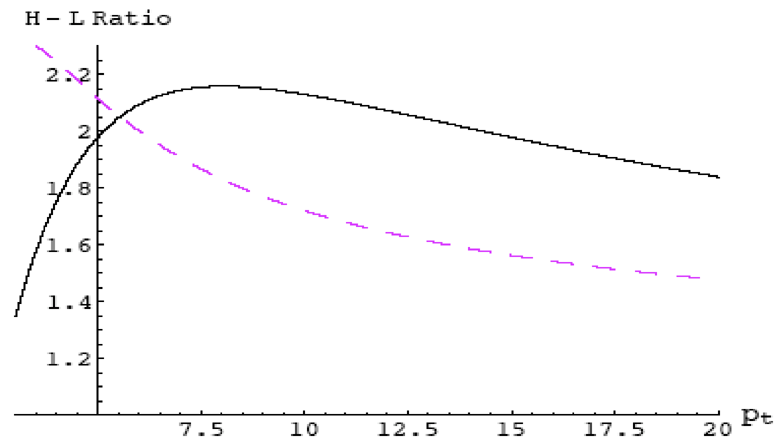
McLerran & Pisarski: large # colors => "quarkyonic" matter
Quarks (deep) in the Fermi *sea*, baryons at the Fermi *surface*.

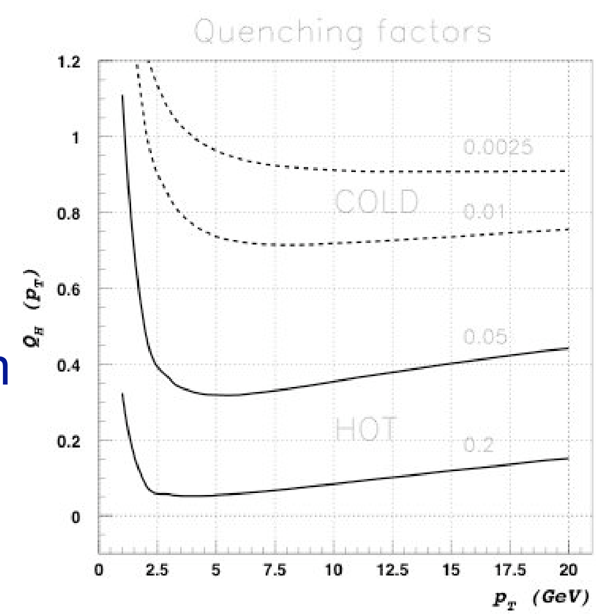
Much richer phase diagram: confined, chirally symmetric phase!
Occurs at *high* T, μ ~ nuclear matter: observable at critRHIC?



Heavy quarks as a probe



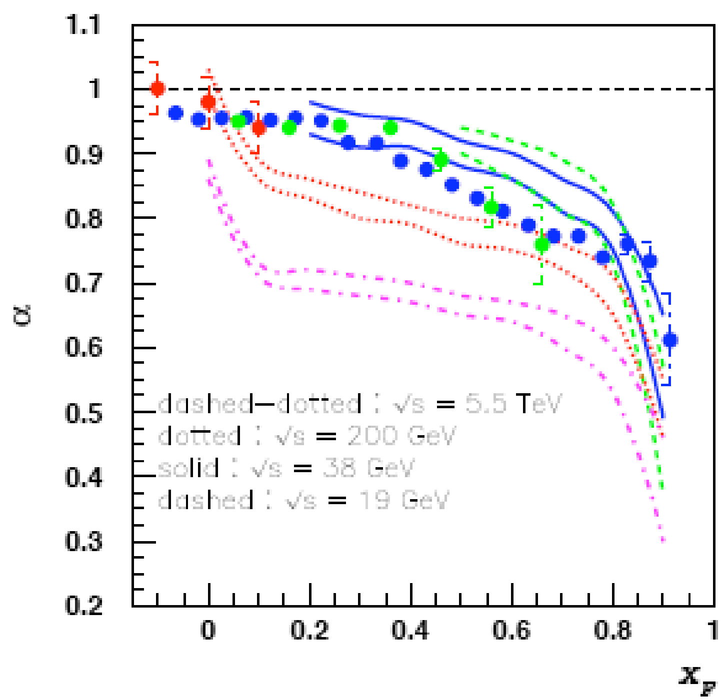




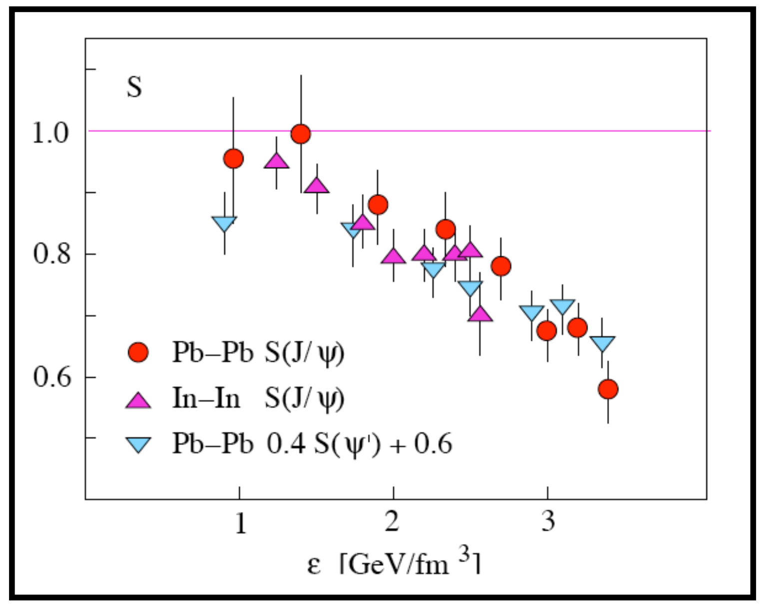
Heavy quark production in the medium -
a crucial test of the energy loss mechanism
("dead cone" suppression of radiative
energy loss) - Yu. Dokshitzer, DK '01

DK,
K.Tuchin

Heavy quarkonium as a probe



DK, K. Tuchin



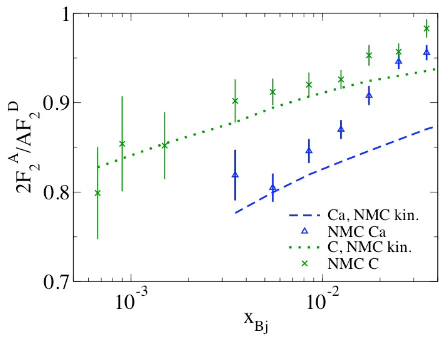
F.Karsch, DK, H.Satz

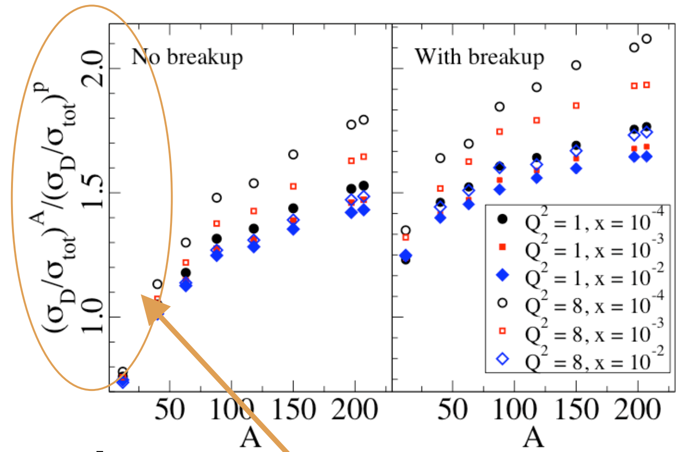
CGC in eA-collisions, the case for EIC

Kowalski, Lappi, Venugopalan, arXiv:0705.3047 [hep-ph]

Saturation model with realistic impact parameter dependence

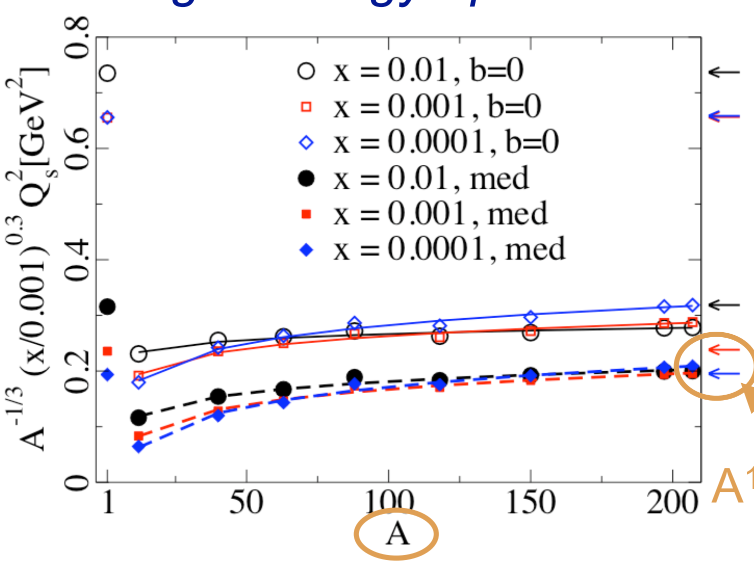
Parameter free description of existing eA data





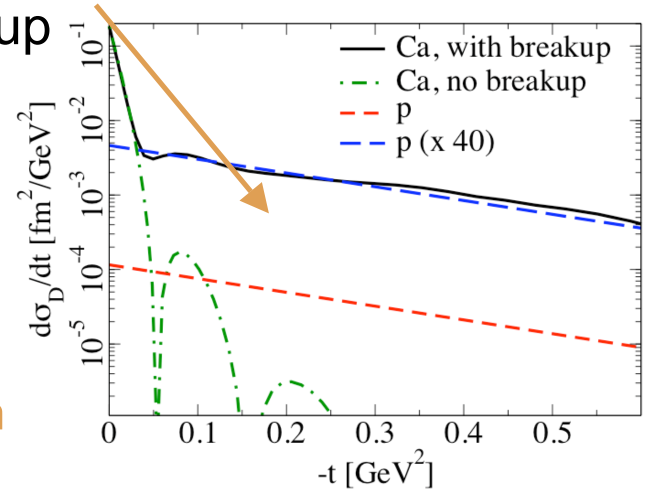
EIC median Q_s equivalent to

14 times larger energy ep-collider



Diffraction:

- Big enhancement wrt ep
- Nontrivial t-distribution and nuclear breakup



Electron-positron pair creation in heavy ion collisions

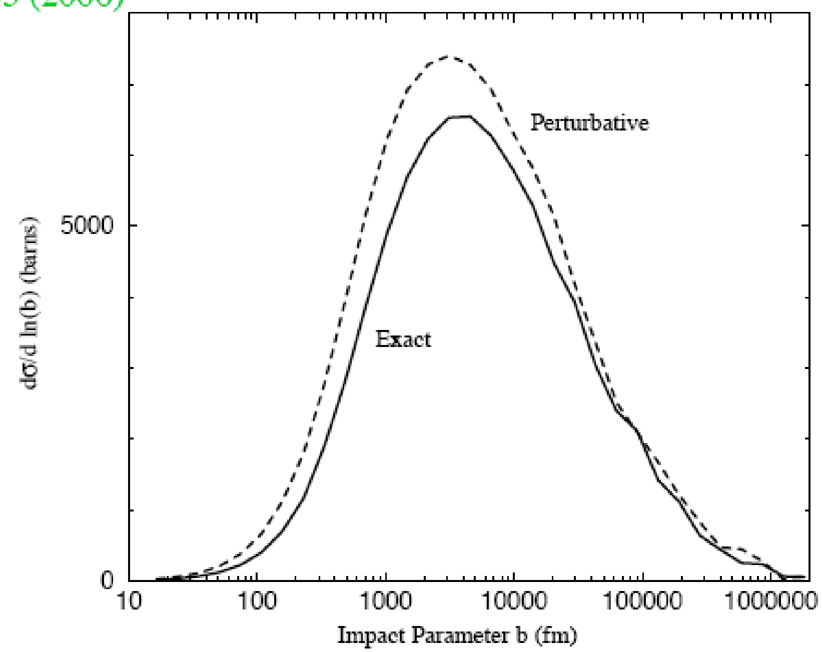
Impact Parameter Dependence of Heavy Ion e^+e^- Pair Production to All Orders in $Z\alpha$

A. J. Baltz, Phys. Rev. C 74, 054903 (2006)

Zero Degree Calorimeter triggering weights smaller impact parameters (b).

b dependence is needed to describe ZDC triggered events such as e^+e^- pairs.

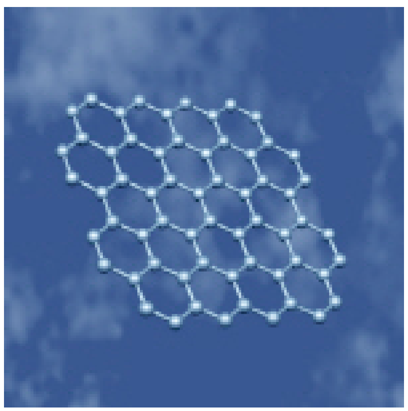
Note that the RHIC total e^+e^- pair production probability is reduced for all impact parameters.

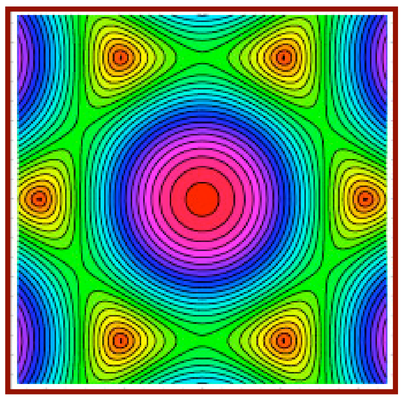


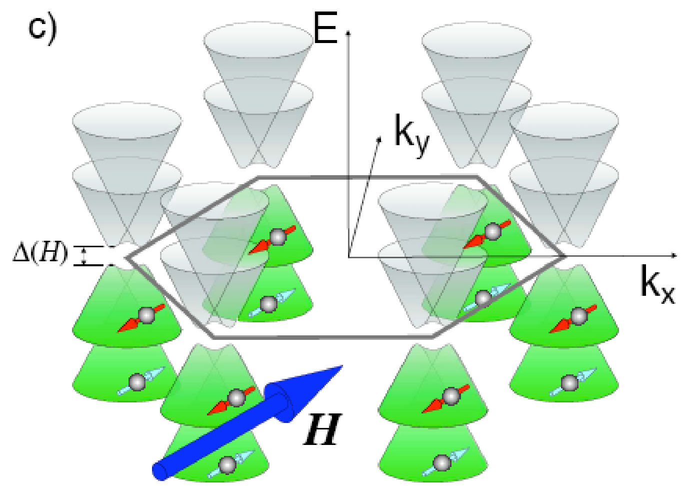
- For the STAR detector, the reduction from perturbation theory is calculated as 27% with ZDC triggering and 17% without.

Interdisciplinary aspects of Nuclear Science

Strongly correlated systems: graphene and quark-gluon plasma







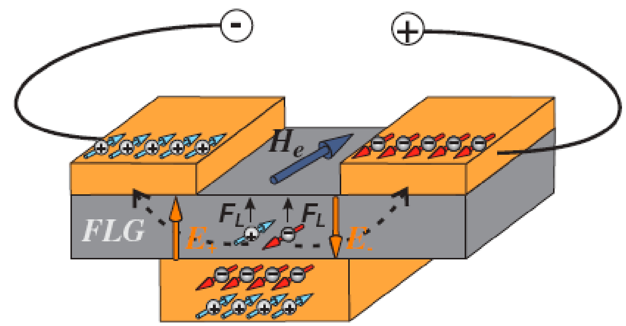
Coulomb attraction between electrons and holes causes instability towards formation of the chiral excitonic condensate (analog of QCD chiral condensate);

The existence of mass gap transforms graphene from a semi-conductor into a dielectric; this may be used for creating spintronic nano-devices…

Interdisciplinary aspects of Nuclear Science

"Spintronic" devices based on graphene-magnet multilayers

("GMM" technology, US pat. 60/892,595, pending)



"This development can open the way for the use of spintronics in practical room temperature devices, an exciting prospect," said DOE Under Secretary for Science Raymond L. Orbach. "The interplay between outstanding facilities and laboratory researchers is a root cause for this achievement, and a direct consequence of the collaborative transformational research that takes place in our DOE laboratories."

The Future

Exploring new frontiers of QCD with the goal of understanding how the theory works: mechanism of confinement; generation of mass; chiral symmetry breaking; the spin of the proton

1. The physics of RHIC: 3D simulations of parton matter evolution, energy loss, heavy quarks

2. The physics of RHIC-II : heavy quarks, hard processes, forward rapidities

3. Spin physics : W production, transverse spin, …

4. The physics of the eRHIC : Deep Inelastic Scattering off nuclei and polarized protons