Particle Production at Forward Rapidites with BRAHMS

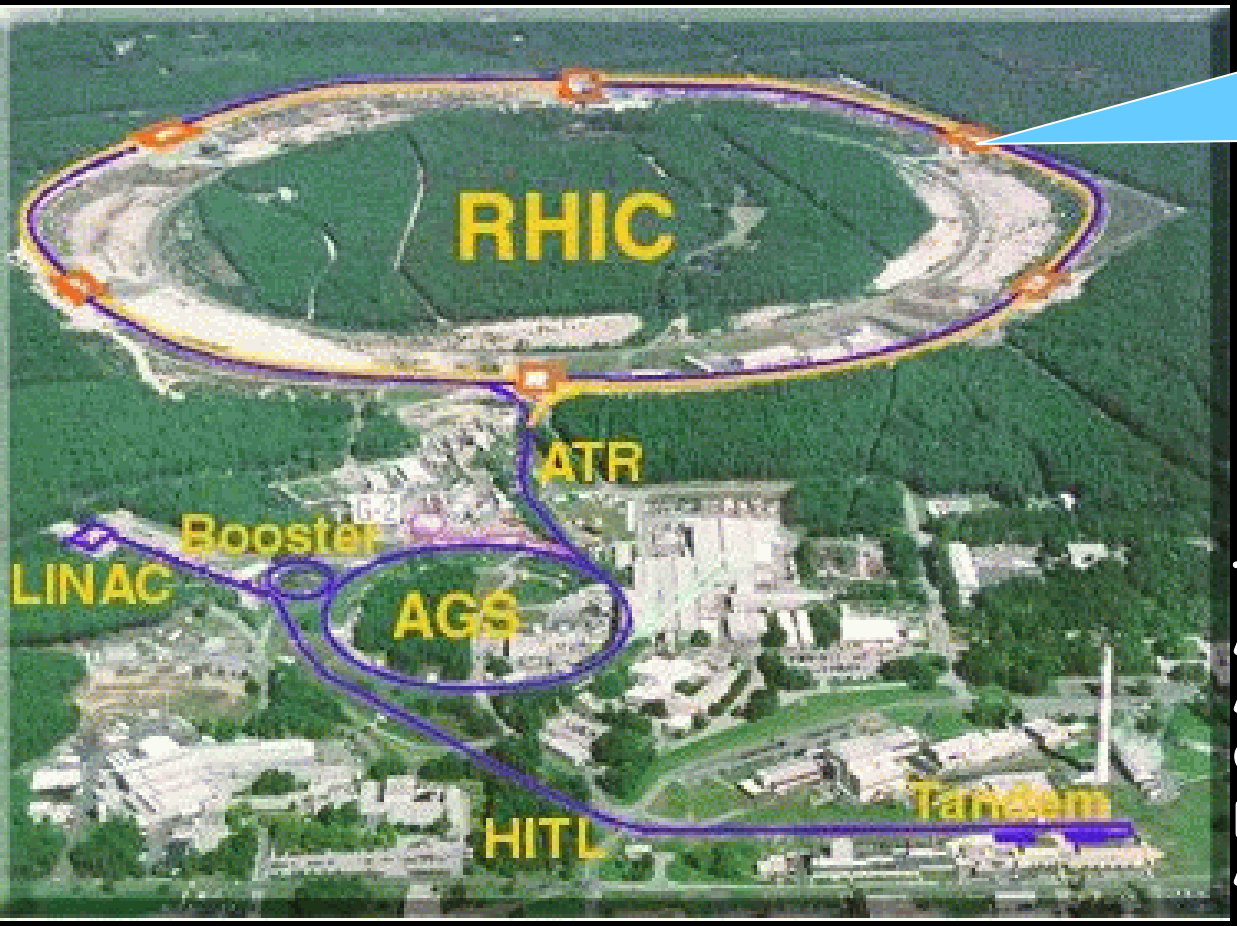
I.G. Bearden,

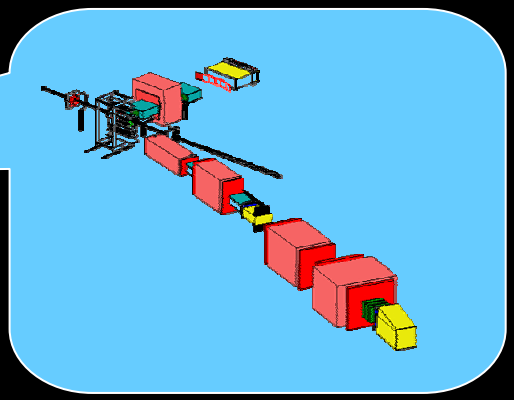
Niels Bohr Institute

For

The BRAHMS collaboration

BRAHMS at RHIC

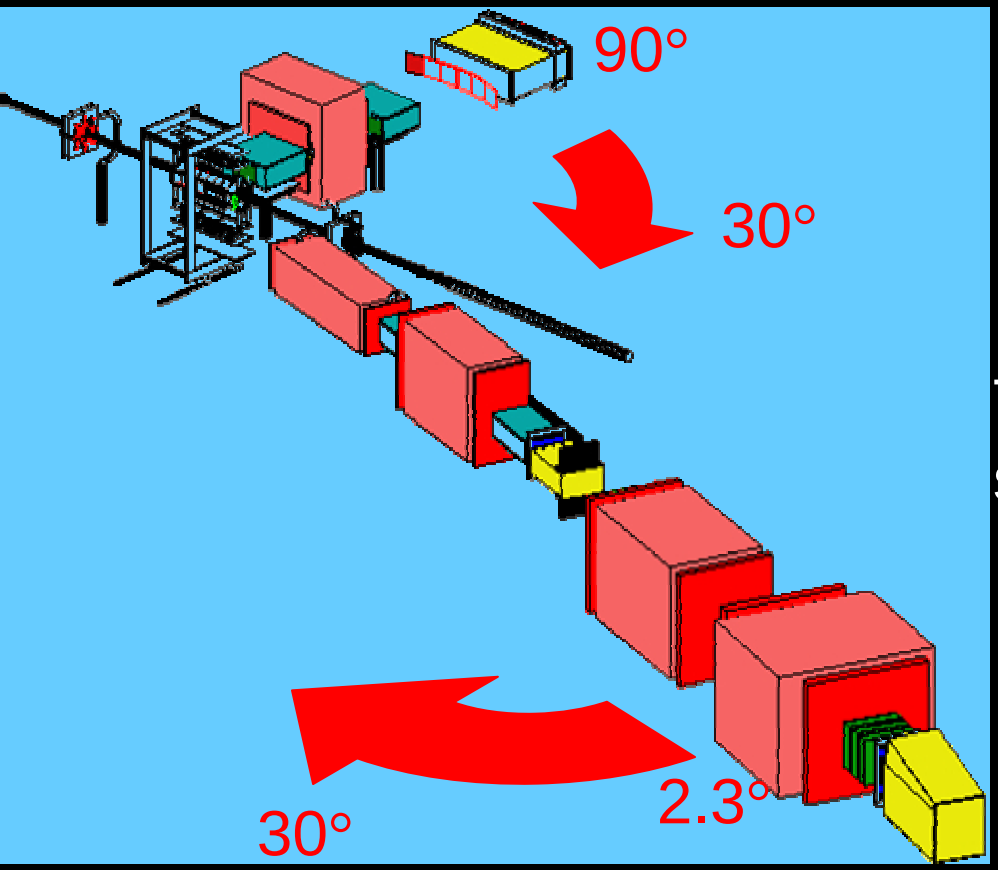




The three first years:

Au+Au at $\sqrt{s_{NN}}$ = 130GeV
Au+Au at $\sqrt{s_{NN}}$ = 200GeV
d+Au at $\sqrt{s_{NN}}$ = 200GeV
p+p at $\sqrt{s_{NN}}$ = 200GeV
Au+Au at $\sqrt{s_{NN}}$ = 62.4GeV

The BRAHMS Experiment



Broad **RA**nge **H**adron **M**agnetic spectrometer**S**

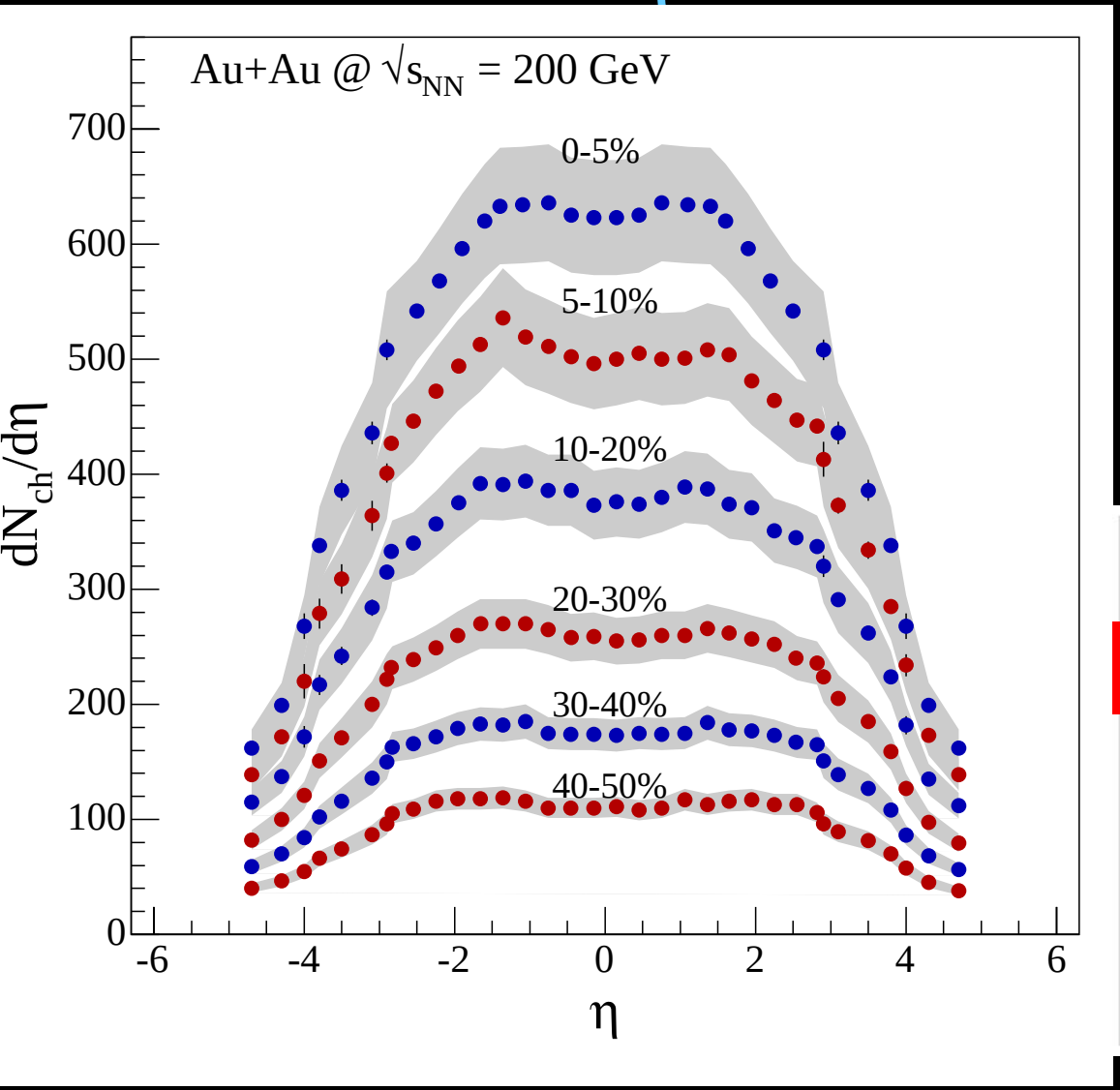
Two small solid angle spectrometers (FS and MRS)

that can rotate from 2.3° to 30° and 30° to 90° (MRS)

provide excellent PID over broad range in y-p_T

Charged Particle Multiplicity

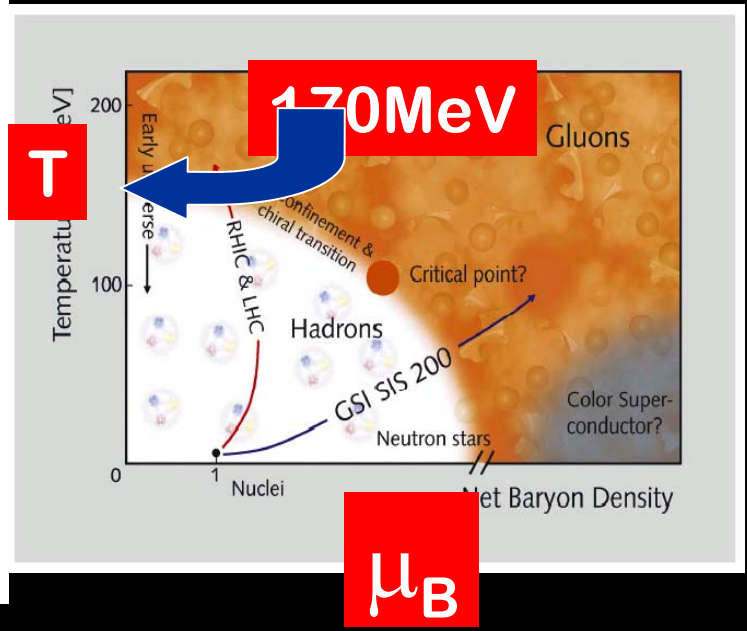
dN/dη



According to Bjorken,

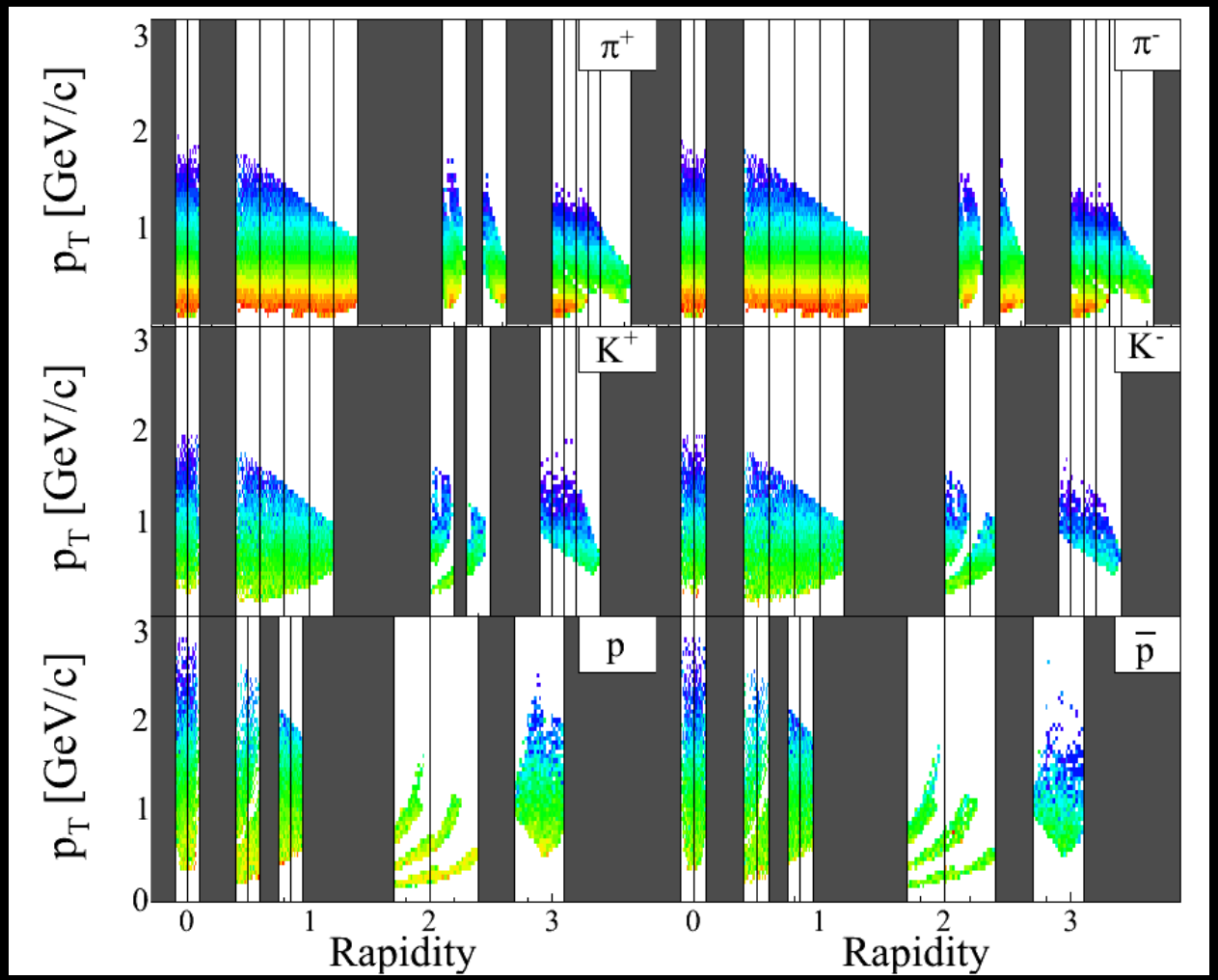
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

ε>5GeV/fm^3



Particle Spectra

After appropriate corrections, we combinine all data sets to obtain final invariant yields over a broad range of rapidity and p_T

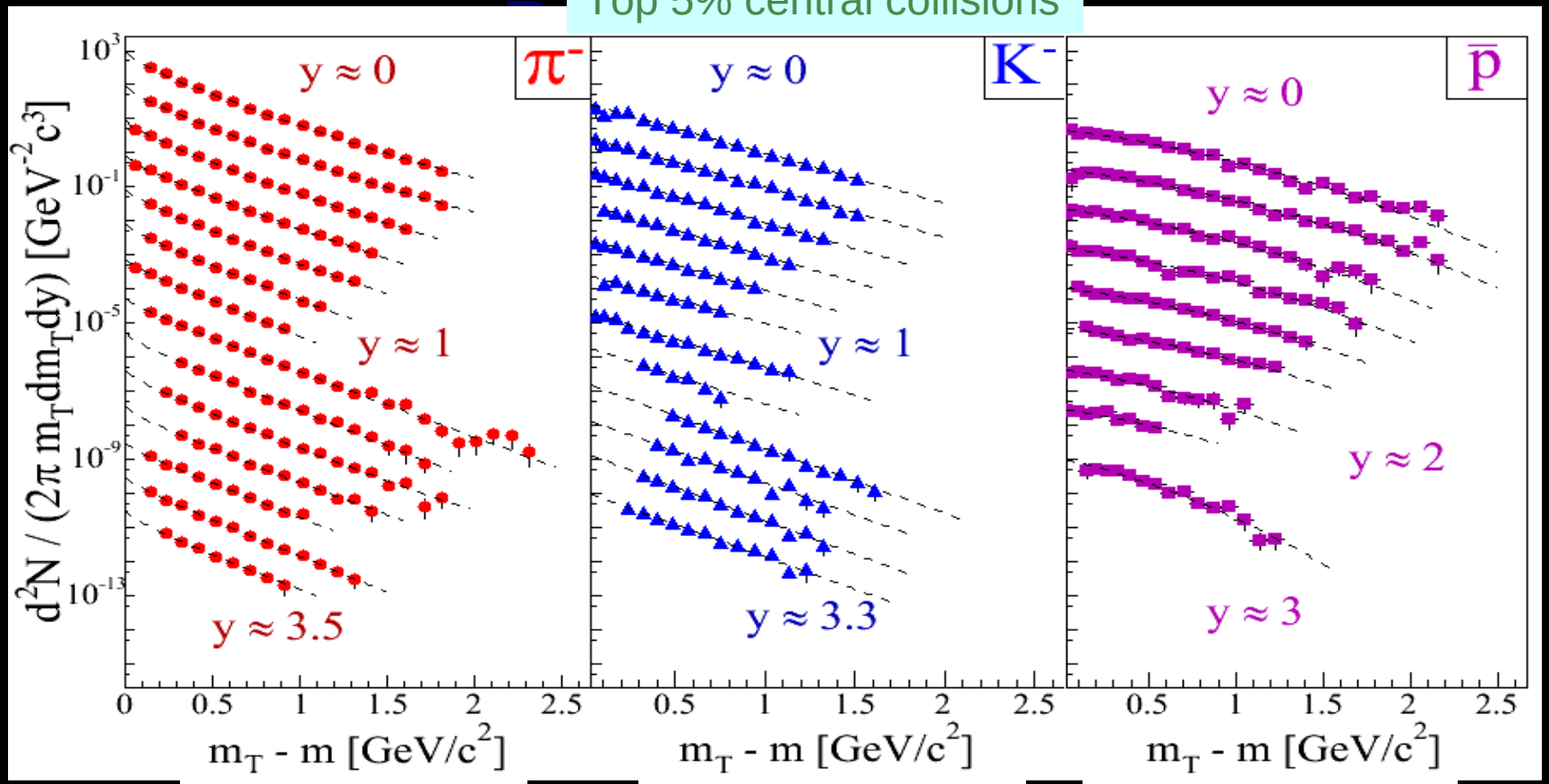


π

K

p

Top 5% central collisions



Pions: power law

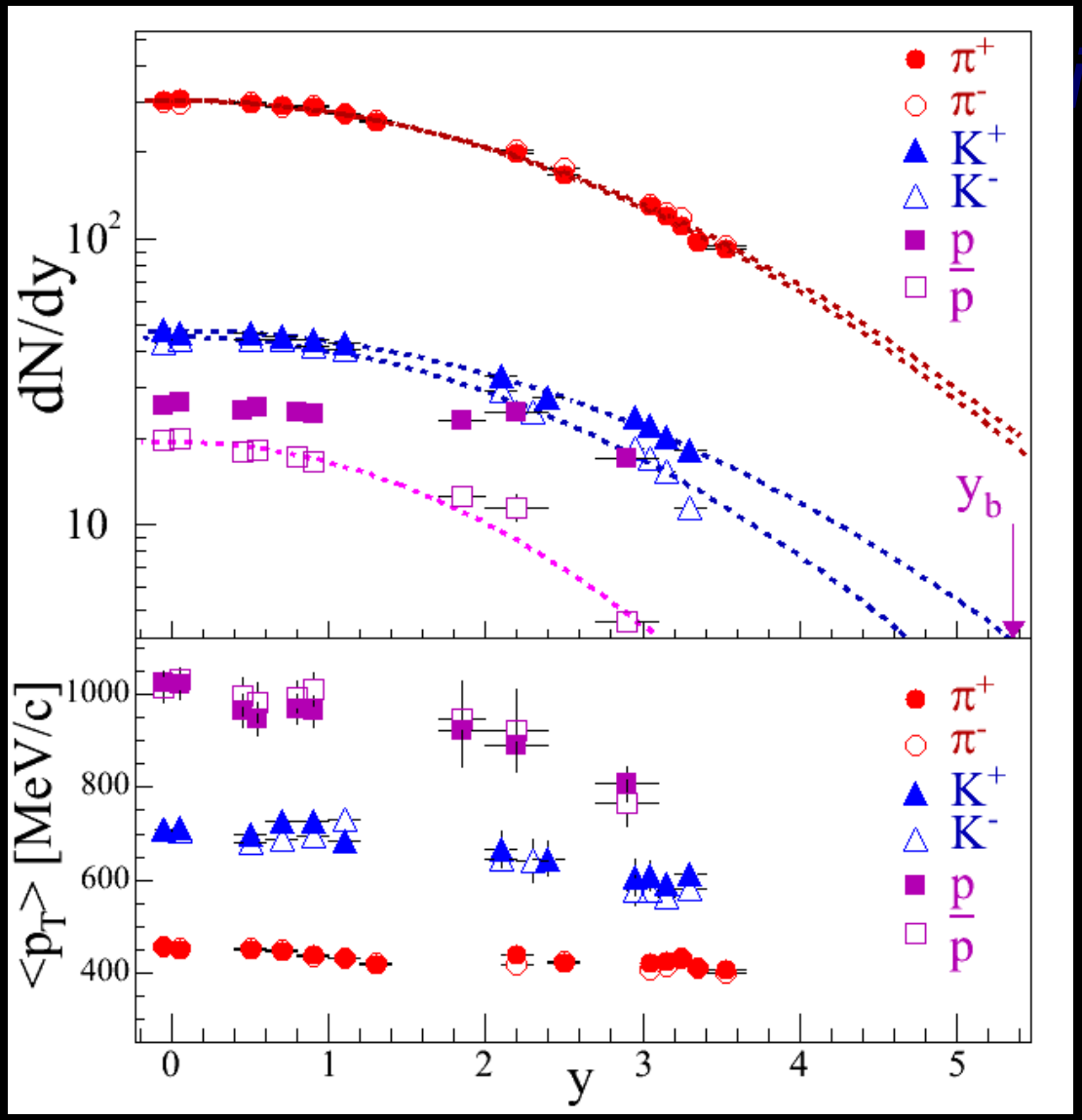
$$A\left(1+\frac{p_T}{p_0}\right)^{-n}$$

Kaons: exponential

$$A\exp\left(-\frac{m_T-m}{T}\right)$$

Protons: Gaussian

$$A\exp\left[-\frac{p_T^2}{2\sigma^2}\right]$$



At y ~ 0, dN/dy is
~ 300 (300) for π^+ (π^-)
~ 47 (44) for K^+ (K^-)
~ 27 (20) for p (pbar)

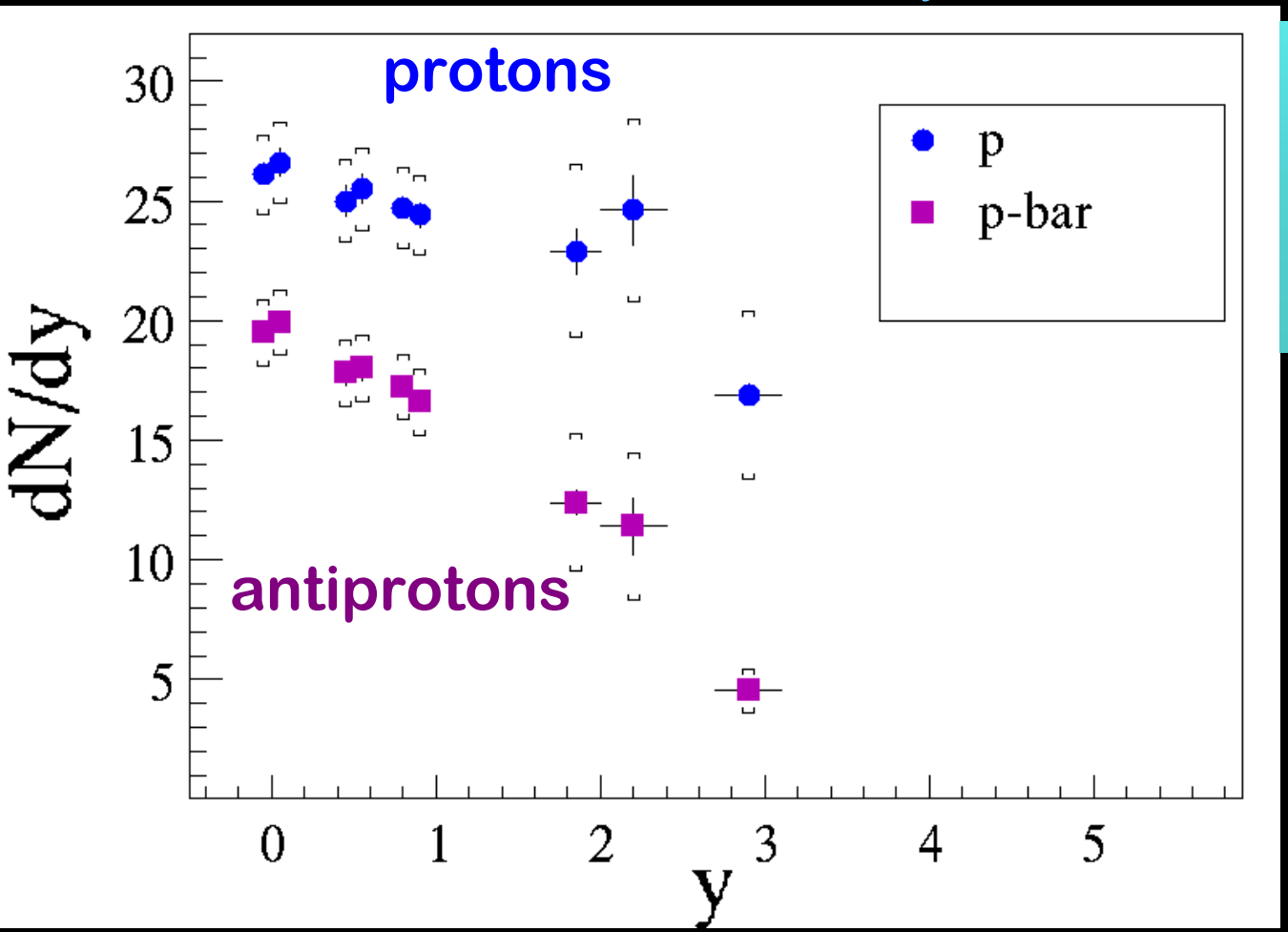
$N(\pi) >> N(K) > N(p)$
$N(\pi^+) = N(\pi^-)$

$N(K^+) > N(K^-)$ and
$N(p) > N(pbar)$
systematically

Integrated multiplicities
(Gaussian fit)

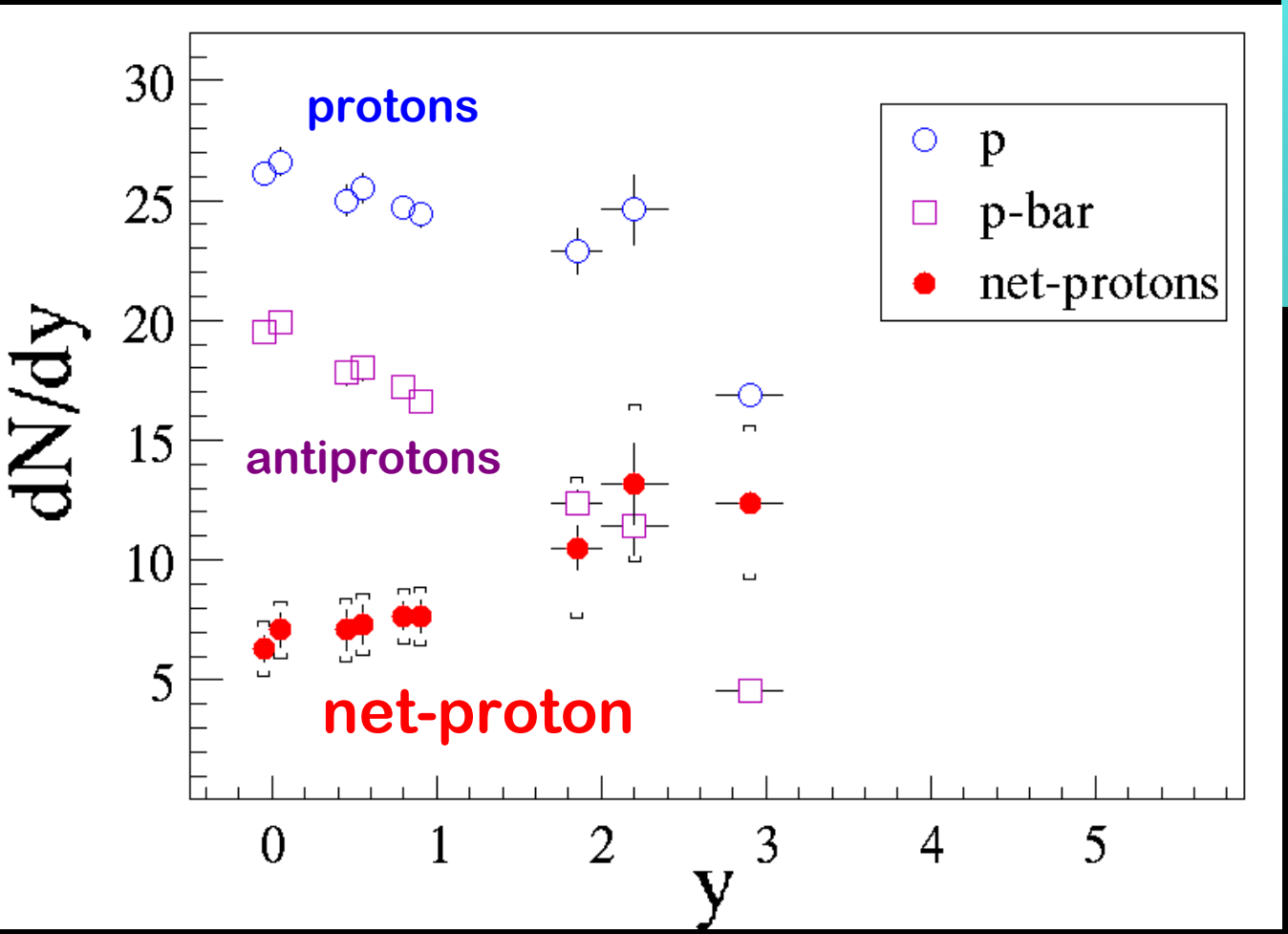
$N(\pi^-)$ ~ 1780 $N(\pi^+)$ ~1760
$N(K^+)$ ~ 290 $N(K^-)$ ~ 240
N(pbar) ~ 85

Proton & antiproton dN/dy (5% central)



BRAHMS, submitted to PRL, 31/12/03
nucl-ex/0312023
P. Christiansen
Ph.D. Thesis, København's Universitet

"Net" Proton= proton - antiproton dN/dy (5% central)



BRAHMS, submitted to PRL, 31/12/03
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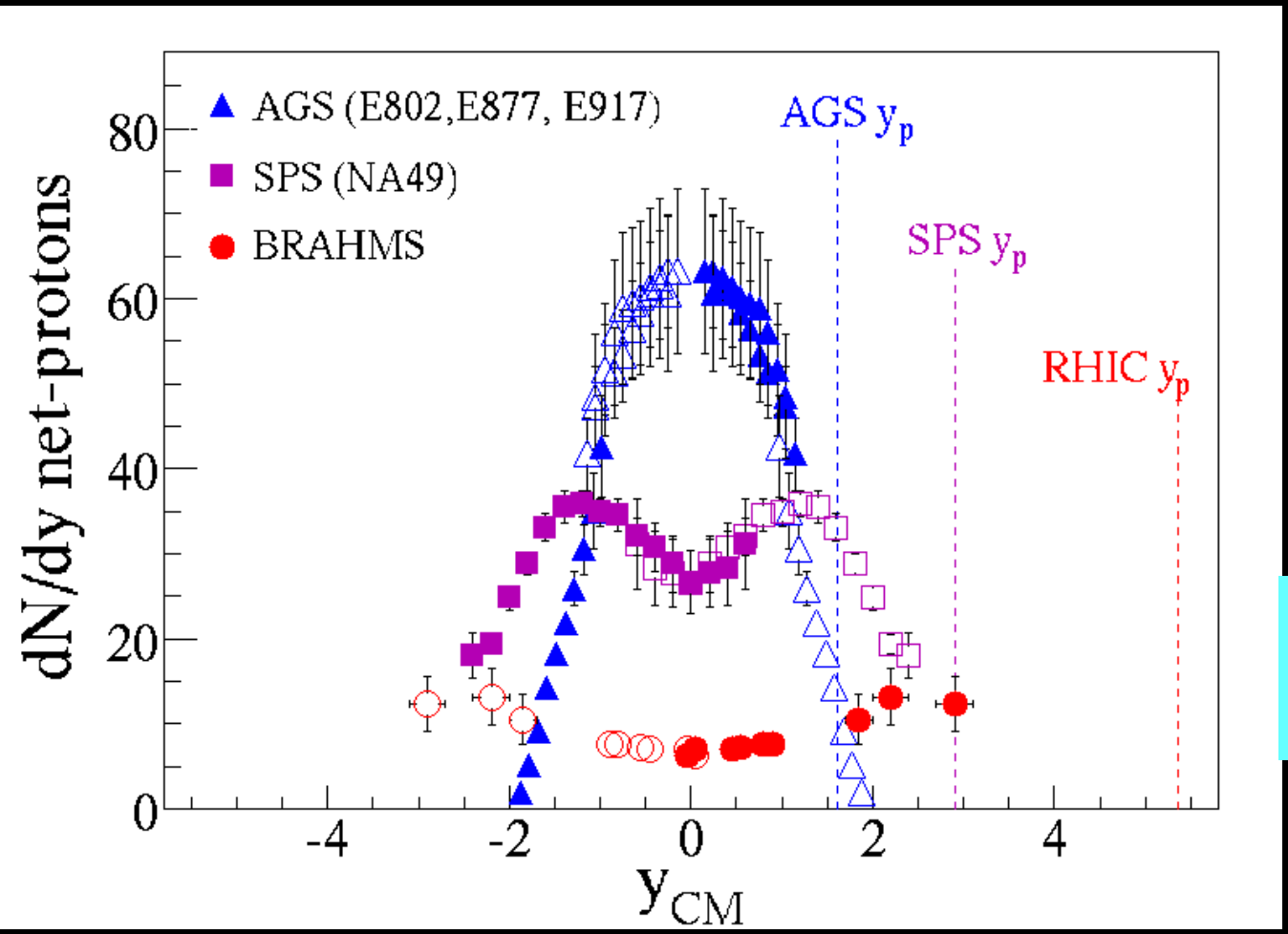
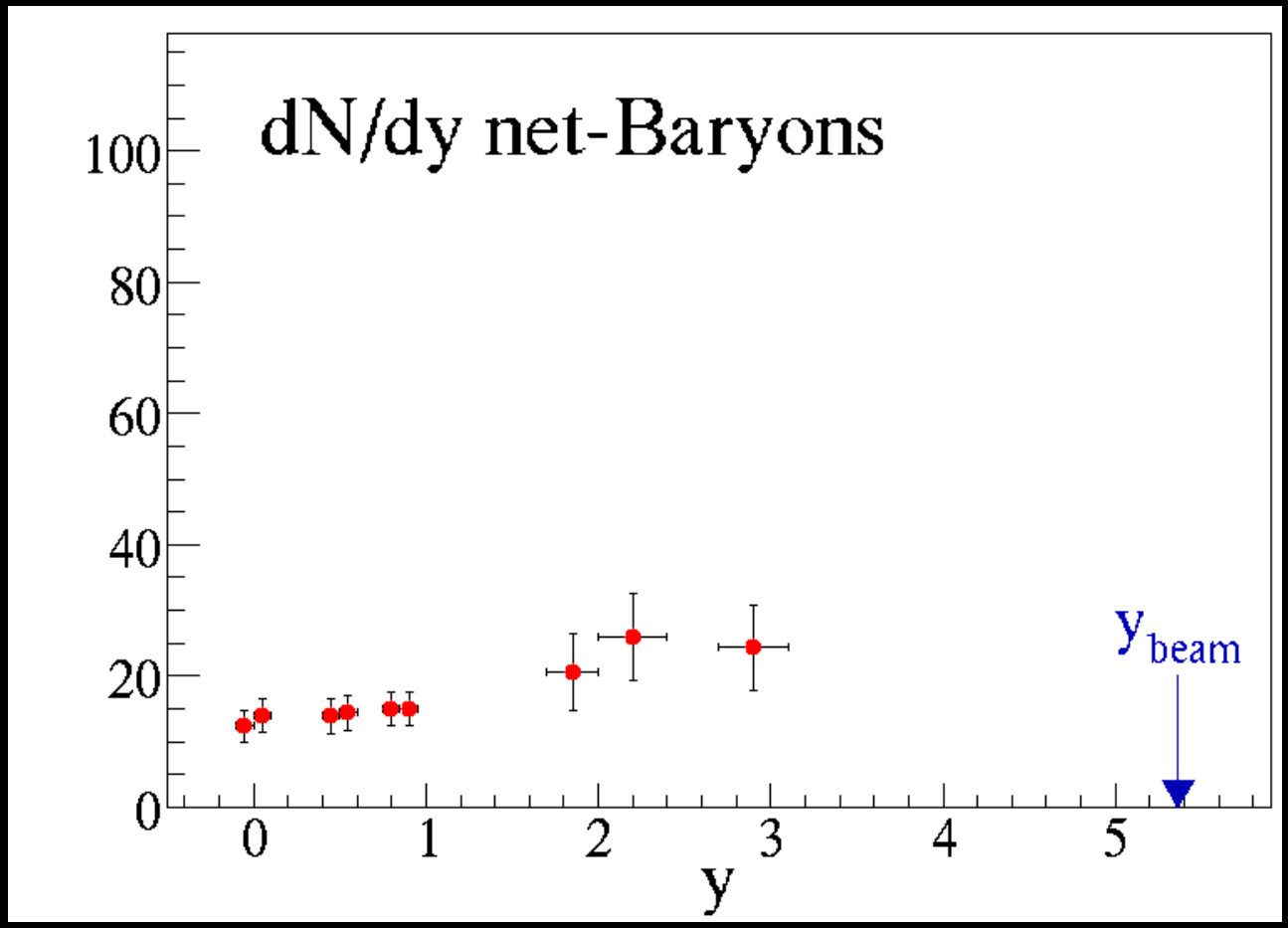
RHIC vs. AGS,SPS:



BRAHMS, submitted to PRL,
nucl-ex/0312023
P. Christiansen
Ph.D. Thesis

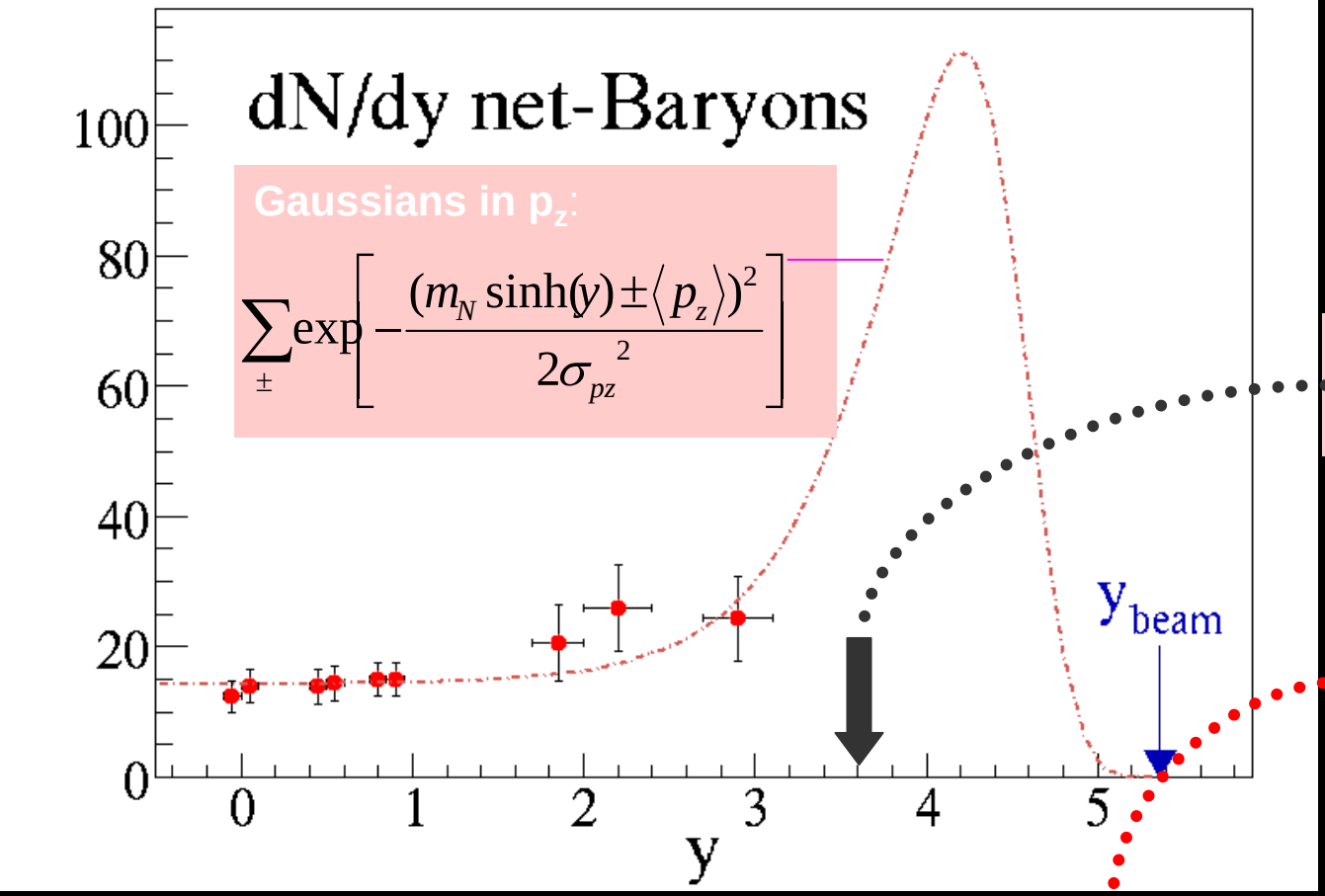
AGS : high stopping
RHIC: more transparent

Net Baryon dN/dy



Calculate net-baryon distribution from net-protons (and y=0 yields of Λ, and Hijing…)

Rapidity loss: gaussian in p_z

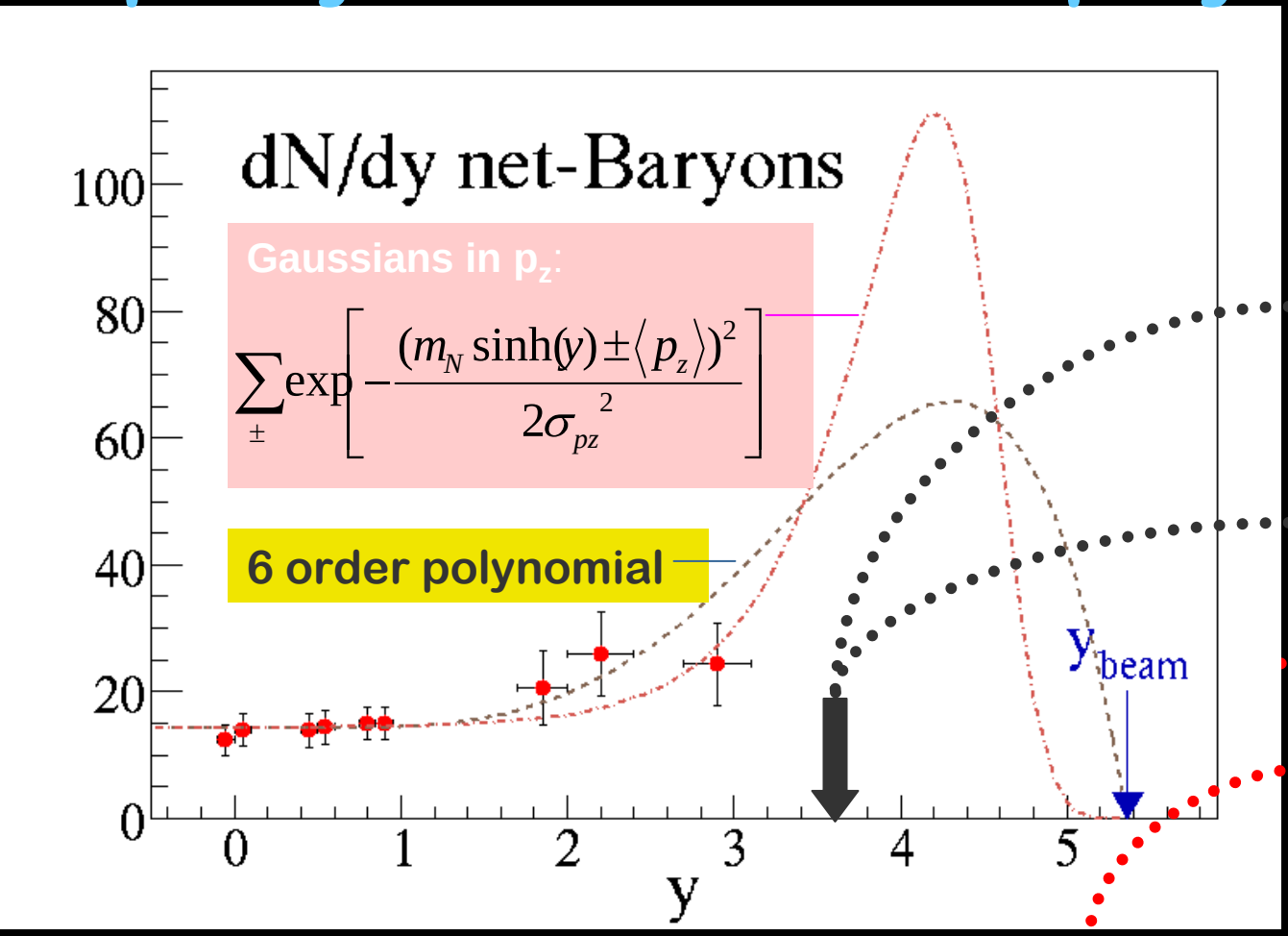


$\langle \delta y \rangle = 2.03 \pm 0.16$

Rapidity loss

$$\langle \delta y \rangle = y_p - \langle y \rangle = y_p - \frac{2}{N_{part}} \int_0^{y_p} y \frac{dN_{(B-\bar{B})}}{dy} dy$$

Rapidity loss: 6th order polynomial



$\langle \delta y \rangle = 2.03 \pm 0.16$

$\langle \delta y \rangle = 2.00 \pm 0.10$

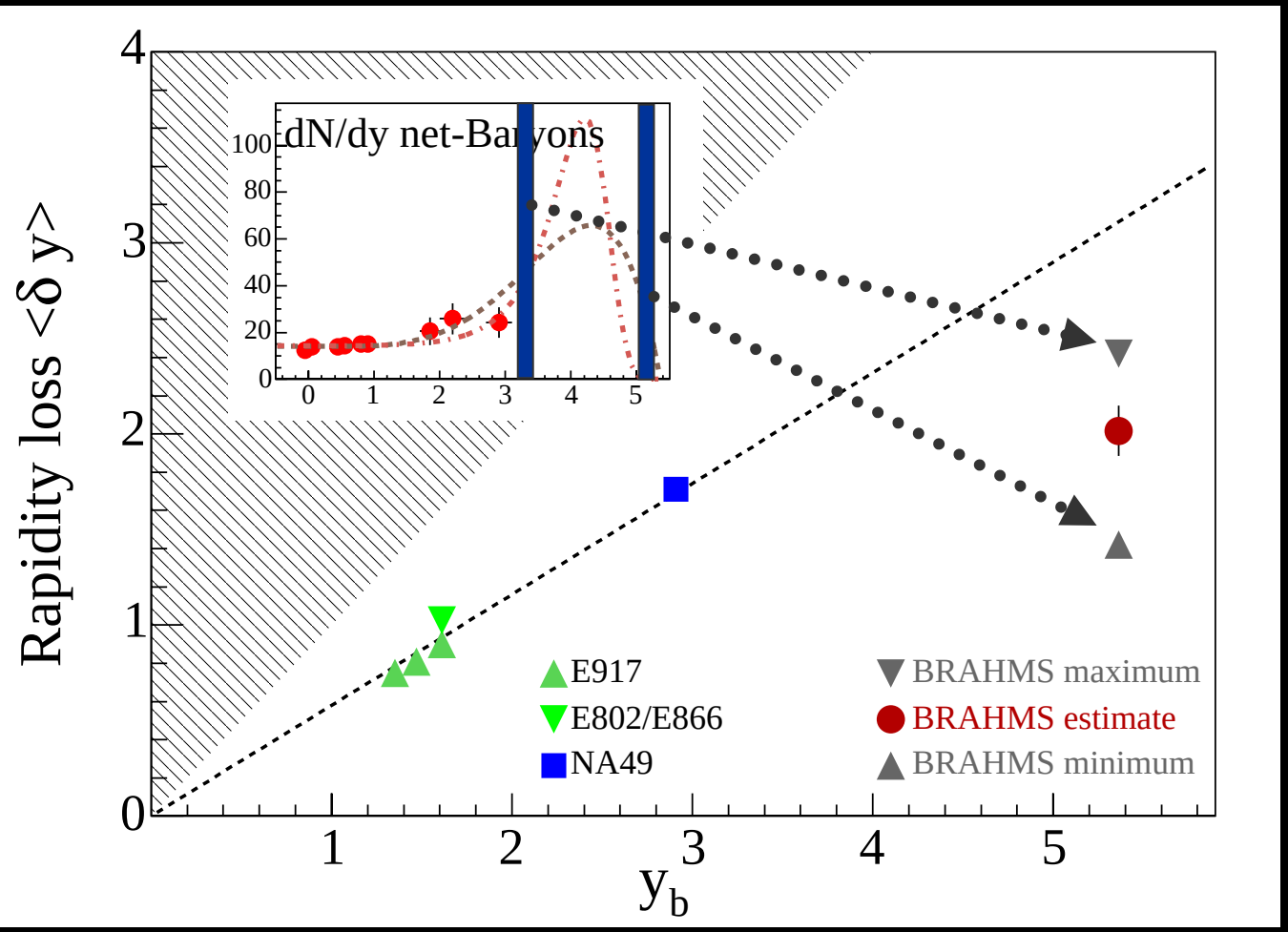
$\int_{-y_p}^{y_p} \langle m_T \rangle_y \frac{dN_{(B-\bar{B})}}{dy} \cosh y \, dy$

Total $\Delta E = 25.7 \pm 2.1$ TeV

Rapidity loss:

$$\langle \delta y \rangle = y_p - \langle y \rangle = y_p - \frac{2}{N_{part}} \int_0^{y_p} y \frac{dN_{(B-\bar{B})}}{dy} dy$$

δy vs. y_{beam}



Even (unphysically) extreme approximations don't change conclusions: scaling broken, large energy available

Total ΔE=25.7±2.1TeV

$$\int_{-y_p}^{y_p} \langle m_T \rangle_y \frac{dN_{(B-\bar{B})}}{dy} \cosh y \, dy$$

Energy Balance…

Energy (in GeV)

p	: 3108	π^0	: 6004
$\bar{p}$	: 428	n	: 3729
K^+	: 1628	$\bar{n}$	: 513
K^-	: 1093	K^0	: 1628
$\pi+$	: 5888	$\bar{K}^0$	: 1093
$\pi-$	: 6117	Λ	: 1879
		$\bar{\Lambda}$	: 342

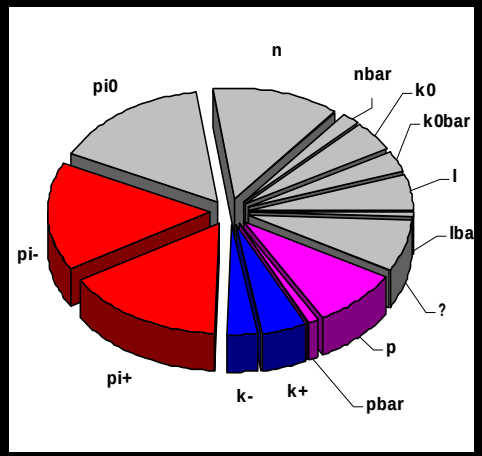
sum: 33.4 TeV
produced: 24.8TeV

NB: the method is very sensitive to the tails of the dN/dy dist. (±10-15%)

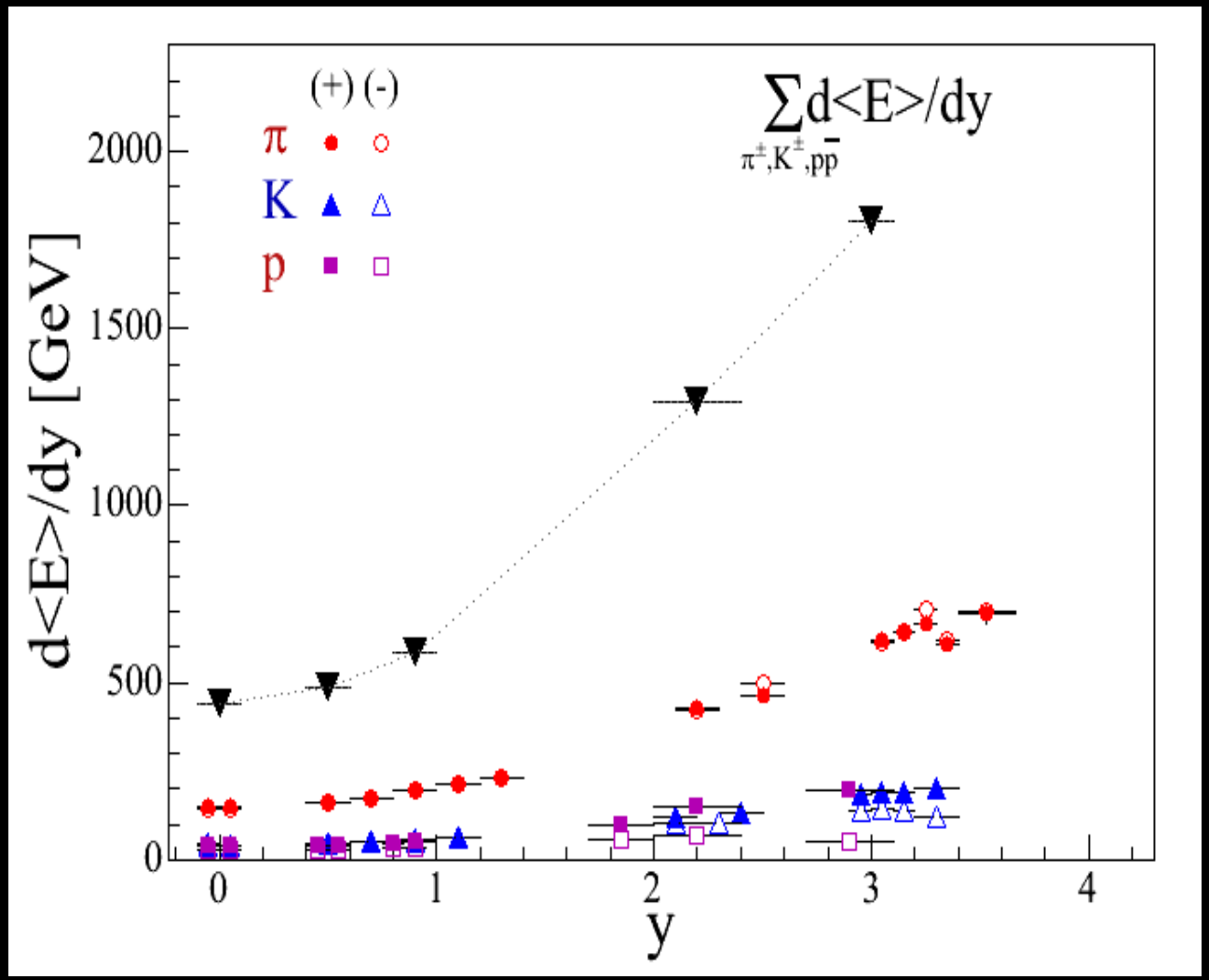
- **Fit π, K and p distributions** (dN/dy and $\langle m_T \rangle$ vs y)
  $\Rightarrow$ total energy of π, K and p
- **Assume reasonable distribution for particles we don't detect (π^0,n,Λ…)**
- **Calculate the total energy…**

$$E_{total} = \sum_{specie} \left[\int \frac{dN}{dy} \langle m_T \rangle \cosh(y)\, dy \right]$$

≈35 TeV ($E_{beam} \times N_{part}$)
of which ≈25 TeV are carried by produced particles.

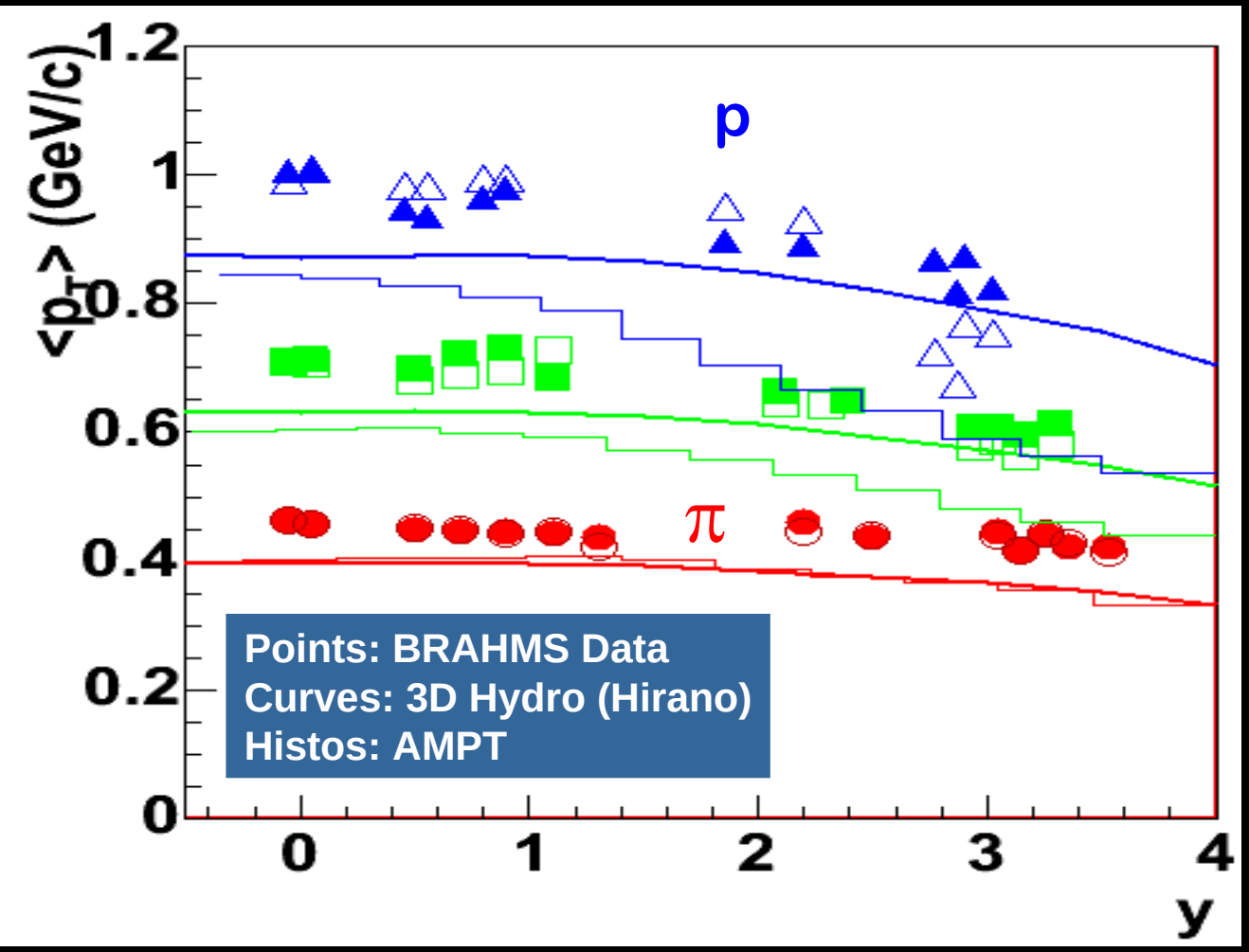


Where is the energy?



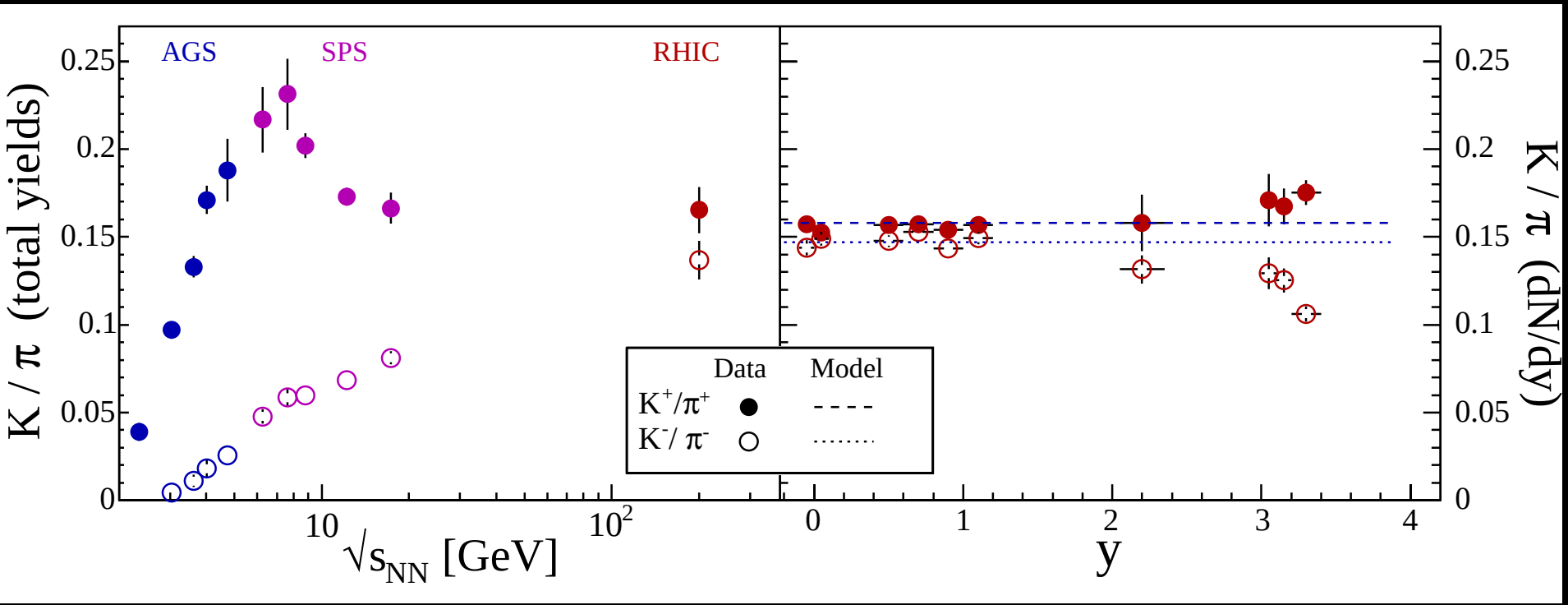
≈9TeV in produced particles in the covered y range -3<y<3

Transverse Flow…



Transverse flow roughly constant over ≈2 units of rapidity. "blast-wave" fit parameters confirm this.

Strange to non-strange meson ratios



$K^-/\pi^- \approx K^+/\pi^+$ at midrapidity

Depend strongly on baryochemical potential

Strangeness with Kaons

RAPIDITY DEPENDENCE

Y < 1 : consistent with Hadron Gas Stat. Model

K^+/π^+ : 15.6 ± 0.1 % (stat)

K^-/π^- : 14.7 ± 0.1 % (stat)

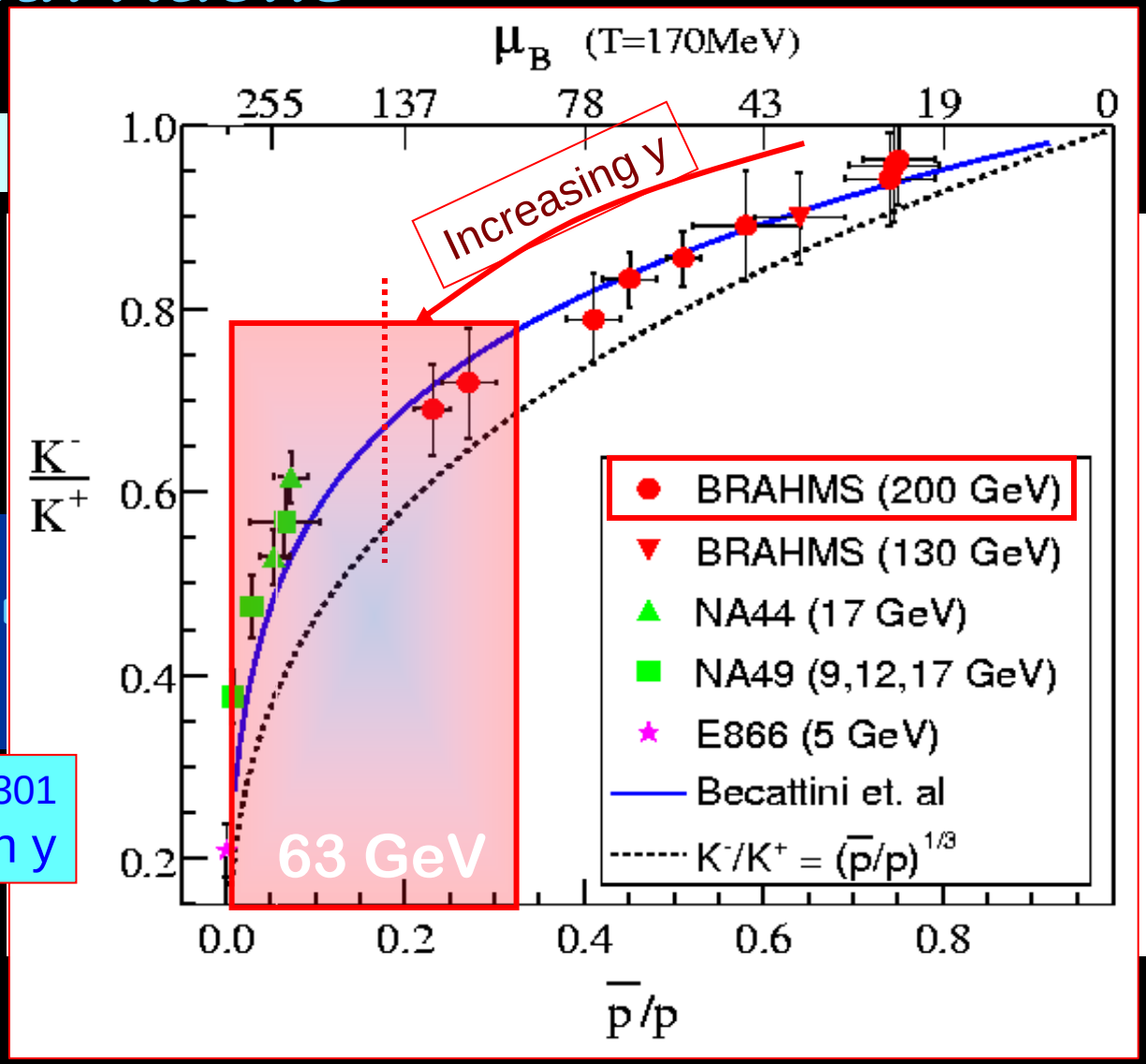
[Phys. Lett. B 518 (2001) 41]

Divergence at higher y : Associated K^+ productio

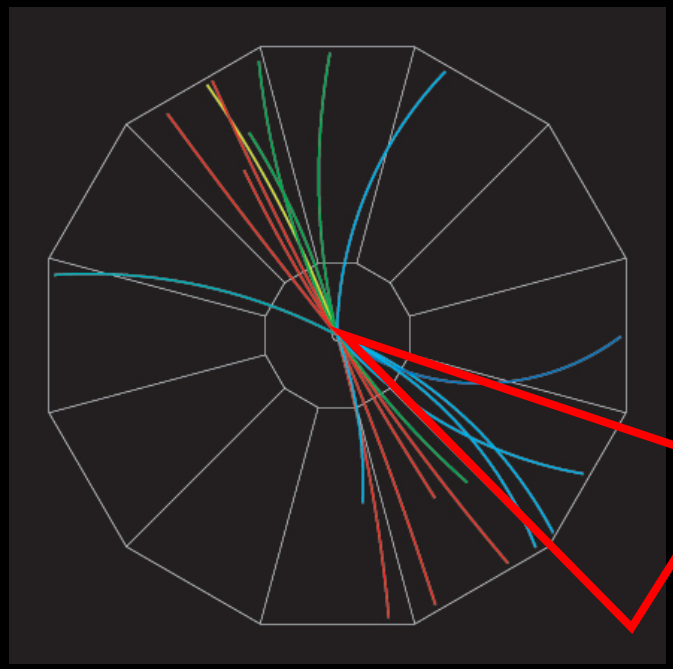
No single source with unique T and μ_B

BRAHMS, PRL90 (2003) 102301

T~constant, μ_B varies with y

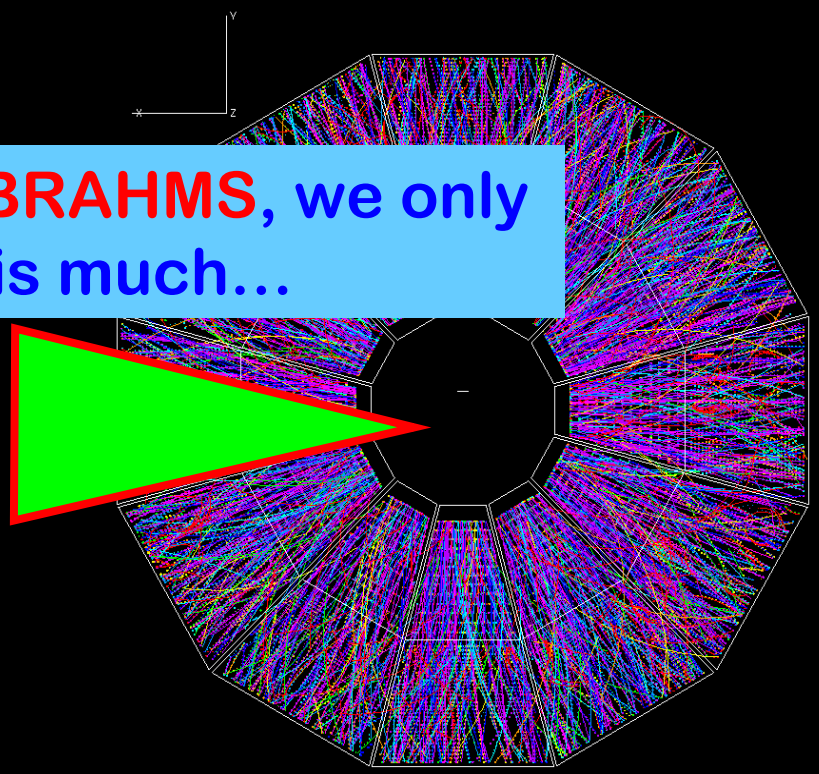


Jets at RHIC

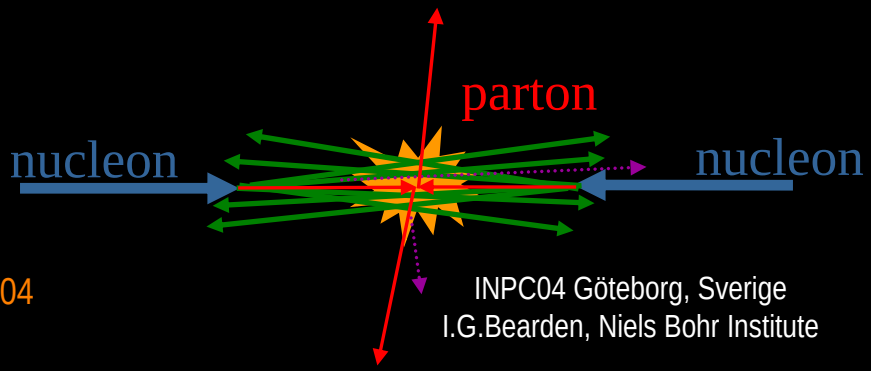


Find this…….in this

And, in BRAHMS, we only "see" this much…

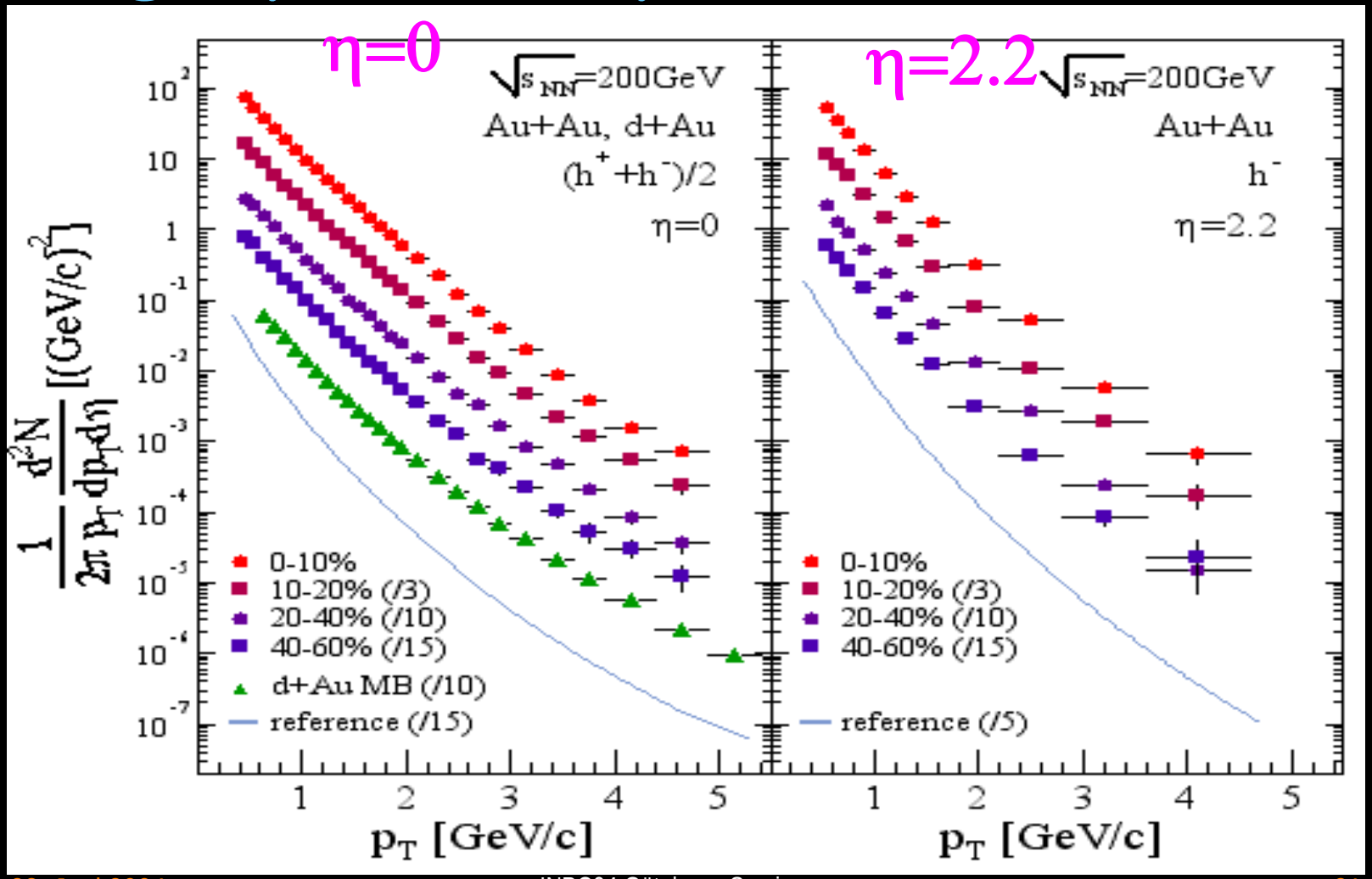


p+p →jet+jet
(STAR@RHIC)



Au+Au →???
(STAR@RHIC)

Characterize "high" p_T by single particle spectra



Nuclear Modification

Quantified by:

$$R_{AB} = \frac{d^2N^{AB}/dp_T d\eta}{\langle N_{bin}\rangle d^2N^{NN}/dp_T d\eta}$$

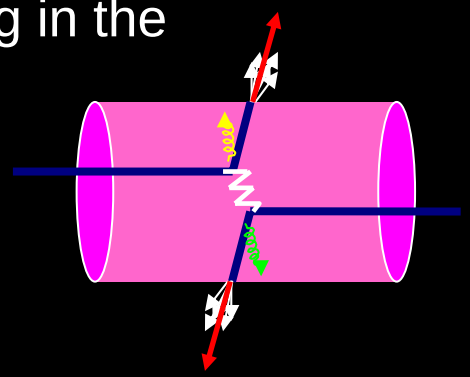
- yield relative to that from N+N collisions, scaled for the nuclear geometry (N_{bin})

- **Cronin Enhancement**
- **Shadowing/Saturation**
- **Jet-quenching**

Jet-quenching

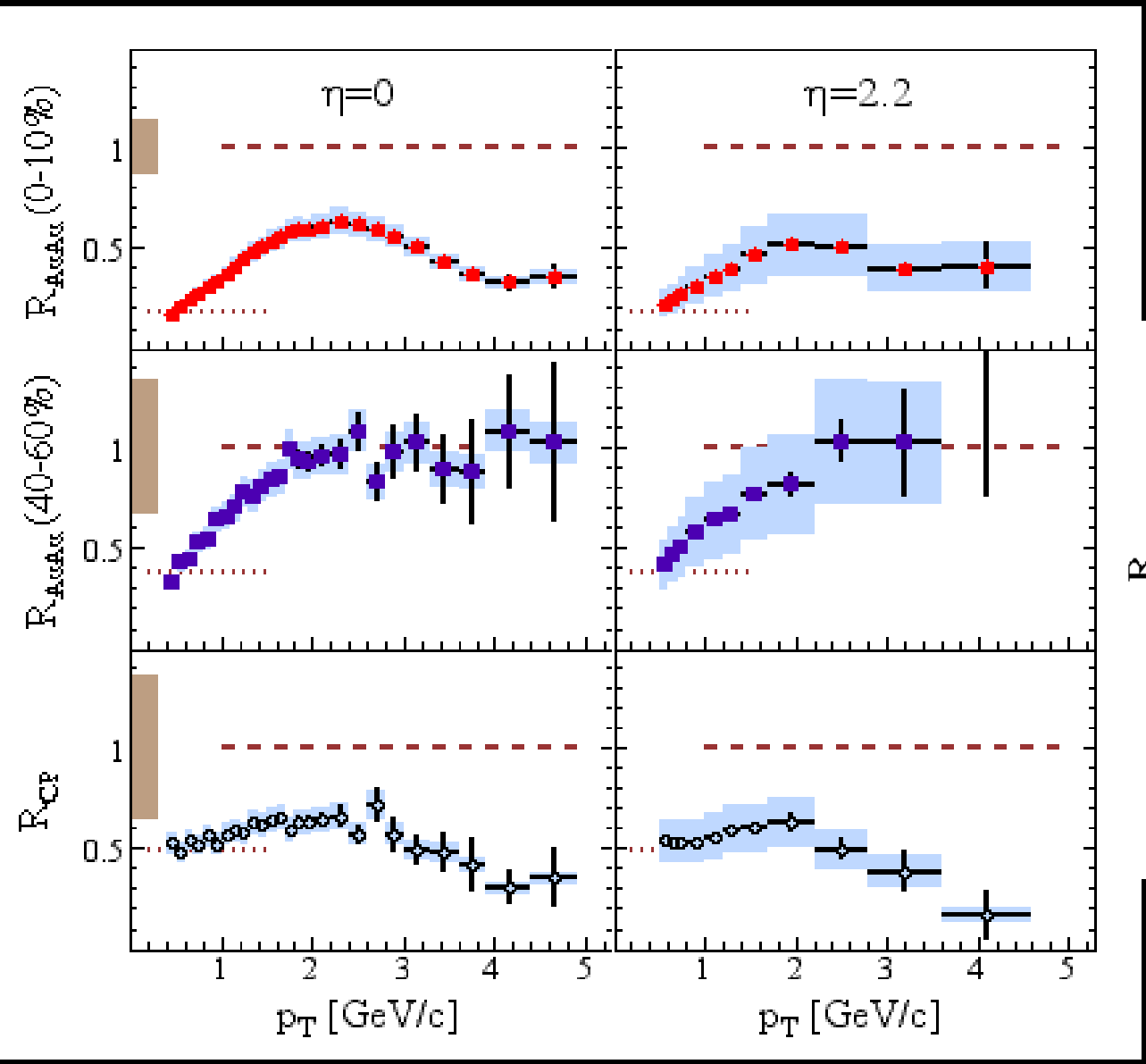
energy loss of high momentum particles in the dense medium due to

- gluon brehmstralung in the colored medium
- hadronic multiple scattering

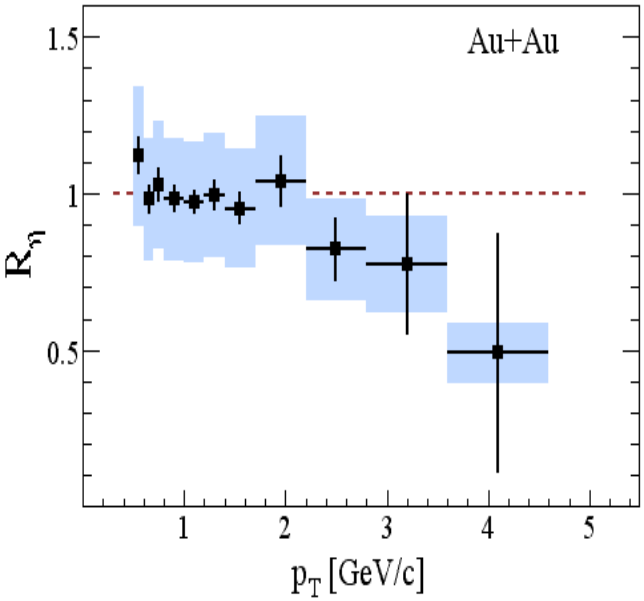


⇒suppression of leading hadrons

- Au+Au at $\sqrt{s_{NN}}$ = 130GeV and 200GeV
- next: energy+rapidity dependence

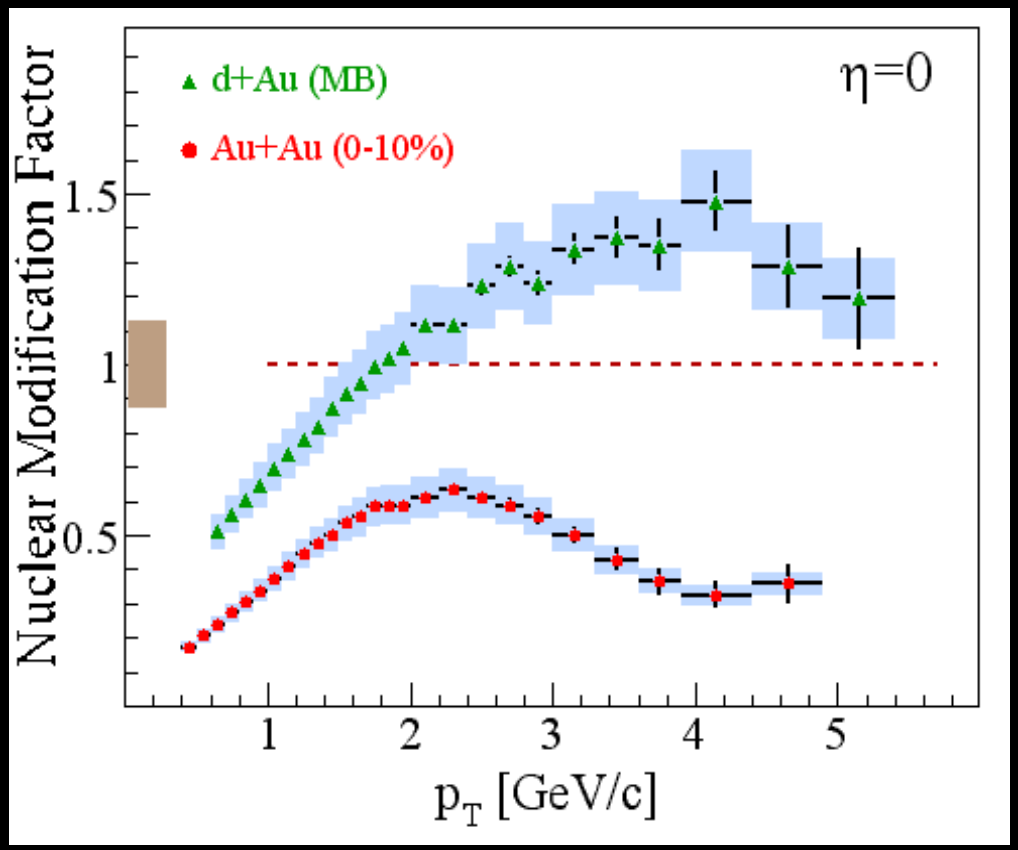


To look at 'only' data, form ratio $R_\eta = R_{cp}(\eta=2.2)/R_{cp}(\eta=0)$



Arsene et al. PRL2003

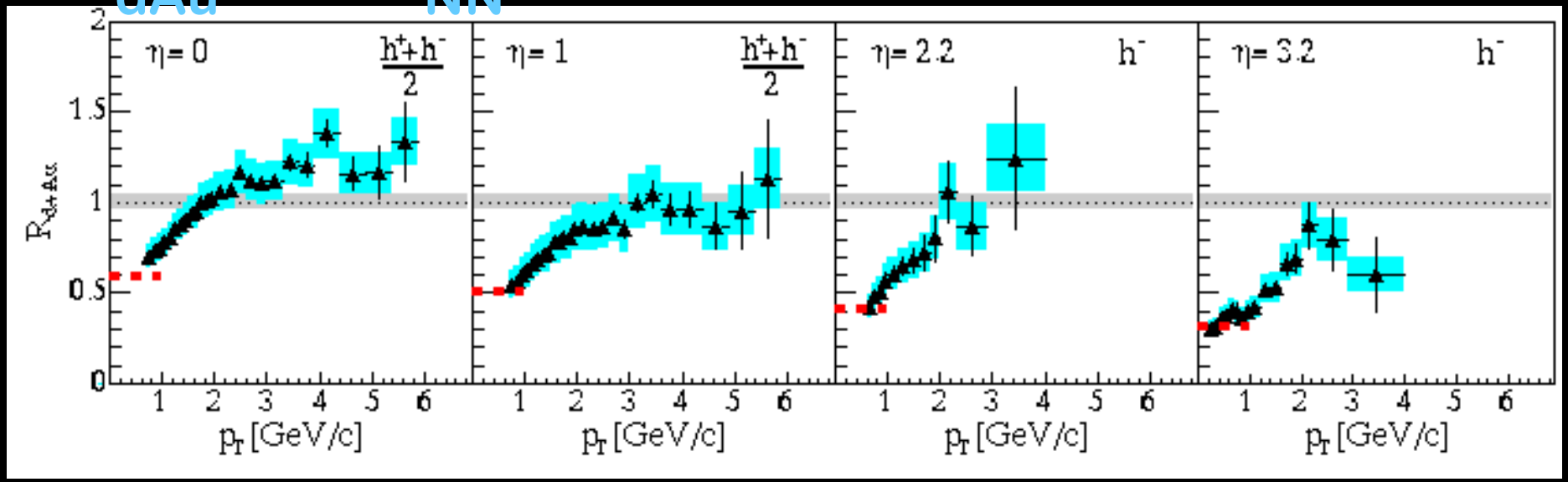
d+Au Nuclear Modification η =0



High p_T enhancement observed in d+Au collisions at $\sqrt{s_{NN}}$=200 GeV.

Comparing Au+Au to d+Au
$\Rightarrow$ strong effect of dense medium

R_{dAu} at $\sqrt{s_{NN}}$ = 200 GeV



Cronin enhancement at η=0

- the "null" experiment that ruled out initial state effect as explanation for Au+Au suppression

submitted to PRL

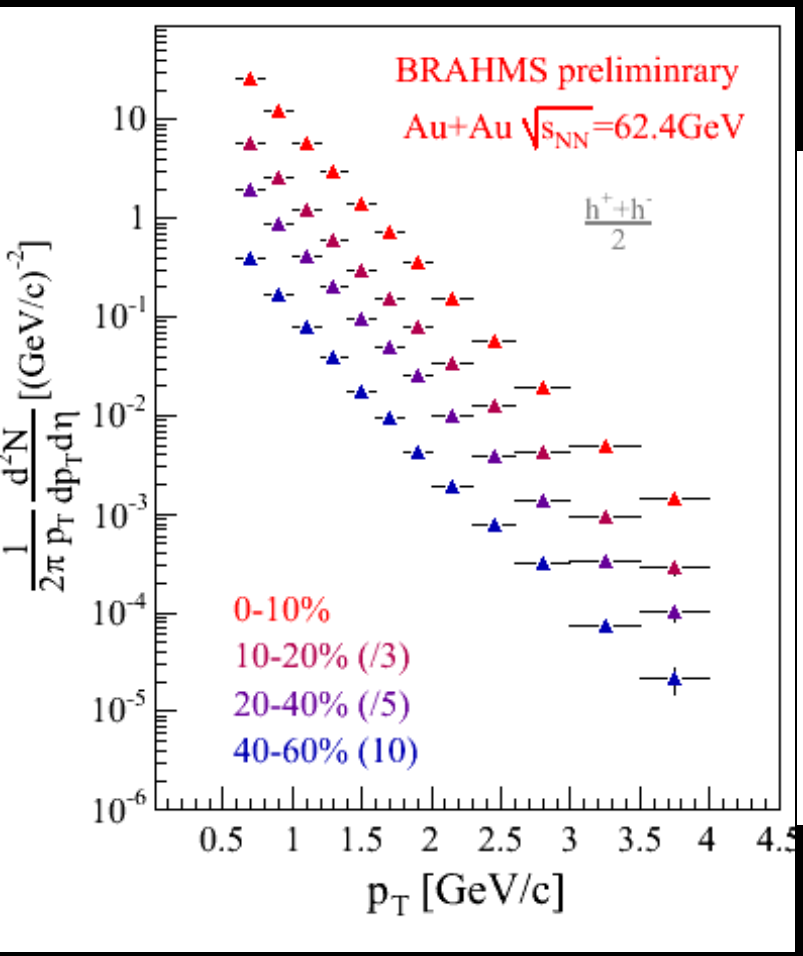
Increasing suppression for $\eta \rightarrow 3$

- window to the low-x partons in the Au nuclei ($Q_S \sim A^{1/3} e^{-\alpha y}$)
- consistent with CGC prediction

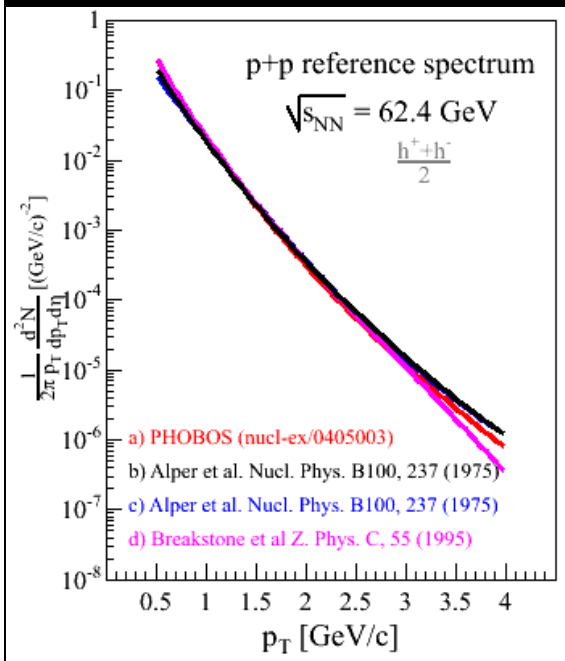
See D. Röhrich after Coffee

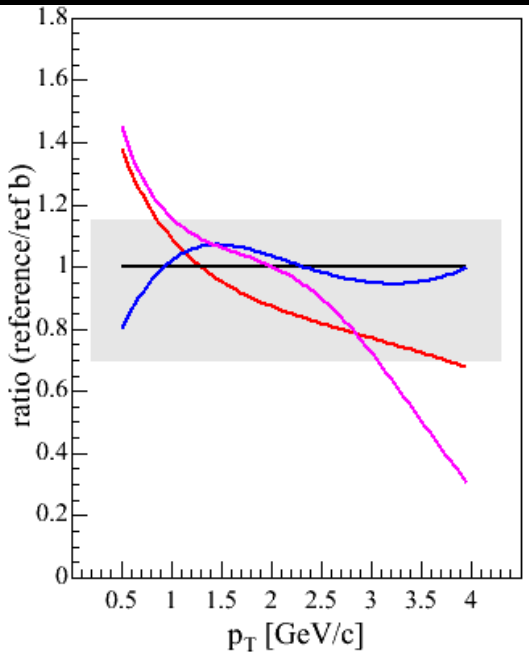
one week of 62.4 GeV running…

New BRAHMS results



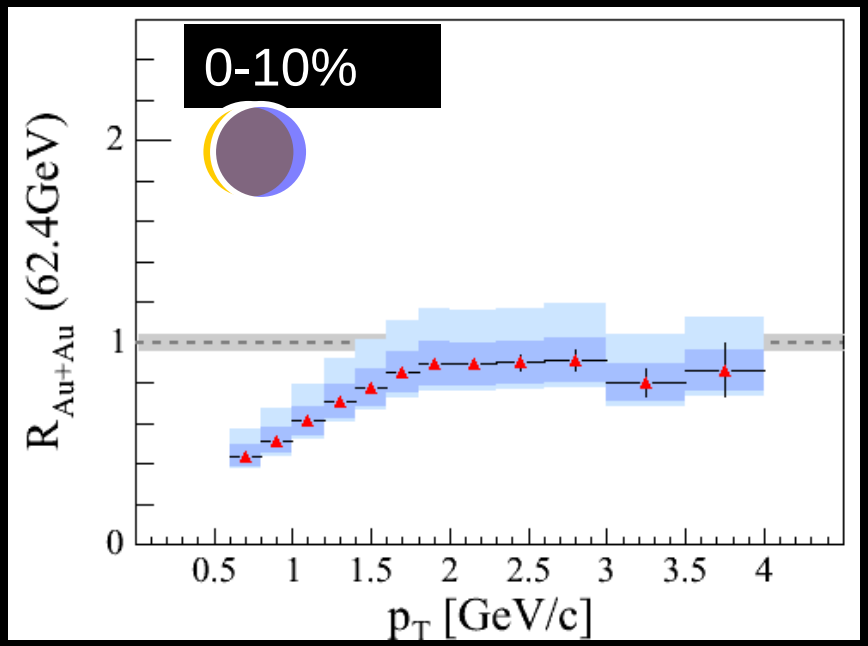
No RHIC p+p running at this energy:
- what should we use as reference?



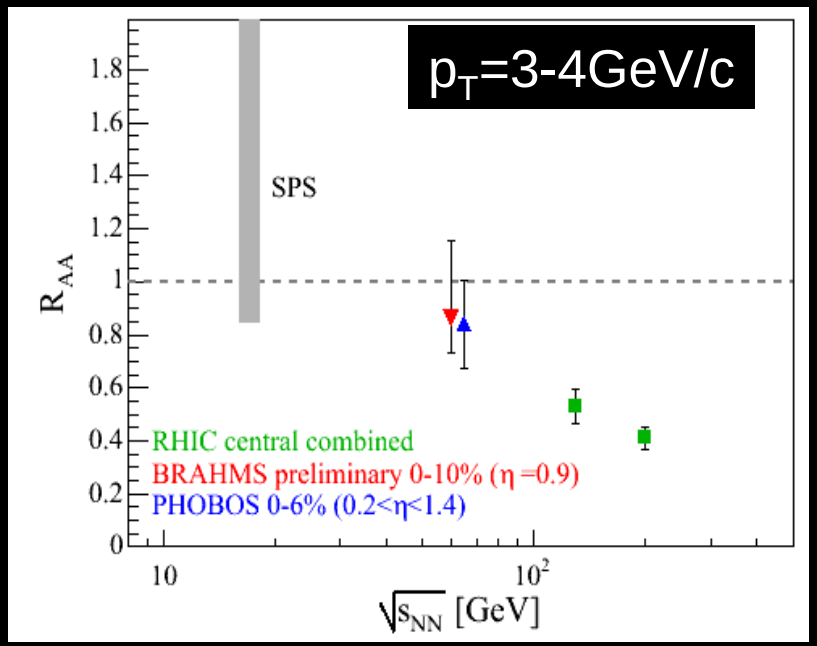


R_{AuAu} at $\sqrt{s_{NN}}$ = 62.4 GeV

Nuclear modification factor R_{AuAu} - different centrality classes



Energy dependence (SPS→RHIC) p_T=3-4GeV/c



Conclusions

- High energy density
- 70% of energy available for particle production
- Source (nearly) same over >1 unit rapidity
- 63 GeV data: climb the K/π "matterhorn"?
- High p_T suppression persists to high y in Au+Au
- More saturation as y increases in d+Au
- Gluon saturation describes data, though not uniquely
- Lots left to do…

The BRAHMS Collaboration

- 12 institutions-

I.Arsene[10],I.G. Bearden[7], D. Beavis[1], C. Besliu[10], Y. Blyakhman[6], J.Brzychczyk[4], B. Budick[6],H. Bøggild[7] ,C. Chasman[1], C. H. Christensen[7], P. Christiansen[7], J.Cibor[4],R.Debbe[1],J. J. Gaardhøje[7],M. Germinario[7], K. Hagel[8], O. Hansen[7], H. Ito[11], E. Jacobsen[7], A. Jipa[10], J. I. Jordre[10], F. Jundt[2], C.E.Jørgensen[7], E. J. Kim[5], T. Kozik[3], T.M.Larsen[12], J. H. Lee[1], Y. K.Lee[5], G. Løvhøjden[2], Z. Majka[3], A. Makeev[8], B. McBreen[1], M. Murray[8], J. Natowitz[8], B. Neuman[11],B.S.Nielsen[7], K. Olchanski[1], D. Ouerdane[7], R.Planeta[4], F. Rami[2], D. Roehrich[9], B. H. Samset[12], S. J. Sanders[11], I. S. Sgura[10], R.A.Sheetz[1], Z.Sosin[3], P. Staszel[7], T.S. Tveter[12], F.Videbæk[1], R. Wada[8] ,A.Wieloch[3],Z. Yin[9]

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[3]Jagiellonian University, Cracow, Poland, [4]Institute of Nuclear Physics, Cracow, Poland
[5]Johns Hopkins University, Baltimore, USA, [6]New York University, USA
[7]Niels Bohr Institute, Blegdamsvej 17, University of Copenhagen, Denmark
[8]Texas A&M University, College Station. USA, [9]University of Bergen, Norway
[10]University of Bucharest, Romania, [11]University of Kansas, Lawrence,USA
[12] University of Oslo Norway

In ’BT’ (Danish morning tabloid) Feb. 2004

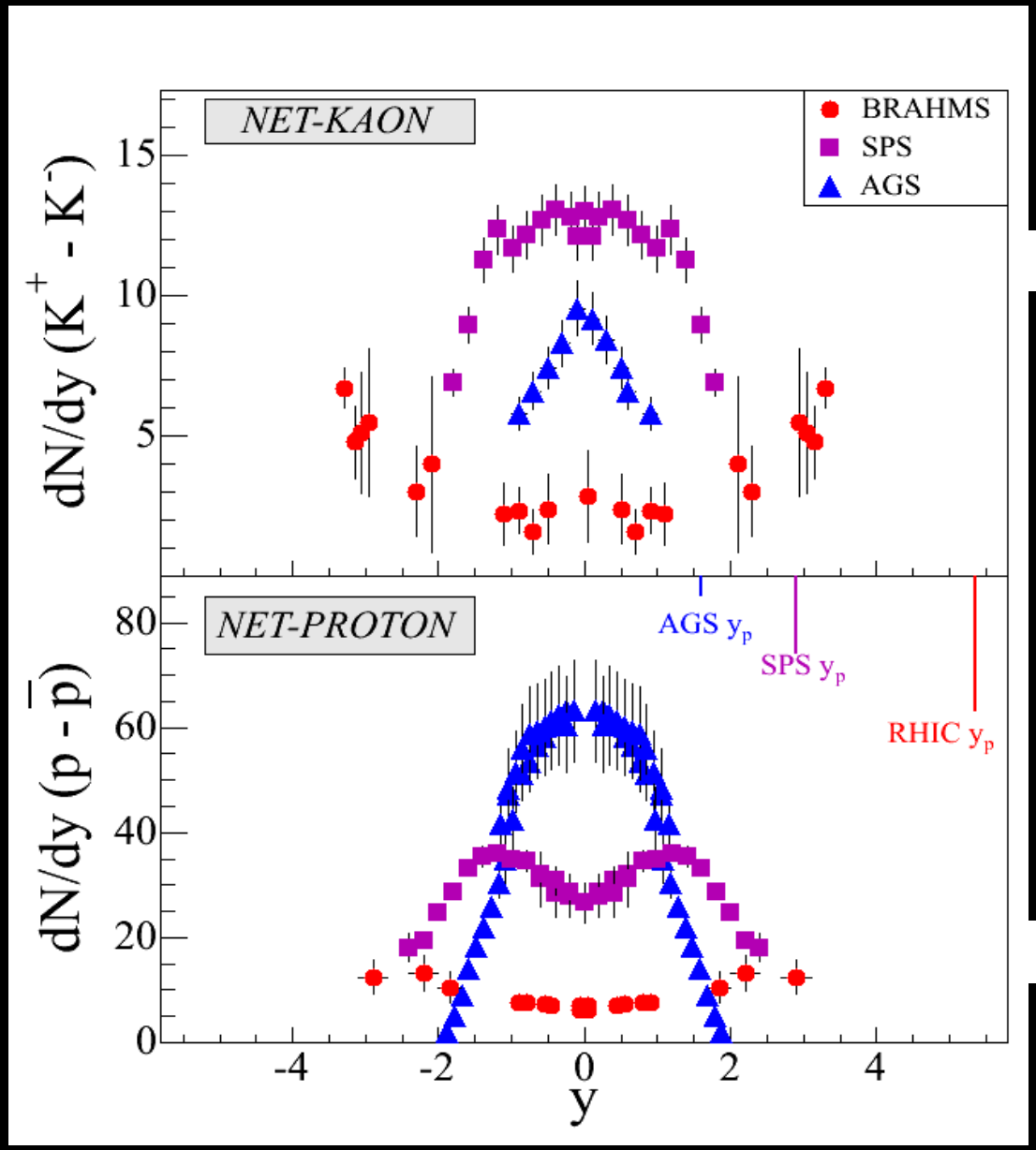
That you can recreate the Big Bang in a particle accelerator is simply a fantastic and earth shattering….

discovery!

At the same level .....

…….as plastic slippers with acrylic lining

Random Back-up slides…



ENERGY DEPENDENCE

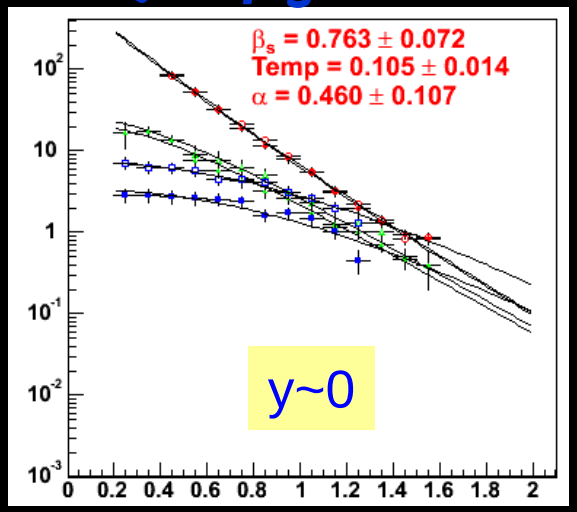
At y = 0, ratios converge to ~ 15 %

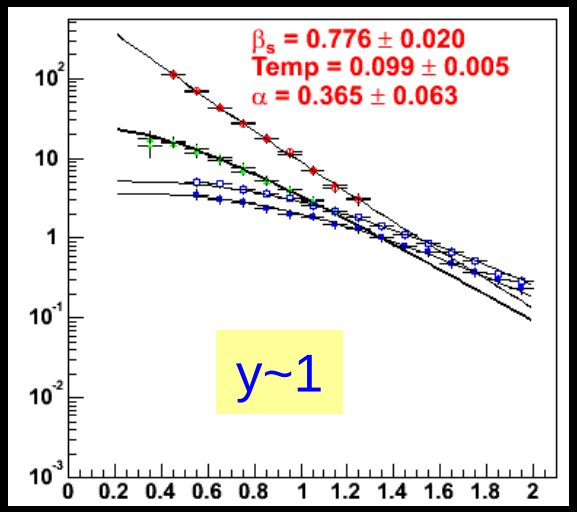
Over the full phase space:
K^+/π^+ = 16.6 ± 1.5 % (syst)
K^-/π^- = 13.7 ± 2.0 % (syst)

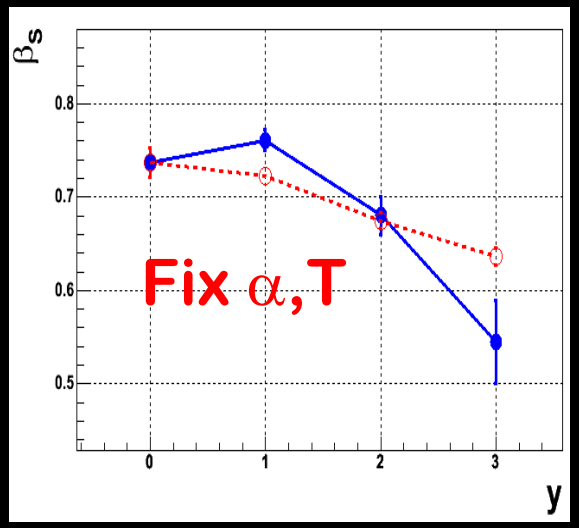
Why this behavior ?
Net-Kaon distribution evolves like net-proton

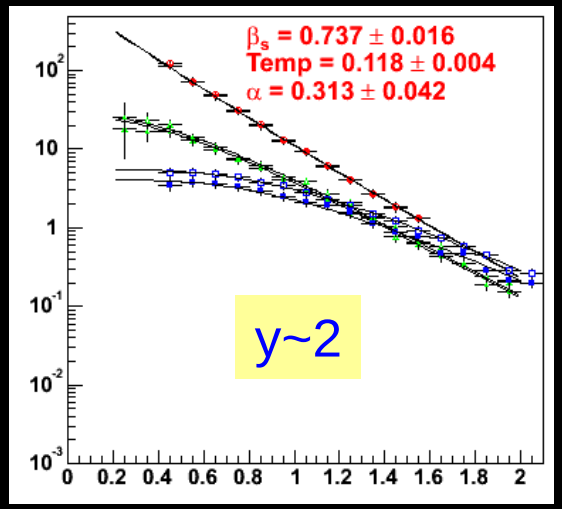
Spectra with BW Fits at y~0,1,2,3
(T, β_s, α in the fit R_{max}=13fm)

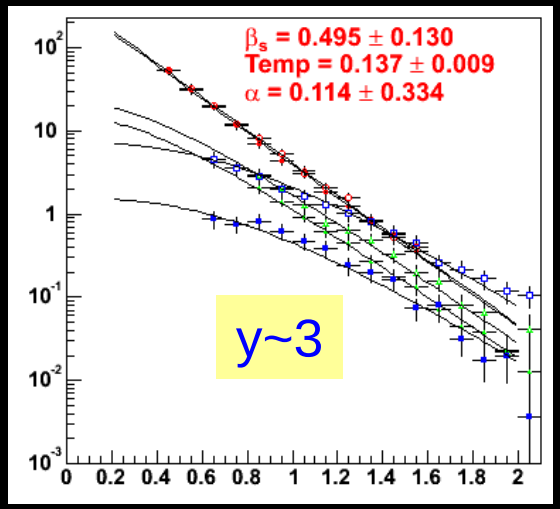
BRAHMS Preliminary

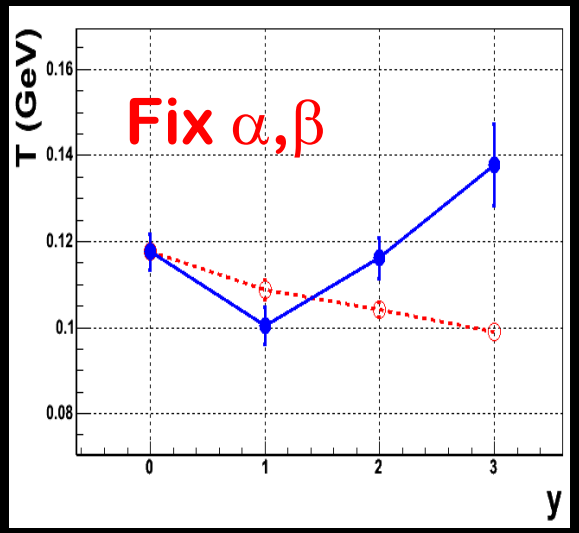






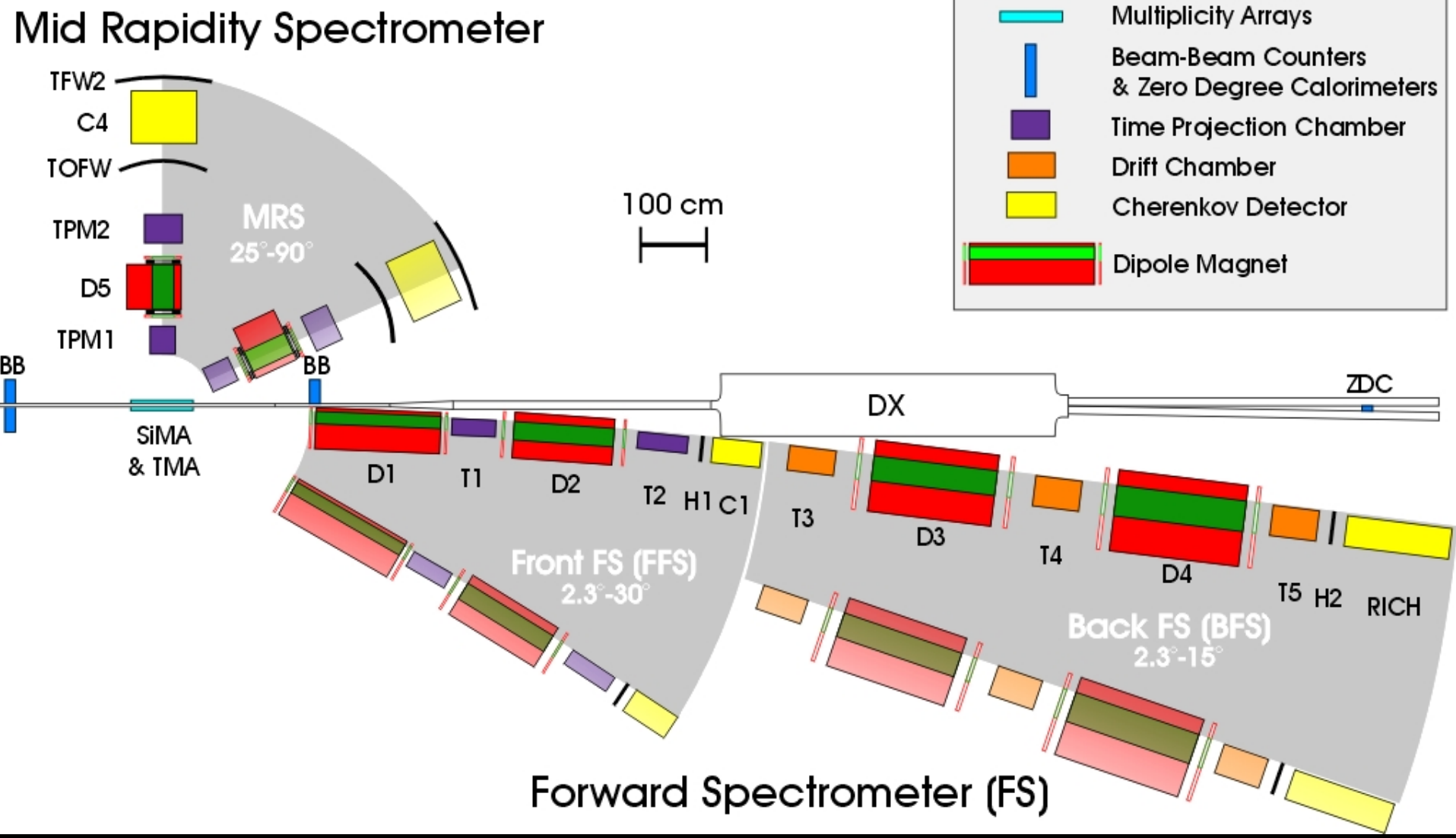




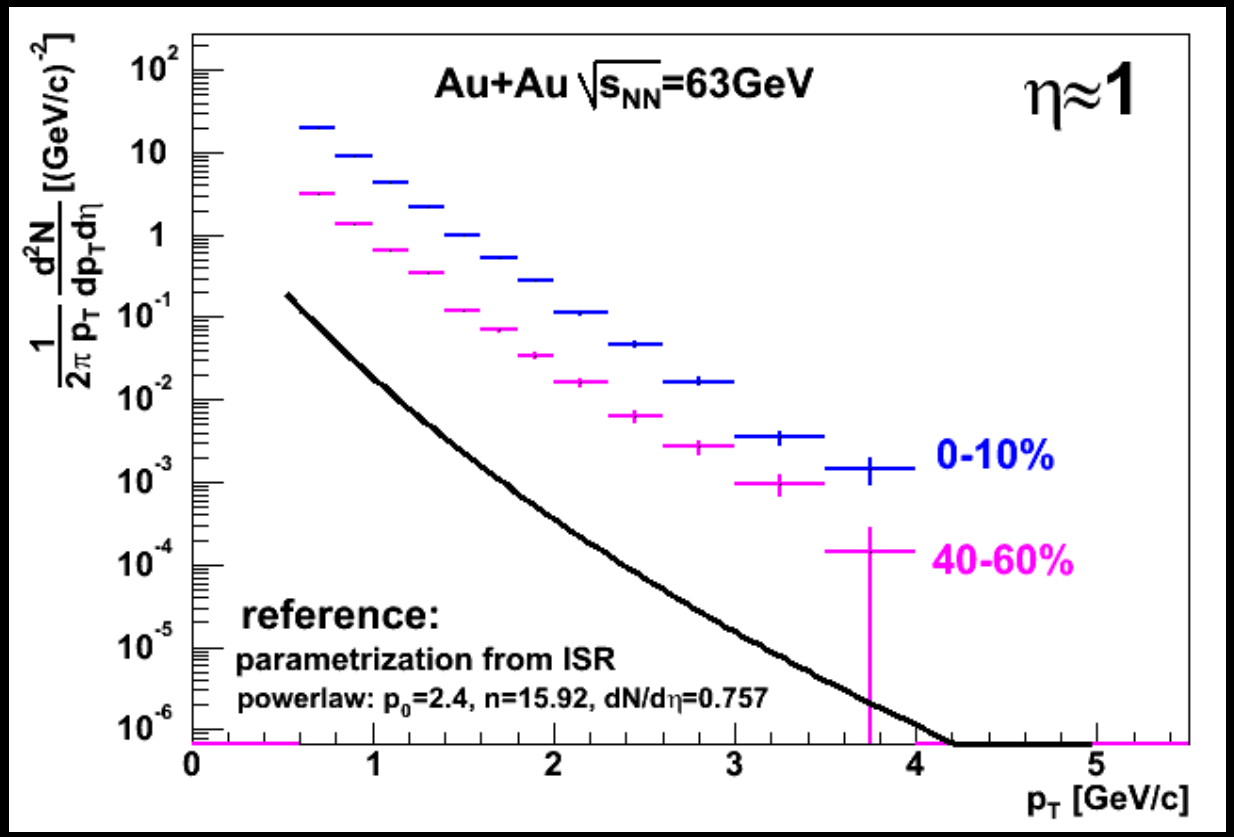


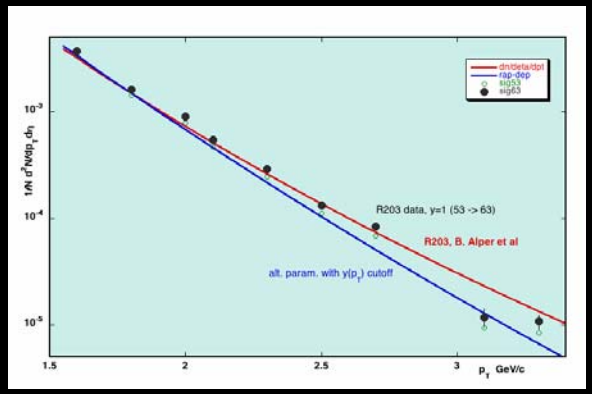
p_T (GeV/c)

BRAHMS Experimental Setup

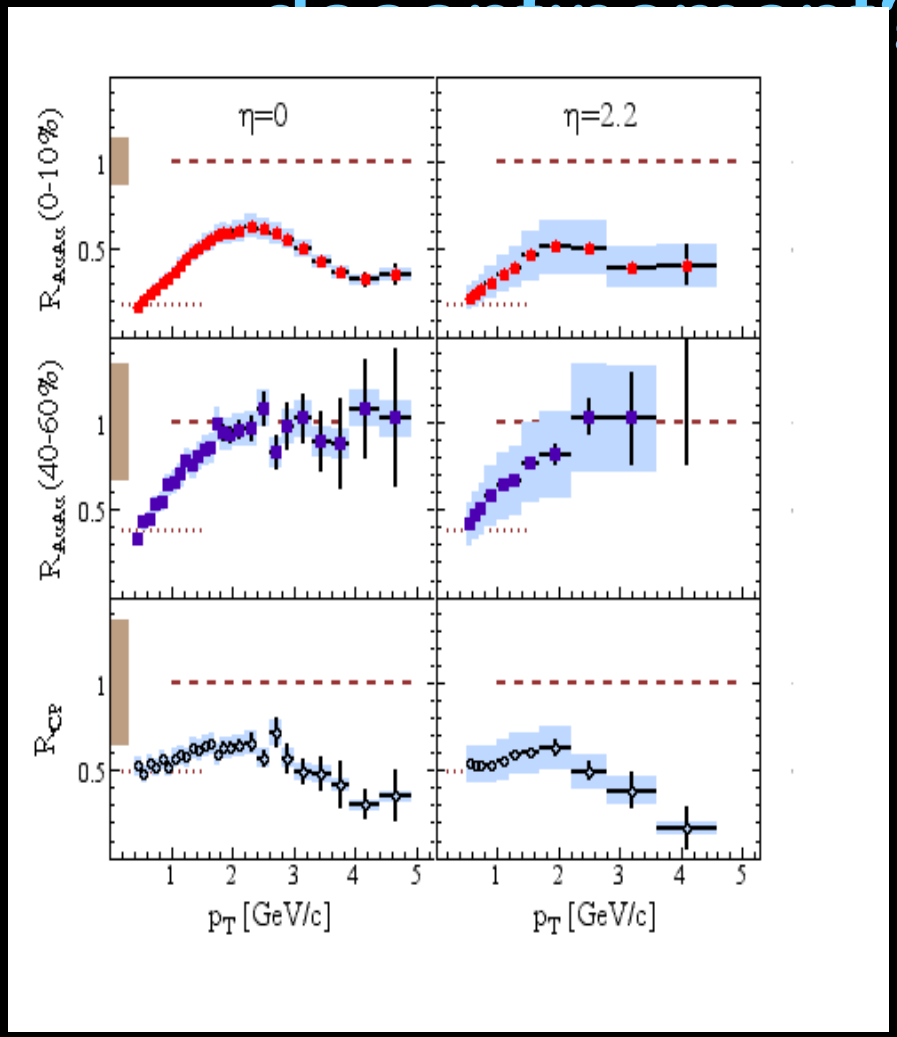


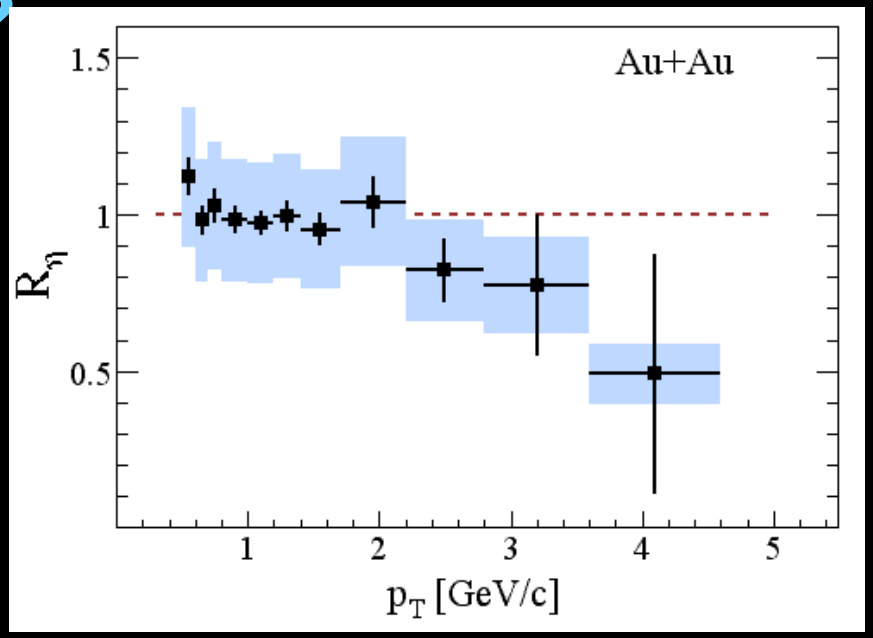
Preliminary results from 63GeV





High pt suppression, jet quenching in Au+Au The smoking gun of deconfinement?





Large high pt suppression also at forward rapidity.

Longitudinally extended medium, boost invariance, CGC or …?

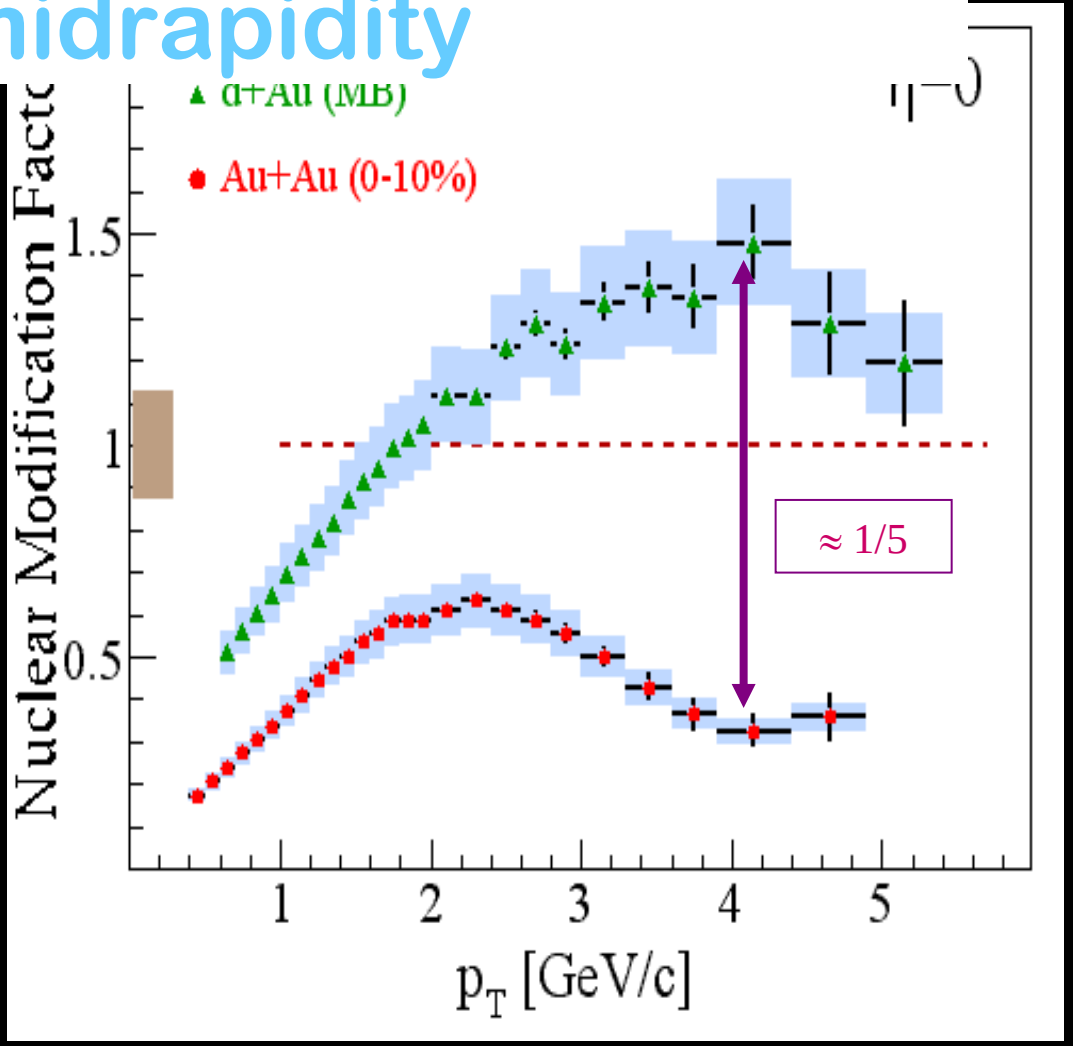
Not quantitatively understood.

Absence of suppression in d+Au at midrapidity

QCD predicts large energy loss from gluon bremsstrahlung in deconfined medium:

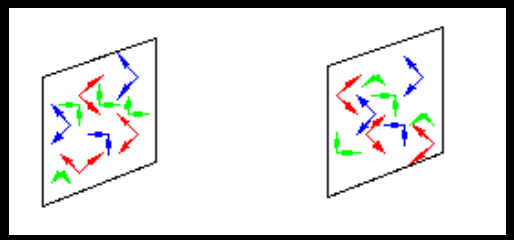
$$\langle \Delta E \rangle \propto \int \rho^g \ln(1/L)\, dz$$

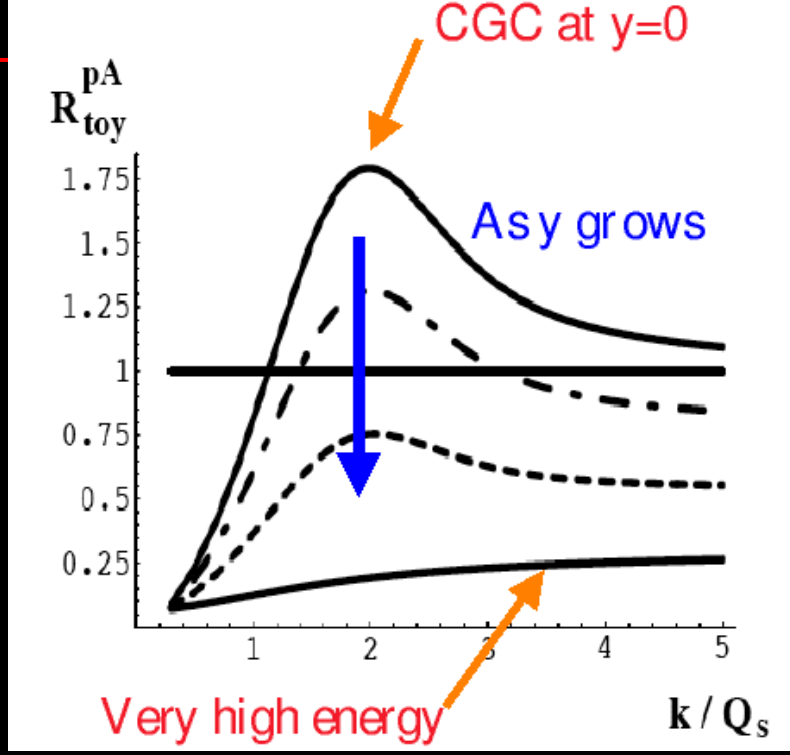
$$\propto \langle L^2 \rangle$$



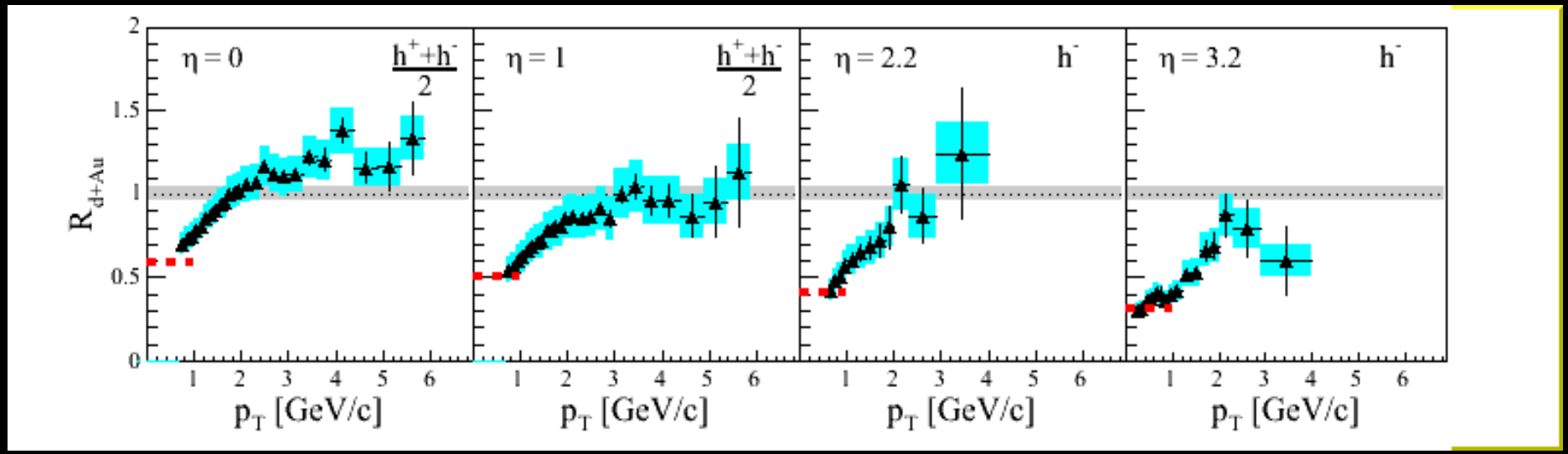
BRAHMS: PRL 91 (2003) 072305

d+Au at forward rapidity. Color Glass Condensate ?





BRAHMS: Submitted to PRL, March 2004



Nuclear Modification

Quantified by:

$$R_{AB} = \frac{d^2N^{AB}/dp_T d\eta}{\langle N_{bin}\rangle d^2N^{NN}/dp_T d\eta}$$

- yield relative to that from N+N collisions, scaled for the nuclear geometry (N_{bin})

- **Cronin Enhancement**
- **Shadowing/Saturation**
- **Jet-quenching**

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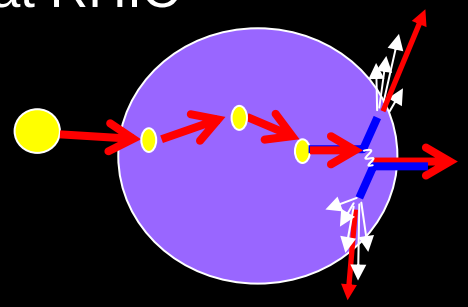
"Cronin effect"

Initial state multiple scattering leading to **Cronin** enhancement (R_{AA}>1)
- heavy ions at lower energy
- d+Au collisions at RHIC



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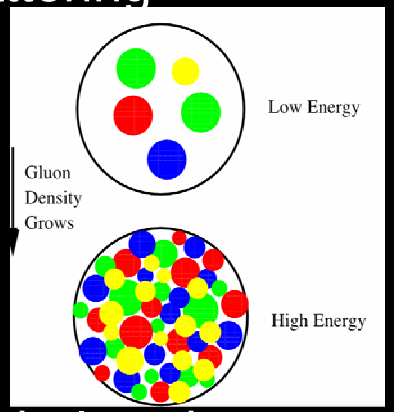
Shadowing/saturation

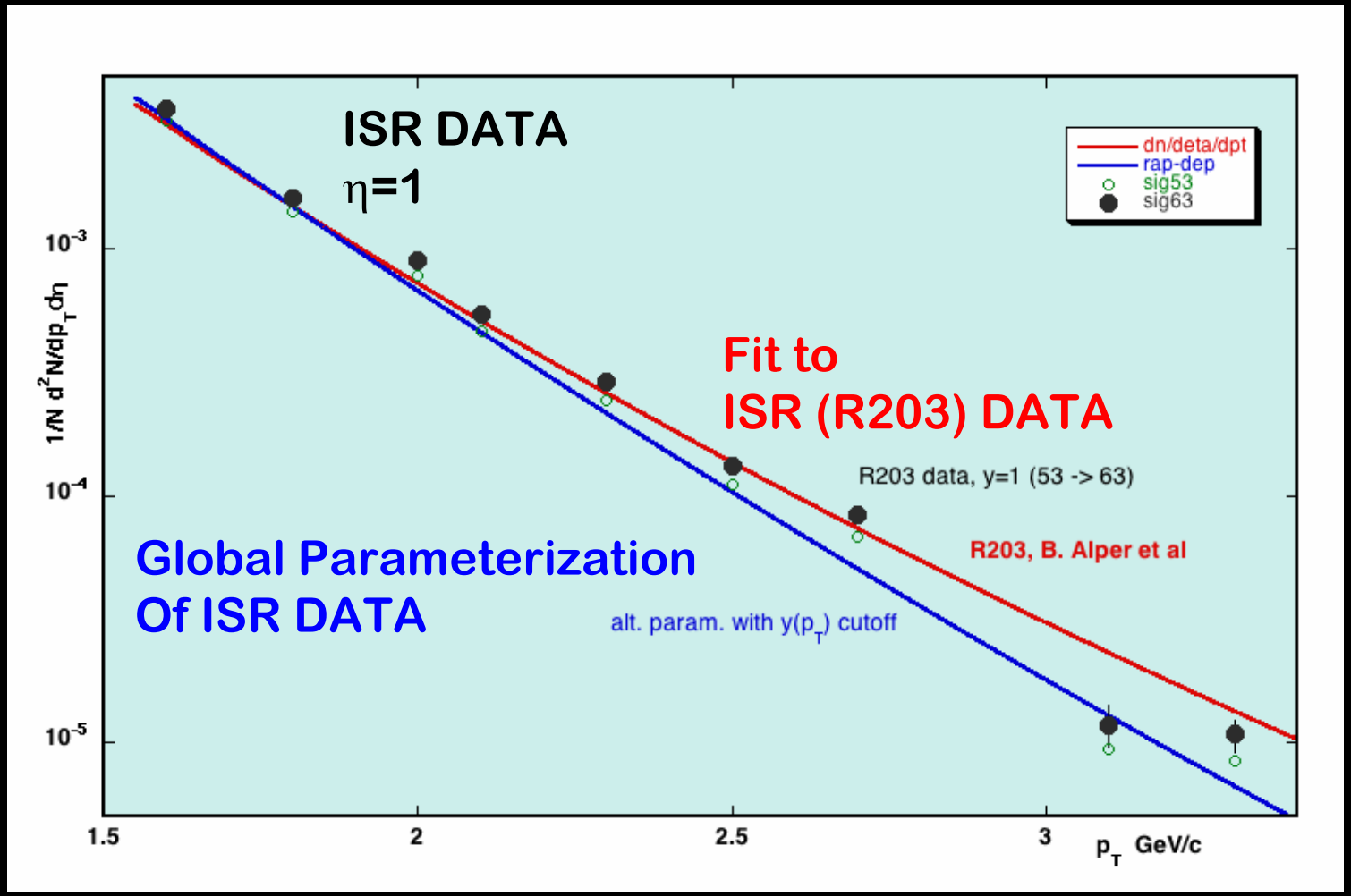
depletion of low-x partons due to:
- coherent multiple scattering
- saturation



leading to suppression below the saturation scale. $Q_S \propto$??

$\Rightarrow$ The Color Glass Condensate (CGC) gives theoretical framework

Reference Spectrum



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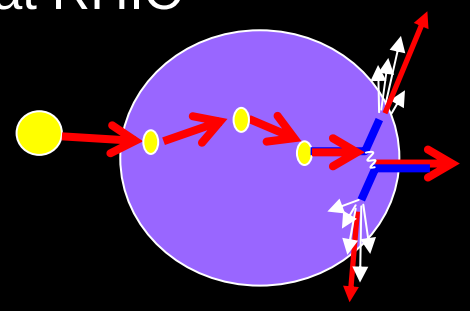

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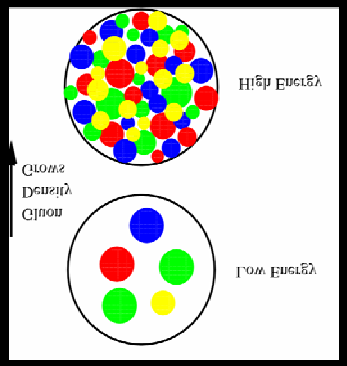

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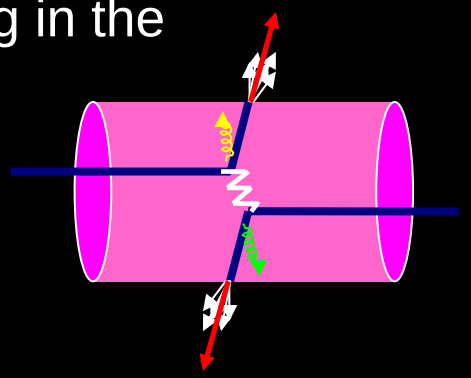
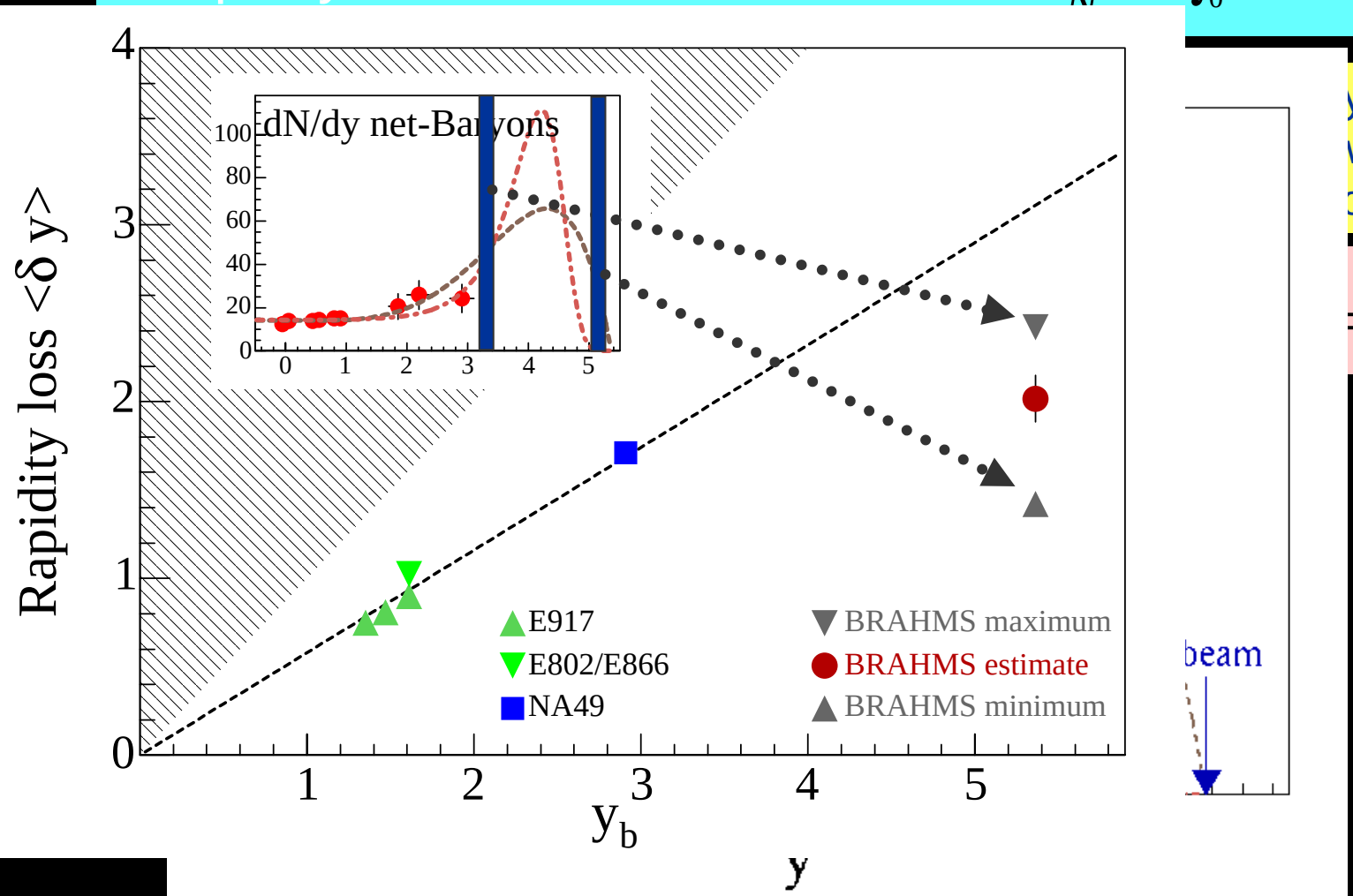
Jet-quenching

energy loss of high momentum particles in the dense medium due to
- gluon brehmstralung in the colored medium
- hadronic multiple scattering



⇒suppression of leading hadrons
- Au+Au at $\sqrt{s_{NN}}$ = 130GeV and 200GeV
- next: energy dependence

Rapidity loss: $\langle \delta y \rangle = y_p - \langle y \rangle = y_p - \frac{2}{N} \int_0^{y_p} y \frac{dN_{(B-\bar{B})}}{dy} dy$



yon after
wn & neutron
ons

= 2.03 ± 0.16

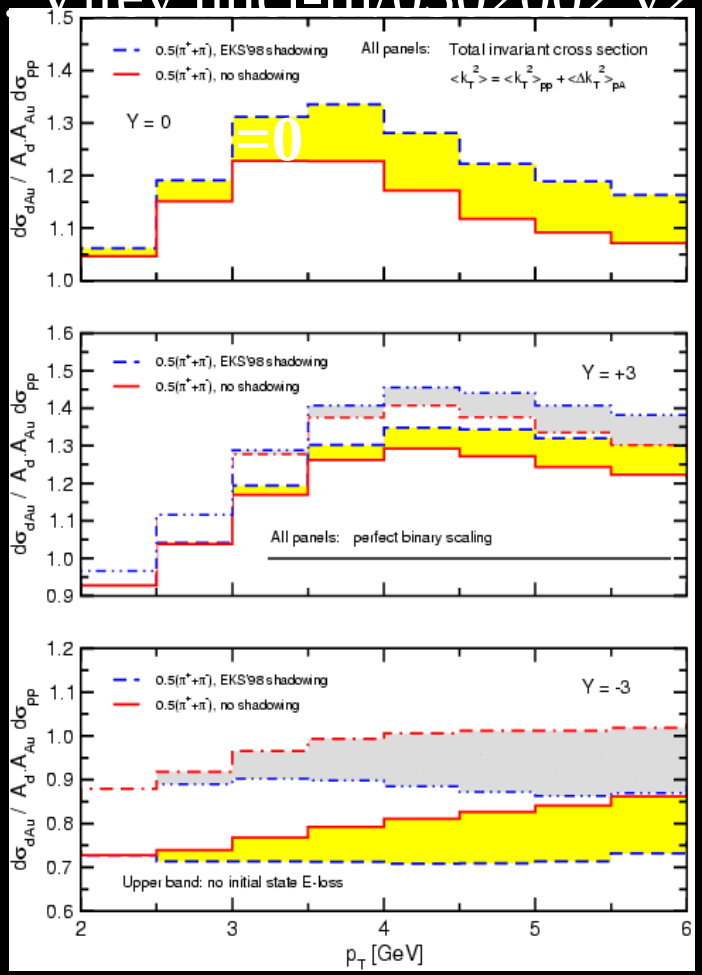
$\langle \delta y \rangle =$ 2.00 ±

Total ΔE=25.7±2

$\int_{-y_p}^{y_p} \langle m_T \rangle_y \frac{dN_{(B-\bar{B})}}{dy}$ co

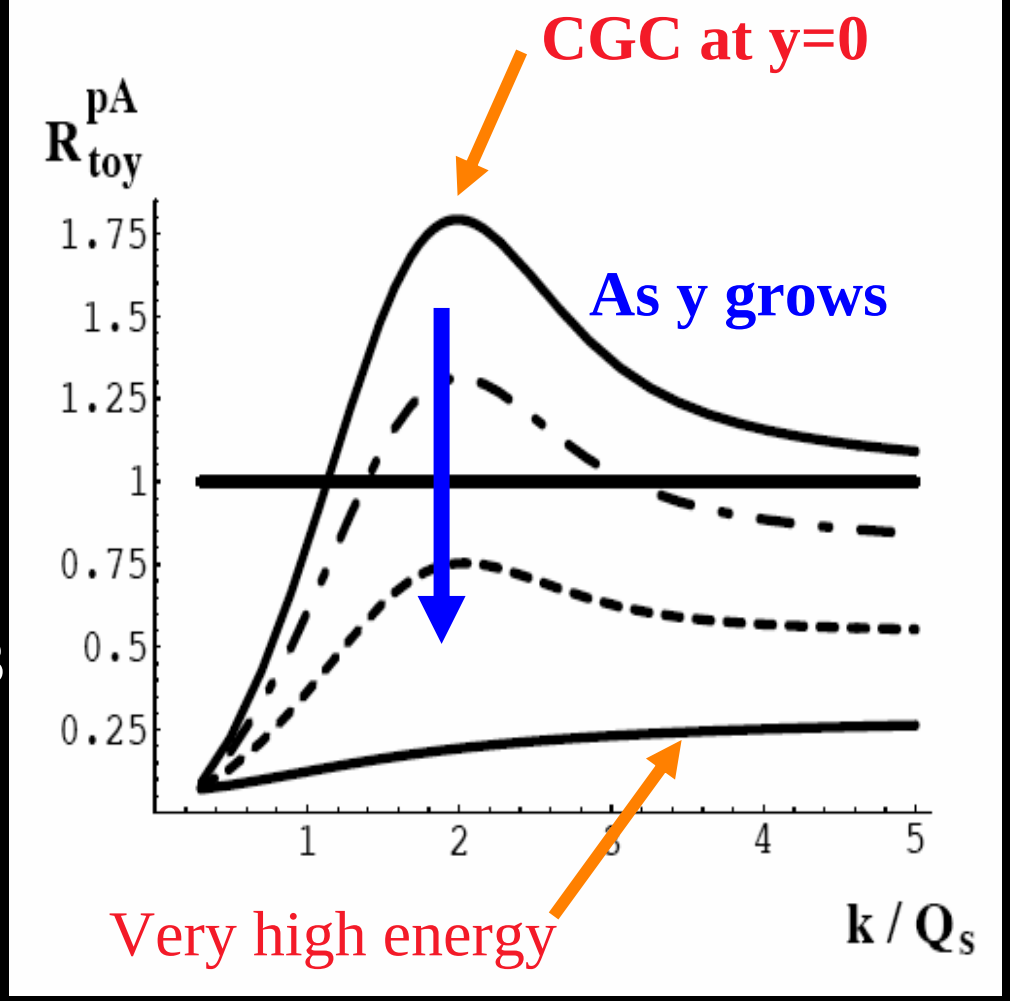
Predictions from theory

I. Vitev nucl-th/0302002 v2



Y=3

Y=-3

D. Kharzeev et al.

Phys.Rev.D68:094013,2003