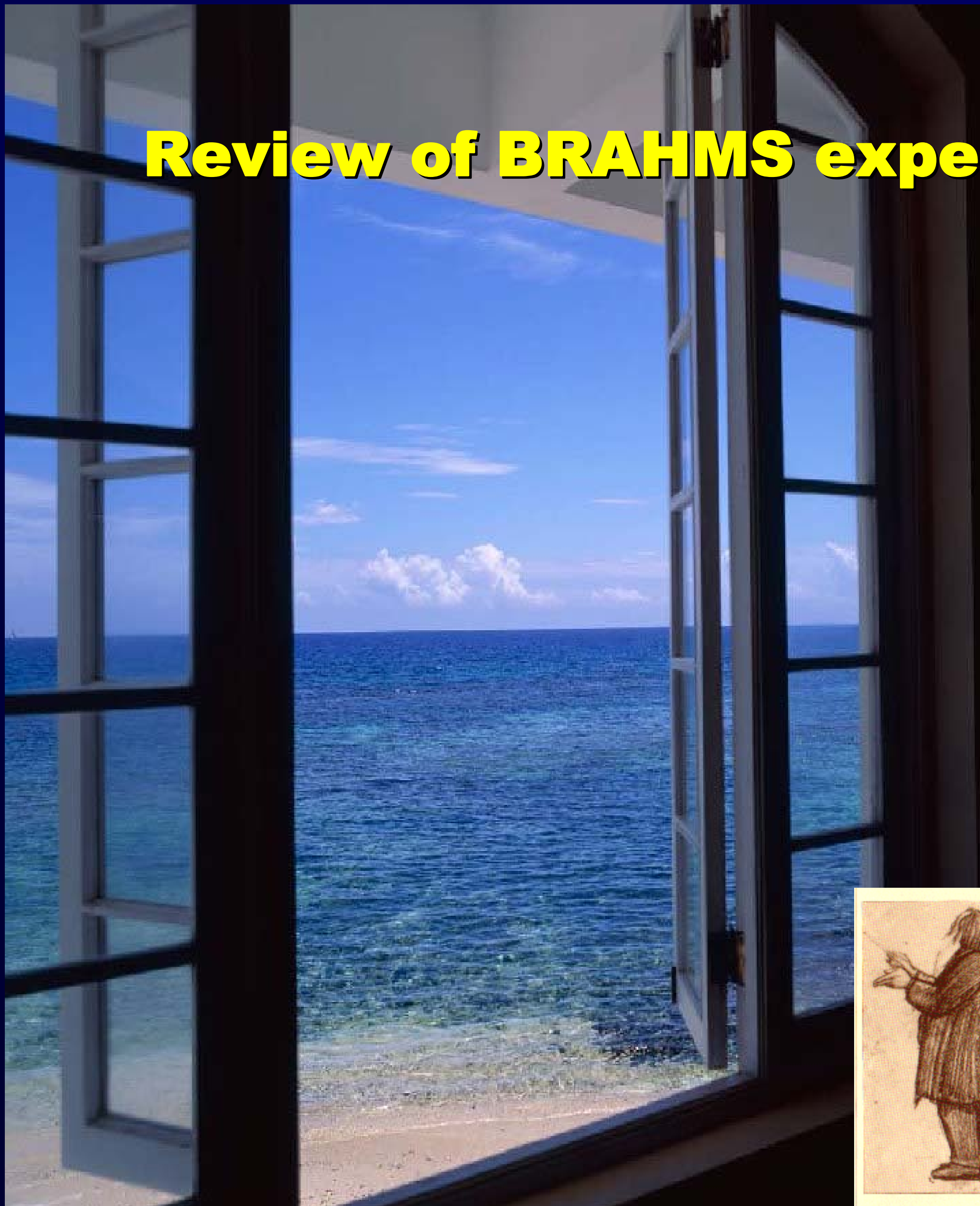
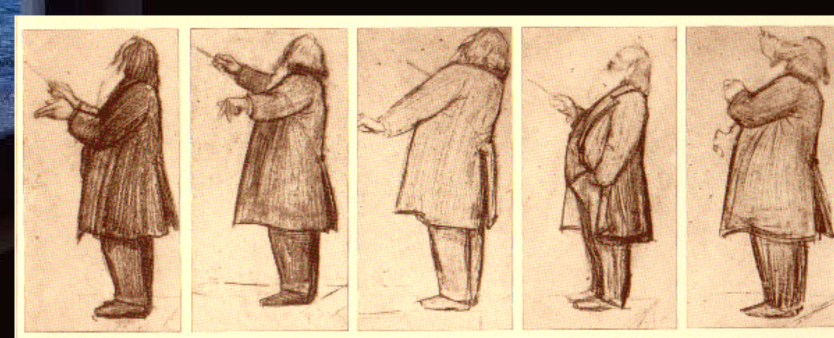
Review of BRAHMS experiment and results.



F. Videbæk

Physics Department

Brookhaven National Laboratory



Overview

- A brief history
- Particle Production in HI; The Hot Dense sQGP
  - Multiplicities
  - Longitudinal properties of particle production
  - Baryon stopping
  - Limiting Fragmentation, thermal aspects

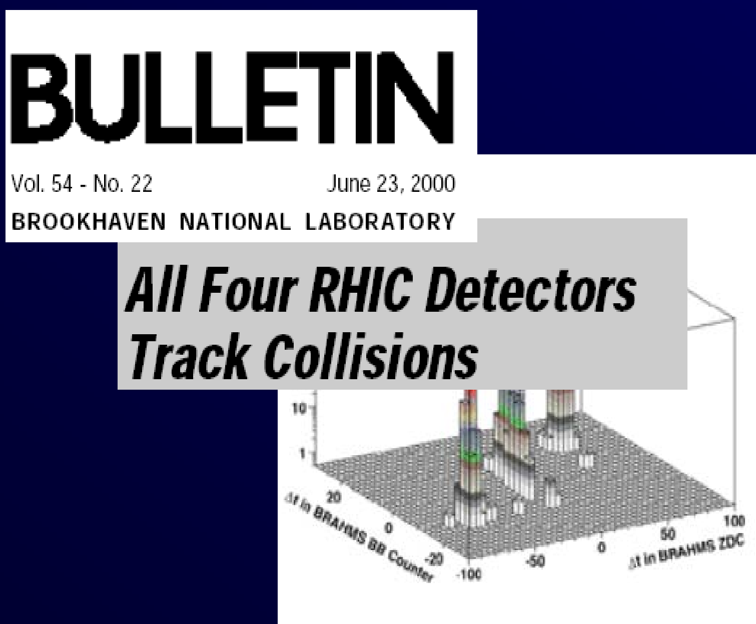
  High-pt suppression (intermediate p_t)
    - Energy , rapidity dependence
- d-Au and the Color Glass Condensate
  - R_{dAu} for charged and identified hadrons
- QCD and Spin Physics via pp
  - Understanding pp in pQCD
  - Transverse Single Spin Asymmetries
- Summary

BRAHMS proposed as LOI3 –in 1990

CDR 94, approved 95, but not funded until 1997

Construction completed in 2001

Took First data in 2000, Last data in June 2006



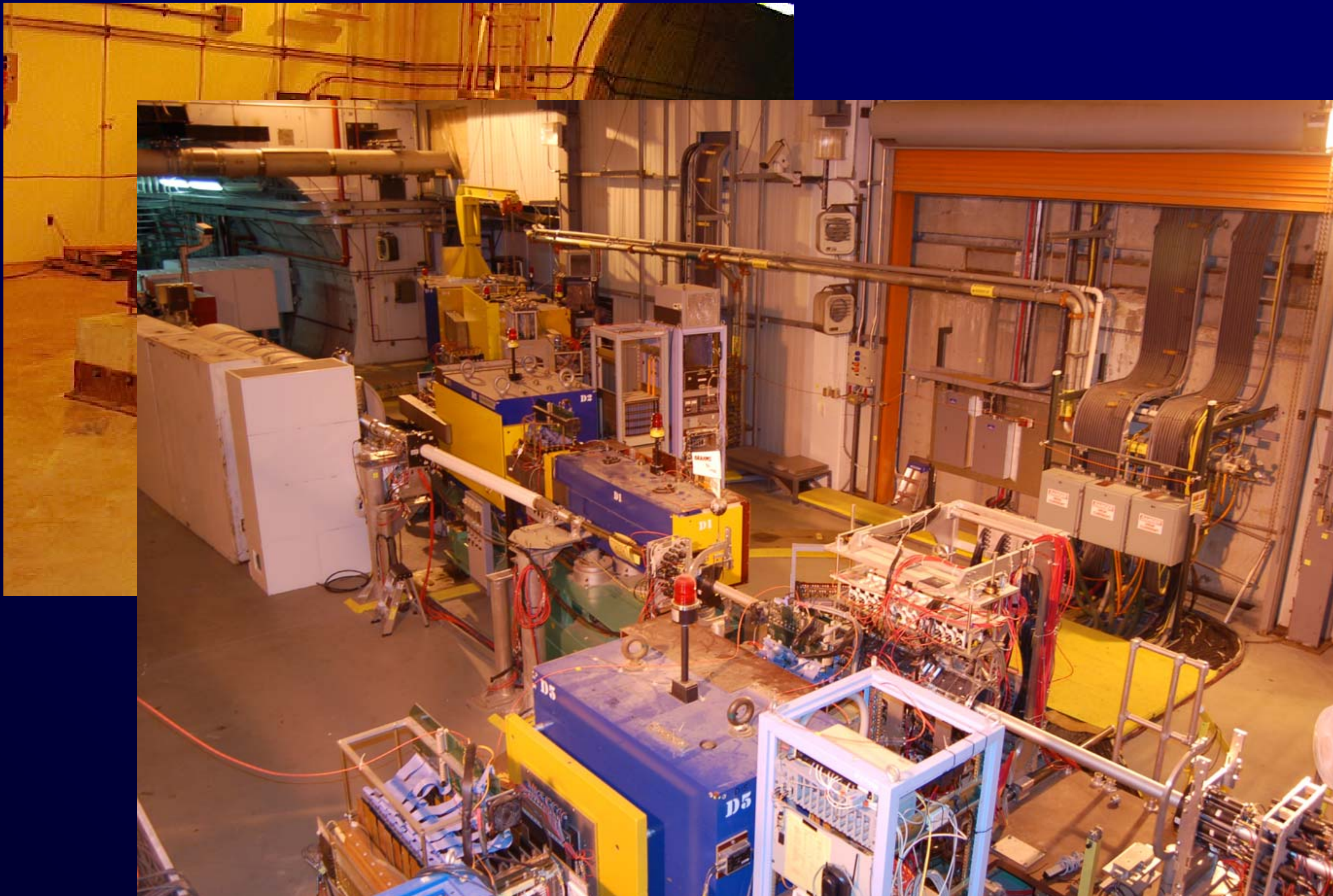
HI data at 200, 130 and 62.4 GeV

Au.Au, CuCu

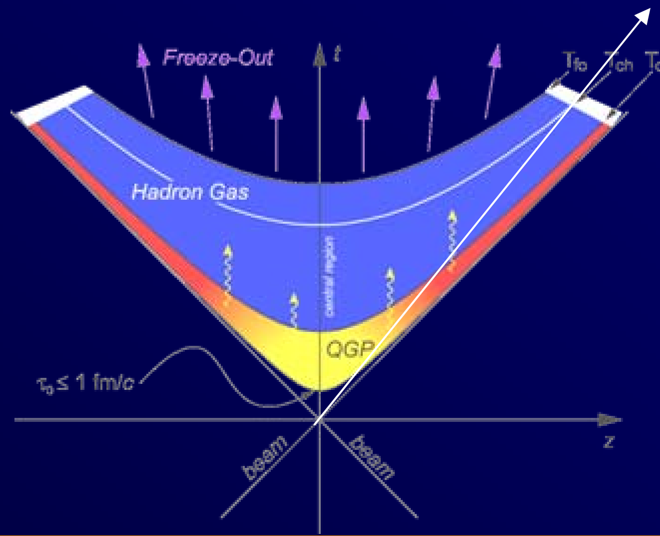
Important Reference data from

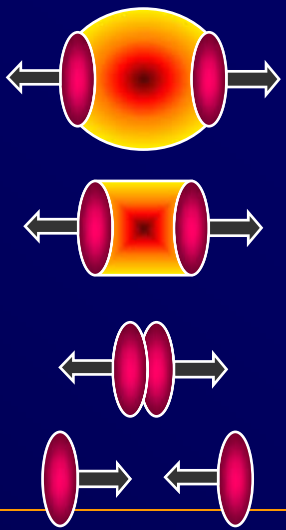
d.Au and pp (200 GeV)

pp spin data at 200 and 62.4 GeV


D2
D1
D5

Mapping Space-time Evolution





Formation of Hot Matter, QGP

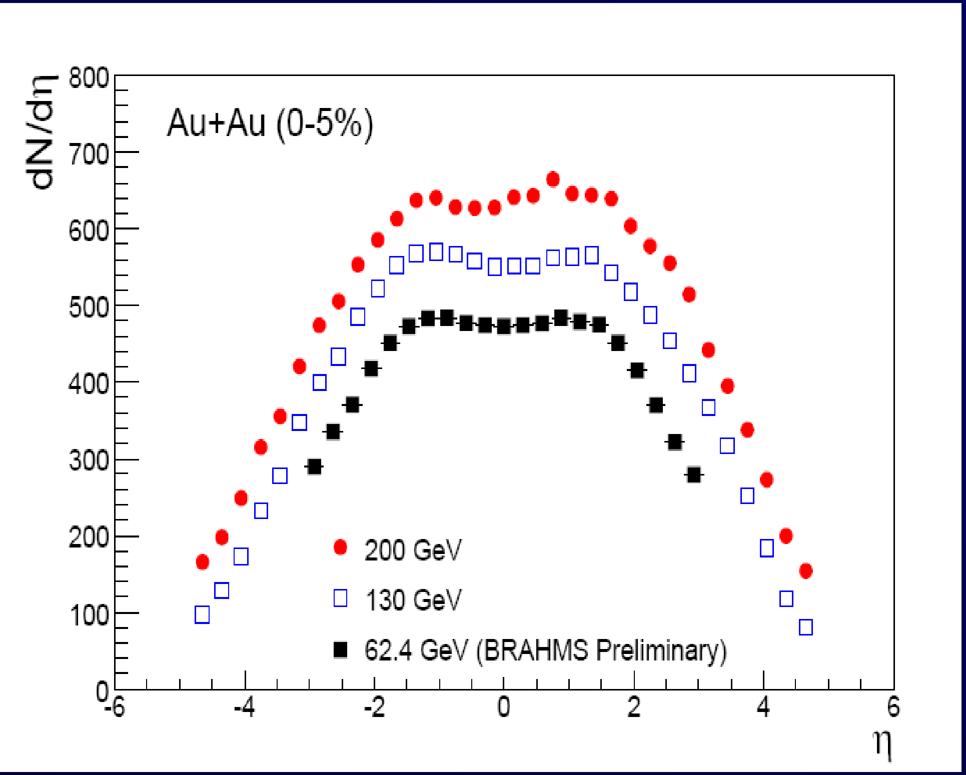
-Identifying and Characterizing the Hot Matter

- How does the system extend/develop? Transverse and longitudinal dynamics

- Strong constraints for theoretical modeling/interpretation

- Initial Conditions/Partonic Dynamics: High-p_T vs. y
- Thermodynamic and freeze-out properties: Temperatures, Particle composition vs y
- Baryon Transport: Net-baryon vs y
- Bulk Properties: multiplicity, dN/dy

Charged Particle Multiplicity



Energy density: Bjorken 1983

$$e_{BJ} = 3/2 \times (\langle E_t \rangle / \pi R^2 \tau_0)\, dN_{ch}/d\eta$$

assuming formation time t_0=1fm/c:

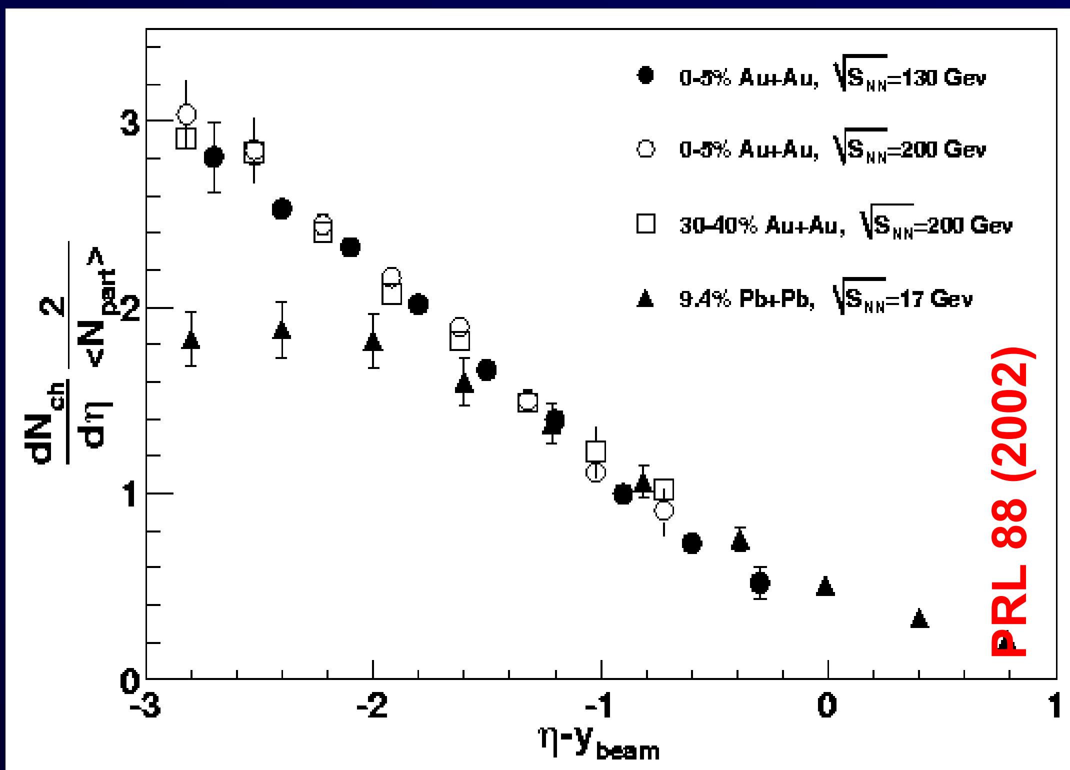
>5.0 GeV/fm³ for AuAu @ 200 GeV

>4.4 GeV/fm³ for AuAu @ 130 GeV

>3.7 GeV/fm³ for AuAu @ 62.4 GeV

Limiting Fragmentation

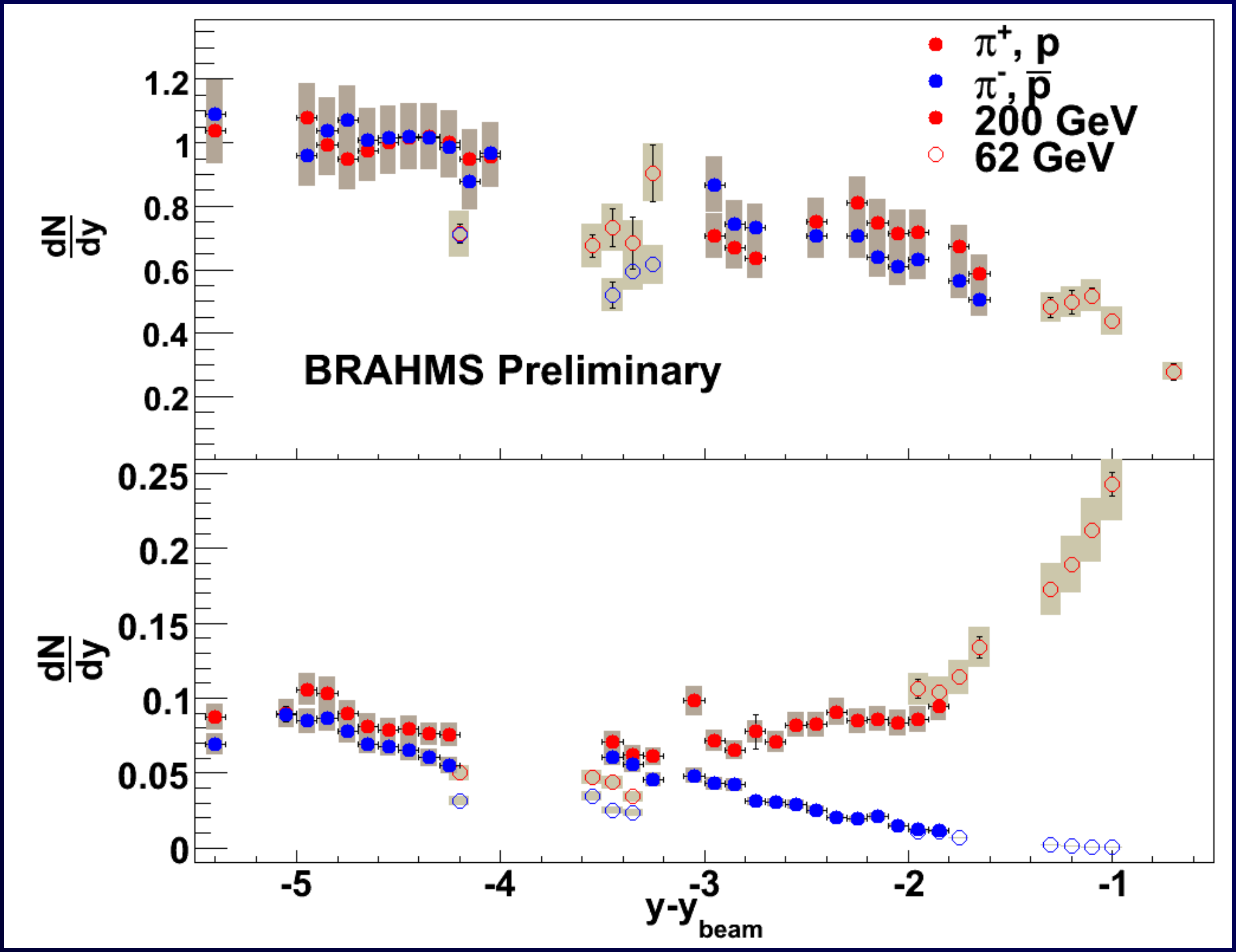
Shift the $dN_{ch}/d\eta$ distribution by the beam rapidity, and scale by $\langle N_{part} \rangle$. Lines up with lower energy ⇒ limiting fragmentation. Collision view in rest frame of projectile nucleus.



Au+Au $\sqrt{s_{NN}}$=200GeV (0-5% and 30-40%)
Au+Au $\sqrt{s_{NN}}$=130GeV (0-5%)
Pb+Pb $\sqrt{s_{NN}}$=17GeV (9.4%)

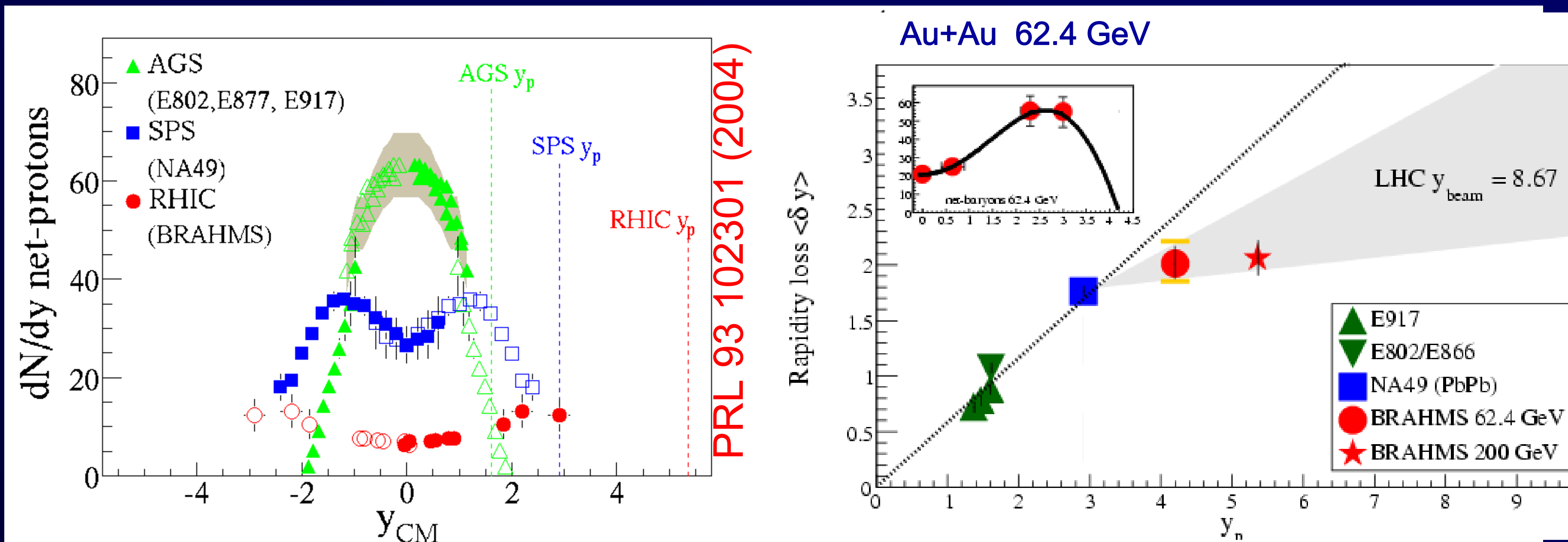
- "Crucial Observation" for universal QCD

Longitudinal Scaling in pp



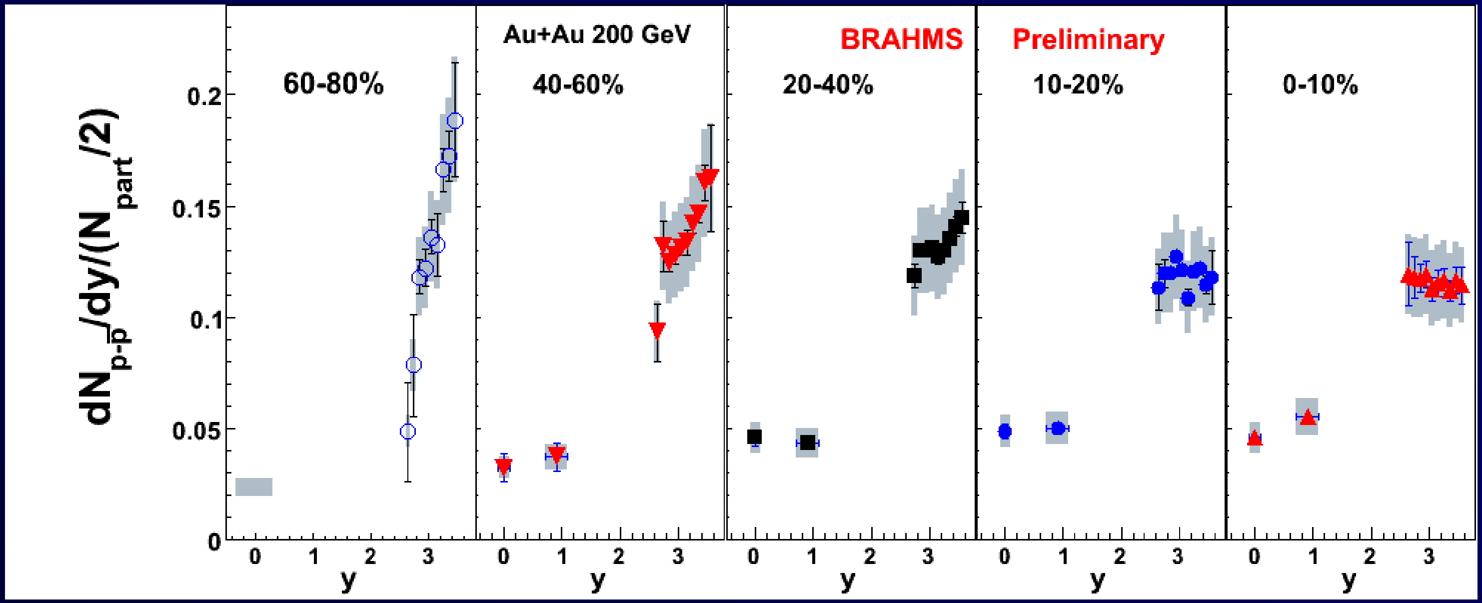
Baryon Transport: How much energy available from the collision?

Au+Au 200 GeV 0-5% Central



- AGS->RHIC : Stopping -> Transparency
- Rapidity Loss <dy>: 2±0.4: not linearly increase with y_{beam}
- Energy loss <dE> per nucleon: 73±6 GeV
- Available energy for particle production: ~26 TeV
- The pp rapidity loss is consistent with <dy> ~ 1

Centrality dependence

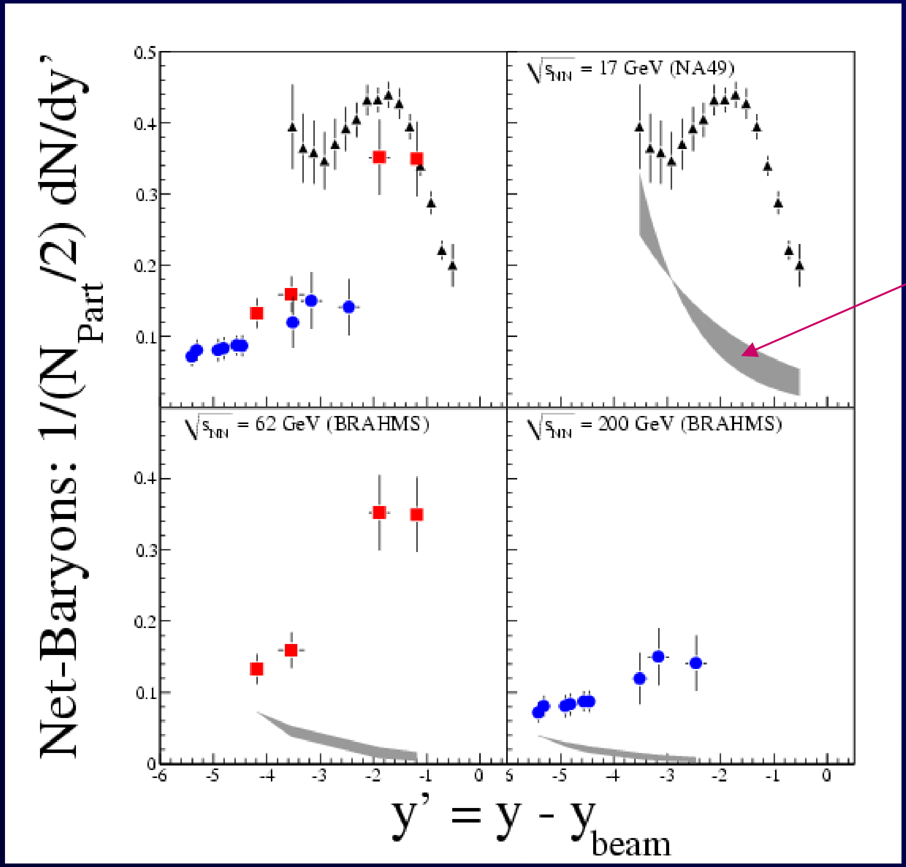


Peripheral collisions (Npart ~16) looks very much like pp

From 20-40% centrality clear change in shape.

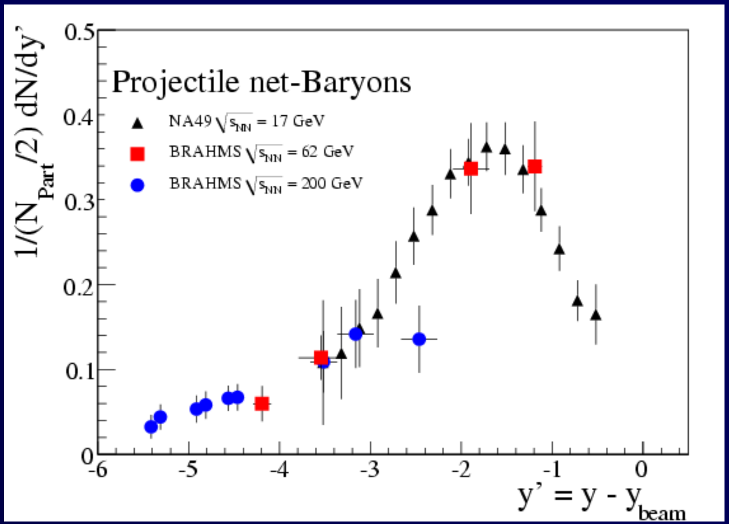
Most central: suppressed at y>3 and increased yield at y~0

Longitudinal scaling for net-p in Au+Au

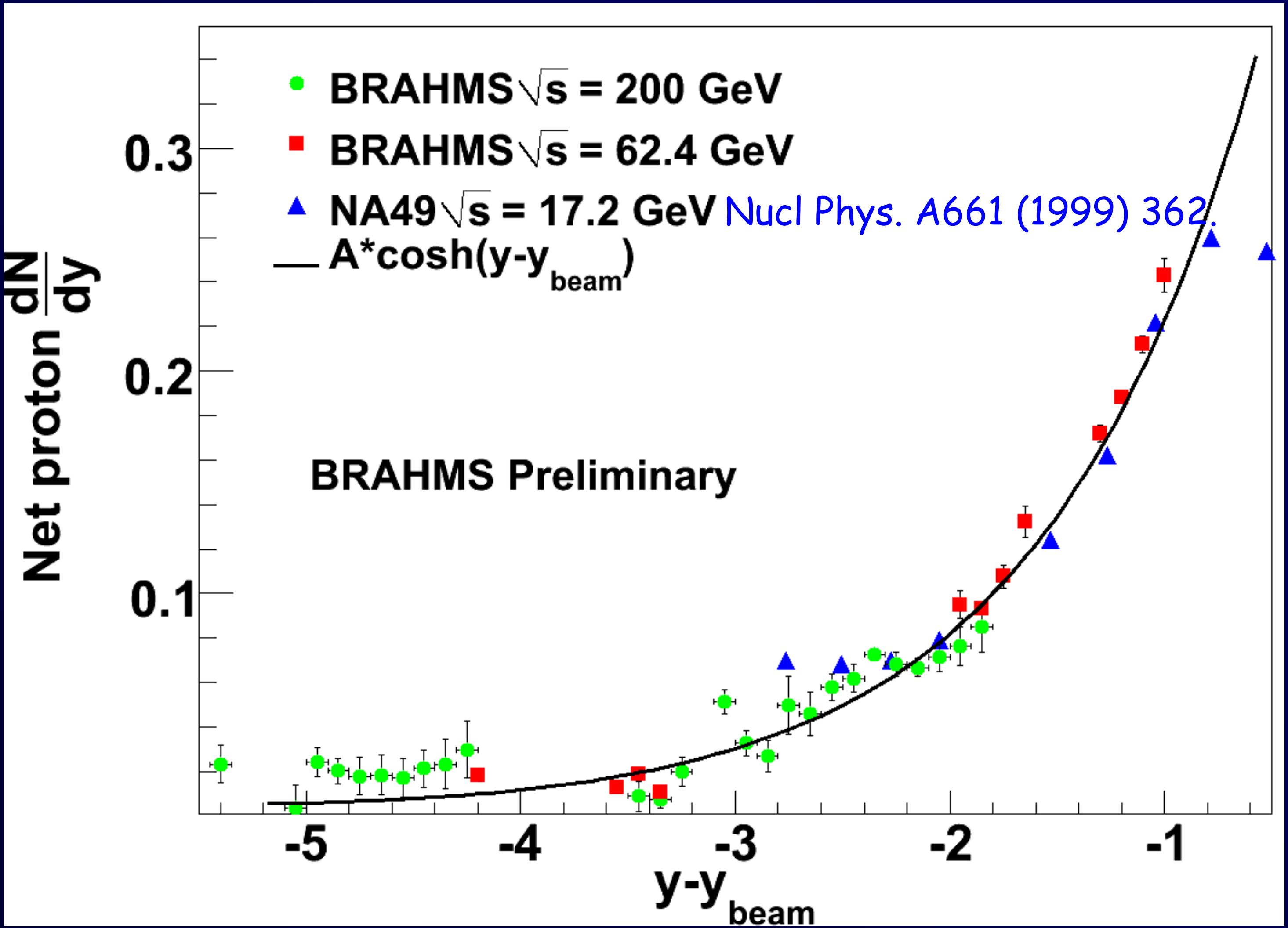


Estimate of target contribution

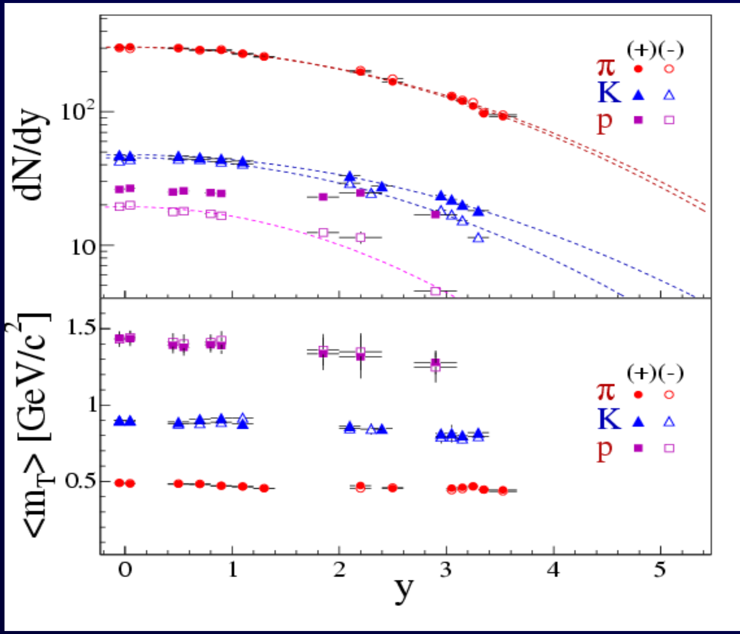
Subtracted.

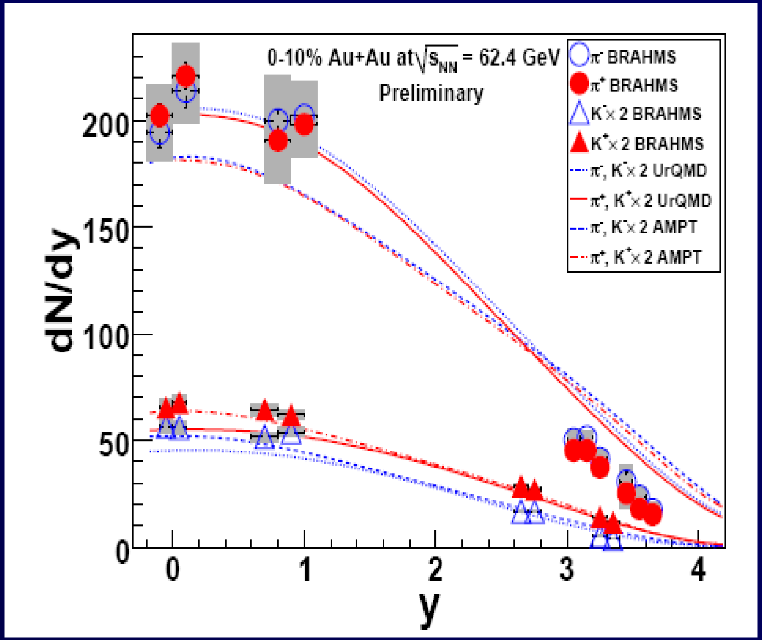


Net proton dN/dy in p+p



Produced Particles

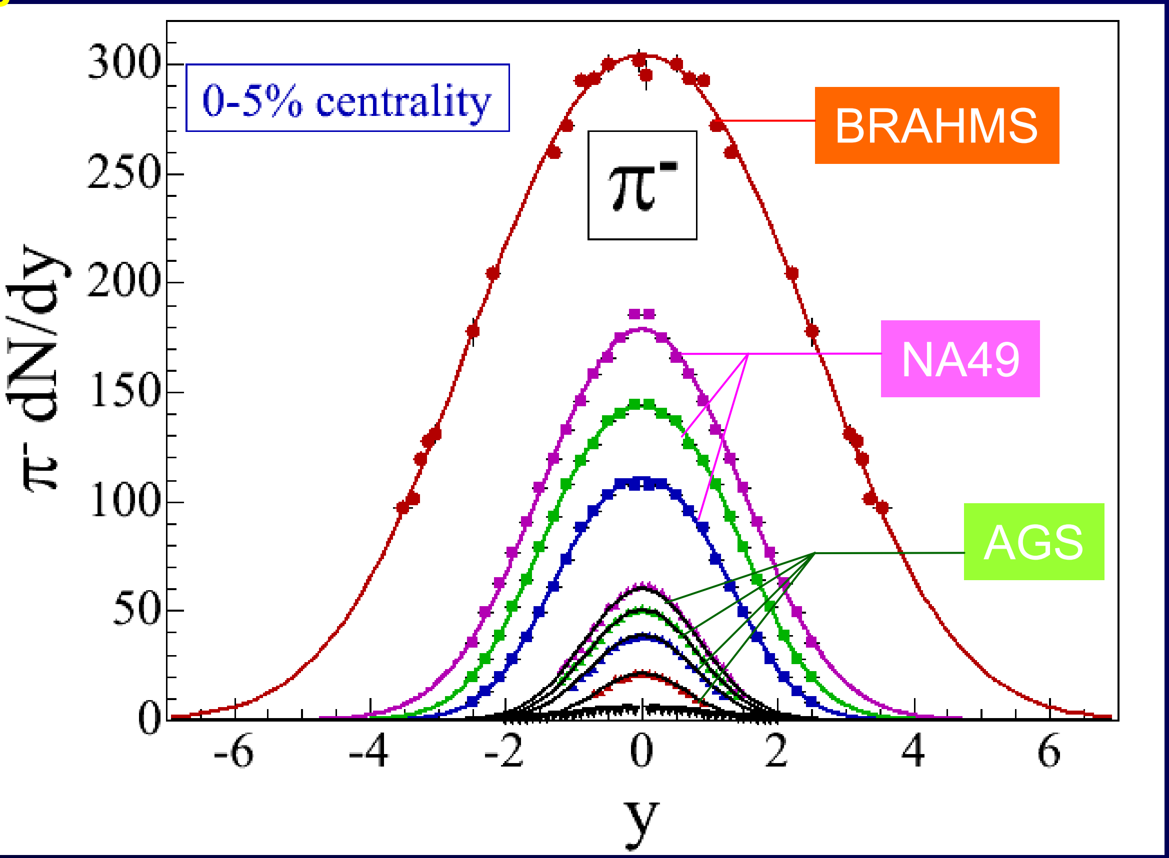




AuAu 200 GeV 0-5% central

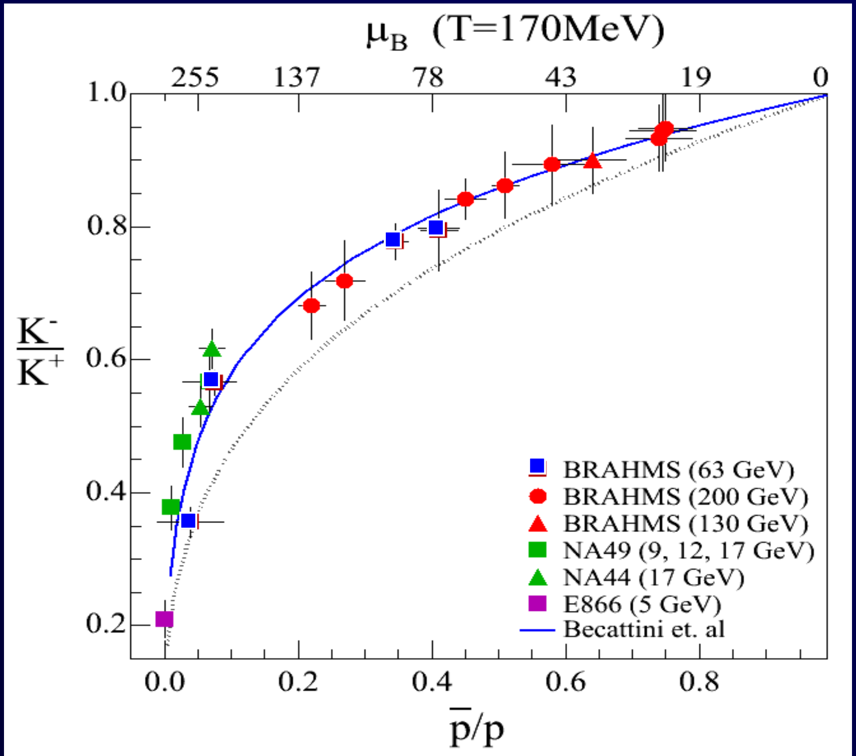
Longitudinal Distributions

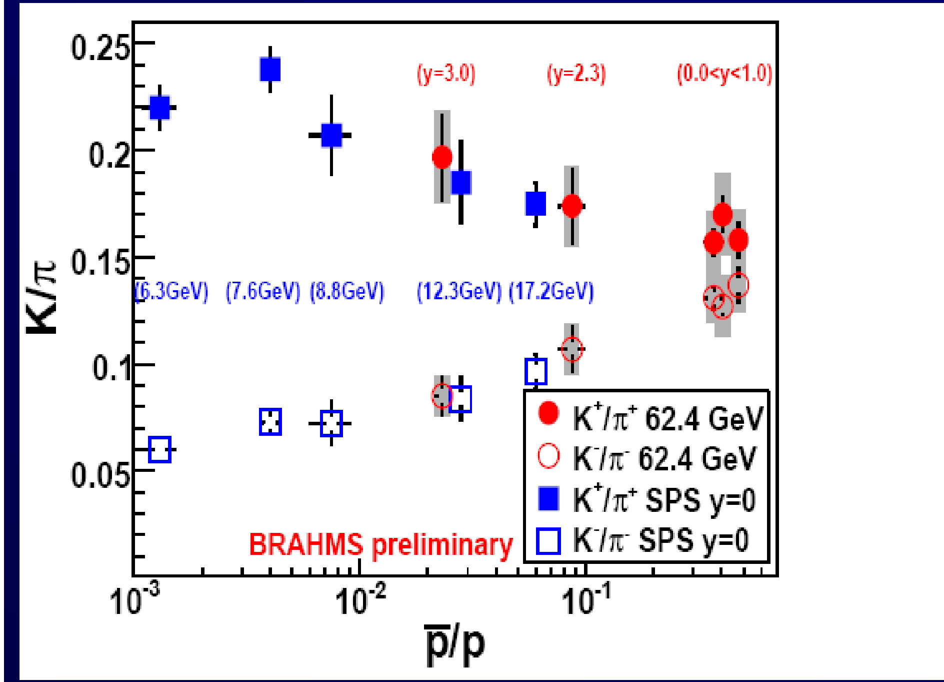
- The dN/dy of pion distributions at all energies are Gaussian with an increasing width.



Anti-particle to particle ratios

⇒ Chemical freeze-out





- **pbar/p verus K^-/K^+ : good statistical model description with $\mu_B = \mu_B(y)$ with T~170MeV**
- **But this describes also energy depencency at y=0 ⇒ only μ_B controls the state of matter**
- **This extends down to SPS range of μ_B**

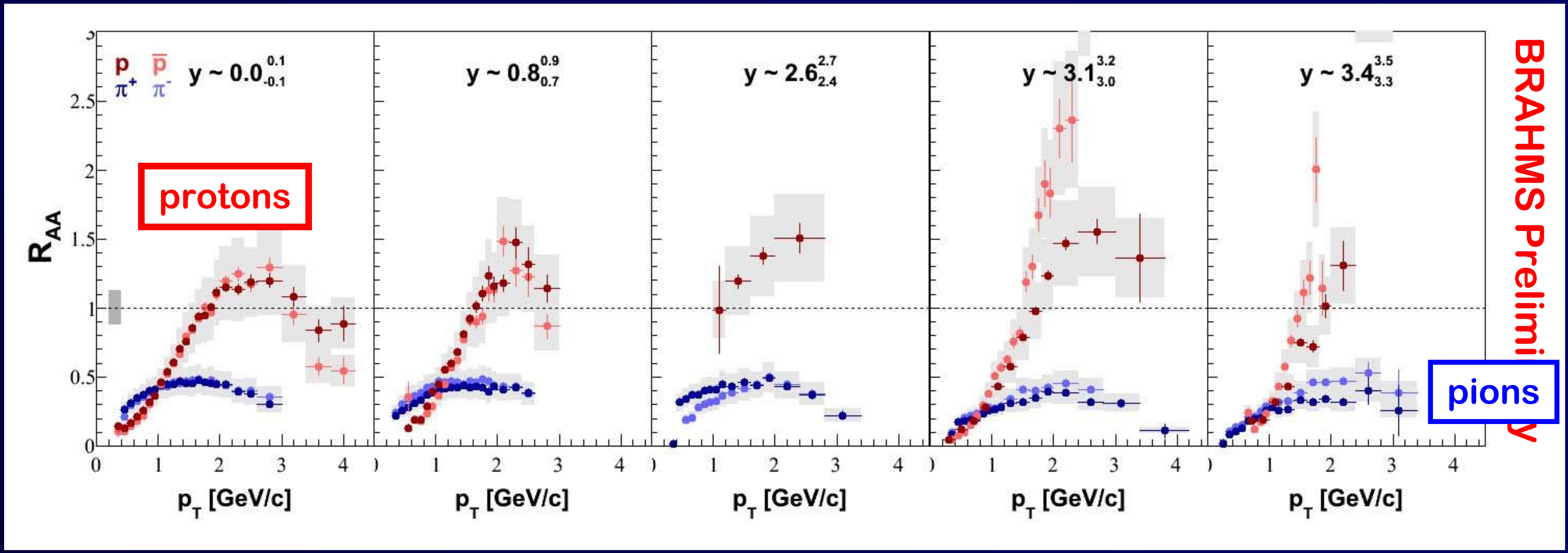
- Also for K/pi do the forward rapidities fall in same range as SPS data

Rapidity Dependent High-p_T (intermediate) Measurement

- At the RHIC energies, hard scattering processes at high-p_T become important
- Partons are expected to loose energy in the dense matter
- Different rapidities provide different densities of the medium: Sensitive to the dynamics
- Largest medium effect at mid-rapidity (“Scale” to multiplicity)?

  increasing “Dissipative Viscous Hadronic Corona”?
- Rapidity dependent high-p_T suppression factors: provide information on dynamical medium effect

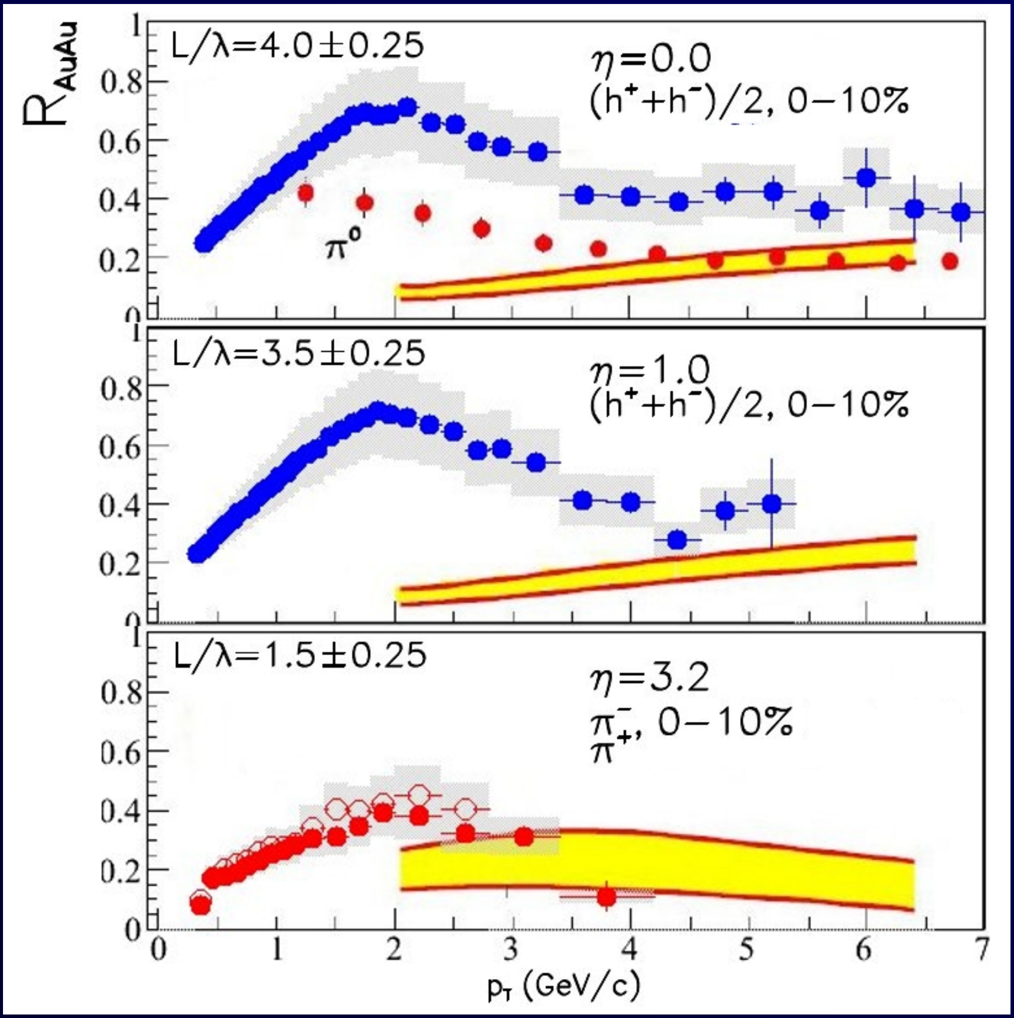
R_{AA} for identified particles (AuAu 200GeV)

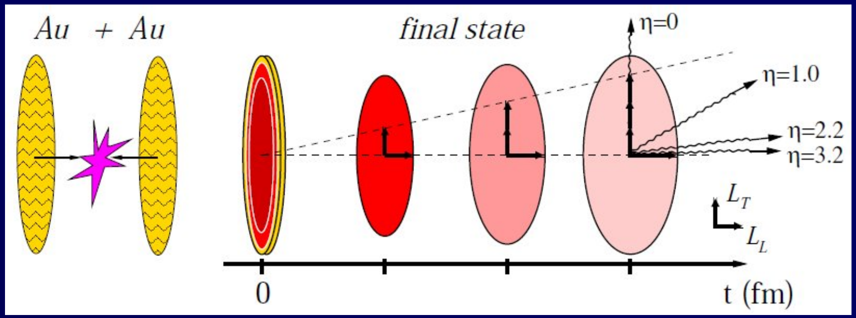


- the charged pion yields are suppressed by a factor of ~ 2-3 as compared with binary scaled p+p pion yields.
- R_{AA} for pions is independent of rapidity
- the proton and antiproton yields in central Au+Au at 200 GeV do not show suppression, baryon meson difference remains

Example of model comparison

Barnafoldi et al. hep-ph 0609023





opacity n = L/λ

- L – effective length of matter
- λ – mean free path

less jet quenching +
stronger initial effects
at higher rapidities

maintain rapidity independent NMF

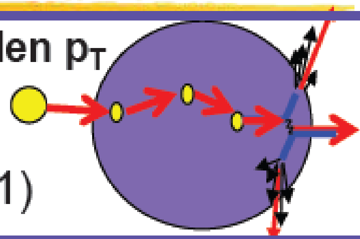
Initial and final effects – dAu at 200 GeV

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

"Cronin effect"

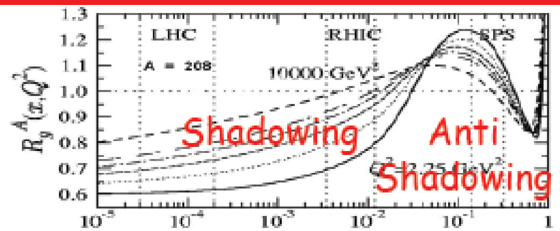
Initial state elastic multiple scattering leading to **Cronin** enhancement (R_{AA}>1)

broaden p_T



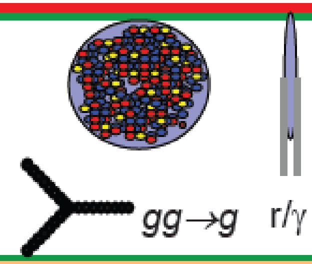
Nuclear shadowing

depletion of low-x partons



Gluon saturation

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



Suppression due to

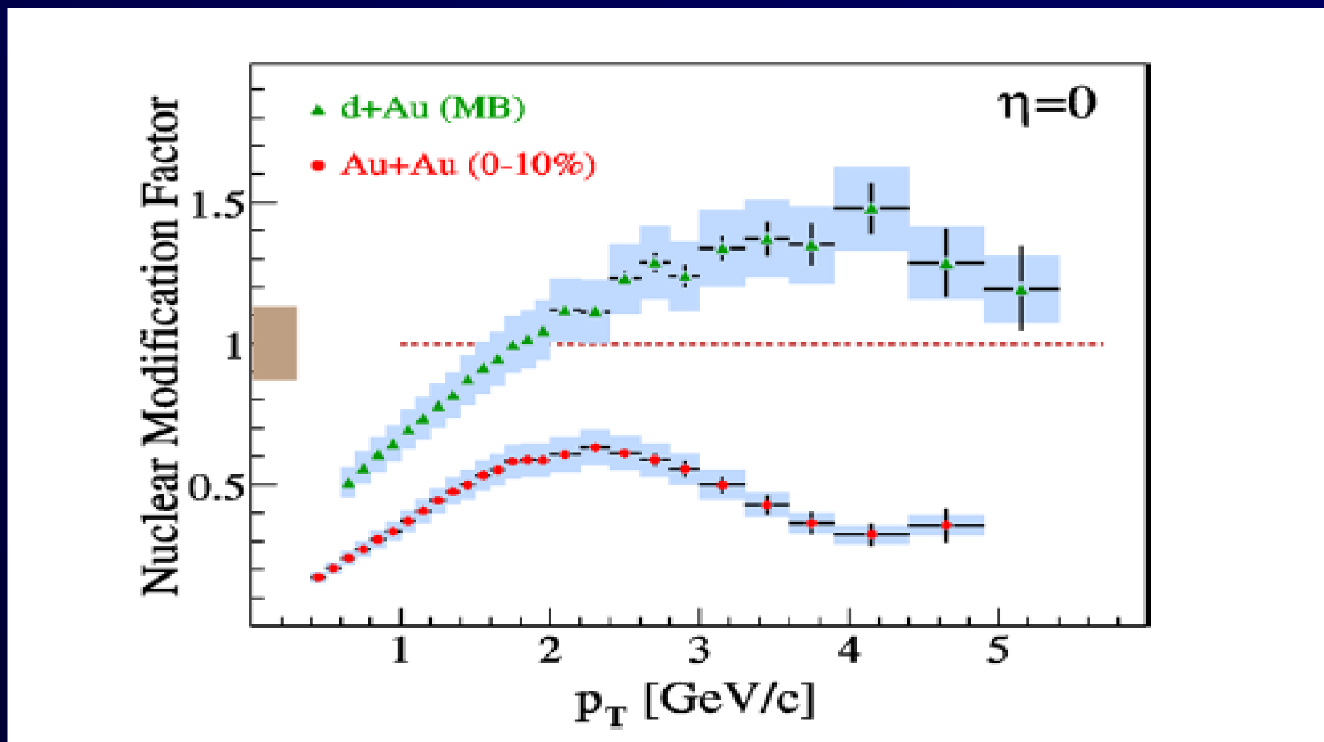
dominance of projectile valence quarks, energy loss, coherent multiple scattering, energy conservation, parton recombination, ...

the Bulletin — BROOKHAVEN NATIONAL LABORATORY

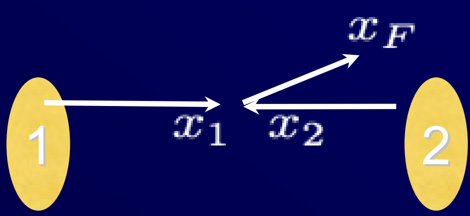
Vol. 57 - No. 21 — June 20, 2003

Exciting First Results From Deuteron-Gold Collisions at RHIC

Findings intensify search for new form of matter



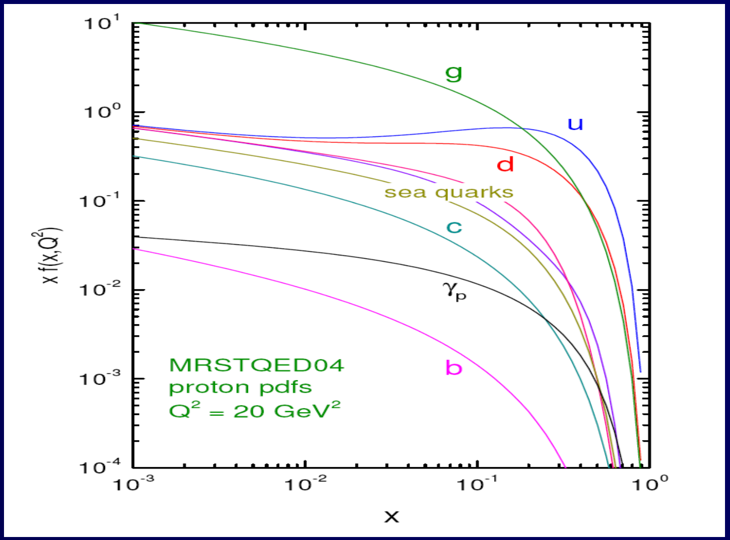
'PRL 91 (2003) 072305'

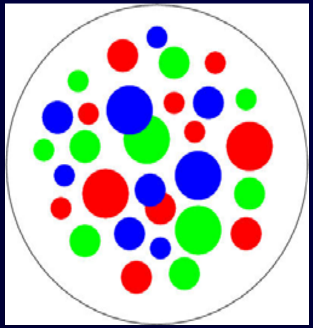


$$x_F = x_1 - x_2$$

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

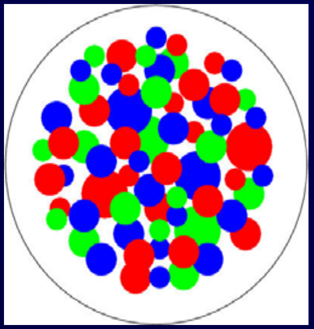
$$x_1 \sim \frac{m_T}{\sqrt{s}} e^{y} \quad x_2 \sim \frac{m_T}{\sqrt{s}} e^{-y}$$





Mid rapidity

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

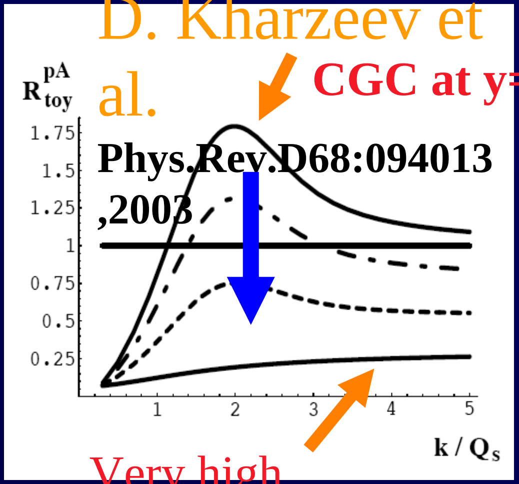


Forward rapidity

D. Kharzeev et al.

CGC at y=0

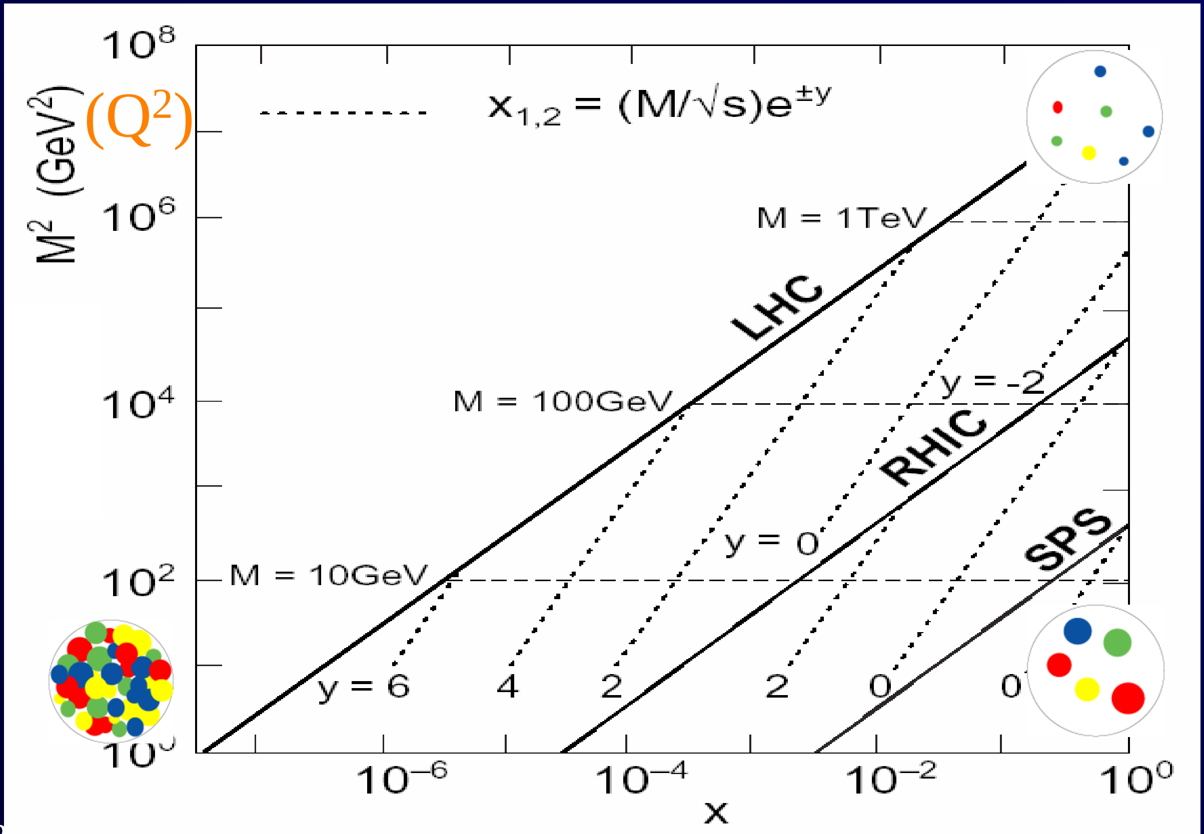
Phys.Rev.D68:094013 ,2003



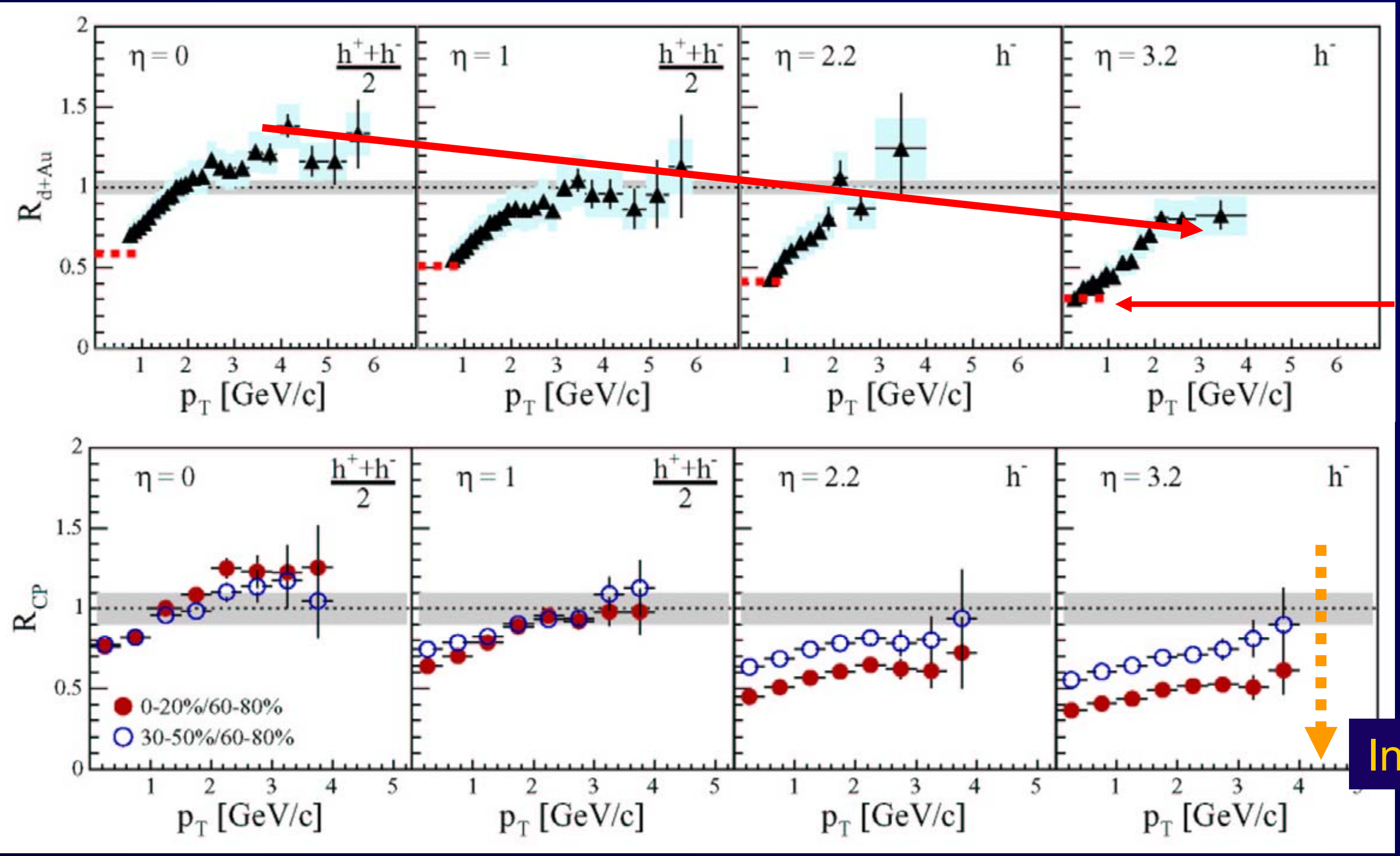
Very high energy

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~3 can reach into $x_2 \sim 10^{-3}$



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/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.

Identified Particle R_{dAu}

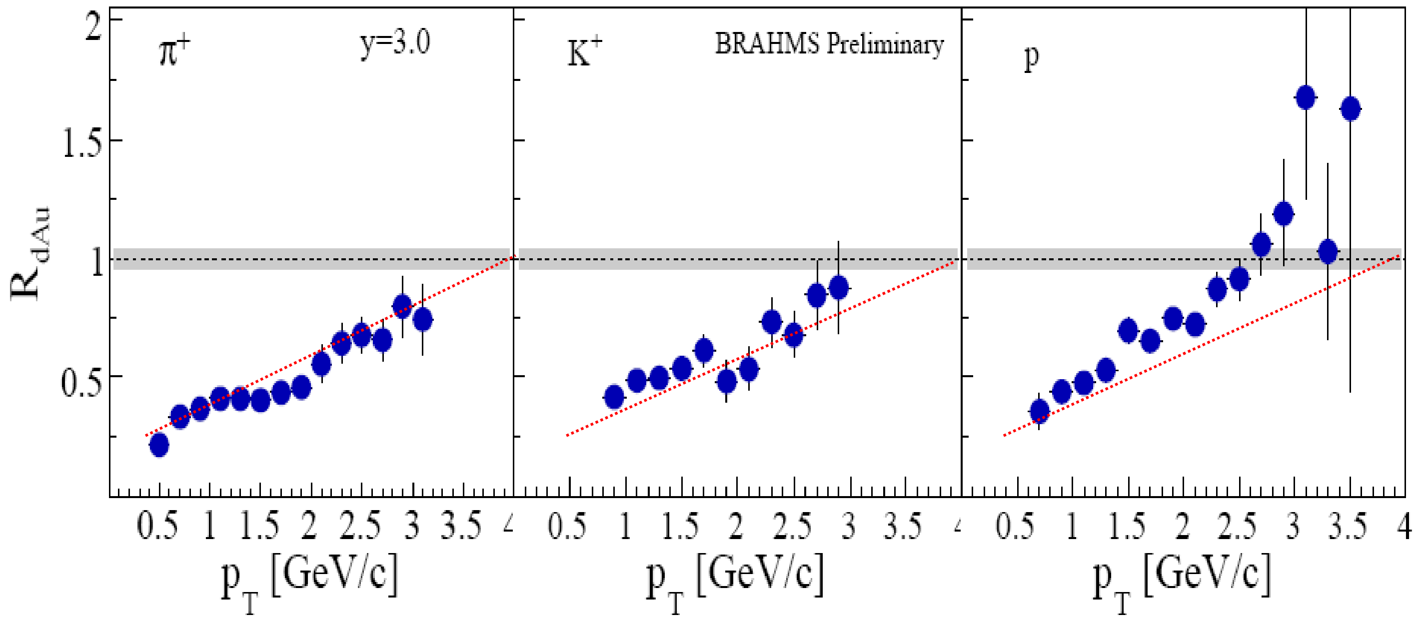
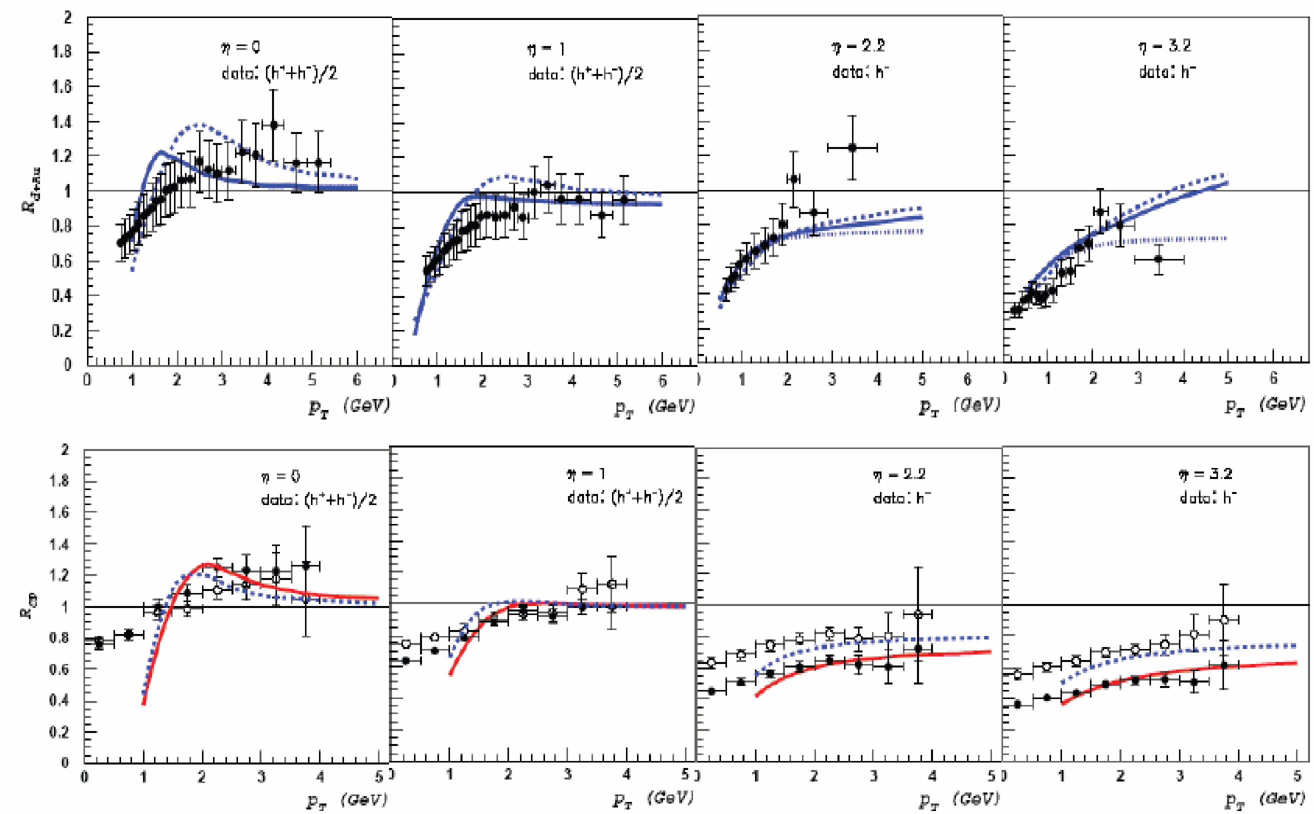


Figure 2. R_{dAu} of π^+, K^+ and protons at forward rapidity $y = 3.0$ in minimum bias d+Au collisions ($< N_{coll} >= 7.2$). A 8% systematic error is included.

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

The protons may exhibit less suppression.

Impact on Theory /comparison..

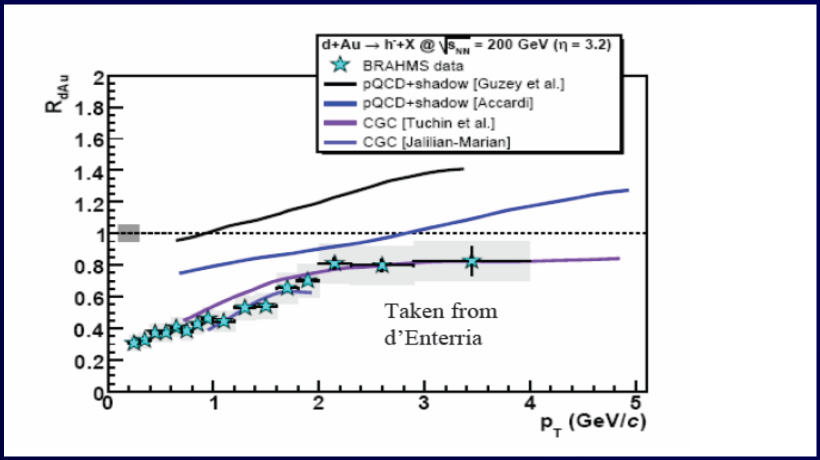


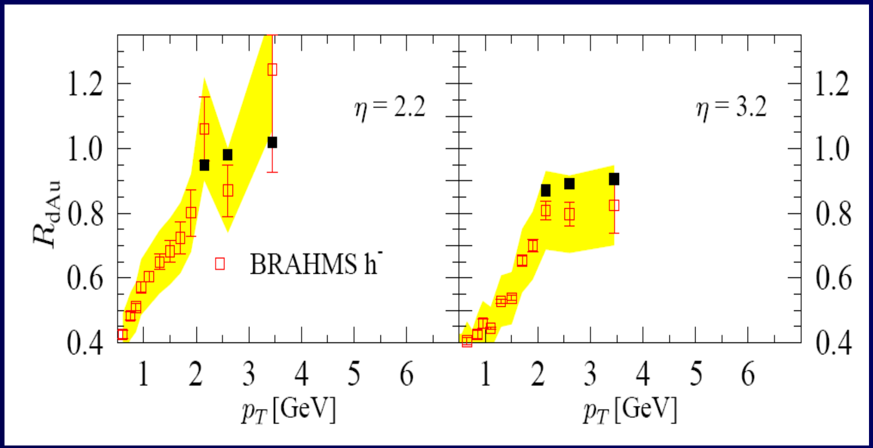
- CGC model describes R_{dAu} and R_{CP}
- Suppression comes in at y > 0.6

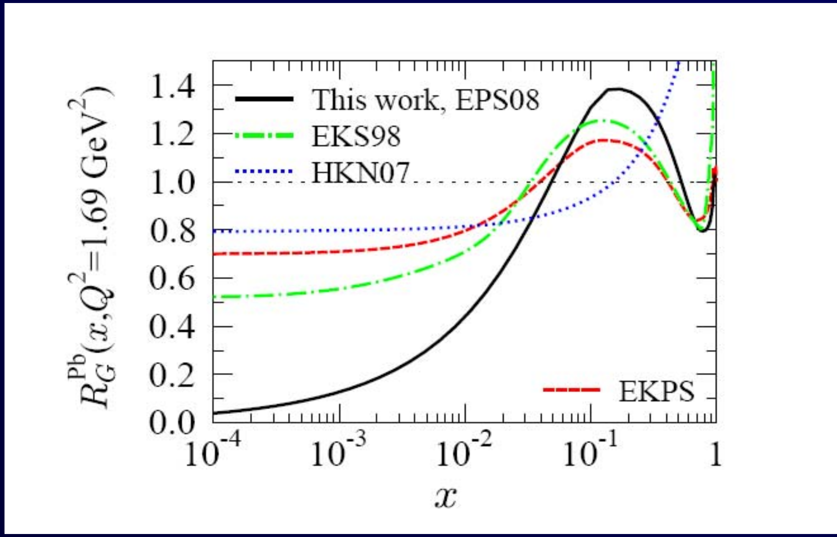
D. Kharzeev, Y.V. Kovchegov, K. Tuchin, hep-ph/0405054 (2004)

18

Shadowing vs. CGC



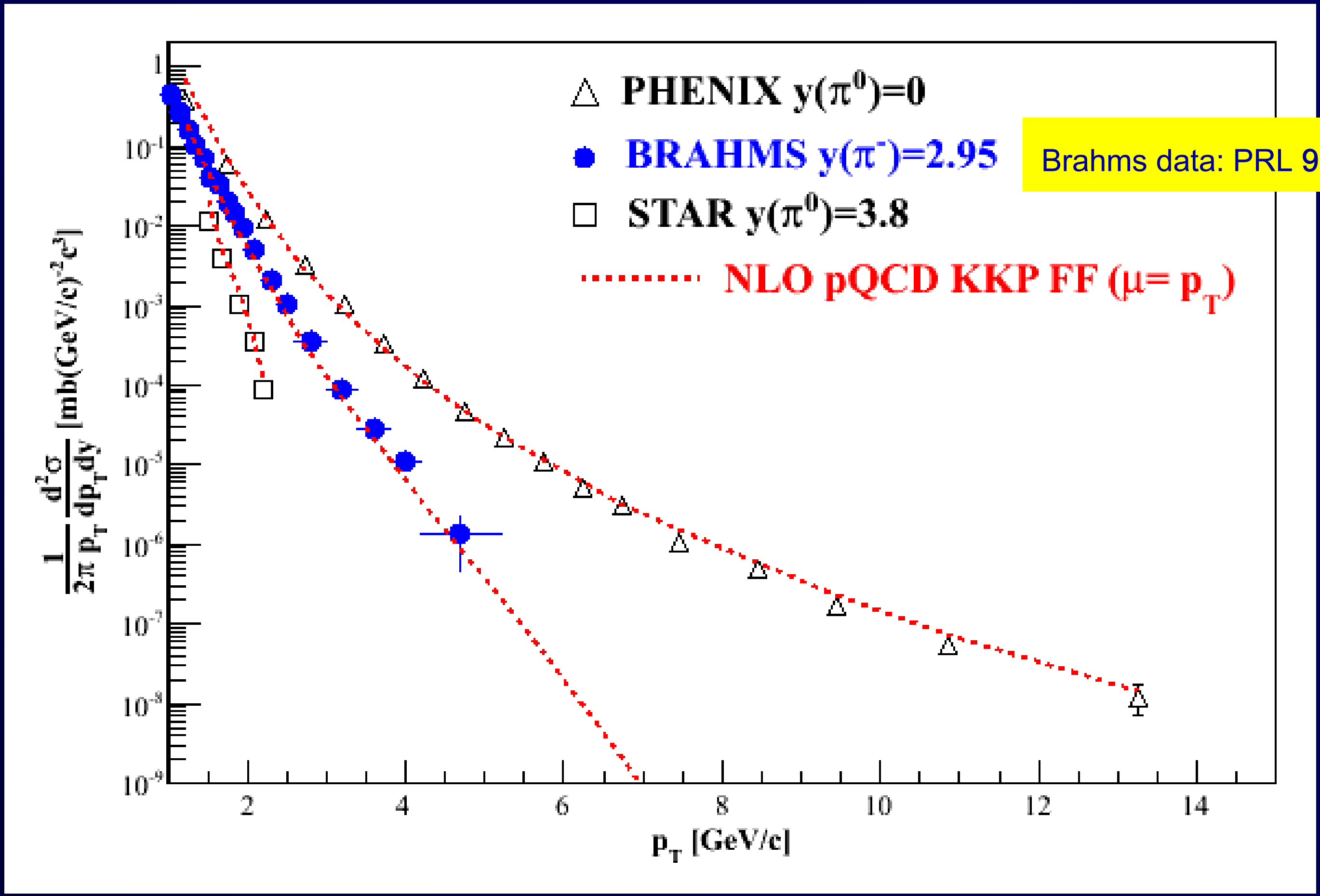




pp

- How well understood is pp in terms of pQCD

Un-polarized Cross-sections at √s=200 GeV .



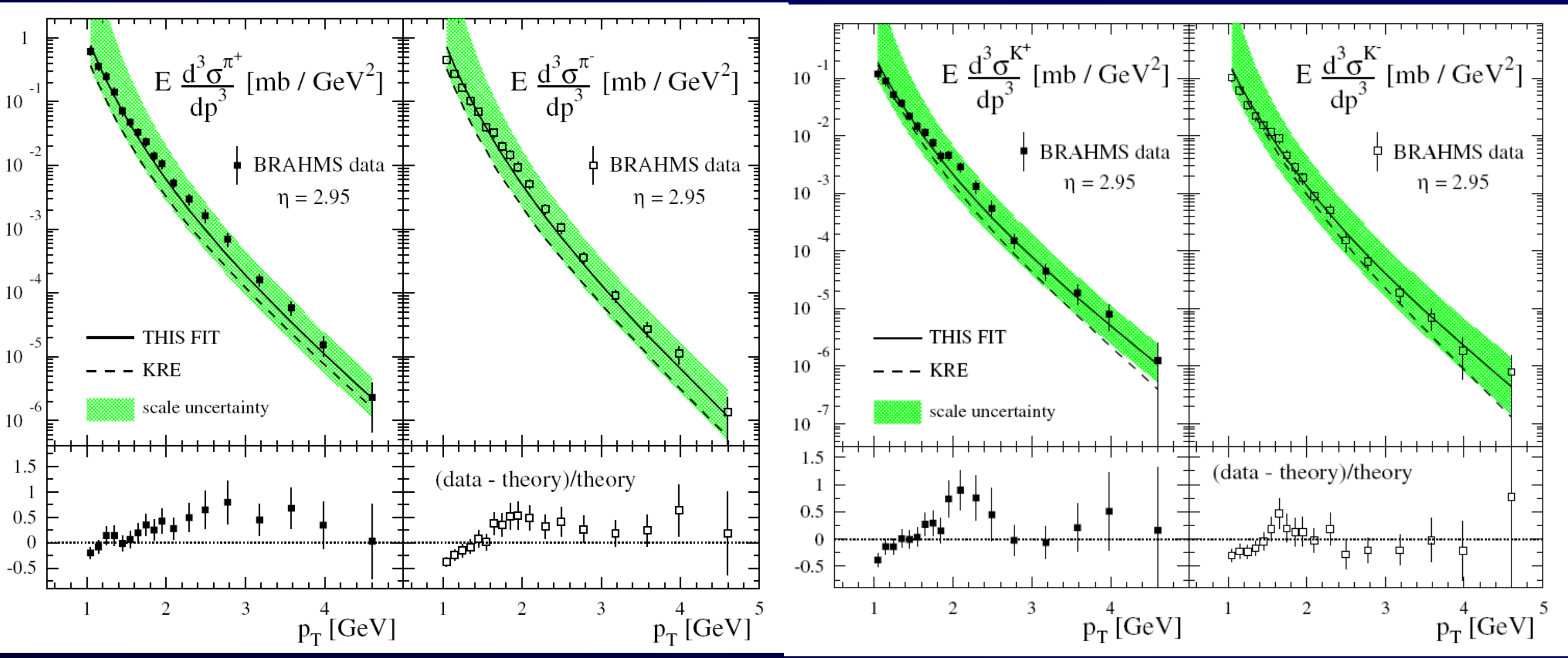
Brahms data: PRL 98, 252001 (2007)

Good description at 200 GeV over all rapidities down to p_T of 1-2 GeV/c.

Global fits to data including BRAHMS large rapidity data

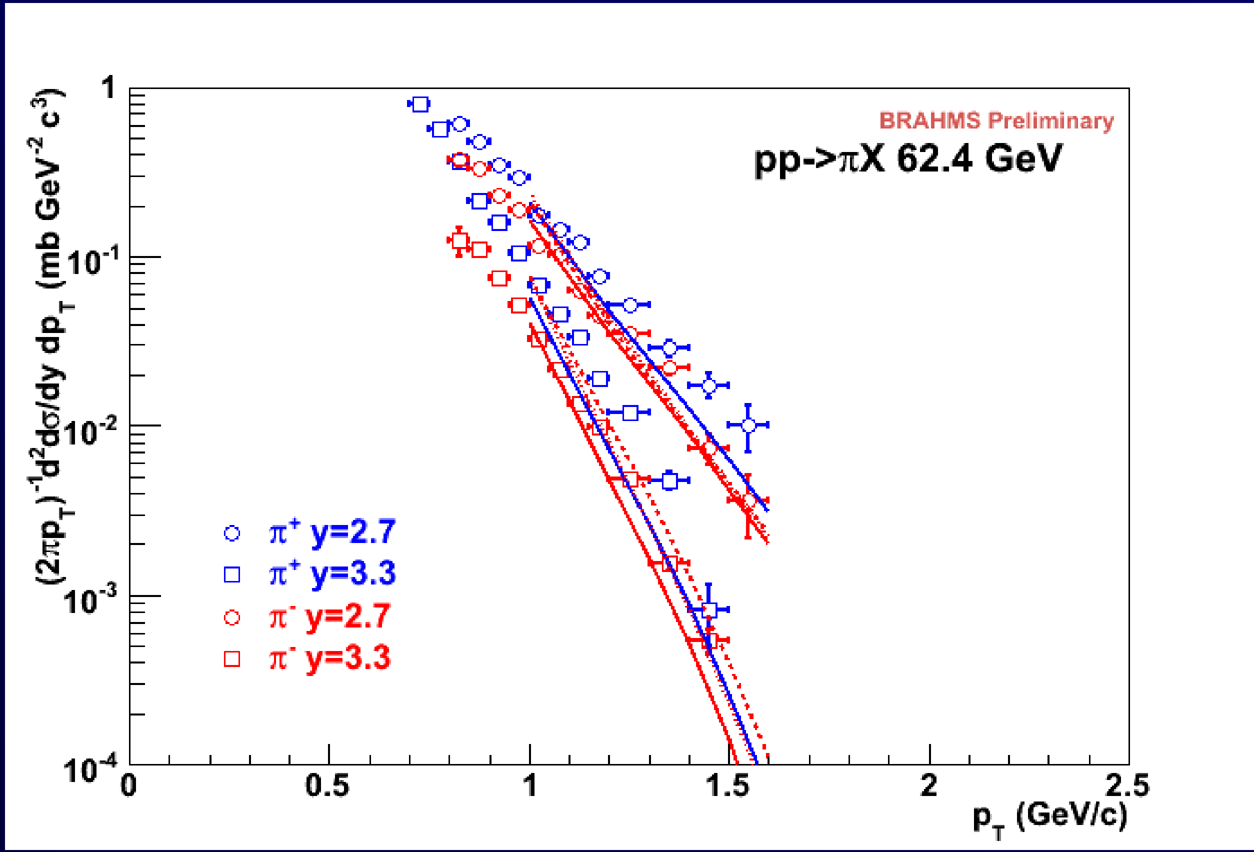
DSS, PRD **75,** 114010 (2007)

Brahms data: PRL 98, 252001 (2007)



Recently deFlorian, Sassot and Stratman performed a global fit including new data from Brahms at high rapidity. PRD **75,** 114010 (2007)

- Charged separated fragmentation functions
- Fragmentation functions significantly constrained compared to previous "state of the art" when adding RHIC data into fits.



Comparison of NLO pQCD calculations (Vogelsang) with BRAHMS π data at high rapidity. The calculations are for KKP (solid) and a scale factor of $\mu=p_T$, DSS with CTEQ5 and CTEQ6.5 are also shown.

The agreement is reasonable, in apparent disagreement with earlier analysis of ISR π^o data at 53 GeV.

BRAHMS and SPIN

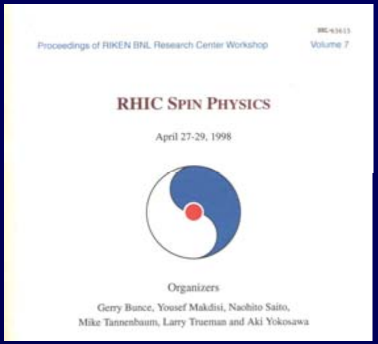
- There is no mentioning of SPIN in LOI, CDR.
- The RHIC spin group and RBRC by the frequent meetings brought the idea to fruition.

The first talk on this was at the RHIC SPIN physics meeting in 98, where I quoted

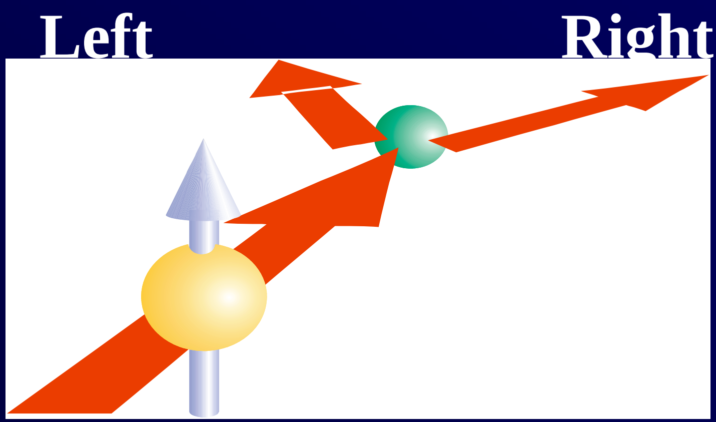
“The BRAHMS detector has capabilities for XF=0.3-0.5”

“need additional effort” – got that from Gerry, Brendan Fox

“1 mo running” - optimistic



BRAHMS and Transverse Spin

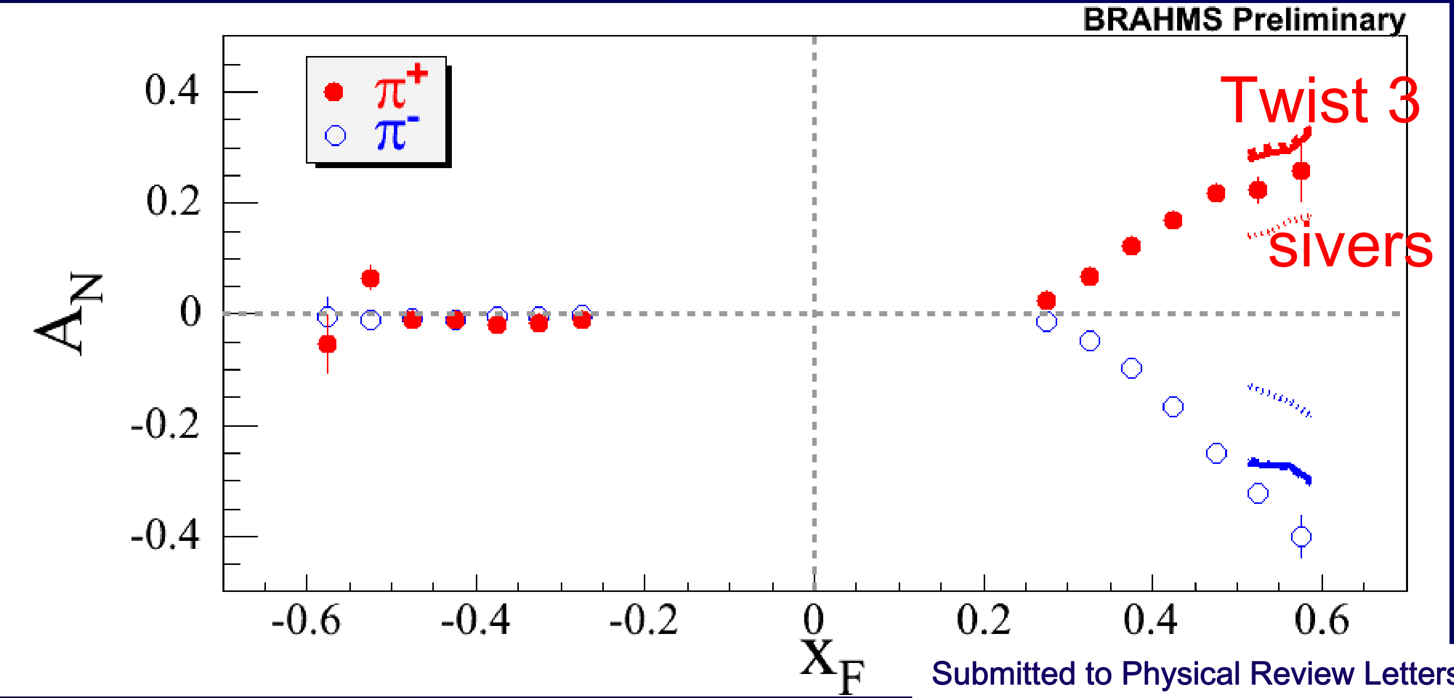


$A_n = (\sigma^+ - \sigma^-) / (\sigma^+ + \sigma^-)$

Where the spin cross section is determined with the spin direction defined by $k_b \times k_{pi}$

- Early (naive) QCD predicted this effect to be small
- Non-zero Single Transverse Spin Asymmetry (SSA/ A_n) requires
  Spin Flip Amplitude and phase difference in intrinsic states
- Such studies may clarify properties of transverse quark structure of the nucleon
- **Sivers effect** [Phys Rev D41 (1990) 83; 43 (1991) 261]
  Flavor dependent correlation between the proton spin , momentum and transverse momentum of the un-polarized partons inside the proton.
- **Collins effect** [Nucl Phys B396 (1993) 161]
  Correlation between the quark spin, momentum and transverse momentum of the pion.

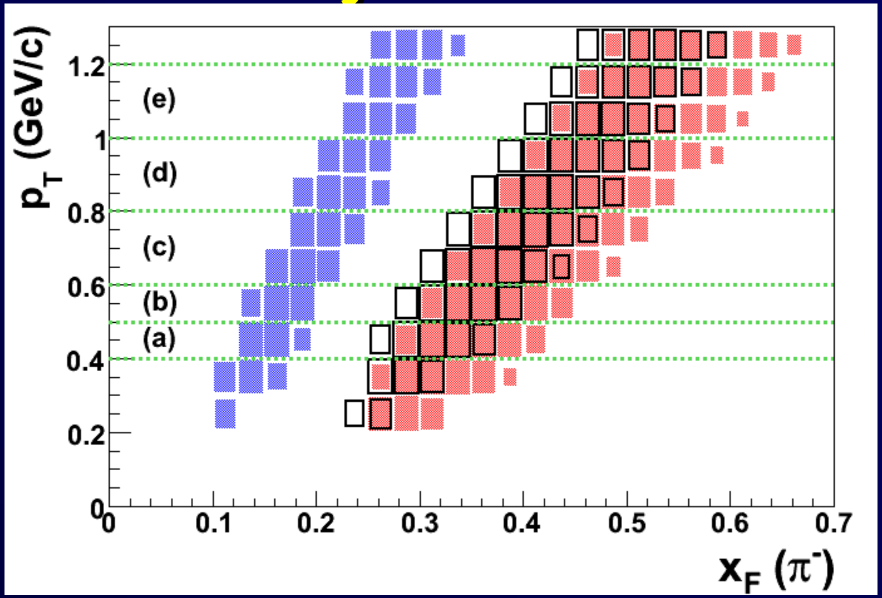
$A_N(\pi)$ at $\sqrt{s}$ = 62 GeV



Submitted to Physical Review Letters
arXiv:0801.1078

- Large $A_N(\pi)$: 0.3-0.4 at x_F~0.6 p_T~1.3 GeV
- Strong x_F -p_T dependence. Though $|A_N(\pi^+)| \sim |A_N(\pi^-)|$ $|A_N(\pi^+)/A_N(\pi^-)|$ decreases with x_F-p_T

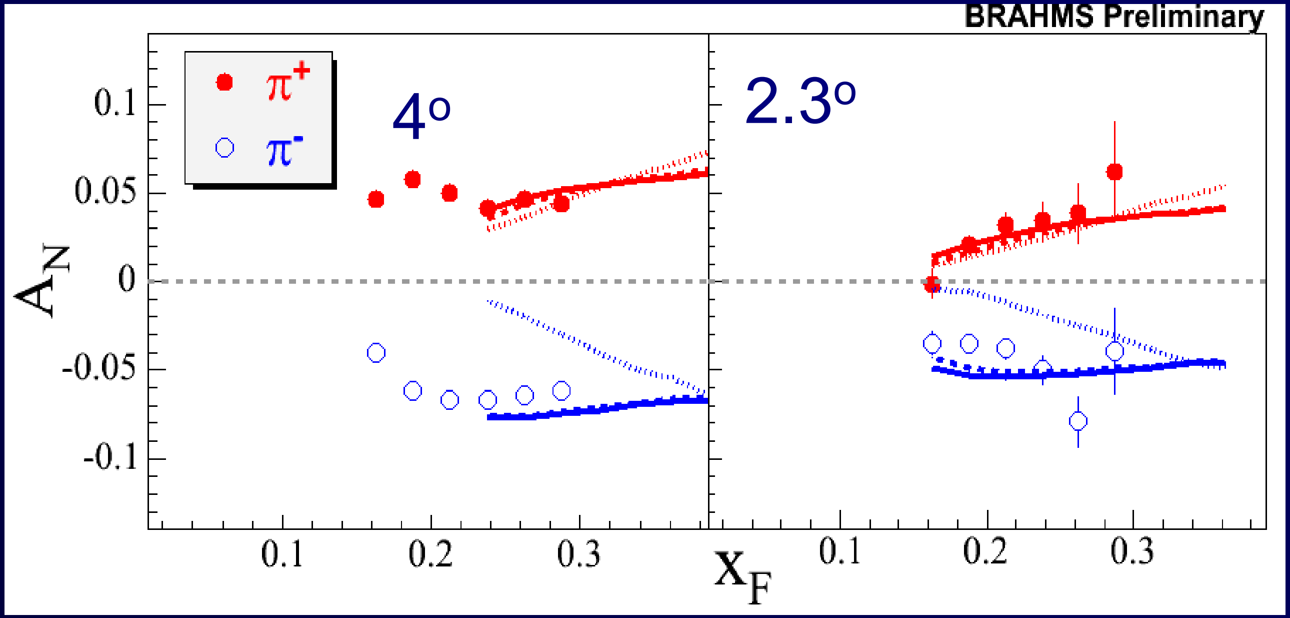
A_N x_F-p_T dependence at $\sqrt{s}$ = 62, 200 GeV



62.4 GeV acceptance ,

3 angle settings of spectrometer (2, 3 and 6 deg)

$A_N(\pi)$ at $\sqrt{s}$ = 200 GeV

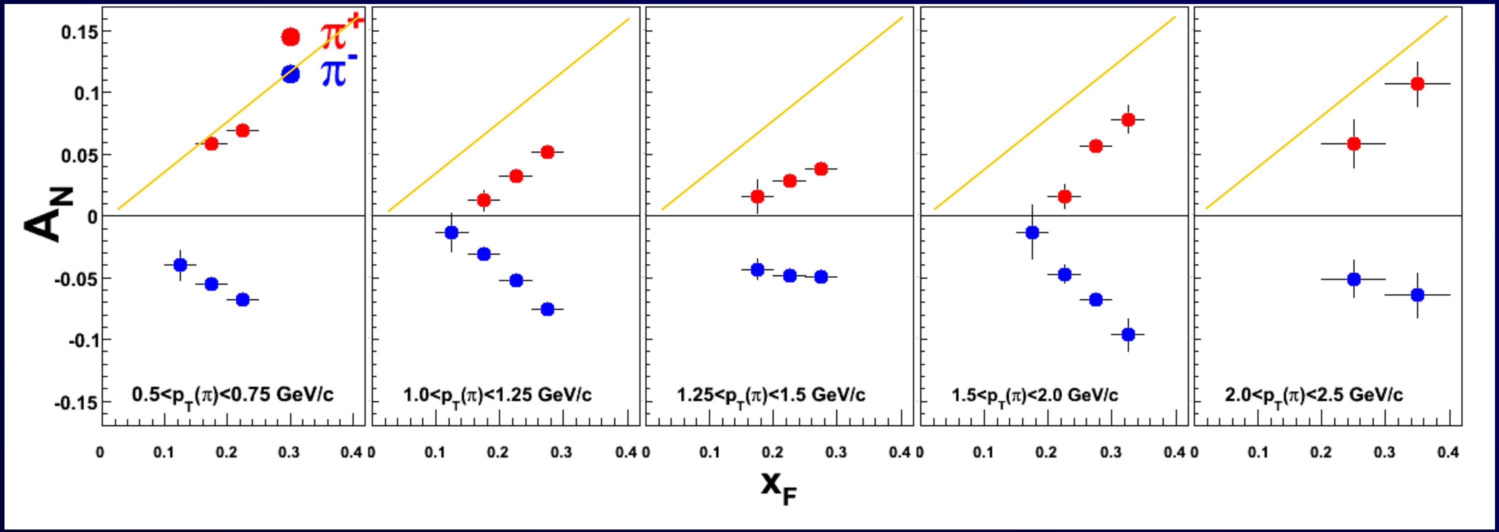


- $A_N(\pi^+)$: positive ~(<) $A_N(\pi^-)$: negative: 4-6% in $0.15 < x_F < 0.3$
- Behavior consistent with a slight decrease with increasing p_T as evident in going from ~4 deg to 2.3 deg setting
- Good agreement with twist-3 calculations which also has the 1/pt-dependence at higher p_T

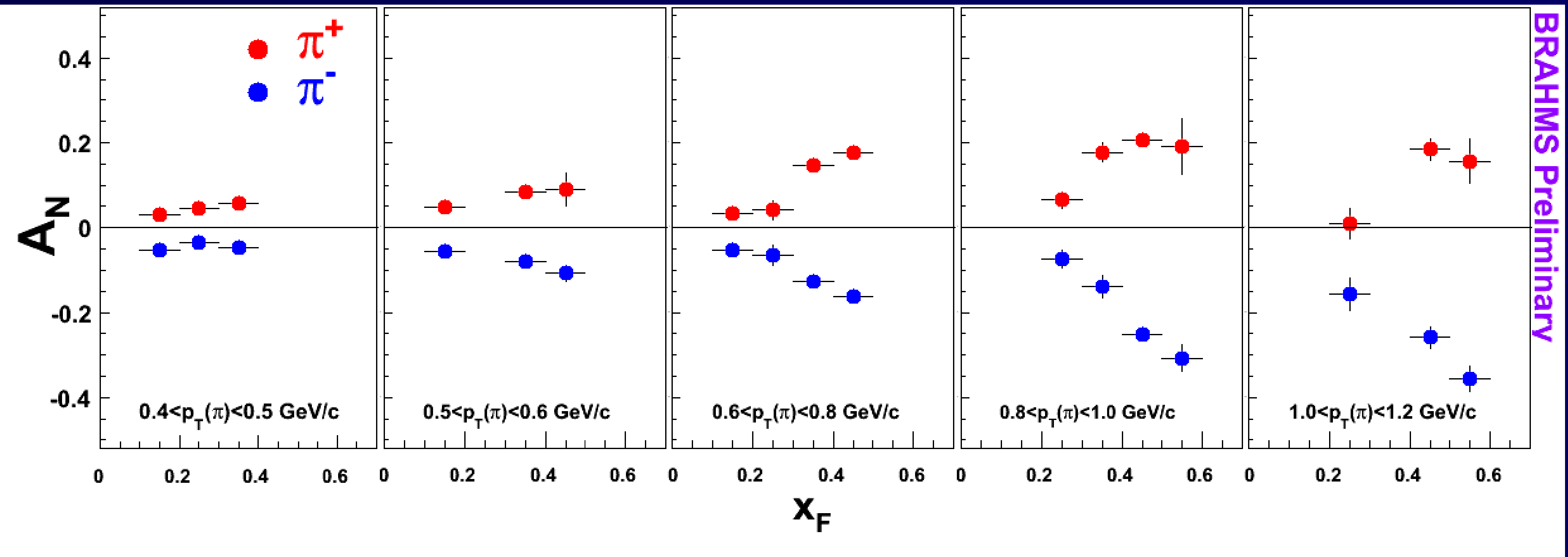
x_F dependence in p_T slices

To gain more insight the data are separated in p_T bin to study x_F dependence 200 GeV π+ and π-

- At all p_T increasing A_N with x_F.
- Magnitude is approximately constant at p_T>1.5 GeV/c

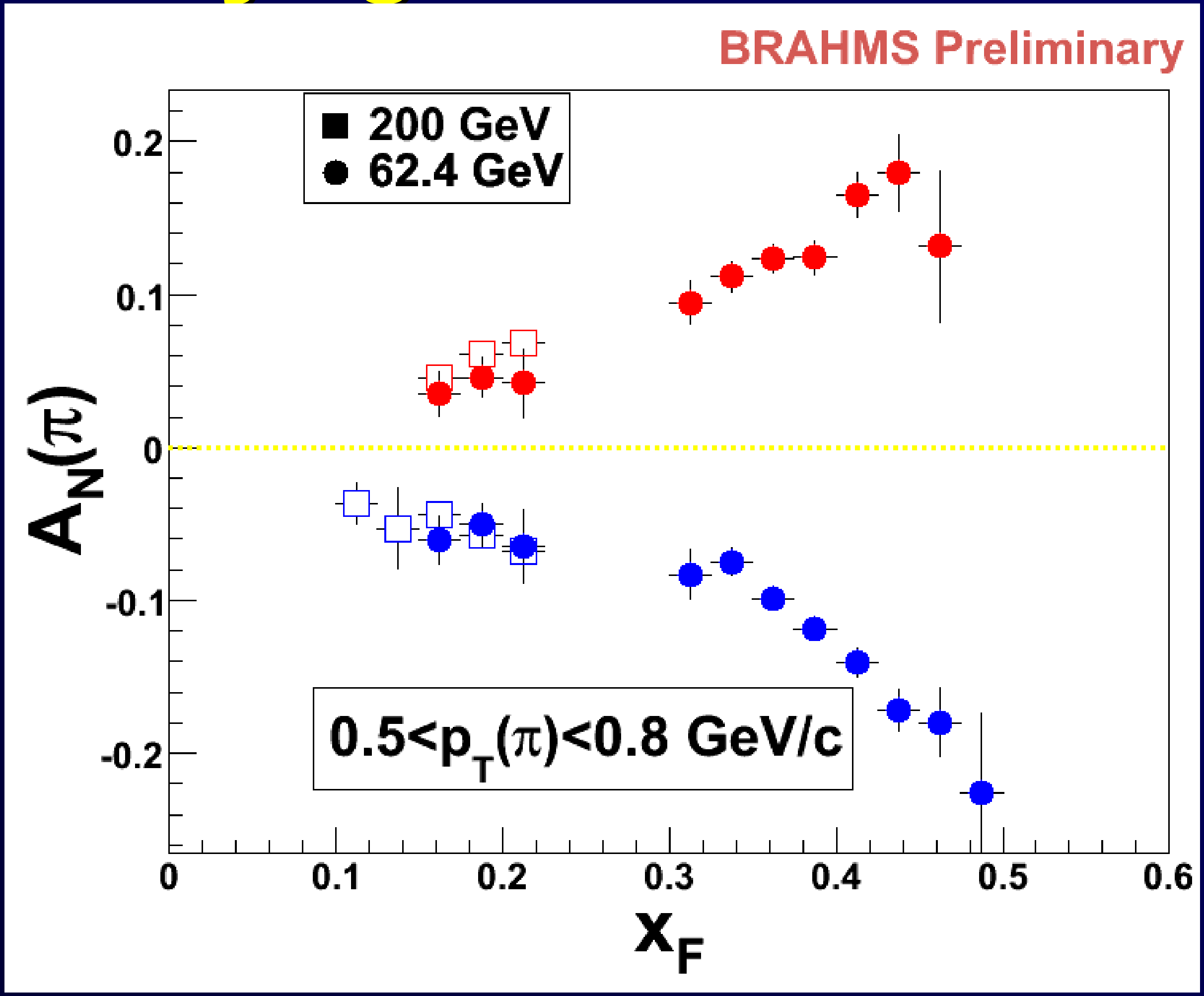


A_N x_F-p_T dependence at $\sqrt{s}$ = 62 GeV

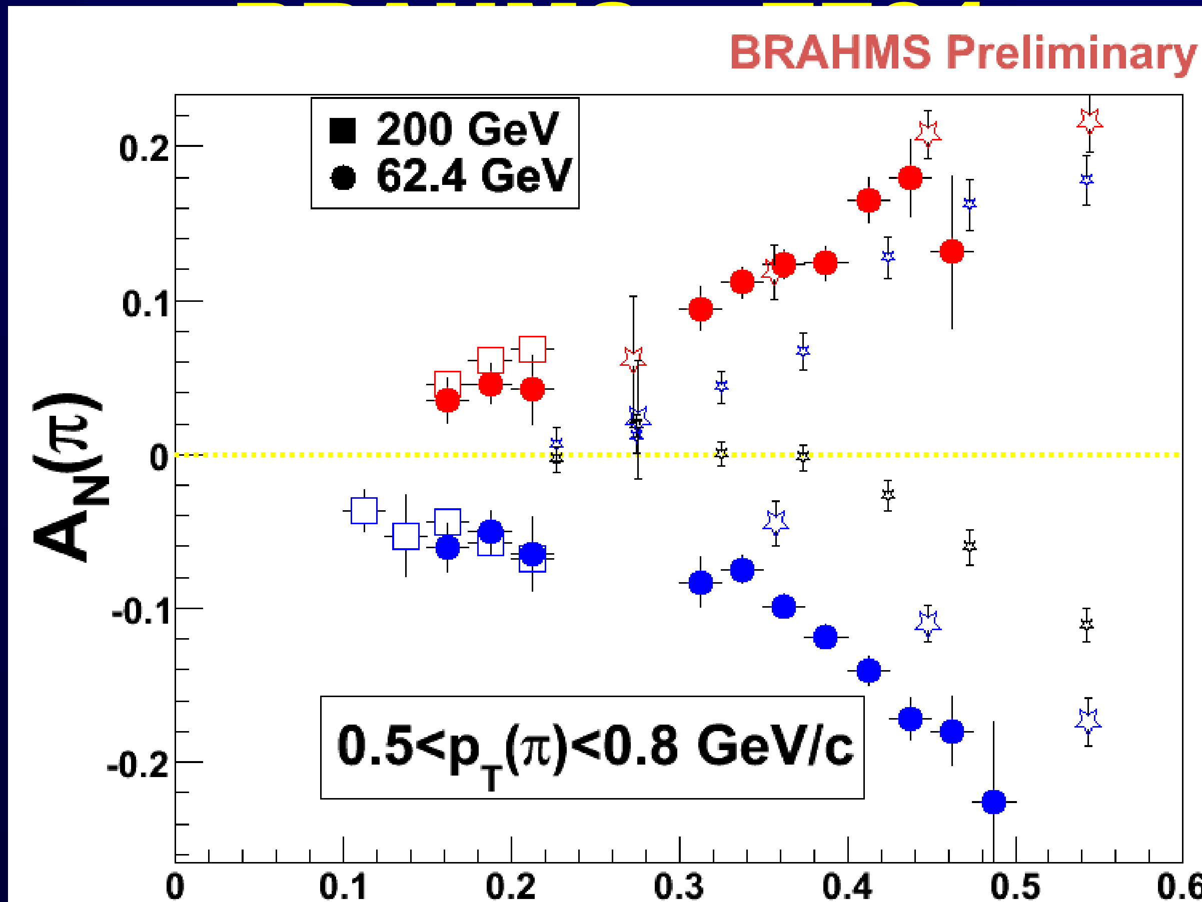


At low-p_T $A_N(\pi)$ increases from low p_T.
(Constraint must be 0 at p_T=0)

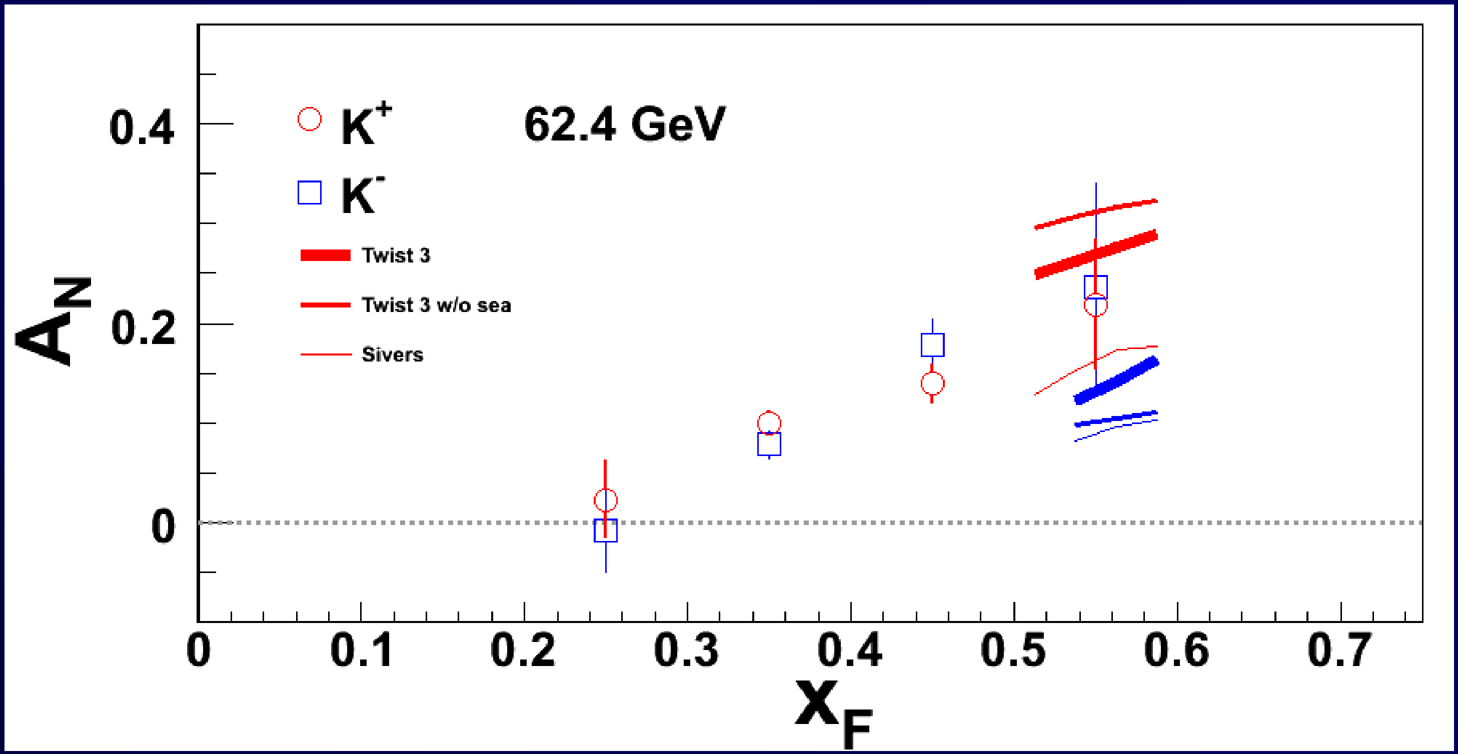
Unifying 62 and 200 GeV



Unifying 62 and 200 GeV



E704 data – all pt (small star) pt>0.7 red star.



- If main contribution to AN at large x_F is from valence quark: $A_N(K+) \sim A_N(\pi+)$ and $A_N(K-) \sim 0$
- Observation clearly different
- Show different models comparisons (only $p_T>1$)

Summary

The RHIC program made enormous progress during the years going from the first surveys, the discoveries, and now precision measurements in heavy ion and pp reactions leading to fundamental understanding of hot dense matter and QCD.

The presence of 4 experiments with the different strengths and competition has been very good for the RHIC program.

- Some questions on RHIC PHYSICS where BRAHMS have had an impact.

”How does matter behave at very high temperature and/or density?”

- – Jet-quenching suppression in AA, not d-A
- – Au-Au, Cu-Cu, pp. Bulk properties energy dependence

”What is the nature of gluonic matter? and how does it behave inside of strongly interacting particles?”

- d Au at high rapidities (low-x)

“What is the spin structure of the nucleon ?”

- – Single Spin Asymmetries at large x_F