Im?Perfect Fluidity in Pb+Pb at LHC and the Critical p+Pb Missing Link

Miklos Gyulassy
FIAS Frankfurt / Columbia Univ

1. **Elliptic Flow at RHIC and its "Perfect Fluid" sQGP core interpretation**
2. **The Color Glass Condensate Challenge to above**
3. **Challenge^2 to CGC sharp surface and the Geometry of AA**
4. **Broken CGC and the rediscovery of the LUND model ?**
5. **Needed pA Control of Initial sQGP Geometry and Eccentricity**

(collab.: D.Molnar, T.Hirano, L.McLerran, A.Adil, …)

Inseparable Links: $pp \leftrightarrow pA \leftrightarrow AA$

Some references:

New forms of QCD matter discovered at RHIC.
Miklos Gyulassy , Larry McLerran Nucl.Phys.A750:30-63,2005. nucl-th/0405013

Perfect fluidity of the quark gluon plasma core as seen through its dissipative hadronic corona.
Tetsufumi Hirano, Miklos Gyulassy **Nucl.Phys.A769:71-94,2006**. **nucl-th/0506049**

Relativistic Hydrodynamics at RHIC and LHC.
Tetsufumi Hirano e-Print: **arXiv:0704.1699**

Hadronic dissipative effects on elliptic flow in ultrarelativistic heavy-ion collisions.
Tetsufumi Hirano et al **Phys.Lett.B636:299-304,2006**. e-Print: **nucl-th/0511046**

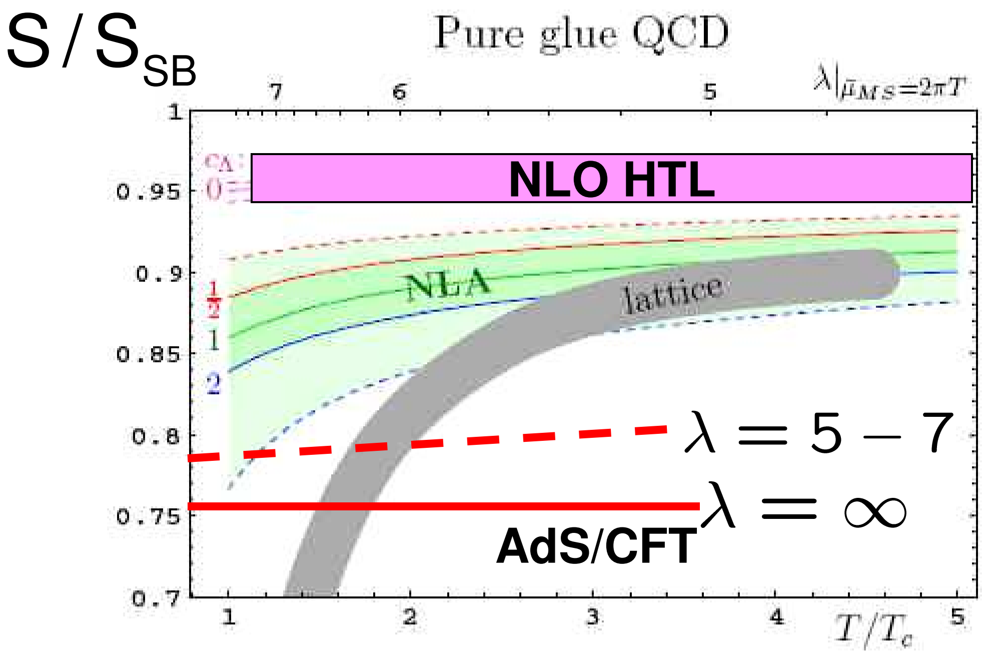
CGC vs Glauber geom refs.

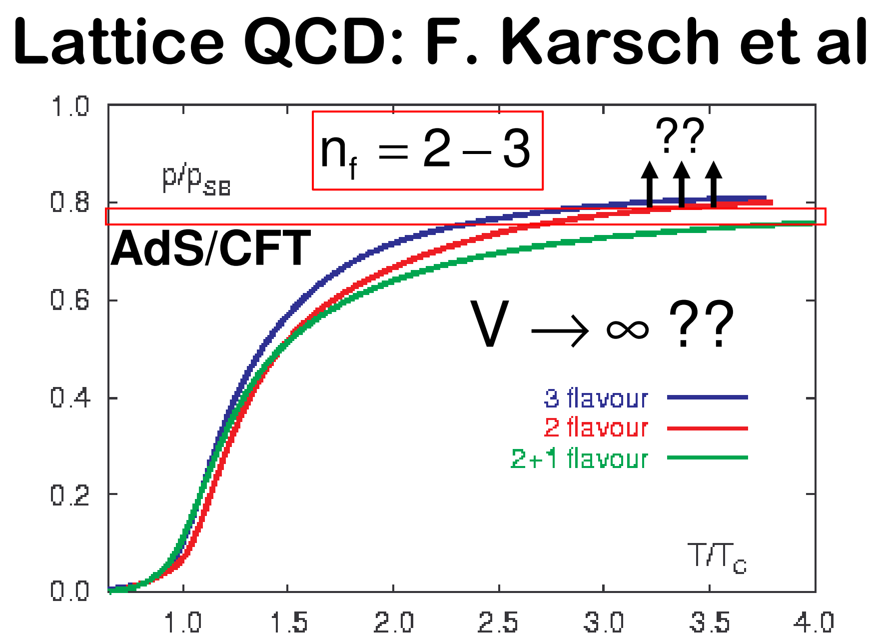
Adil & Gyulassy, Phys. Rev. C 72 (2005) 034907

Adil, Gyulassy & Hirano , Phys. Rev. D 73 (2006) 074006

Adil, Drescher, Dumitru, Hayashigaki & Nara, PRC 74 (2006) 044905

What is a strongly coupled Quark Gluon Plasma (sQGP) ?





How to explain LQCD tiny 15% deviation from Stefan-Boltzmann for T> $2T_c$?? Is the sQGP an AdS_5 Black Hole?

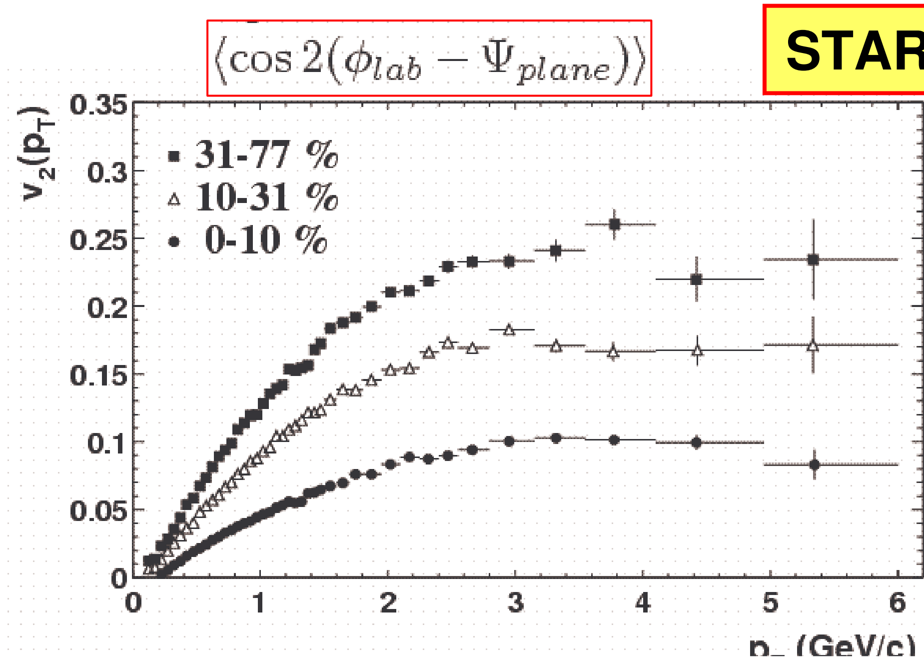
or simply a screened massive quasiparticle gas?

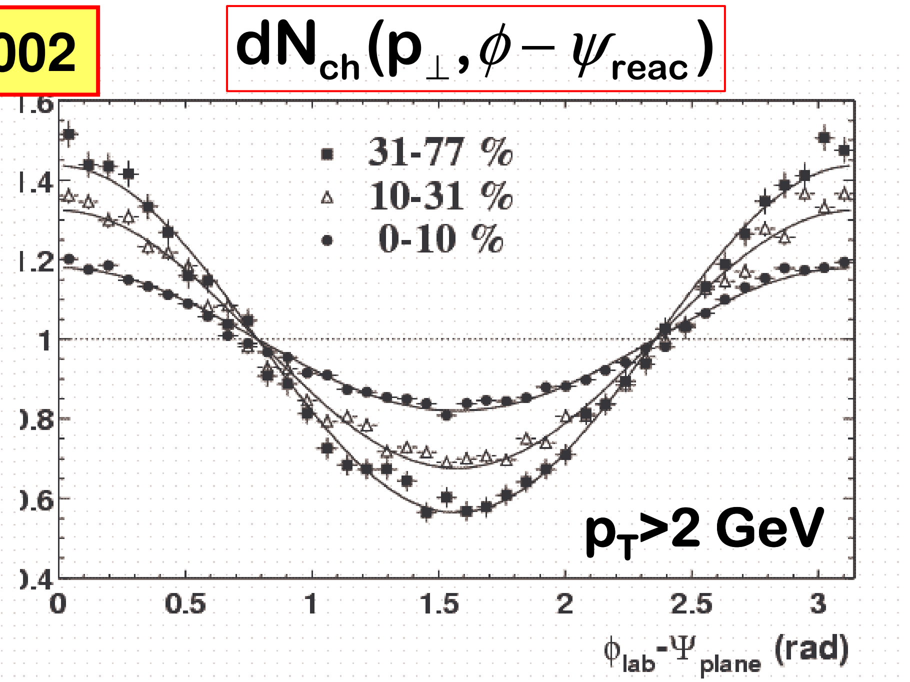
No approximation is accurate enough yet to tell

Hard-thermal-loop entropy of supersymmetric Yang-Mills theories.
J.-P. Blaizot, E. Iancu, U. Kraemmer, A. Rebhan e-Print: **hep-ph/0611393**

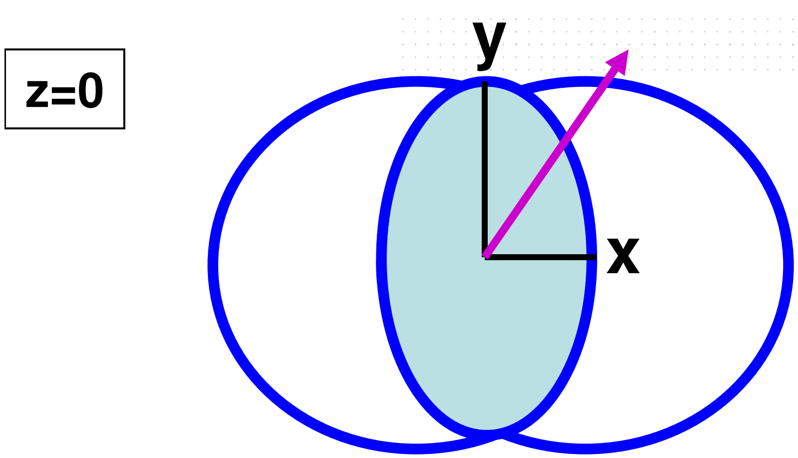
Discovery of Transverse Elliptic Flow in Non-central Au+Au at RHIC

STAR 2002

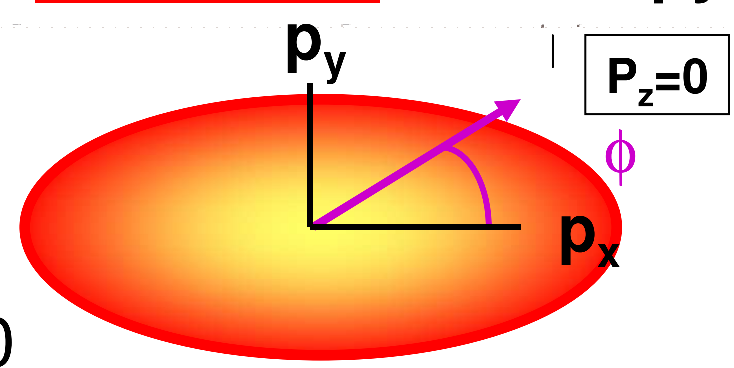




Initial *spatial* anisotropy



Final *momentum* anisotropy



$$\partial_\mu T^{\mu\nu}(x) = 0$$

Stoecker, Greiner 84, Ollitrault 92

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

nature

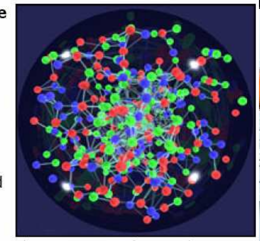
by Mark Peplow
news@nature.com

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms. BBC NEWS



The impression is of matter that is more strongly interacting than predicted

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

http://www.bnl.go

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Print-friendly E-mail Article

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remar
many new questions

April 18, 2005

TAMPA, FL -- The four detector group
Relativistic Heavy Ion Collider (RHIC
the U.S. Department of Energy's Broo
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articles of
markable t
marizing th
ead of behaving like a gas of free quarks and
he matter created in RHIC's heavy ion collisions

New State of Matter Is 'Nearly Perfect' Liquid

Physicists working at Brookhaven National Laboratory announced today that they have created what appears to be a new state of matter out of the building blocks of atomic nuclei, quarks and gluons. The researchers unveiled their findings--which could provide new insight into the composition of the universe just moments after the big bang--today in Florida at a meeting of the American Physical Society.

SCIENTIFIC AMERICAN

Image: BNL

There are four collaborations, dubbed BRAHMS, PHENIX, PHOBOS and STAR, working at Brookhaven's Relativistic Heavy Ion Collider (RHIC). All of them study what happens when two interacting beams of gold ions smash into one another at great velocities, resulting in thousands of subatomic collisions every second. When the researchers analyzed the patterns of the atoms' trajectories after these collisions, they found that the particles produced in the collisions tended to move collectively, much like a school of fish does. Brookhaven's associate laboratory director for high energy and nuclear physics, Sam Aronson, remarks that "the degree of collective interaction, rapid thermalization and extremely low viscosity of the matter being formed at RHIC make this the most nearly perfect liquid ever observed."

Universe May Have Begun as Liquid, Not Gas

The Washington Post

Associated Press
Tuesday, April 19, 2005; Page A05

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence.

The coming year will see a number of interesting developments as the Large Hadron Collider (LHC) goes online. The enormous amount of data generated by the LHC will force us to refine our methods—and explore new ones—for extracting and interpreting information from high energy collisions. This work should lead to new insights into the masses of elementary particles and the consequences of various models for particle physics and cosmology.

Also of interest is the recent application of string theory to the physics being done at the Relativistic Heavy Ion Collider (RHIC), where string theory permits some calculations that would otherwise be intractable. The idea at RHIC is to better understand the strong force that binds together the elements of a nucleon, and 2007 may see the theoretical advances of string theory inform the experimental results from RHIC.

—Lisa Randall, Harvard University

Of course, some may disagree…

…but in the end the "right" approach will be validated by both qualitative concepts, and quantitative predictions

New Yorker, Jan. 8, 2007

(from P. Steinberg, LRP07)

How does QCD/Nuclear matter Flow ??

$$\eta_{H_2O} = 1\,\mathrm{cP} = 2\times10^{-15}\ \frac{\mathrm{GeV}}{\mathrm{fm}^2\bullet c}$$

$$\eta_{Lava} = 10^5\ \mathrm{cP}$$

$$\eta_{Hadron} = \frac{T}{\sigma_H\, c} = \frac{1}{10}\left(\frac{\mathrm{GeV}}{\mathrm{fm}^2\bullet c}\right)\left(\frac{T}{T_c}\right) = \left(5\times10^{13}\ \mathrm{cP}\right)\left(\frac{T}{T_c}\right)$$

$$\eta_{Hadron} \sim 100\ \eta_{Granite}$$

Fluid Evolution in 1+1D Bjorken Expansion

Entropy Density

Shear (+ ¾ Bulk) Viscosity

$$d\epsilon/d\tau = -sT/\tau$$ ← Perfect Euler Fluid

$$= -(sT/\tau)[1 - 4(\eta/s)/3T\tau]$$ ImPerfect Fluid

Energy Density

(first order Navier-Stokes)

At early times $\tau \sim 1/T$ the dimensionless ratio η/s
Measures the importance of dissipative effects
That reduced the transfer of heat into collective flow

At late times $\tau >> (\eta/s)\, 1/T$ longitudinal gradients are small
But 1D ->3 D and T drops rapidly below Tc

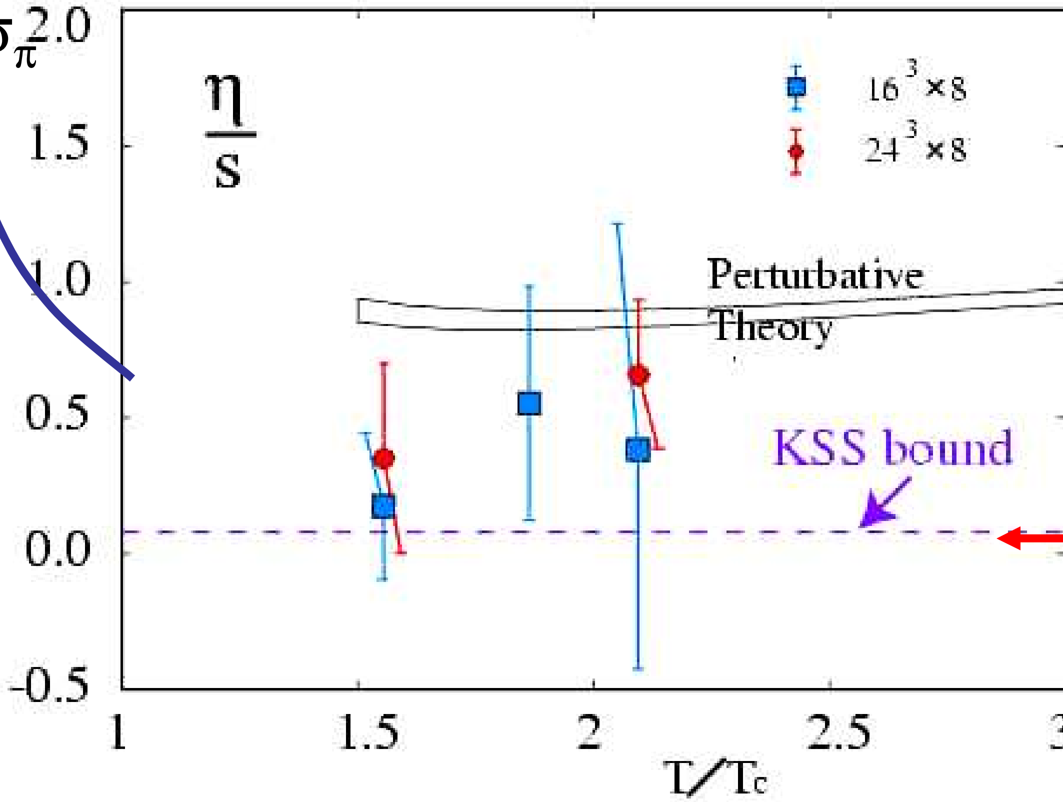
Transport coefficients of a gluon plasma

Lattice QCD *vs* pQCD *vs* AdS/CFT N=4 SYM

Gavin 85

$$\frac{1}{T^2\sigma_\pi}$$

Lattice QCD: A.Nakamura,S.Sakai, 2004



N=4 SUSY KSS: Kovtun,Son,Starinets 04

Danielewicz, MG, (1985) *

Perturbative QCD

$$\frac{T\,\lambda_{pQCD}}{5} \approx \frac{(0.3)^2}{\alpha^2 \log 1/\alpha} \sim 1$$ *

$$\left(\frac{\eta}{\sigma}\right)_{adS/CFT} = \frac{1}{4\pi}$$

N=4 SUSY

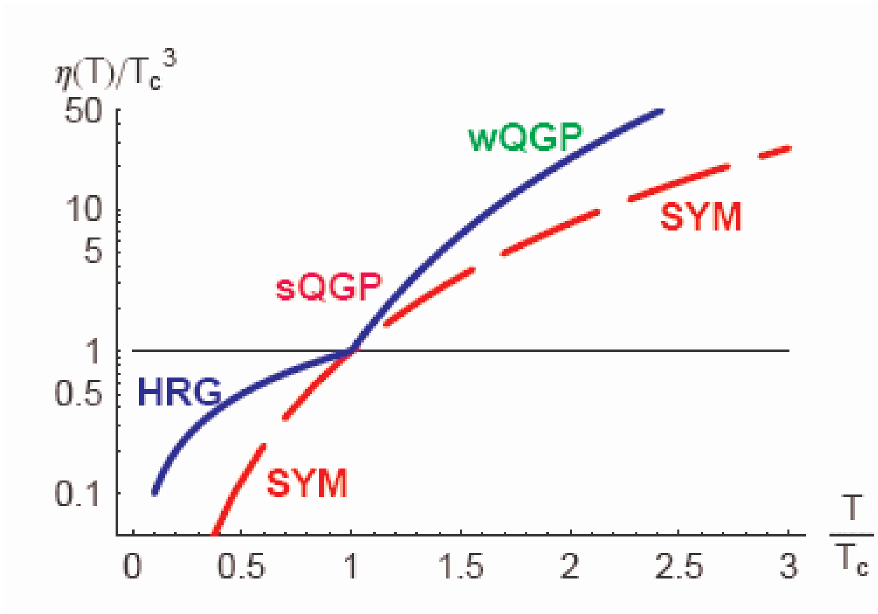
$g^2N_c \to \infty$

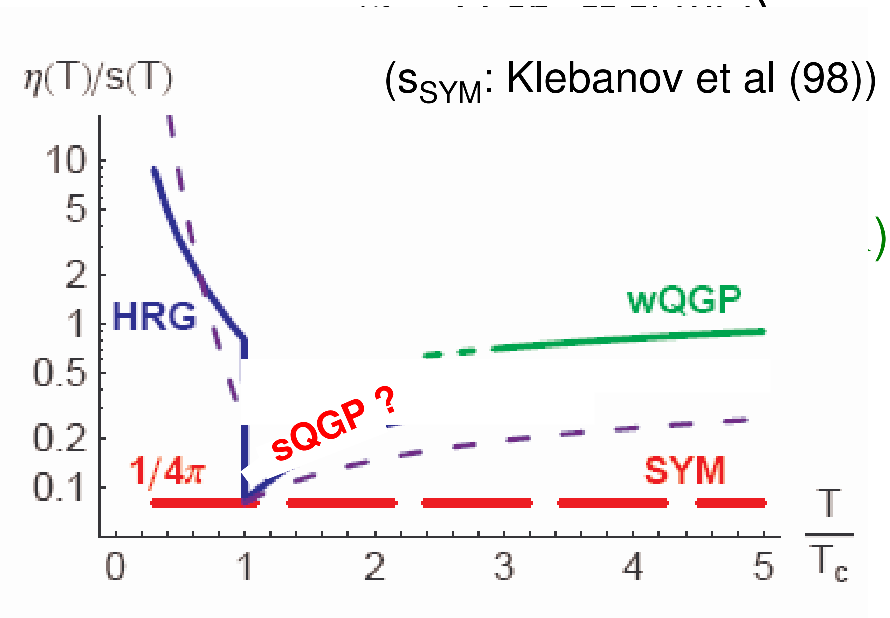
$$\frac{T\lambda_{min}}{5} \approx \frac{\hbar = 1}{15}$$ *

The Perfect Fluidity of QGP Core may be a Signature of Deconfinement

T. Hirano and MG Nucl.Phys.A769:71-94,2006

$\eta(T)$: shear viscosity and $s(T)$: entropy density





- Absolute value of viscosity

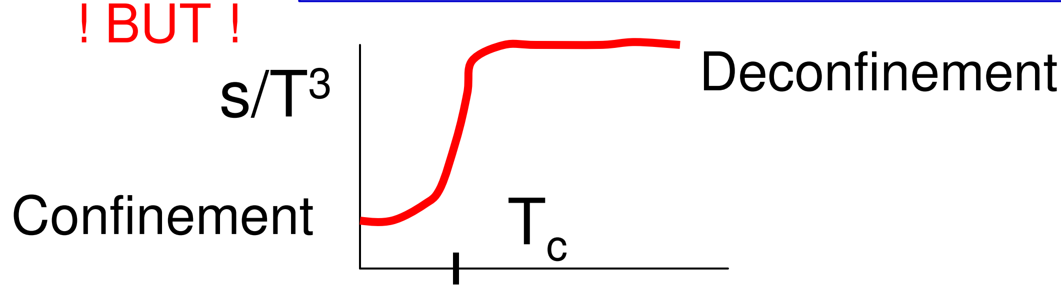
$\eta(\text{sQGP}) > \eta(\text{hadron})$

Viscosity is monotonic
Increasing with T

- Ratio to entropy density

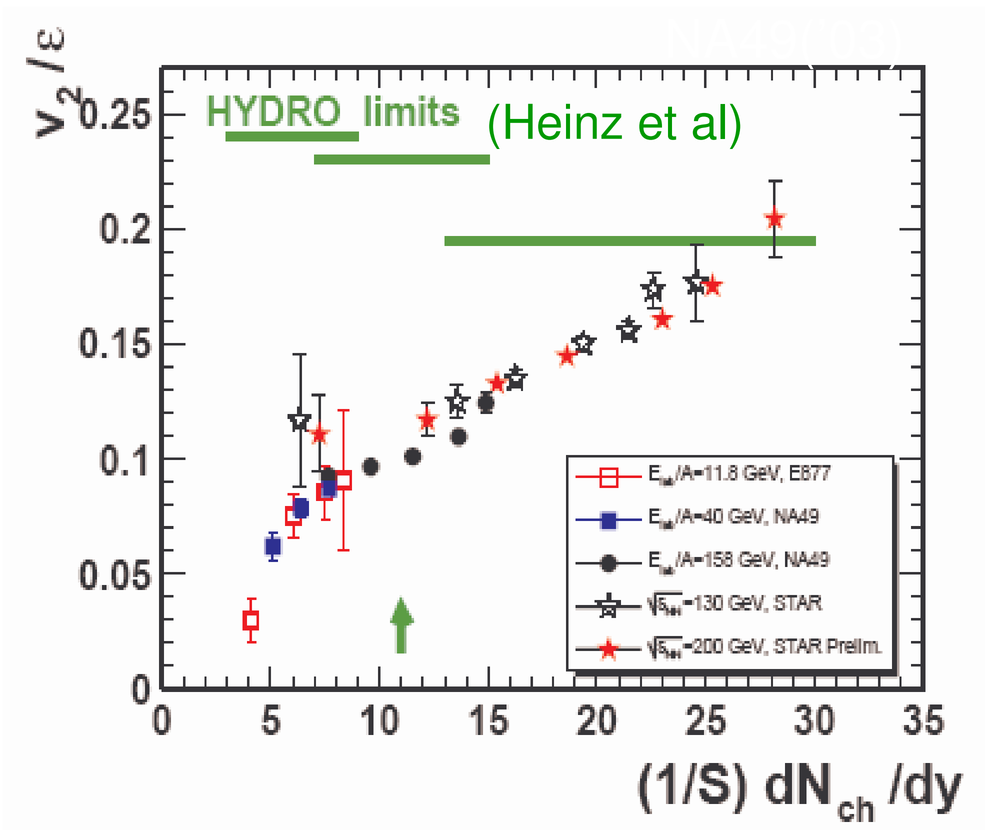
$\eta/s(\text{sQGP}) \ll \eta/s(\text{hadron})$

! BUT !

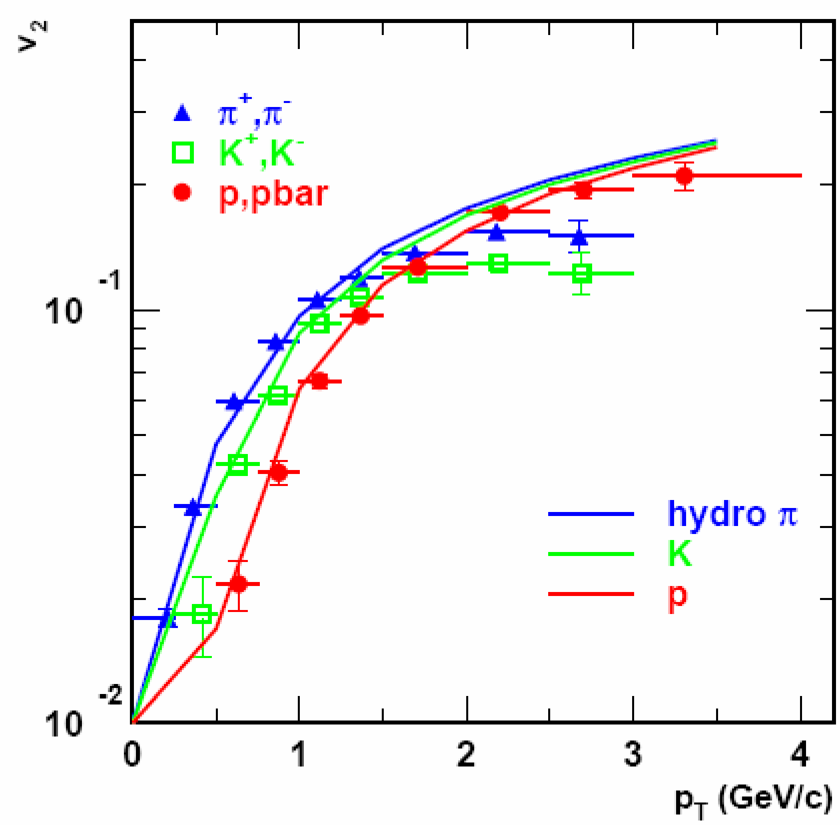


Basis of the BNL Press Release

Integrated elliptic flow



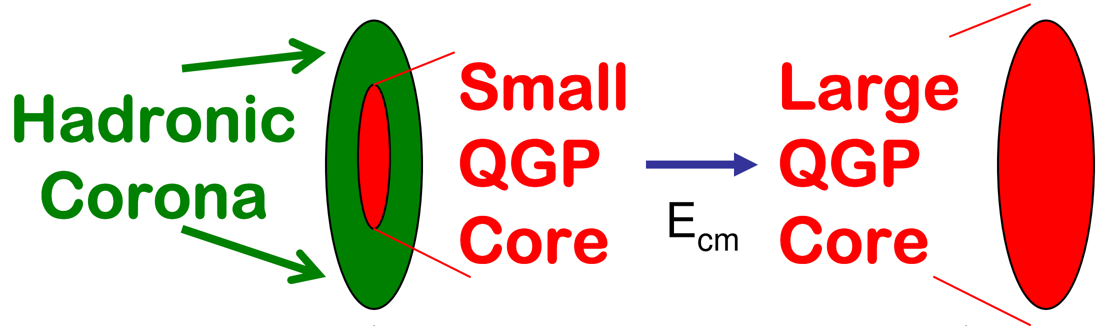
Differential elliptic flow



Perfect Fluid (zero viscosity) Hydrodynamics appears to do "work" for the first time in central AuAu at highest RHIC energy

At lower energies Perfect Fluidity is Obscured by the highly dissipative Hadron Resonance Corona

Bass, Dumitru,…
Teaney, Shuryak
Hirano, Nara



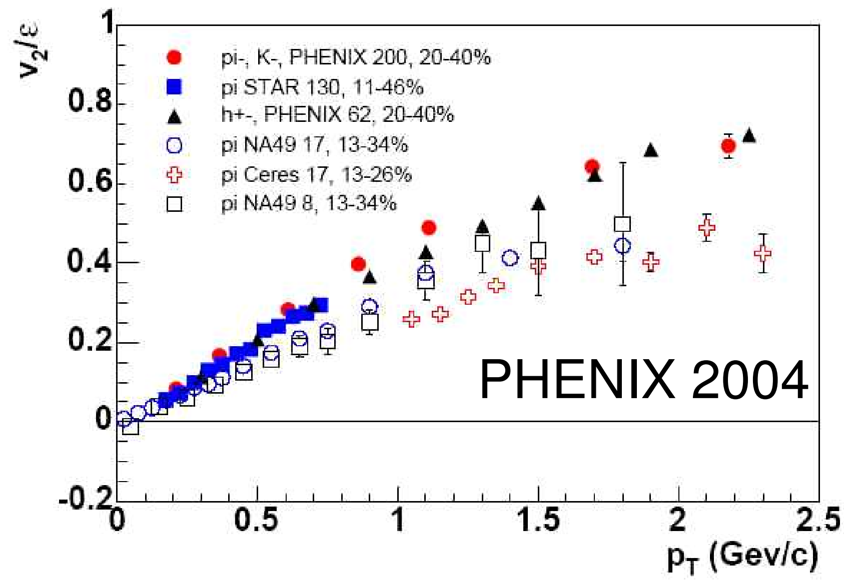


FIG. 16: $v_2(p_T)/\varepsilon$ versus p_T for mid-central collisions at RHIC (filled symbols) and SPS (open symbols). Dividing by eccentricity removes to first order the effect of different centrality selections across the experiments.

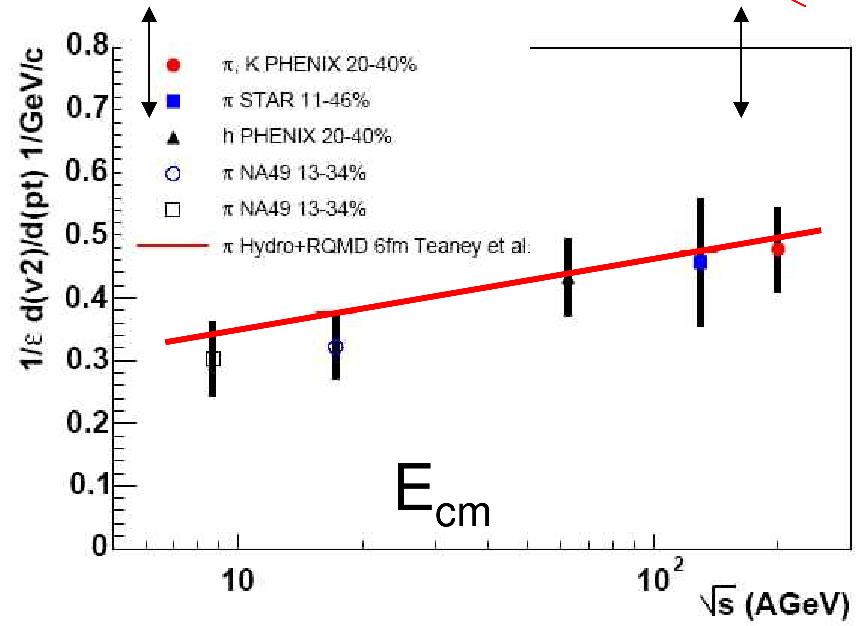
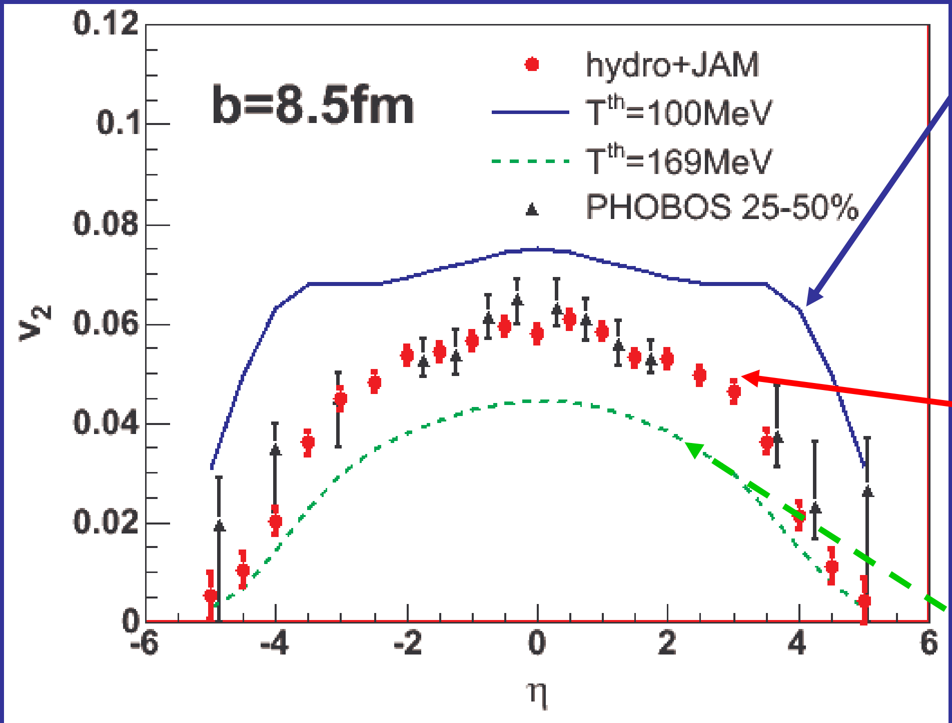


FIG. 17: The slope of the scaled elliptic flow, $(dv_2/dp_T)/\varepsilon$, for mid-central collisions at RHIC (filled symbols) and the SPS (open symbols). The slope is calculated for the data $p_T < 1$ GeV/c. The solid error bars are the systematic errors that include the systematic error on v_2 and ε.

T.Hirano et al.('06)

Elliptic Flow --Rapidity Dependence--



QGP+hadron perfect fluids

• overshoots data
Away from mid rapid

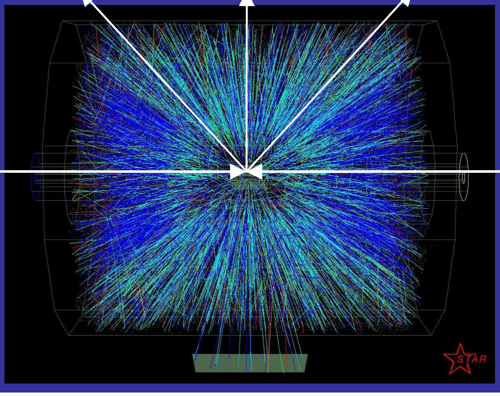
QGP perfect fluid core
+ hadron gas corona

•Agrees with data

QGP fluid only ($T_F=T_c$)
no hadronic rescatterings

•undershoots data in
whole region

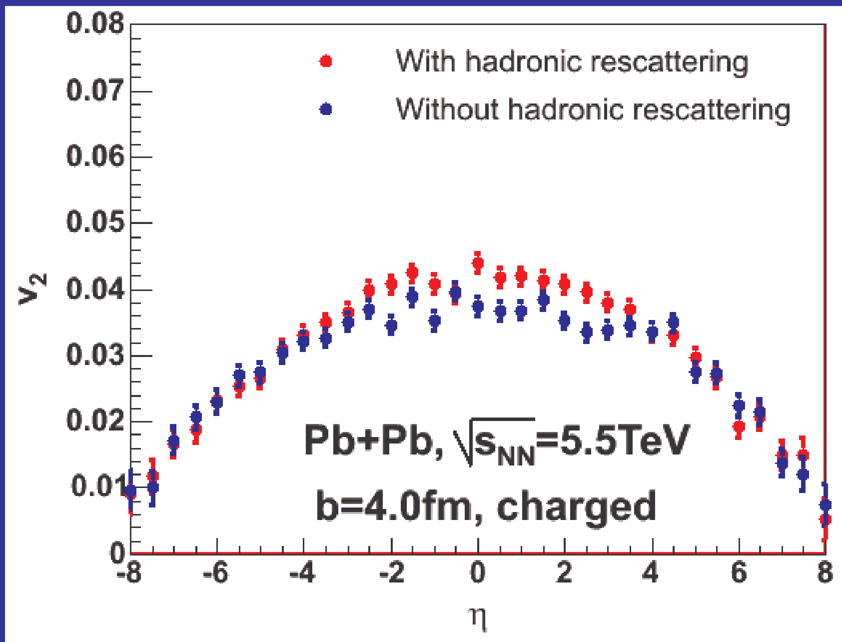
η<0 η=0 η>0

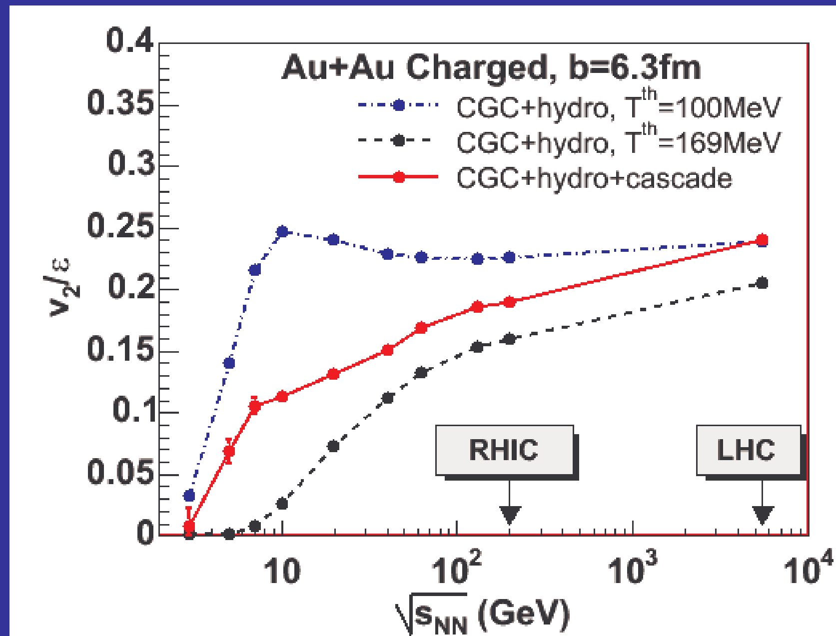


LHC Prediction

THirano et al.('06)

$v_2(\eta)$ @ and $v_2(sqrt(s_{NN}))$





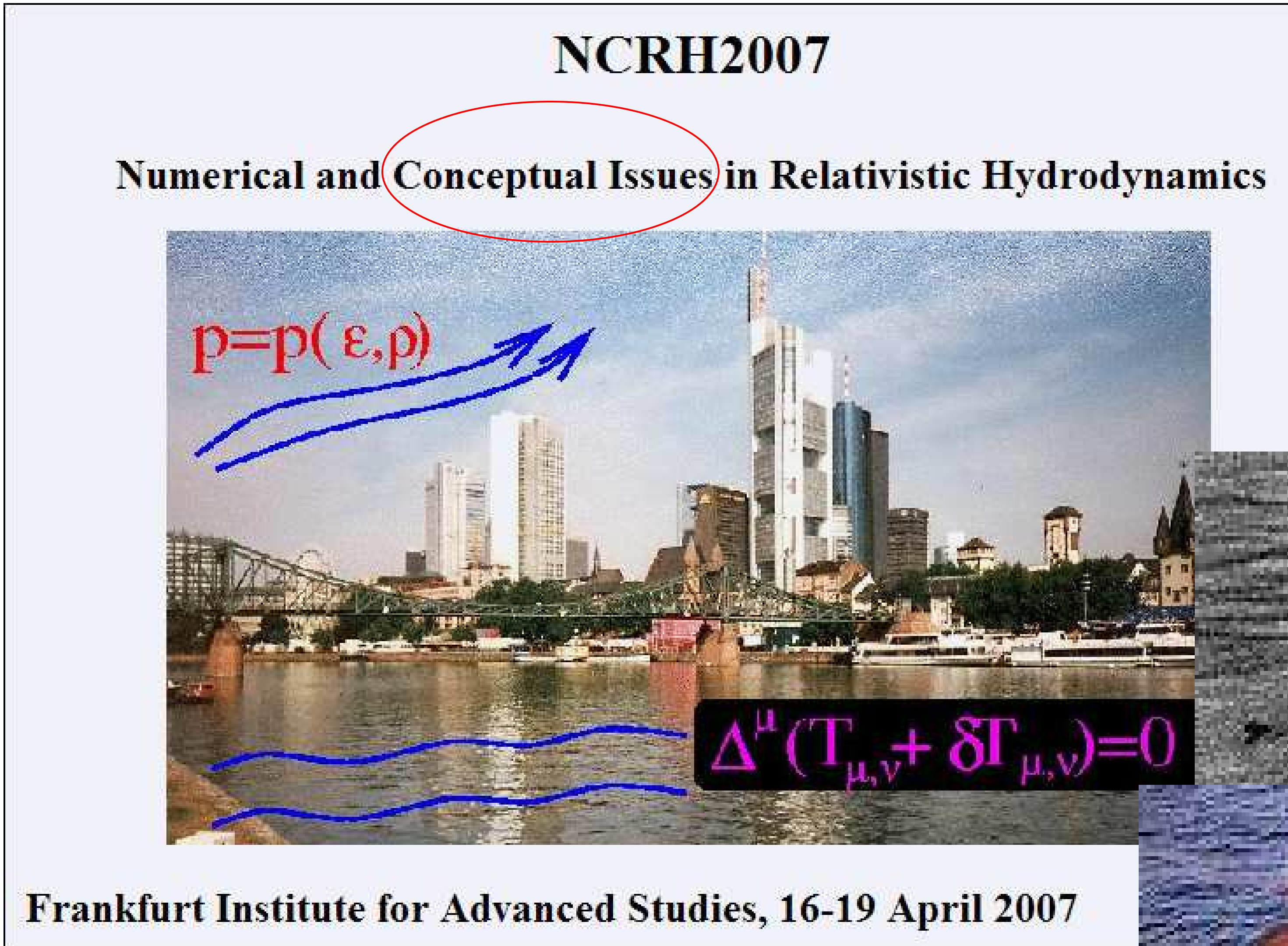
- Total v_2 generated mainly in the sQGP core

- v_2/ε increases somewhat in this hybrid Q Fluid + H Gas model

v_2^{LHC} can increase substantially only IF Initial geometry does!

Teaney et al.('02)

Wrestling with Monsters and Uncertainties in the Perfect Fluid



http://th.physik.uni-frankfurt.de/~ncrh/
Giorgio Torrieri (ITP)

Complex competing Interplay of 3+1D Hydro in A+A

1) Elliptic Flow
2) Radial Flow
3) Longitudinal Flow

Chemical FreezeOut leads to more rapid cooling
That amplifies azimuthal flow asymmetry.
This requires Hadronic dissipation to reduce asymmetry

In Chem Equilib less rapid cooling keeps v2 near data
and there is no room for dissipation but at
the unacceptable cost of losing the Hadron Chemistry

A Cold Splash on the Perfect Fluid?

Part II: The CGC_{KLN} Challenge to sQGP

CGC Initial Conditions

+ Perfect sQGP Fluid core

+ Hadron Gas corona

= Overprediction of v2 !

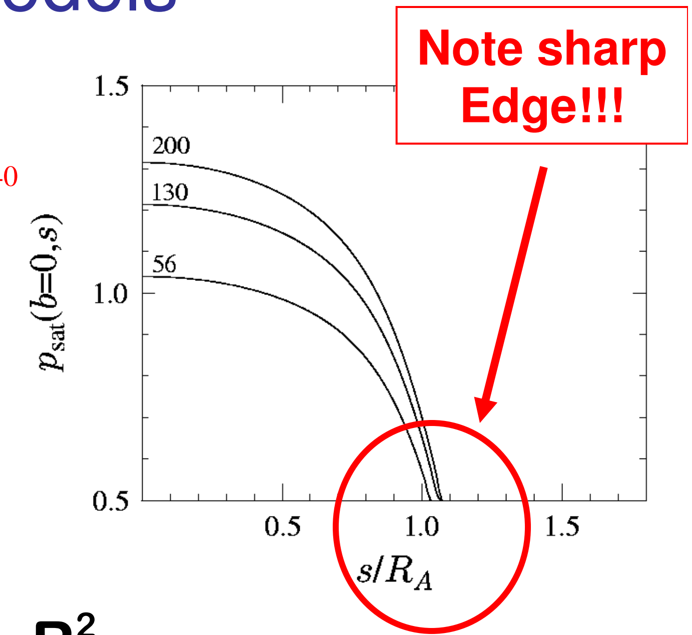
Hirano, Nara, Heinz, Kharzeev, …
Dumitru, Nara, Drescher

Gluon Saturation Models

- **EKRT: Final State Saturation**

$$\frac{3}{2}\frac{dN_{ch}}{dy} \overset{\Delta S=0}{=} \frac{dN^{pQCD}_{AA\to g}}{dy} = Q^2_{sat}R^2 \approx 1.16\,A^{0.92}\,(\sqrt{s})^{0.40}$$

$$Q_{sat}(A,s) \approx 0.208\,A^{0.128}\,(\sqrt{s})^{0.191}$$



- **Mueller, Qiu, Blaizot : Initial State Saturation**

$$\frac{dN^{max}_{glue}}{dy} = 2\,xG_A(x,Q^2_{sat})\Big]_{x=2Q/\sqrt{s}} = \left(\frac{c_s}{g^2}\right) Q^2_{sat}R^2$$

- **McLerran, Venugopalan, Krasnitz: Color Glass Condensate**
  Classical Yang-Mills on a Lattice

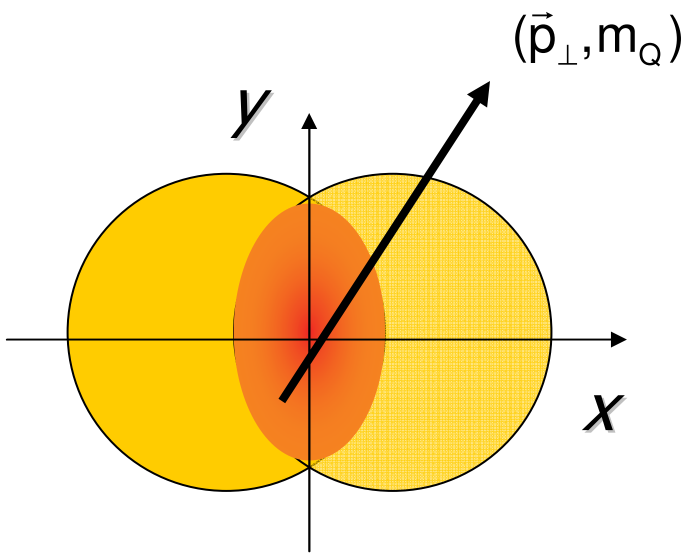
- **Kharzeev, Levin, Nardi : Analytic CGC Model**

$$\frac{dN^{CGC}_{g}}{dy} = 2\,x\,G_A\left(x=\frac{2Q_{sat}}{\sqrt{s}}, Q^2_{sat}\right) = c\,\frac{Q^2_{sat}R^2}{\alpha_s\left(Q^2_{sat}\right)}$$

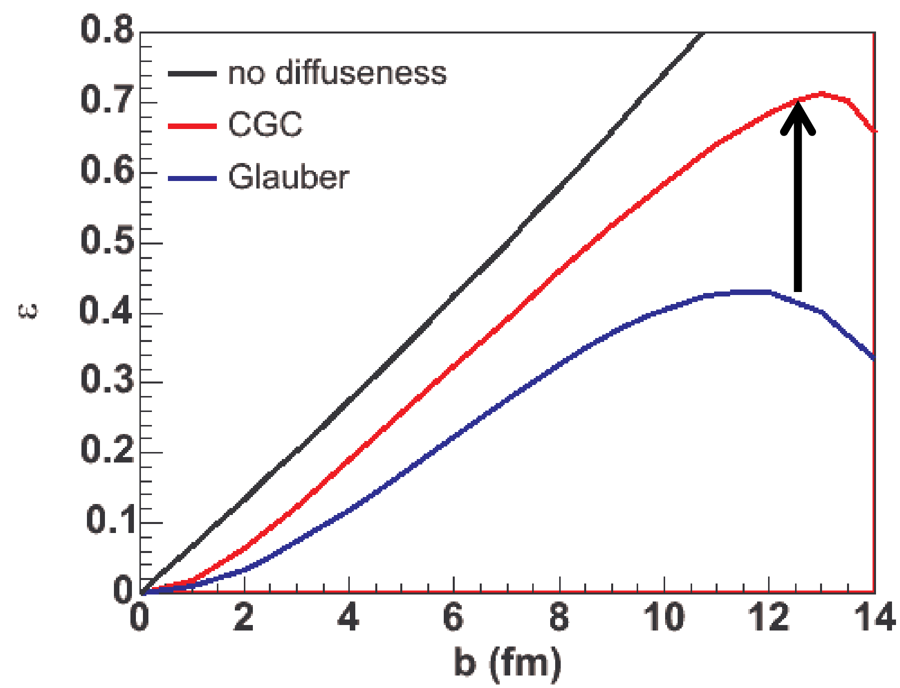
Hirano et al 06

Initial Transverse Geometry: CGC vs Glauber

Sharper edge
Increases ε



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$



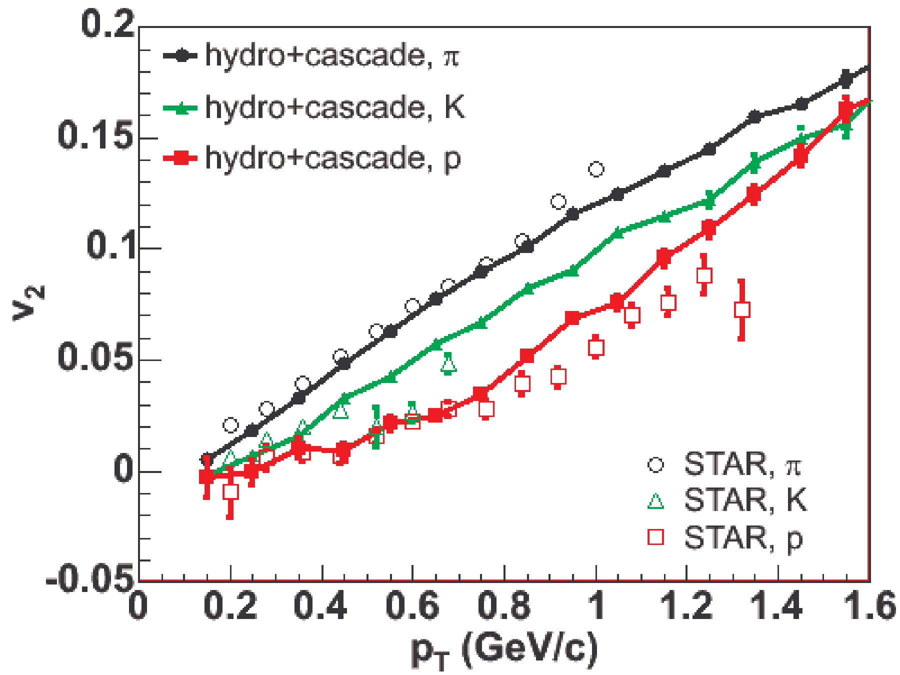
Data => Perfect Fluid core only if $v_2^{exp} \approx 0.2\, \varepsilon_{geom}$

Data => Imperfect (viscous) if $v_2^{exp} < 0.2\, \varepsilon_{geom}$

Hirano, Nara, et al 06

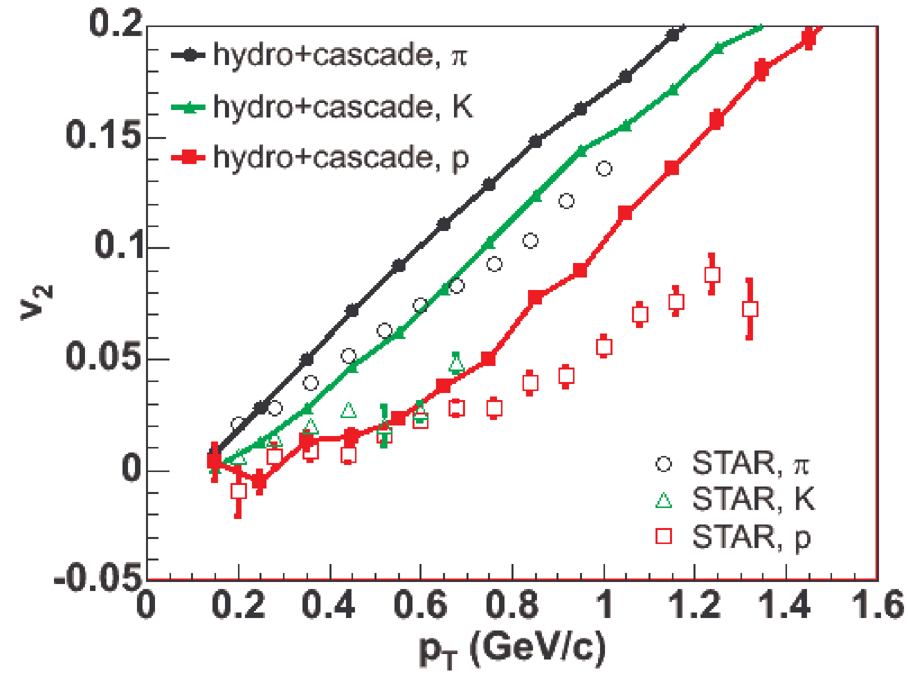
Differential Elliptic Flow $v_2(p_T, m)$ for identified hadrons π, K, p

Glauber Initial Condition



v_2(Glaub) ~ v_2(data)

CGC Initial Condition



v_2(CGC) > v_2(data) !!

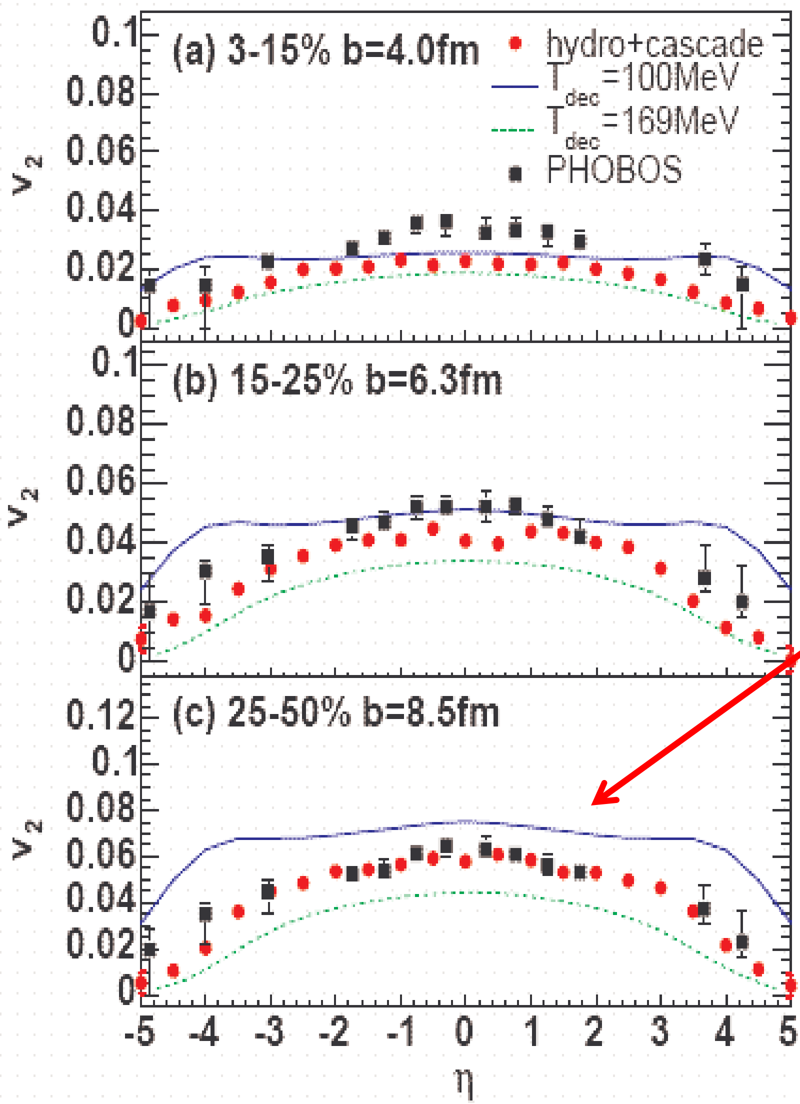
Glauber Geom + v2 Data => “sQGP” is Perfect Fluid

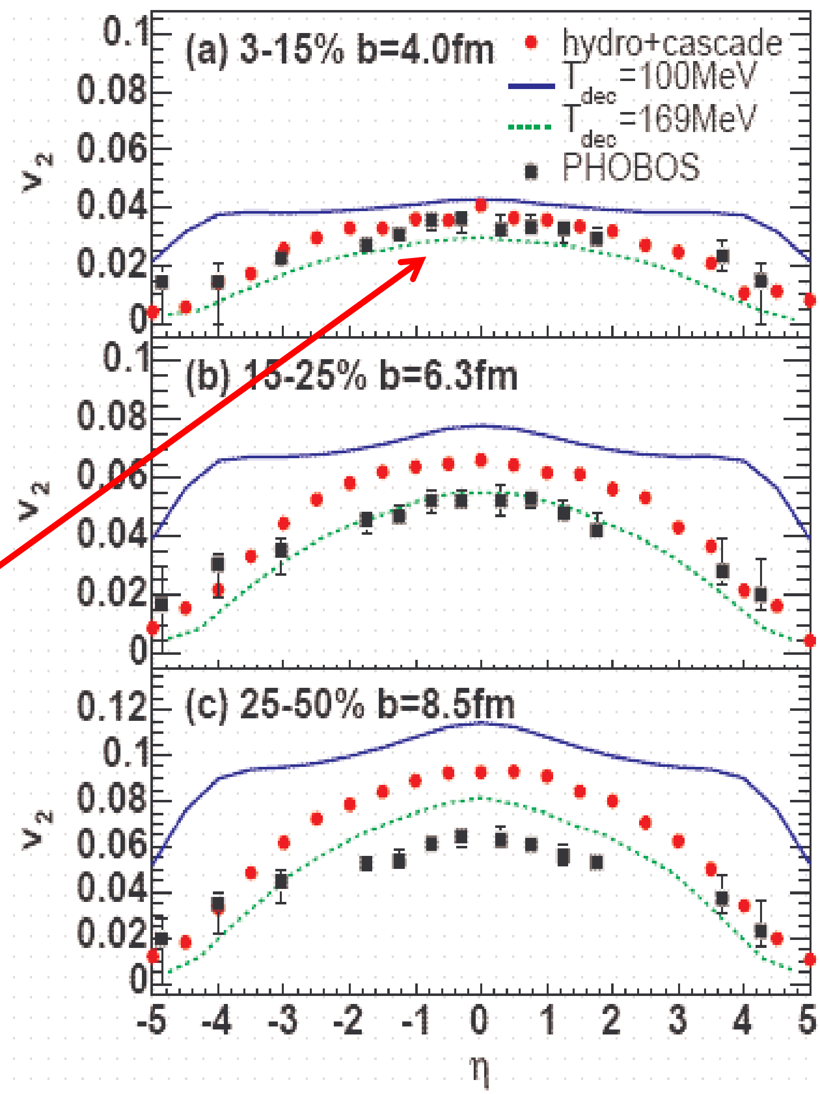
CGC Geom + v2 Data => “sQGP” is Imperfect Fluid !!

Perfect or Imperfect Fluidity ★ Depends on Initial Conditions ★

Hirano, Nara, et al 06

Glauber Participant Geometry | **Color Glass Initial Conditions**





Glauber best in Peripheral

CGC best in Central

My conclusion so far:

Perfect Fluid sQGP core can only “work”
If Initial AA geometry evolves from

Diffuse Glauber at large impact parameters

To

Sharp CGC geometry at small impact params

Equivalently: Glauber is right when $Q_{sat} < 1$ GeV
CGC May be right when $Q_{sat} > 1$ GeV

Dilute Surface region is always Glauber

Part III

- Closer look at theory of AA

  Initial Conditions

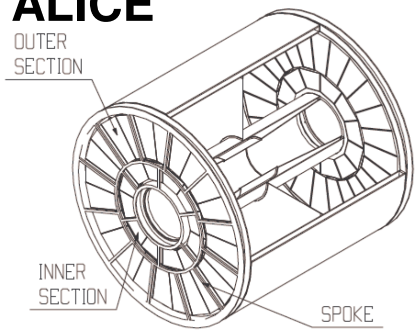
Hydro is simply a map from a given IC
To a specified FO=freeze-out hypersurface

$$IC(x,p) \rightarrow T^{\mu\nu}(t_0,\vec{x})\,; \quad \partial T = 0 \quad ; \quad T(\Sigma_{f.o.}),u^{\mu}(\Sigma_{f.o.}) \rightarrow dN/dydp_T$$

We have to control both IC and FO to extract viscosity/s

ALICE: Technical proposal for a large ion collider experiment at the CERN LHC.
(CERN) , CERN-LHCC-95-71, CERN-LHCC-P-3, Dec 1995. 252pp.

1995 ALICE



1995 Predictions

similar to 2007 prediction !

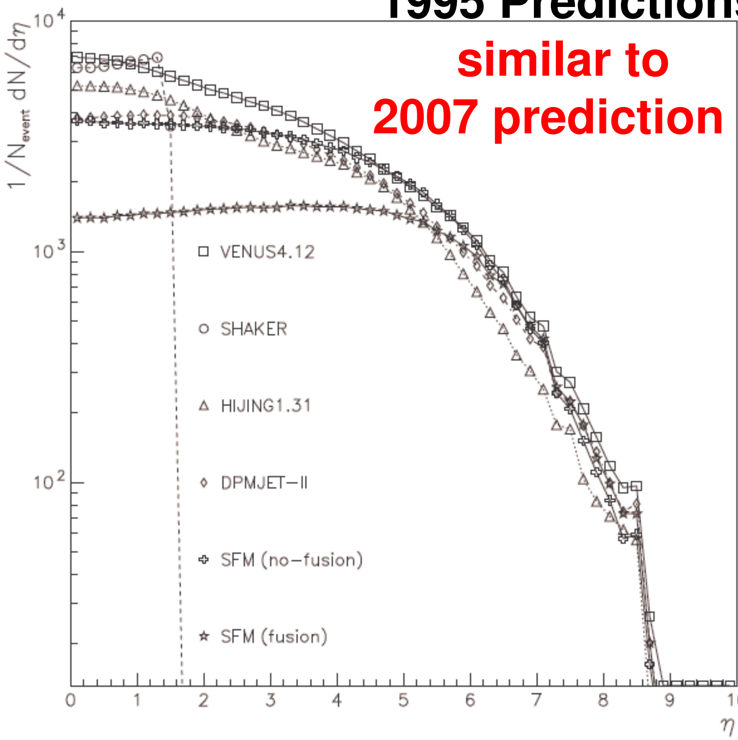


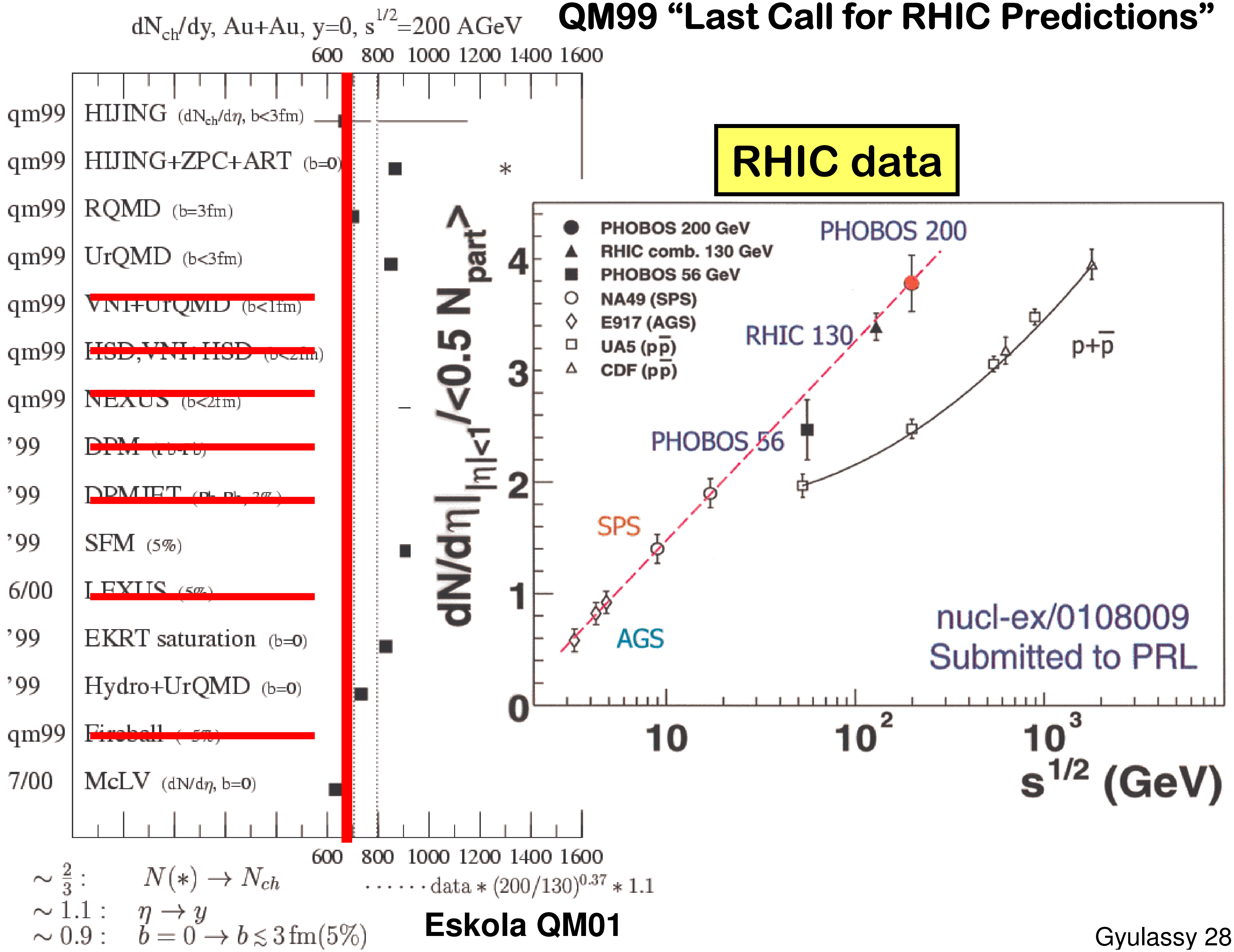
Figure 11.1: Charged particle multiplicities for central Pb–Pb events at a beam energy of 3 TeV per nucleon. The generators have been ordered by decreasing multiplicity at $\eta = 0$.

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS
J. Phys. G: Nucl. Part. Phys. **32** (2006) 1295–2040 doi:10.1088/0954-3899/32/10/001

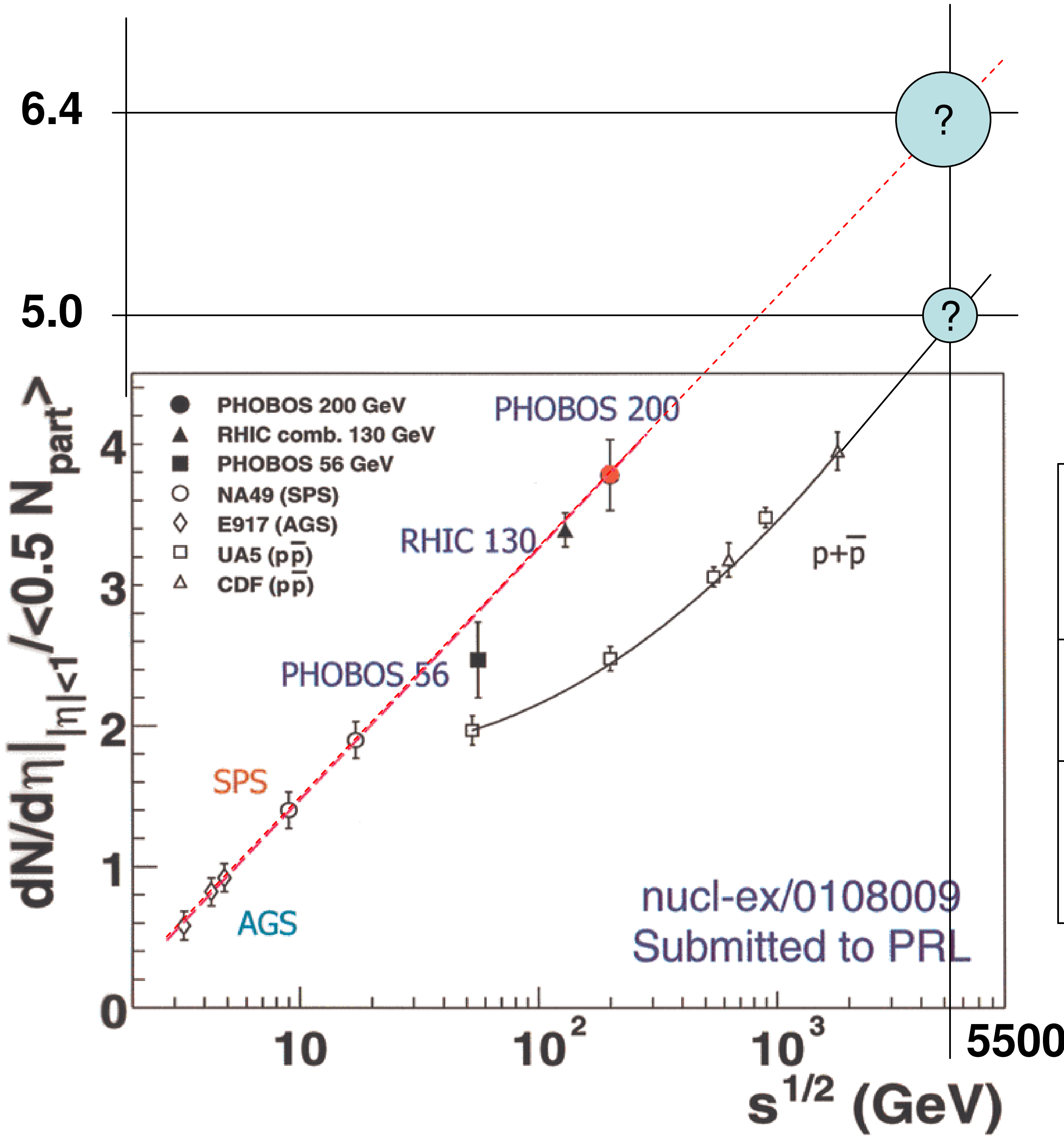
ALICE: Physics Performance Report, Volume II

2007 ALICE Today

QM99 “Last Call for RHIC Predictions”



Most Conservative PHOBOS LHC Extrapolation



Pb + Pb

$$\frac{dN_g}{dy}^{LHC} \sim 1700$$

$$s_{LHC} \sim 1.7\, s_{RHIC}$$

$$T_{LHC} \sim 1.2\, T_{RHIC}$$

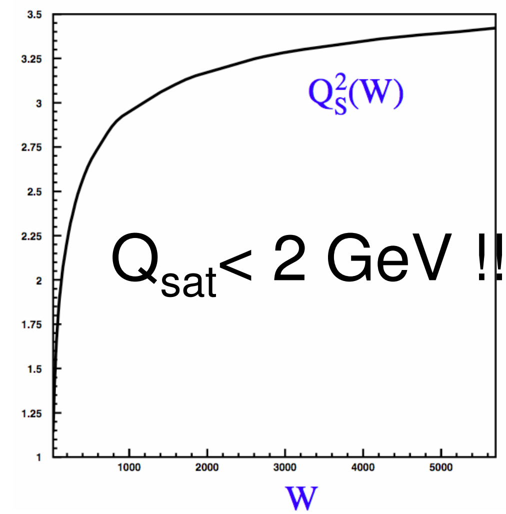
$\sqrt{s}$	$\frac{dN^{PbPb}}{208 \times dN^{pp}}$
200	**1.52**
5500	**1.28**

decrease ?

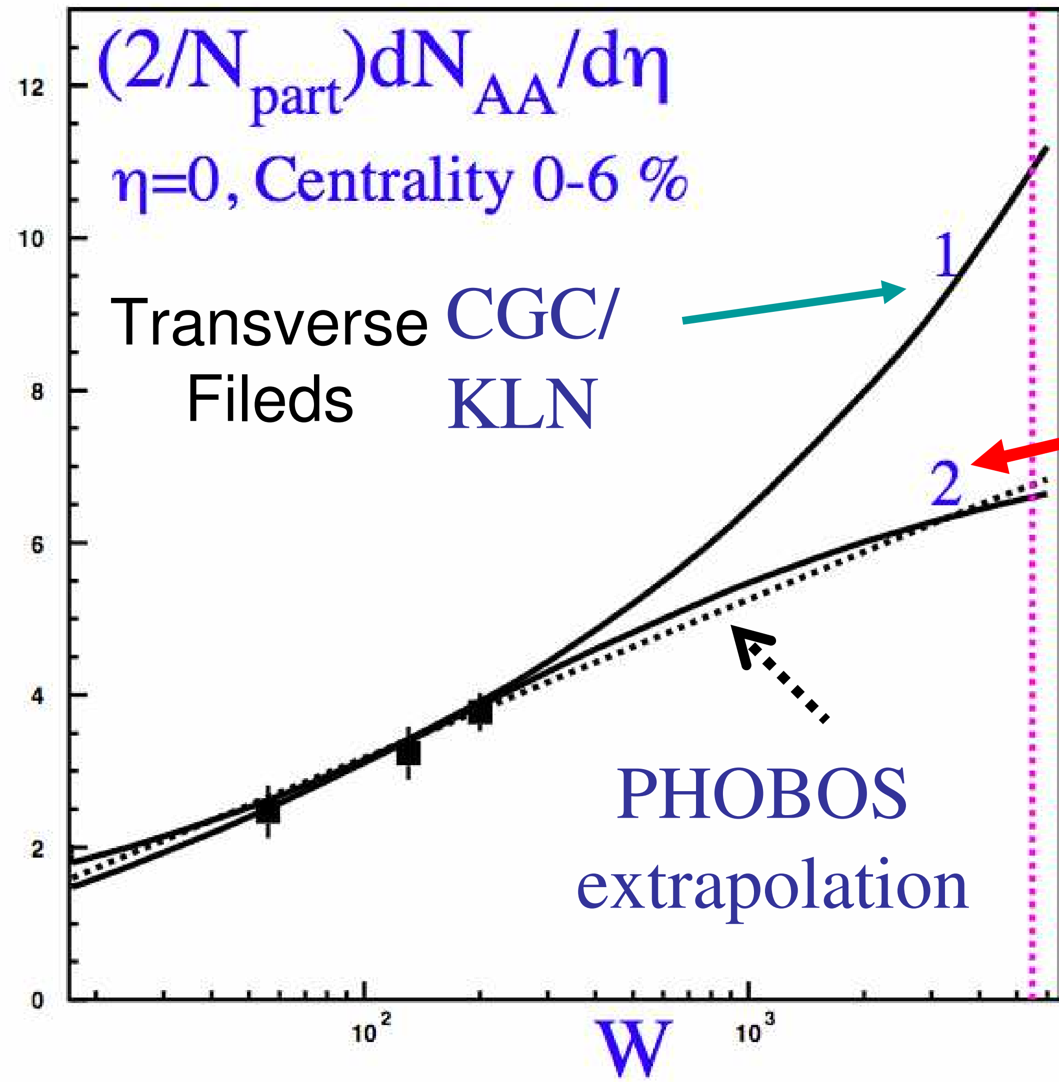
Kharzeev, Levin: Saturated Saturation

The Broken Color Glass?

(or the rediscovery of the LUND model)



Q_{sat}< 2 GeV !!



Transverse Fileds

CGC/ KLN

New Longitudinal field dominated CGC

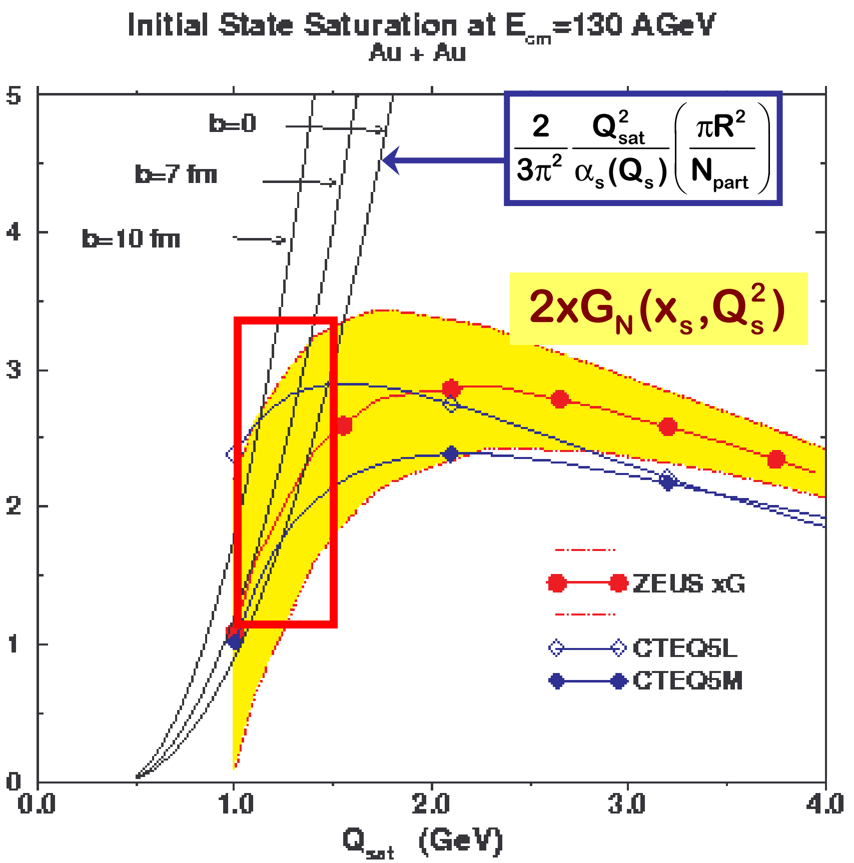
PHOBOS extrapolation

Kharzeev seminar CERN 5/14/07

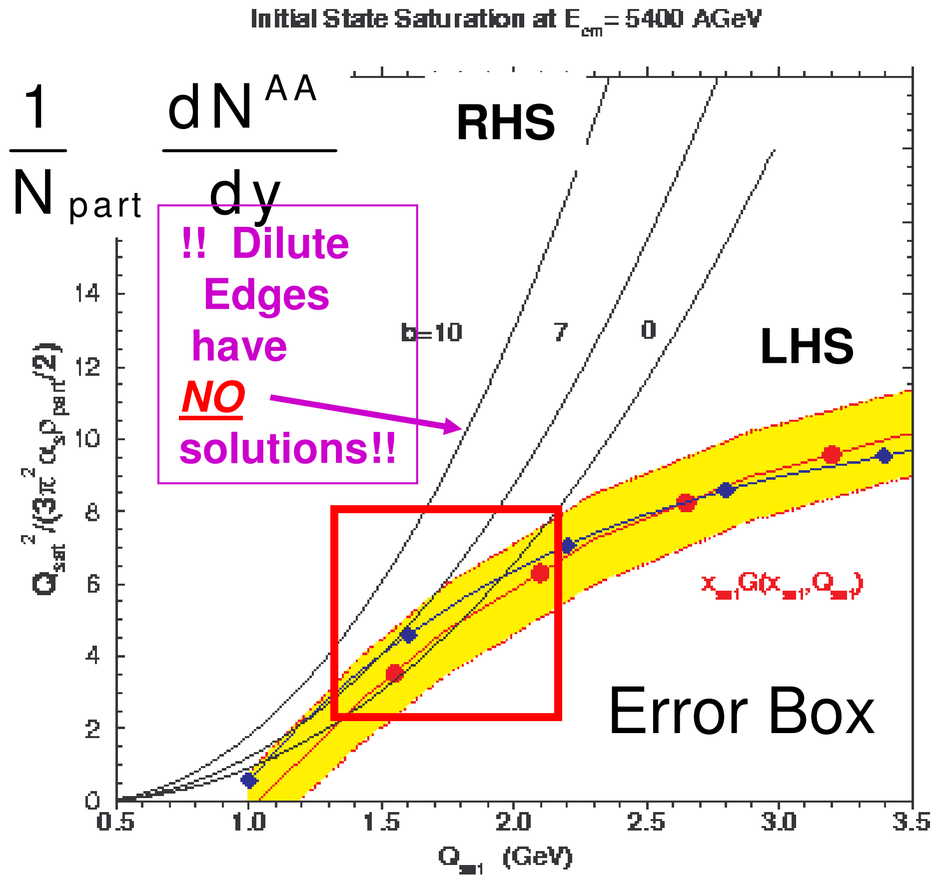
Initial State Saturation RHIC vs LHC

MGyulassy 02
unpublished

RHIC



LHC



$$2xG_A\left(x=\frac{2Q_{sat}}{\sqrt{s}},Q_{sat}^2\right)=\frac{2c}{3\pi^2}\frac{Q_{sat}^2 R^2}{\alpha_s(Q_s)}$$

$$2xG_p\left(x=\frac{2Q_{sat}}{\sqrt{s}},Q_{sat}^2\right)=\frac{2c}{3\pi^2}\frac{Q_{sat}^2}{\alpha_s(Q_s)}\left(\frac{\pi R^2}{N_{part}}\right)$$

$$Q_s \propto A^{1/6}s^{\lambda/4} \quad ,\lambda \approx 0.3$$

$$\frac{dN^{LHC}}{dy} \approx 800-3200$$

OK, our problem is that theoretically
The initial conditions at both RHIC and LHC
Are only understood to a factor ~ 2

And saturation models have large systematic uncertainties
In dilute regions of high b and/or interaction corona

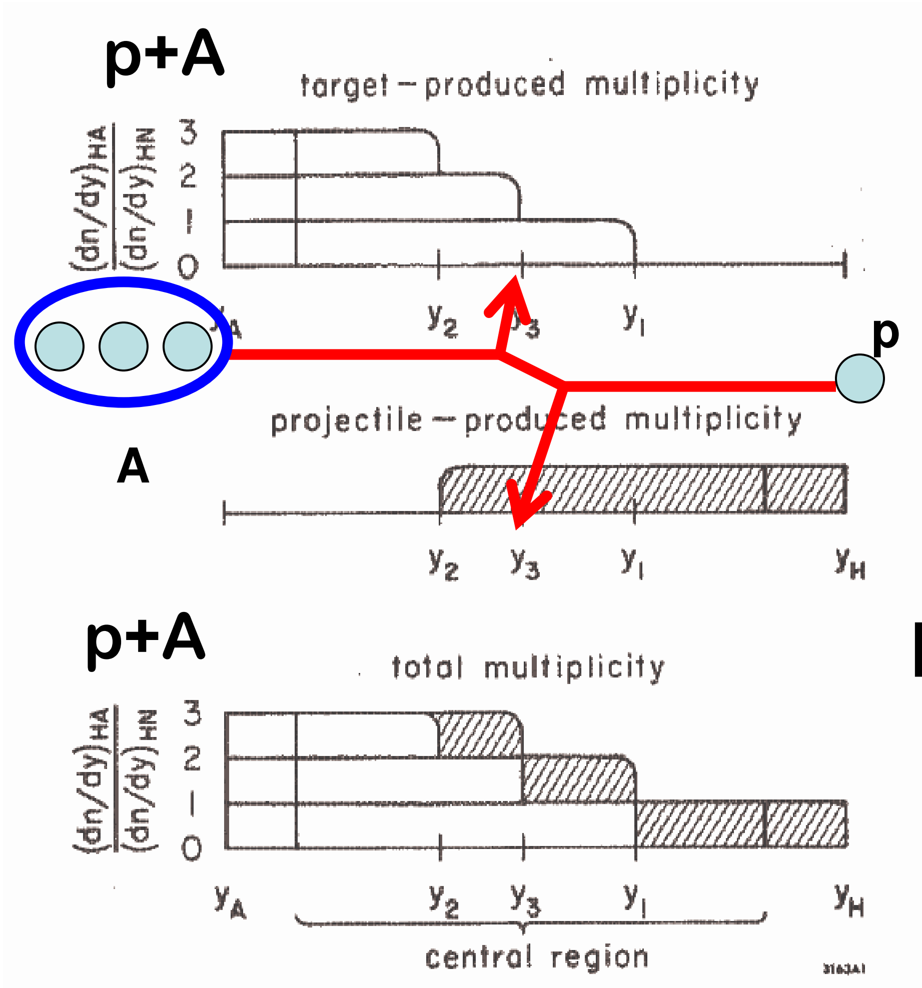
This is not good enough to resolve the perfection fluidity
Via $v_2(p_T,s,b)$ observables

We need independent experimental input
To help guide the theory

p+A at LHC please!

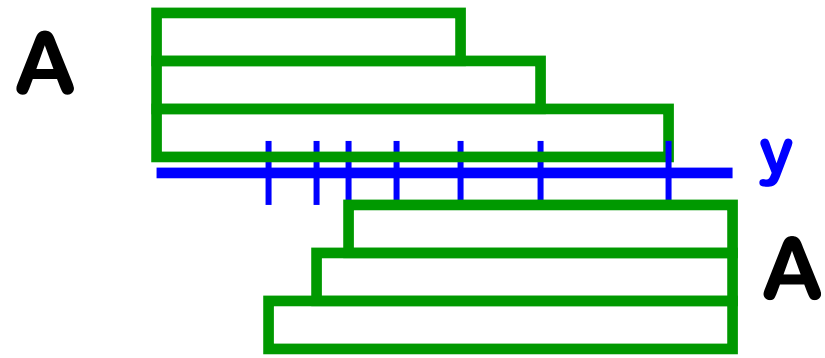
Brodsky, Gunion, Kuhn, PRL39(77)1120

Multi-string Extensions of pp to p+A to A+A



DPM: Capella et al

LUND: Anderson et al



Predicted "AA Trapezoid"

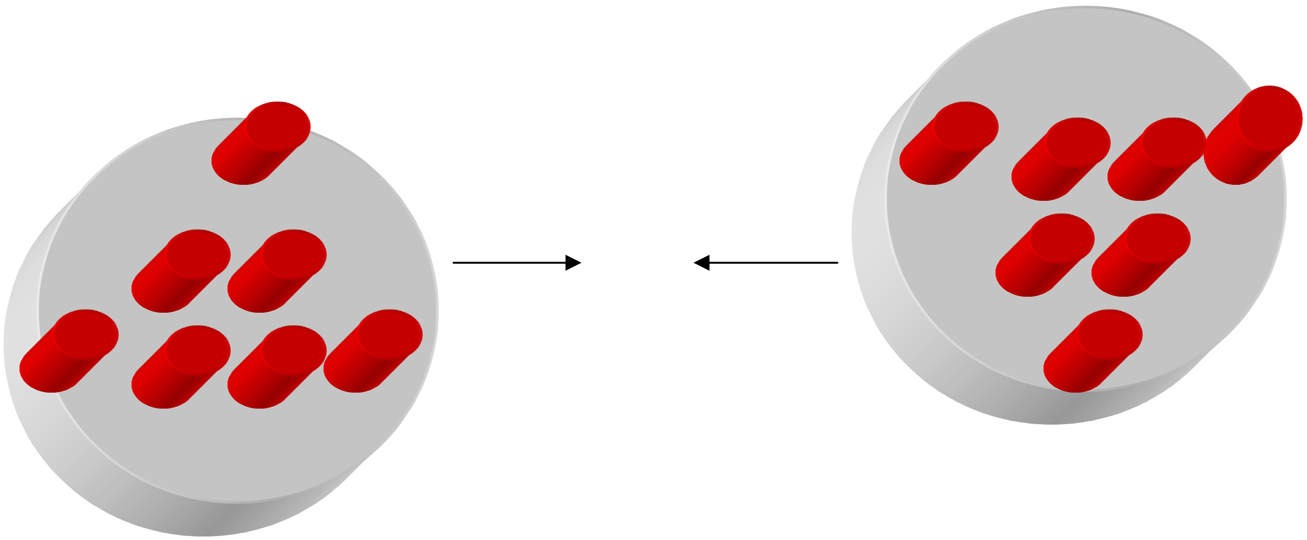
$$1 \leq \frac{dN_{AA}}{A \times dN_{pp}} \leq 2$$

$$A^{1/3} \geq \frac{dN_{pA}}{dN_{pp}} \geq 1$$

"pA Triangle" ←

Key Test and controls Initial Matter Geometry!

At finite impact parameter AA requires understanding pA and pp



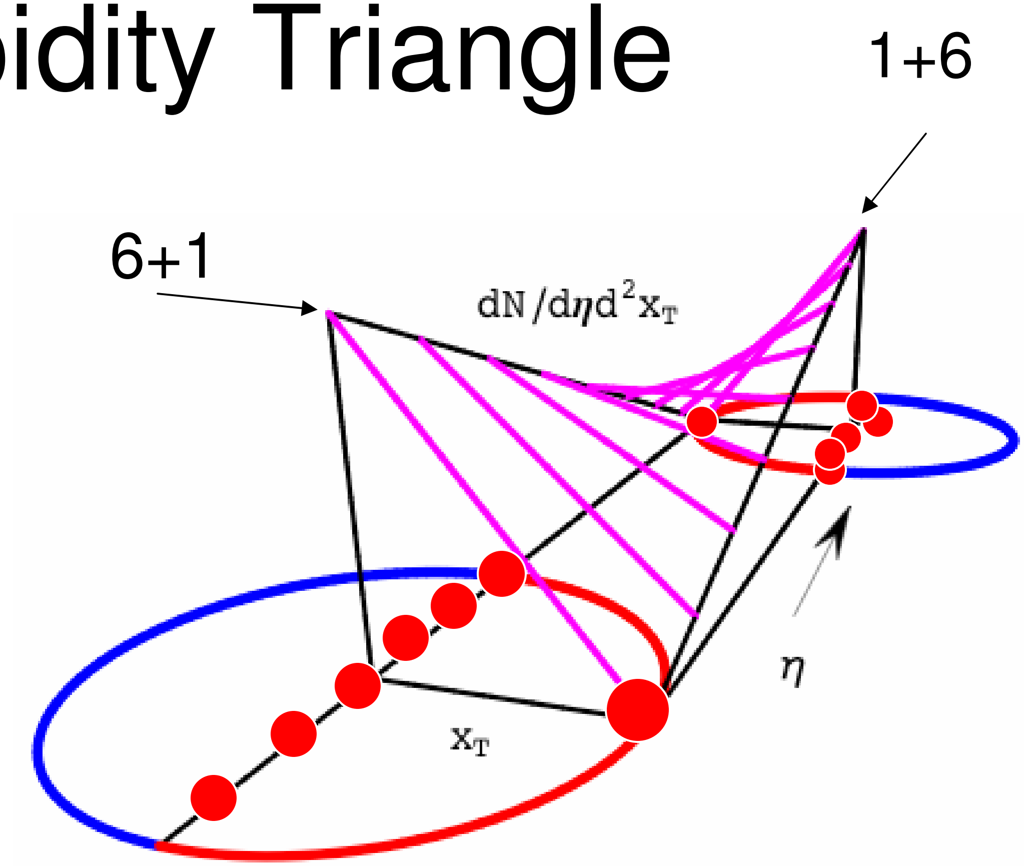
1on 4

2 on 2

4 on 1

The surface edges are controlled by equivalent p+A and intrinsically dilute physics. Need data to constrain Models of this.

Local Rapidity Triangle



- Rapidity dependent local participant density with BGK
- Note *globa*l multiplicity is boost invariant for A = B but the local density is NOT!

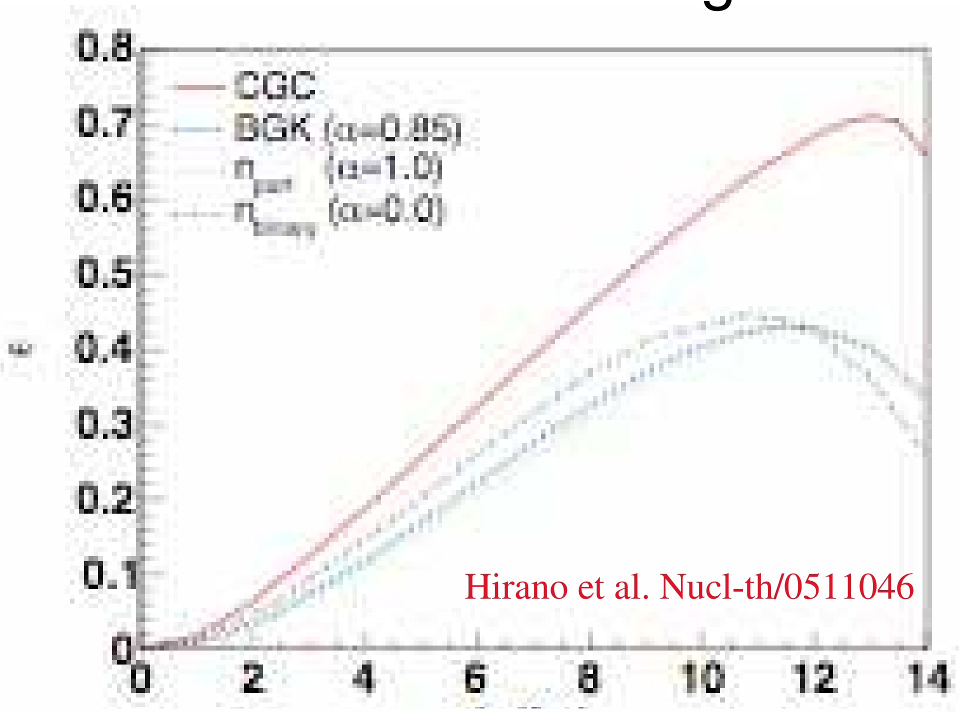
$$\rho_{Part}(\vec{x}_\perp) \propto e^{-\frac{y^2}{\sigma_y^2}} \left(\rho^{a}_{Part} \left(1 + \frac{y}{Y}\right) + \rho^{B}_{Part} \left(1 - \frac{y}{Y}\right) \right)$$

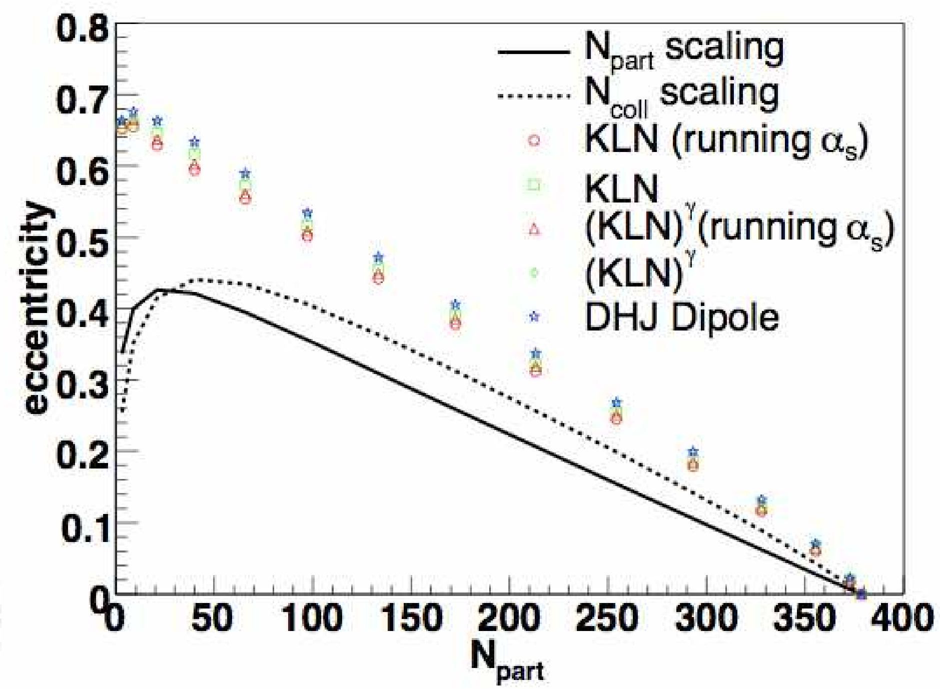
Leads to rapidity triangular edges where local physics is like p+A

A.Adil, MG (06)

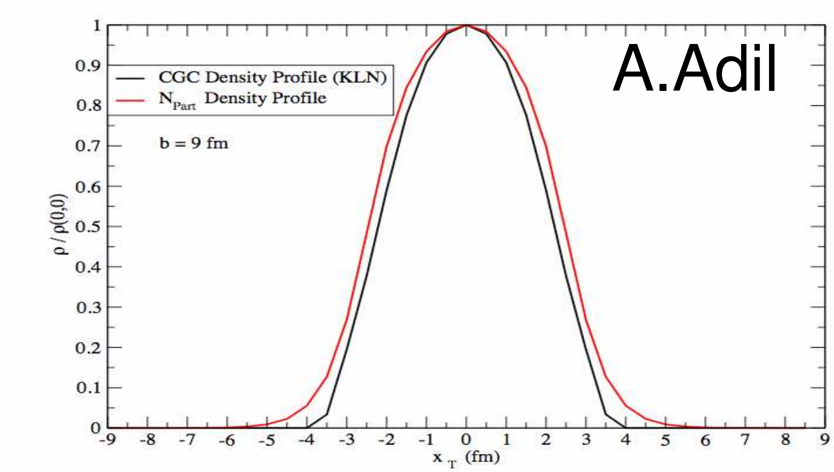
CGC has sharper edges than Glauber

Leads to higher transverse space eccentricity





H.Drescher et al



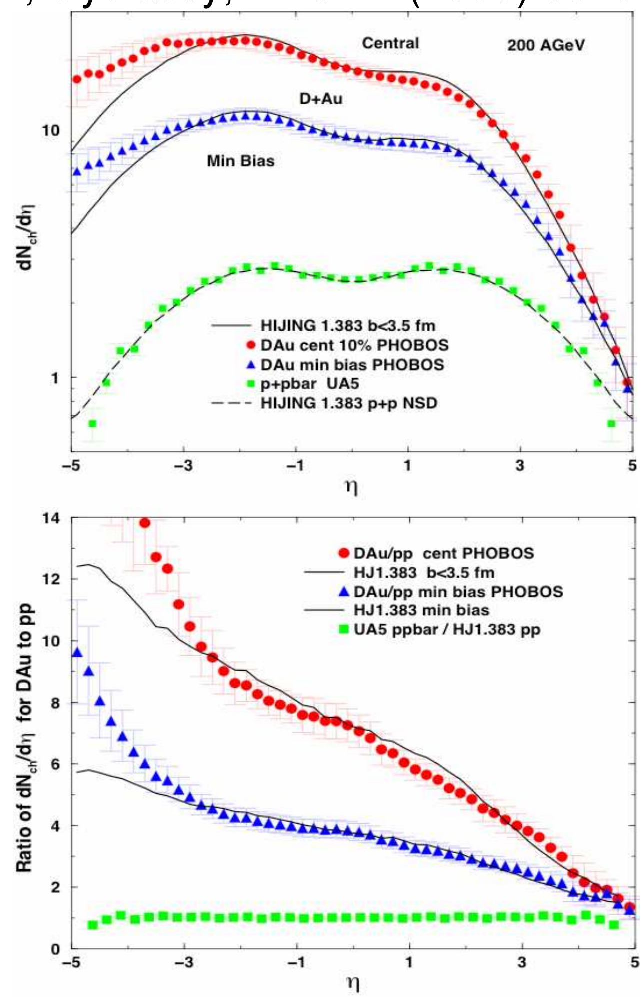
More eccentric CGC leads to too Higher elliptic anisotropic flow!

and thus

Requires viscosity to compensate

Critical Consistency test for Glauber p+A geometry

Adil, Gyulassy, PRC 72 (2005) 034907



- Monte Carlo HIJING based on Glauber geometry works well
- D+A at RHIC shows the expected rapidity triangle quantitatively.

With CGC/KLN pp and pA parameters have to be tuned independently of AA to reproduce these data !!

(Use also high pT Tomography to further Differentiate Adil et al,Phys. Rev. D 73 (2006) 074006)

My conclusion part III:

Current CGC/KNL model overpredicts eccentricity
And therefore elliptic flow because it incorrectly extrapolates
Central AA to the p+A and p+p edges of the reaction
Transverse plane.

Key experiment at LHC to test different models
of geometries will be the p+Pb “rapidity triangle”
and its dependence on the pT

I predict that the correct answer will interpolate between
CGC-like geom for Q_{sat} >1 GeV and Glauber like for Q_{sat} < 1 GeV

The im?Perfection of the sQGP fluid at LHC will only be
quantified once the initial geometry is fixed by
independent observables in pp and pPb