

Forward Physics with BRAHMS in pp and dA collisions at RHIC

Connections to QCD, low-x and the Color Glass Condensate

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Renaissance

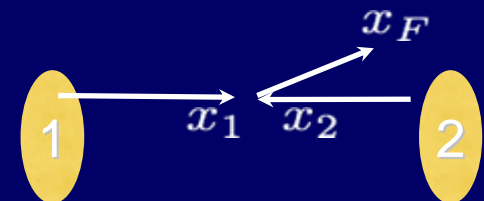
Outline of the presentation

- Background.
- pp at 200 and 62 GeV
 - results and comparisons to pQCD.
- dA Results
 - Is gluon saturation important at high rapidities?
 - R_{dA} , R_{cp} (rapidity, centrality dependence)
- Summary

Introduction

- Forward rapidity at RHIC collider $\sqrt{s} = 200$ GeV offers insight into pp, p(d)A and AA in
 - Low-x region (for target like p, A)
 - Probing larger x_F region where kinematic constraints may be important.

- Opportunities to study if pQCD works at RHIC energies at large rapidities



$$x_F = x_1 - x_2$$

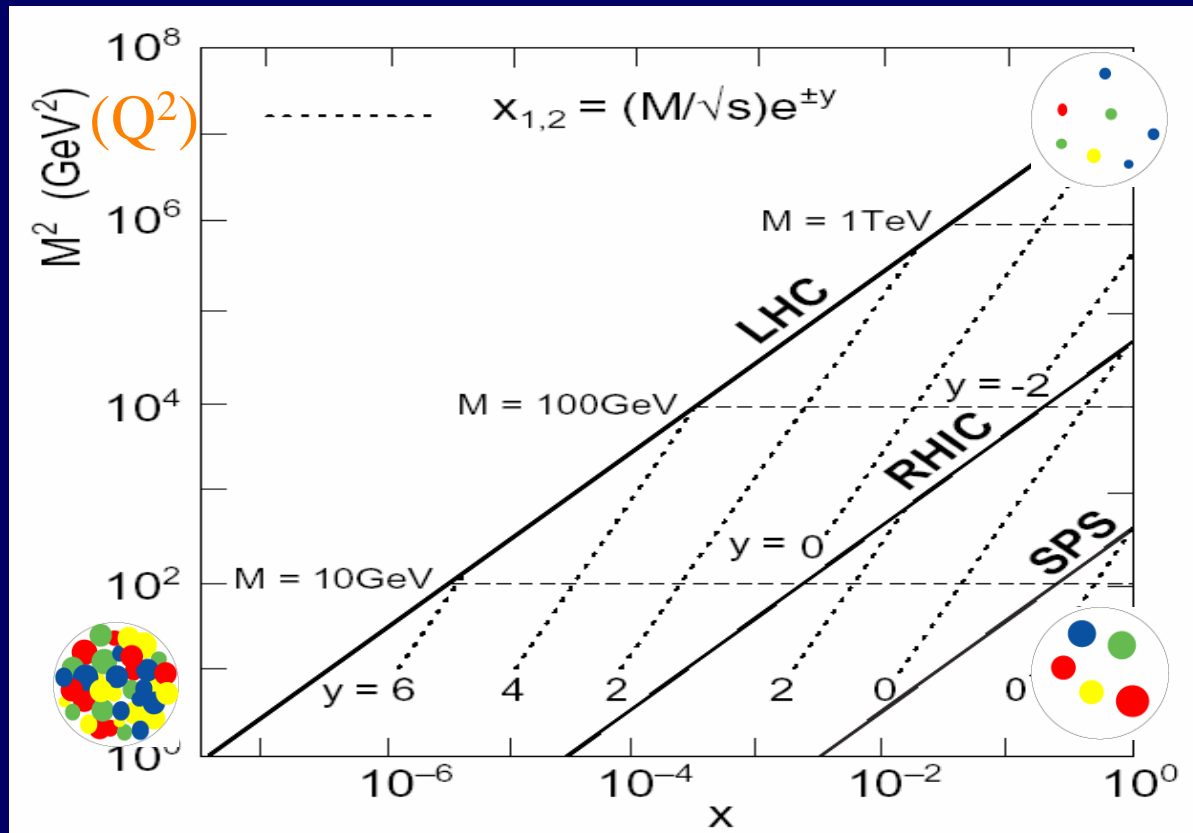
$$x_1 x_2 = \frac{m_T^2}{s}$$

$$x_1 \sim \frac{m_T}{\sqrt{s}} e^y \quad x_2 \sim \frac{m_T}{\sqrt{s}} e^{-y}$$

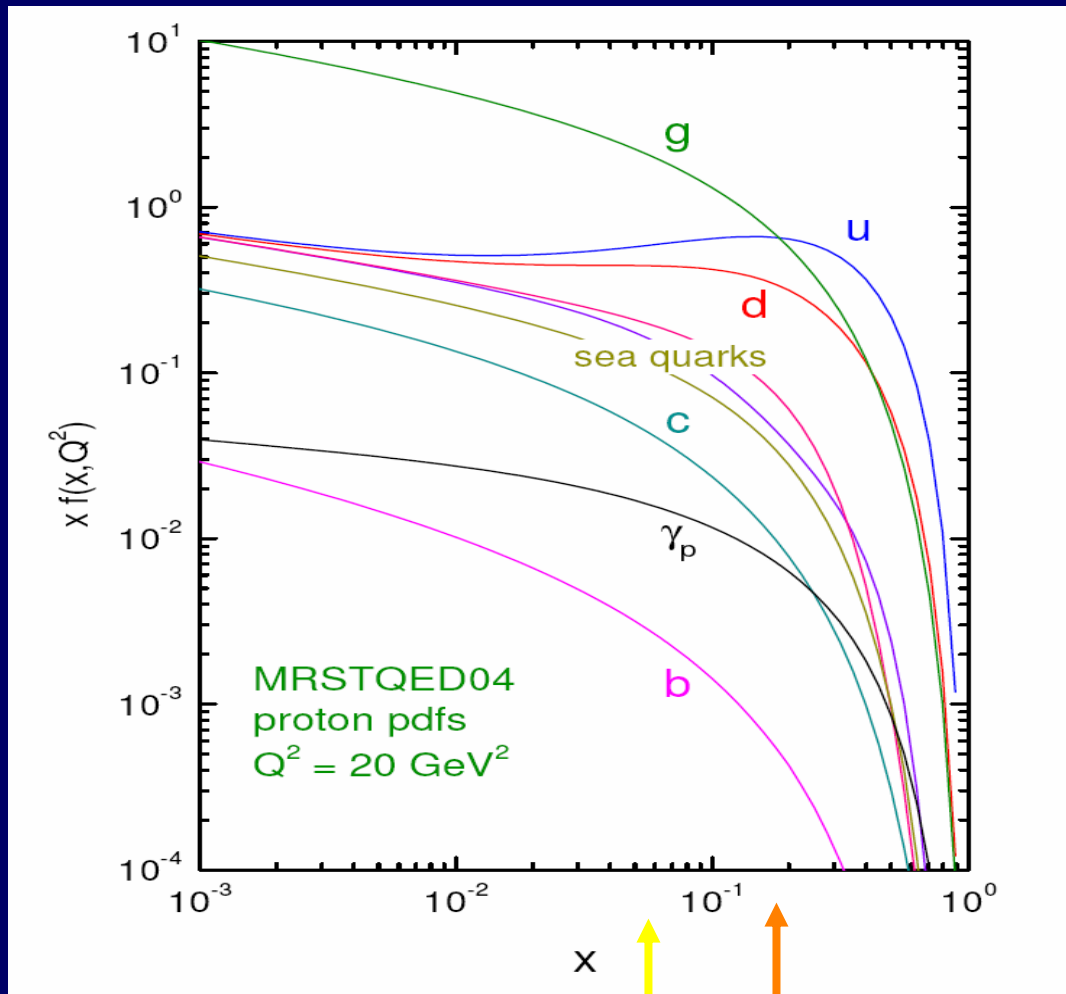
Access to range of Q^2 and x

The x - Q^2 region accessible is illustrated in the following. Note the region reachable at RHIC.

In $p(d)A$ the saturation will decrease the effective x -range by $A^{1/3}$. At RHIC at $y \sim 3$ can reach into $x_2 \sim 10^{-3}$.



Parton Distribution Functions



X_2 range

X_1 range

Measurements at high rapidity set the dominant parton type:
Projectile ($x_1 \sim 1$) mostly valence quarks.

Target ($x_2 < 0.01$) mainly gluons.

Some questions:

How well does NLO pQCD work at RHIC and at large rapidities?

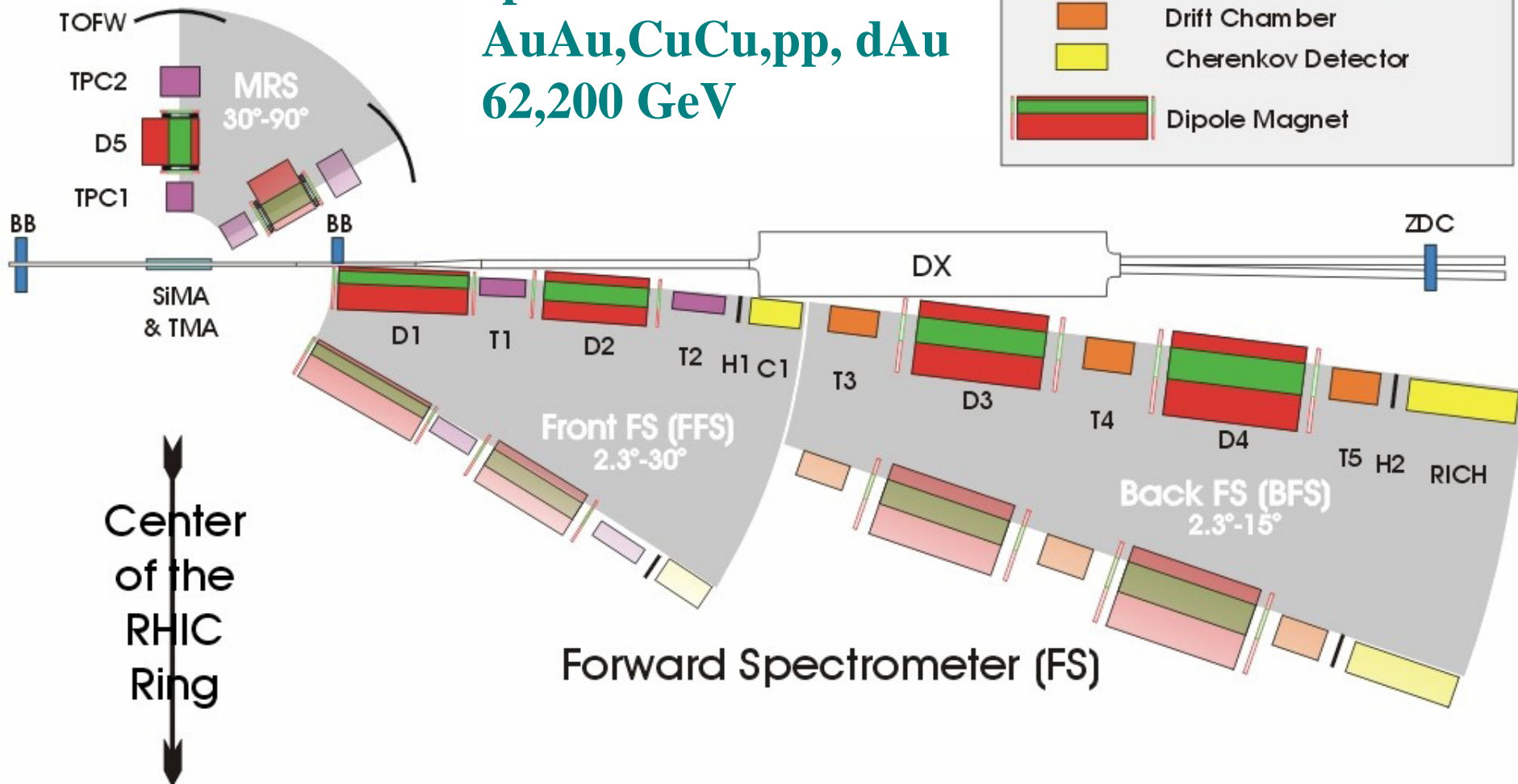
Are there effects from small- x at large y ?

BRAHMS Experimental Setup

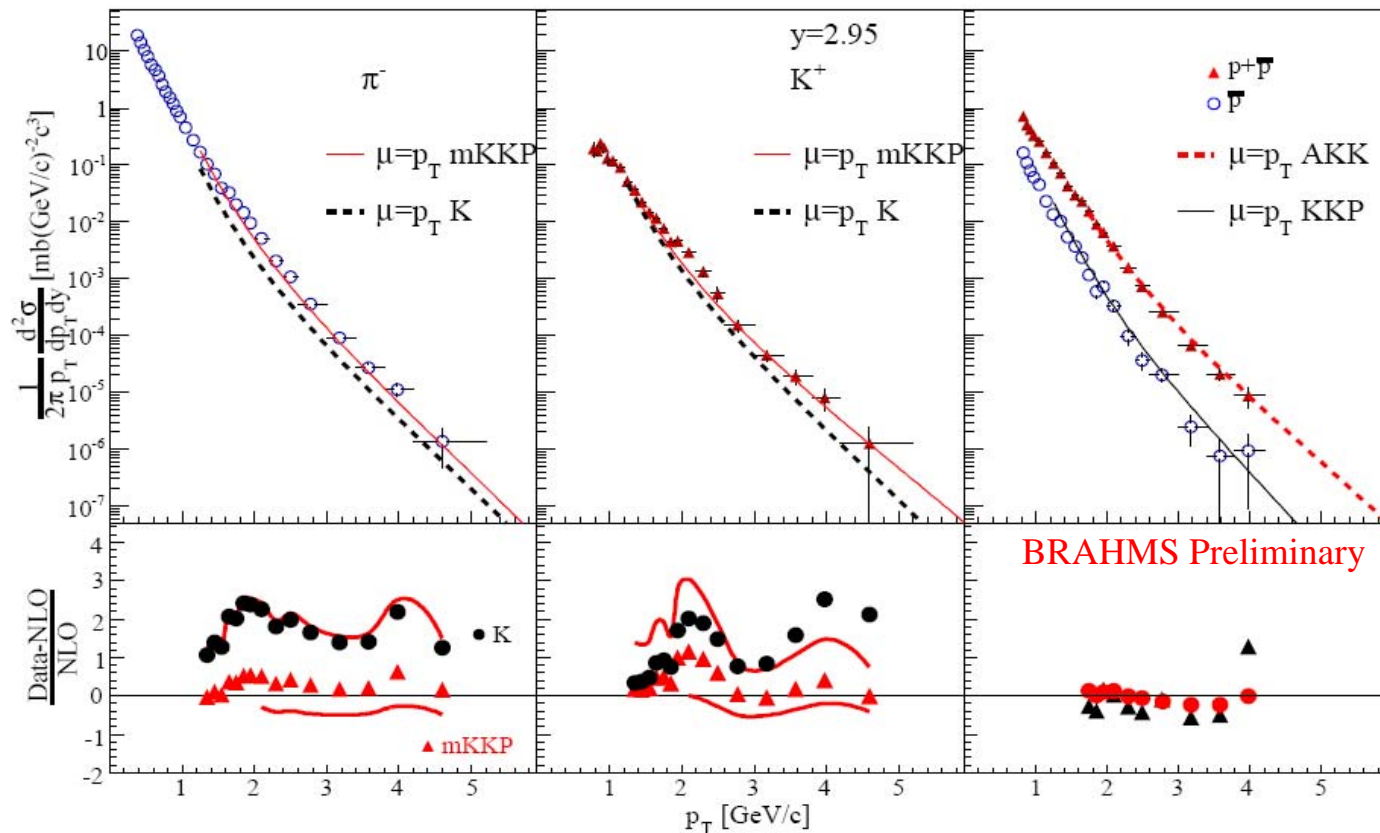
Mid Rapidity Spectrometer

Heavy Ion Exp, pp, pp
spin 2000-2006

AuAu, CuCu, pp, dAu
62,200 GeV



NLO pQCD comparisons to BRAHMS data

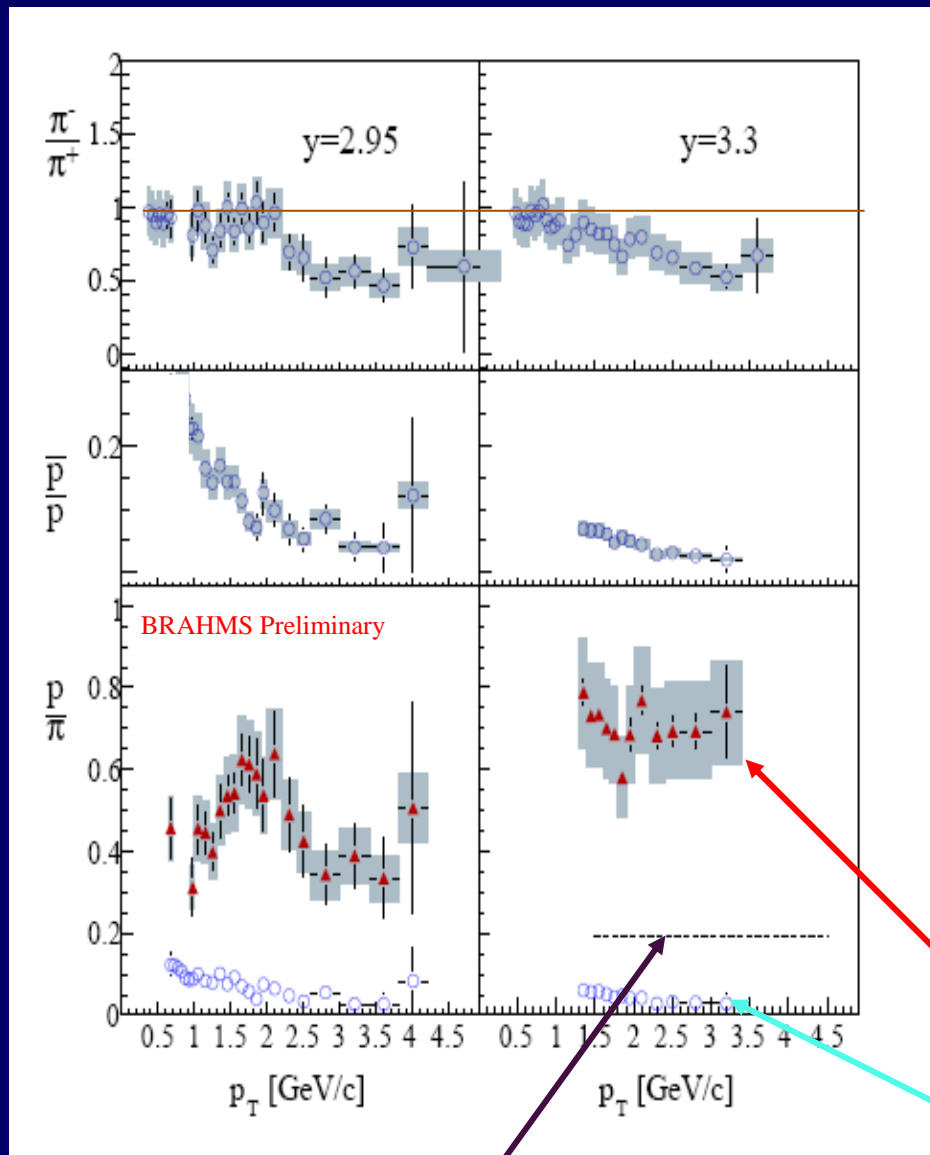


Calculations done by W. Vogelsang. Only one scale $\mu=p_T$ and the same fragmentation functions as used for the PHENIX/STAR comparisons.

KKP has only π^0 frag. Modifications were needed to produce charged pions

KKP FF does a better job compared to Kretzer, Pi and Kaon production still dominated by gg and gq at these rapidities apart from the highest p_T

Ratios p/π^+ at $y=3.0$ and 3.3



The π^-/π^+ ratio is consistent with dominance of valence quarks at these rapidities at the higher p_T .

Small \bar{p}/p ratio eliminates possible strong gluon $\rightarrow p$ or \bar{p} fragmentation ($p/\bar{p} \sim 1$)

The difference between protons and anti-protons indicates fragmentation (as AKK) is not dominant mechanism.

Related to projectile baryon content, but why to high p_T ?

Red: p/π^+

Blue: \bar{p}/π^-

A newly posted paper uses these BRAHMS data in a global fit to e+e- SIDIS, and pp data to extract fragmentation functions and explicitly check factorization. An example of their fit to our K+- data are shown. The RHIC pp data are important to obtain flavor separated fragmentation functions.

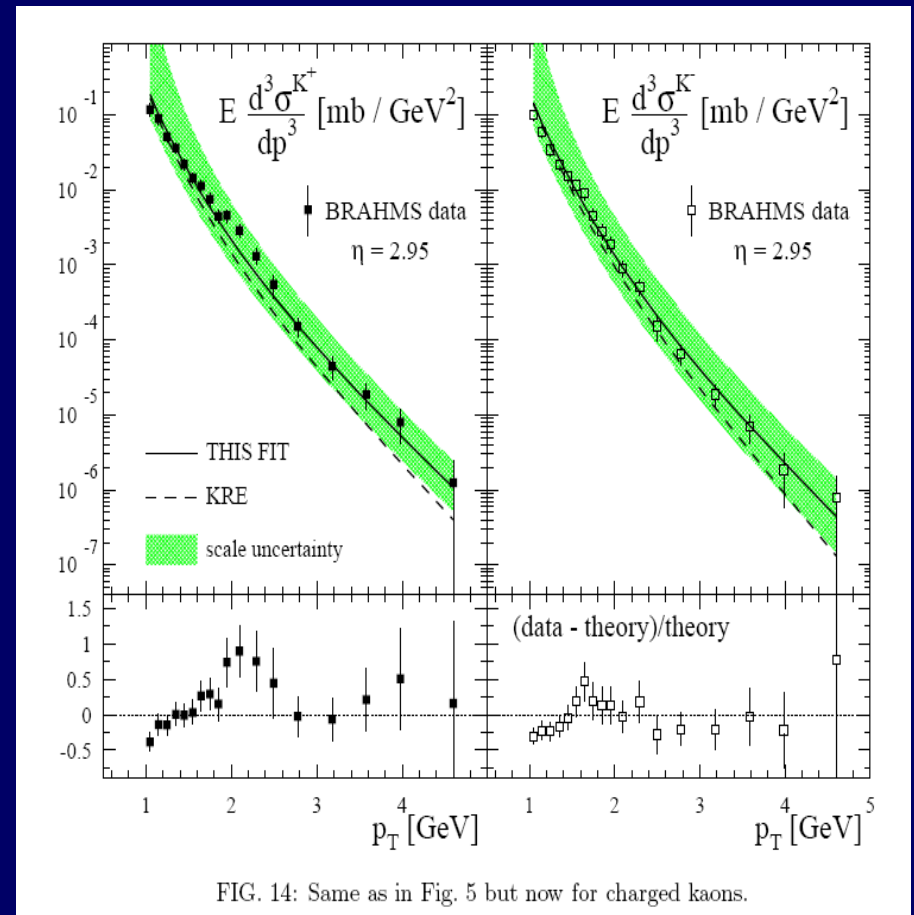
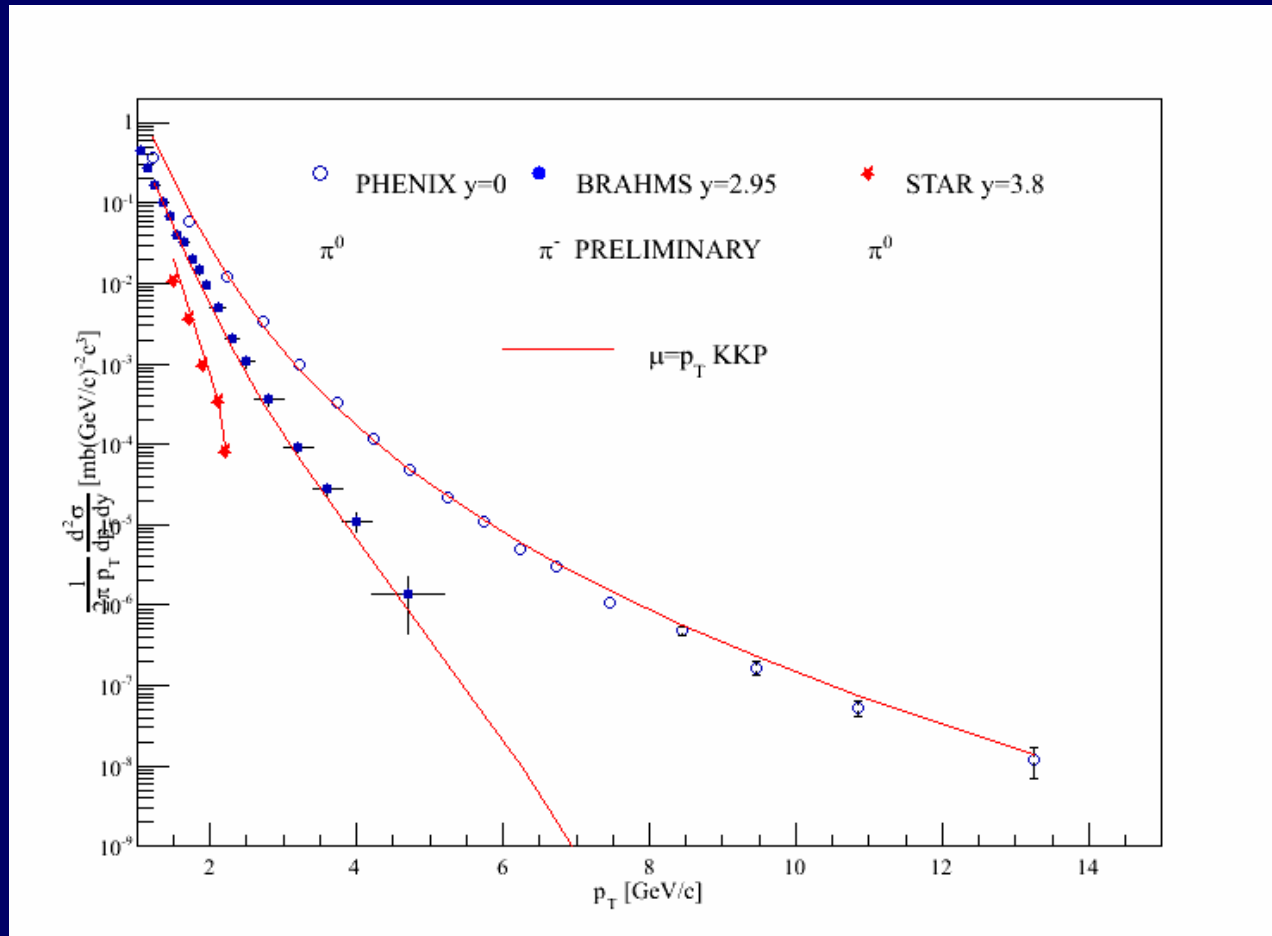


FIG. 14: Same as in Fig. 5 but now for charged kaons.

D.Florian, R.Sassot and M.Stratman,
Hep-ph/0703242

Another view of rapidity dependence .



NLO pQCD works at all rapidities at RHIC 200 GeV.

pp at 62 GeV

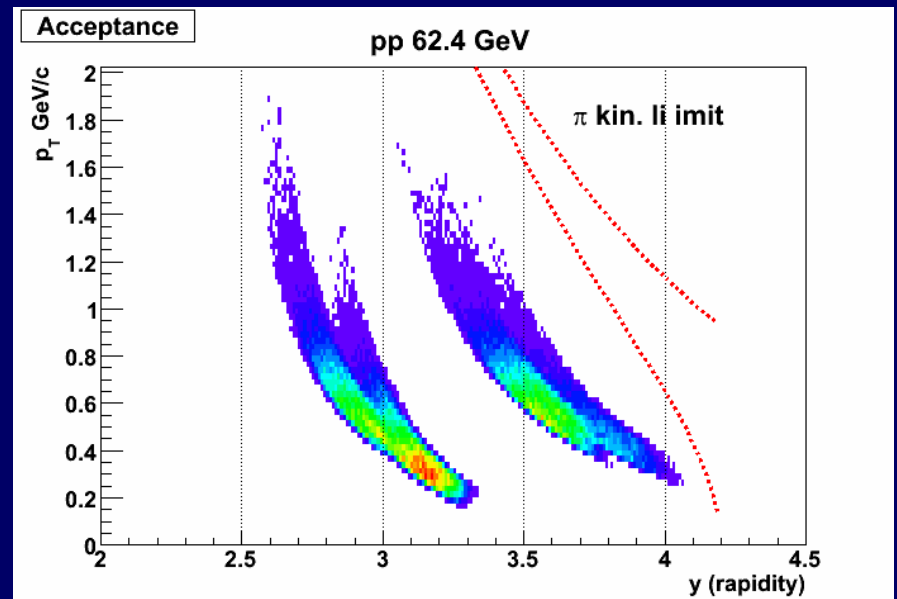
Brahms took data during the two-week 62.4 GeV in June 2006.

The focus was on

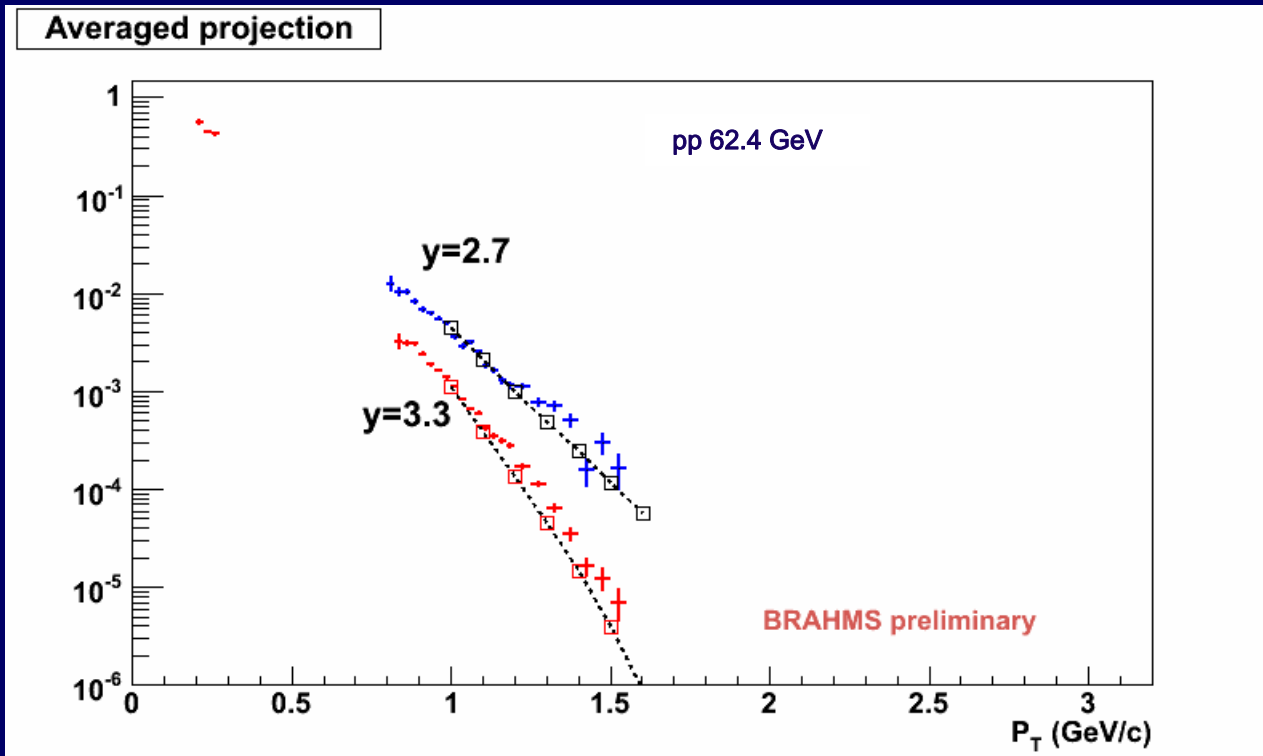
Reference spectra for AuAu

Single Spin asymmetries.

Coverage for π^- at forward rapidities. Note the kinematic limits



High rapidity $pp \rightarrow \pi^- X$



Comparison of NLO pQCD calculations (Vogelsang) with BRAHMS π^- data at high rapidity. The calculations are for KKP and a scale factor of $\mu=p_t$.

The agreement is surprisingly good in view of analysis of slightly lower ISR data at large y [C.Bourrely and J.Soffer Eur.Phys. J.C36,371 (2004)] which failed to describe π^0 at larger x_F .

Summary pp spectra

- At RHIC we now have identified charged particle production at high rapidity to large p_T
- NLO pQCD calculations describe the pion and kaon production with fragmentation functions known as mKKP. This agreement imply a dominance of gq and gg processes at these high rapidities as was the case for the measurements of neutral pions at mid-rapidity.
- Even at 62.4 GeV the NLO pQCD describes the data at high rapidity. This is surprising in view of the previous studies (Soffer). It may be related to the kinematic range studied in our data.

2. d-Au results

Nuclear medium effects:

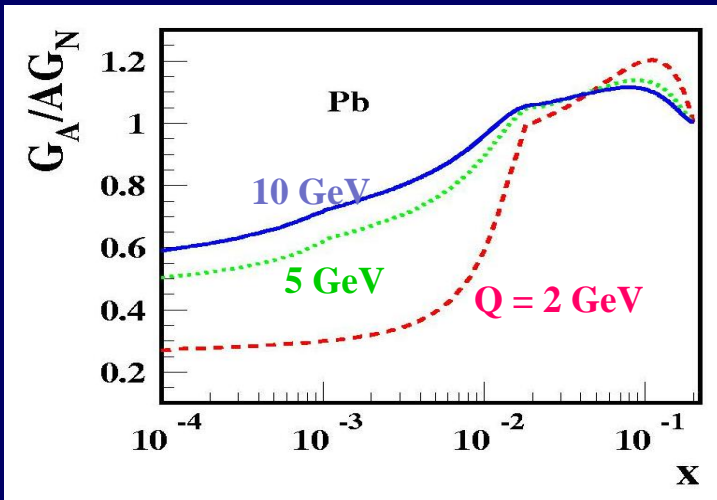
- High p_T suppression in d+Au collisions
- Cronin effects at mid-rapidity in d+Au collisions
- Manifestations of Color Glass Condensate (Gluon Saturation) effects at forward rapidity (low-x) in d+Au collisions?

Nuclear Modification Factor

$$R_{dAu} = \frac{d^2 N^{d+Au} / dp_T dy}{N_{coll} d^2 N^{p+p} / dp_T dy}$$

R_{cp} is a similar ratio but with peripheral collisions used as a reference.

Shadowing or formation of a CGC



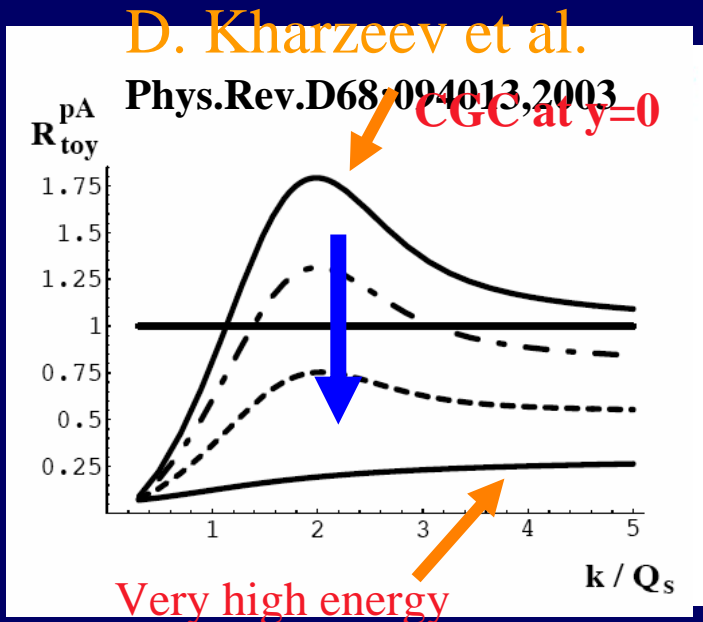
Leading twist gluon shadowing, e.g.:

- Gerland, Frankfurt, Strikman, Stocker & Greiner (hep-ph/9812322)
- phenomenological fit to DIS & DY data, Eskola, Kolhinen, Vogt hep-ph/0104124 and many others

On nuclear modification factor.

Gluon distribution grow at small x (HERA)

The CGC description of evolution of initial state can be probed in nuclear system. (MLV...)

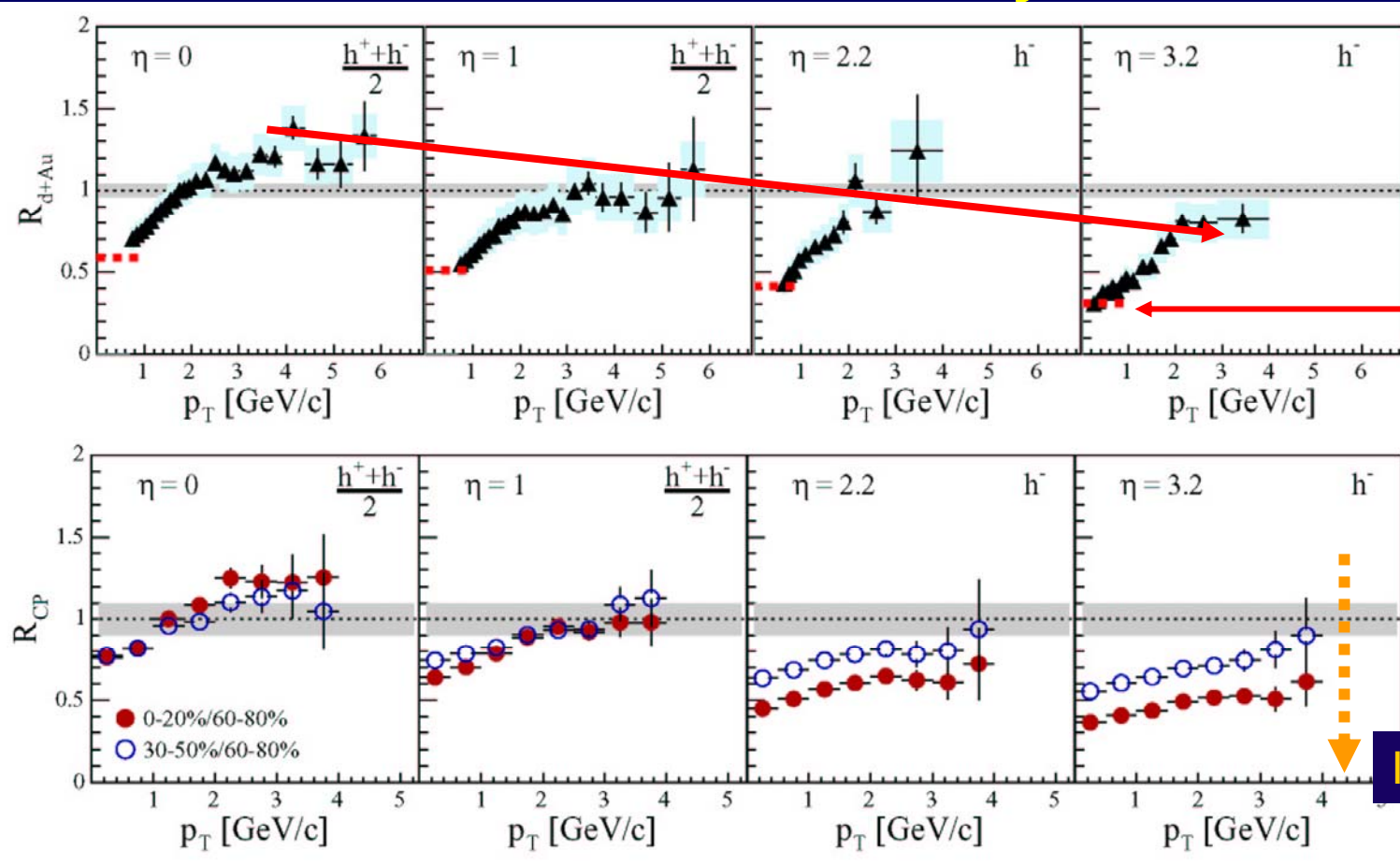


P_T suppression can be related to modification Saturation via quantum evolution (fusion processes).

Evolution from high p_T with linear cross sections to 'saturated' region at lower p_T .

The saturation scale $Q_s^2 \sim A^{1/3} e^{\lambda y}$ $\lambda \sim 0.2-0.3$

BRAHMS d+Au results as function of rapidity and centrality



$$R_{dAu} = \frac{Y_{dAu}}{N_{coll} Y_{pp}}$$

Normalized
ratio of
measured
(integrated)
 $dN/d\eta$
Npart
scaling

Increasing centrality

BRAHMS, PRL 93, 242303

R_{cp} ratios are constructed in wide η bins.

The data have given rise to many interpretations and additional measurements.

Identified Particle R_{dAu}

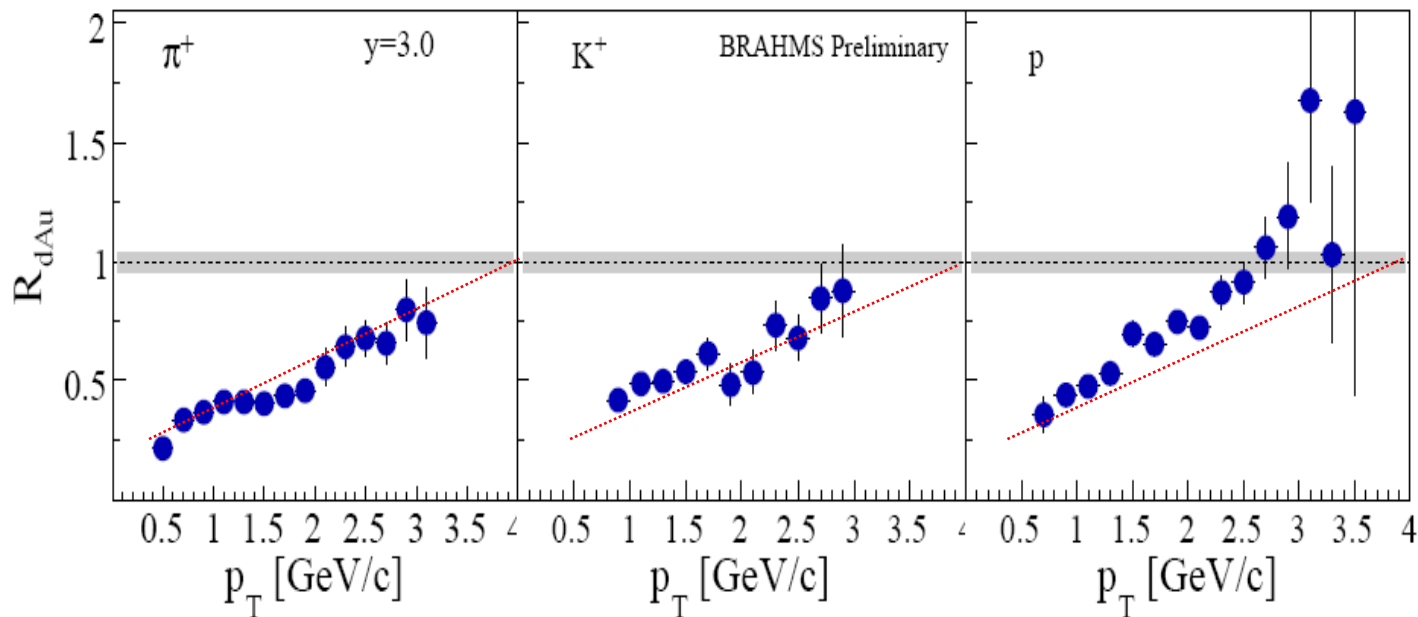
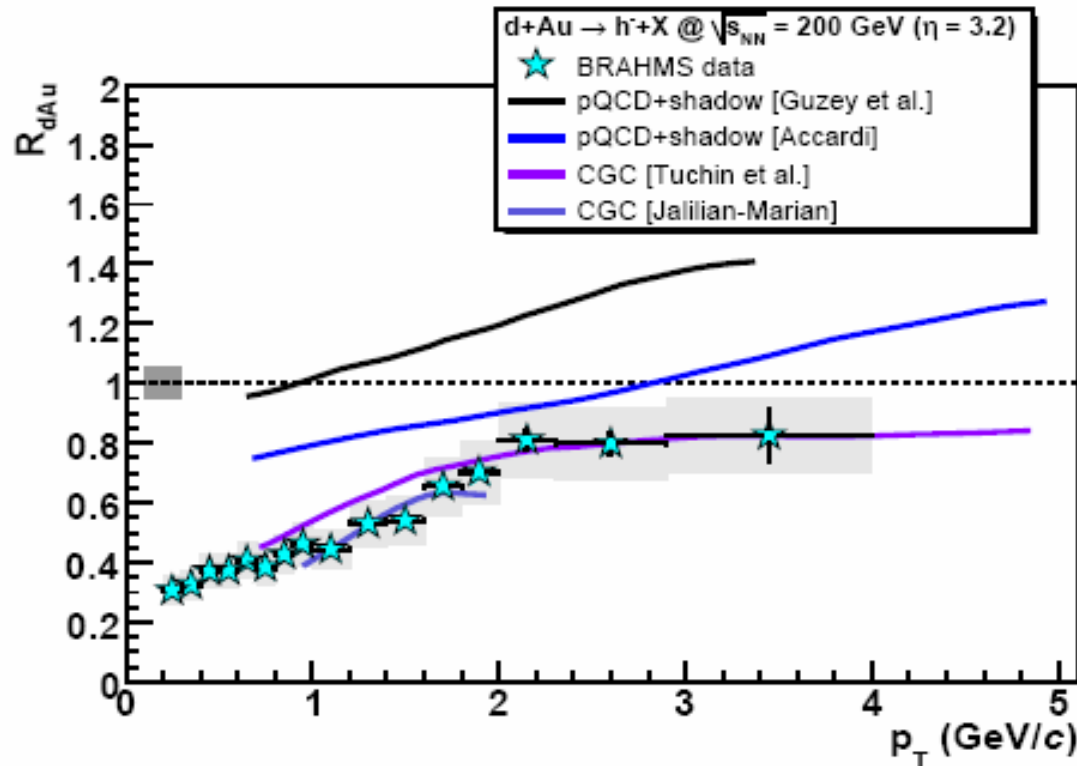


Figure 2. R_{dAu} of π^+ , K^+ and protons at forward rapidity $y = 3.0$ in minimum bias d+Au collisions ($\langle N_{coll} \rangle = 7.2$). A 8% systematic error is included.

R_{dAu} for identified particle consistent with
charged hadrons and all exhibiting $R_{dA} \leq 1$
for $p_T < 3$ GeV/c

The protons may exhibit less suppression.

Comparing pQCD and CGC



Taken from d'Enterria

Leading order pQCD.

No higher twist and possible coherence effects.

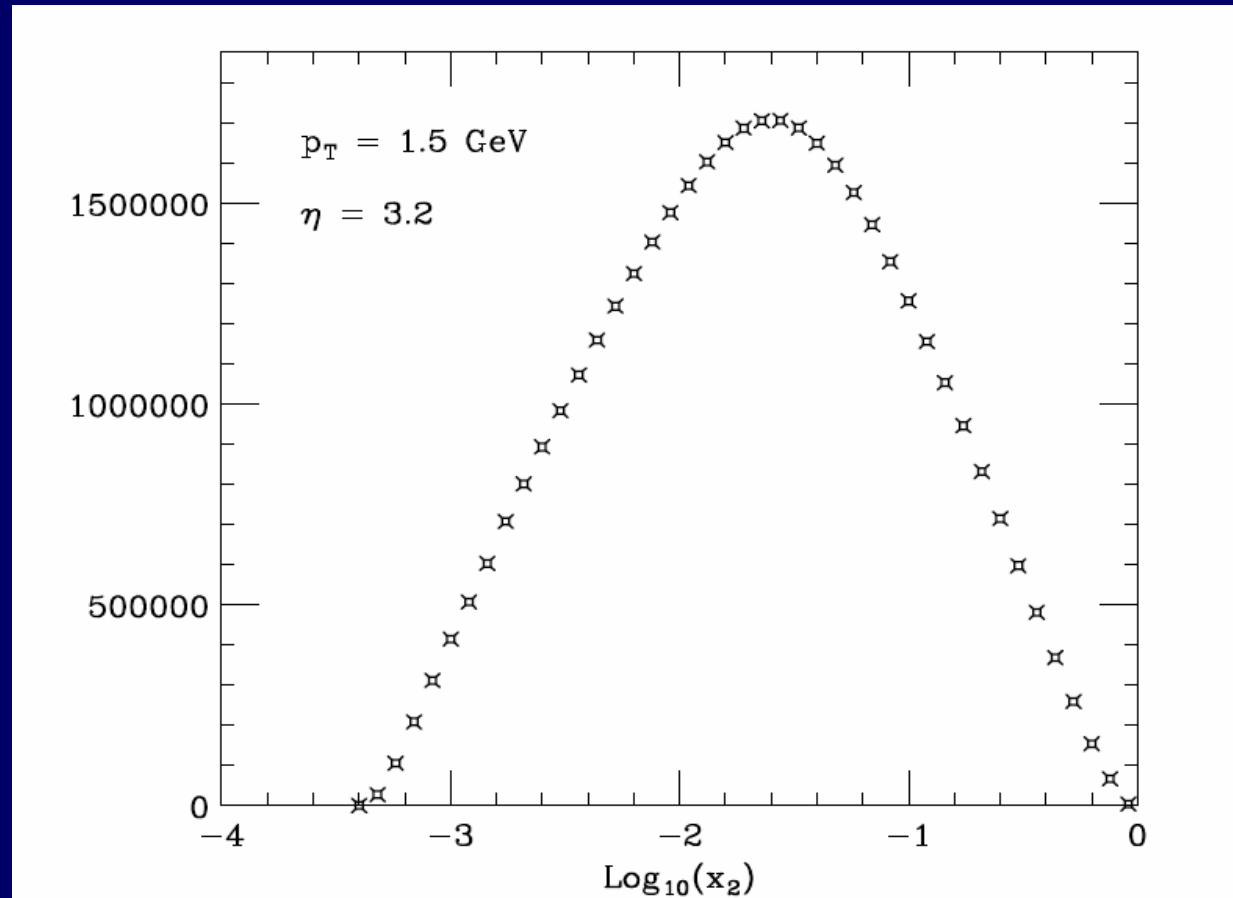
Comment on X-range probed in 2-2 processes

At 4 degrees ($y \sim 3$ for pions) and $p_T = 1$ GeV/c one can reach to values as low of $x_2 \sim 10^{-4}$

But one has to remember that that low number is a lower limit, not a typical value.

From Guzev,
Strikman, and
Vogelsang.

Most of the data
collected at 4
degrees have
 $x_2 \sim 0.01$



B.Kopeliovich (PRC72(2005)054606)

- Sudakov Suppression, not low-x phenomena.
- Reproduce p_T trend and centrality dependence.

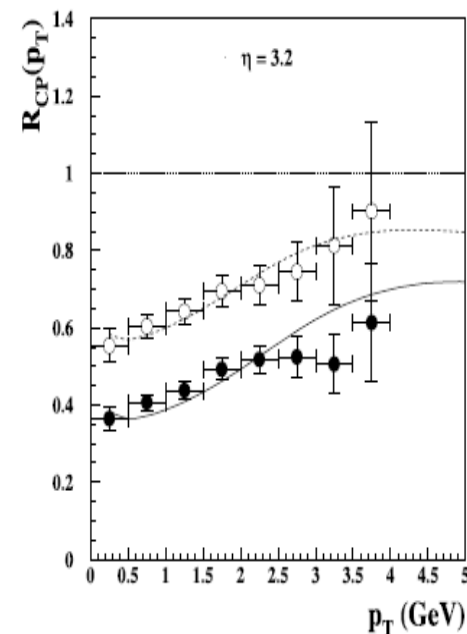
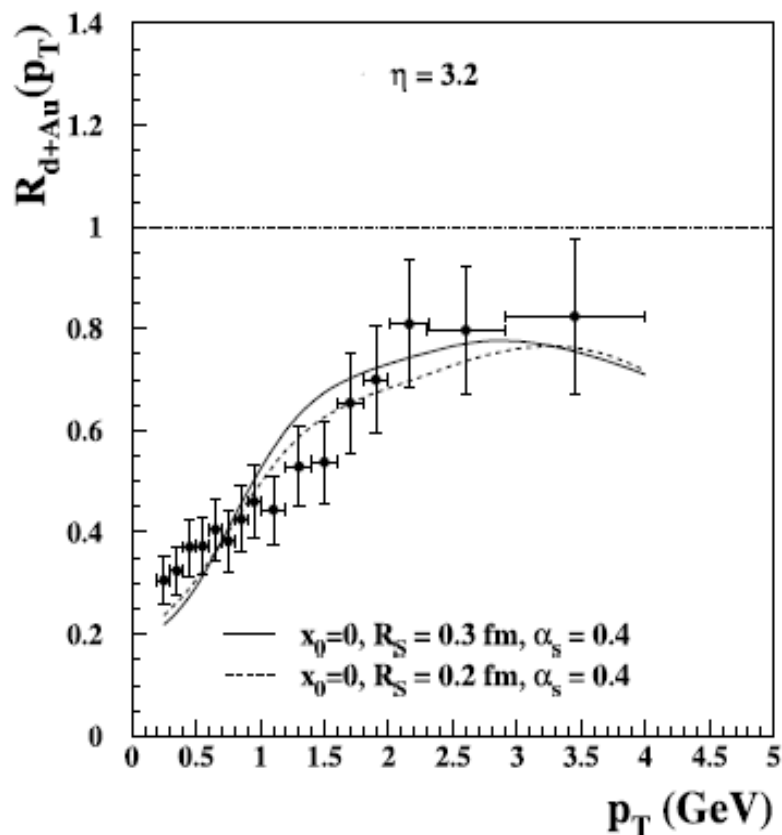


FIG. 5: Ratio of negative particle production in central (0-20%) and semi-central (30-50%) to peripheral (60-80%) d -Au collisions, shown by closed and open points respectively. The results of the corresponding calculations are depicted by solid and dashed curves.

dA summary

- The suppression and in particular the inversion vs. centrality of R_{dA} at high rapidity may be a signature for the gluon saturation and the small- x evolution. The x -range probed is in range of 10^{-3} - 10^{-2} .
- The data are consistent with CGC prediction. Alternate explanations e.g. in terms of Sudakov suppression works quite well too.

Summary

- Forward rapidities at RHIC has given additional insight into hadron scattering
- Pions and kaons pp well described in pQCD; Failure of proton indicates other mechanism.
- dA suppression at high rapidity consistent with saturation picture, but at RHIC energy, x and p_T reach may be too small to decisively settle this.
- LHC is promising for studying low- x physics in great detail covering large x and p_T range.