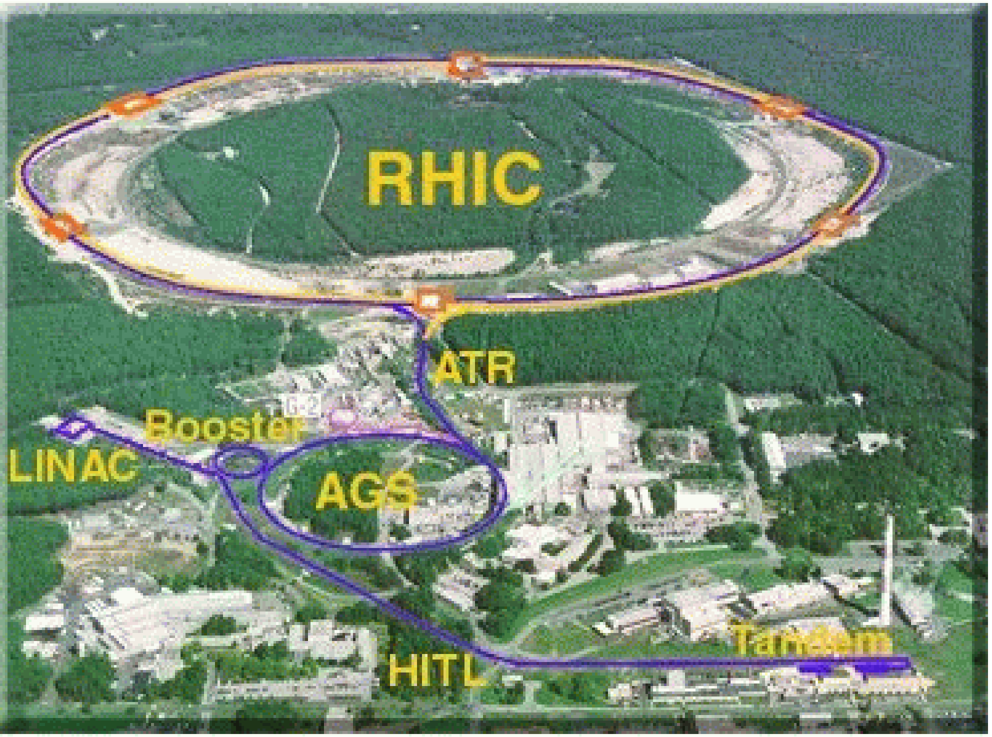
Forward Physics with BRAHMS at RHIC



Dieter Roehrich
University of Bergen

BRAHMS collaboration

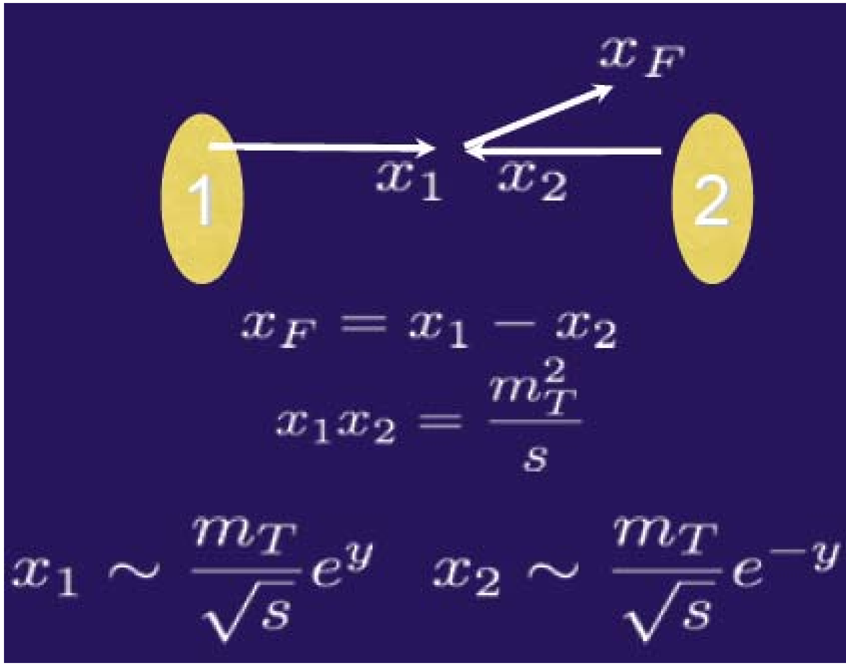
Physics at forward rapidities

- systems
  - p+p at 200 and 62 GeV
  - d+Au collisions at 200 GeV
  - Au+Au collisions
- observables
  - pt-spectra
  - nuclear modification factor

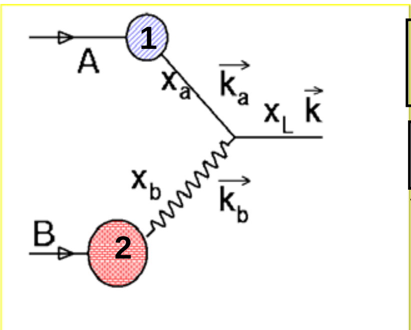
Introduction

Forward rapidity at RHIC collider at 200 GeV offers insight into pp, dA and AA:

- 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
- energy loss of partons in dense matter
  (central AA collisions)

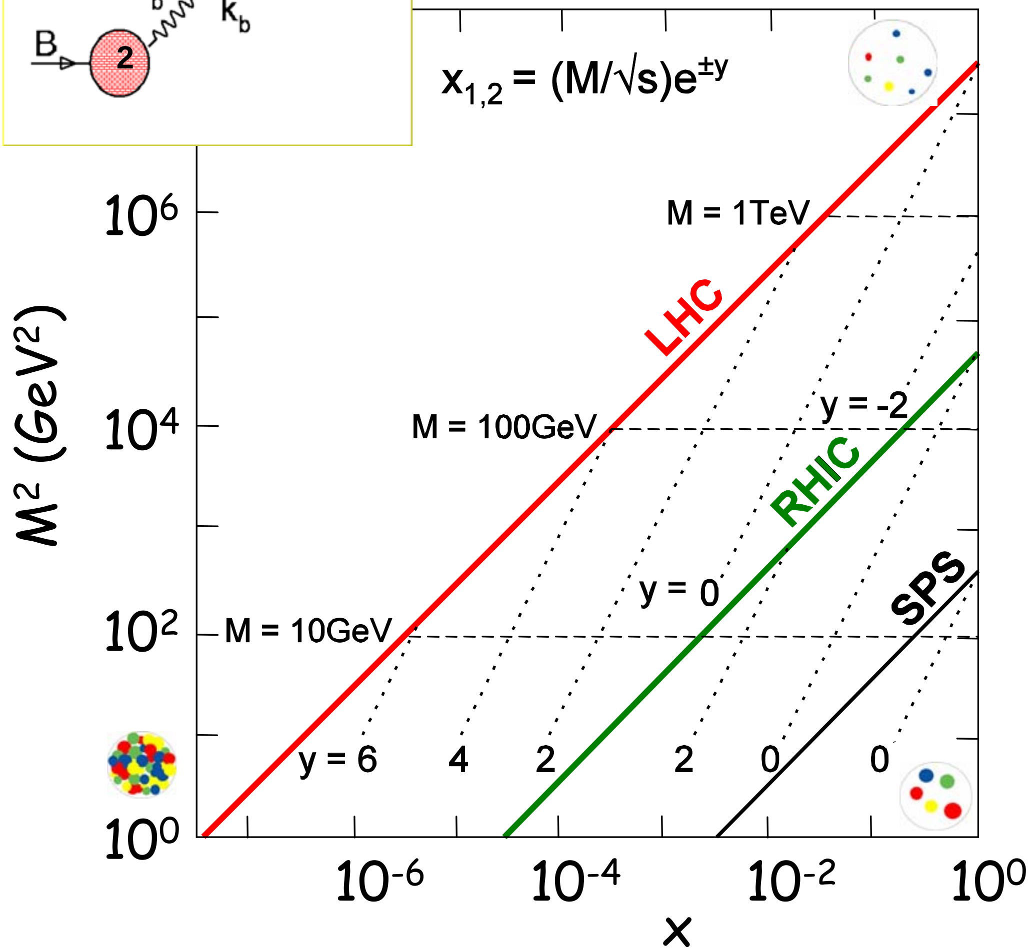


Kinematics



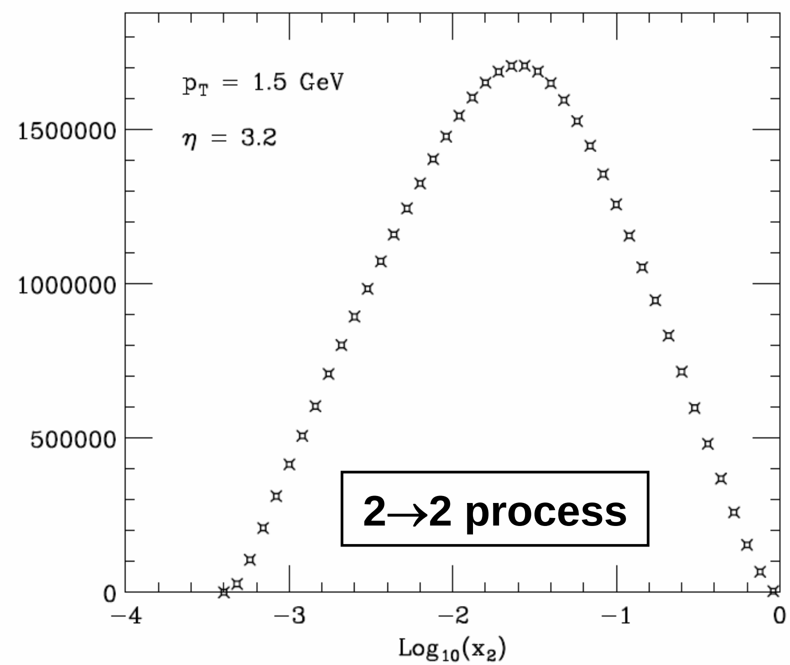
2→1 process

y=rapidity of (x_L, **k**) system



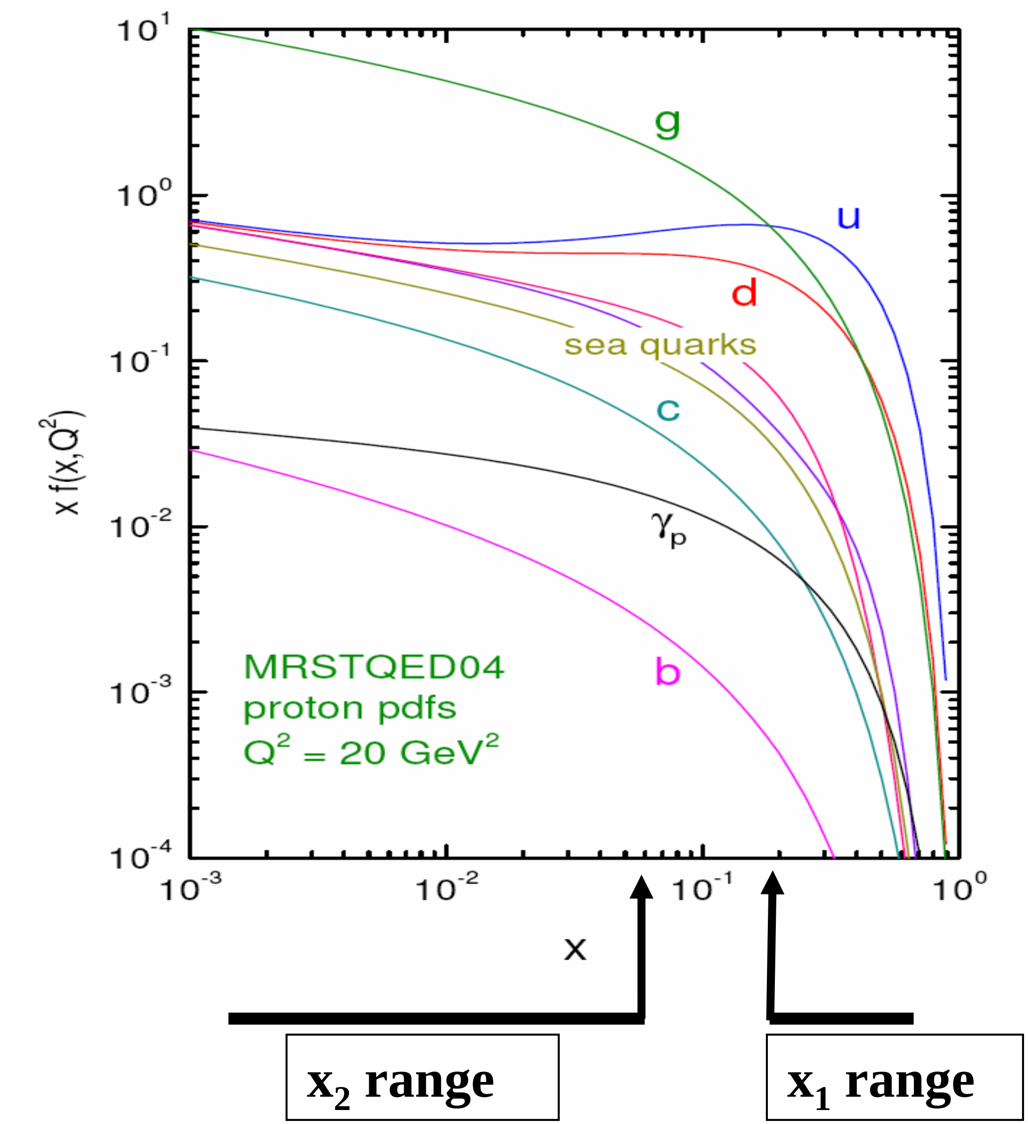
RHIC example

- At 4° (y~3 for pions) and p_T=1 GeV/c one can reach values as low of $x_2 \sim 10^{-4}$
- This is a lower limit, not a typical value: most of the data collected at 4° would have x_2~0.01



Guzev, Strikman, and Vogelsang (hep-ph/0407201)

Parton Distribution Function



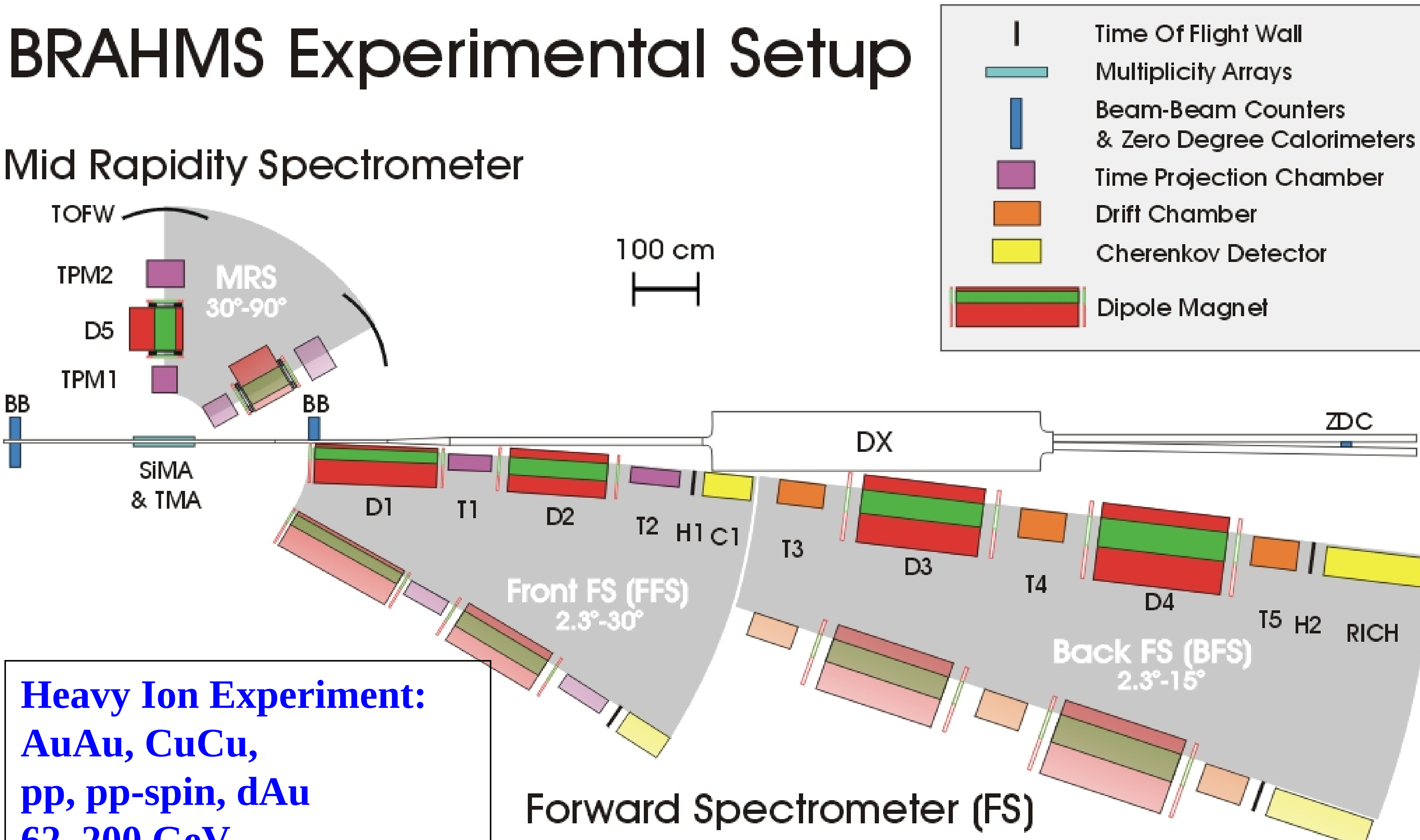
Measurements at high rapidity set the dominant parton type:

- **projectile (x_1 ~1) mostly valence quarks**
- **target (x_2<0.01) mainly gluons**

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

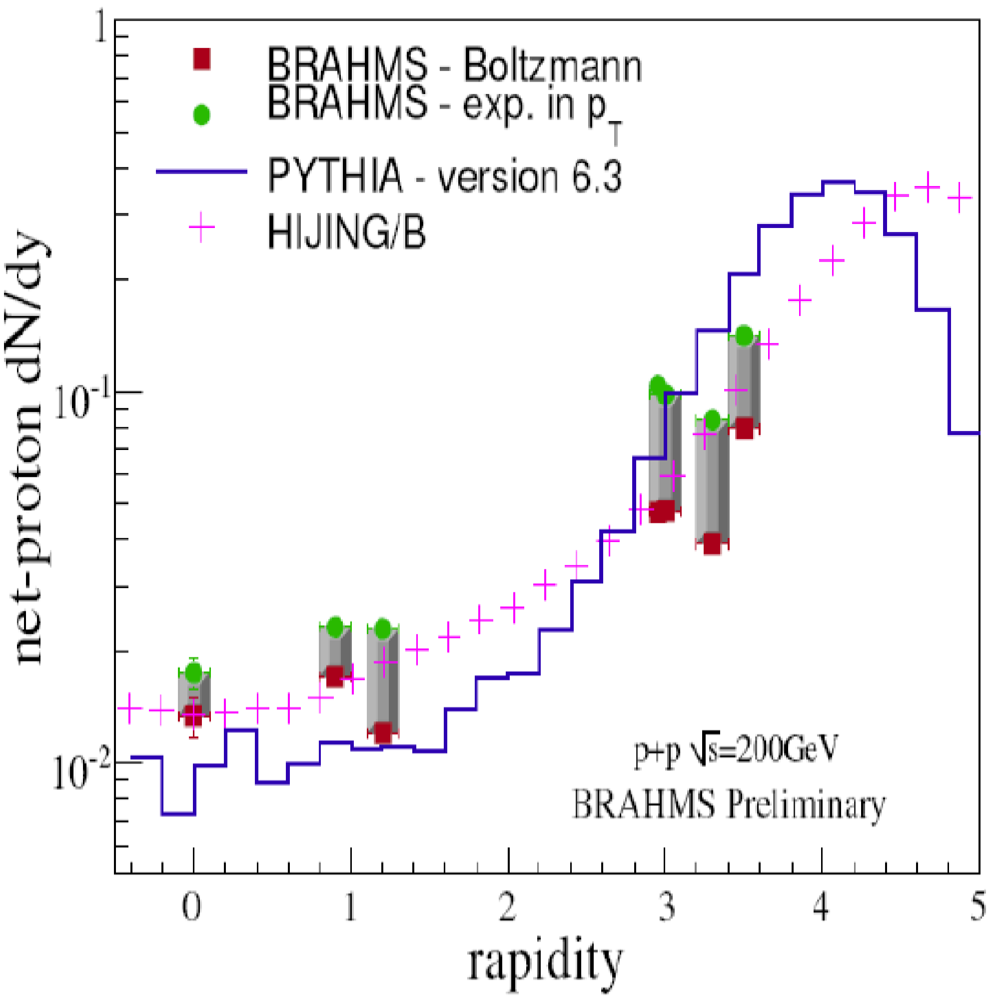
Are there effects from small-x at large y?

Experiment



Heavy Ion Experiment:
AuAu, CuCu,
pp, pp-spin, dAu
62, 200 GeV

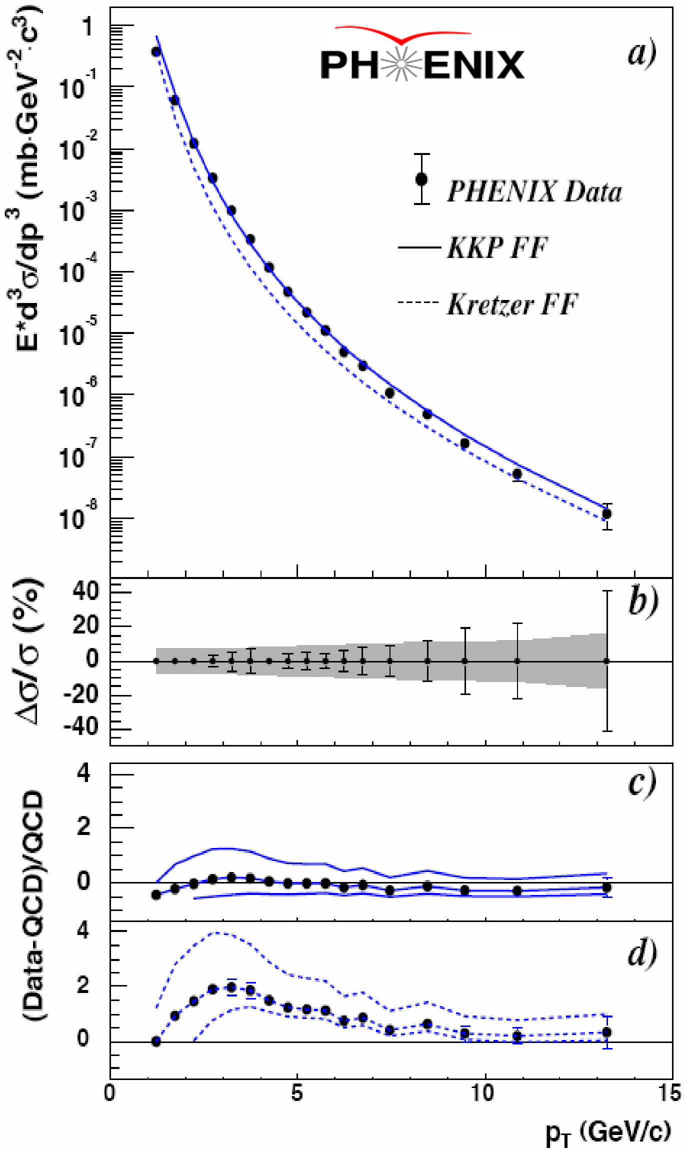
pp at 200 GeV – stopping



Net-proton rapidity distribution

- **Despite large systematic uncertainties better agreement with the baryon transport in HIJING/B**

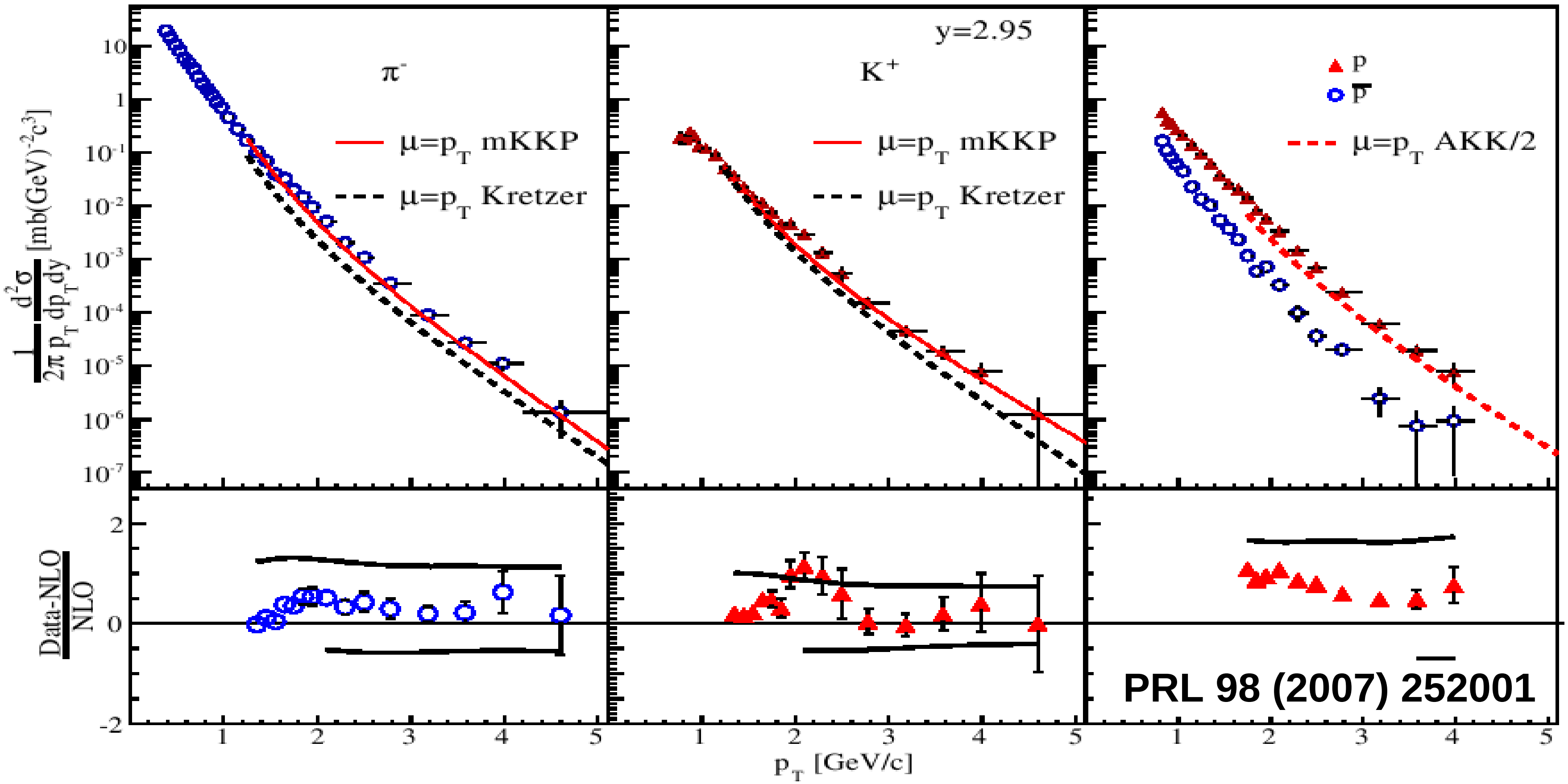
pp at 200 GeV – midrapidity



$$pp \longrightarrow \pi^0 X$$

- **NLO pQCD can reproduce the data at RHIC energies**
- **The fragmentation functions differ by the amount of g->π**

pp at 200 GeV – forward rapidity (1)



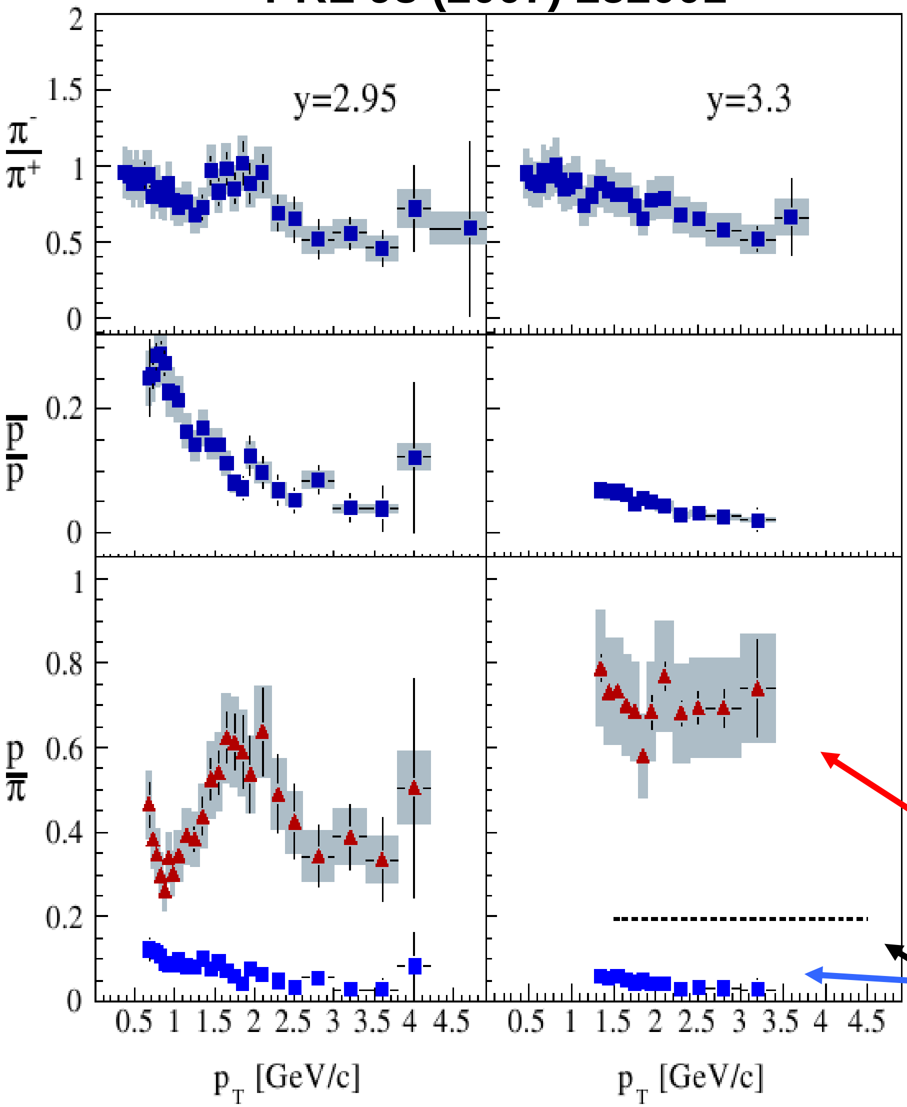
Calculations done by W. Vogelsang. Only one scale $\mu=p_T$ and the same fragmentation functions as used for the PHENIX comparison.

KKP has only π^0 fragmentation. Modifications were needed to calculate charged pions. KKP FF does a better job compared to Kretzer, π and kaon production still dominated by gg and gq at these rapidities apart from the highest p_T

No agreement with proton data

pp at 200 GeV – forward rapidity (2)

PRL 98 (2007) 252001



Ratios p/π at y=3.0 and 3.3

- **Excess of positive pions: ratio ->1/2 (valence quark counting)**
- **Small $\bar{p}$/p ratio eliminates possible strong g -> p or $\bar{p}$ fragmentation**
- **The difference between protons and anti-protons indicates that fragmentation (as AKK) is not the dominant mechanism**

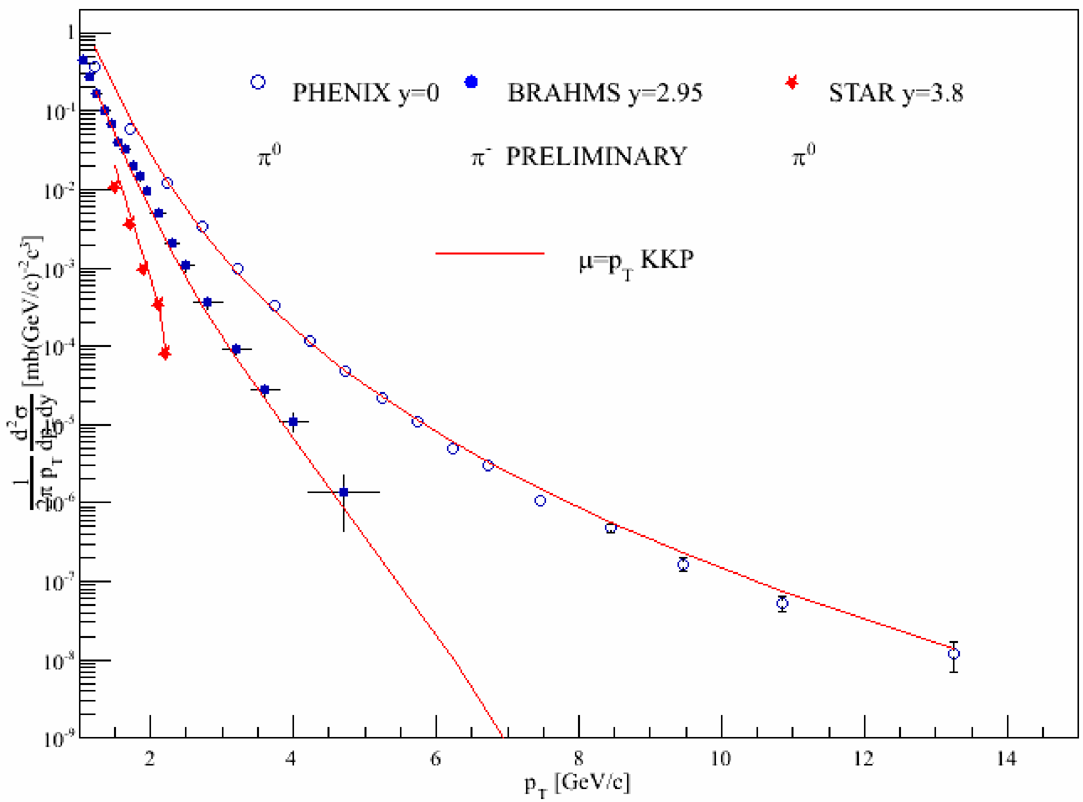
Red: proton/π^+

Blue: antiproton/ π^-

e^+e^- p+pbar/π^++ π^- ALEPH

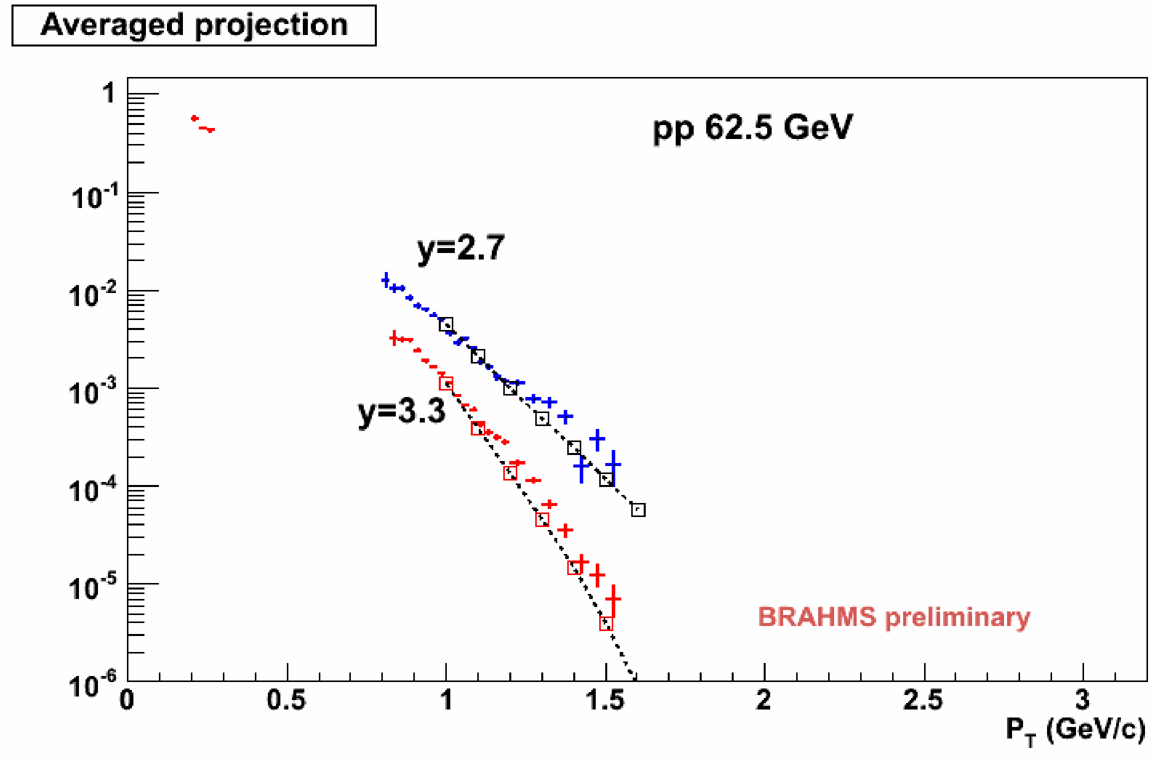
Conclusions – pp at 200 GeV

rapidity dependence



- **NLO pQCD describes data at all rapidities at 200 GeV**
- **mKKP fragmentation function reproduces the pion and kaon production. This agreement implies a dominance of gq and gg processes at these high rapidities as was the case for the measurements of neutral pions at mid-rapidity.**
- **But: large proton/pion ratio at intermediate/high pt at large y?**

pp at 62 GeV – forward rapidity



π^- spectra at forward rapidities

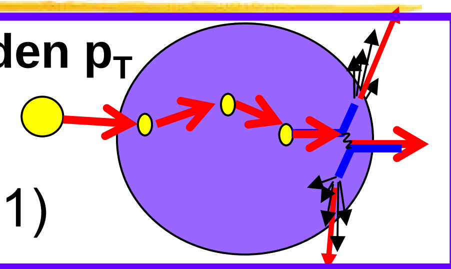
- **Comparison of NLO pQCD calculations (Vogelsang) with BRAHMS data at high rapidity. The calculations are for KKP and a scale factor of μ=p_t.**
- **The agreement is surprisingly good in view of analysis of slightly lower ISR data at large y which failed to describe π^0 at larger x_F.**

Initial and final effects – dAu at 200 GeV

- **Initial effects**
  - Wang, Levai, Kopeliovich, Accardi

"Cronin effect"

broaden p_T

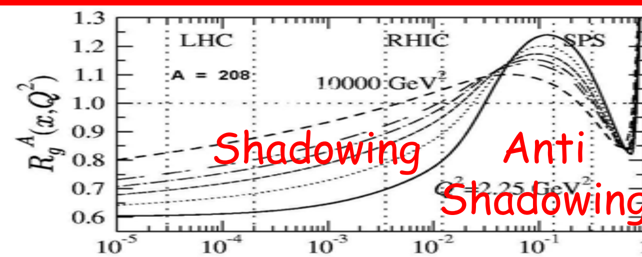


Initial state elastic multiple scattering leading to **Cronin** enhancement (R_{AA}>1)

- **Especially at forward rapidities:**
  - Eskola, Kolhinen, Vogt, Nucl. Phys. A696 (2001) 729-746
  - HIJING
  - D.Kharzeev et al., PLB 561 (2003) 93

Nuclear shadowing

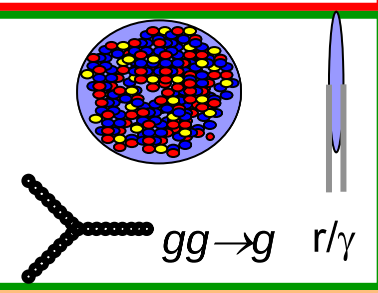
depletion of low-x partons



- **Others**
  - B. Kopeliovich *et al.*, hep-ph/0501260
  - J. Qiu, I, Vitev, hep-ph/0405068
  - R. Hwa et al., nucl-th/0410111
  - D.E. Kahana, S. Kahana, nucl-th/0406074

Gluon saturation

depletion of low-x gluons
due to gluon fusion
"Color Glass Condensate (CGC)"

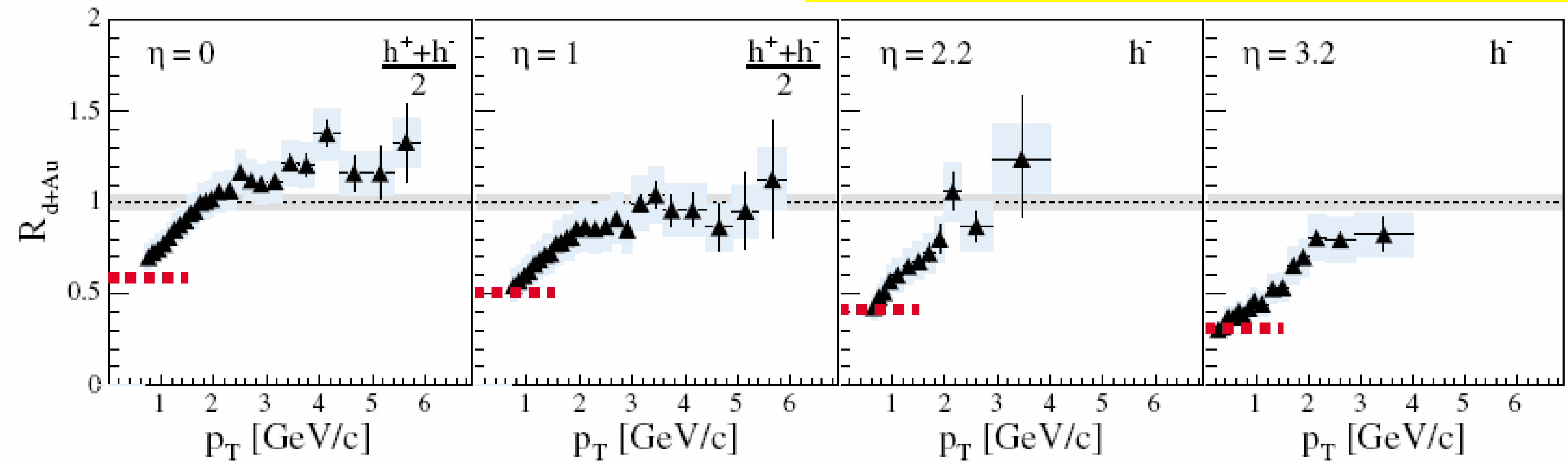


Suppression due to

dominance of projectile valence quarks, energy loss, coherent multiple scattering, energy conservation, parton recombination, ...

Charged hadrons – R_{dAu} at different pseudorapidities

BRAHMS: PRL **93,** 242303 (2004)



$$R_{dAu} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N^{d+Au}/dp_T d\eta}{d^2N^{pp}_{inel}/dp_T d\eta}$$

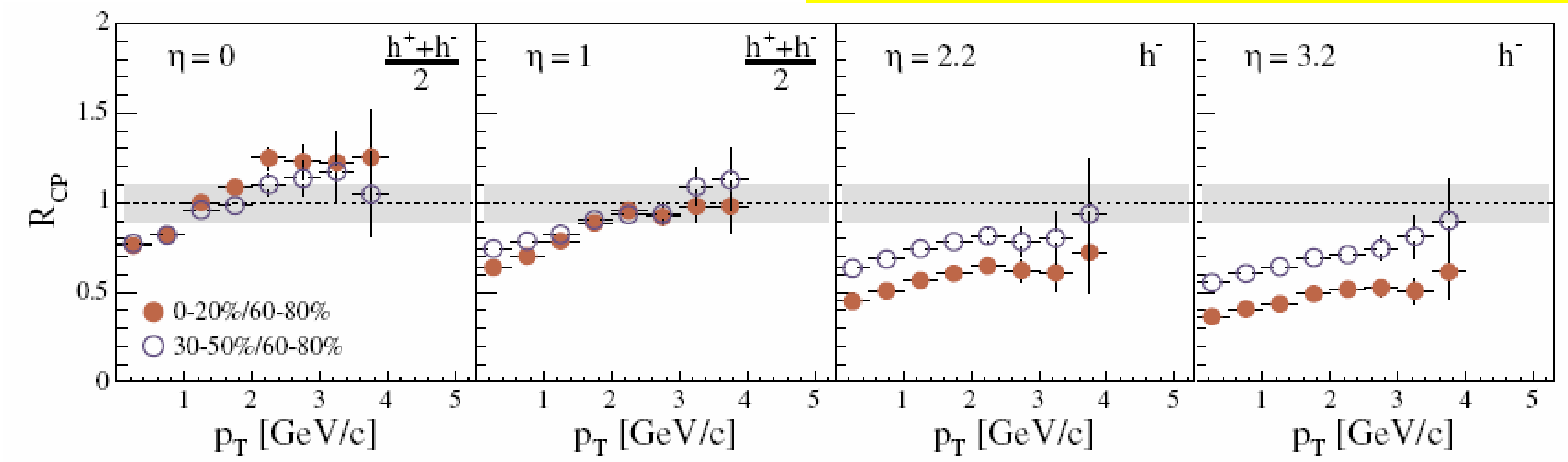
where $\langle N_{coll} \rangle = 7.2 \pm 0.3$

Nuclear Modification Factor

- **Cronin-like enhancement at η=0**
- **Clear suppression as η changes from 0 to 3.2**

Charged hadrons – centrality dependence of enhancement/suppression in d+Au

BRAHMS: PRL **93,** 242303 (2004)



- **R_{cp} is a similar ratio but with peripheral collisions used as a reference**
- **Change of R_{CP} from mid- to forward rapidities is stronger for central collisions than for semi-peripheral collisions**

R_{dAu}: pions, kaons and protons (y=3)

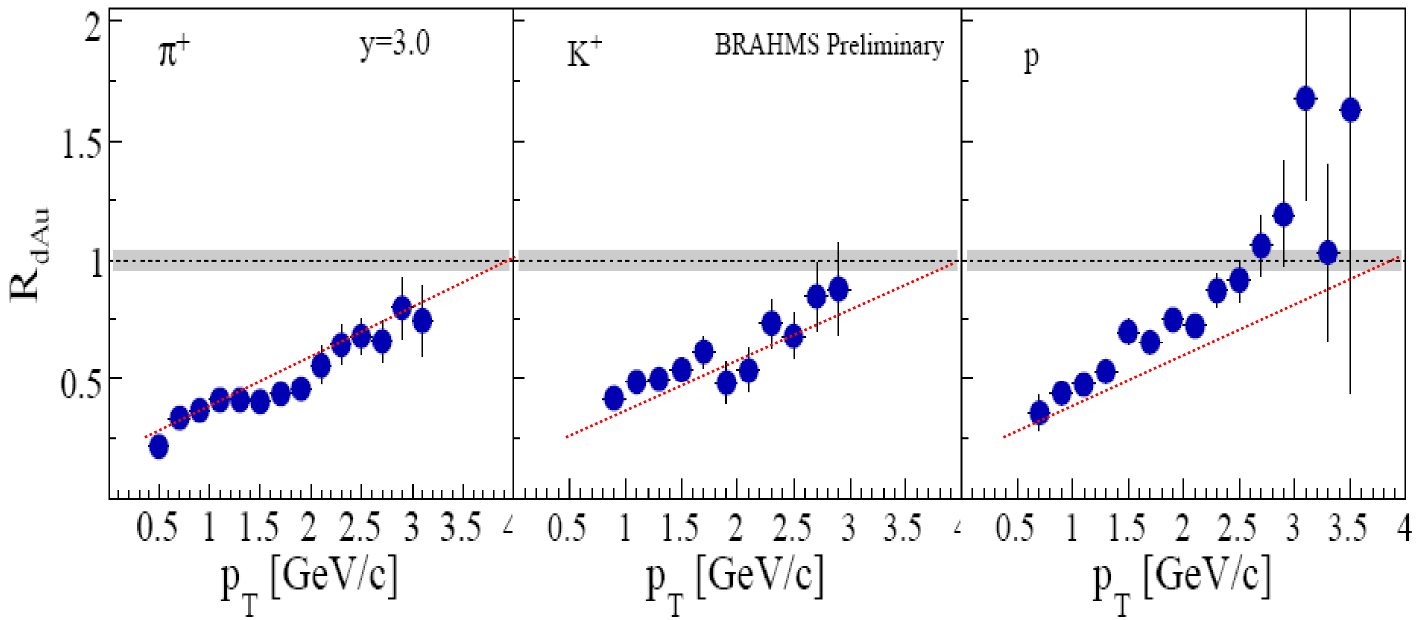


Figure 2. R_{dAu} of π^+, K^+ and protons at forward rapidity $y = 3.0$ in minimum bias d+Au collisions ($< N_{coll} >= 7.2$). A 8% systematic error is included.

- **R_{dAu}**
  - **Suppression for π and K – consistent with charged hadrons**
  - **Less suppression for protons**

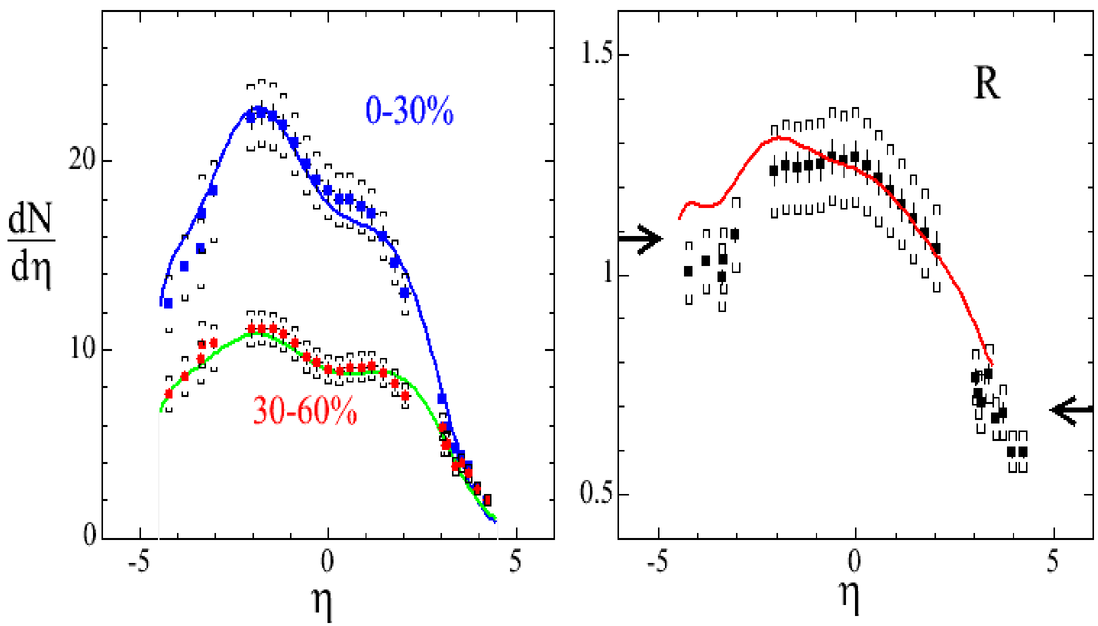
Experimental facts – dAu at RHIC

- **At midrapidity**
  - Cronin enhancement observed for several particle species in R_{dAu} and R_{CP} (magnitude differs by a factor of 2)
  - Cronin effect (baryons) > Cronin effect (mesons)
- **At forward rapidities**
  - Increasing suppression of charged hadrons, h^-, π^+, π^0 ,K^+ with increasing (pseudo)rapidity
  - less suppression of protons

CGC saturation model (1)

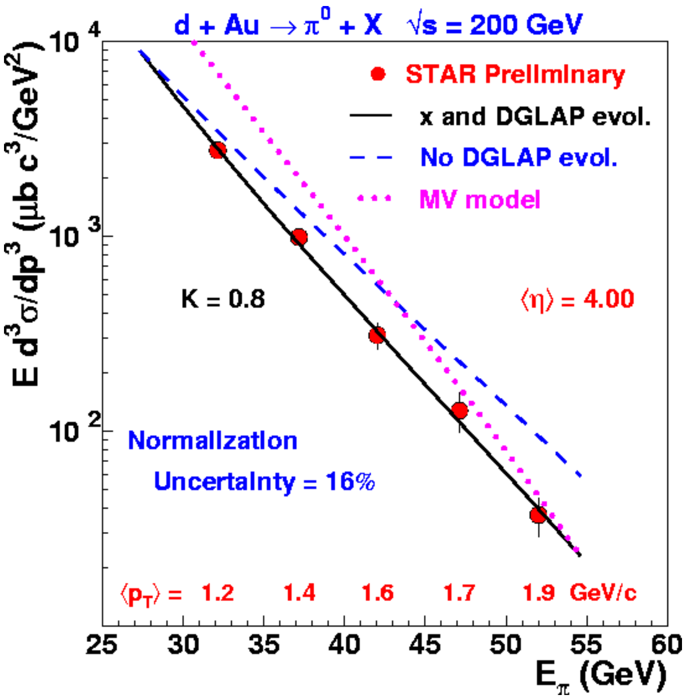
- **CGC describes dn/dη and π^0 inv. CS at forward rapidities**

Data: BRAHMS, submitted to PRL, nucl-ex/0401025



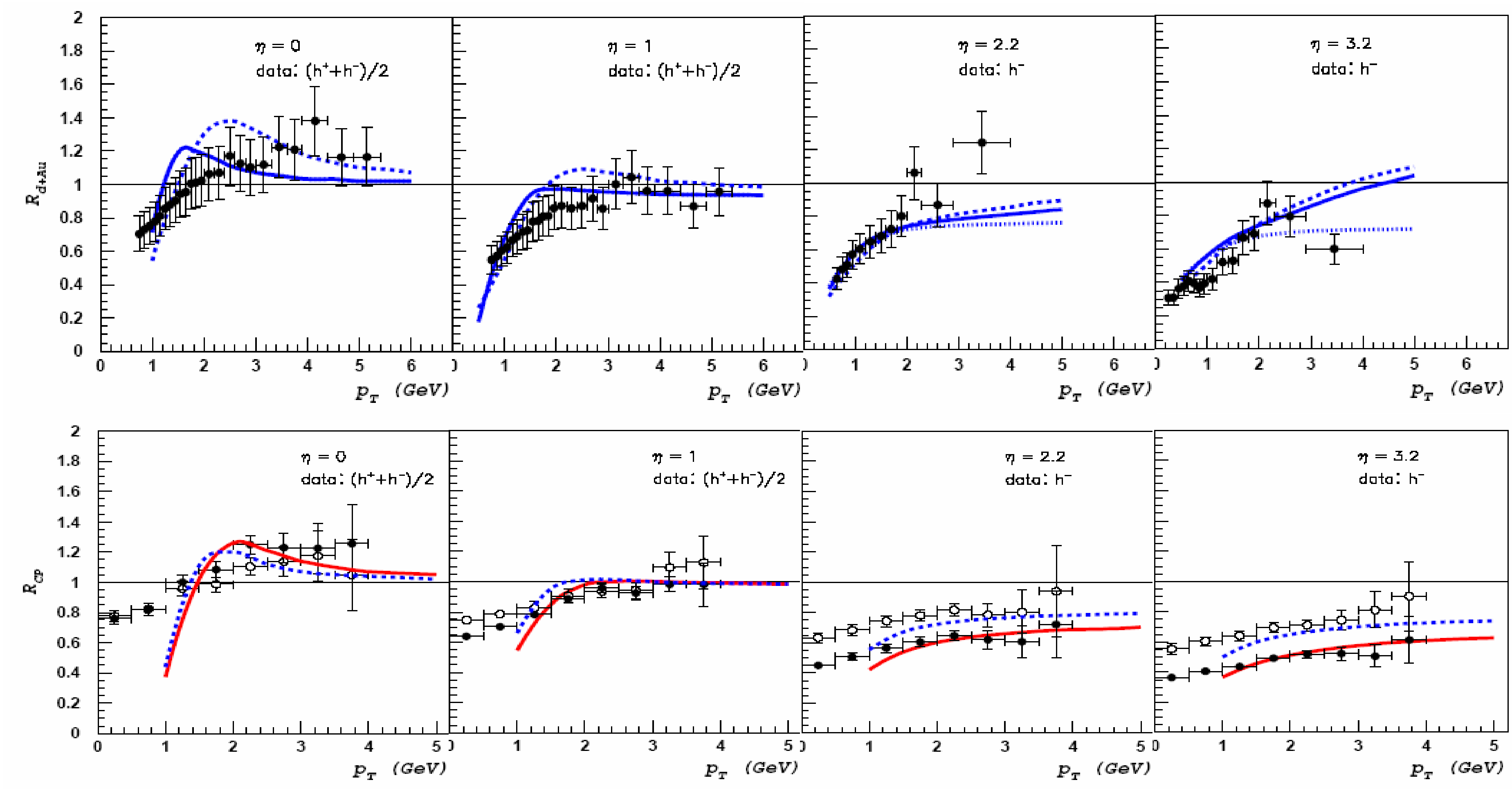
Model: Kharzeev, Levin, Nardi. Nucl. Phys. A 730 (2004) 448

Data: B. Mohanty (STAR), QM2005



Model: A. Dumitru, A. Hayashigaki, J. Jalilian-Marian, hep-ph/0506308

CGC saturation model (2)

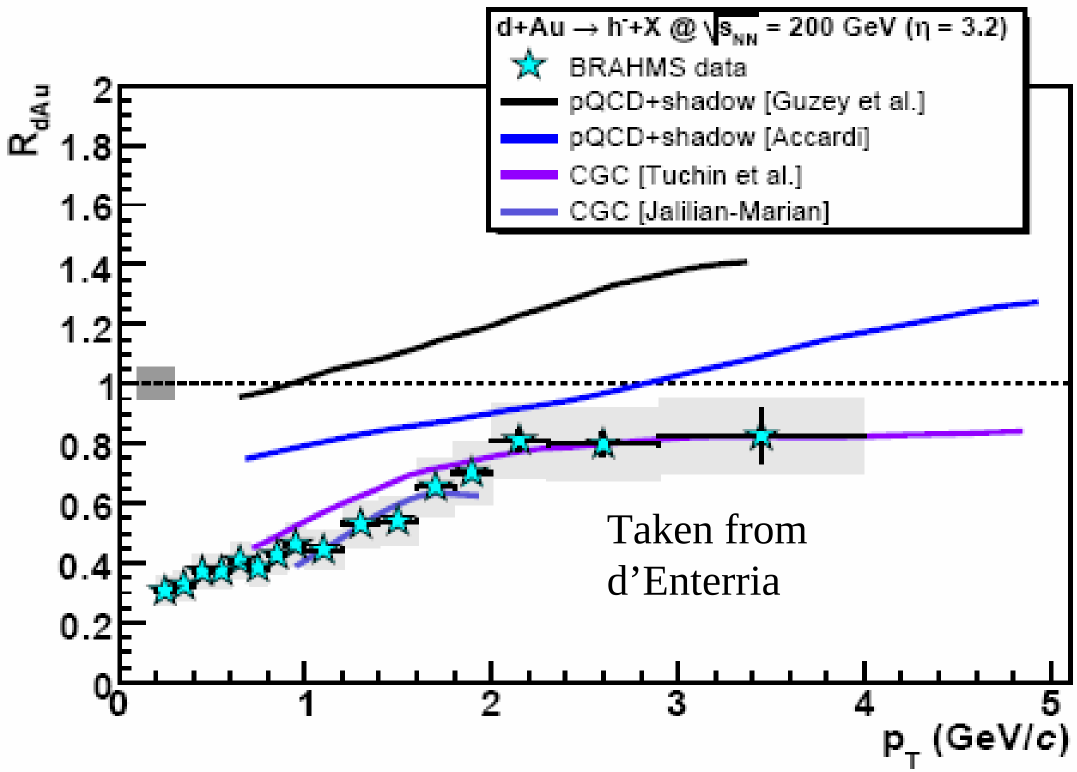


- **CGC model describes R_{dAu} and R_{CP}**
- **Suppression comes in at y > 0.6**

D. Kharzeev, Y.V. Kovchegov,
K. Tuchin, hep-ph/0405054 (2004)

Comparison pQCD vs CGC

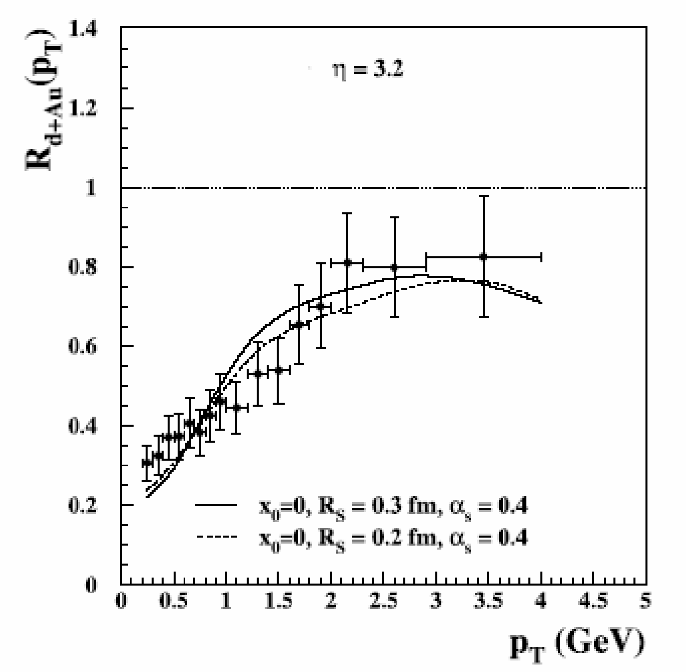
- **LO pQCD calculation**
  - **Nuclear shadowing**
- **CGC**

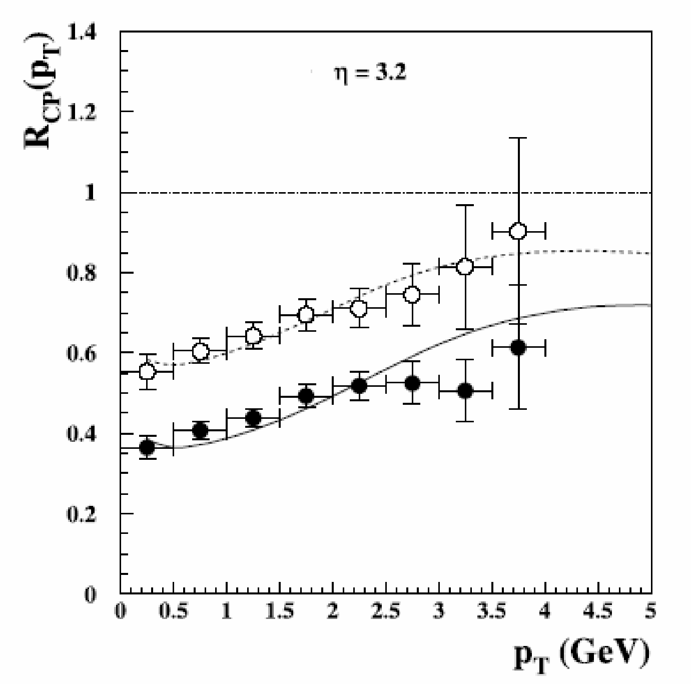


Phenomenological models

B. Kopeliovich *et al*., hep-ph/0501260; PRC72(2005)054606

- **Suppression at large x_F**
  - **Forward region is dominated by the fragmentation of valence quarks**
  - **Induced energy loss via increased gluon bremsstrahlung in cold nuclear matter**
  - **Momentum conservation forbids particle production at $x_F \to 1$**





Conclusions (dAu)

- **Suppression phenomena at forward rapidities at RHIC energies**

- **The suppression and in particular the inversion vs. centrality of R_{dAu} 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}**

- **Alternate explanations e.g. in terms of Sudakov suppression works quite well too**

Final state effects – A+A collisions

Gallmeister et al., PRC67 (2003) 044905

Hadronic absorption of fragments

Fries, Muller, Nonaka, Bass, nucl-th/0301078

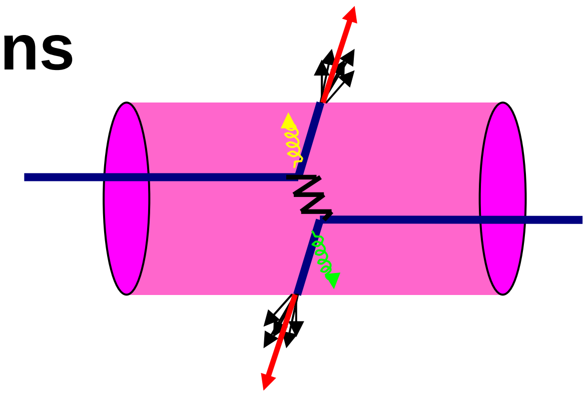
Lin, Ko, PRL89 (2002) 202302

Parton recombination

(up to moderate p_T)

R. Hwa et al., nucl-th/0501054

Energy loss of partons in dense matter

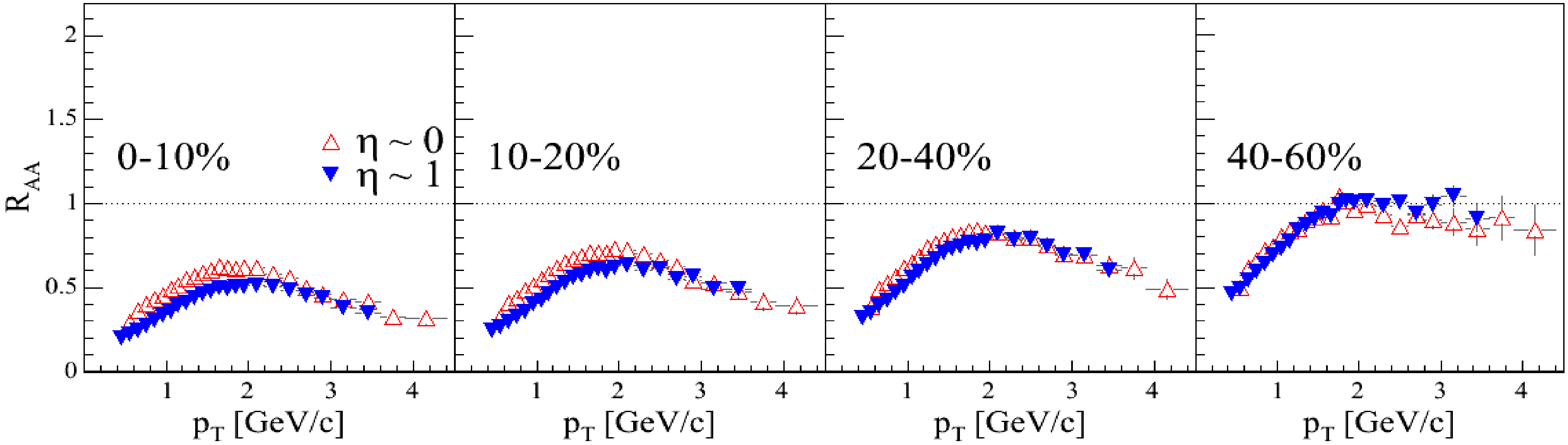


Gyulassy, Wang, Vitev, Baier, Wiedemann…

e.g. nucl-th/0302077

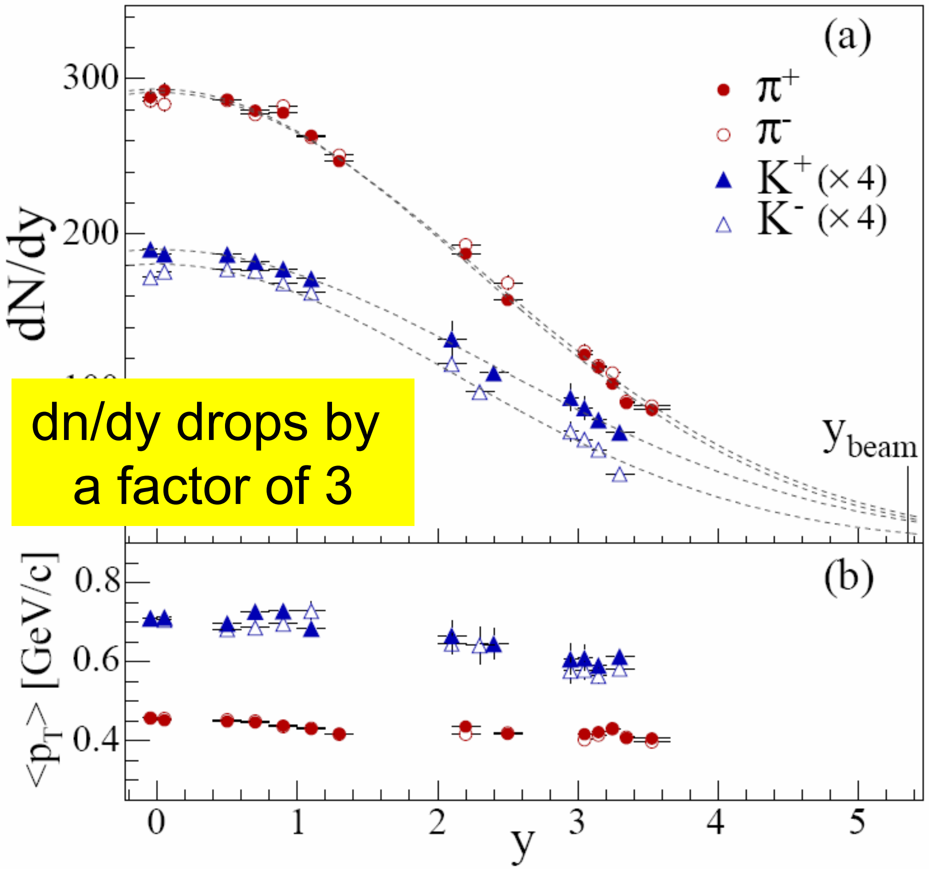
R_{AuAu}: charged hadrons – Au+Au at 200 GeV (midrapidity)

- **Nuclear modification factor**
  - **Strong suppression of hadron production at intermediate/high pt in central Au+Au collisions**



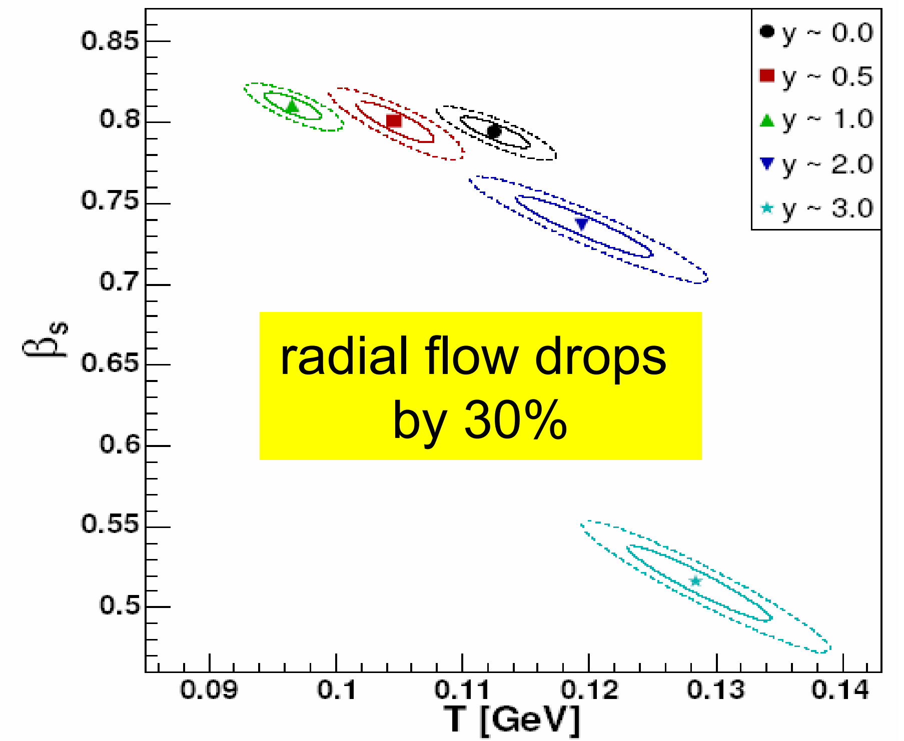
$$R_{AA} = \frac{d^2N/dp_T d\eta\ (A+A)}{N_{Coll} d^2N/dp_T d\eta\ (p+p)}$$

Matter at forward rapidity (1)



dn/dy drops by a factor of 3

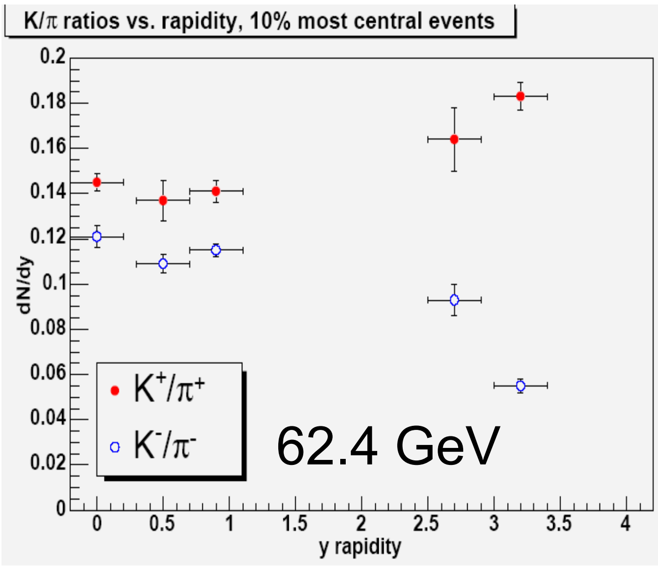
BRAHMS, Phys. Rev. Lett. 94 (2005) 162301

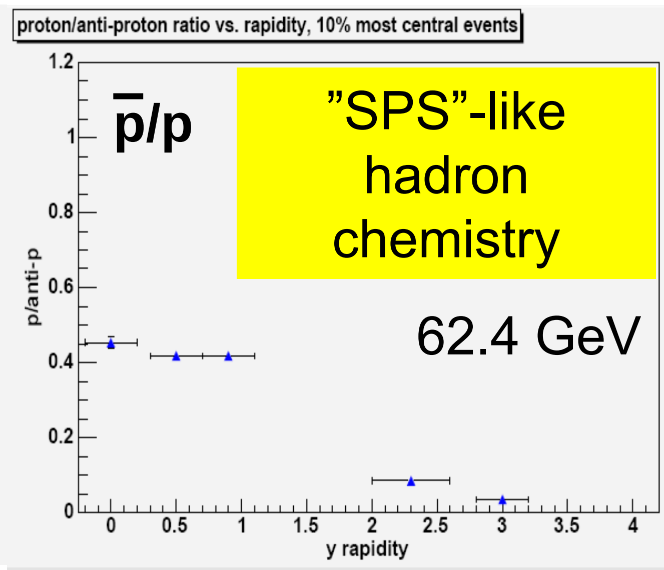


radial flow drops by 30%

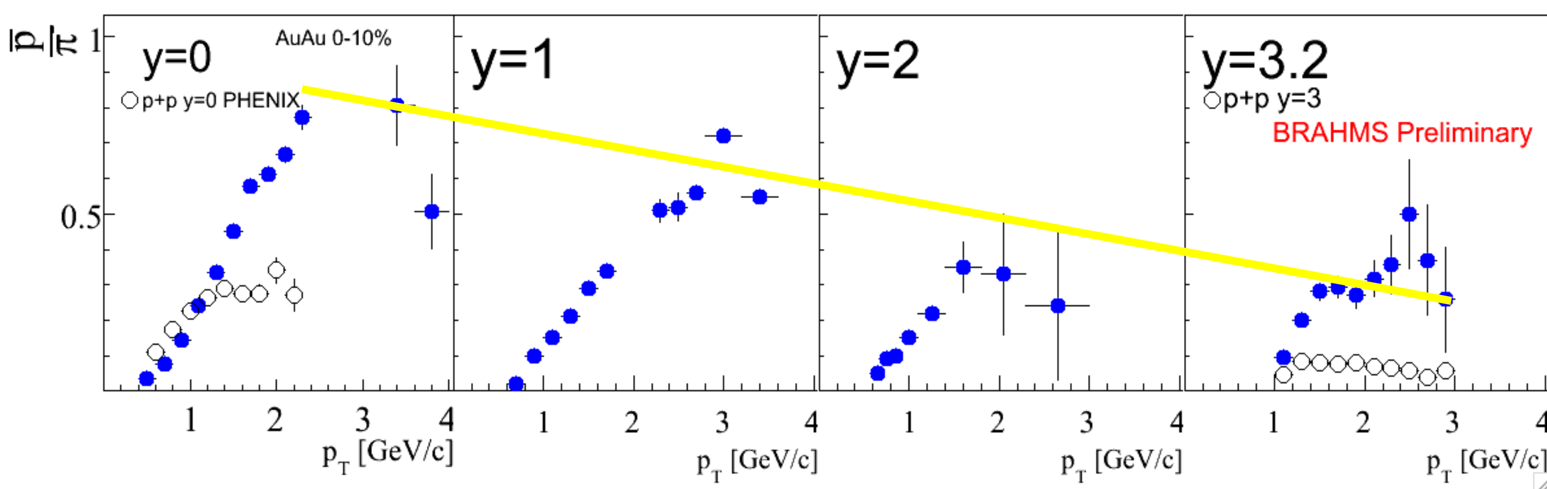
J.I. Jørdre (BRAHMS), PhD thesis (2004)

Matter at forward rapidity (2)

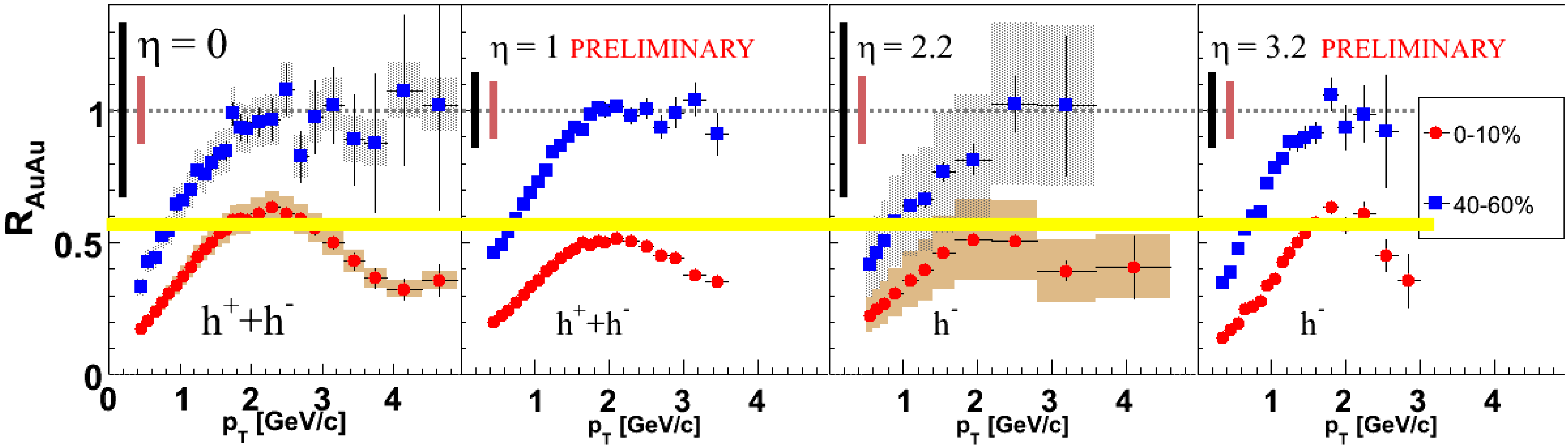




Drastic change of antiproton/pion ratio



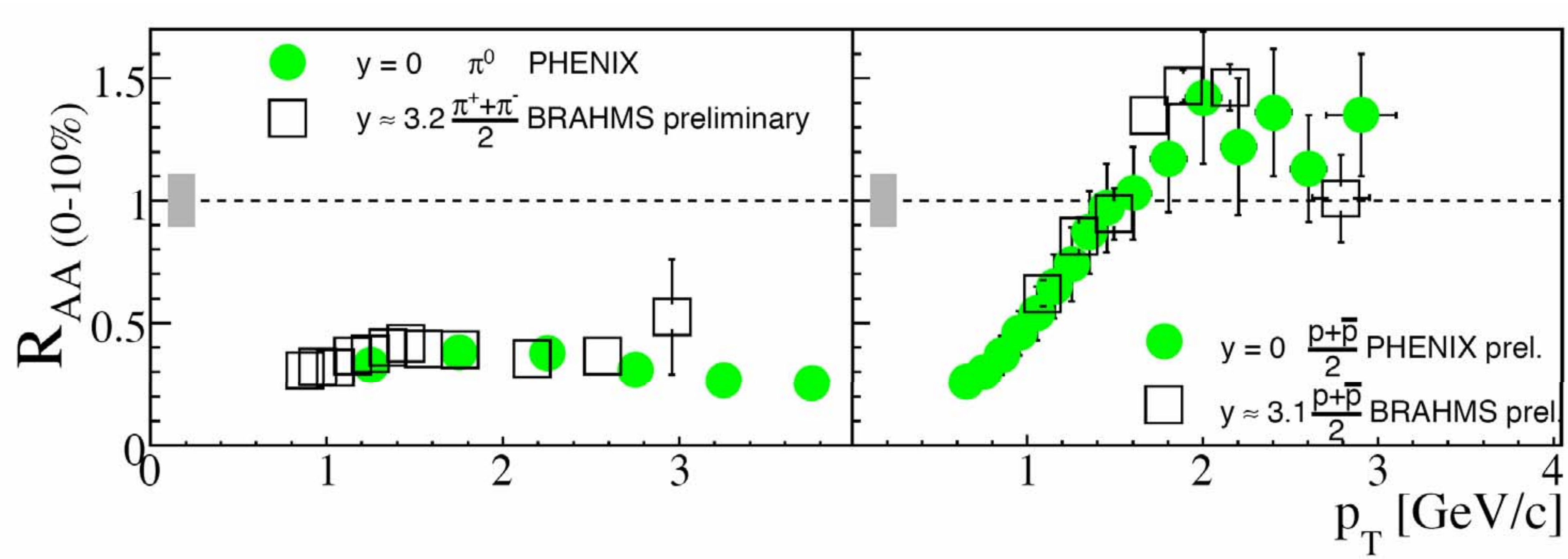
R_{AuAu}: charged hadrons – Au+Au at 200 GeV



- **NO** change of R_{AuAu} with rapidity

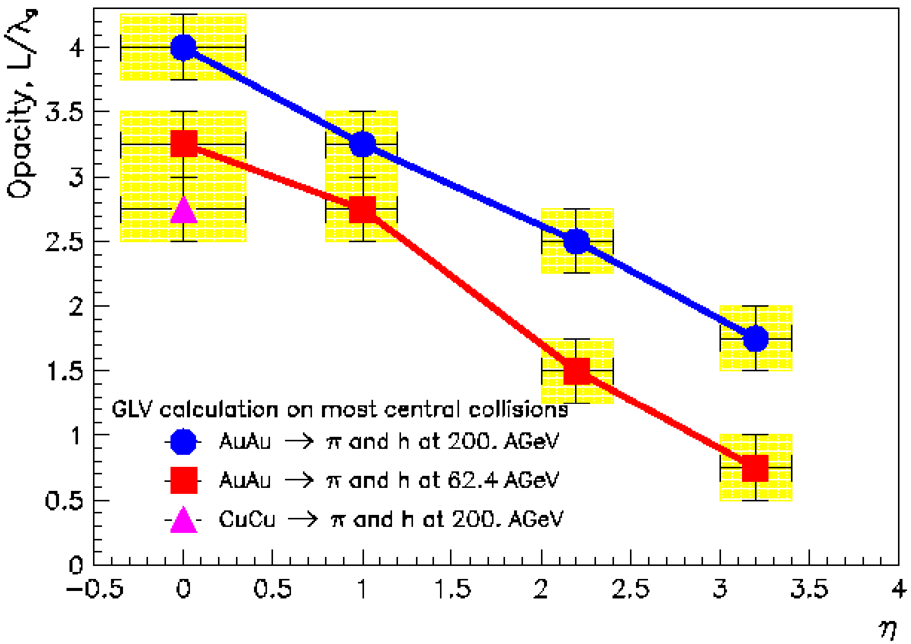
R_{AuAu}: identified hadrons – Au+Au at 200 GeV midrapidity vs η=3.2

pions **protons**



- **Strong** pion suppression
- **NO** change of R_{AuAu} with rapidity

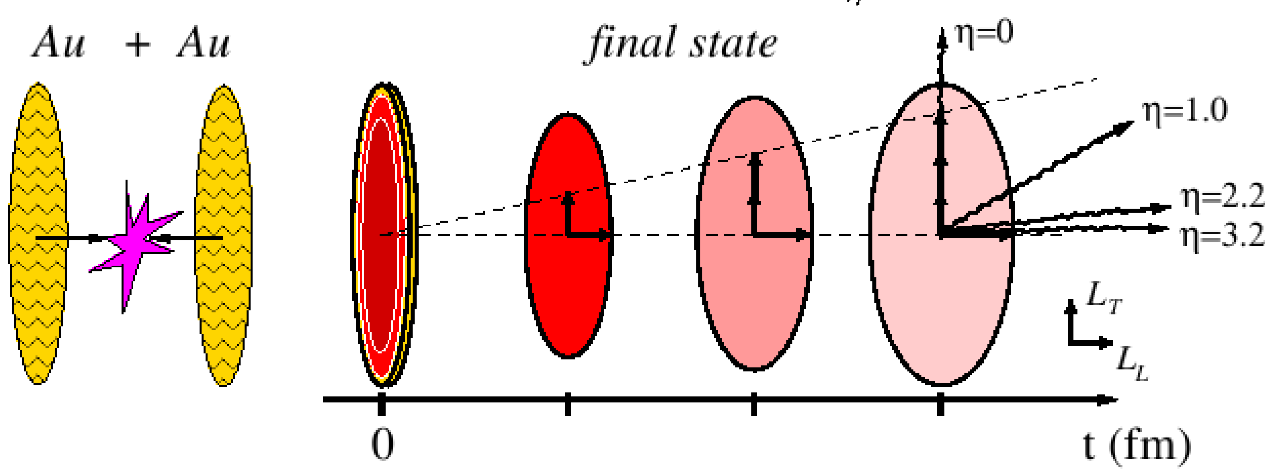
Opacity at forward rapidity



G. G. Barnafoldi et al.
Eur. Phys. J. C49 (2007)333

pQCD + GLV fit to $R_{AA} \rightarrow L/\lambda$

- **Co-moving dynamics of jet and longitudinally expanding surface of the compressed matter**



- **Initial geometry: longitudinally contracted dense deconfined zone**

Conclusions (AuAu)

- **Nuclear modification**
  - Strong pion suppression at all rapidities
  - Protons are enhanced at all rapidities (R_{AuAu}) and moderate p_T
  - No dependence of R_{AuAu} on rapidity

Summary

- Forward rapidities at RHIC has given additional insight into hadron scattering
- Pion and kaon production in pp well described in pQCD; failure of protons indicates other mechanism
- dAu 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
- Strong suppression effects at all rapidities in central Au+Au collisions

The BRAHMS Collaboration

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