# EXPERIMENTAL OVERVIEW OF SATURATION AT RHIC

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**Emerging Spin and Transverse Momentum Effects in p+p and p+A Collisions**
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Brookhaven National Laboratory

Much of this material is taken from Albacete and Marquet arXiv:1401.4861 (2014)

# Saturation

- Saturation, or something like it has to true
- The question is not whether saturation is right, but whether we are in the saturation regime at RHIC
  - *A second question: what model is correct? Is the CGC the right model?*
  - *Do other explanations work? e.g. twist-3. Are they just the same thing in a different language or realm of applicability?*
- Saturation (e.g. the CGC) comes is a variety of guises: Recombination, the MV model, ..
  - *Leads to various modeling tools, e.g. KLN, MC-KLN,rcBK, MC-rcBK, IP-Glasma*
    - Which for example, treat the nucleus as a solid sphere, as a WoodsSaxon, sample it to add fluctuations
    - Need to take errors (or just the results from the spread in models/model parameters) seriously
- Must look at all the evidence, and collect data on a variety of observables
  - *The right model must explain many signatures; free parameters should be consistent*

"Preponderance of evidence"

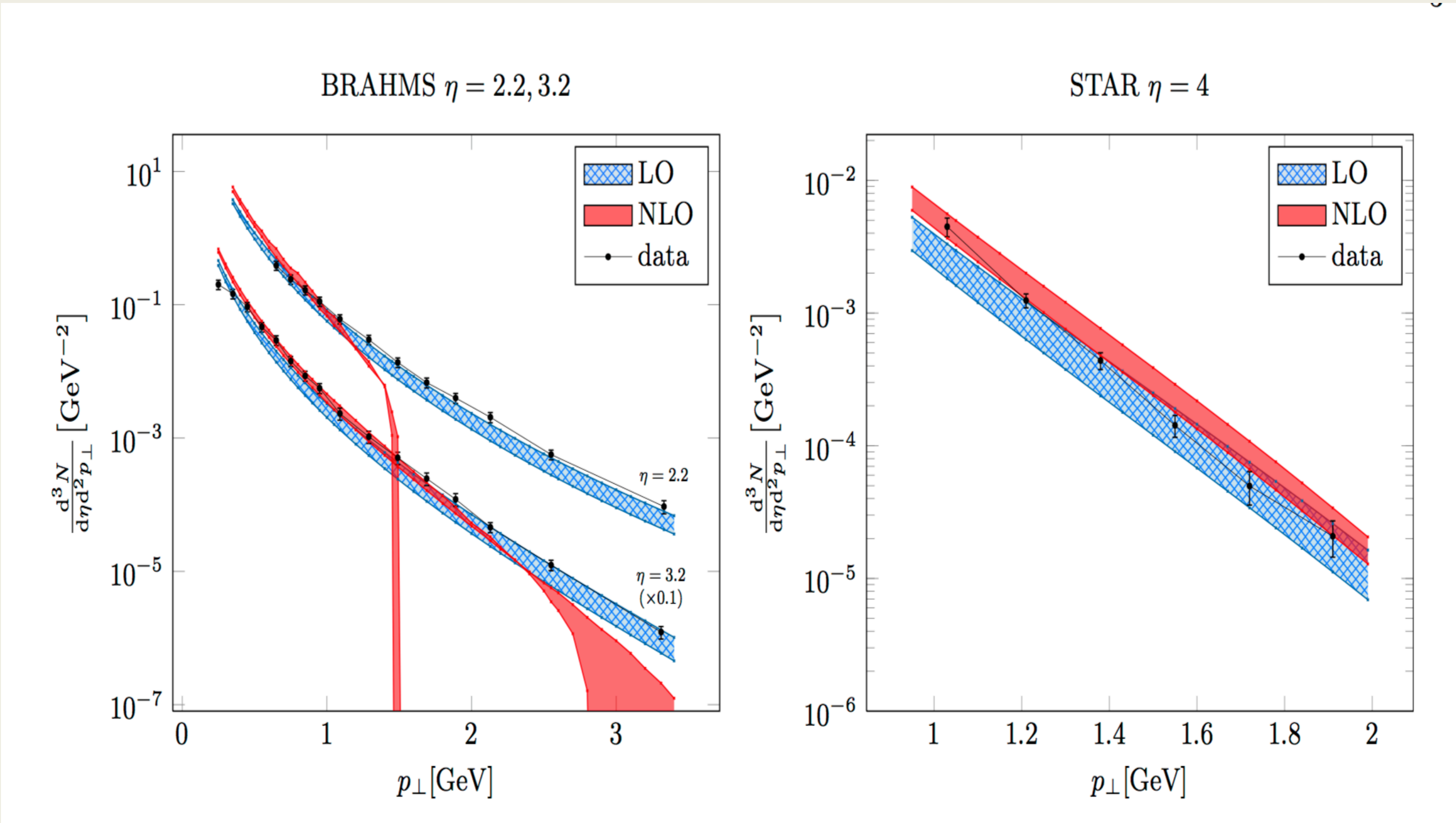
Note: the heavy ion community needs to know the answer to this questions

# Are we in the saturation regime? The "Tests"

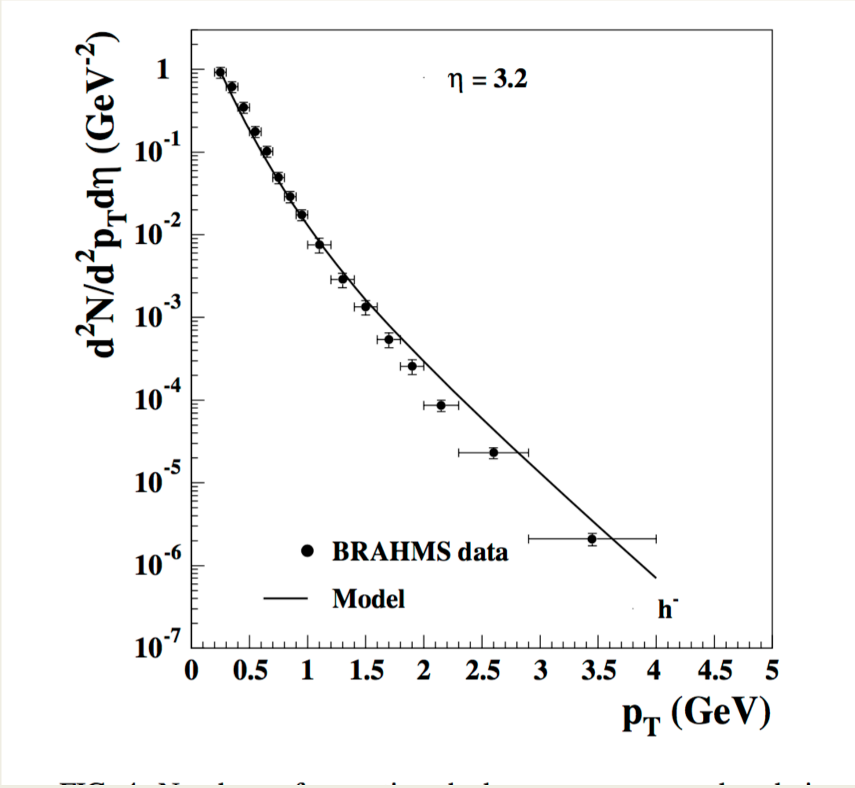
- dAu at forward rapidity
  - *Singles spectrum*
  - *$R_{dAu}$ – suppression in Cold Nuclear Matter?*
  - *Back to back particle distributions*
    - vs $x_{frag}$
  - *Multiplicities*
    - vs centrality (Au+Au)
    - vs rapidity
  - *SSA in pA*
- dAu/AA- include evolution of the "QGP"
  - *Flow*
    - Au+Au, v1-v5
    - p+Au, d+Au, He3+Au, v2 and v3

| signature | Yes/No |
| --- | --- |
| Singles | |
| RdAu | |
| Back to back | |
| Back to back vs "x" | |
| SSA in p+A | |
| Multiplicity vs centrality AA | |
| Multiplicity rapidity dAu | |
| Flow in AuAu | |
| Flow in dAu, v2 and v3 | |

# Singles distributions, LO and NLO



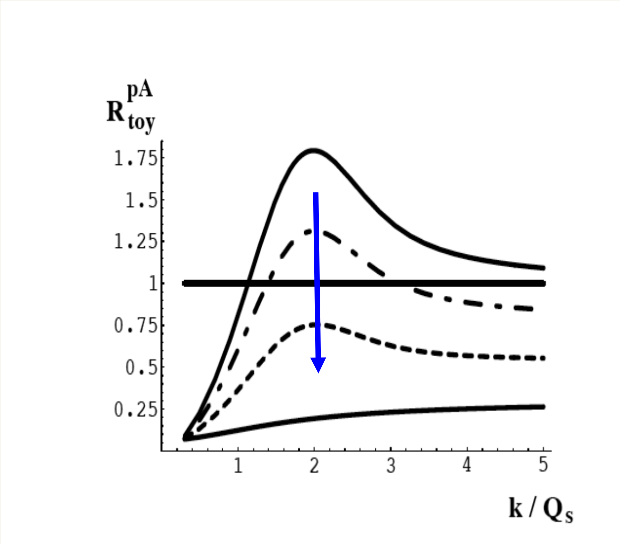

Stasto, Xiao, Zaslavsky, ArXiv:1307.4057(2013)

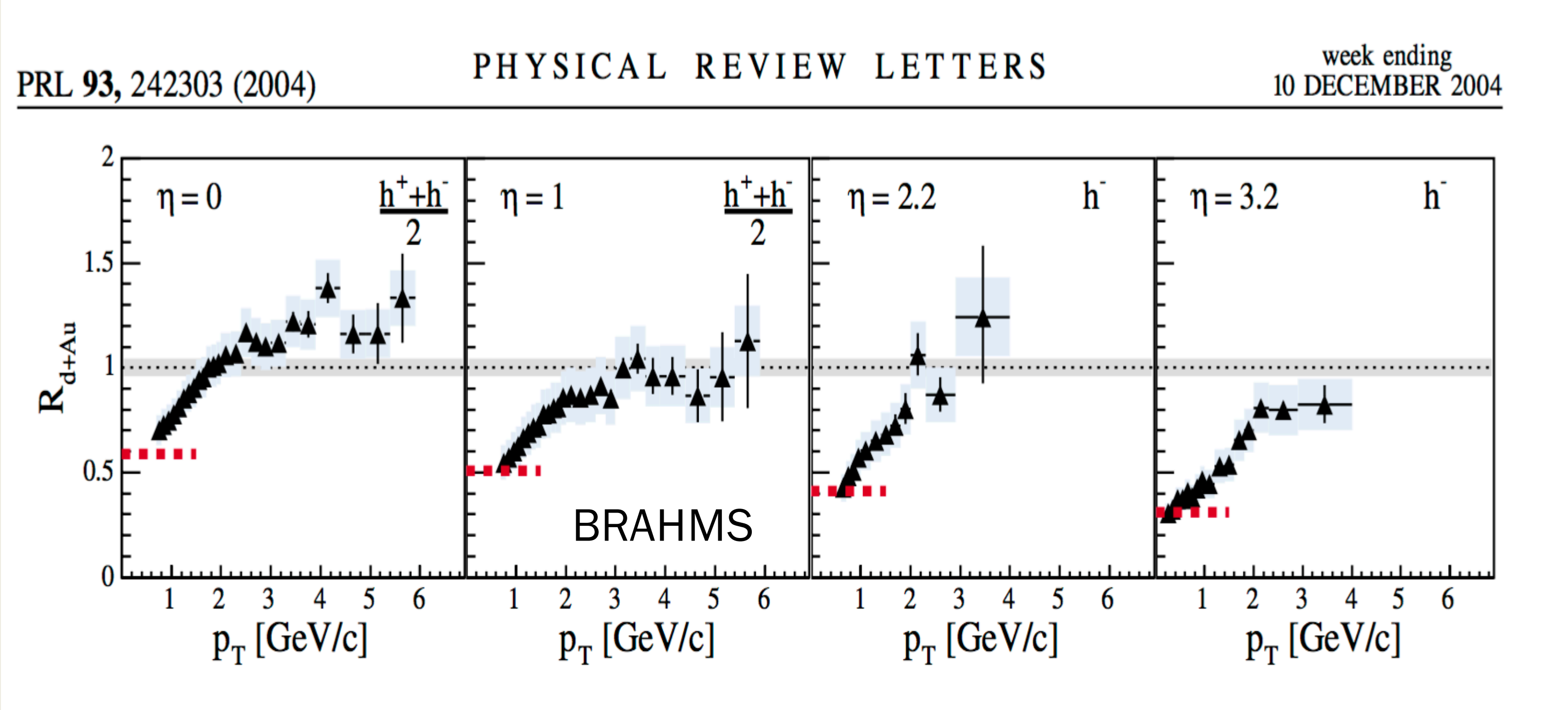



Non-CGC
Kopeliovich et al, PRC 72, 054606(2005)

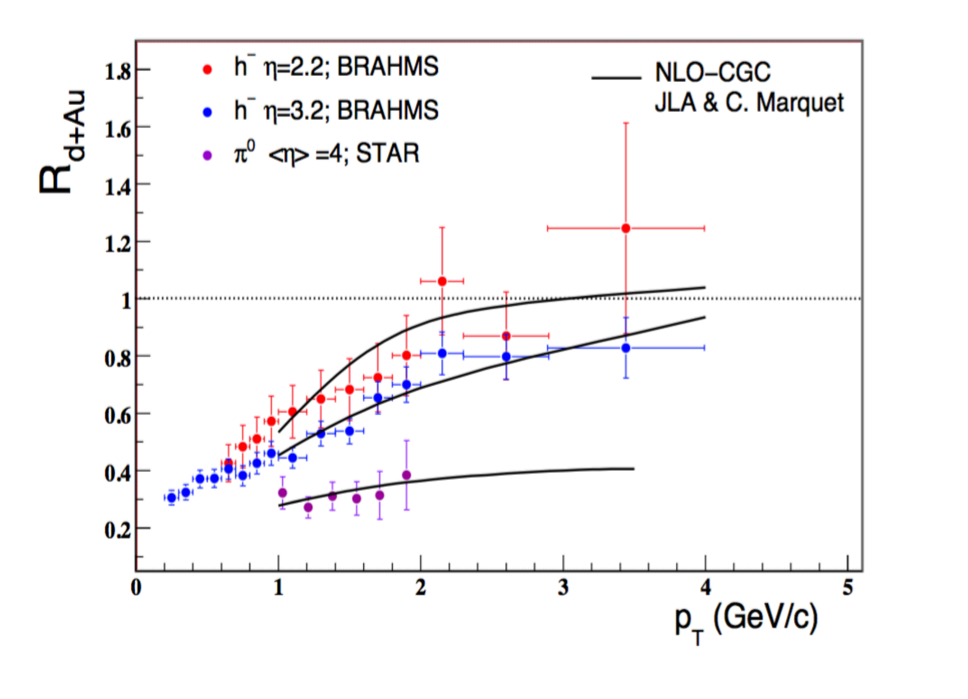
# CNM and Nuclear modification factors at forward rapidity

At central rapidity RdAu=1

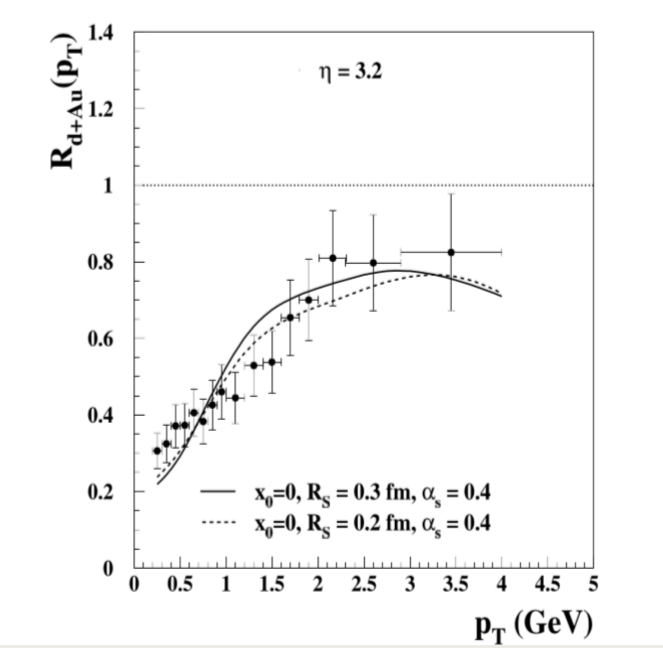


# Nuclear Modification Factor Comparison to Models

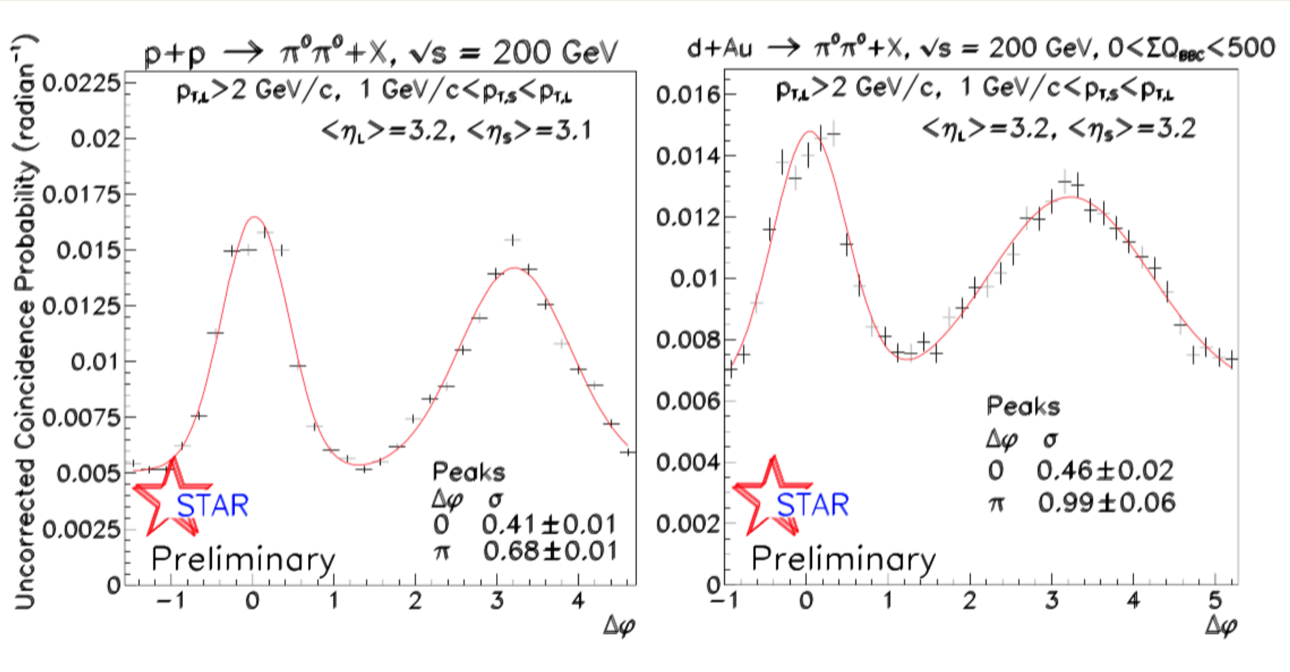


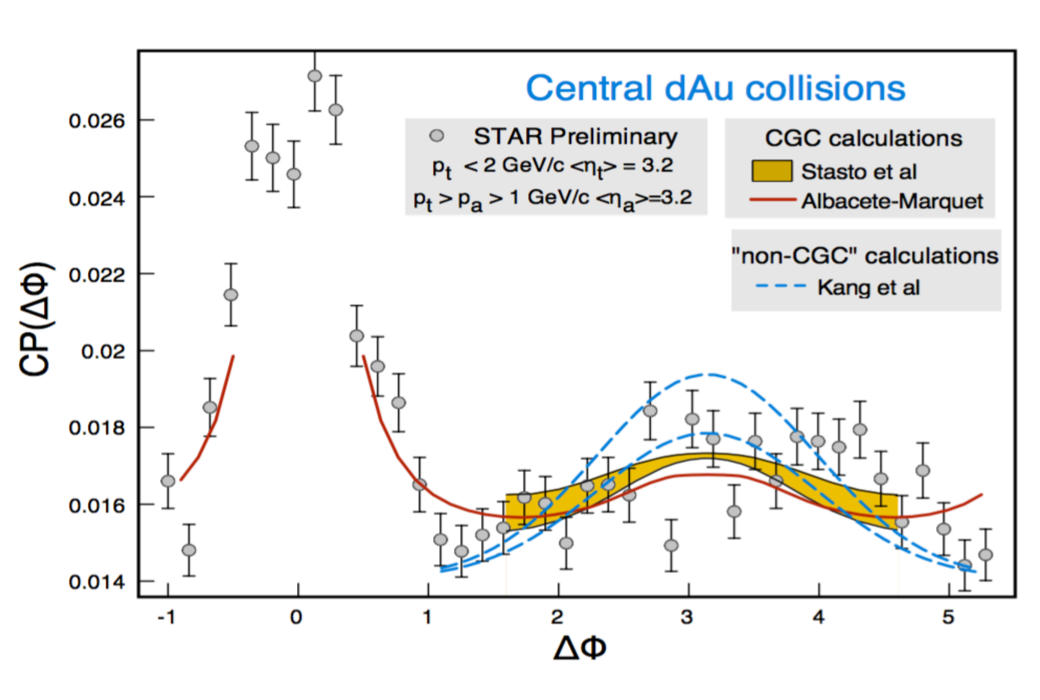

NLO CGC




Non-CGC
Kopeliovich et al, PRC 72, 054606 (2005)
Energy conservation

# Back to Back Hadrons



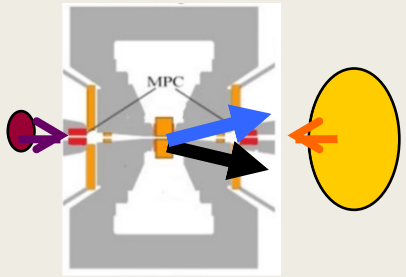

Data: Braidot (arXiv:1008.3989)

Albacete, Marquet: PRL 105,162301(2010)
Stasto et al: Ariv:1109.1817 (2012)

Non–CGC; Kang: initial and final state multiple scattering , energy loss arXiv:1112.6021(2011)

# Back to back pairs: dAu/pp

Getting to low-x:
Require 2 back to back
Forward particles in MPC



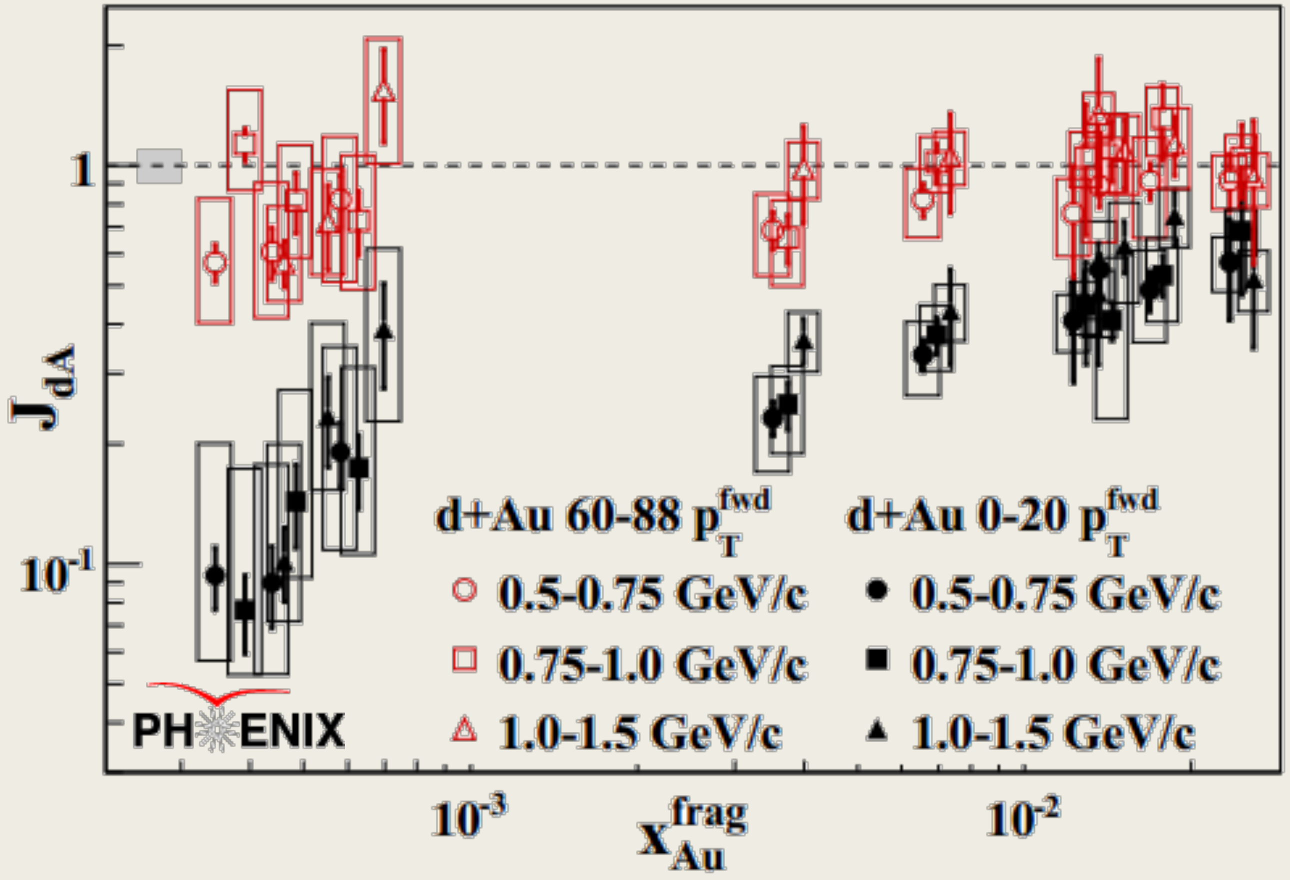

$J_{dA} = I_{dA}\, R_{dA} : \dfrac{xG_{Au}(x,Q^2)}{AxG_p(x,Q^2)}$

$I_{dA}$=Ratio of Conditional Yields

$$x_{Au}^{frag} = \frac{p_{T1}e^{-\eta_1} + p_{T2}e^{-\eta_2}}{\sqrt{s_{NN}}}$$

Forward+Forward

Forward+Mid




PRL 107, 172301 (2011)

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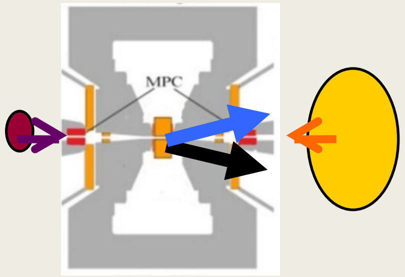


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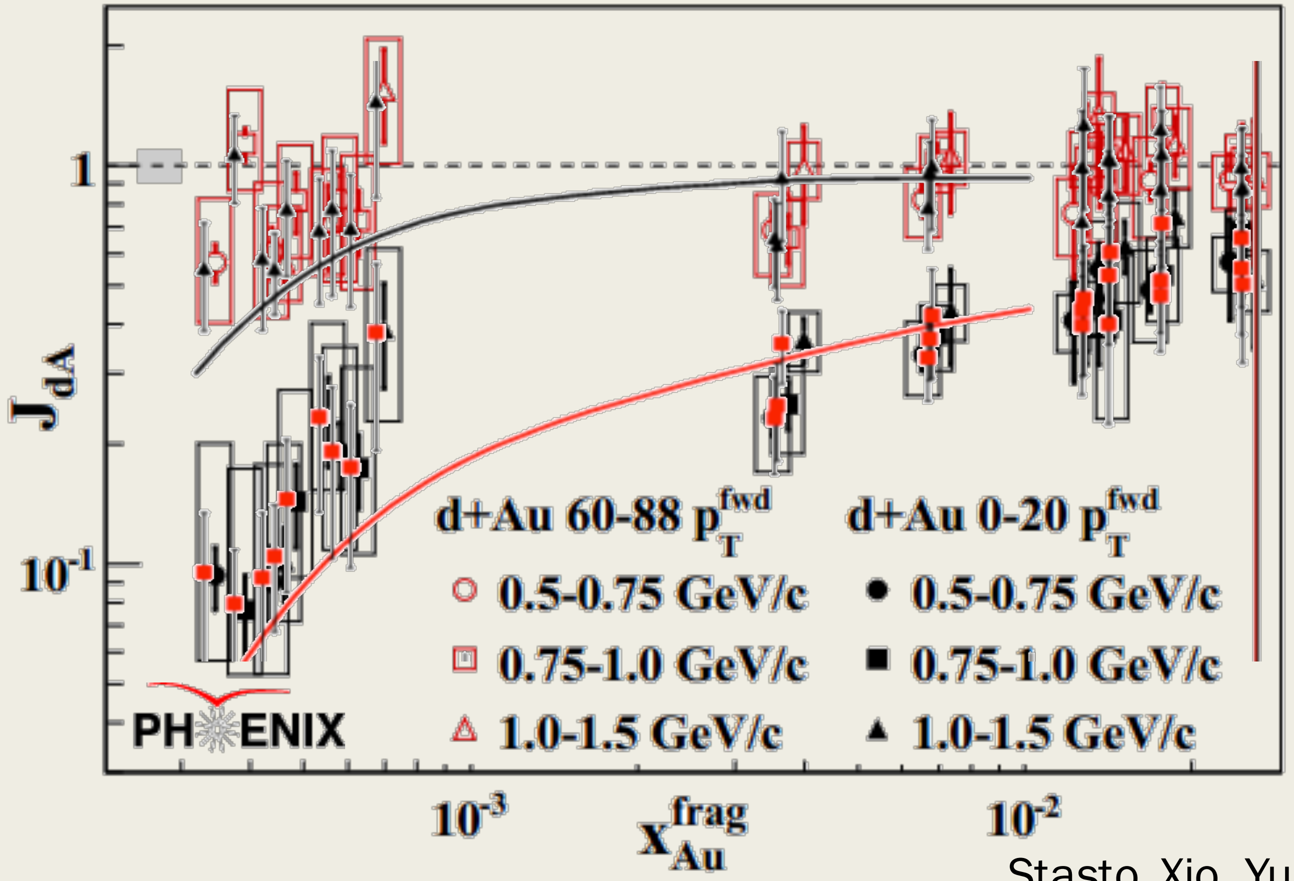
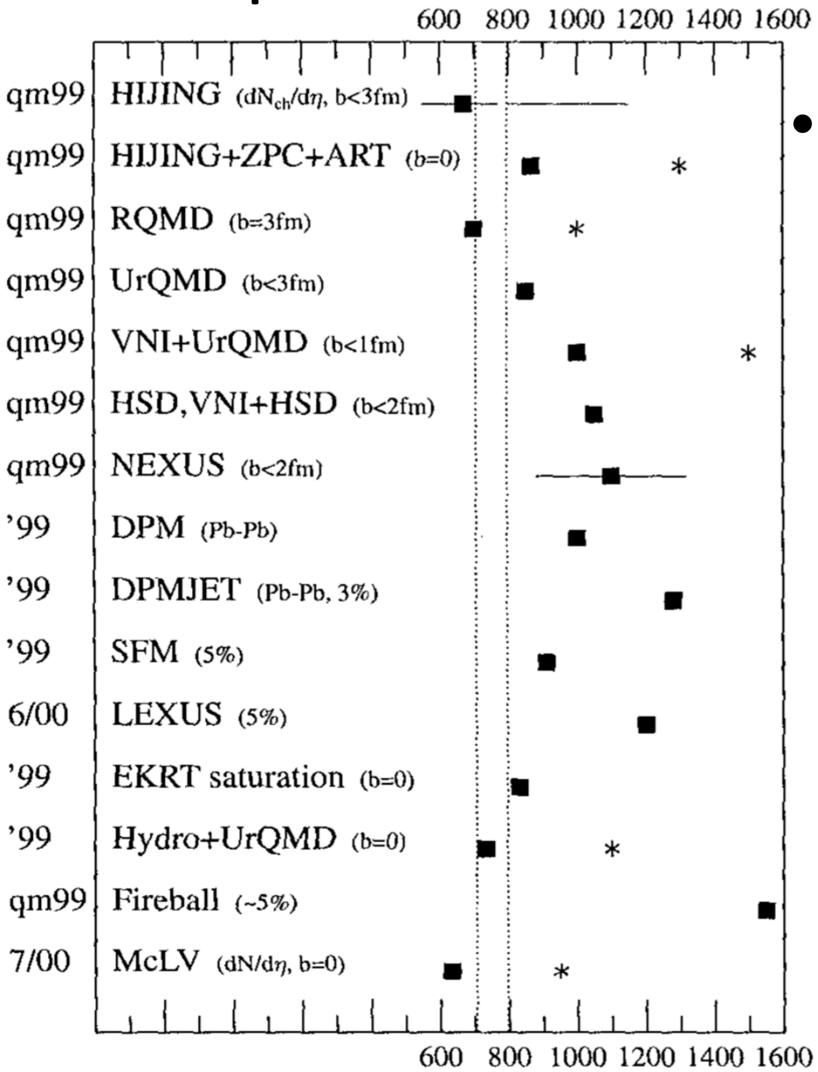



PRL 107, 172301 (2011)

Stasto, Xio, Yuan
arXiv:1109.1817

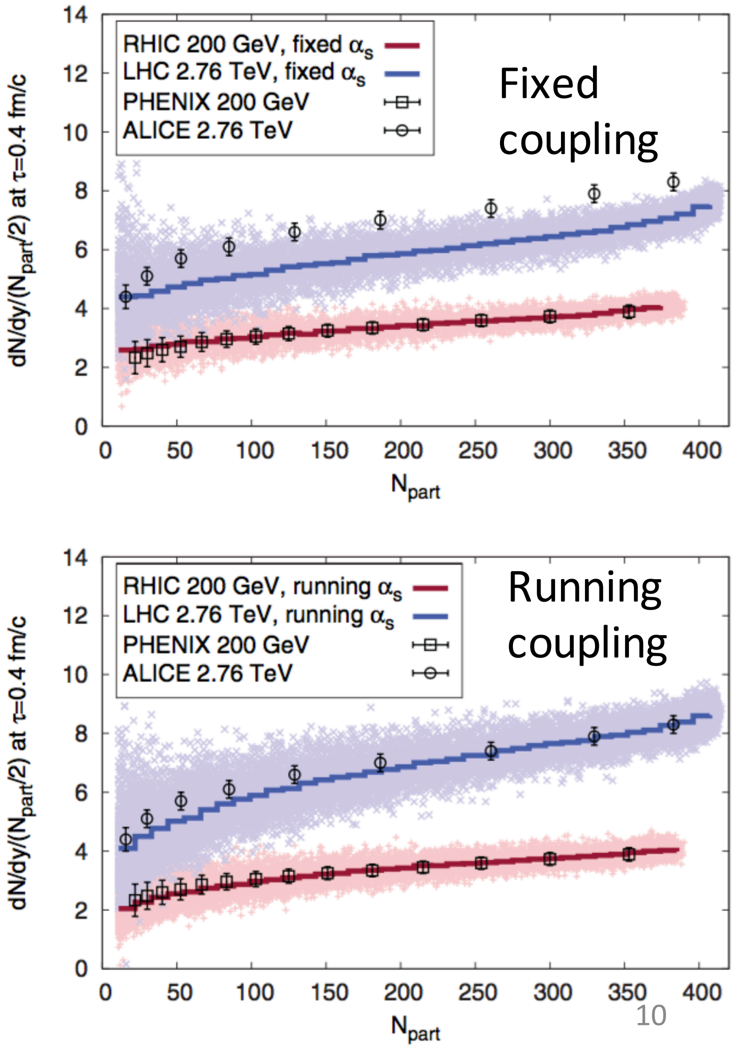
# Multiplicities AA




PHOBOS early result

- Au+Au
  - First multiplicity results
    - On low end
    - Prejudice: QGP would produce high multiplicity
  - Saturation naturally provides solution
    - Bulk of particles come from $x<10^{-2}$

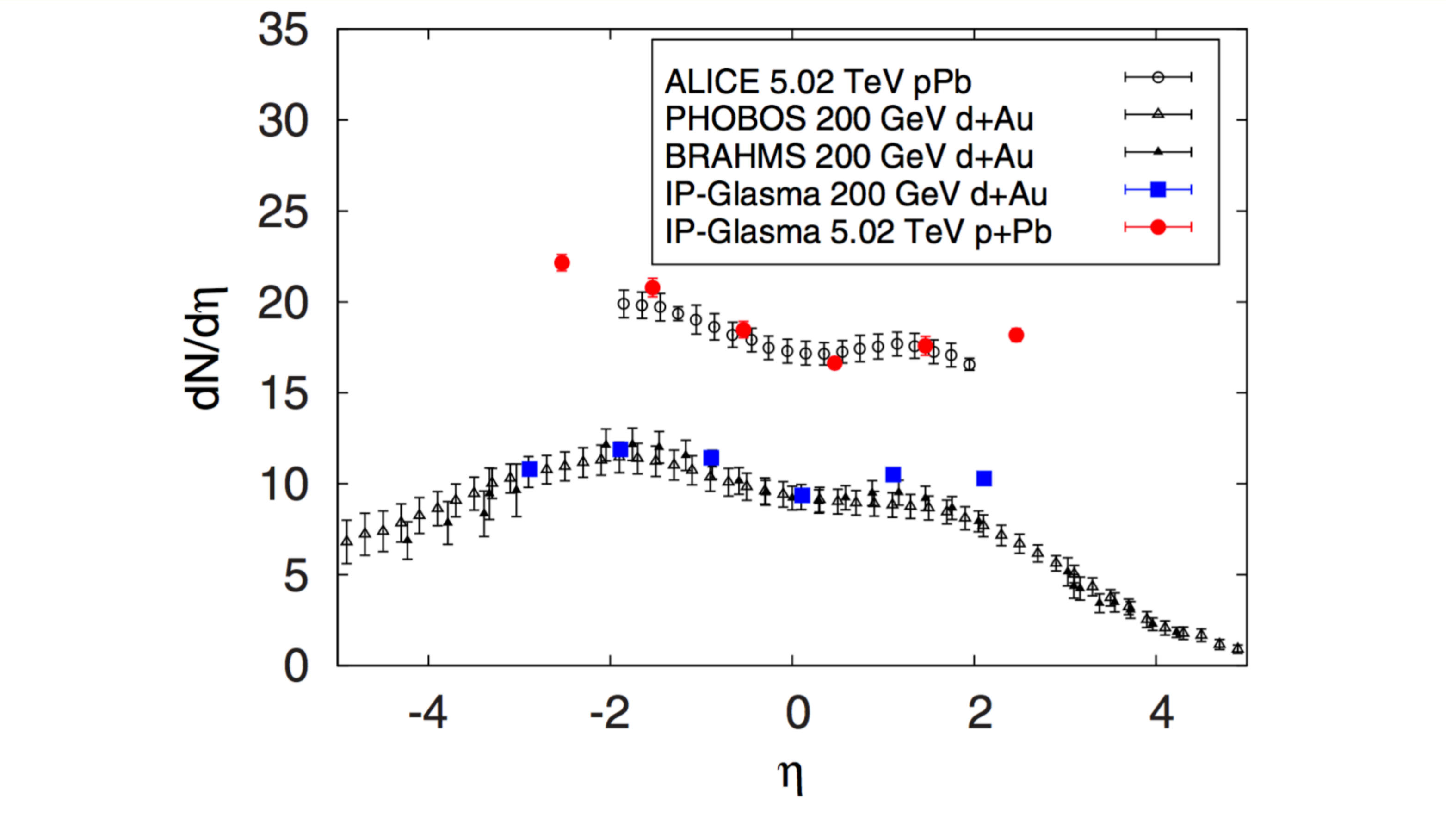
$$\frac{dN_{gluon}}{dy}*2/3 \sim \frac{dN_{charged}}{dy}$$




NLO calculation

Schenke, Tibedy, Venugopalan
PRC 86 034908 (2012)

# d+Au rapidity dependence




Data:PHOBOS, BRAHMS

NLO calculation
Schenke, Tibedy, Venugopalan
PRC 86 034908 (2012)

# Spin Dependent Cross section in pA

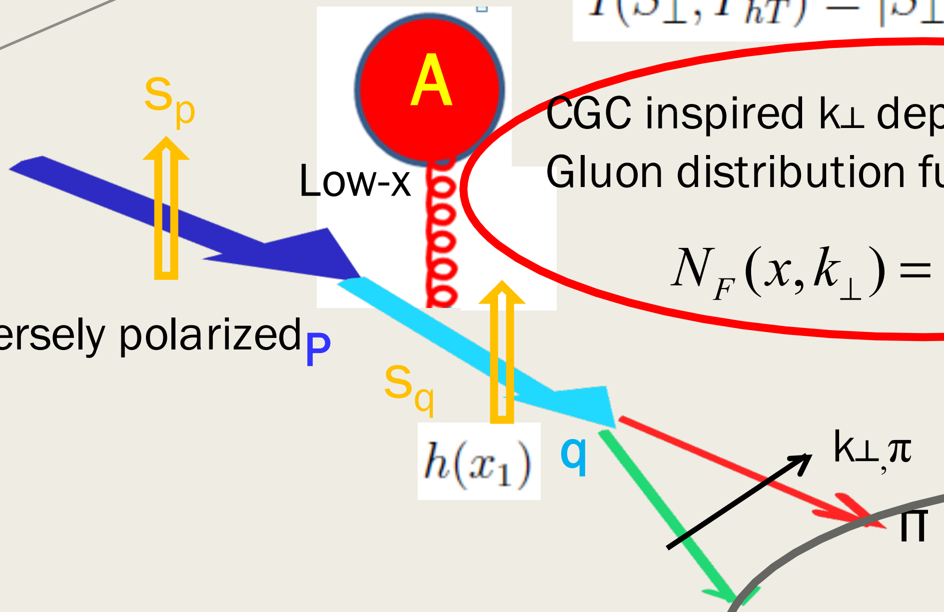
Kang, Yuan: PRD 84, 034019 (2011)

$$\frac{d\Delta\sigma}{dy_h d^2P_{h\perp}} = \frac{K}{(2\pi)^2}\int_{x_F}^{1}\frac{dz}{z^2}\int d^2P_{hT} I(S_\perp, P_{hT}) x_1 h(x_1) N_F(x_2, k_\perp)\delta\hat{q}(z, P_{hT})$$

$$\mathbf{P}_{h\perp} \approx z\mathbf{k}_\perp + \mathbf{P}_{hT}$$

$$I(S_\perp, P_{hT}) = |S_\perp||P_{hT}|\sin(\phi_h - \phi_s)$$

Relative to Quark jet




Transversely polarized proton P

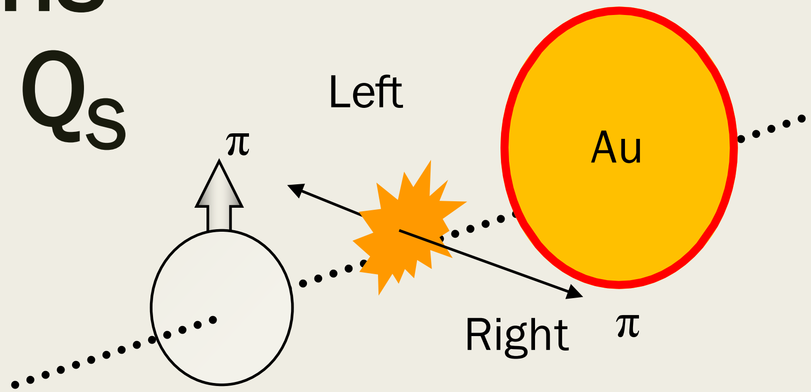
CGC inspired k⊥ dependent unintegrated Gluon distribution function

$$N_F(x, k_\perp) = \frac{1}{Q_S^2} e^{-k_\perp^2/Q_S^2}$$

Collins Fragmentation Function

$$\delta\hat{q}(z, p_\perp^2) \sim \frac{1}{(\Delta^2 - \delta^2)^{3/2}} e^{-p_\perp^2/(\Delta^2-\delta^2)}$$

# *Polarized* p+A Collisions as a measurement of $Q_S$

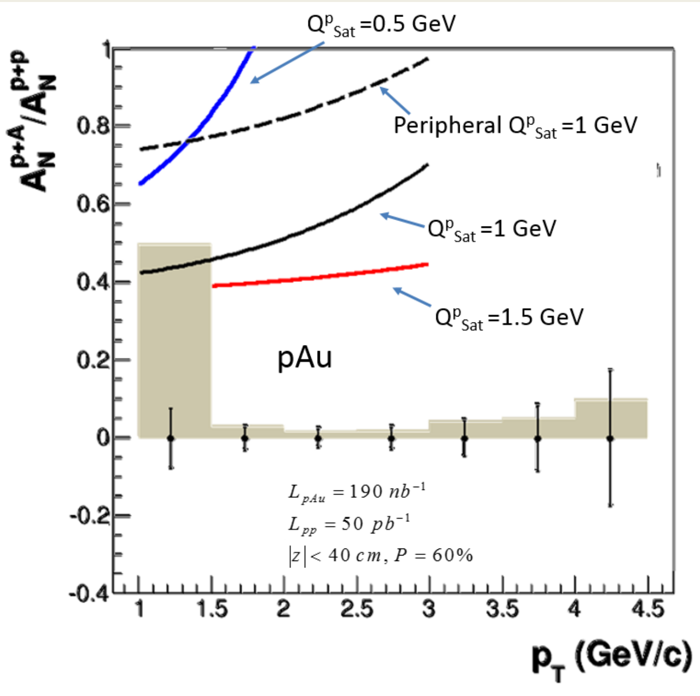



$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 << Q_{sA}^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{P_{h\perp}^2 \delta^2 / Q_{sp}^2}$$

$$Q_{sat,A}^2 = cA^{1/3} Q_{sat,proton}$$

Kang, Yuan: PRD 84, 034019 (2011)

This is one mechanism. Others:
e.g. Sivers: see Boer et al. PRD 74, 074018
Kang-Xiao arXiv 1212.4309
Odderon (3 gluon)exchange: Kovchegov arXiv:1201.5890
And some who expect no suppression




- Expect suppression
- ➢ *Find $Q_S$*

# STAR – $A_N$ in p+Au; $\pi^0$s in the FMS (2.5>η>4)

- On first glance very little suppression
  - *Grey band is systematic error from BBC (on Au going side) – (take it seriously)*
- Observation in pp that the $A_N$ is largest for isolated $\pi^0$ true in pA
- PHENIX should have similar results from the MPC-EX (3>η>4)

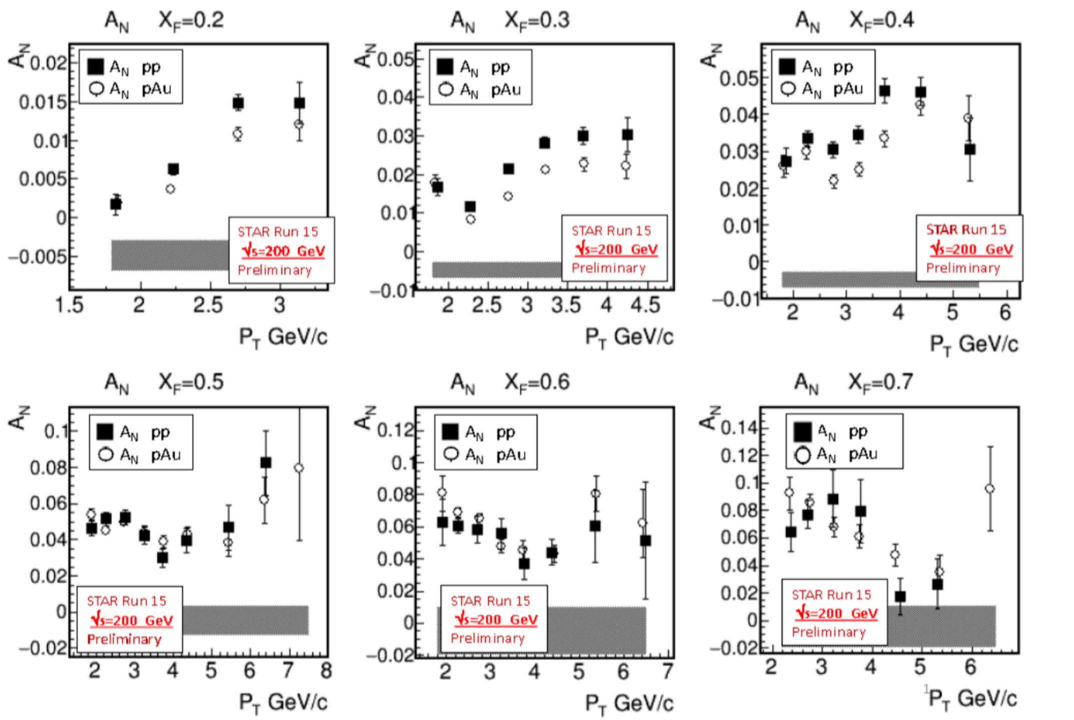
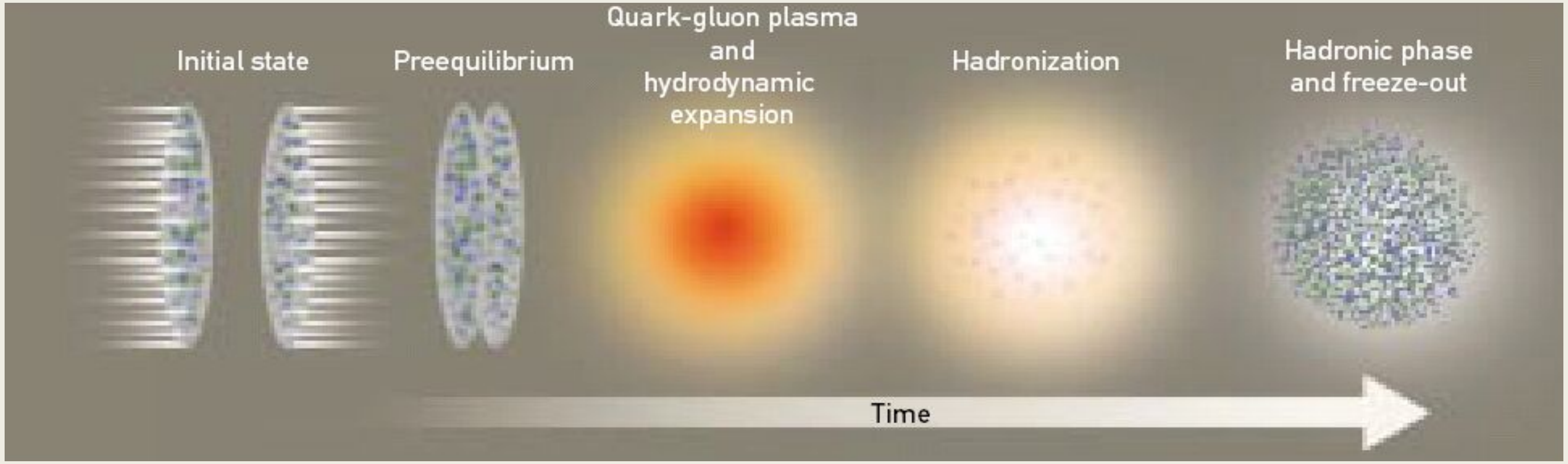



Figure 1-10: $A_N$ for $\pi^0$-mesons measured in the rapidity range $2.5 < \eta < 4.0$ as function of $p_T$ and Feynman-x ($x_F = x_1 - x_2$) for transversely polarized p+p and p+Au collisions measured by STAR. Similar results are expected from the PHENIX MPC-EX [31]

"The RHIC Cold QCD Plan for 2017 to 2023" (2016)

Wed: Chris Dilks

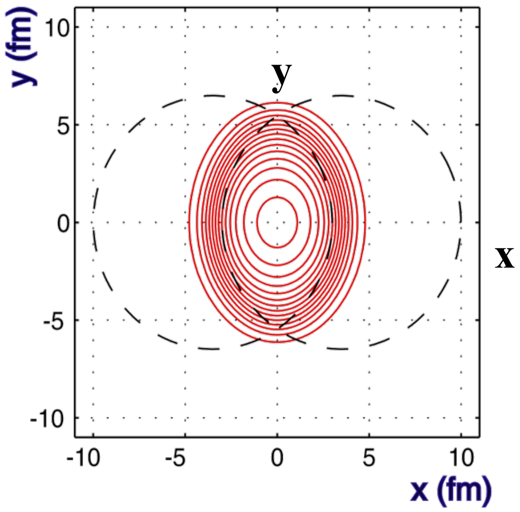
# Flow: Modeling the later parts of the collision



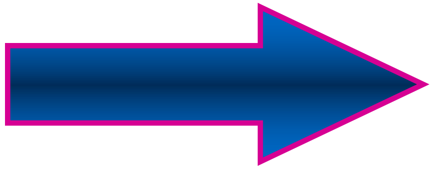

- Heavy Ion Theory had made great advances – reliable tools
  - *3+1 D viscous Hydrodynamical models are now available (e.g. Music, Schenke, Jeon, Gale, PRC 82, 014903 (2010)*
- Signatures such as various flow moments rely on initial conditions and can be used to test saturation models such as the CGC.
- Complications
  - *Initial conditions (CGC, Glauber)*
  - *Pre-equilibrirum in the case of a CGC scenario (Glasma)*
  - *Hydrodynamic expansion*
  - *Hadronization (Cooper – Frye Prescription)*

# Azimuthal anisotropy e.g. v2 "Elliptic flow"

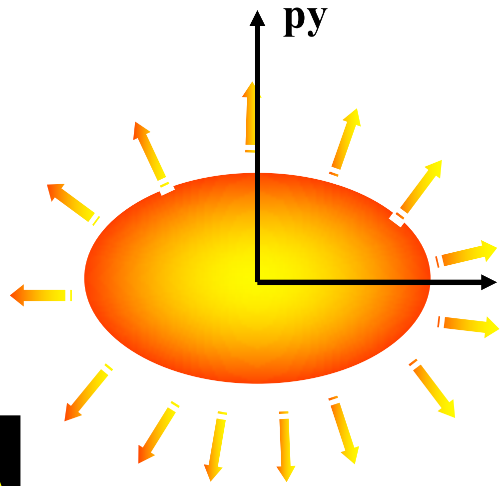
Coordinate space: initial asymmetry



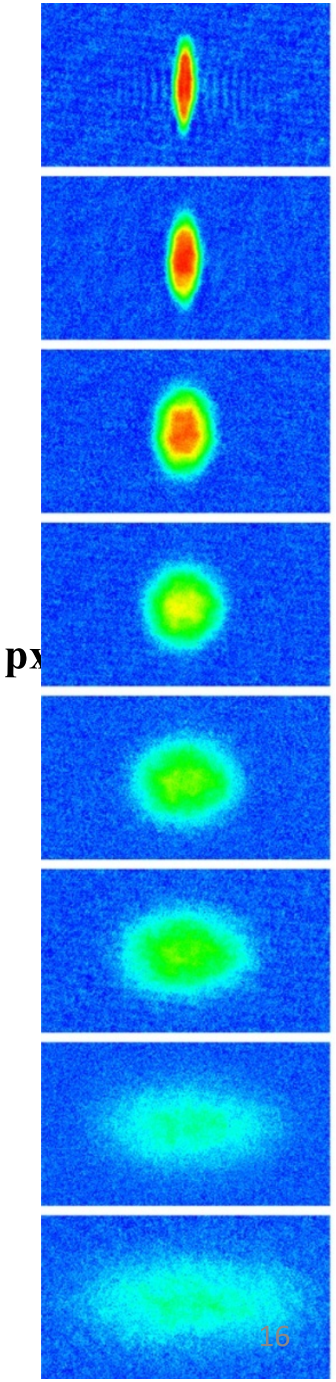

Hydrodynamics (pressure gradients strongest along x)



Momentum space: final asymmetry

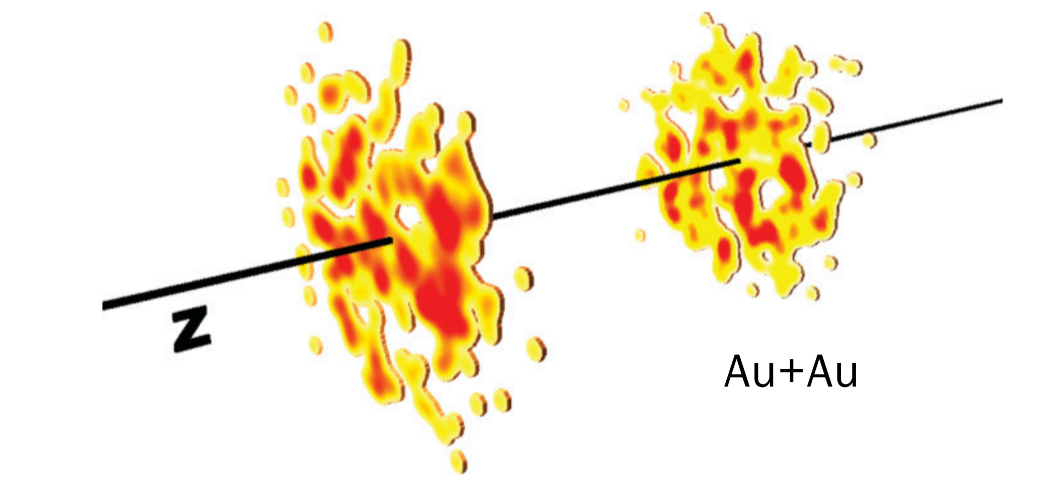



$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos 2\varphi \rangle$$



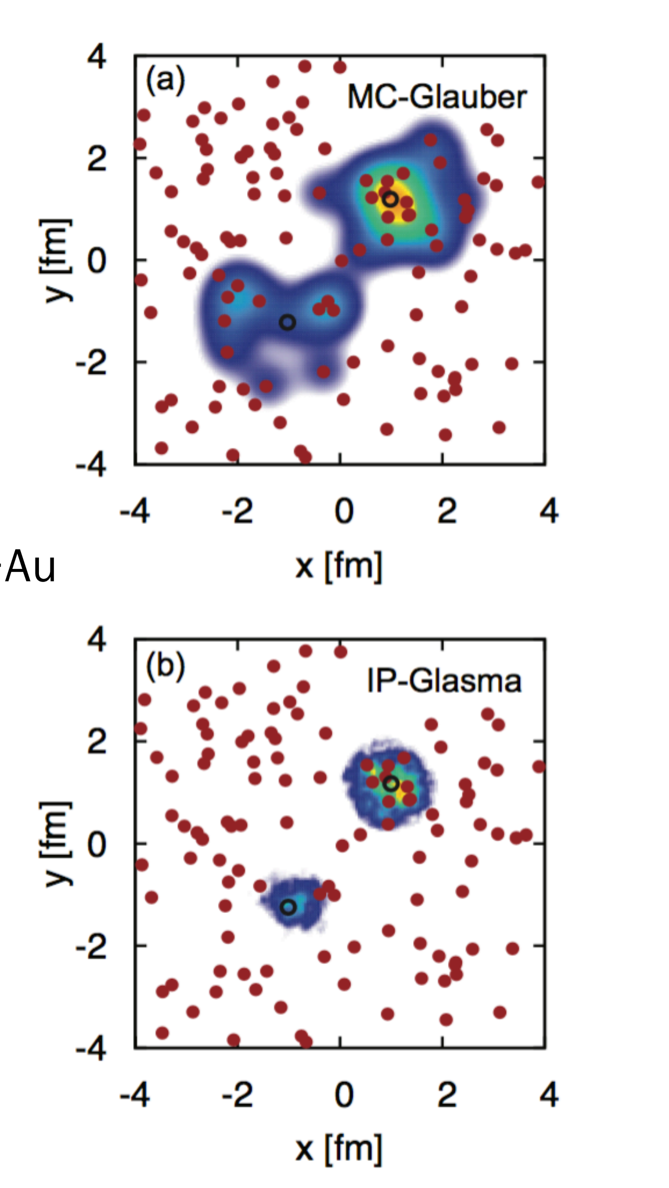

- Can get higher moments v3,v4
- Depends on initial state before expansion starts
  - Geometry
  - Fluctuations

# Initial Conditions

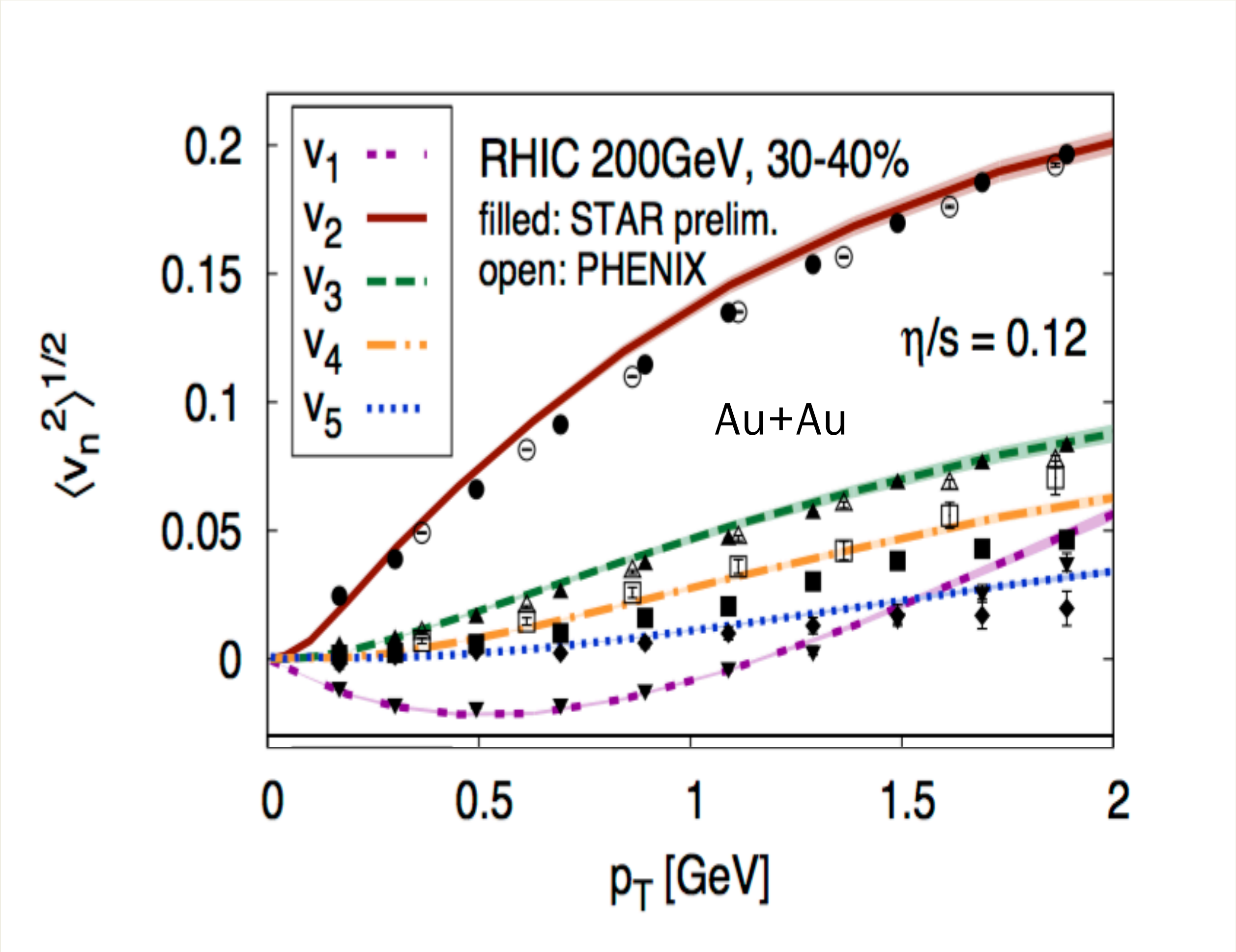



- MC-Glauber
- IP-Glasma

d+Au



# How well does it work? Au+Au



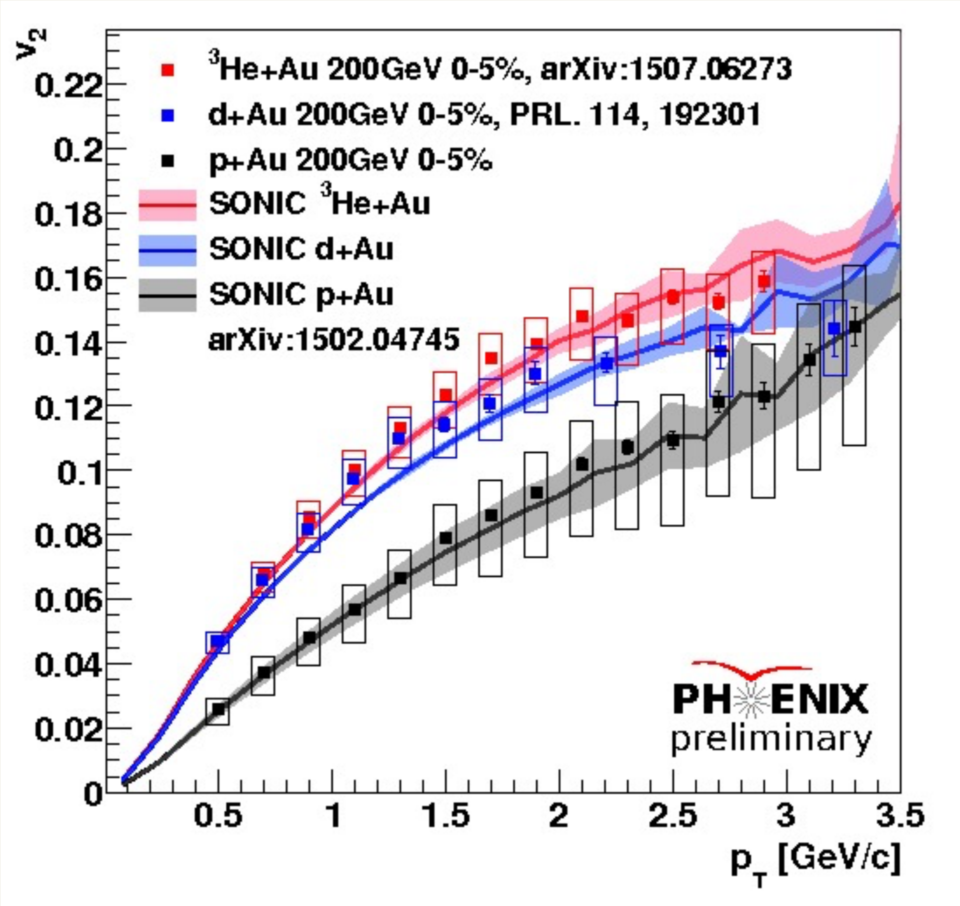

Works!
 Ip-Glasma initial conditions
We want to measure characteristics of the QGP

$$\frac{\eta}{s} = 1.5\frac{1}{4\pi}$$ (no errors yet)

Gale et.al, ArXiv:1209.6330 (2012)

# Simple systems

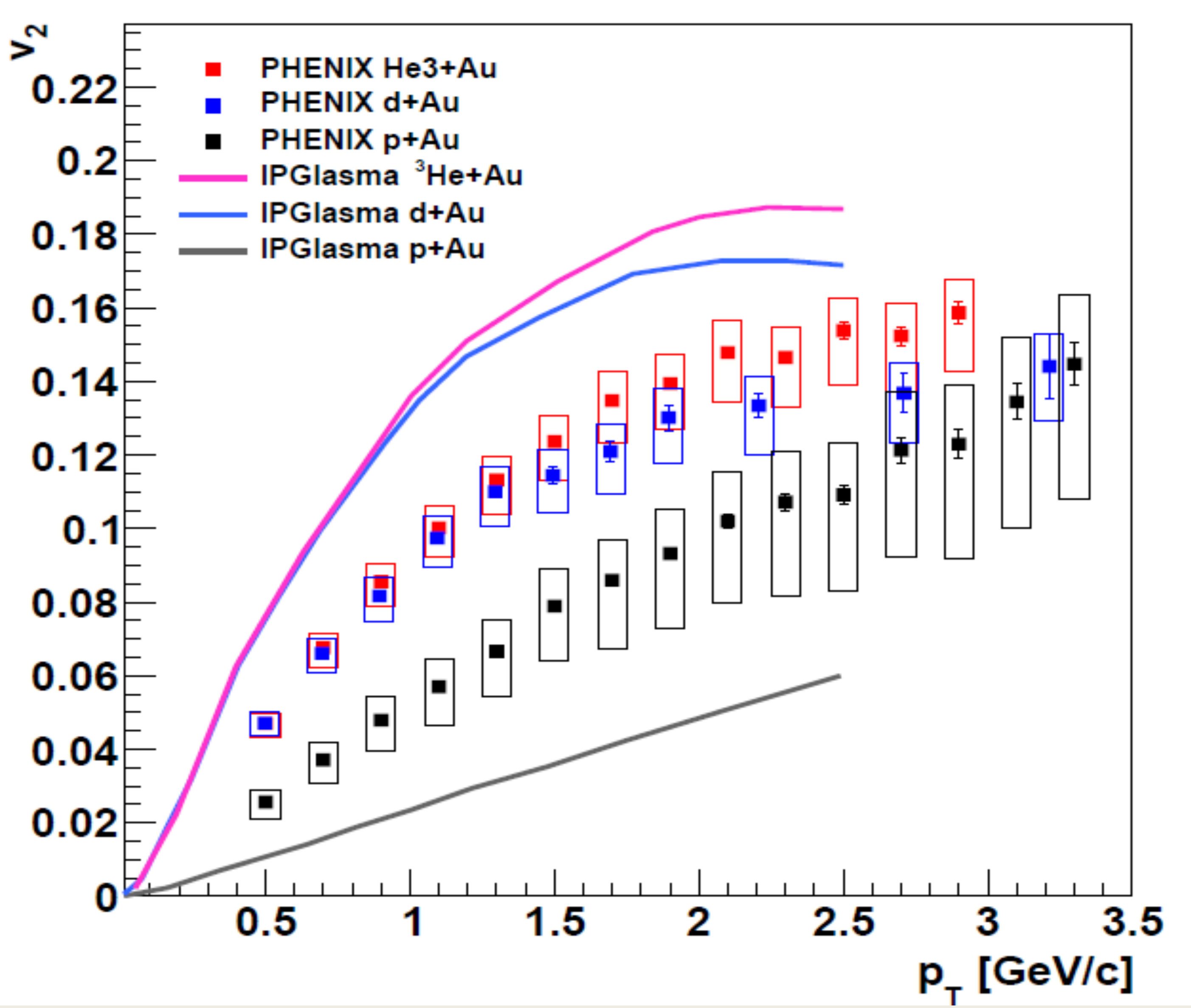
- Surprise!
  - *Simple systems*
    - At RHIC: p+p,p+Au, d+Au, He3+Au
  - *Observed long range correlations and flow*
    - Note: CERN has see correlations in p+p. So far RHIC experiments have not, though this is an active area of study
  - *Model using Glauber initial conditions works*




RHIC: p+Au, d+Au, He3+Au

# Alas....

- But $\frac{\eta}{s} = 1.5\ \frac{1}{4\pi}$ and you would expect it to be higher that Au+Au
  - *Might be able to match d+Au and He3+Au*
  - *Solution for proton: give it substructure*




Schenke, Venugopalan arxiv:1407.7557(2014)

# Score Card

| signature | Saturation |
|---|---|
| Singles | Y |
| RdAu | Y |
| Back to back | Y |
| Back to back vs “x” | Y |
| SSA in pA | N?? |
| Multiplicity vs centrality AA | Y |
| Multiplicity rapidity dAu | Y |
| Flow in AuAu | Y |
| Flow in dAu, v2 and v3 | N, so far |

# Summary

- Saturation models have had a great deal of success at RHIC
- Will, the SSA, and flow in simple systems kill it??? I don't know
- There is latitude in this models
  - *the CGC model*
  - *The parameters and method you use with it*
    - E.g. Viscosity, Freeezeout temperature…

In my mind – There are two reasons to study saturation

a) to see if it is there, and to understand it. We should strive to understand it in pA collisions Ultimately it will take the EIC.
"(the EIC) *will explore a new quantum chromodynamics* (QCD) *frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei." from the LRP*

*b) To understand the initial conditions for the QGP – i.e. to understand how it is born. The EIC will probably not take data till the end of the next decade. The Heavy Ion Community will not wait. Understanding what we can, with the tools we have (e.g. p+Au) is crucial.*