The Physics of RHIC

(4) d+Au Collisions

HUGS 2007

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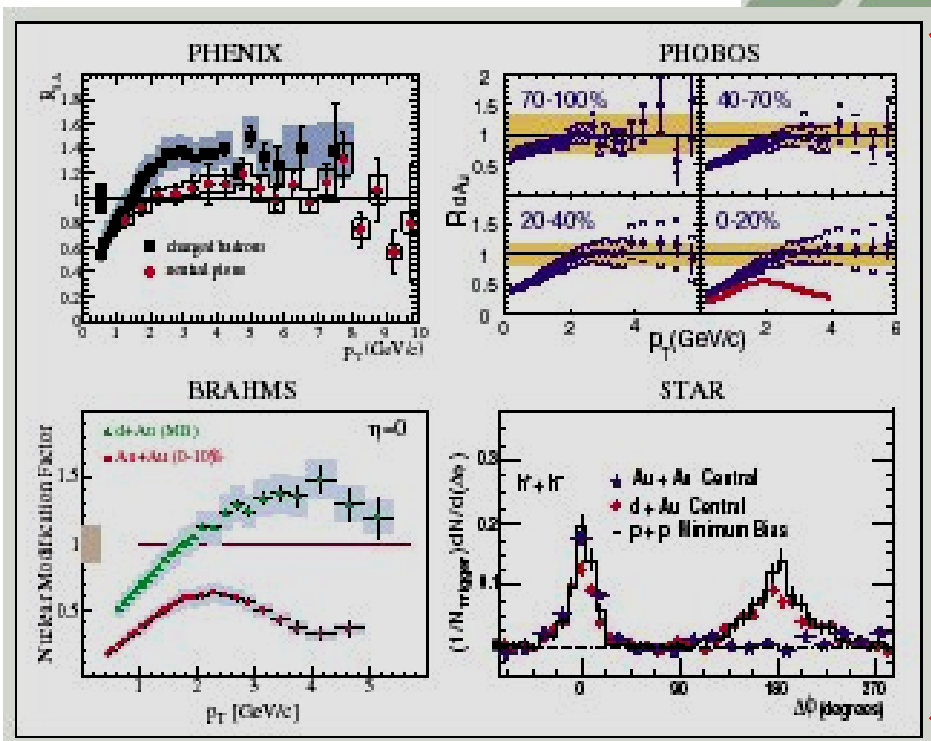
d+Au collisions at RHIC

- A control experiment to identify novel effects in Au+Au
  - Is jet quenching an initial-state effect or a final-state effect?
  - Shadowing in a new kinematic domain
  - Gluon shadowing is not well constrained by fixed-target data
- Has evidence been found for gluon saturation?

Phys Rev Lett 91, 072302/3/4/5



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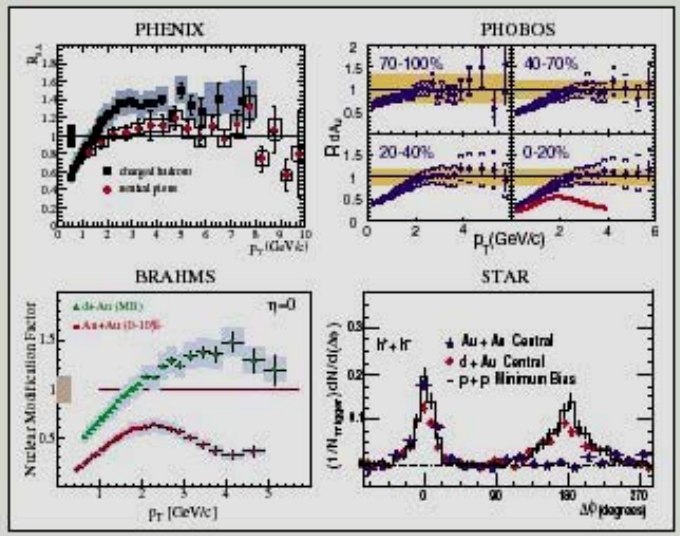
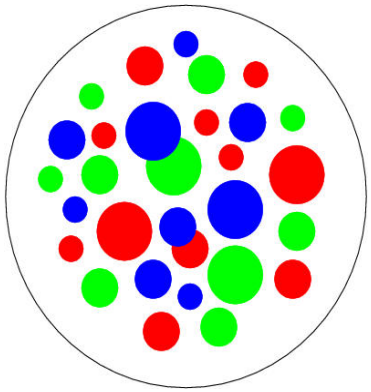


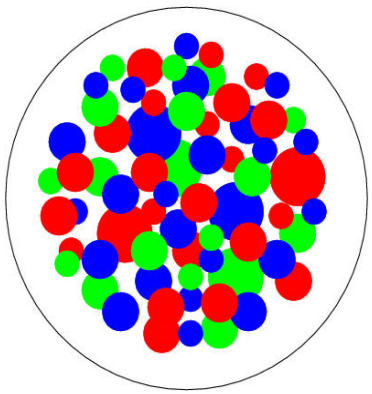
Published by The American Physical Society

Mid-rapidity vs. forward rapidity

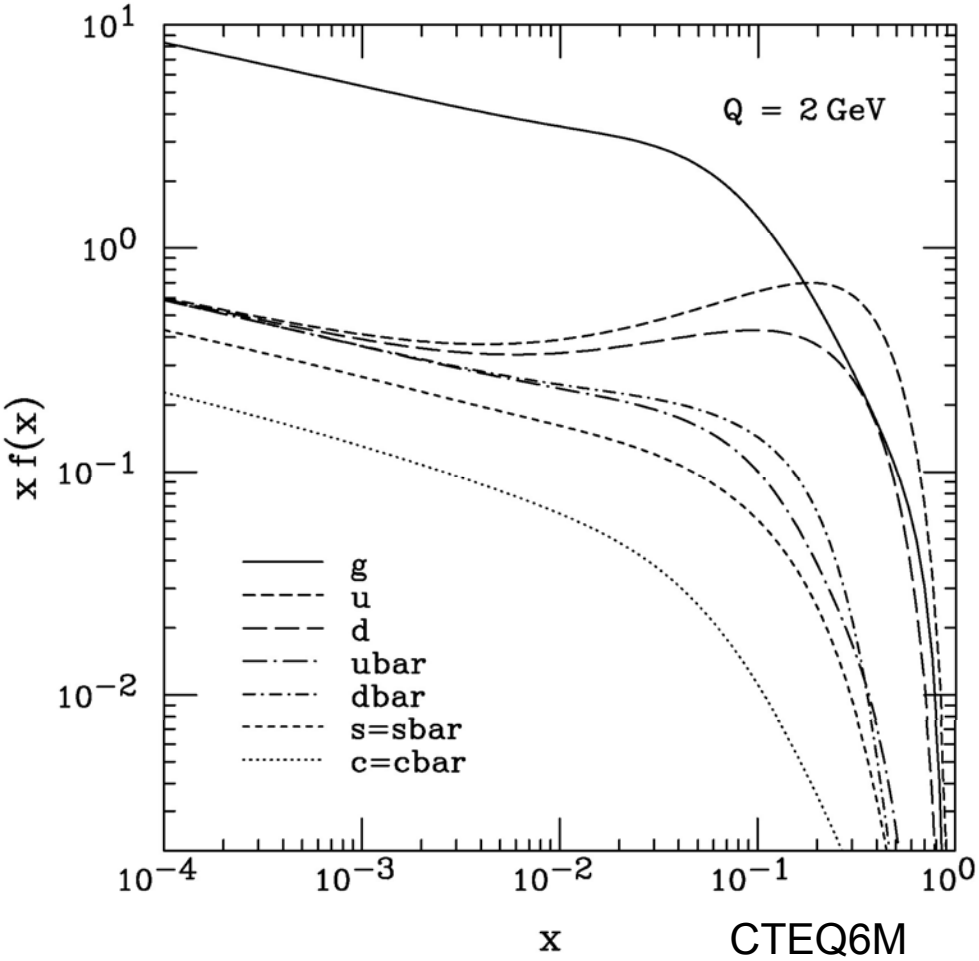


Mid Rapidity

$$x \sim \frac{2\,p_T}{\sqrt{s}} e^{-y}$$

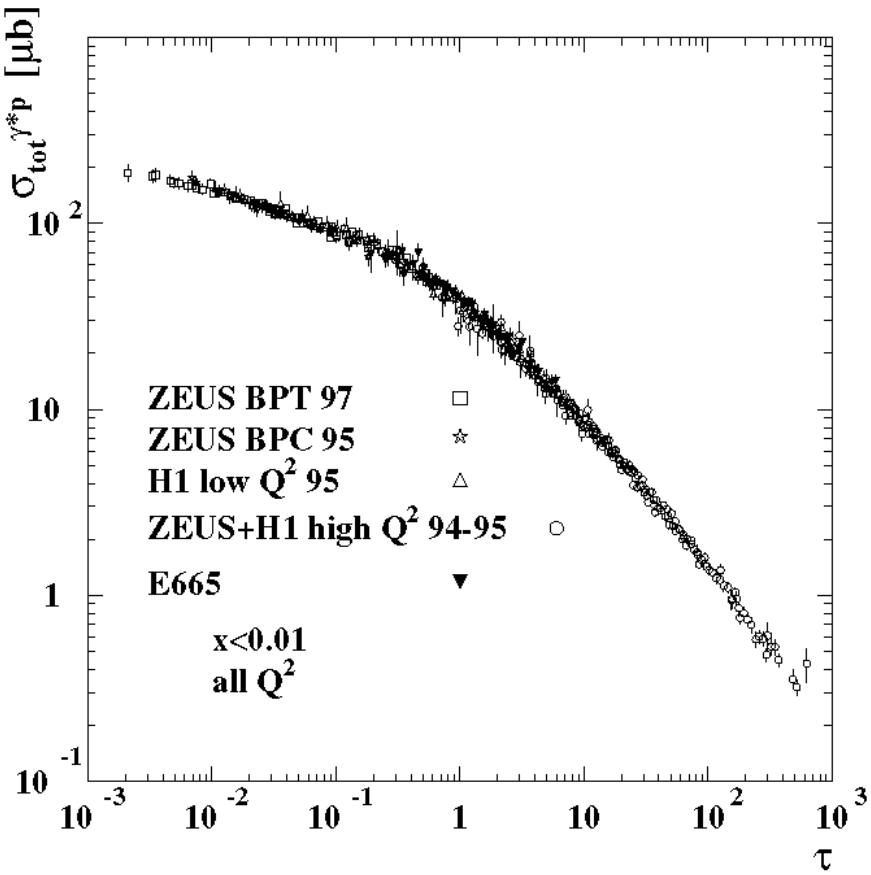


Forward Rapidity



- Gluon density can't grow forever.
- Saturation should set in when gluons overlap.
- Where does this happen?

Geometric scaling in γ^*+p at HERA



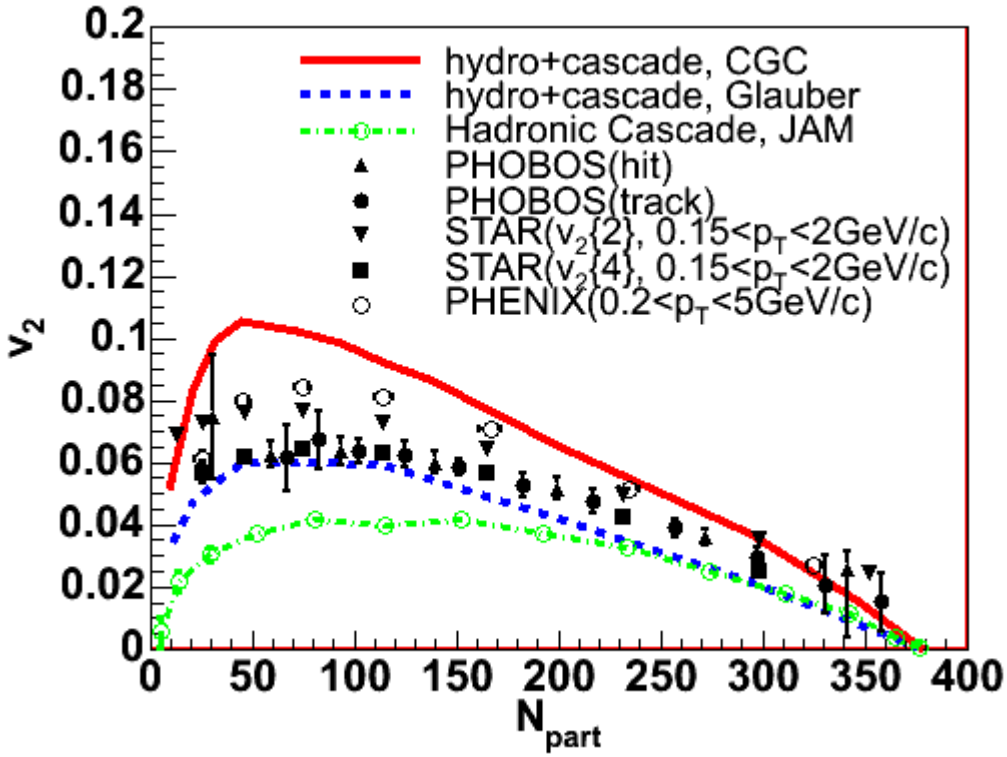
Stasto, Golec-Biernat, and Kwiecinski, PRL 86, 596

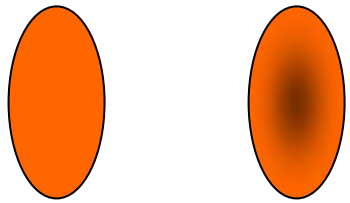
Note:
$\tau \sim Q^2/Q_S(x)^2$

- Scaling of the γ^*+p cross section for $x < 0.01$ may indicate the saturation scale is playing an important role
- Ambiguity with ep and pp measurements: What is the proper reference?

Glauber vs Color Glass Condensate

Hirano et al, PLB 636, 299



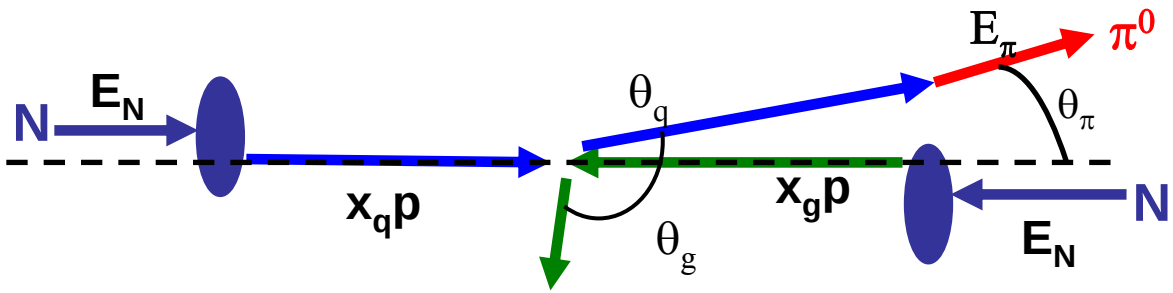


CGC Glauber

CGC: Treats the nucleus as a saturated gluon field

- Do we have **Glauber matter distribution + perfect liquid**, or **Color Glass Condensate distribution + viscous matter**?
- Is the gluon field in the Au nucleus saturated?
- **Forward d+Au collisions** provide information about the gluon density in Au at low gluon momentum fractions

Forward π^0 production at a hadron collider



$$\sqrt{s} = 2E_N \qquad x_F \approx \frac{2E_\pi}{\sqrt{s}}$$

$$\eta = -\ln(\tan(\frac{\theta}{2})) \qquad z = \frac{E_\pi}{E_q}$$

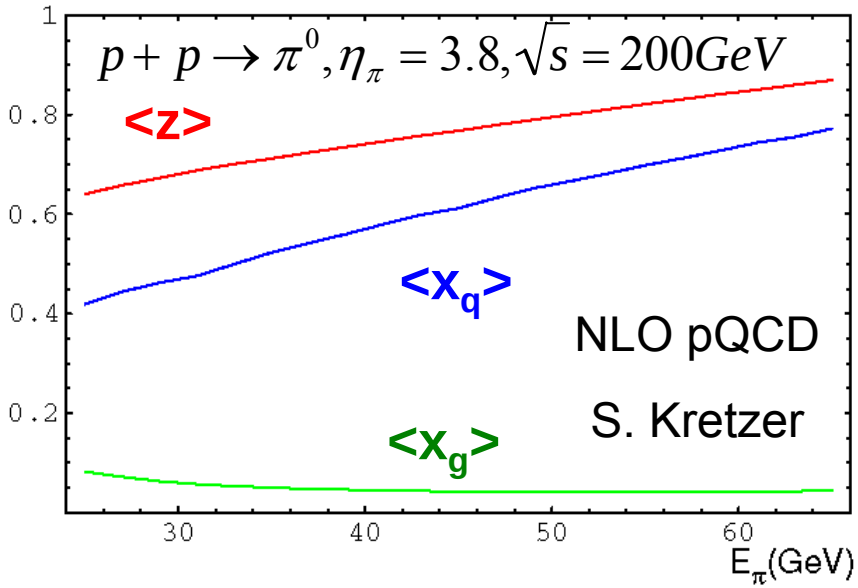
$$x_q \approx x_F / \langle z \rangle \qquad x_g \approx \frac{p_T}{\sqrt{s}} e^{-\eta g}$$

(collinear approx.)

- Large rapidity π production (η~4) probes asymmetric partonic collisions

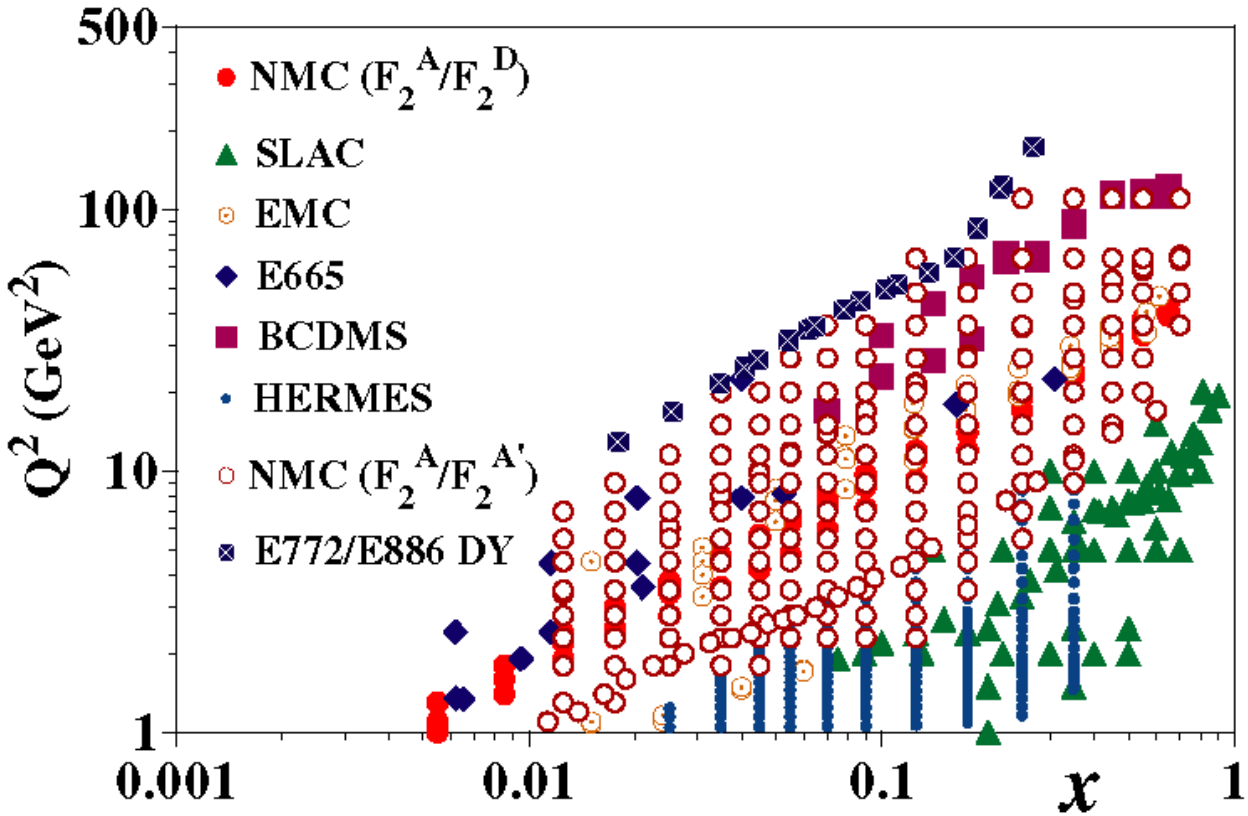
- Mostly high-*x* quark + low-*x* gluon
  - $0.3 < x_q < 0.7$
  - $0.001 < x_g < 0.1$
- <z> nearly constant and high ~ 0.7-0.8

- A probe of low-*x* gluons



Gluon density in nuclei

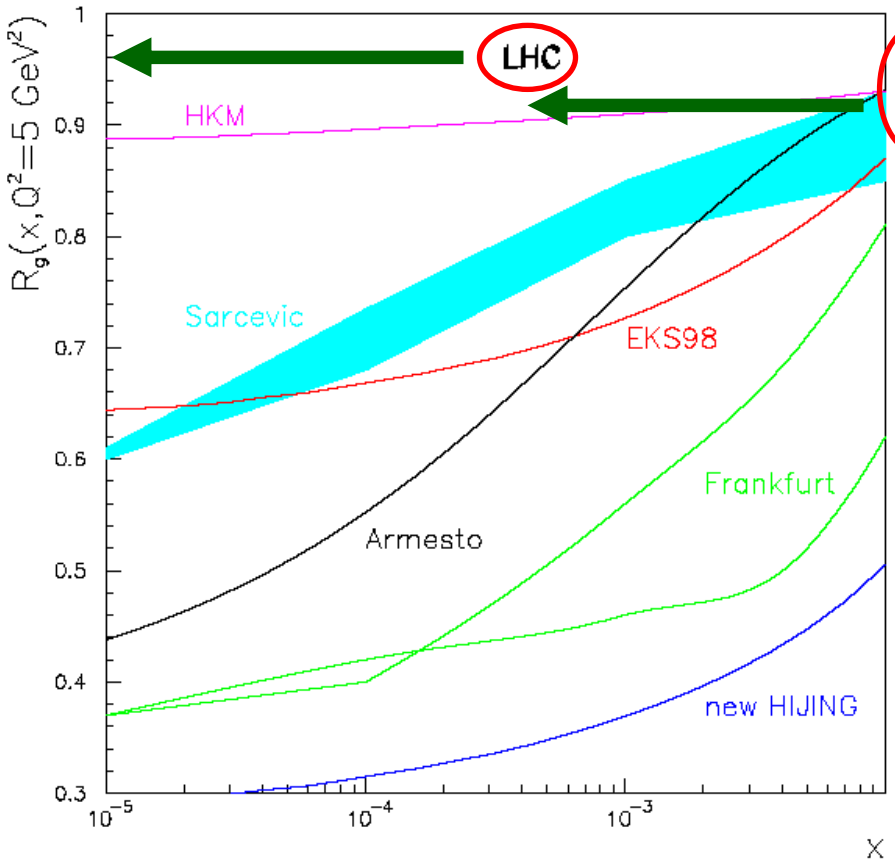
e.g., see M. Hirai, S. Kumano, T.-H. Nagai, PRC 70, 044905



World data on nuclear DIS only constrain nuclear modifications to gluon density for x_{gluon} >~ 0.02

Models for the gluon distribution in Pb

Armesto, J Phys G 32, R367



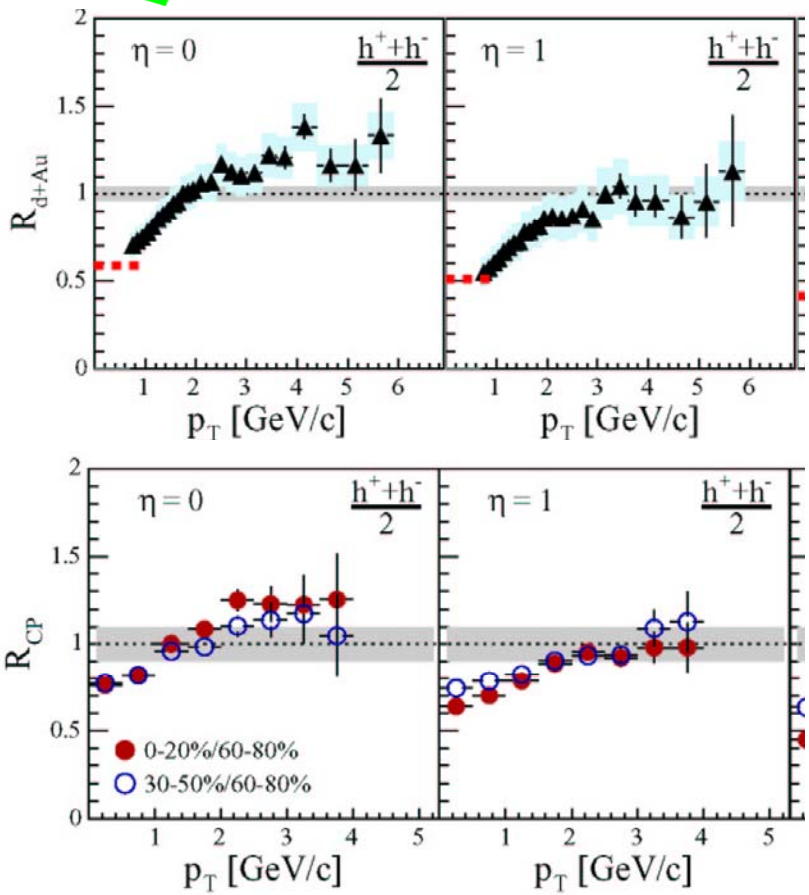
***x* at η=0**

Increasing *y*

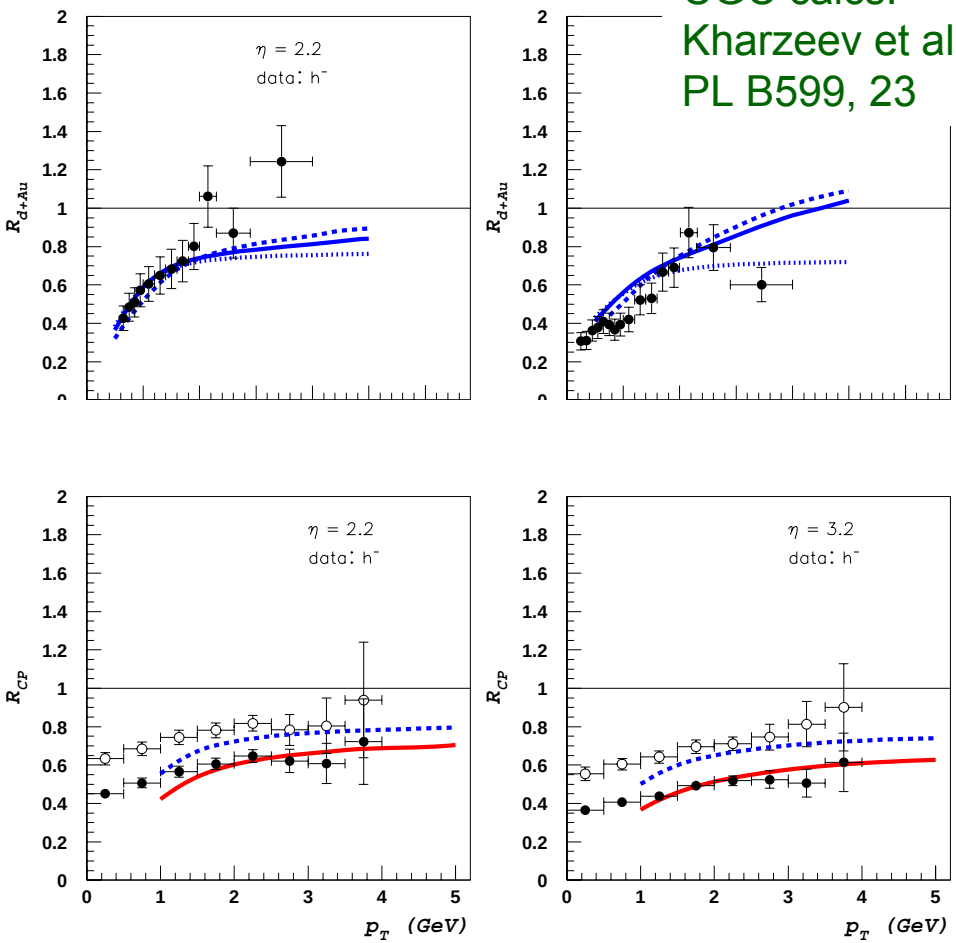
- In the region without experimental constraints, the model predictions vary by large factors
- Can be explored at RHIC, LHC, EIC

Forward particle production in d+Au collisions

BRAHMS PRL 93, 242303



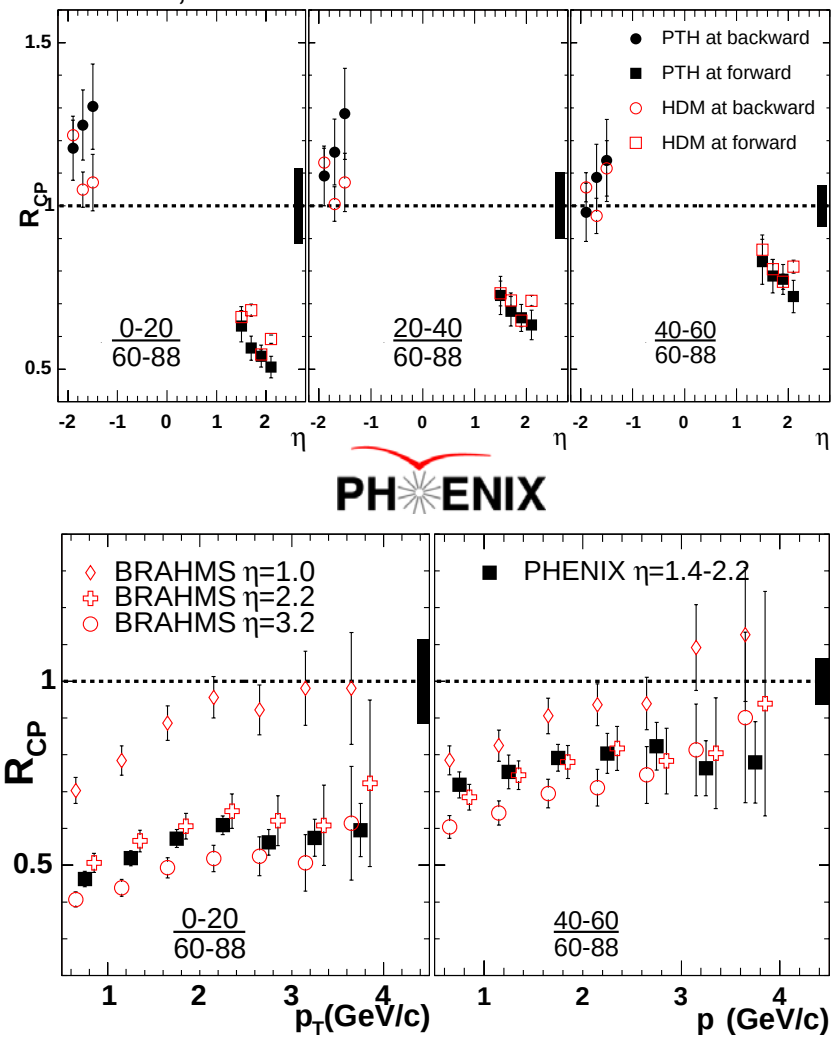
CGC calcs: Kharzeev et al, PL B599, 23



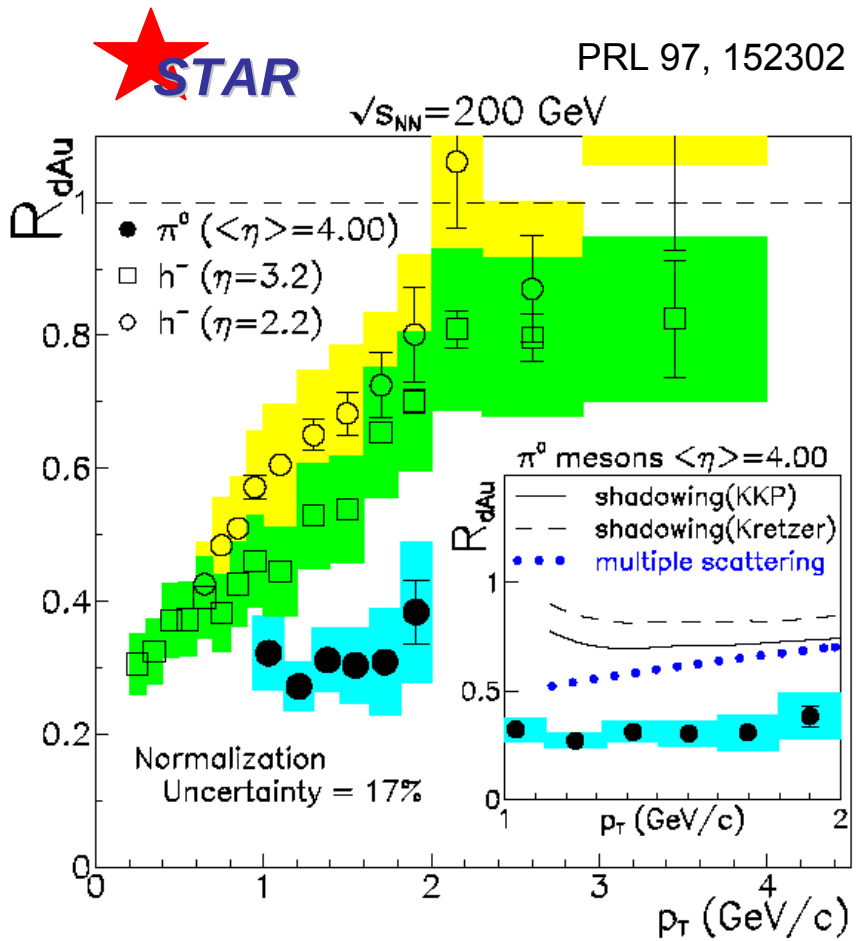
- Sizable suppression of charged hadron yield in forward d+Au
- Evidence for a saturated gluon field in the Au nucleus?

PHENIX and STAR report similar effects

PRL 94, 082302



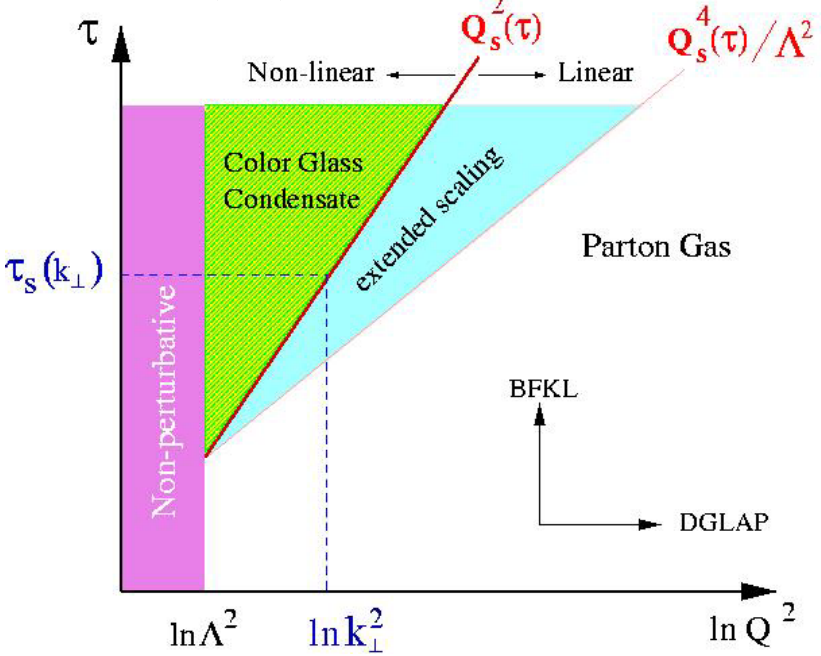
PRL 97, 152302



- Charged particles and π^0 are suppressed in the forward direction
- pQCD+shadowing calculations overpredict R_{dAu} at $\eta = 4$

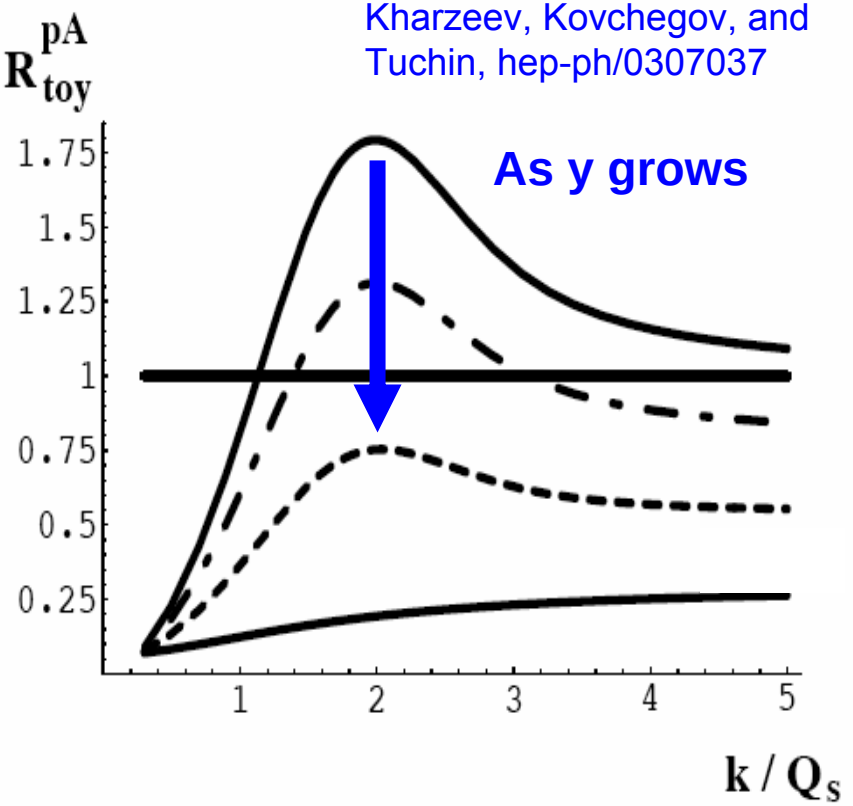
Expectations for a color glass condensate

$\tau = \ln\left(1/x\right)$ τ related to rapidity of produced hadrons.



Iancu and Venugopalan, hep-ph/0303204

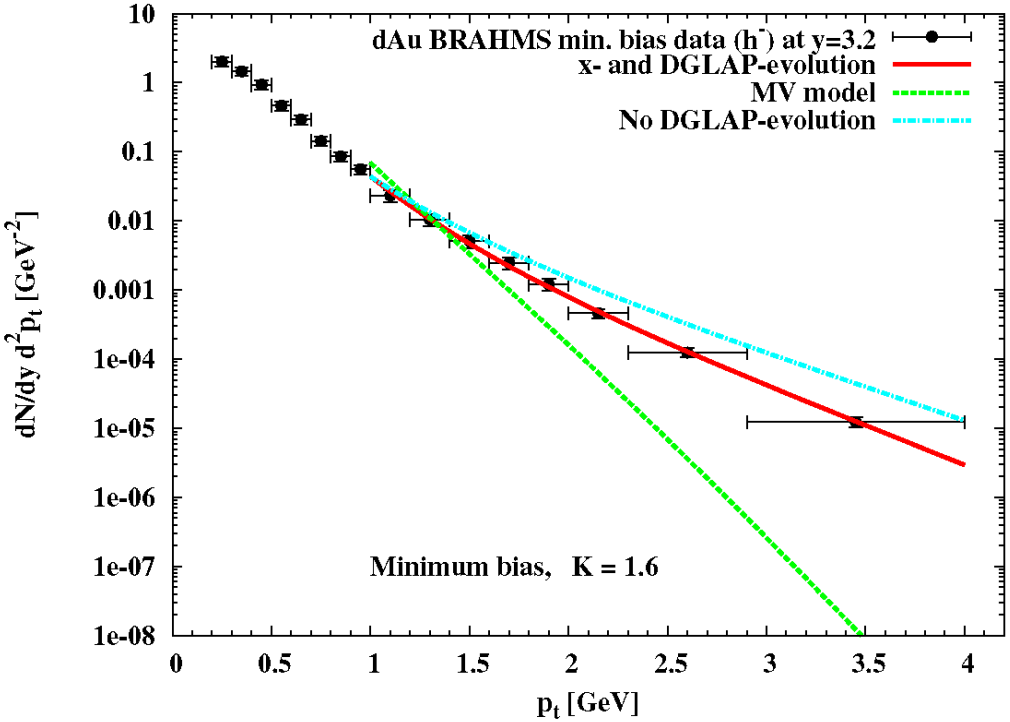
Kharzeev, Kovchegov, and Tuchin, hep-ph/0307037

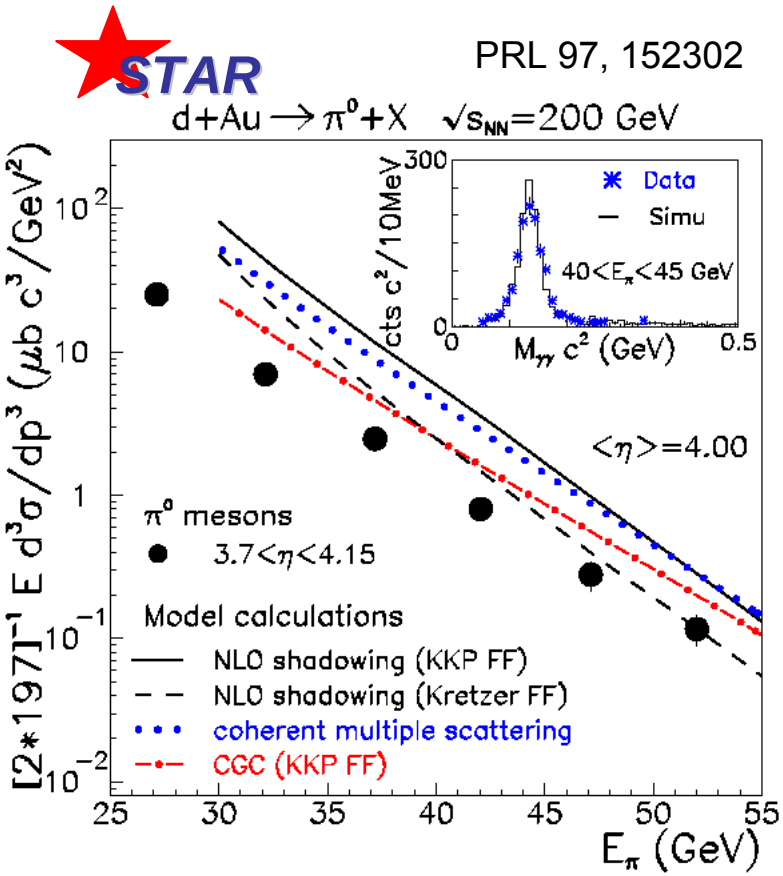


Are the forward d+Au results evidence for **gluon saturation at RHIC energies**?

Recent saturation model calculation

(Dumitru, Hayashigaki, and Jalilian-Marian, NP A765, 464)



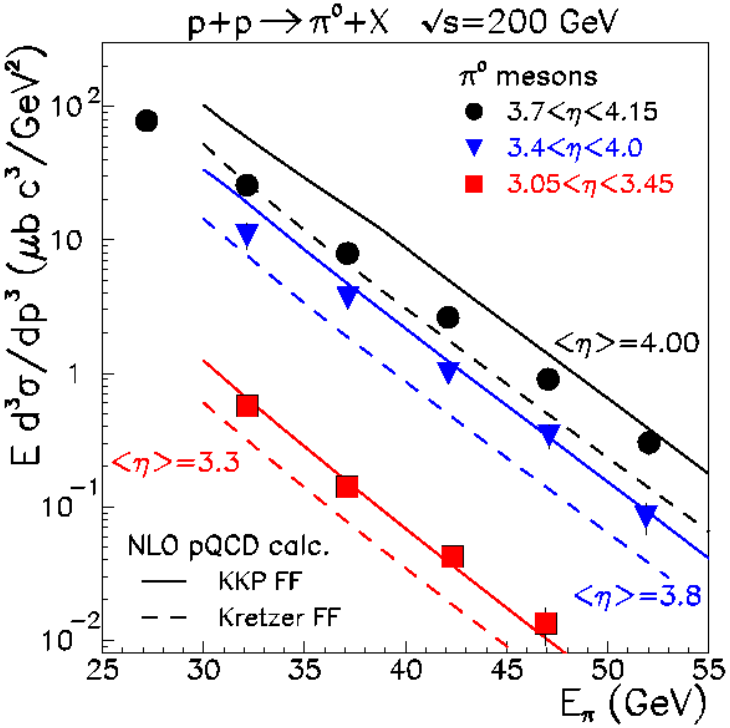


Good description of the p_T dependence for negatively charged hadrons at η = 3.2 and identified π^0 at η = 4.0, but the data prefer different K factors

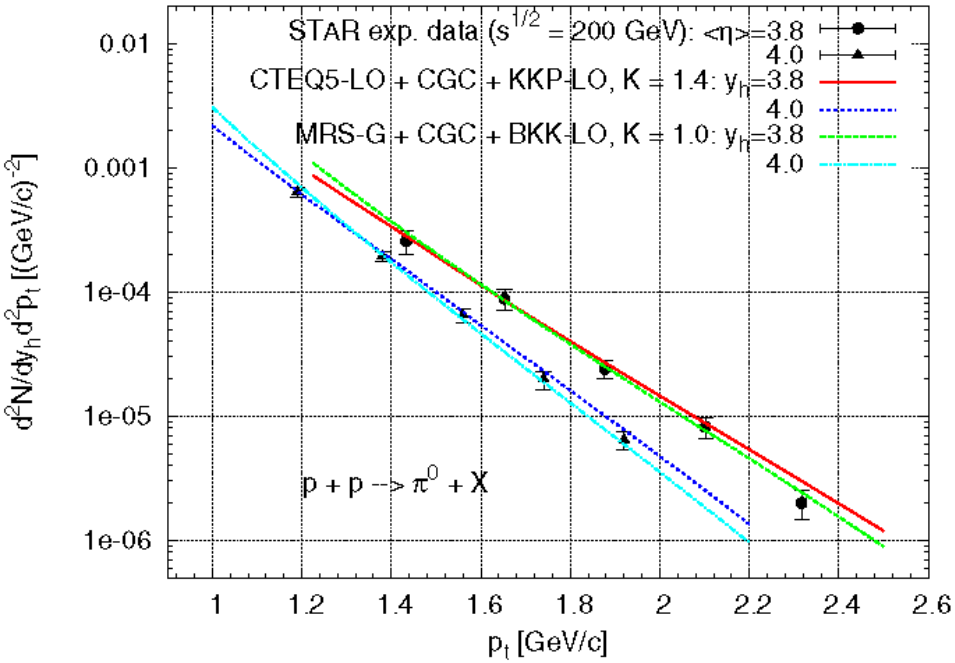
(K=0.8 gives best fit for STAR data)

p+p → π^0+X at 200 GeV

STAR PRL 97, 152302

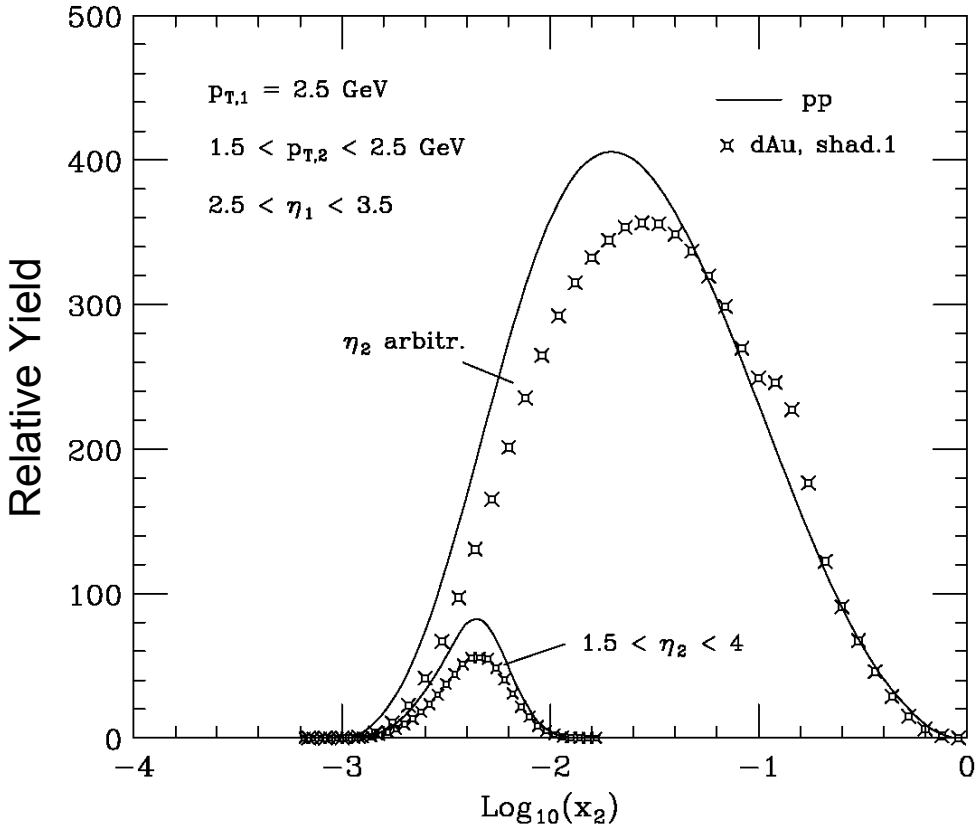


Boer, Dumitru, and Hayashigaki, PRD 74, 074018



- In p+p, the forward inclusive π^0 cross section is consistent with NLO pQCD for p_T >~ 1.7 GeV/c
- At lower p_T, data trend from KKP fragmentation prediction to Kretzer fragmentation, as occurs at mid-rapidity.
- CGC calculation that treats the "target" in the extended scaling region gives a very good description of the data for all p_T.

Is saturation really the explanation?



Difficult to explain BRAHMS results with standard shadowing, but in NLO pQCD calculations $\langle x_g \rangle \sim 0.02$ is not that small

(Guzey, Strikman, and Vogelsang, PL B603, 173)

In contrast, $\langle x_g \rangle \lesssim 0.001$ in CGC calculations

(Dumitru, Hayashigaki, and Jalilian-Marian, NP A765, 464)

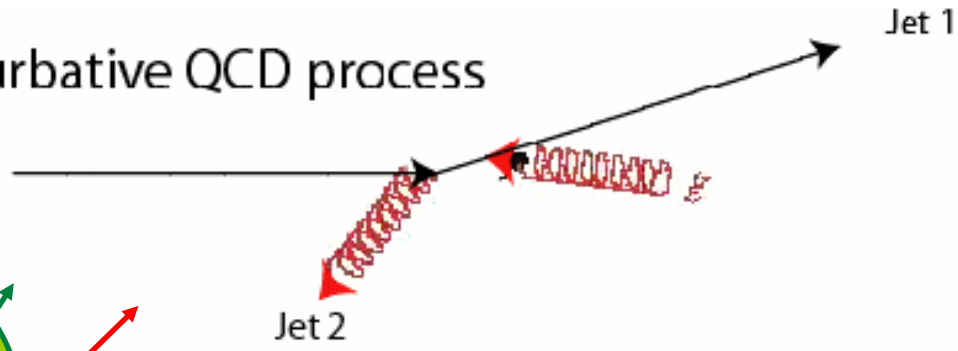
Basic difference:

pQCD: 2 → 2

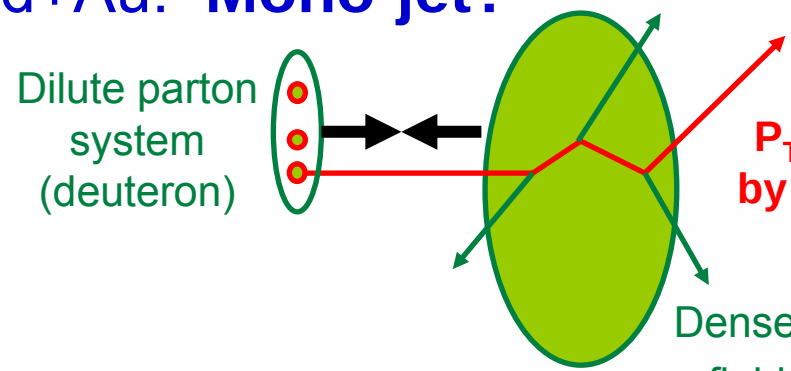
CGC: 2 → 1

Any difference between p+p and d+Au?

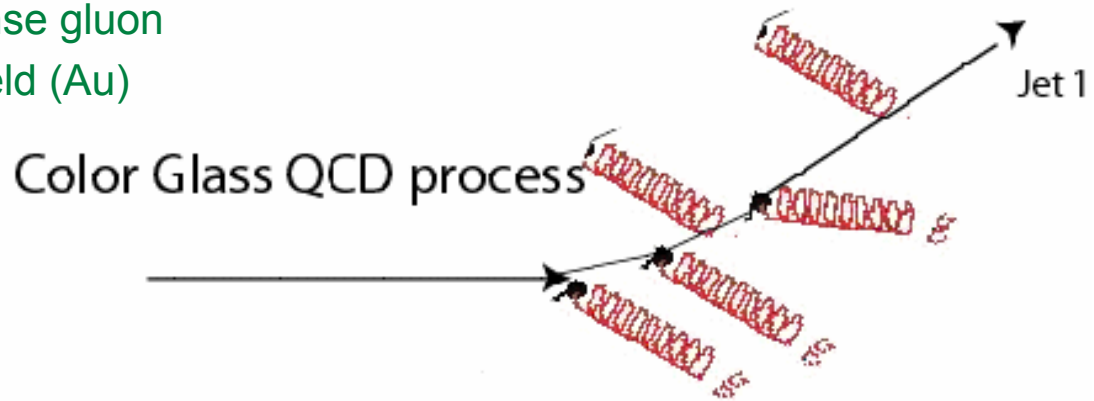
p+p: **Di-jet**



d+Au: **Mono-jet?**

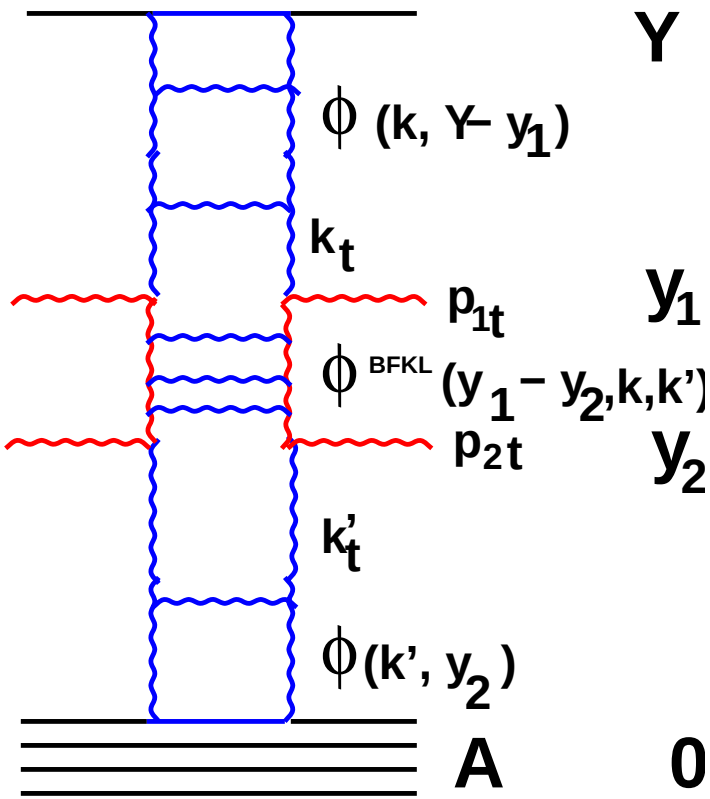


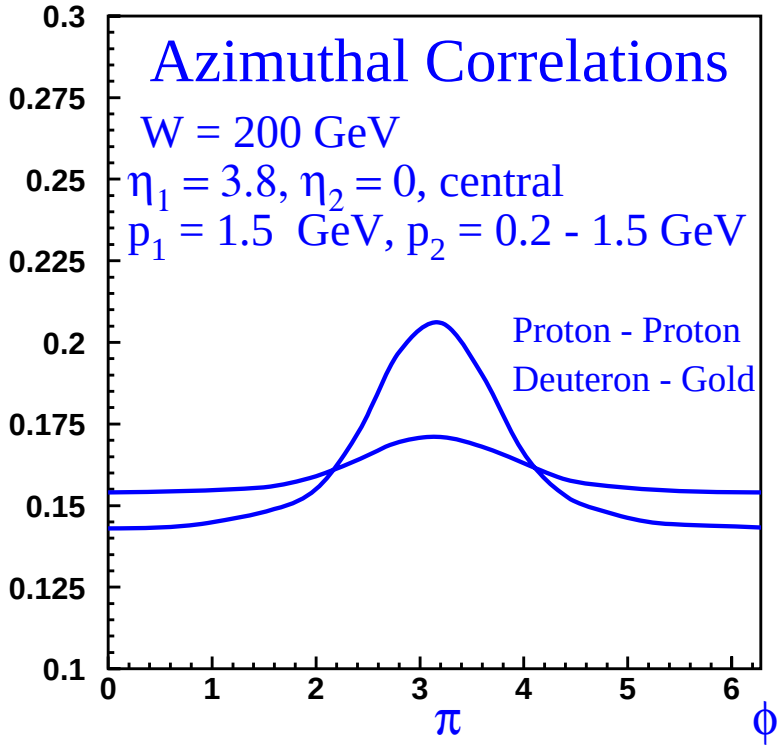
Kharzeev, Levin, McLerran gives physics picture (NPA748, 627)



Color glass condensate predicts that the **back-to-back correlation** from p+p **should be suppressed**

Back-to-back correlations with the color glass

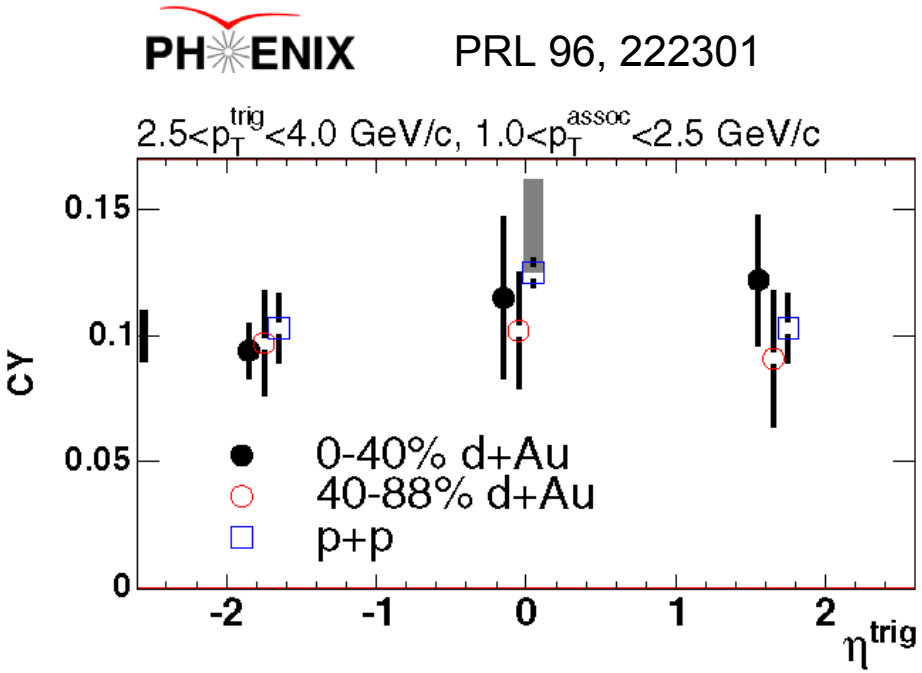


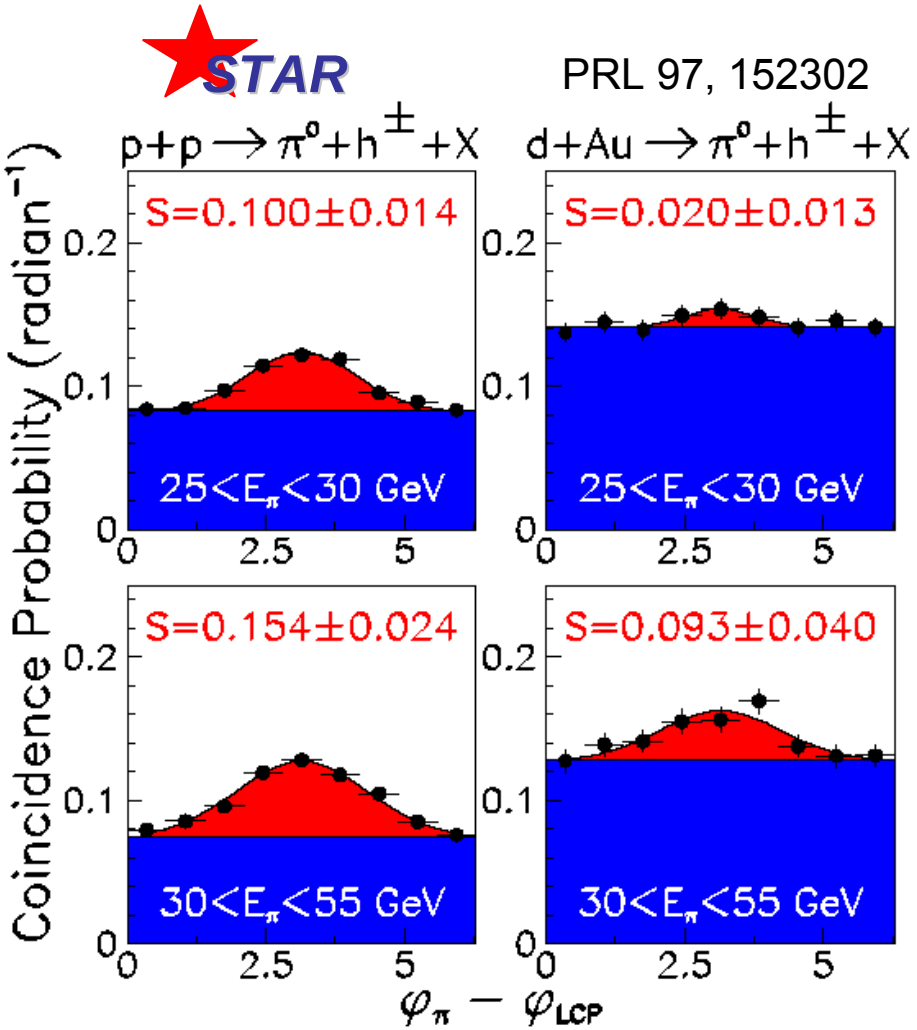


The evolution between the jets makes the correlations disappear.

(Kharzeev, Levin, and McLerran, NP A748, 627)

Forward-midrapidity correlations in d+Au





π^0: $|\langle\eta\rangle| = 4.0$

$h^{\pm}$: $|\eta| < 0.75$, $p_T > 0.5$ GeV/c

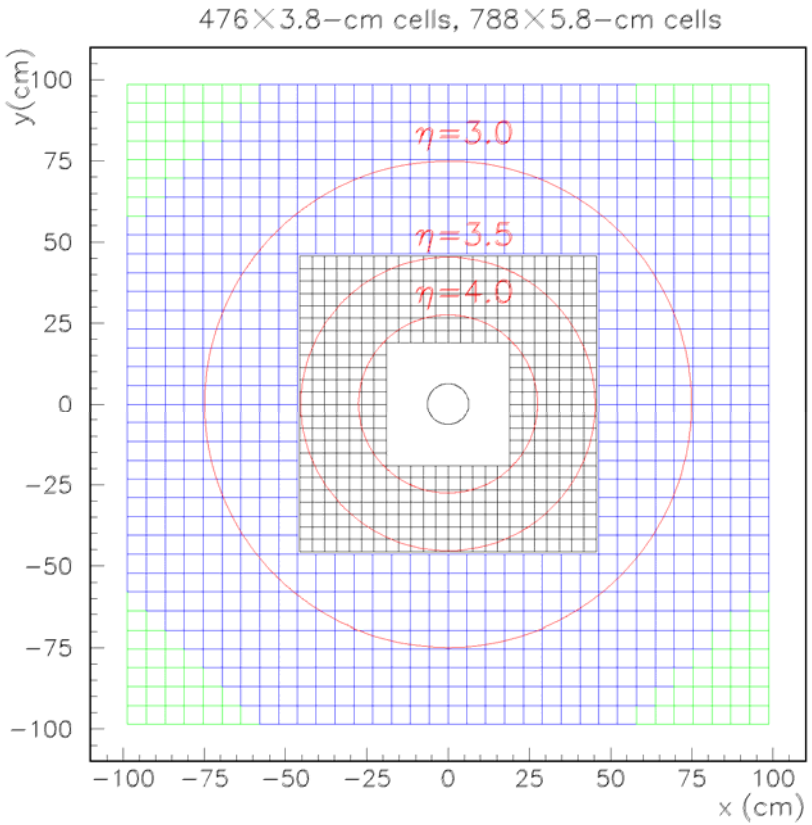
- PHENIX doesn't see any changes for $\langle x_g \rangle \sim 0.015$
- STAR might see suppression for $\langle x_g \rangle \sim 0.006$

Alternative explanations

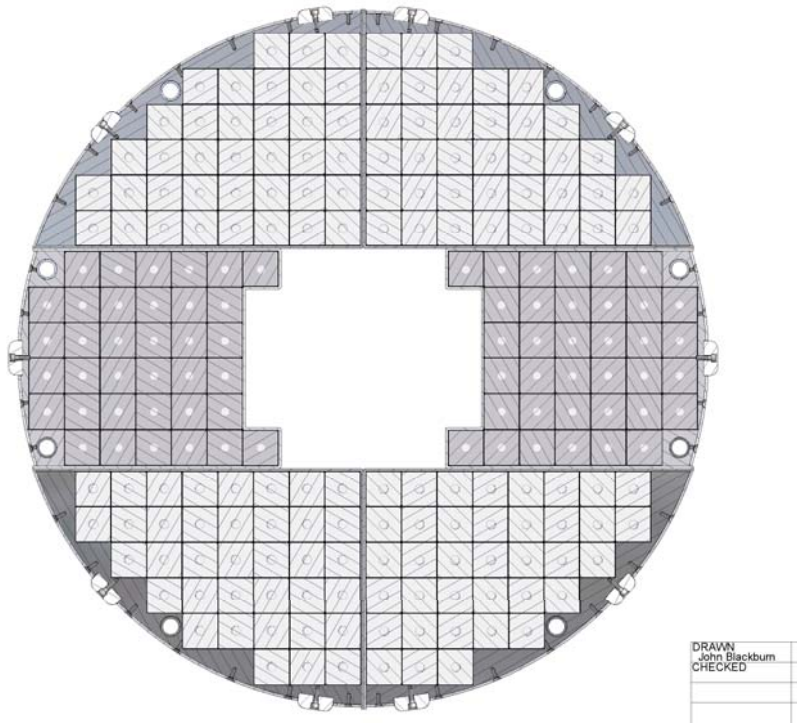
- Saturation is **not the only proposed explanation**
- Alternative explanations for suppression of forward yields and/or correlations:
  - Multiple scattering
  - Factorization breaking
  - Shadowing
  - Parton recombination
  - Black-disk limit
  - Incident parton energy loss
  - . . . . .
  - Others that I've forgotten off hand

New detectors for the next d+Au run

STAR Forward Meson Spectrometer
$2.5 < \eta < 4$



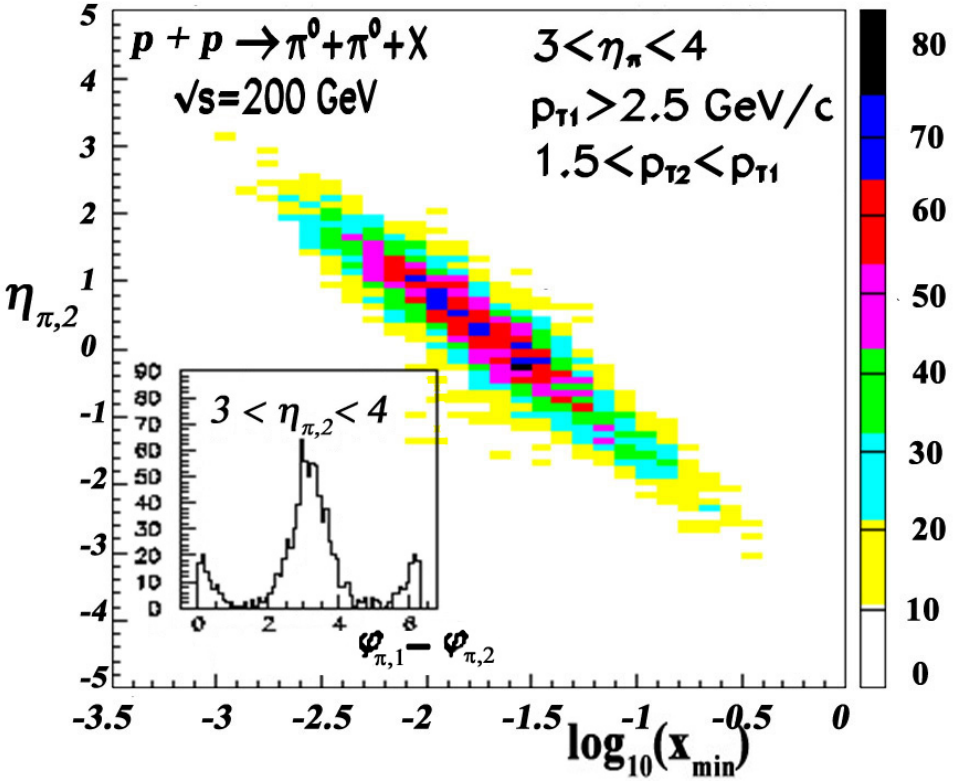
PHENIX Muon Piston Calorimeter
$3.1 < \eta < 3.9$



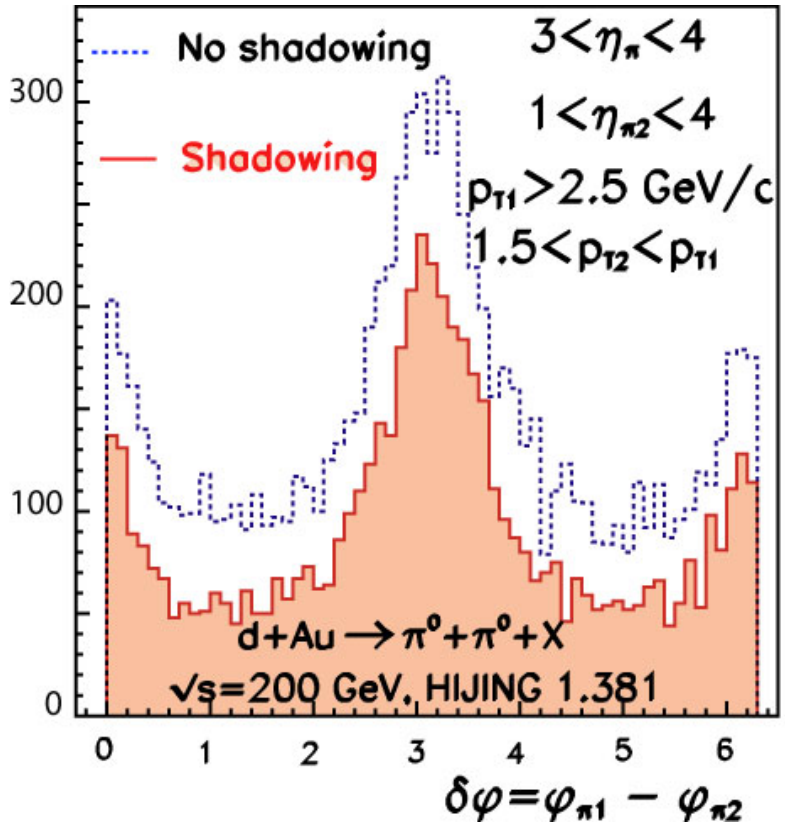
- Significant improvements in forward detection capabilities
- Crucial for small-*x* physics (important for spin physics, too!)

p+p and d+Au → π^0+π^0+X correlations with forward π^0

p+p in PYTHIA



d+Au in HIJING hep-ex/0502040

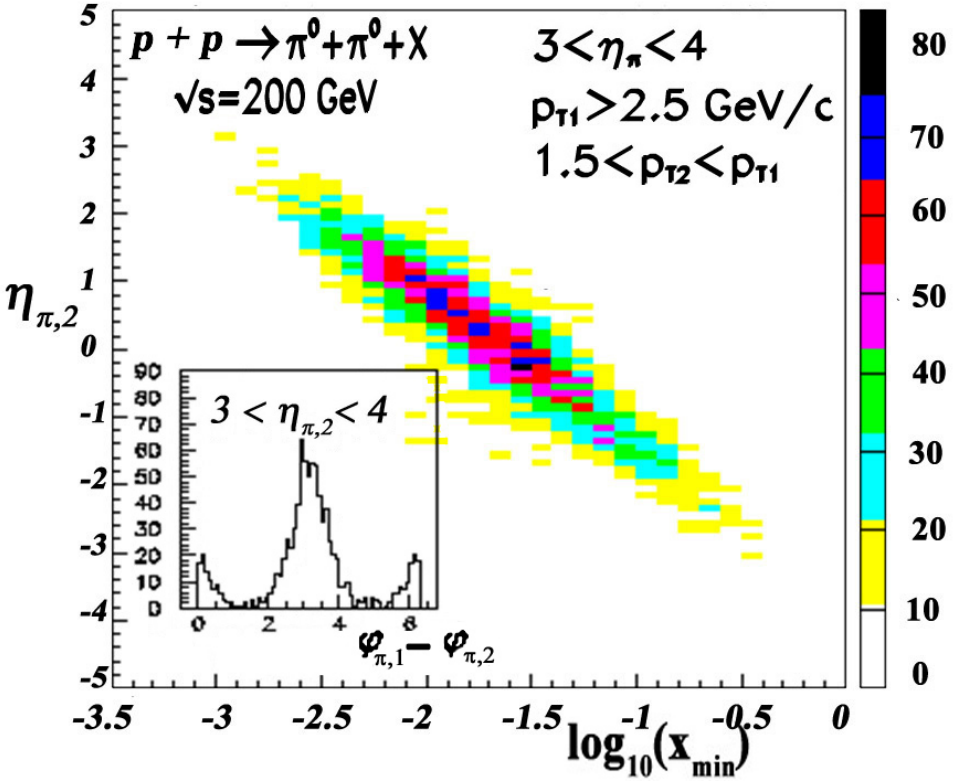


Conventional shadowing will **change yield, but not angular correlation**.
Saturation will **change yield and modify the angular correlation**.

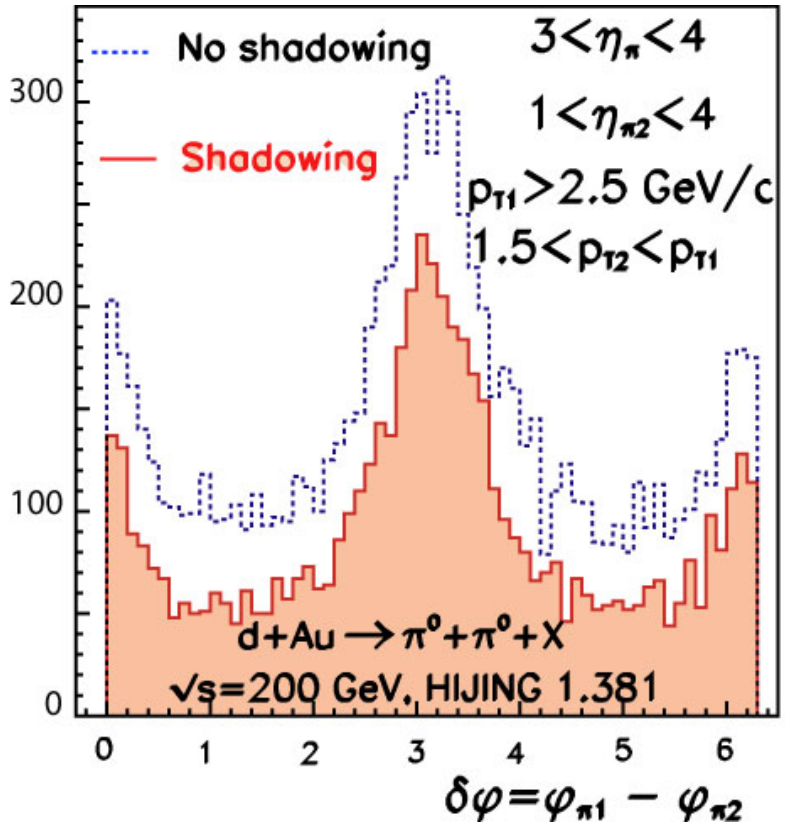
Sensitive down to x_g ~ 10^{-3} **in pQCD** scenario; **few x** 10^{-4} **in CGC** scenario.

p+p and d+Au → π^0+π^0+X correlations with forward π^0

p+p in PYTHIA



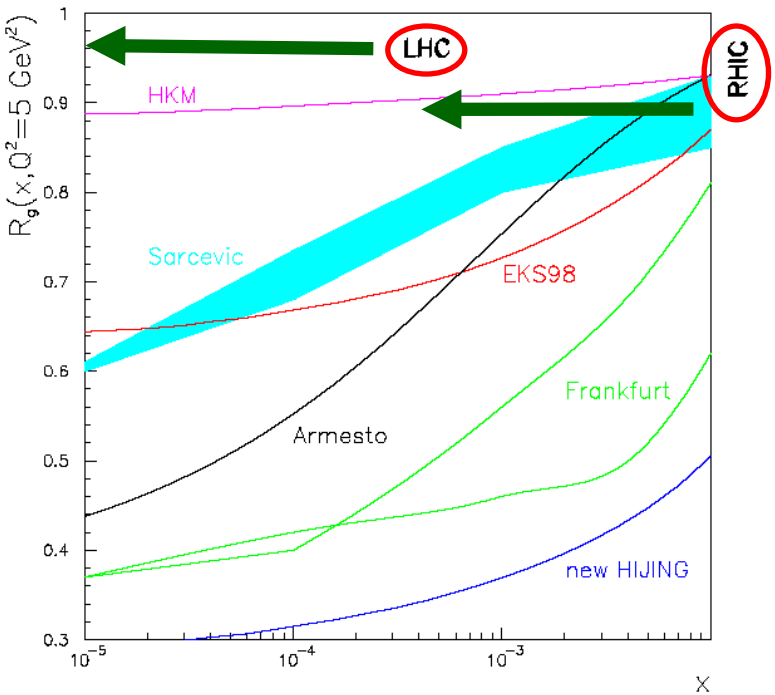
d+Au in HIJING hep-ex/0502040



Alternative analysis: Fix $\eta_{\pi,2}$ and vary $\eta_{\pi,1}$ over the range $2.75 < \eta_{\pi,1} < 3.75$; this spans $0.25 <\sim x_q <\sim 0.65$ while keeping $x_g \sim$ constant.

Tests for incident parton energy loss effects.

The next generation: RHIC-II and LHC



- Two possibilities:
  - RHIC-II explores the onset of saturation; LHC looks deep in the saturation domain
  - RHIC-II is dominated by other effects; LHC observes those other effects in combination with saturation
- In either case, **RHIC-II and LHC will be complementary**

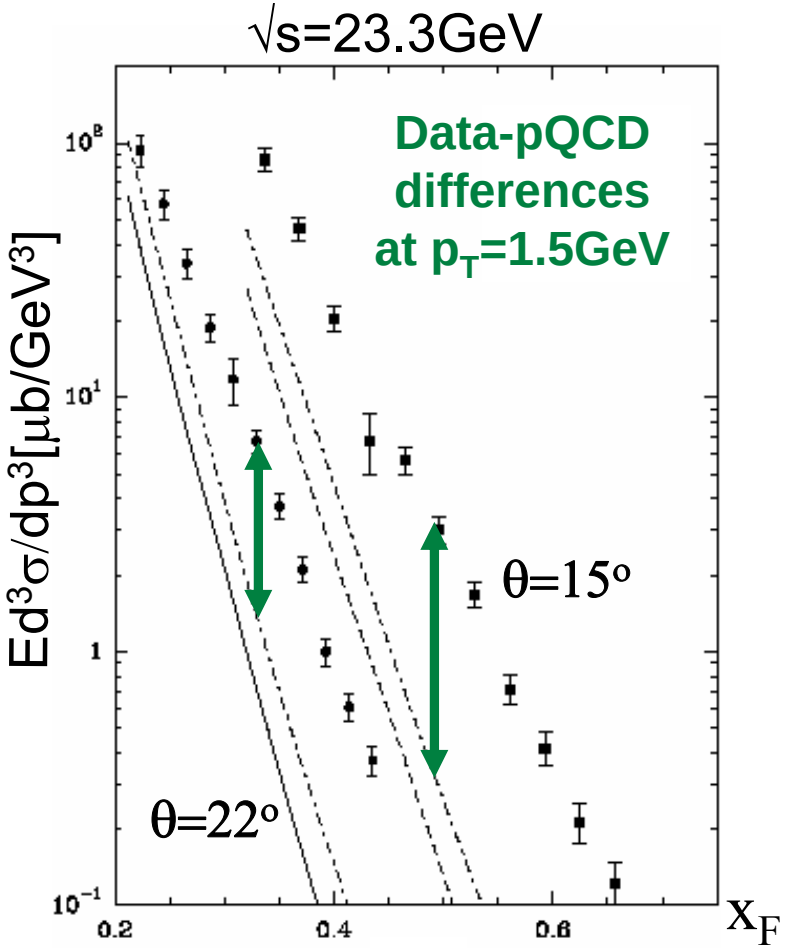
- EM probes will provide important new observables (no fragmentation uncertainties):
  - Direct photons
  - Intermediate mass di-leptons
  - Drell-Yan
  - **Will need RHIC II luminosities**

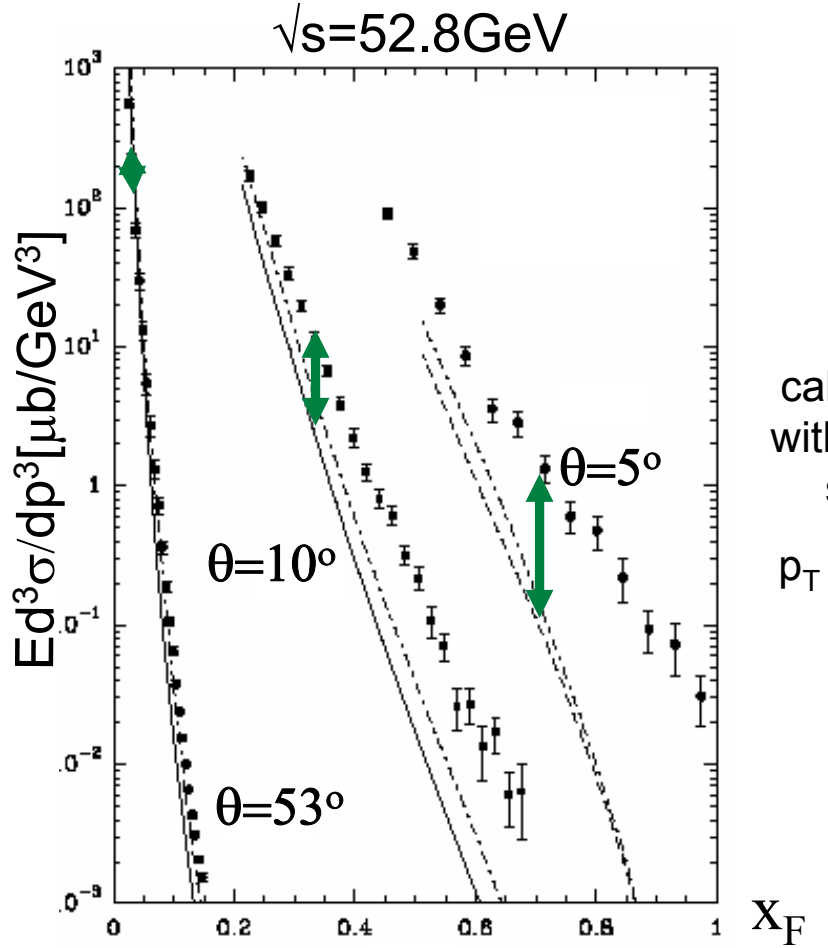
Conclusions

- What is the nature of glue at high density?
  - How do strong fields appear in hadronic or nuclear wave functions at high energies?
  - What are the appropriate degrees of freedom?
  - How do they respond to external probes or scattering?
  - Is this response universal (ep, pp, eA, pA, AA)?

- Detailed understanding will require complementary high-precision measurements at **RHIC-II, LHC, and EIC**.

Do we understand forward π^0 production in p + p?





NLO calculations with different scales:

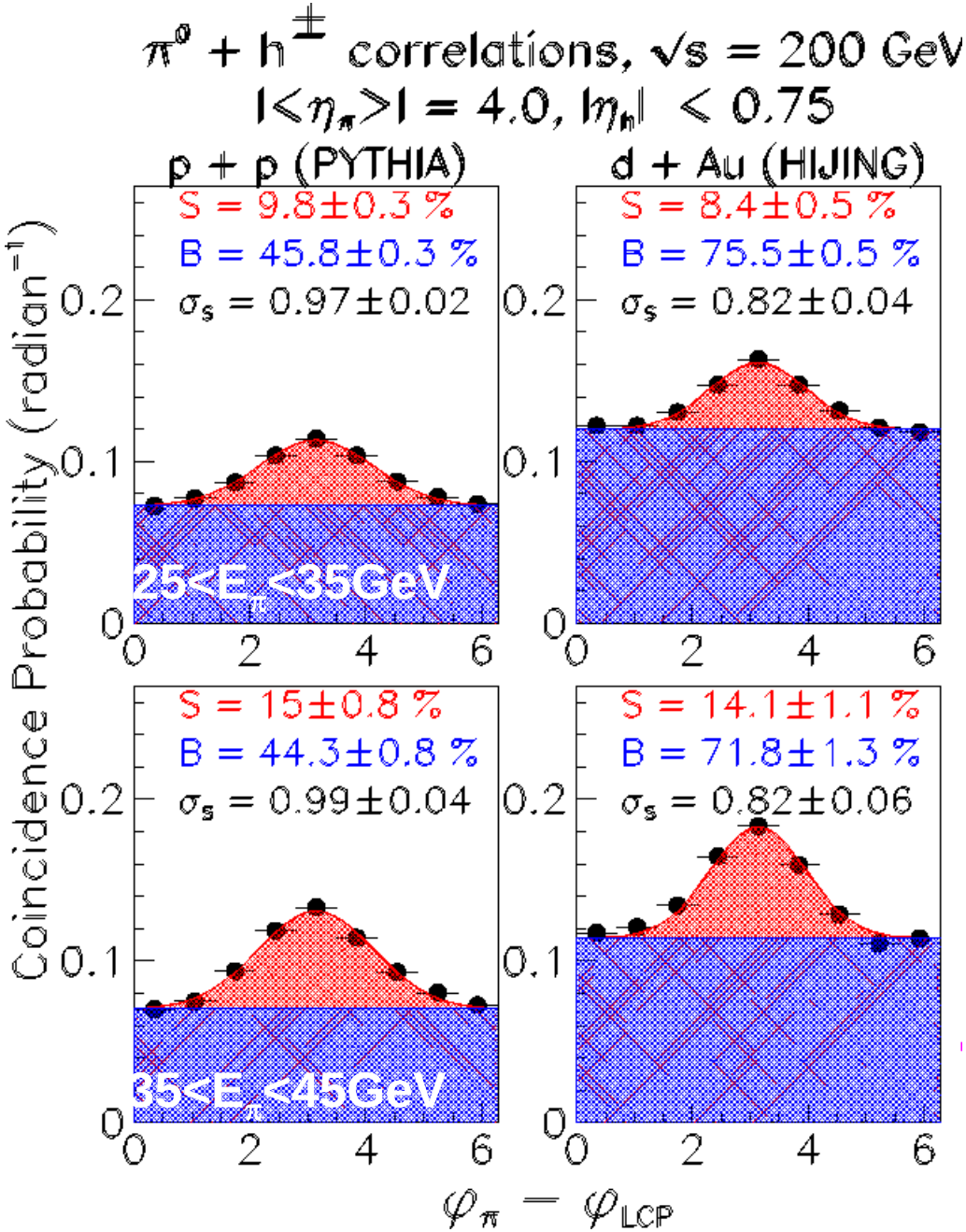
p_T and $p_T/2$

Bourrely and Soffer, EPJ C36, 371:

NLO pQCD calculations underpredict the data at low √s from ISR

Ratio appears to be a function of angle and √s, in addition to p_T

Forward + mid-rapidity di-hadron correlations



- HIJING predicts **similar correlations in d+Au** as PYTHIA predicts for p+p.
  - -- Sizable increase in the combinatorial background.
  - -- Small reduction in the coincidence signal.