Forward Physics at RHIC

Connections to QCD and the Color Glass Condensate

Flemming Videbaek
Physics Department, BNL

BRAHMS

BROOKHAVEN NATIONAL LABORATORY

Office of Science U.S. DEPARTMENT OF ENERGY

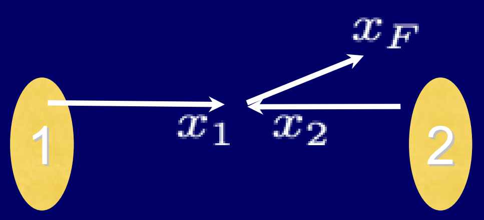
Outline of the presentation

- Background.
- pp at 200 GeV
    - results and comparisons to pQCD.
- dA Results
    - R_{dA}, R_{cp} (rapidity, centrality dependence)
    - Discussion relating to saturation
    - Future measurements
- A-A at high rapidity

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 constraint may be important. $\sqrt{s}$

- Longitudinal properties of hot and dense medium (AA)



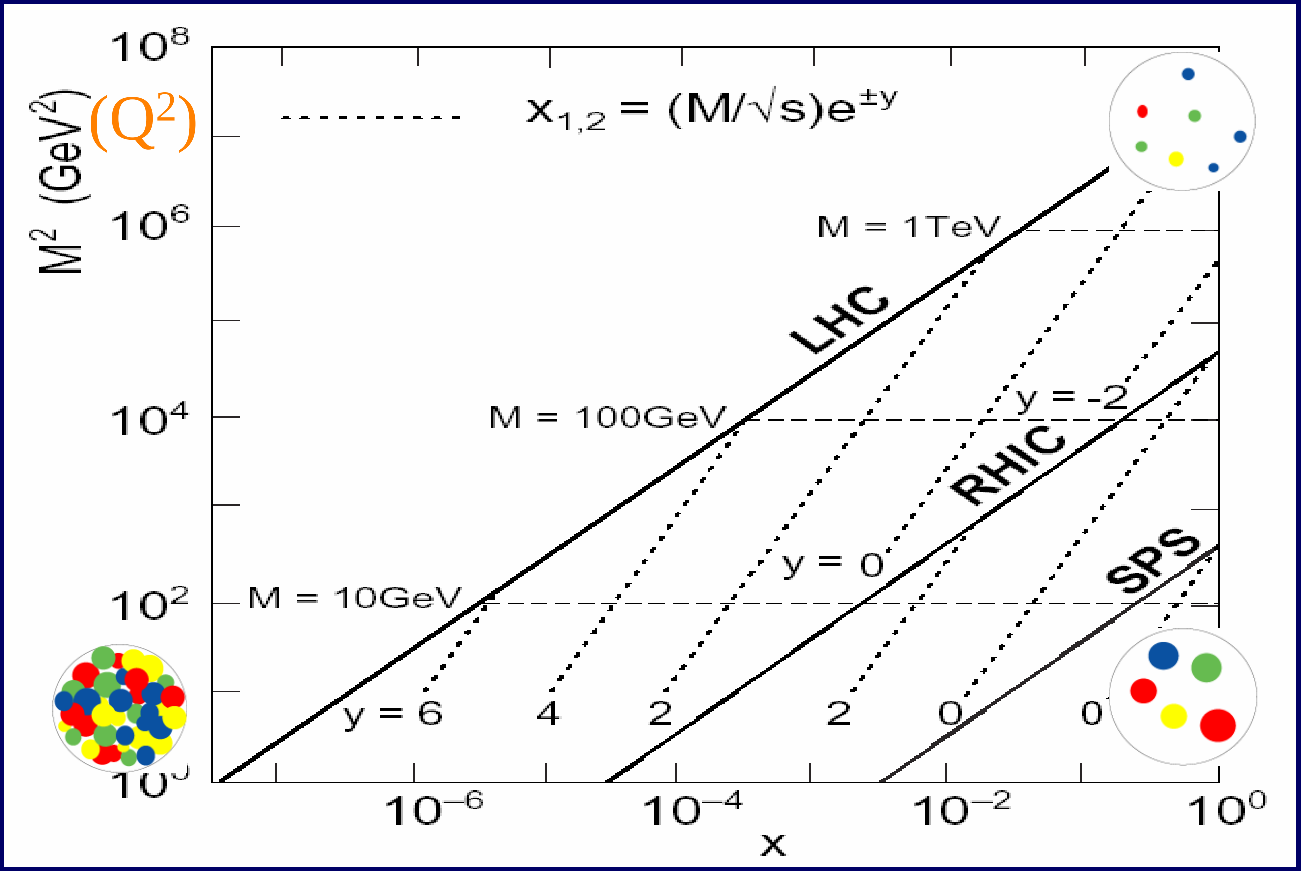
$$x_F = x_1 - x_2$$

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

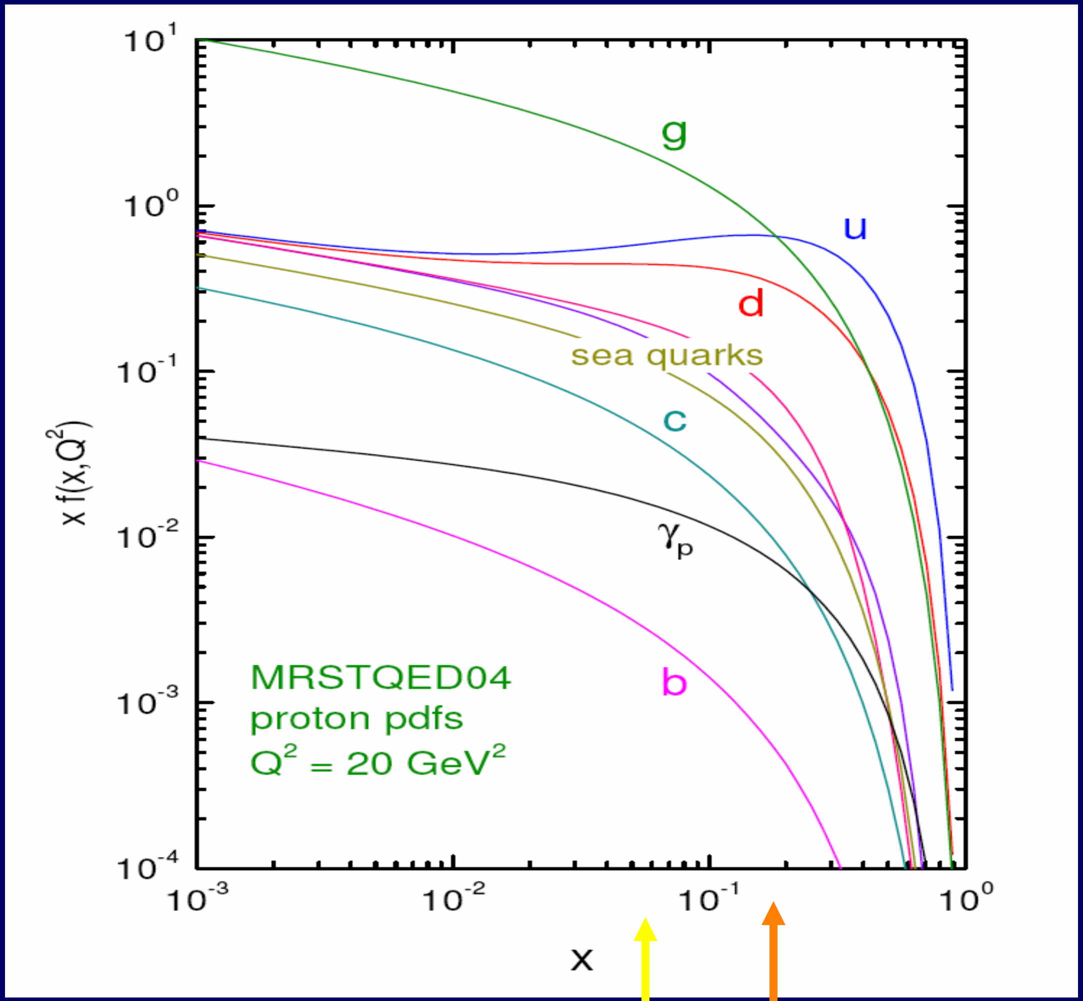
$$x_1 \sim \frac{m_T}{\sqrt{s}} e^{y} \quad x_2 \sim \frac{m_T}{\sqrt{s}} e^{-y}$$

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 x-range by $A^{1/3}$



Parton Distribution Functions



X_2 range

X_1 range

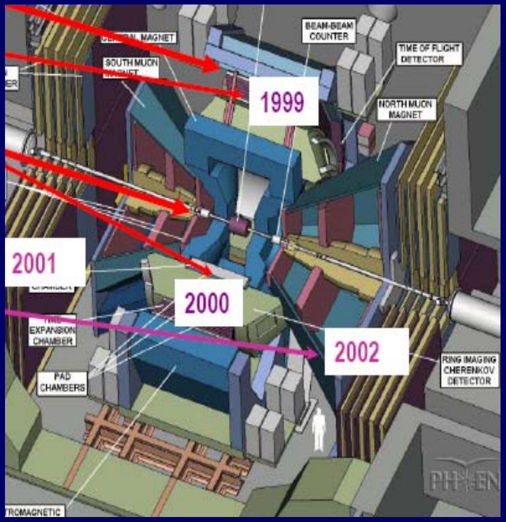
Measurements at high rapidity set the dominant parton type:
Projectile (x_1 ~1) mostly valence quarks.

Target (x_2<0.01) mainly gluons.

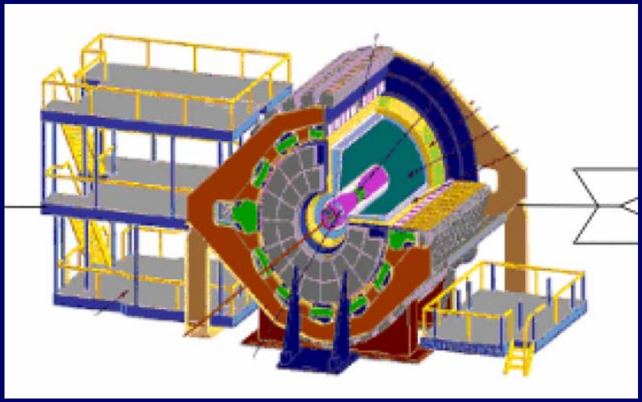
Some Q's:

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

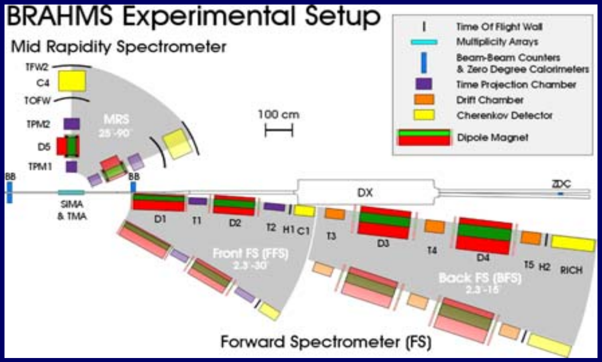
PHENIX: muons inferred
hadrons at h~ 2 moderate p_T
Identified particles at |h|<.35



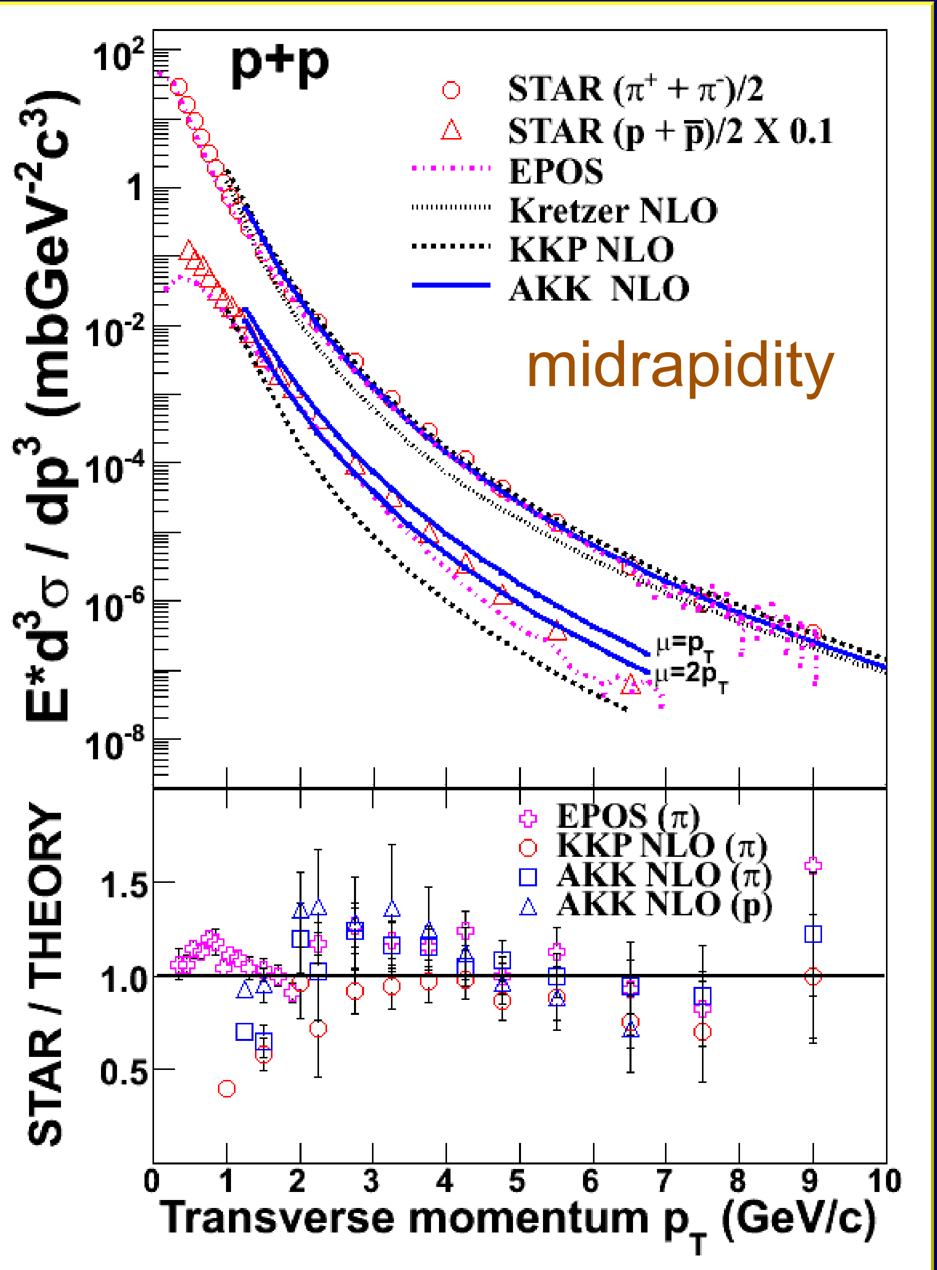
STAR: π^0 at h ~3.2-4.5 . Charged hadrons correlations at $|\eta|$ < 1



BRAHMS : small solid angle spectrometer with charged hadron ID for 0<h < 4. Moderate p_T < 4 GeV/c



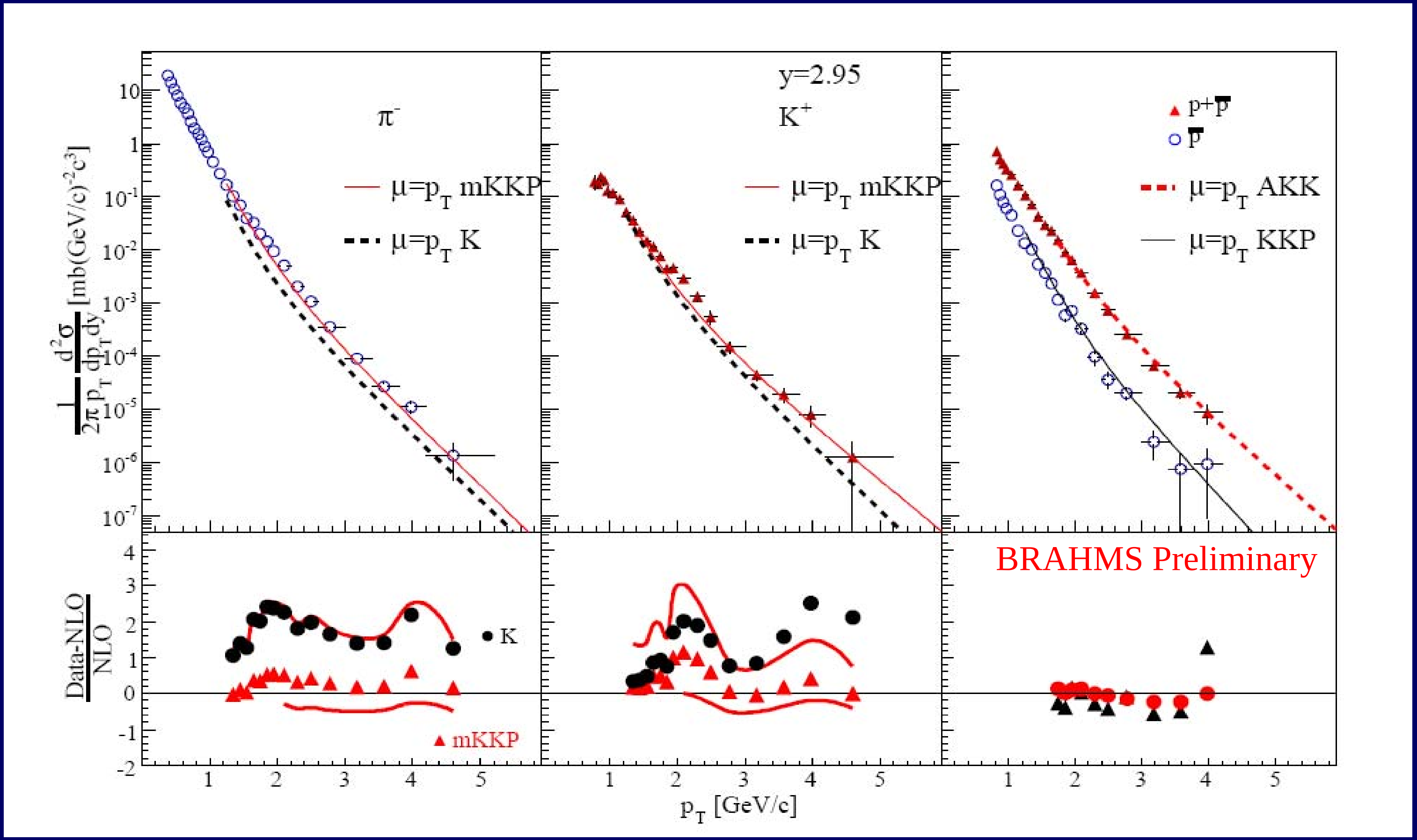
NLO pQCD for proton+anti-proton compared to data



A recent update of the KKP fragmentation function is used for this comparison: AKK coming from flavor separated analysis of e+e-. (gq importance)

The AKK PDF does well at y=0 (STAR p+p) where the ratio anti-p/p~1 can be seen as consistent with dominance of gg or gq processes; Consistent with approximate equal # p and p-bar

NLO pQCD comparisons to BRAHMS data

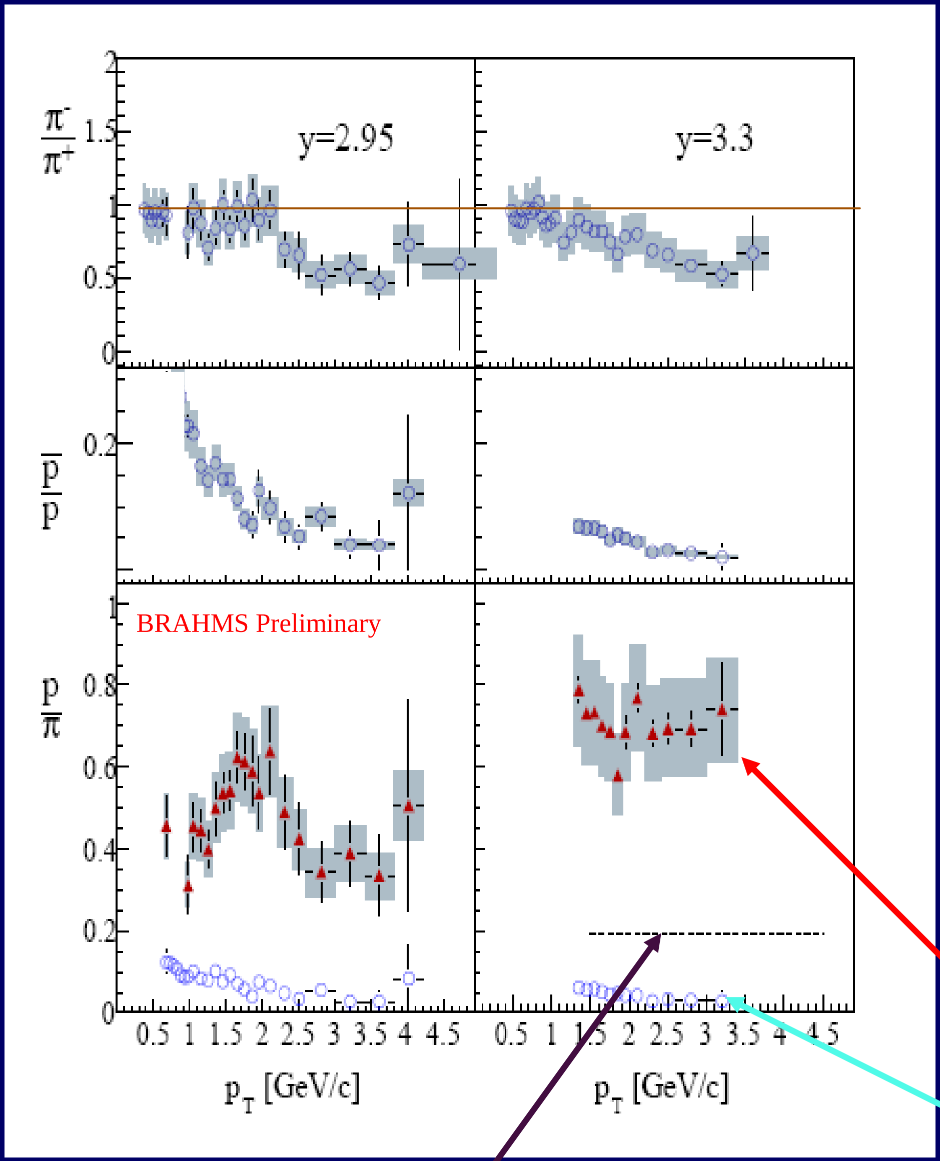


Calculations done by W. Vogelsang. Only one scale $\mu=p_T$ and the same fragmentation functions as used for the PHENIX/STAR comparisons.

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 -> p or $\bar{p}$ fragmentation ($p/\bar{p}$~1)

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

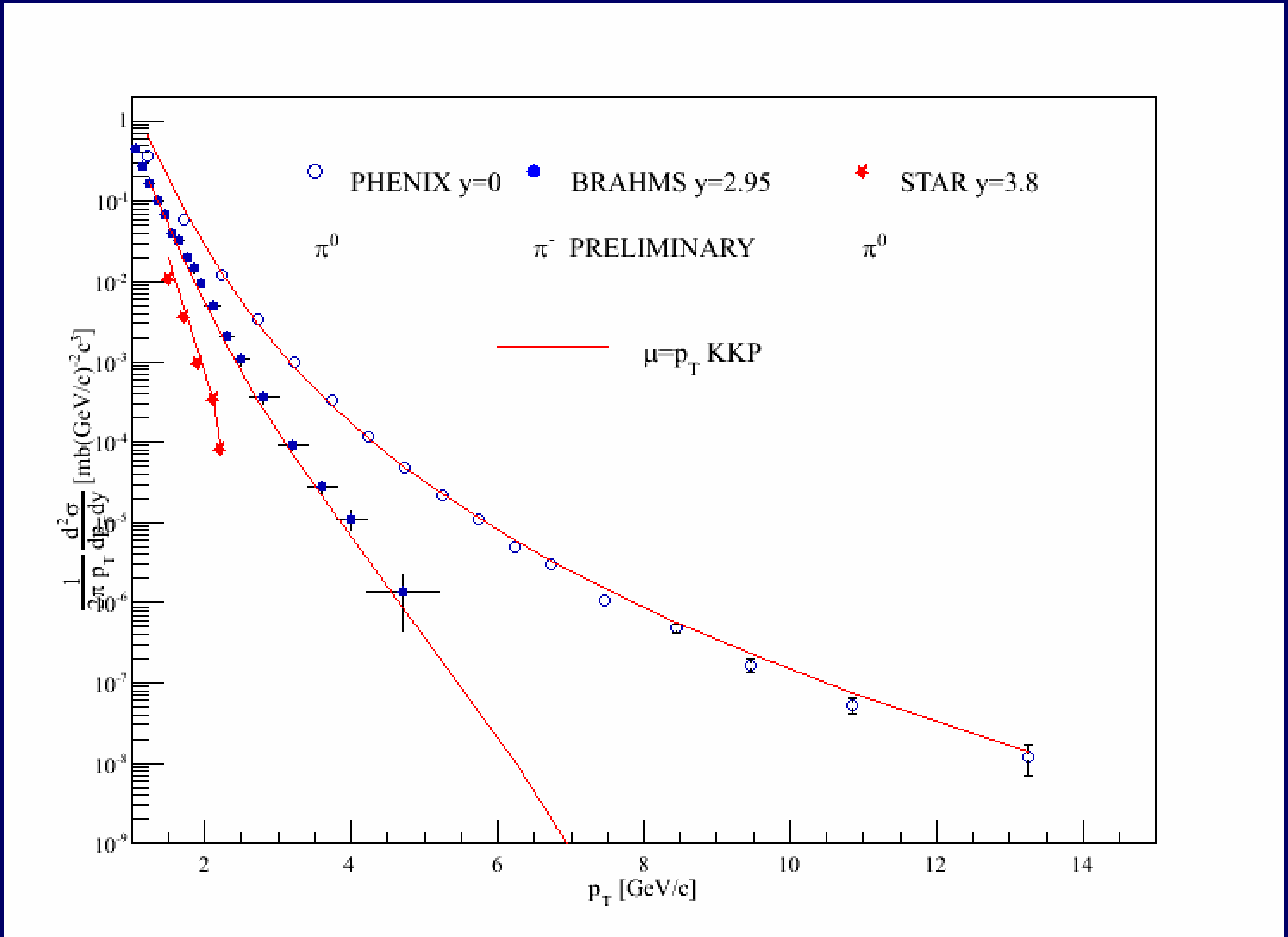
Related to projectile baryon content, but why to high p_T?

Red: p/π^+

Blue: $\bar{p}/\pi^-$

e^+e^- p+pbar/π^++ π^- ALEPH

Another view of rapidity dependence .



Notice the significant change in shape due to available phase space

Summary pp

- 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.
- The behavior of protons around y=3 cannot be explained with NLO calculation and the abundance of protons (with respect to positive pions) at high p_T is an open question clear related to baryon transport; Protons have larger mass-scale and larger number of constituents

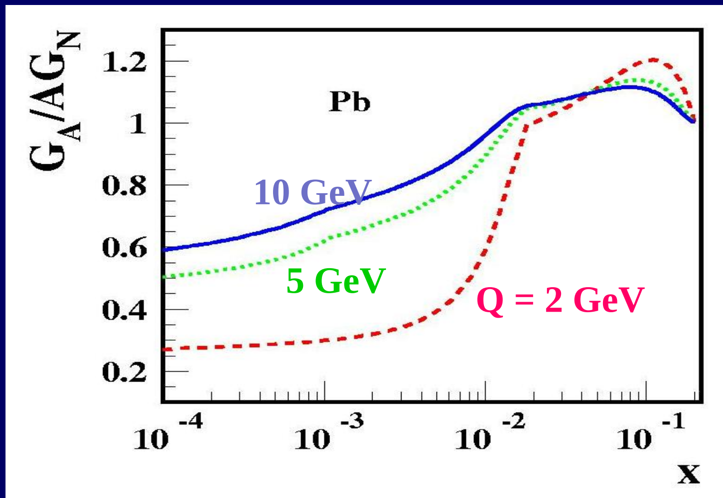
2. d-Au results

- 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:

$$R_{dAu} = \frac{d^2N/dp_T d\eta \ (d+Au)}{N_{Coll} d^2N/dp_T d\eta \ (p+p)}$$

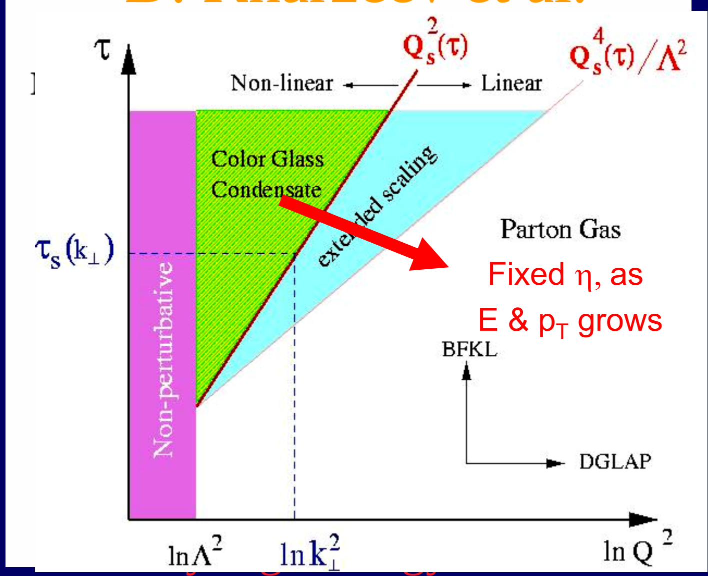
R_{cp} similar ratio by defined relative to peripheral collisions.

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**

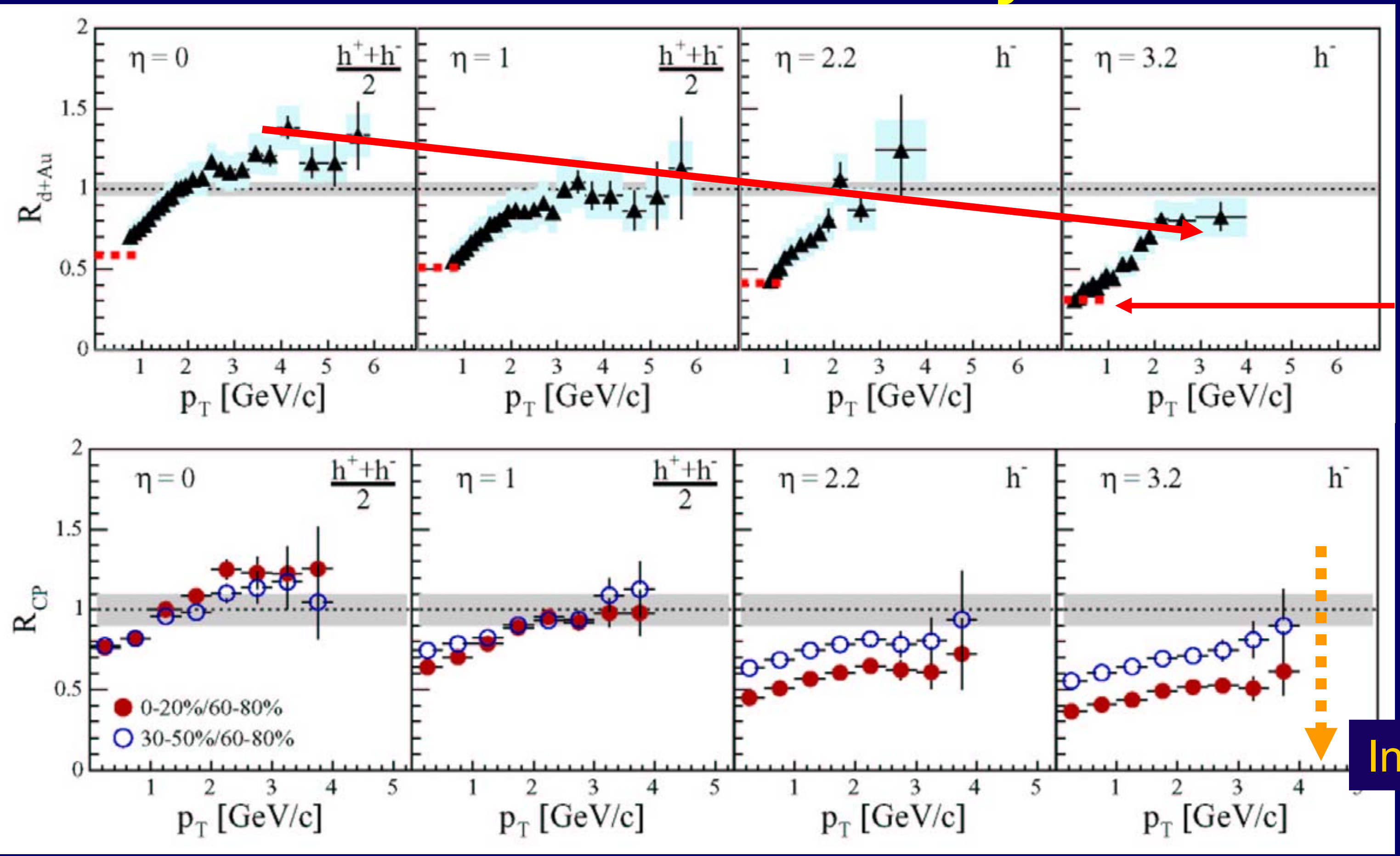
D. Kharzeev et al.



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 pt-t with linear cross sections to 'saturated' region at lower p_T.
The saturation scale $Q_s^2 \sim A^{1/3} e^{\lambda y}$ λ ~0.2-03

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/dη) Npart scaling

Increasing centrality

BRAHMS, PRL 93, 242303

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

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

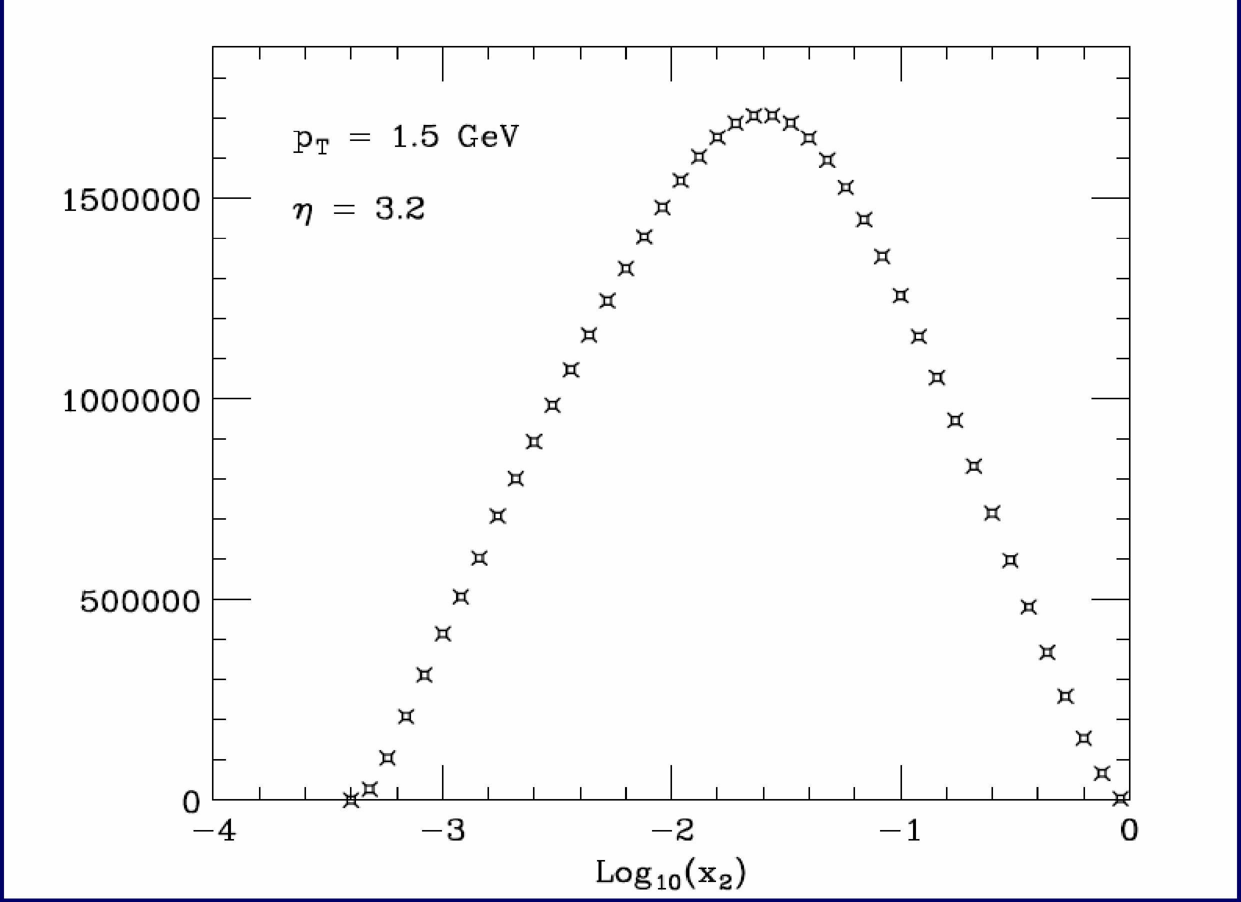
X-range probed in 2-2 processes

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

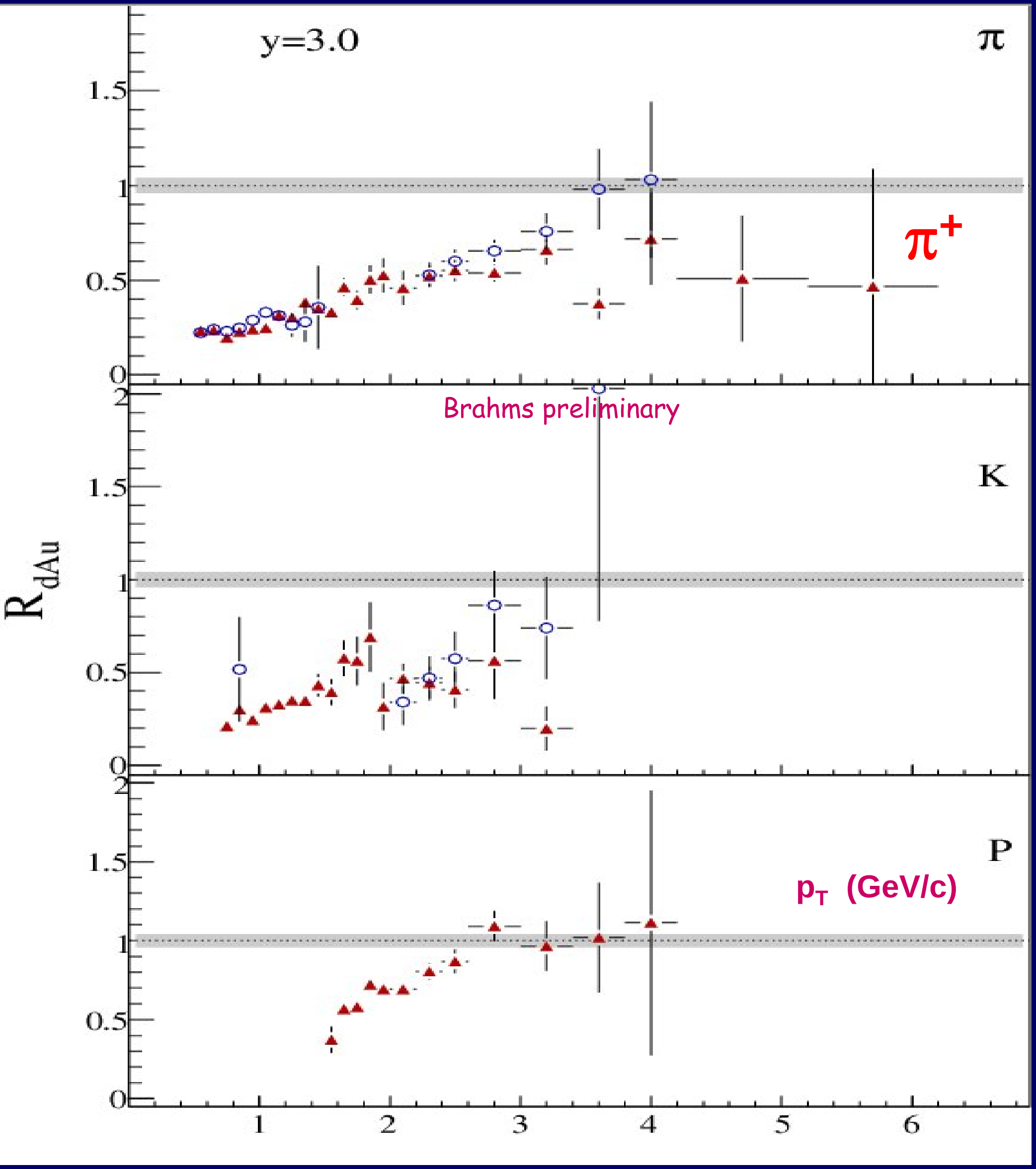
But one has to remember that that low number is a lower limit, not a typical value.

From Guzev, Strikman, and Vogelsang.

Most of the data collected at 4 degrees have x_2~0.01



Identified Particle R_{dAu}



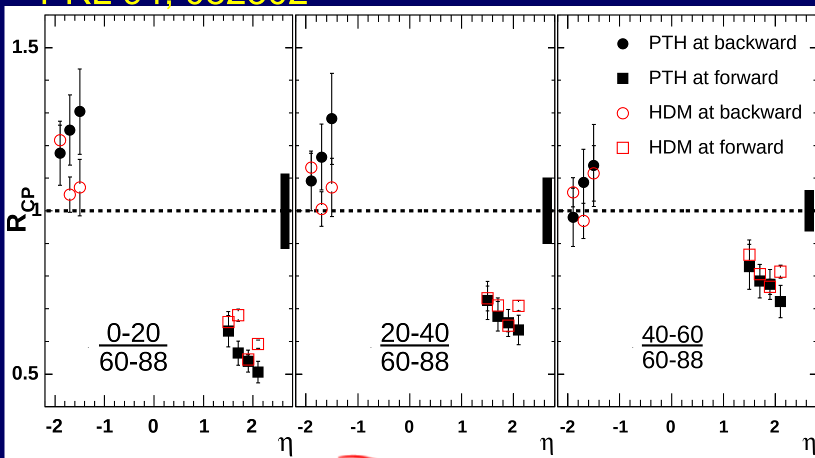
As expected there is a difference between positive and negative pions driven by a "suppression" of negative pions in p+p (isospin)

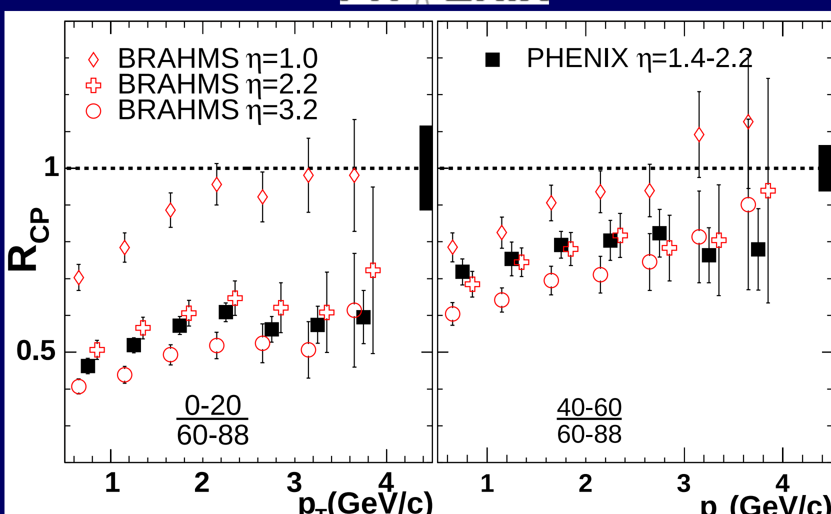
R_{dAu} of identified particle consistent with charged all exhibiting $R_{dA} <=1$

The protons may exhibit less suppression.

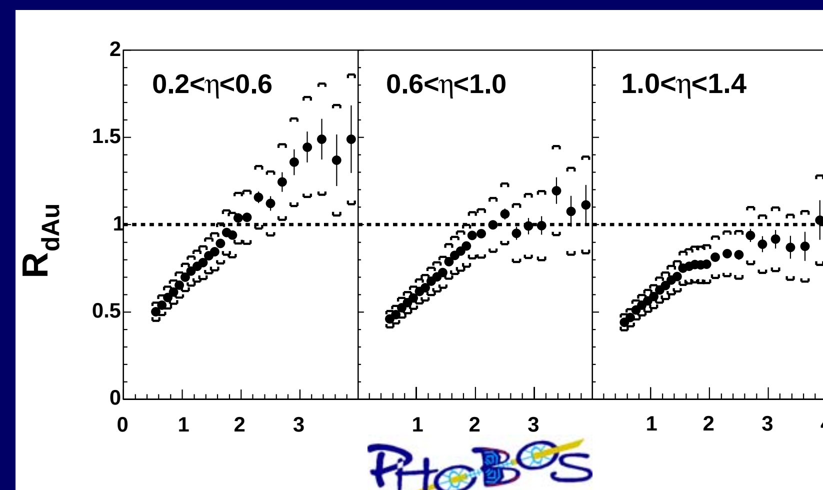
Similar effects measured by PHENIX and PHOBOS

PRL 94, 082302



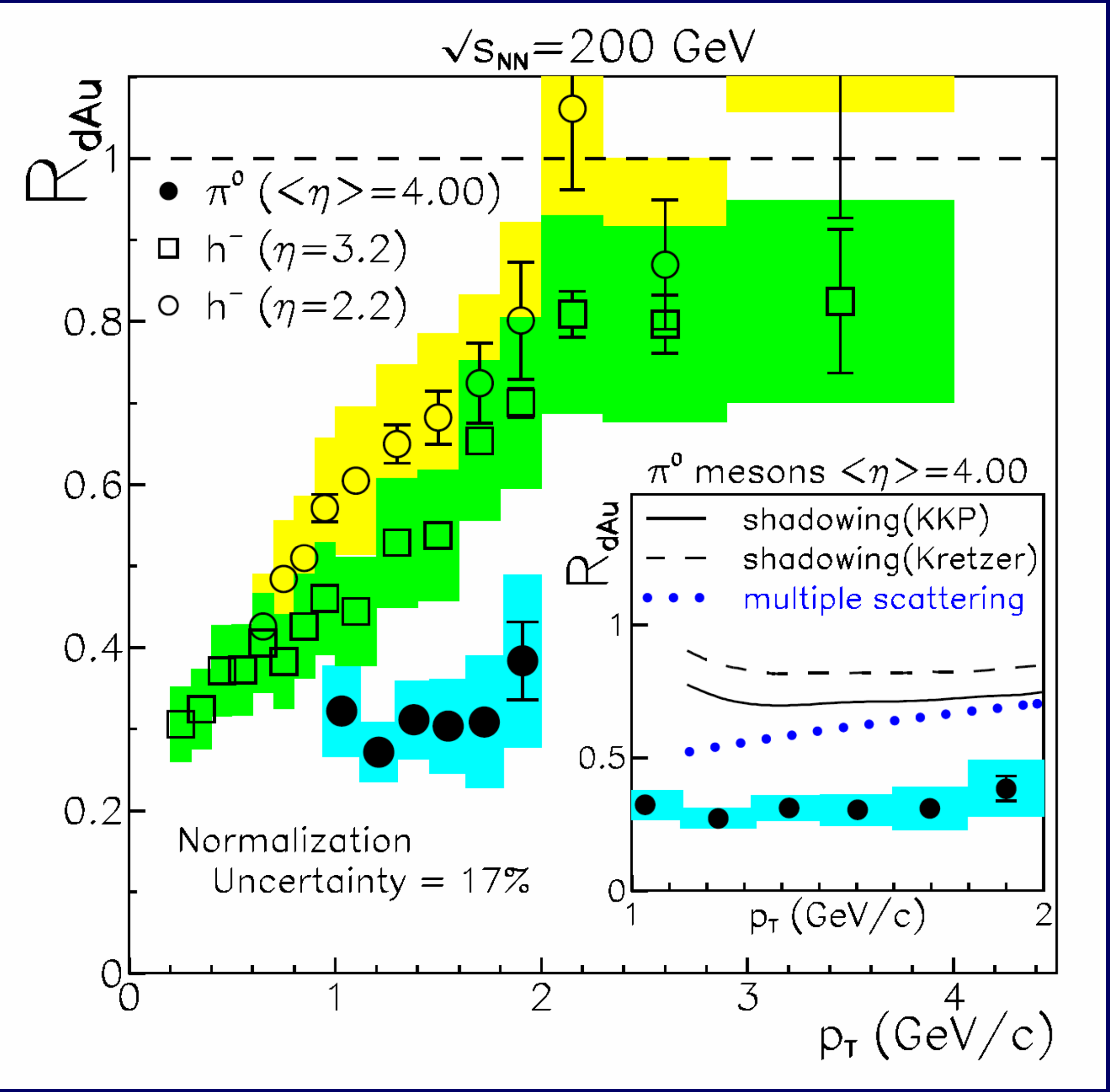


PRC 70, 061901(R)



Suppression in the d direction and enhancement in the Au frag. region

STAR Nuclear Modification Factor at high rapidity



$$R^{Y}_{\mathrm{dAu}} = \frac{\sigma^{pp}_{\mathrm{inel}}}{\langle N_{\mathrm{bin}}\rangle \sigma^{dAu}_{\mathrm{hadr}}} \frac{E\, d^3\sigma/dp^3(d+Au \rightarrow Y+X)}{E\, d^3\sigma/dp^3(p+p \rightarrow Y+X)}$$

The STAR result is consistent with published BRAHMS once an isospin suppression of h^- in p+p is taken into account.

Gluon Saturation

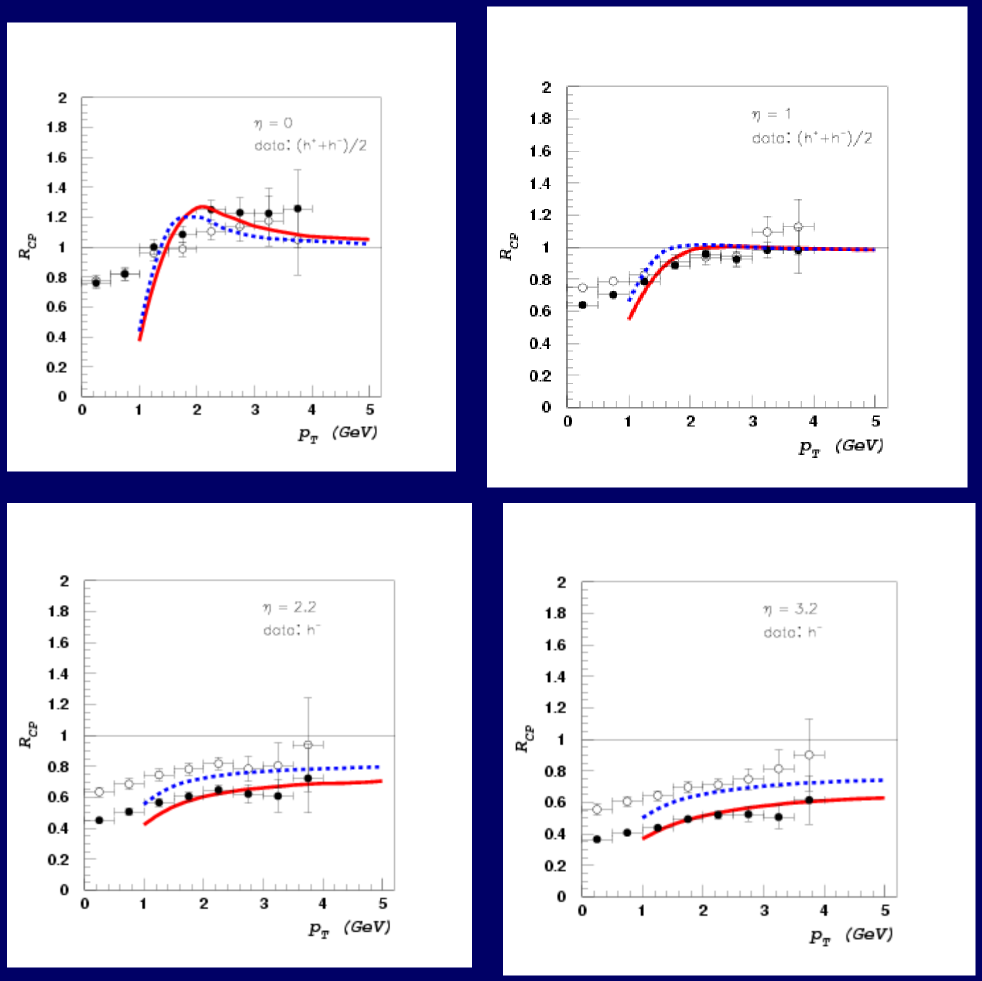
BRAHMS data analyzed by Kharzeev, Kovchegov and Tuchin using the CGC as underlying description for a quantitative analysis.

Cronin effect at y~0

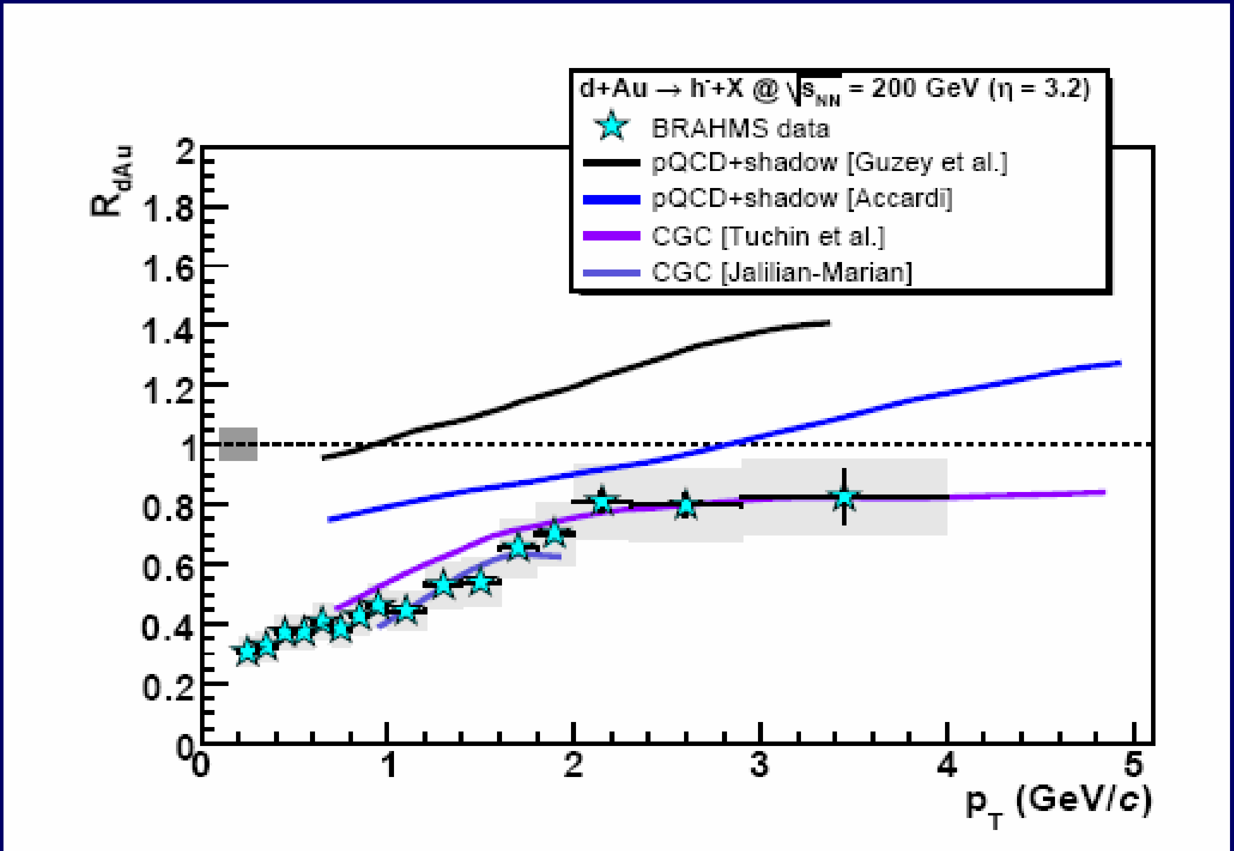
Suppression at forward rapidity/ low-x

Suppression increases with centrality.

Good agreement with BRAHMS data.



Comparing pQCD and CGC

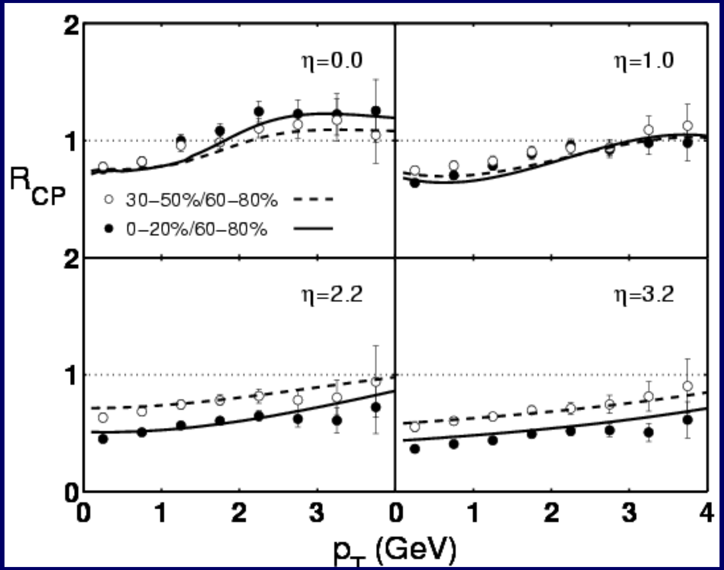


Taken from d'Enterria

Leading order pQCD.
No higher twist and possible coherence effects.

Parton recombination (R.Hwa, C.B.Yang & R.J.Friese)

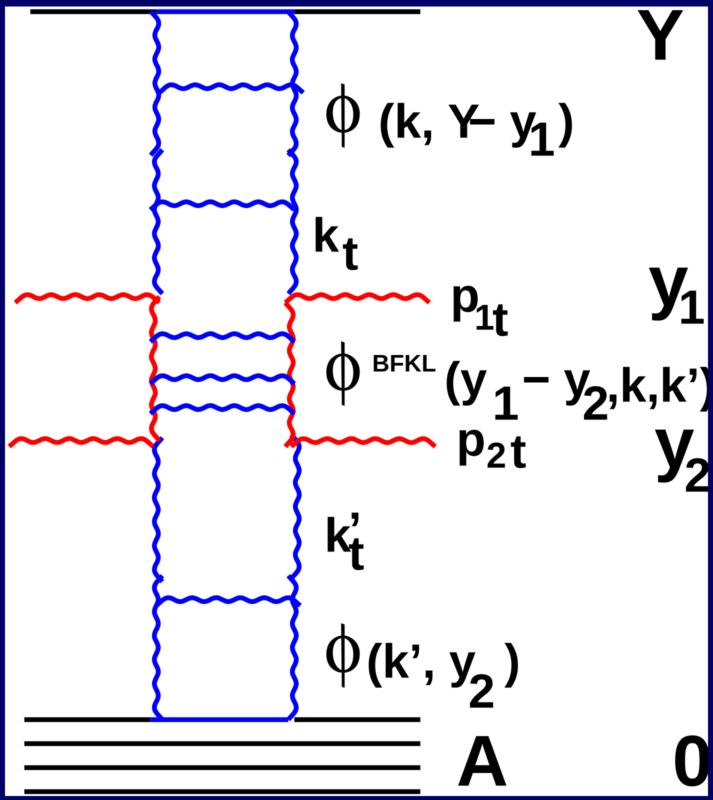
- Parameterized soft component (pi's) vs. rapidity centrality. Essentially from $dN/d\eta$.
- Additional final state hadrons created from lower pt-partons (density dependent)
- Good description of p_t-dependence. The reversal of centrality dependence comes from $dN/d\eta$ (primarily).

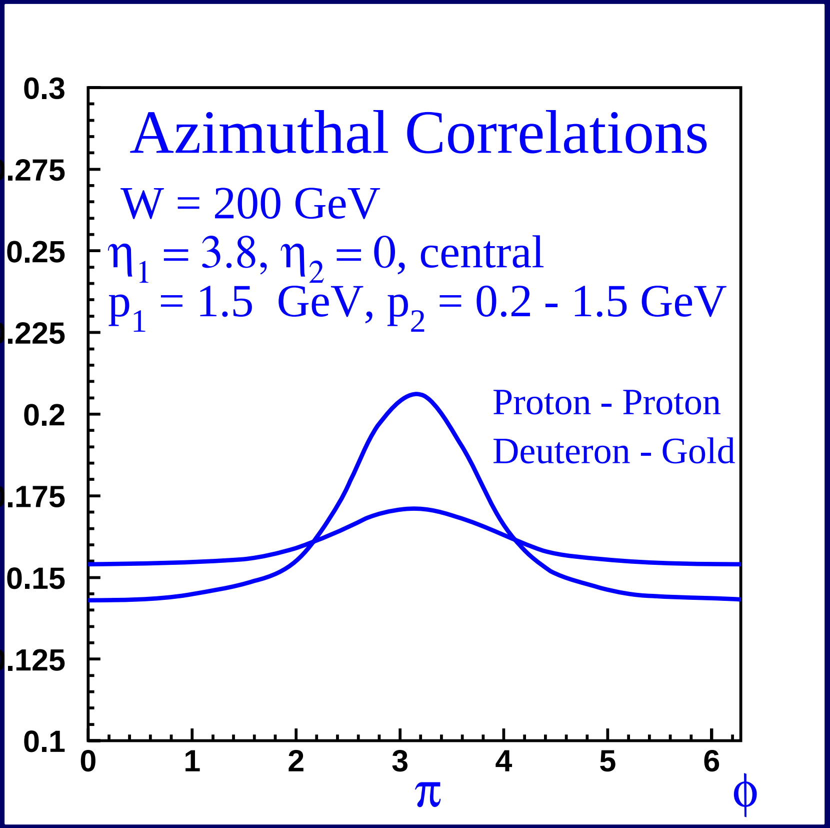


Nucl-th/0410111

One important feature, that also exist in saturation picture is that an important point is that the lowest p_T reproduce the integral dN/dh at that rapidity. (i.e. scales as Npart in centrality dependence)

Back-to-back azimuthal correlations
Basis for possible future experiments.

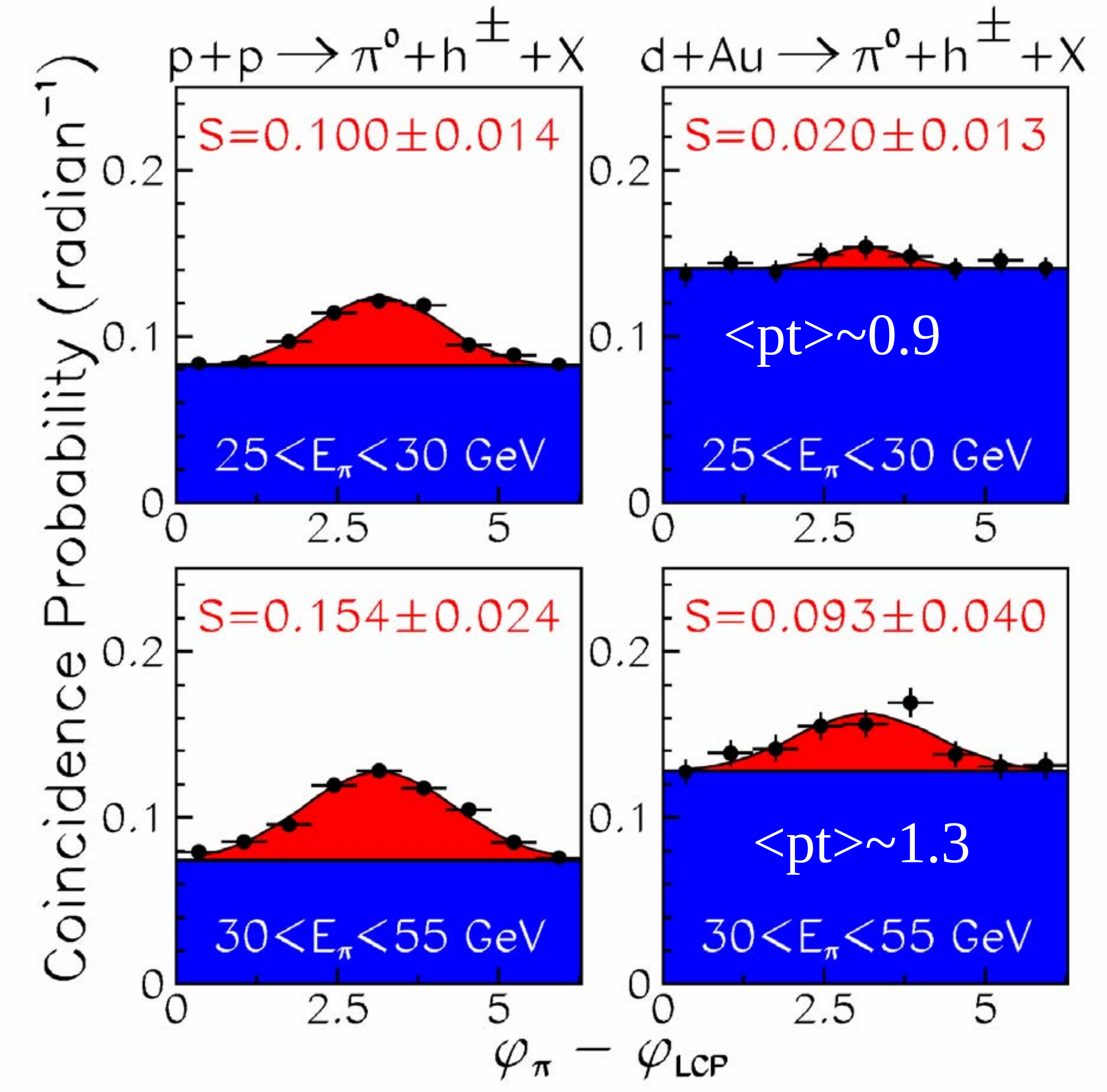




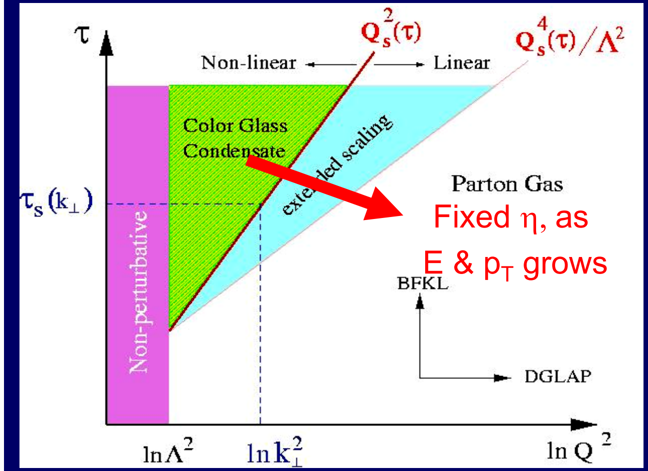
The emission of gluons ($p_T \sim Q_s$) between the jets makes the correlations disappear.

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

Back-to-back Correlations in d+Au



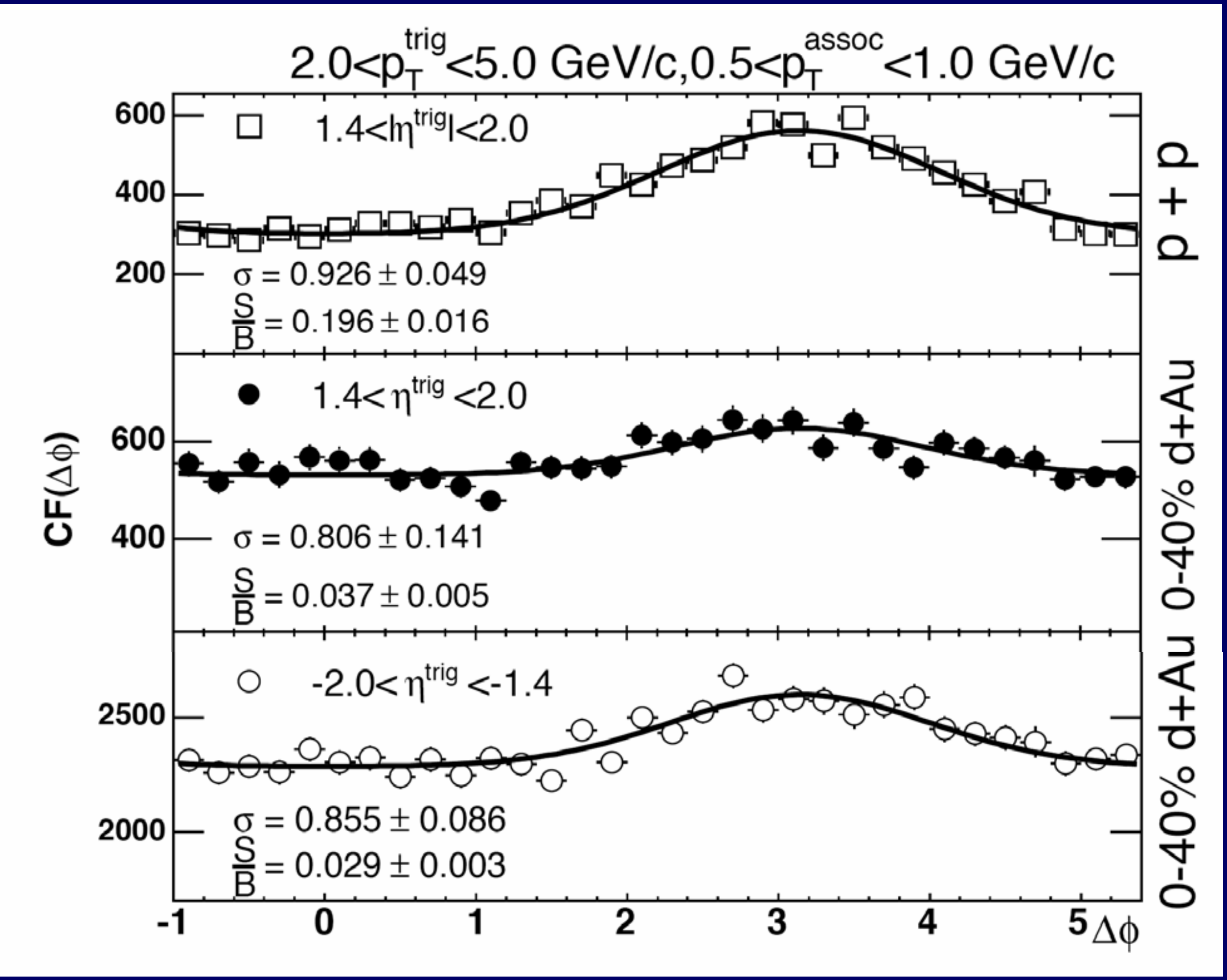
φ_π of forward pion is correlated with leading (p_T>0.5GeV/c) h^{+-} at mid-rapidity.



Azimuthal correlations are suppressed at small $<x_F>$ and $<p_{T,\pi}>$

Qualitatively consistent with CGC picture

PHENIX Azimuthal Angle correlations



Azimuthal angle correlation between charged hadrons.

Trigger :

1.4<η< 2 d muon-arm

-1.4>η>-2 Au muon-arm

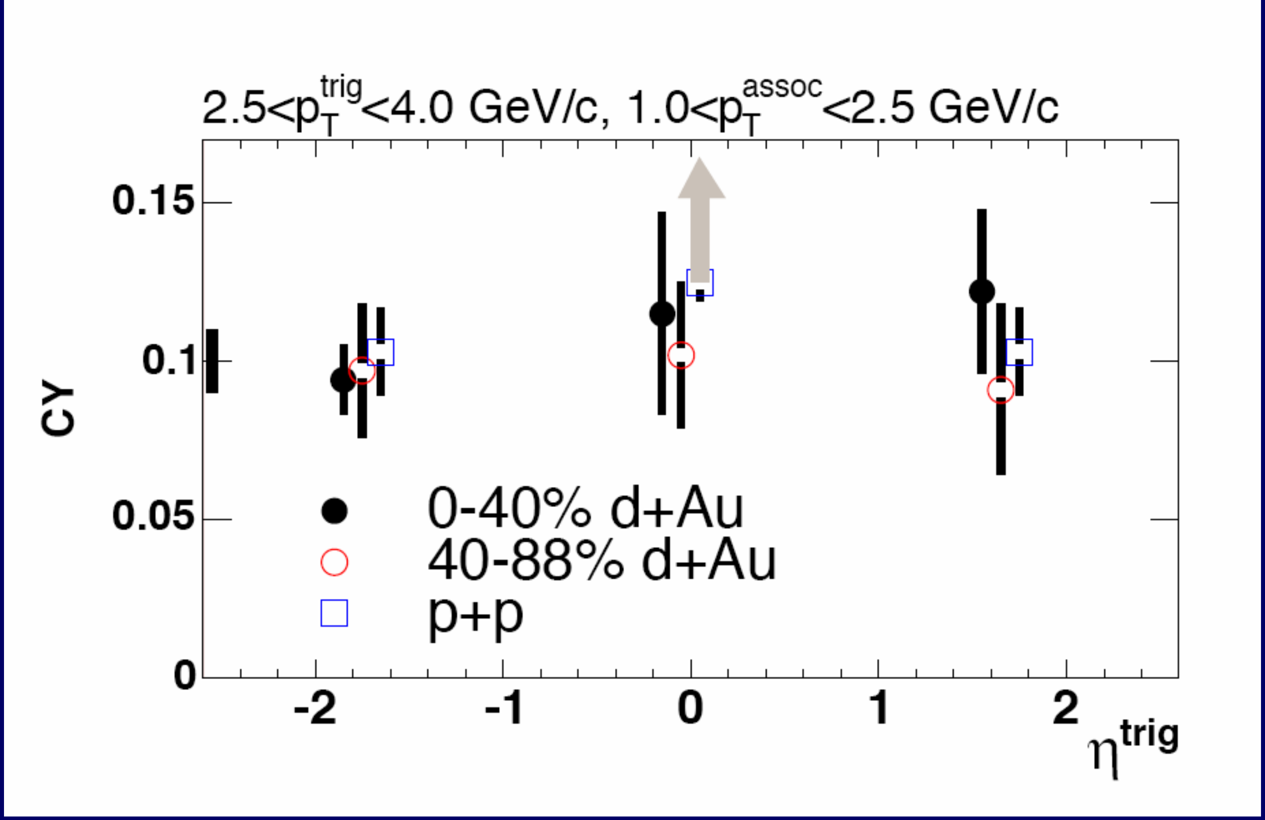
Associated particle:
$|\eta|<0.35$ $0.5<p_T<1$ GeV/c

$$CF = \frac{dN(\Delta\phi)/d(\Delta\phi)}{acc(\Delta\phi)}$$

Two-part. Acceptance from event mixing

PHENIX Azimuthal Angle correlations

The strength of the correlation is displayed with the conditional yield CY = $N_{pair}/\varepsilon_{assoc}/N_{trig}$



All points are consistent with no rapidity effect.

This CY is the same for pp and dA (~1)
Expected to drop below 1 in the presence of mono-jets, if p_T is at Qs scale.

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}.
- PHENIX observes **no** reduction in correlations at h~2.2 and p_T > 2 GeV/c (higher x region ~.02) , while STAR at higher h in fact observes a r
  correlations (lower x region <0.005).
- The data are consistent with CGC prediction. But, there are also several other descriptions that does equally well, several that I have not mentioned today.

Sorry Boris and Sid

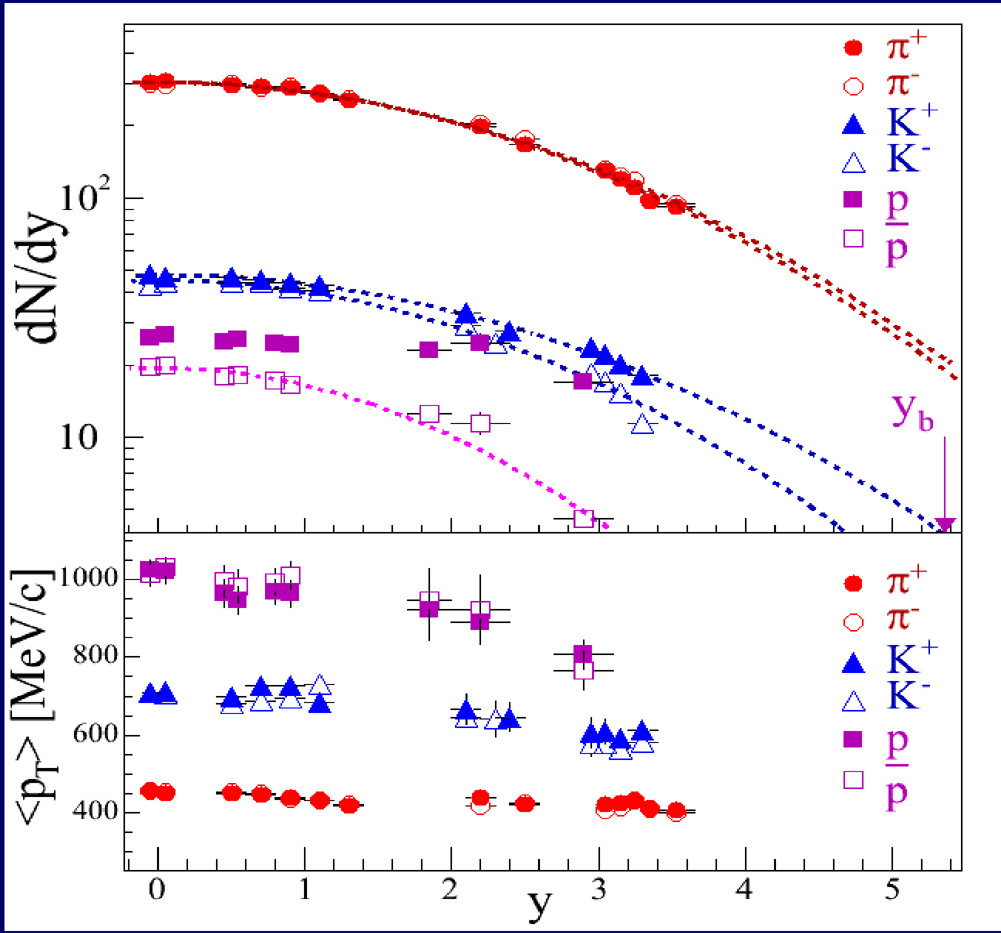
A few words on A-A

Probing rapidity dependence of the collisions can give important constraints on the longitudinal expansion and extension of the hot and dense matter formed in Heavy Ion collisions.

Density Distributions in AA

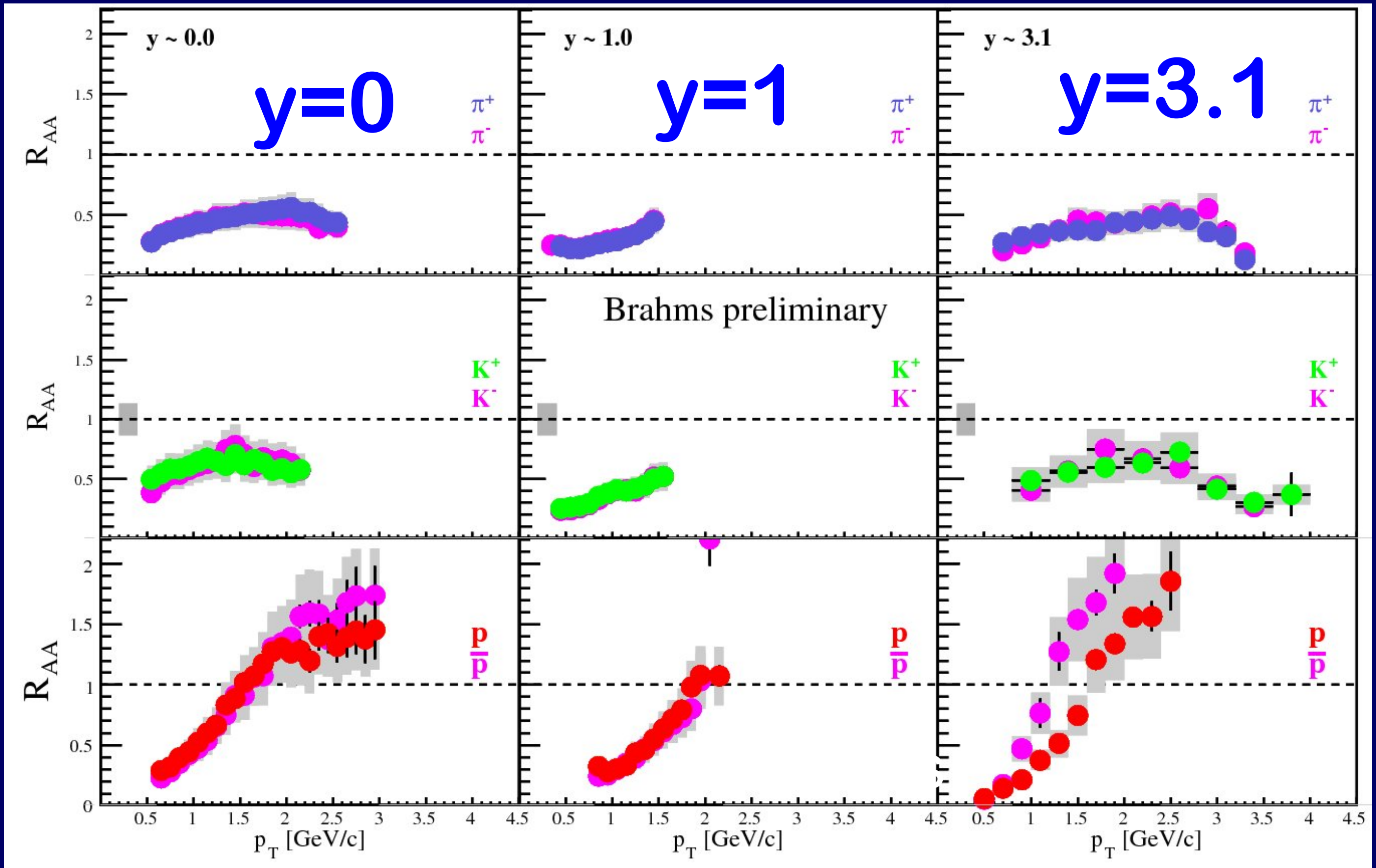
Not as a Bjorken scenario

The *local* densities drop by factor of 2. This is still appreciably above the critical density and will expect pt suppression in hadron production.

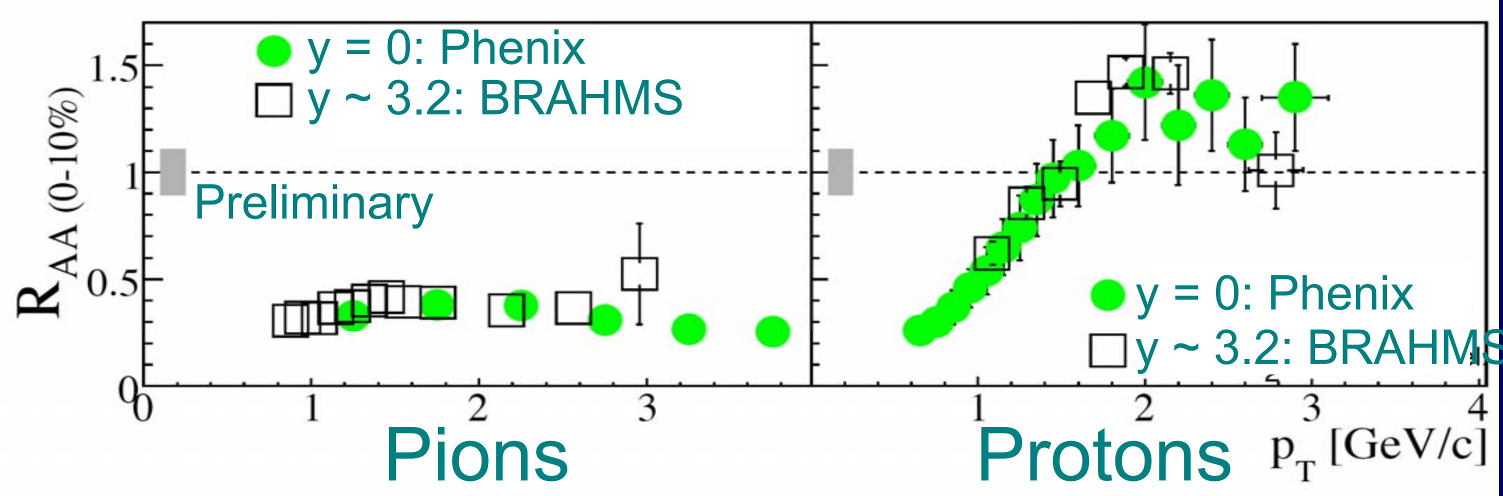


Nuclear Modification Factors vs. rapidity

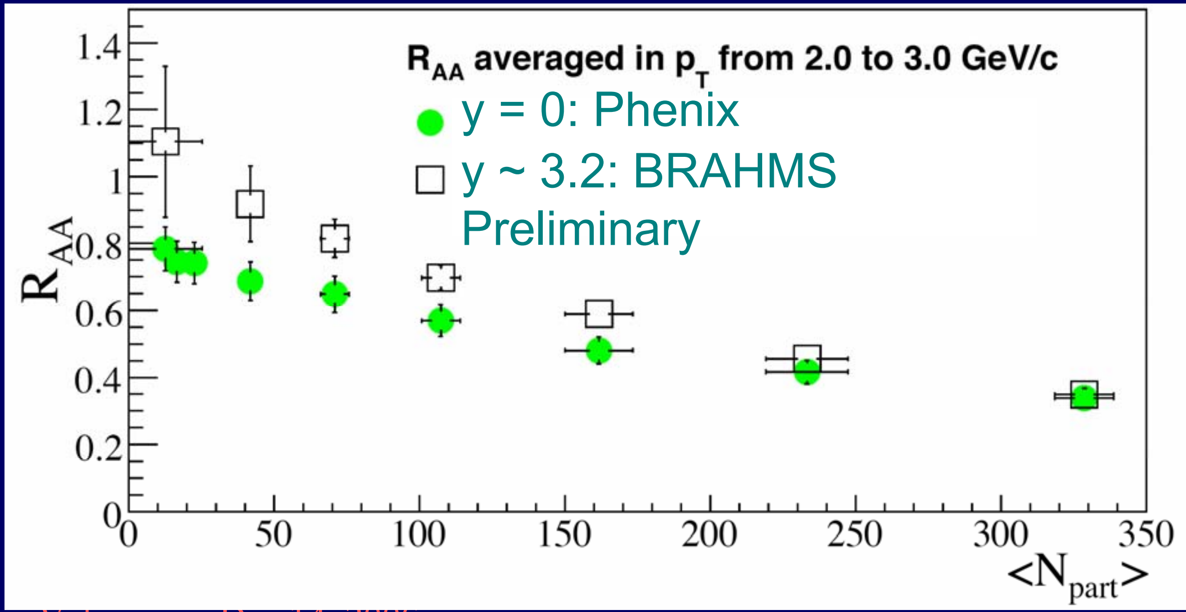
$$R_{dAu} = \frac{d^2N/dp_T d\eta\ (d+Au)}{N_{Coll} d^2N/dp_T d\eta\ (p+p)}$$



Comparing y~0 and y~3.2



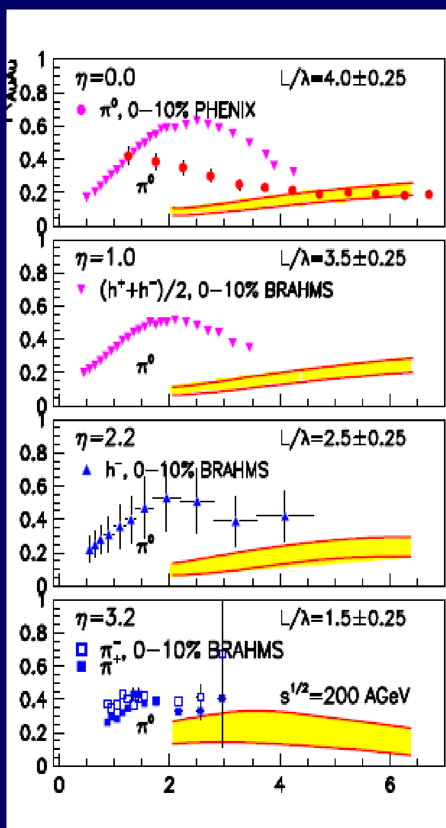
- There is a stronger dependence of suppression on centrality for the forward pions than the mid-rapidity pions.

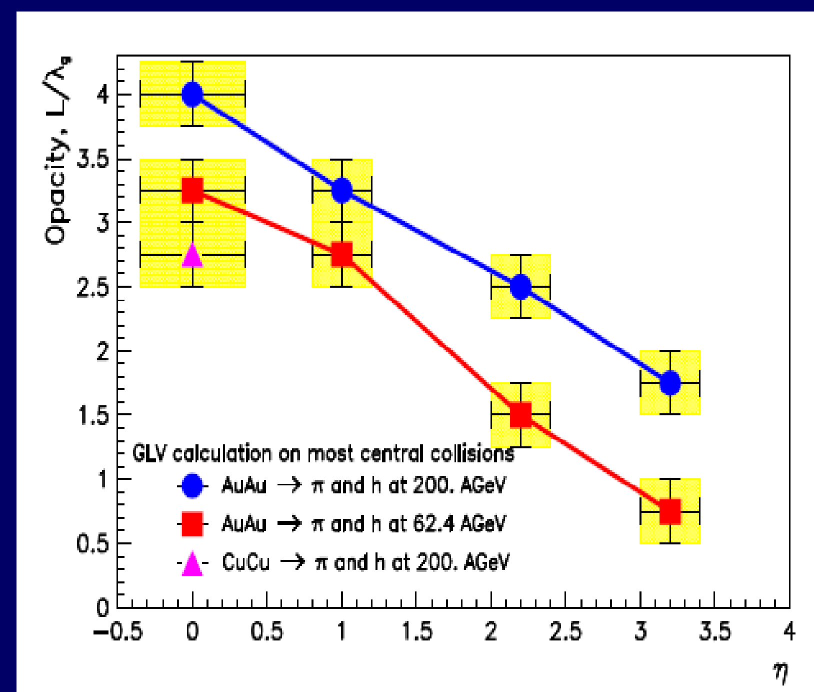


Jet Tomography at large h

- G.G. Barnafoldi, P. L´evai1, G. Papp, and G. Fai hep-ph/0610111

The calculation takes into account the time-evolution of the hot matter. The L/L is smaller at high eta due to smaller thickness (dn/dη 0) and underlying spectrum.



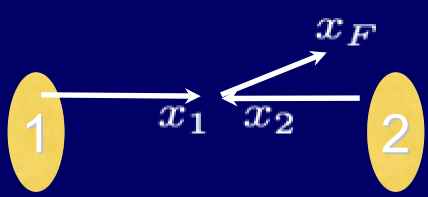


Summary AA.

- There is considerable suppression also in AA at forward rapidity. Overall pictures similar to mid-rapidity results. Interpretation may though be different and corresponds to much less energy loss and possible even losses in hadronic phases.
  - Important difference due to
    - Lower local densities
    - Different dynamics (in a space-time picture the is a longitudinal z-distribution)
    - Change of underlying reference spectra.
    - Saturation effects, shadowing.

Future at LHC.

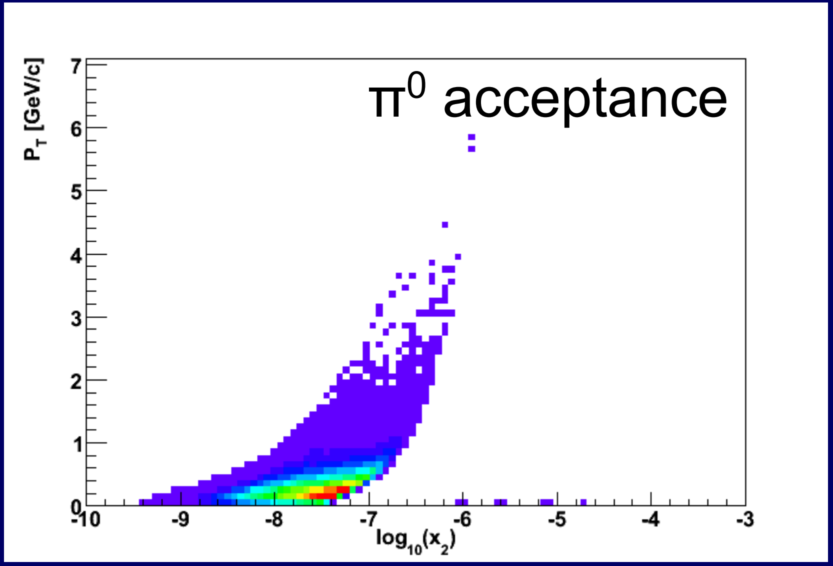
At LHC much smaller x_2 can be probed, in particular at forward rapidities. Case study from ATLAS



$$x_F = x_1 - x_2$$

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

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



ZDC will be used for centrality and Ultraperipheral Pb+Pb

Also reconstructs neutral particles at very high rapidities: physics processes at <u>very</u> low x, e.g. Color Glass Condensate

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 consistent with saturation picture, but RHIC energy, x and pT reach may be too small to decidedly settled this.
- STAR and PHENIX considers this region important and have several upgrades underway that will be carried out in coming years.
- LHC is promising for studying low-x physics in great detail covering large x and p_T range.