Bulk hadron production at high rapidities

Gluon saturation and physics at large rapidities

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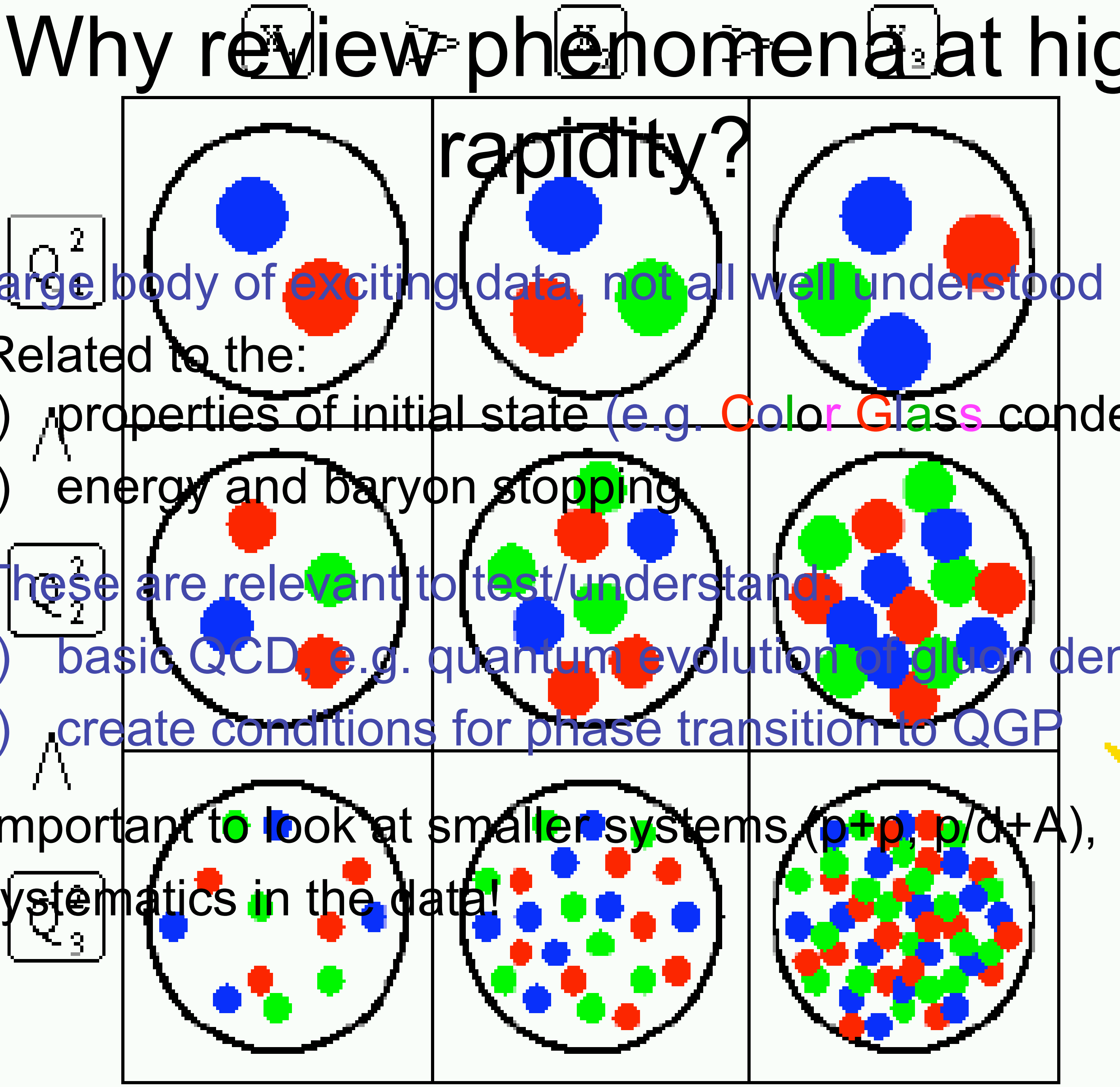
Eötvös Loránd University, Budapest

and

Massachusetts Institute of Technology, Cambridge

Quark Matter 2005, Budapest, August 8, 2005

Why review phenomena at high rapidity?



- Large body of exciting data, not all well understood
- Related to the:

a) properties of initial state (e.g. Color Glass condensate)

b) energy and baryon stopping

- These are relevant to test/understand:

a) basic QCD, e.g. quantum evolution of gluon densities

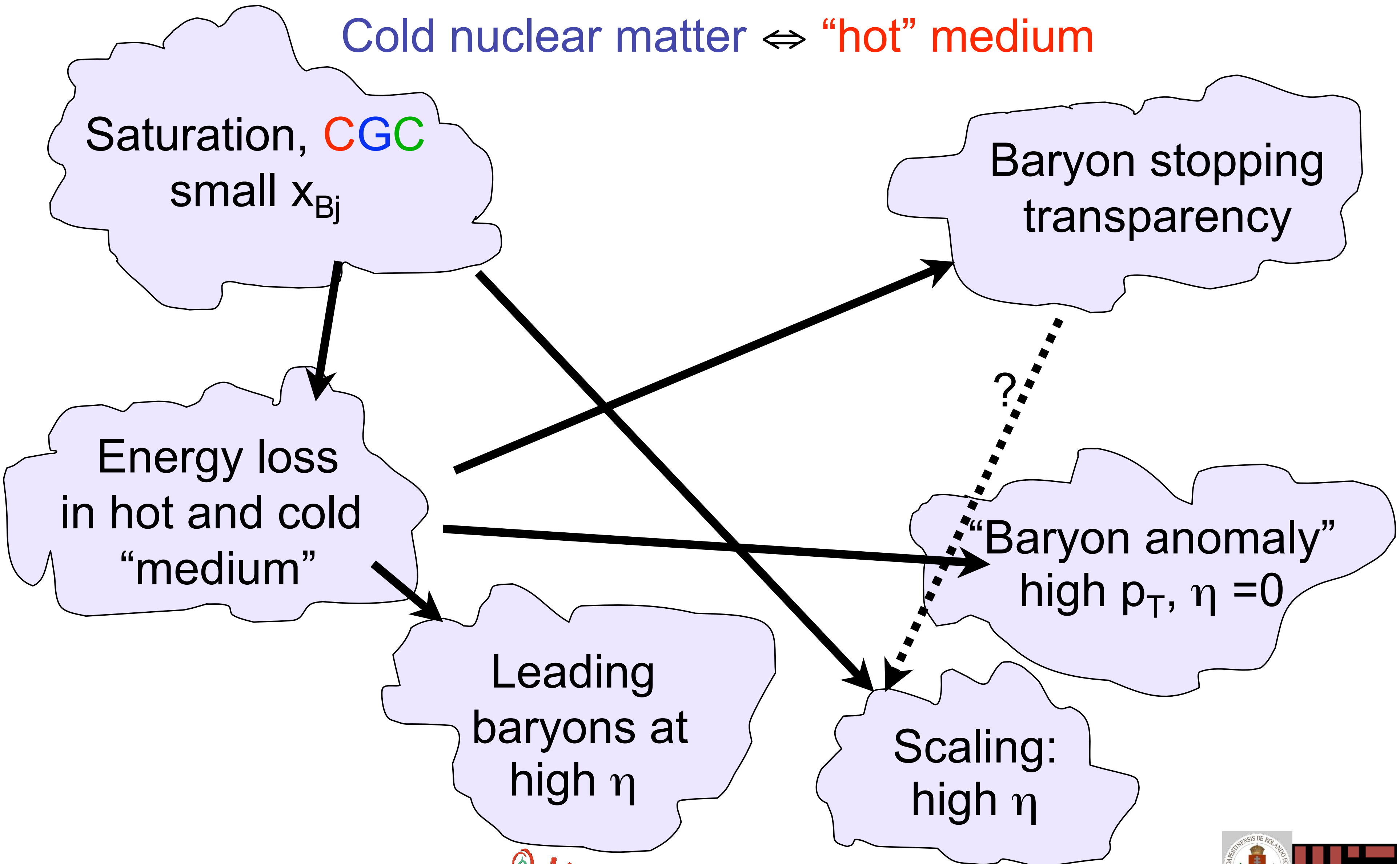
b) create conditions for phase transition to QGP

- Important to look at smaller systems (p+p, p/d+A), systematics in the data!

Questions

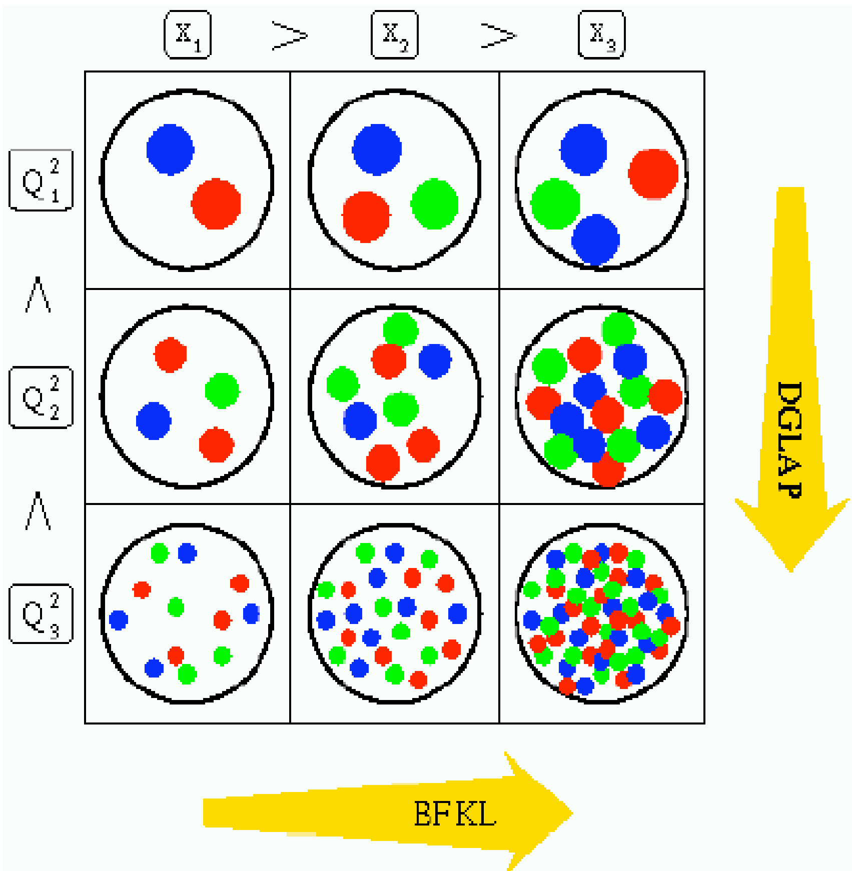
Initial state ⇔ final state

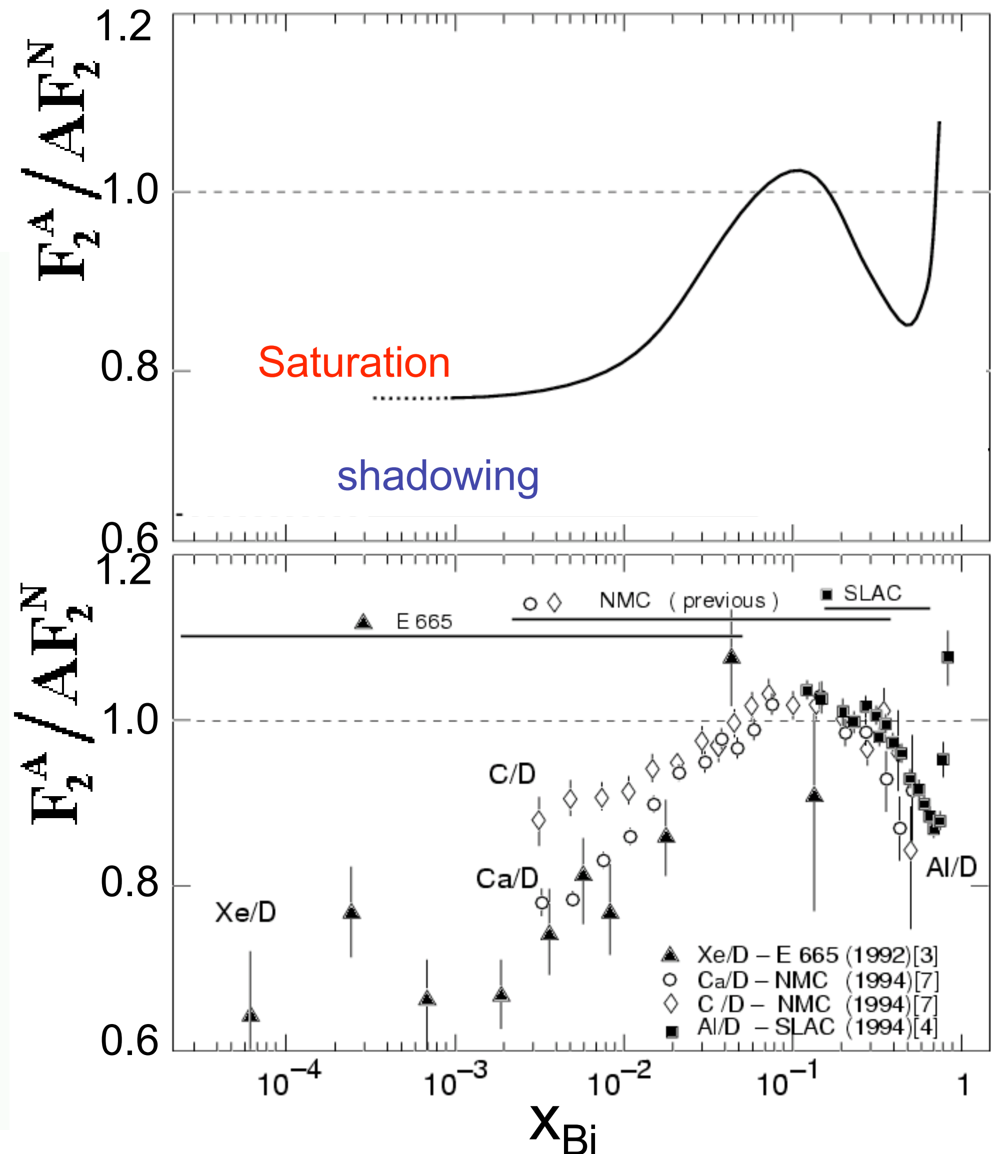
Cold nuclear matter ⇔ “hot” medium



Physics at forward rapidities

Saturated initial state gluons





Kinematics

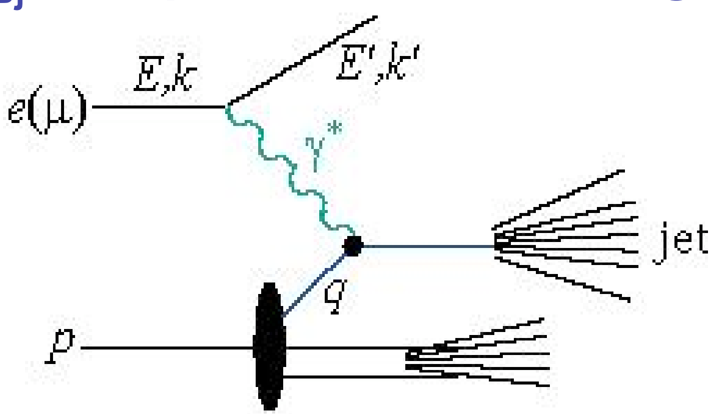
$$p_z = m_T \sinh y = p_T \sinh \eta = \frac{\sqrt{s}}{2} x_F$$

Rapidity: generalized velocity

Pseudorapidity ≈ y: easier to measure

Feynman x: ∝ p_z

x_{Bj} : deep inelastic scattering



$$Q^2 = 2(EE' - \vec{k}\cdot\vec{k}')$$

$$\nu = E - E'$$

$$x = Q^2/2M\nu$$

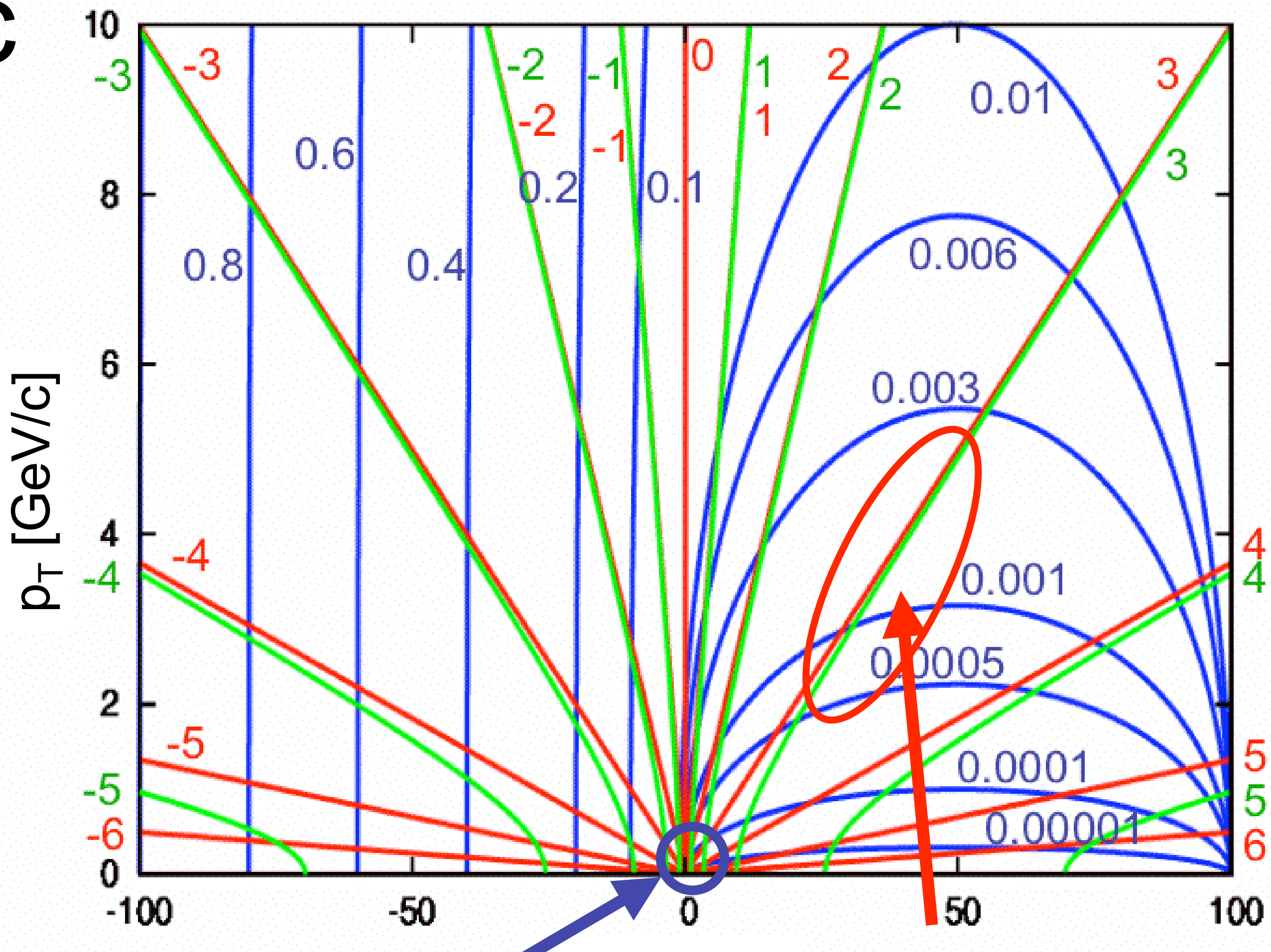
In the c.m. system:

$$x_{Bj} \approx \frac{p_T e^{-\eta}}{\sqrt{s} - p_T e^{\eta}}$$

Kinematic variables

x_{Bj}^{Au}, y_p, η

at $\sqrt{s}$=200 GeV



RHIC: only a <u>small region of phase</u> space where x_{Bj} is in d+Au: small "enough" and Q^2 is large "enough"!

PHOBOS low-p_T

low-x, low-Q^2

Au direction

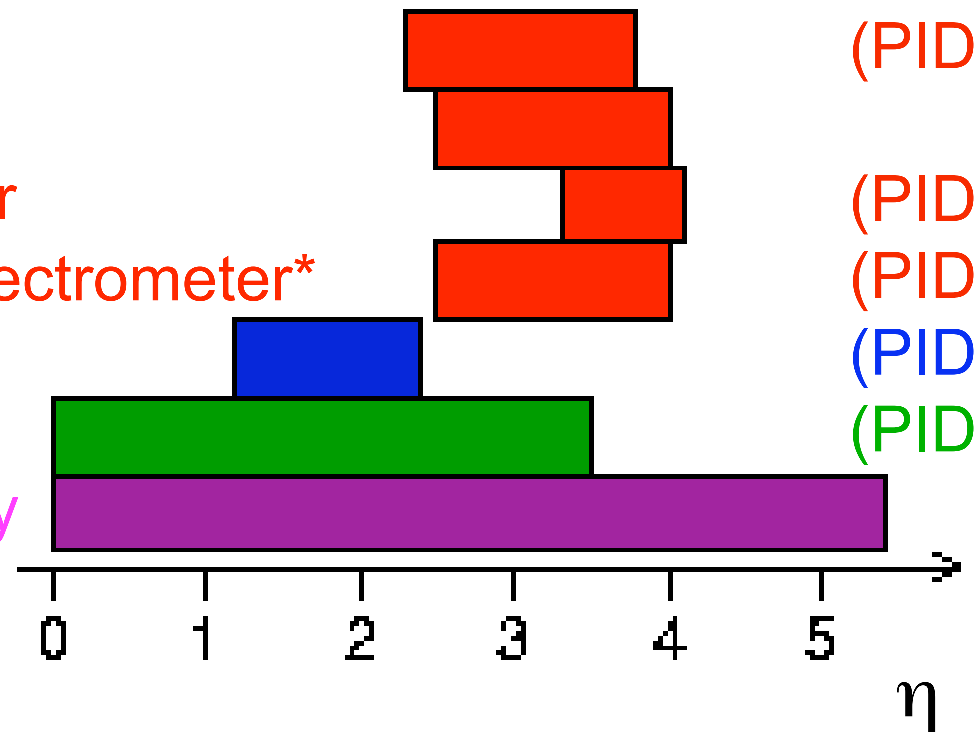
BRAHMS, STAR, PHENIX

low-x, "high"-Q^2

d direction

η coverages at RHIC

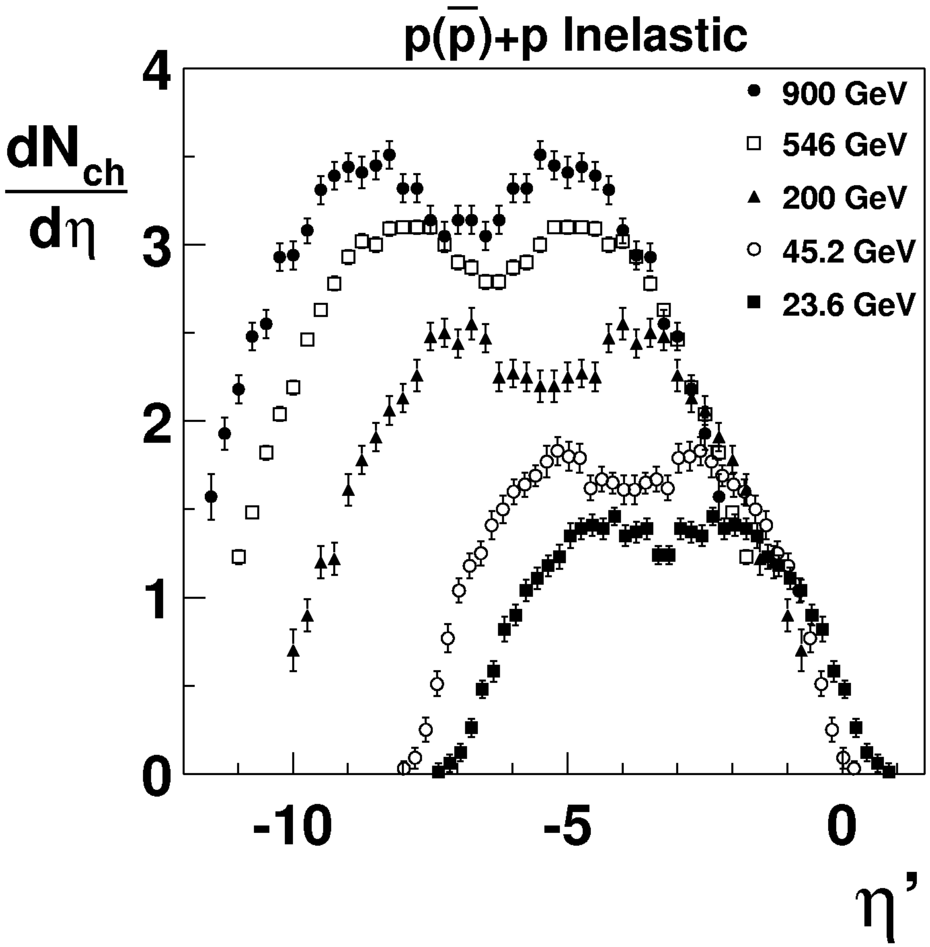
STAR photon detector (PID)
STAR Forward TPC
STAR Forward π^0 detector (PID)
STAR Forward meson spectrometer* (PID)
PHENIX μ stations (PID)
BRAHMS spectrometers (PID)
PHOBOS multiplicity array
(*planned)



Collision energy dependence of high-η particle production

(longitudinal scaling)

p+p collisions

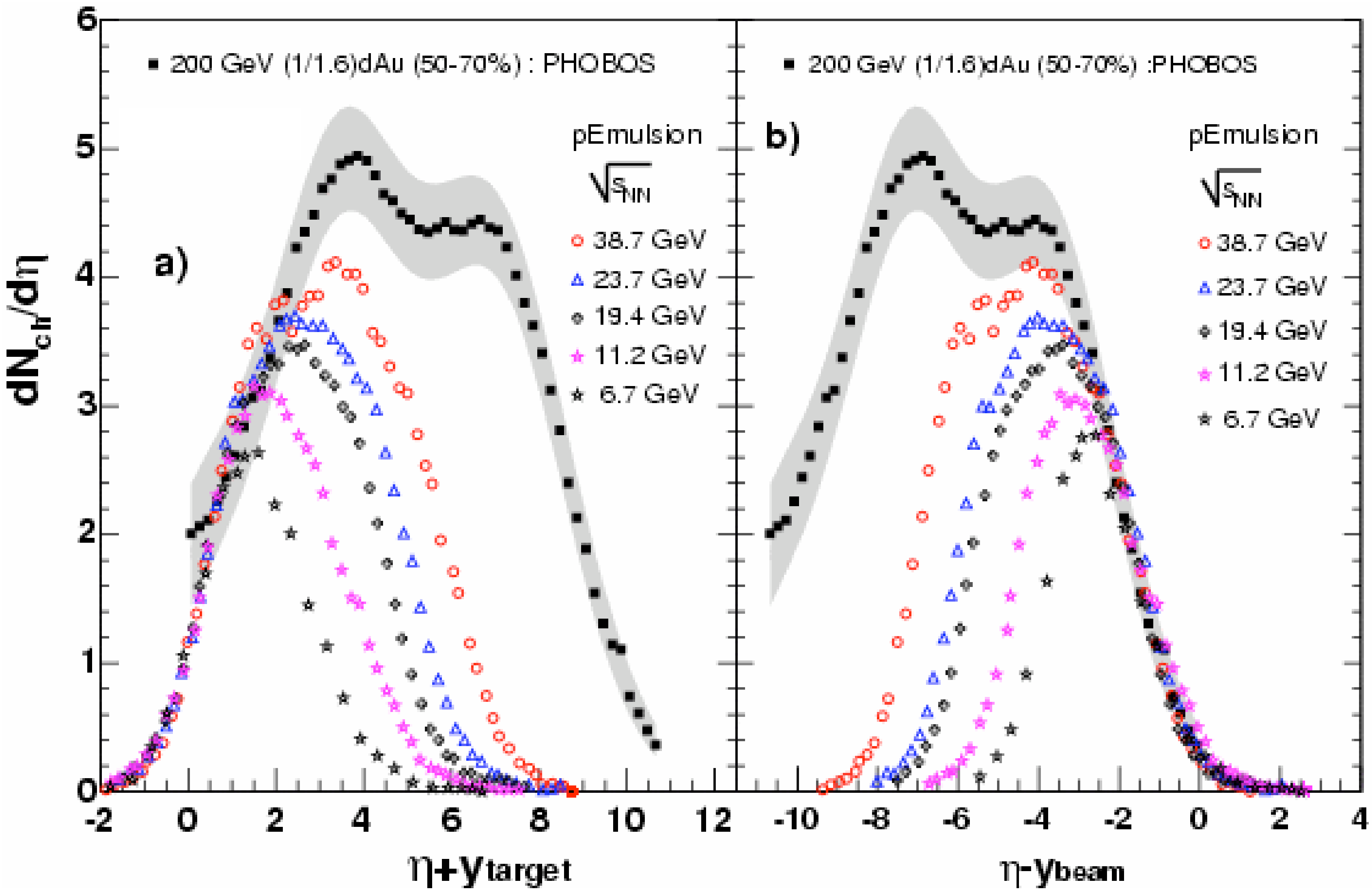


Data over a factor of ~50 in $\sqrt{s}$ show limiting fragmentation at high η

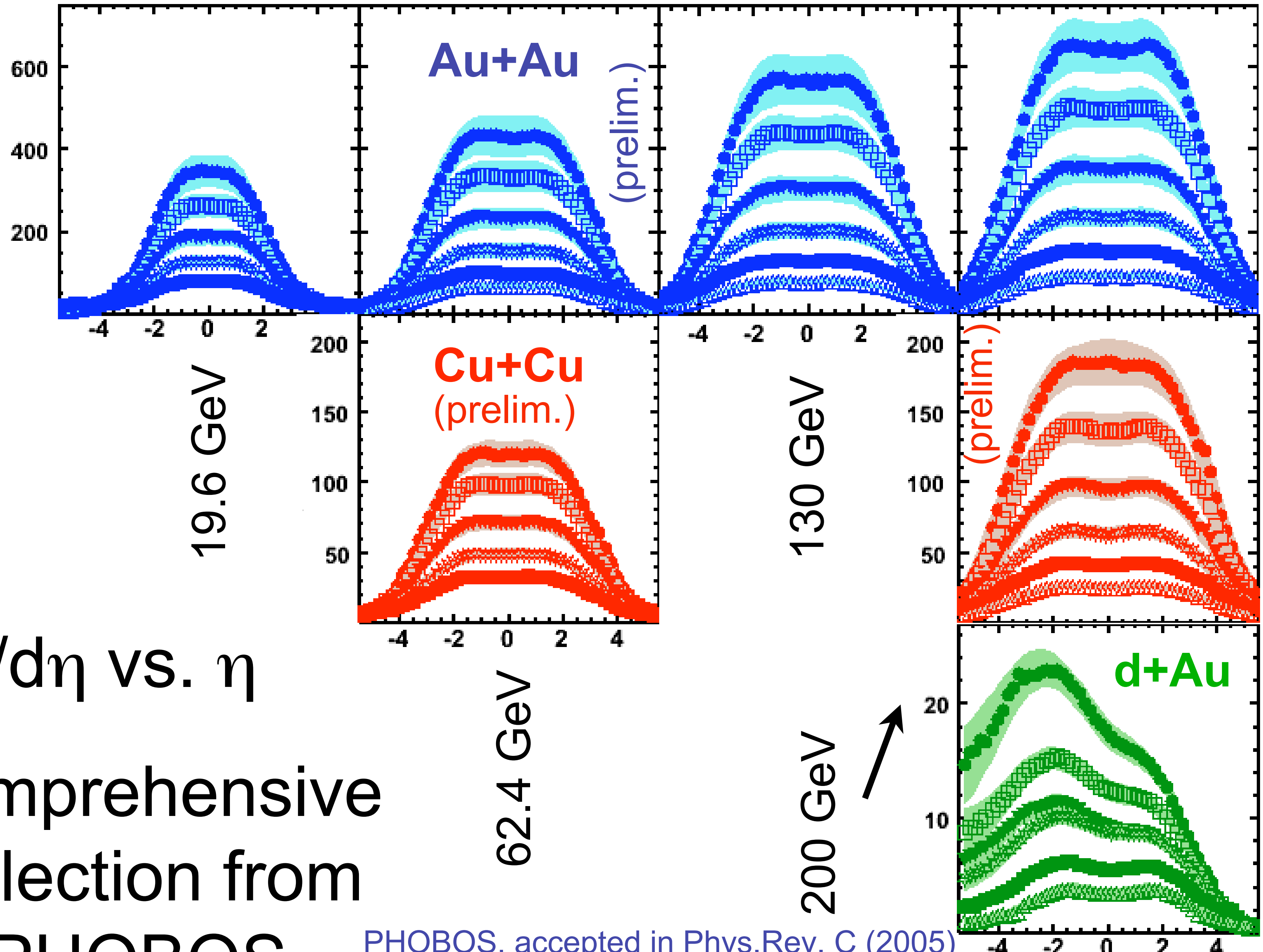
$\eta' = \eta - y_{beam}$

CDF (900) Phys.Rev D 41 (1990) 2330
UA5 (200,546) Z.Phys.C 43 1 (1989)
ISR (23.6,45.2) Nucl.Phys B 129 365 (1977)

p(d)+A collisions



PHOBOS, accepted in Phys.Rev. C (2005)

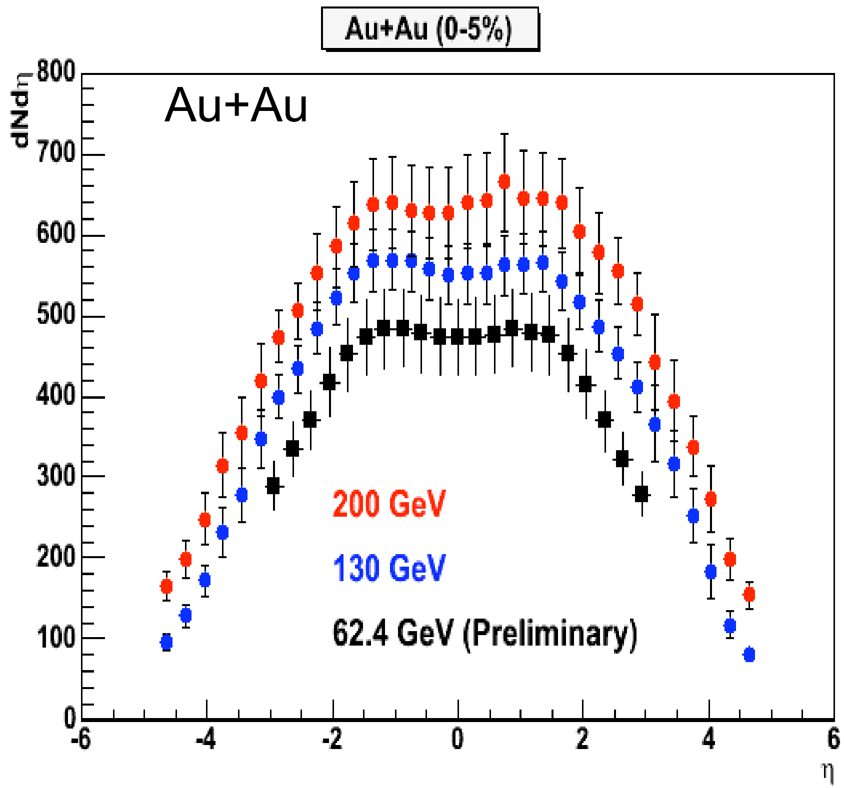


dN/dη vs. η

Comprehensive collection from PHOBOS

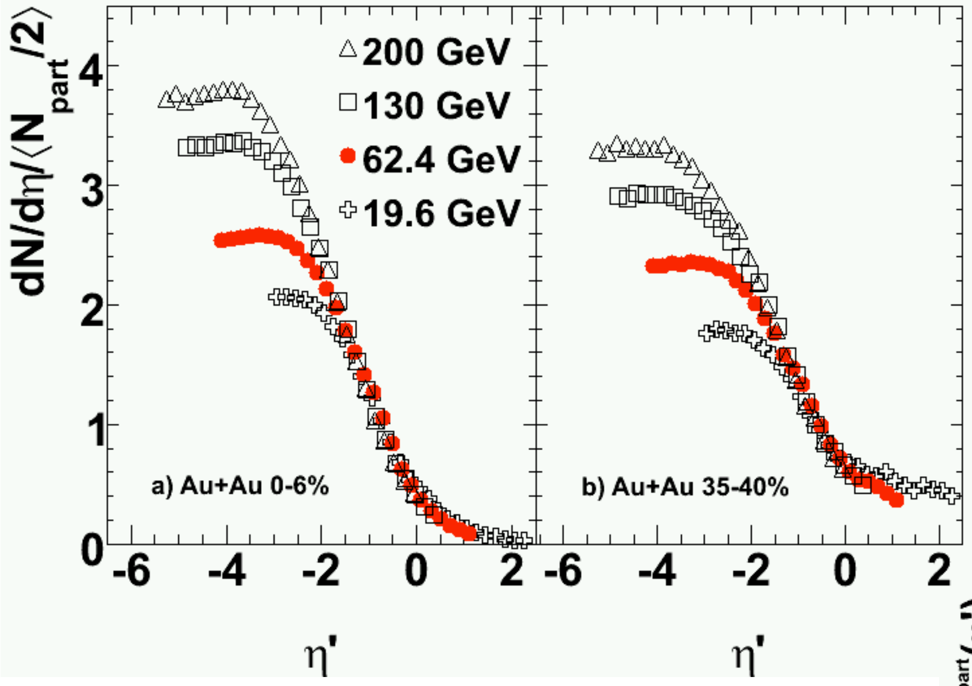
PHOBOS, accepted in Phys.Rev. C (2005)
Nucl. Phys. A 757 28 (2005)

New data on dN/dη from BRAHMS



Phys. Rev. Lett. 88, 202301 (2002)
Phys. Rev. Lett. 94, 032301 (2005)

Extended longitudinal scaling

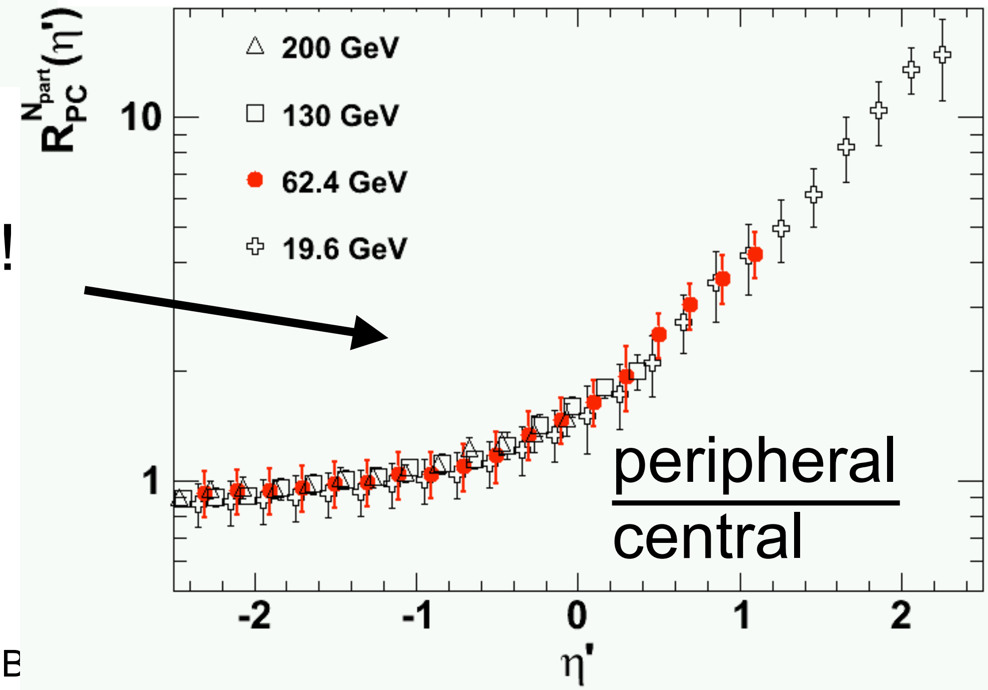


Energy independence
in a large η range...

…in a centrality
dependent way.

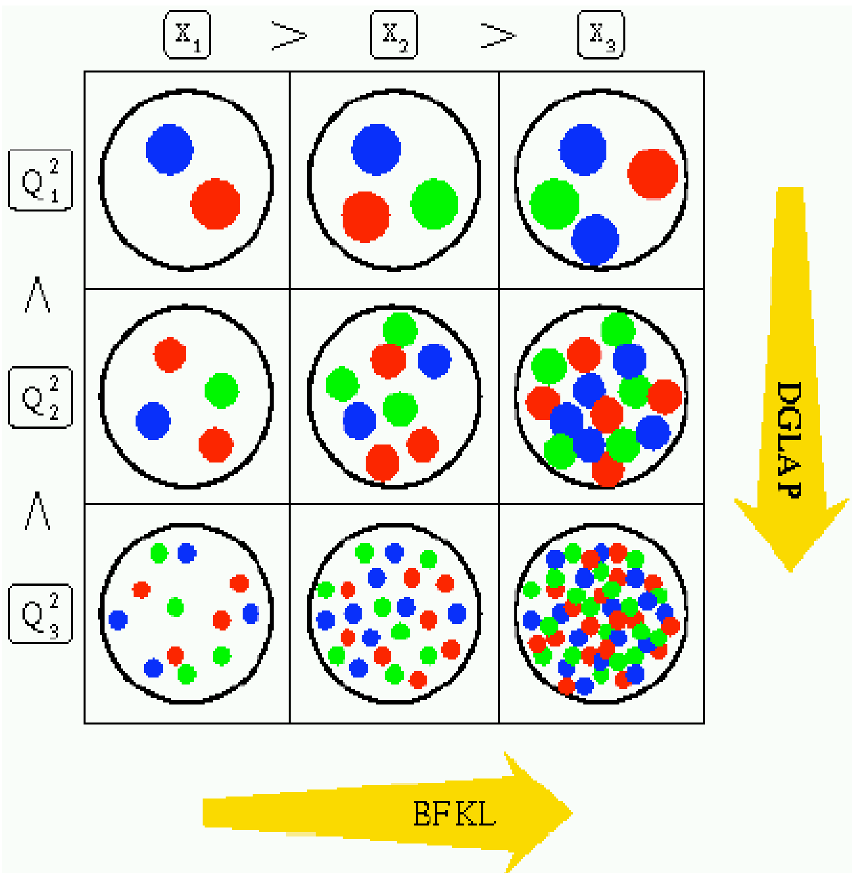
But the centrality and
energy dependence factorizes!

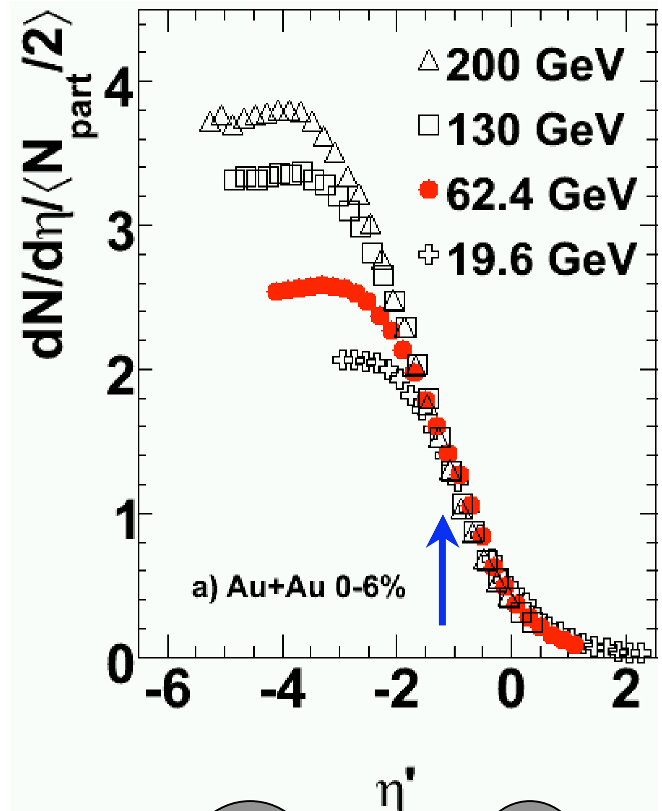
(note the precision)

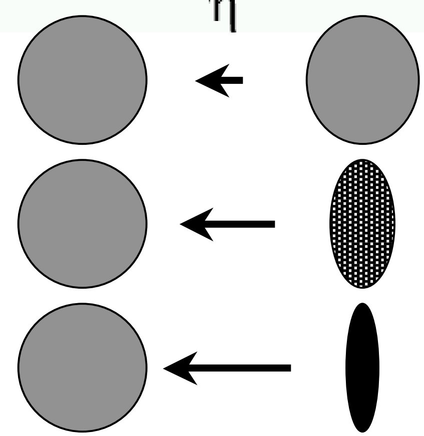


Nucl. Phys. A 757 28 (2005)

Scaling and saturation model/CGC

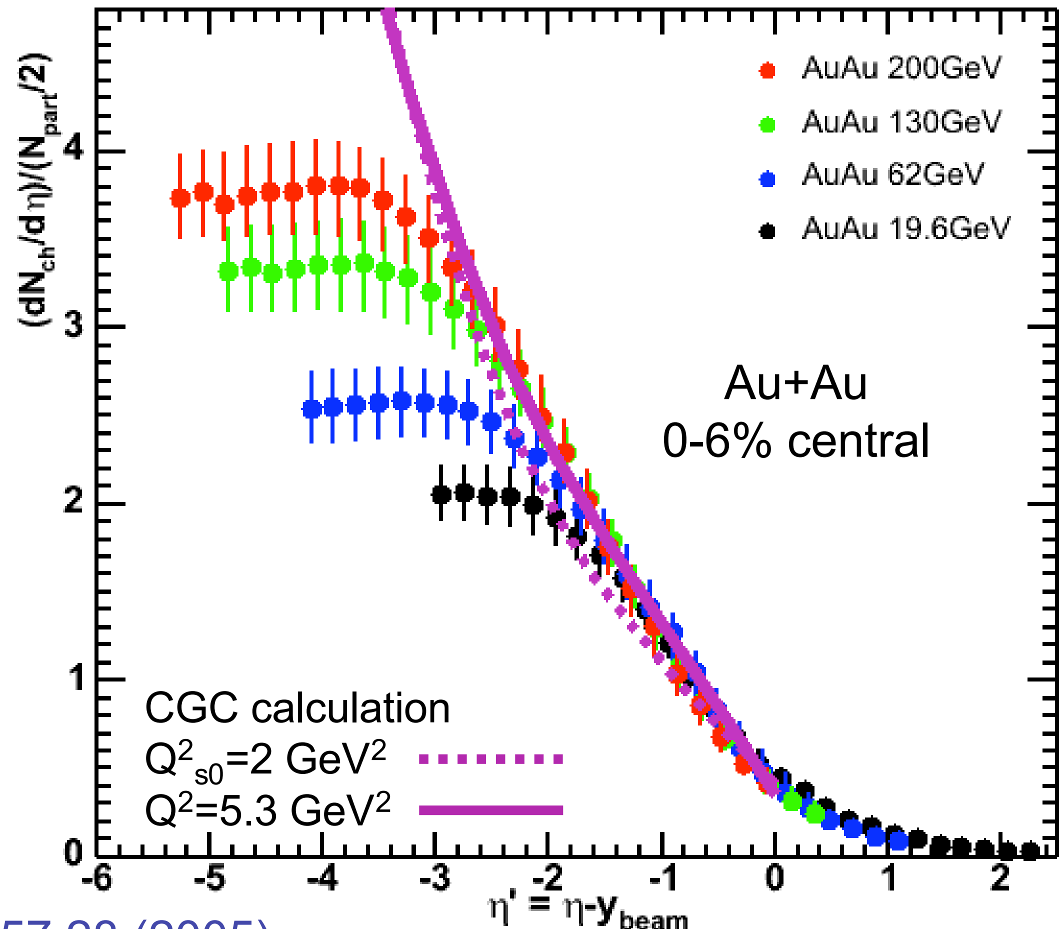






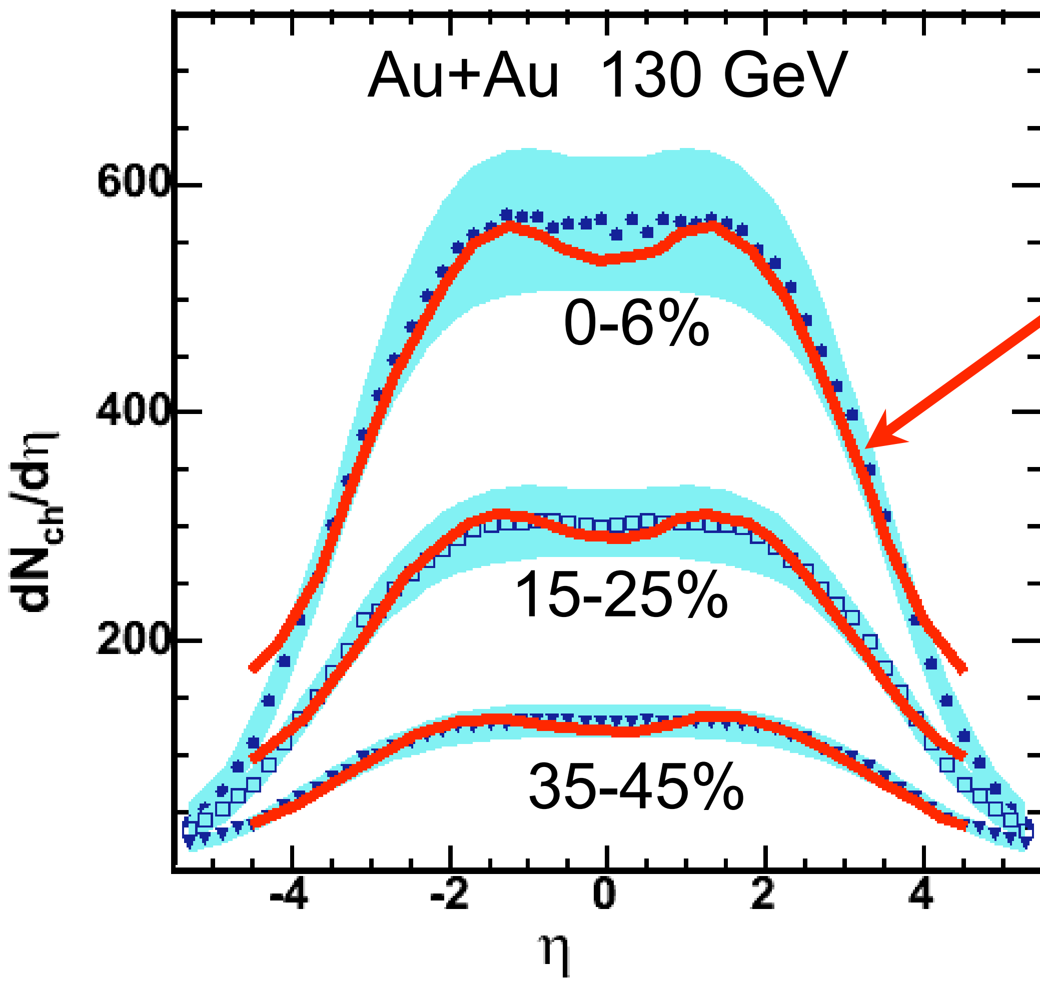
Nucl. Phys. A 757 28 (2005)

Longitudinal scaling described by Color Glass Condensate



Nucl. Phys. A 757 28 (2005)
Phys.Rev.C70 027902 (2004)

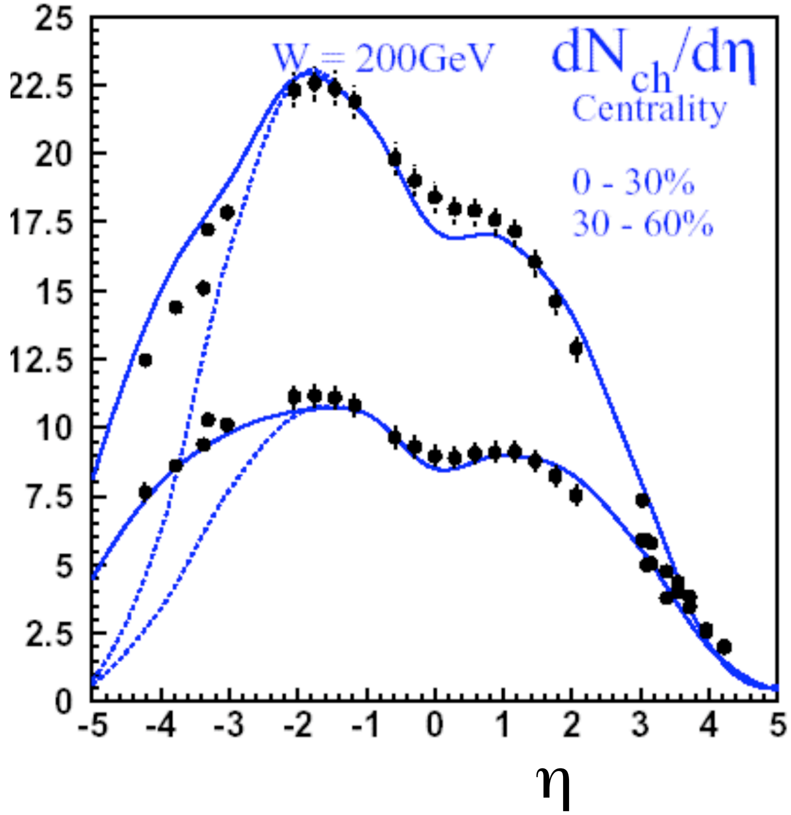
Centrality dependence: A+A

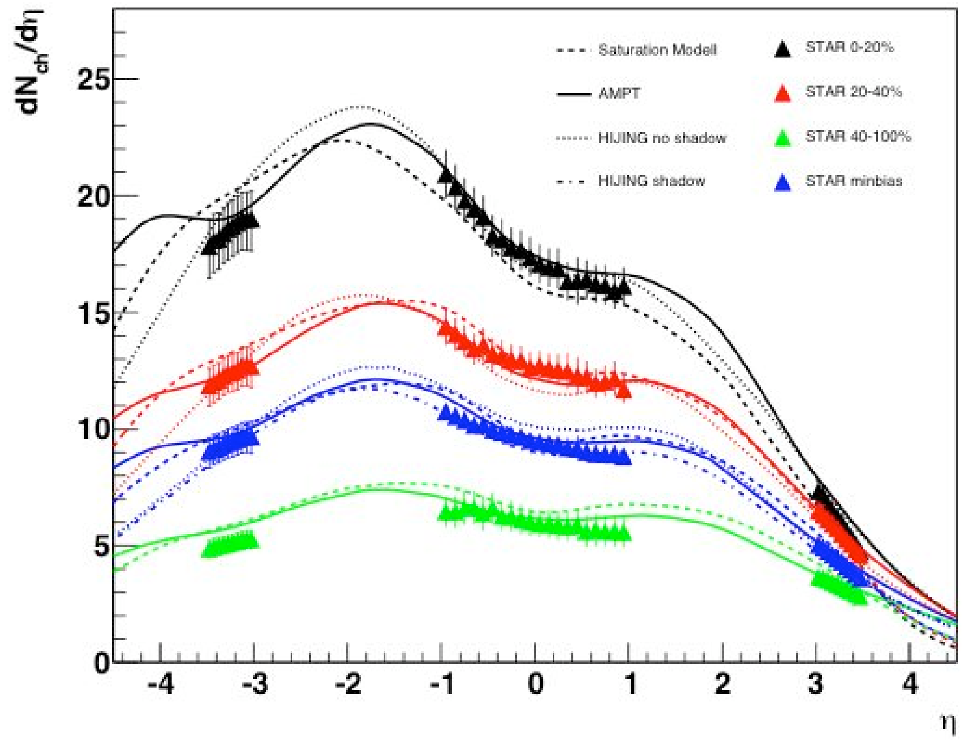


Saturation model provides a good description of the dN/dη data

Nucl. Phys. A 757 28 (2005)
J.Phys.G 30 S751(2004)

Centrality dependence: d+A





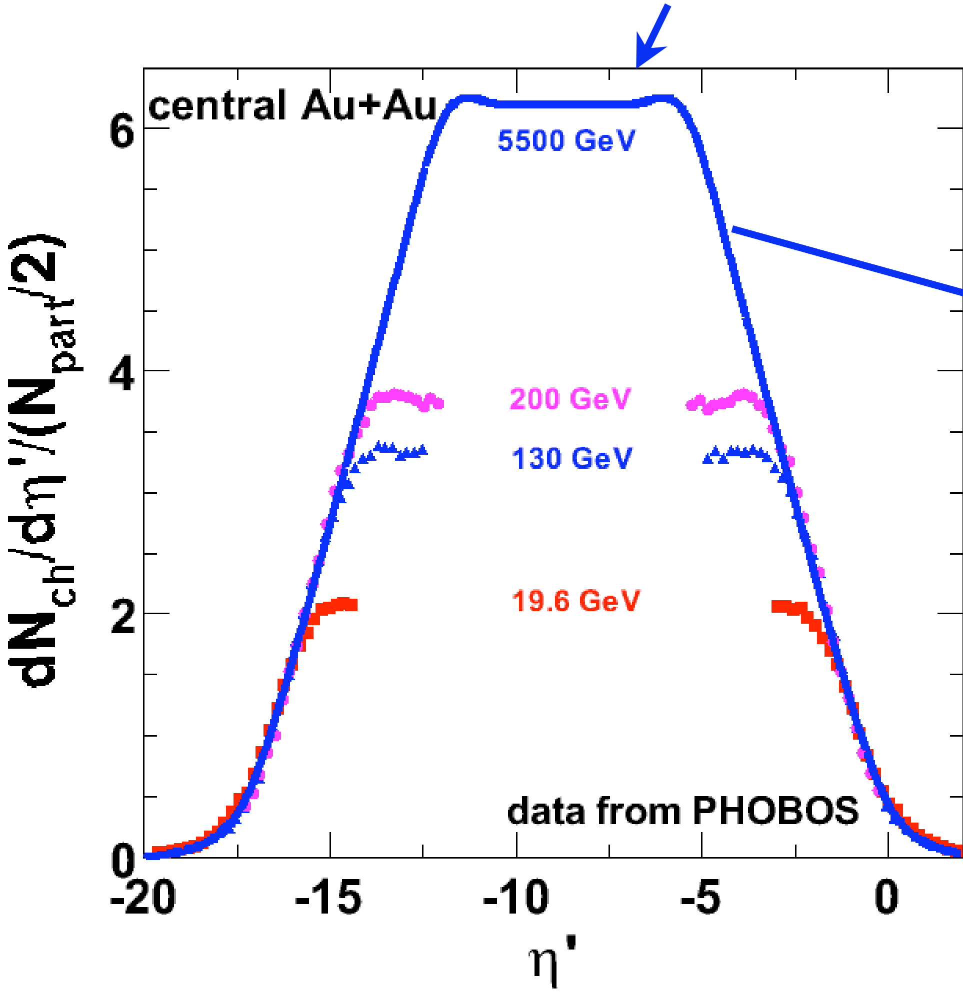
Phys. Rev. Lett. 94, 032301 (2005)
Nucl.Phys.A 730 448 (2004)
Erratum-ibid. A 743 329 (2004)

STAR Preliminary (d+Au),
Using the TPC and forward TPC

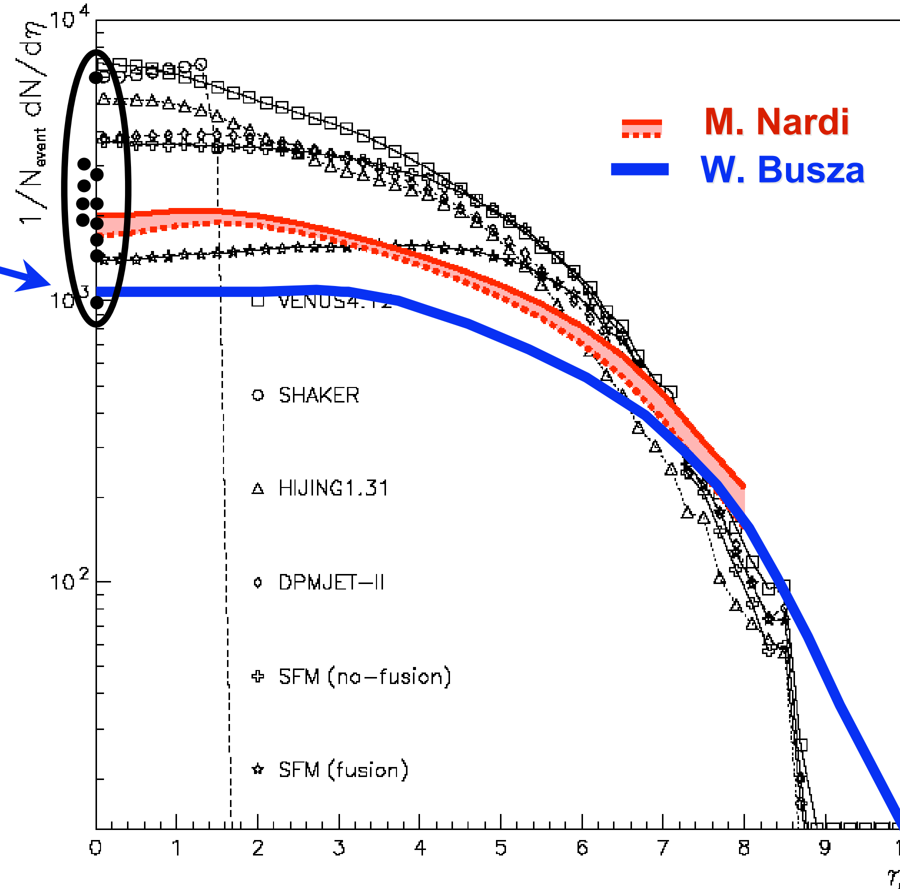
dN/deta extrapolations to LHC

Central Pb+Pb collisions at LHC energy

Assuming: dN/dη grows ∝log(s) and *linear* scaling at high η holds



Acta Phys.Polon.B35 2873 (2004)

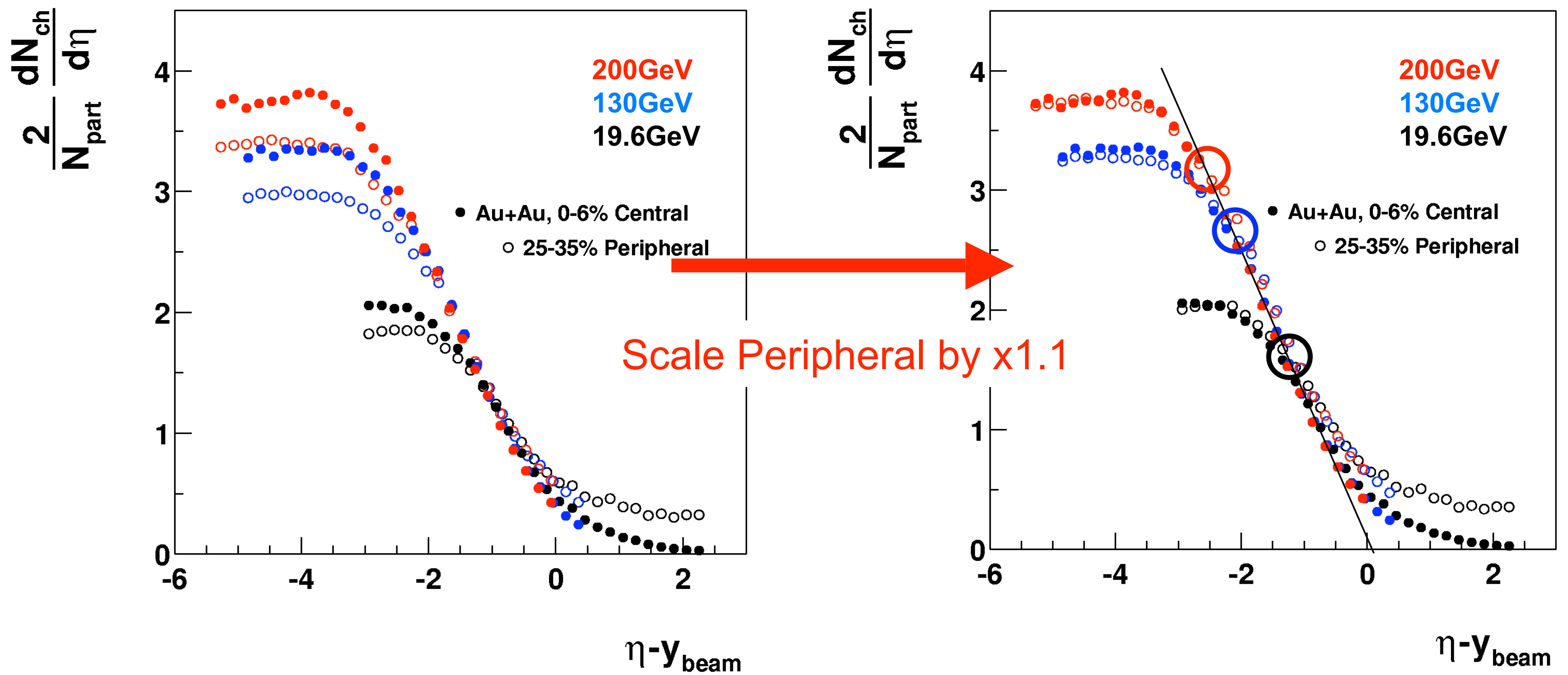


ALICE Tech. Proposal,
M. Nardi, various models and fits

…what else can we learn?

how saturation breaks down as we increase x_{target}

Departure point from limiting curve



departure point depends on energy

but not on centrality… is that consistent with the

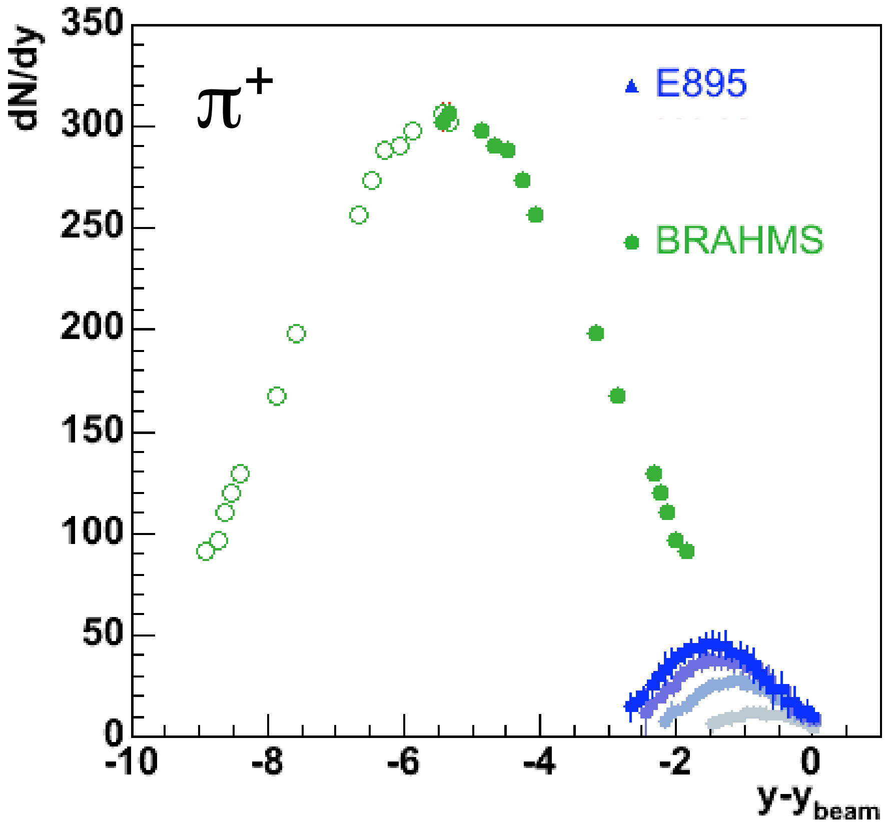
saturation picture?

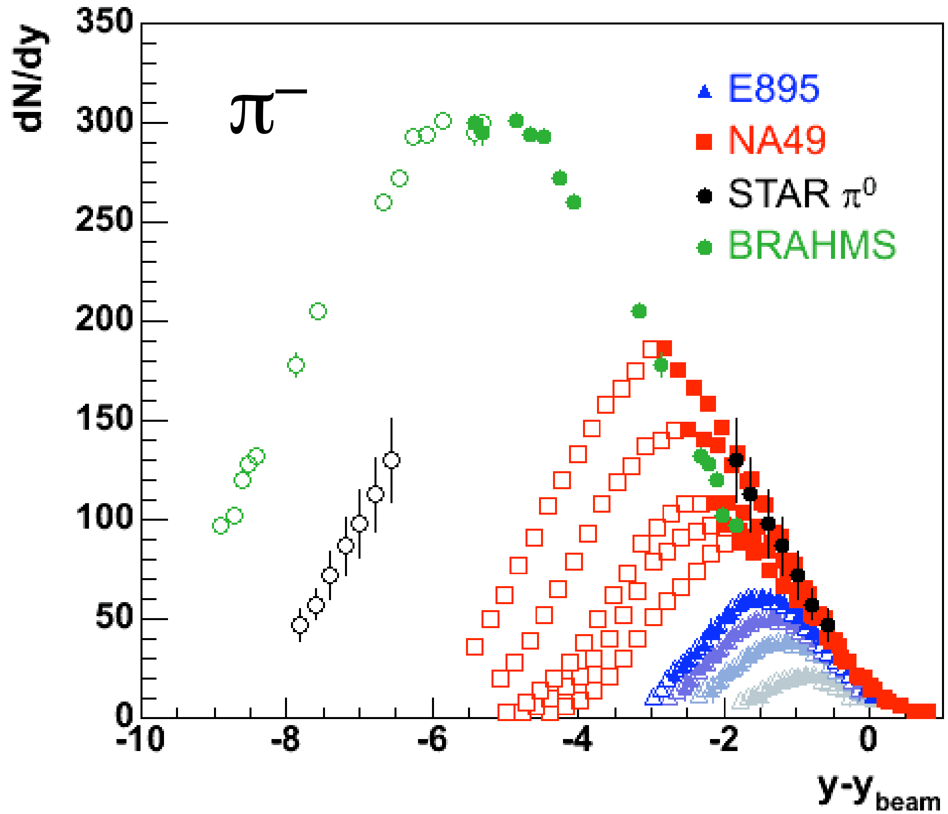
data from Nucl. Phys. A 757 28 (2005)

Identified particles

…what else can we learn? Species dependence:

Do pions scale at high η?





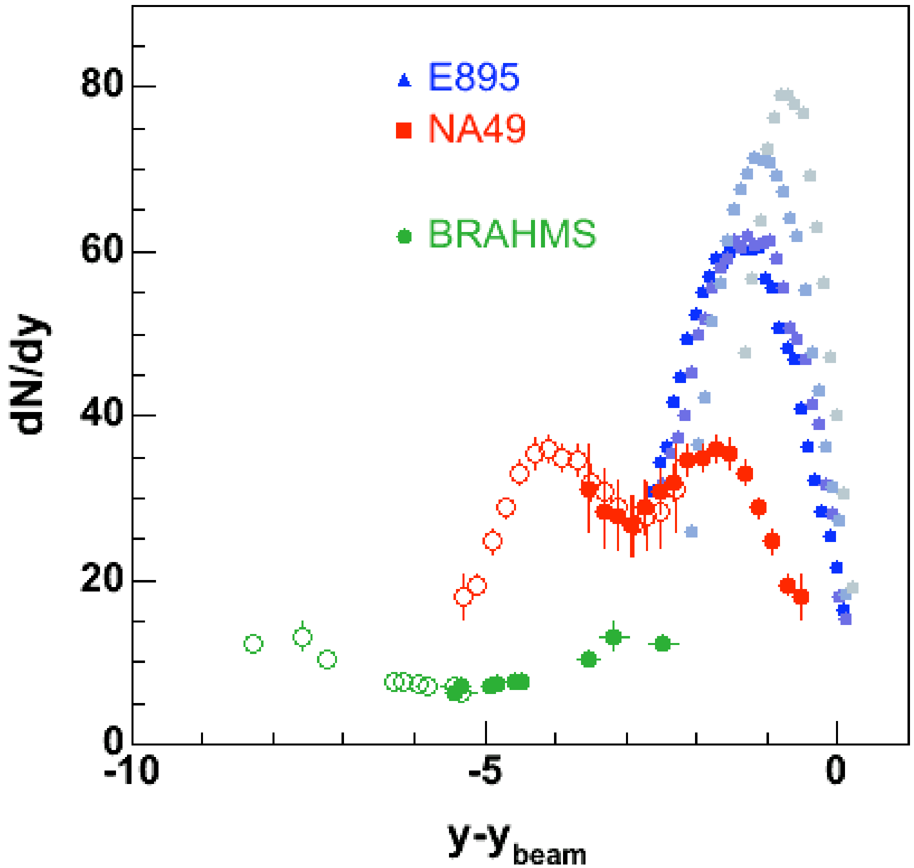
$\sqrt{s}$=2.63, 3.28, 3.84, 4.29,
6.27,7.62,8.76,12.32,17.27,200 GeV
Au+Au, Pb+Pb

NA49: PRC 66 054902
Brahms: PRL 94 162301 (2005)
E895: PRC 68 054905 (2003)

Do net protons scale with energy?

A+A collisions (?)

Useful quantity: $y' = y - y_{beam}$



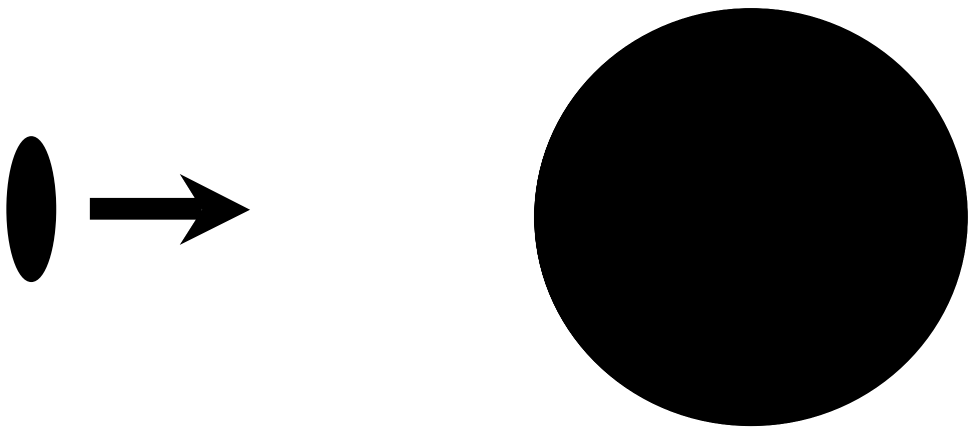
conserved quantity, completely different dynamics from mesons

↓

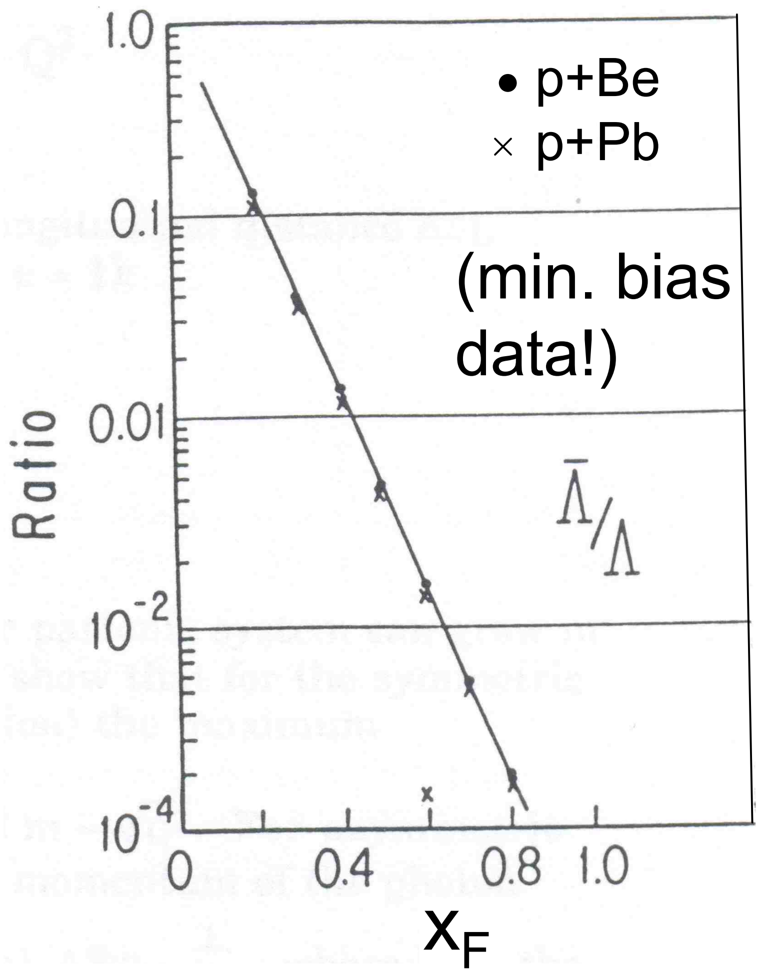
No scaling is observed at high η…

Brahms: PRL 93 102301 (2004)
NA49: PRL 82, 2471 (1999)
E895: PR C66 054905 (2003)

Baryon stopping and nuclear transparency

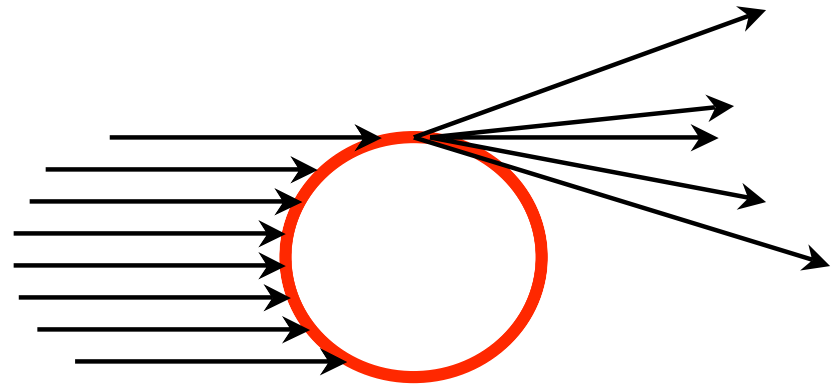


$\bar{\Lambda}/\Lambda$ puzzle in p+A data



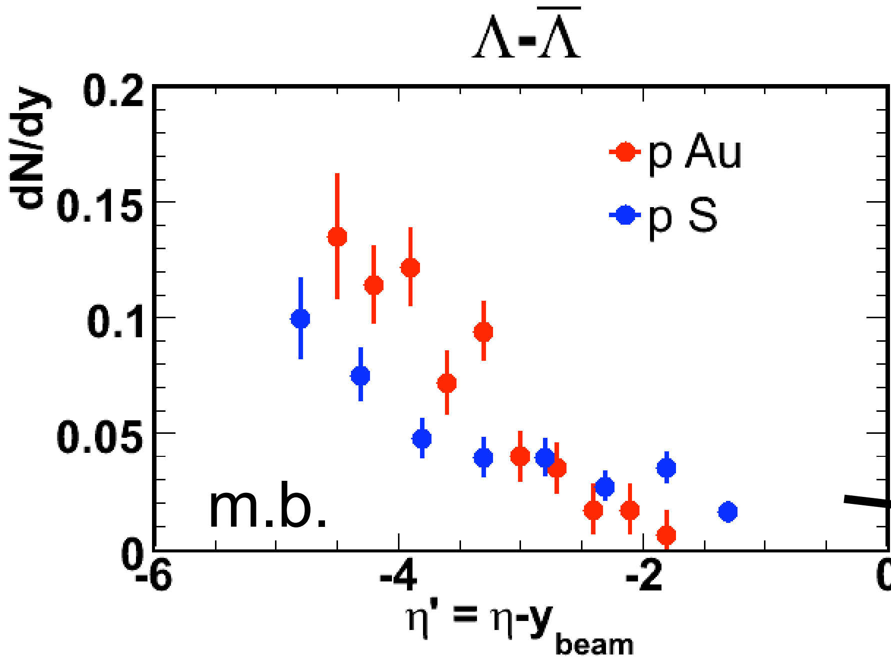
Phys. Rev. D18:3115 (1978)

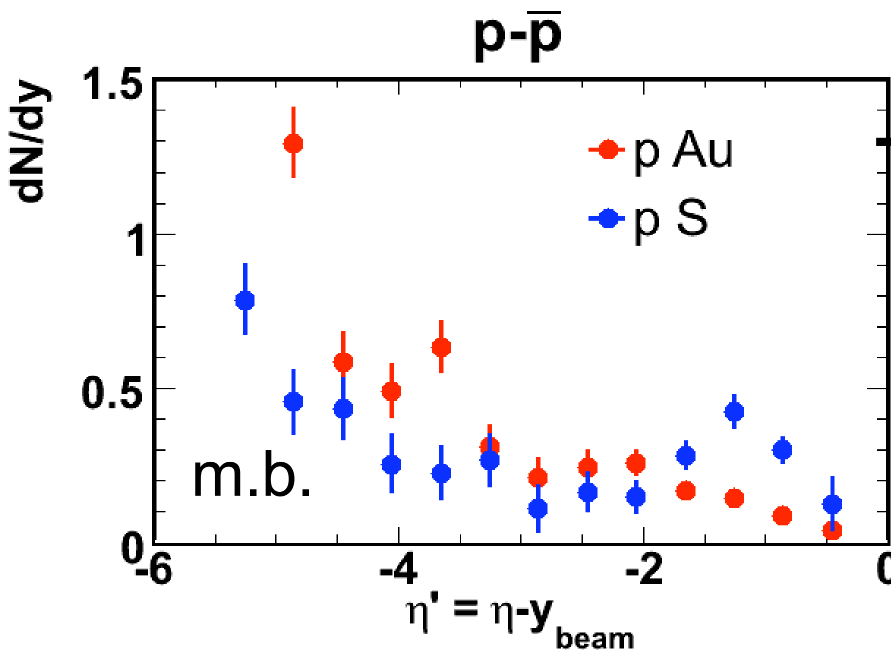
Ratio does not depend on A?!?



could be explained by extremely attenuating nuclear matter…

→ Centrality measurement is important !!!





Eur. Phys. J. C2:643 (1998)

p+A from NA35

(200 GeV, minimum bias collisions)

Not necessarily contradicting:

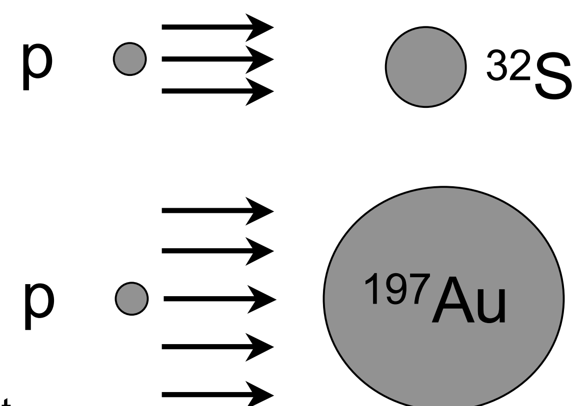
$\Lambda - \bar{\Lambda}$, not $\Lambda / \bar{\Lambda}$

Stopping of *net* Λ-s

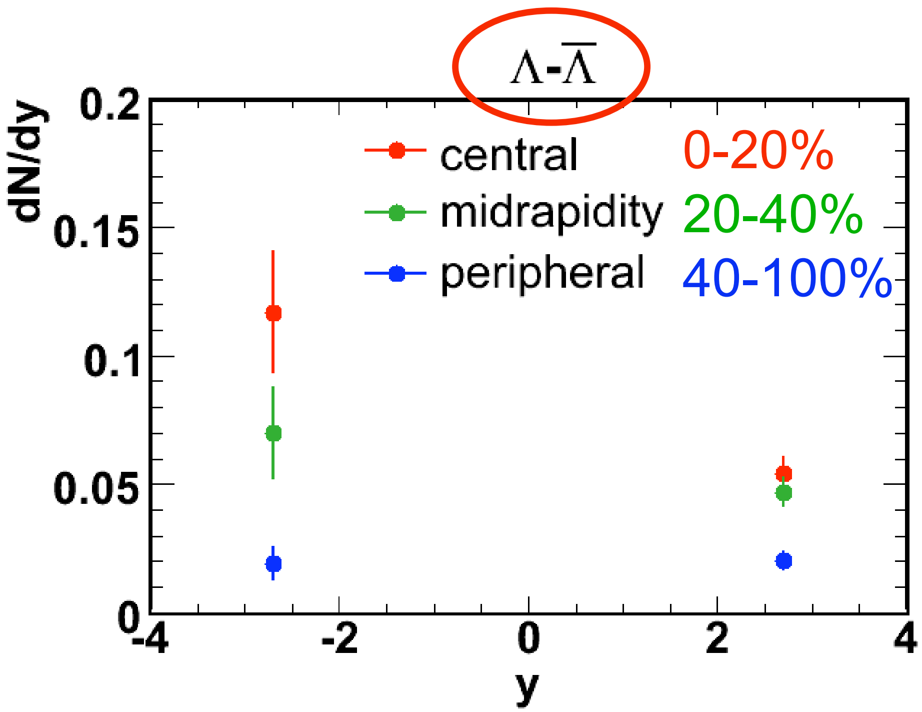
Similar new data from BRAHMS

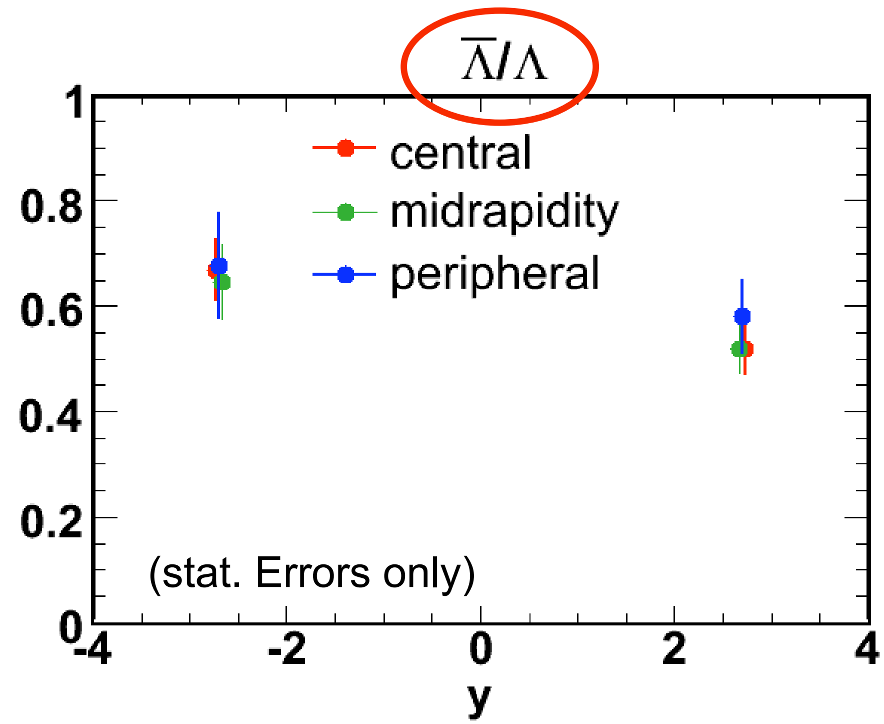
Stopping of *net* protons

Not perfectly black nucleus!



Λ, $\overline{\Lambda}$ in d+Au at 200 GeV

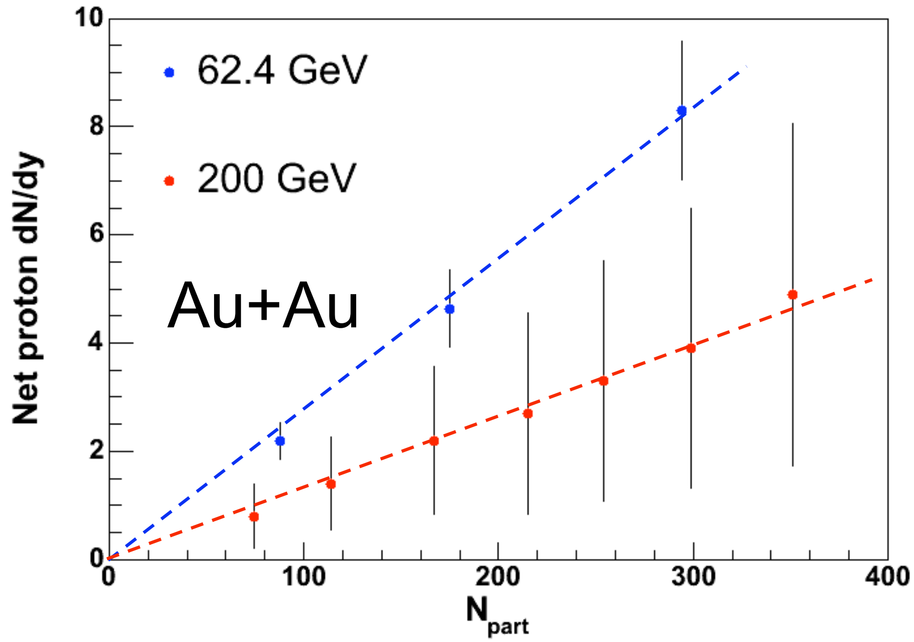




Net Λ–s are centrality dependent… …but their ratio is not!

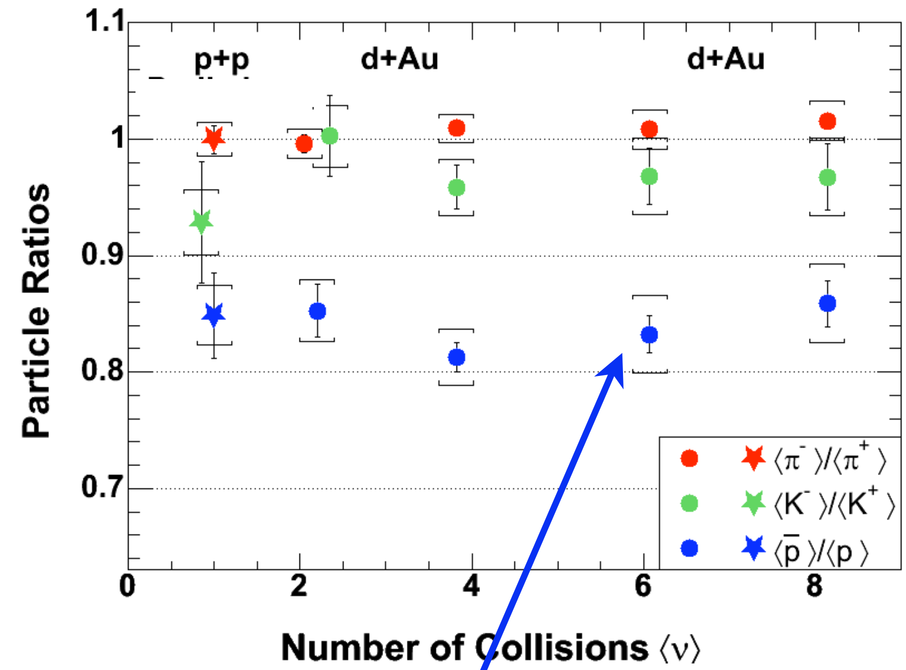
data: STAR preliminary
talk by Frank Simon, SQM'04

Net protons and $\bar{p}/p$ ratio



data: PHOBOS and PHENIX
(C. Henderson, PhD thesis)

Net protons increase
Linearly with N_{part} (Au+Au)



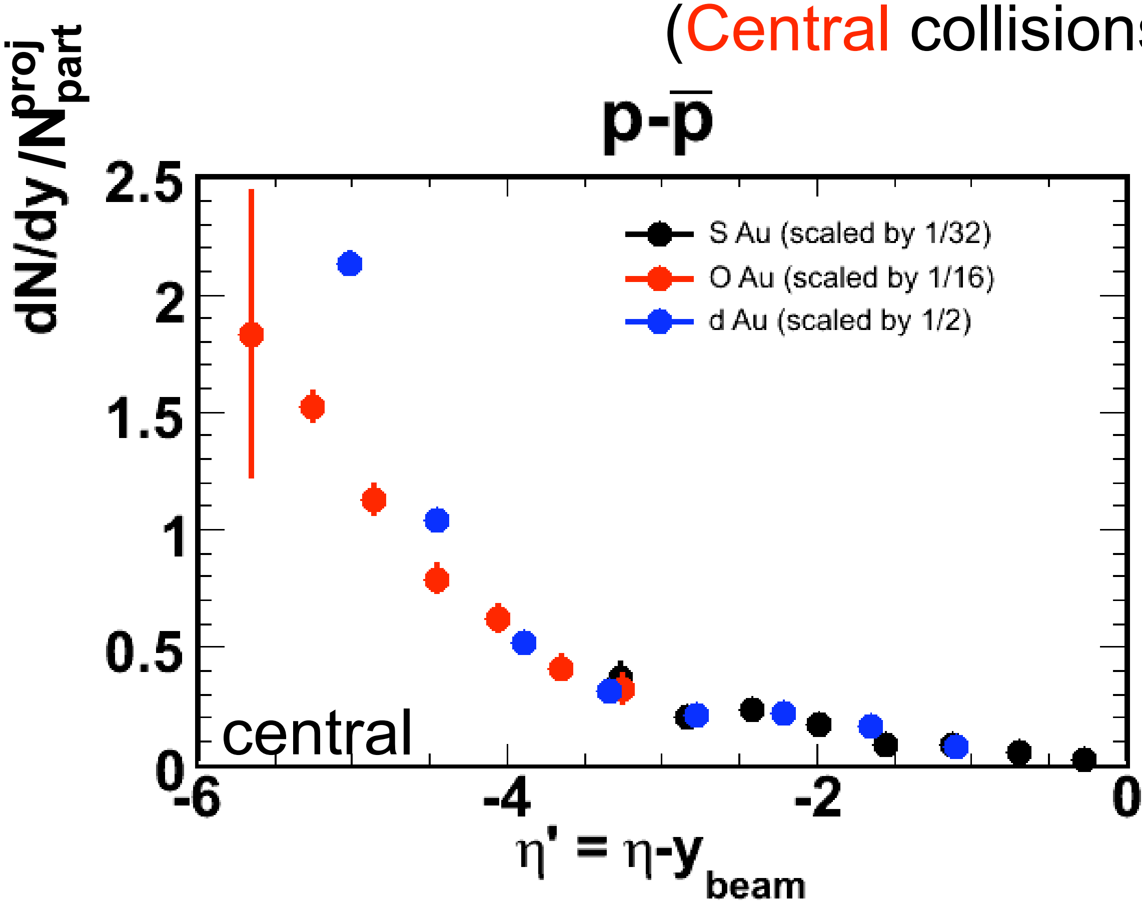
Phys. Rev. C70, 011901(R) (2004)

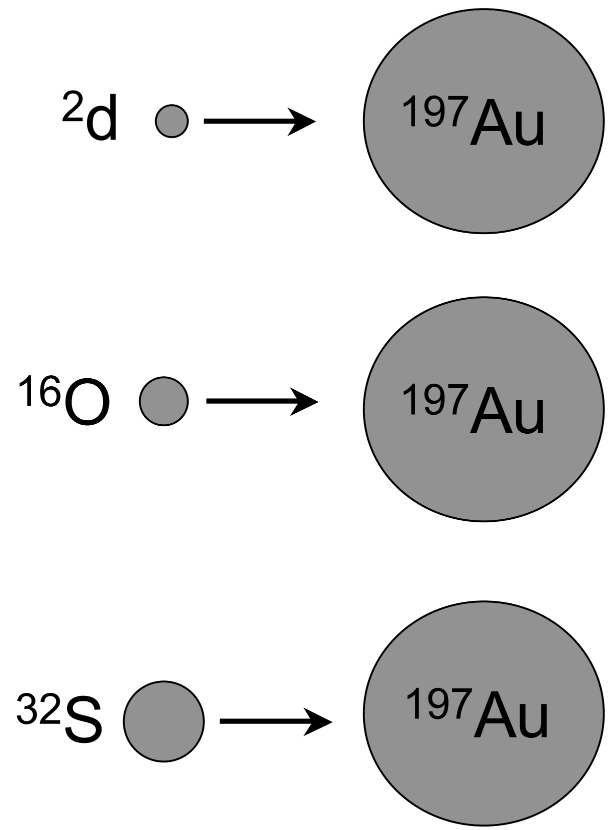
$\bar{p}/p$ is constant with centrality (d+Au)

If "pair production" is proportional to "stopping",
baryon ratio and difference measurements can be consistent!

Net protons at 200 GeV

(Central collisions)



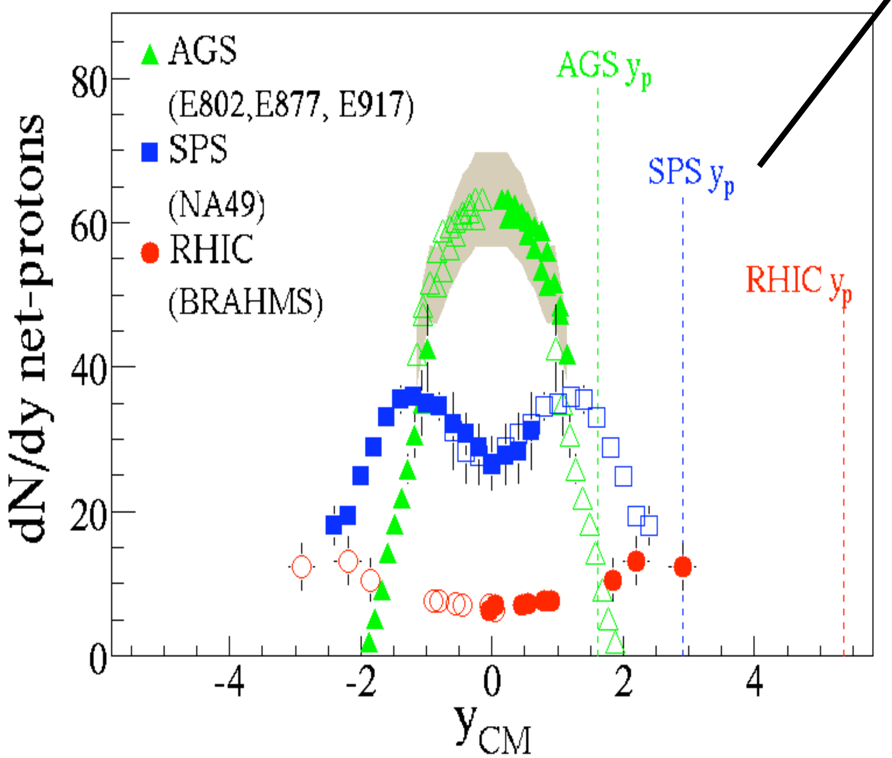


Eur. Phys. J. C2:643 (1998)

N_{part} scaling!

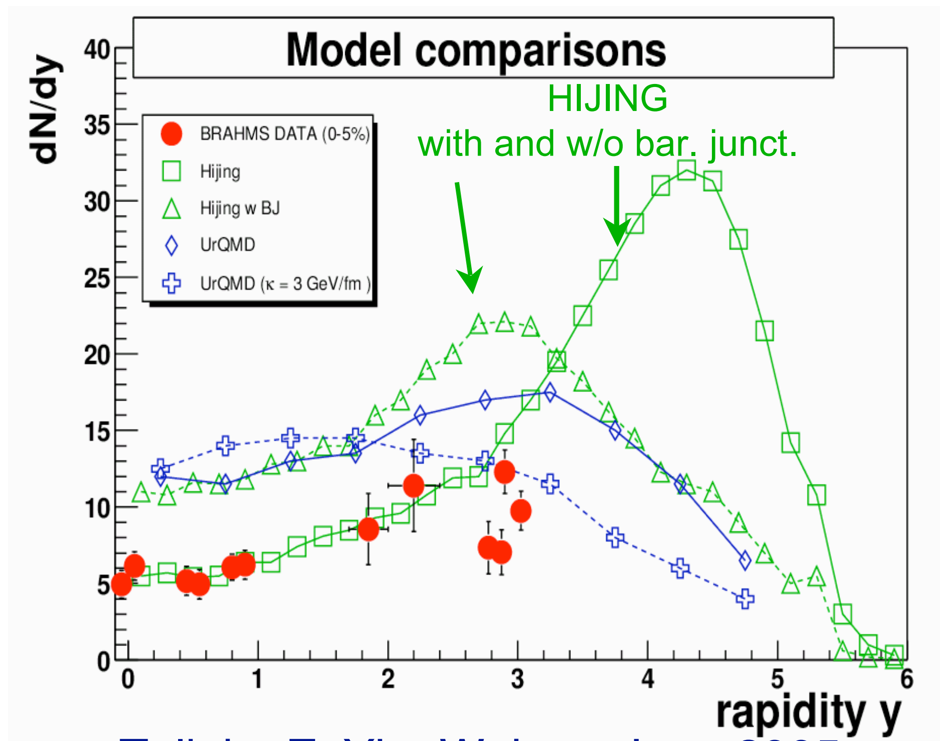
Target size matters, but projectile size is irrelevant.

Net protons in A+A collisions



PRL 93, 102301(2004)

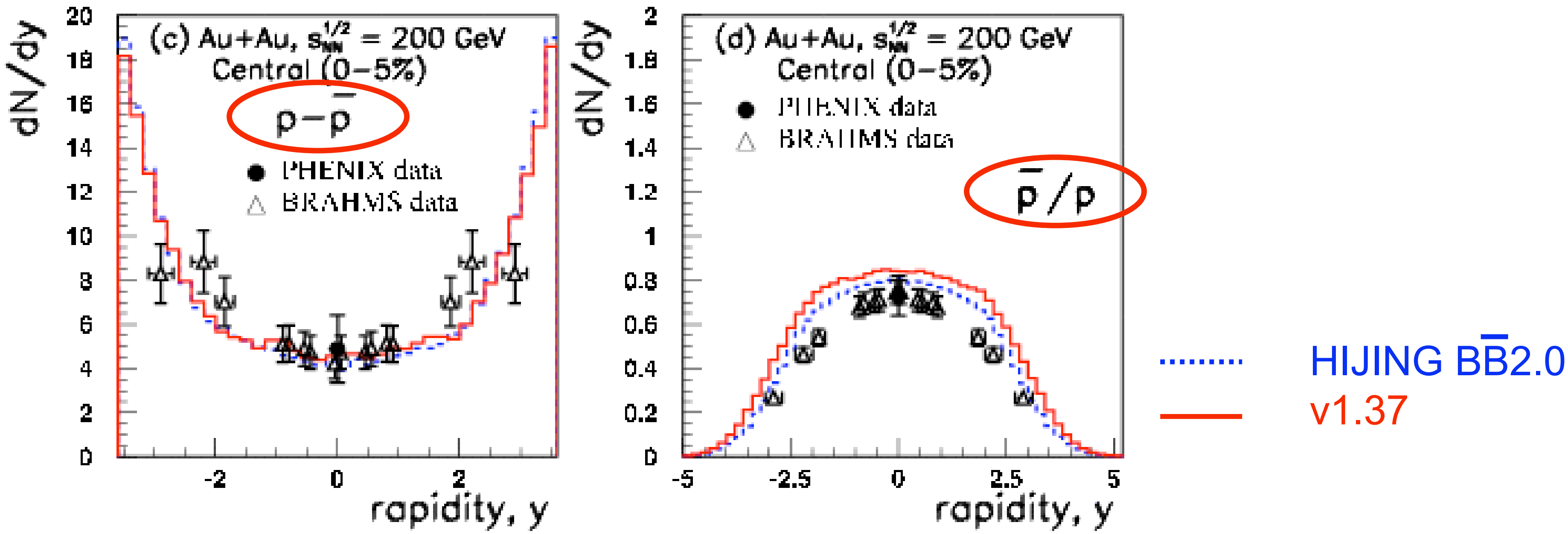
Does this really mean increasing transparency with energy?… Can models describe stopping?



Talk by Z. Yin, Wuhan, June 2005

Nature of baryons

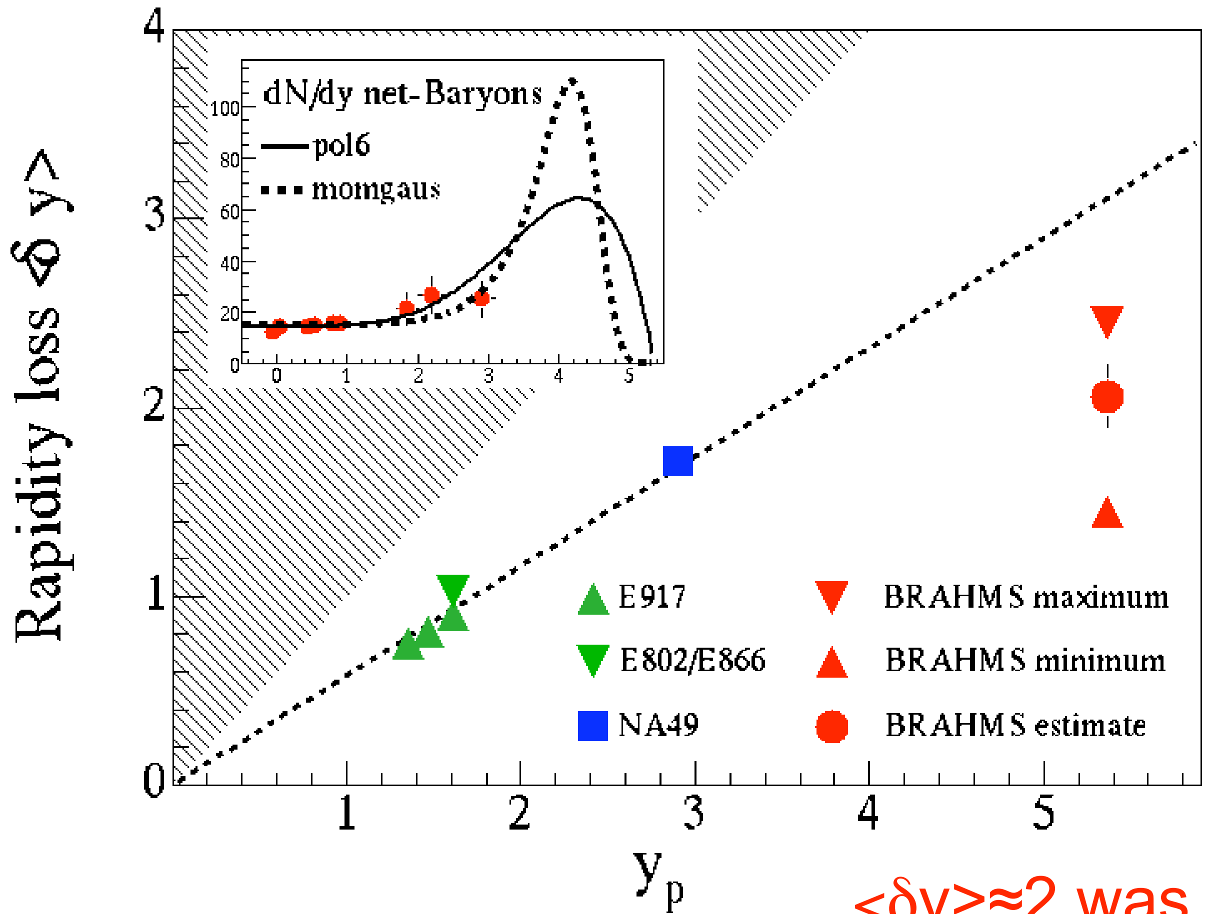
Important to look at ratios as well as difference of $\bar{p}$ and p



New HIJING w/ baryon junctions agrees with BRAHMS data

Vasile Topor-Pop
private commun.

Quantifying baryon stopping



PRL 93, 1020301, (2004)

$$\delta y = y_b - < y >$$

$$< y > = \int_0^{y_b} y \frac{dN}{dy} dy \Big/ \int_0^{y_b} \frac{dN}{dy} dy$$

rapidity loss at RHIC energies does not scale as at low energy…

$<\delta y> \approx 2$ was found in p+A as well…

Ann.Rev.Nucl.Part.Sci.38:119 (1988)

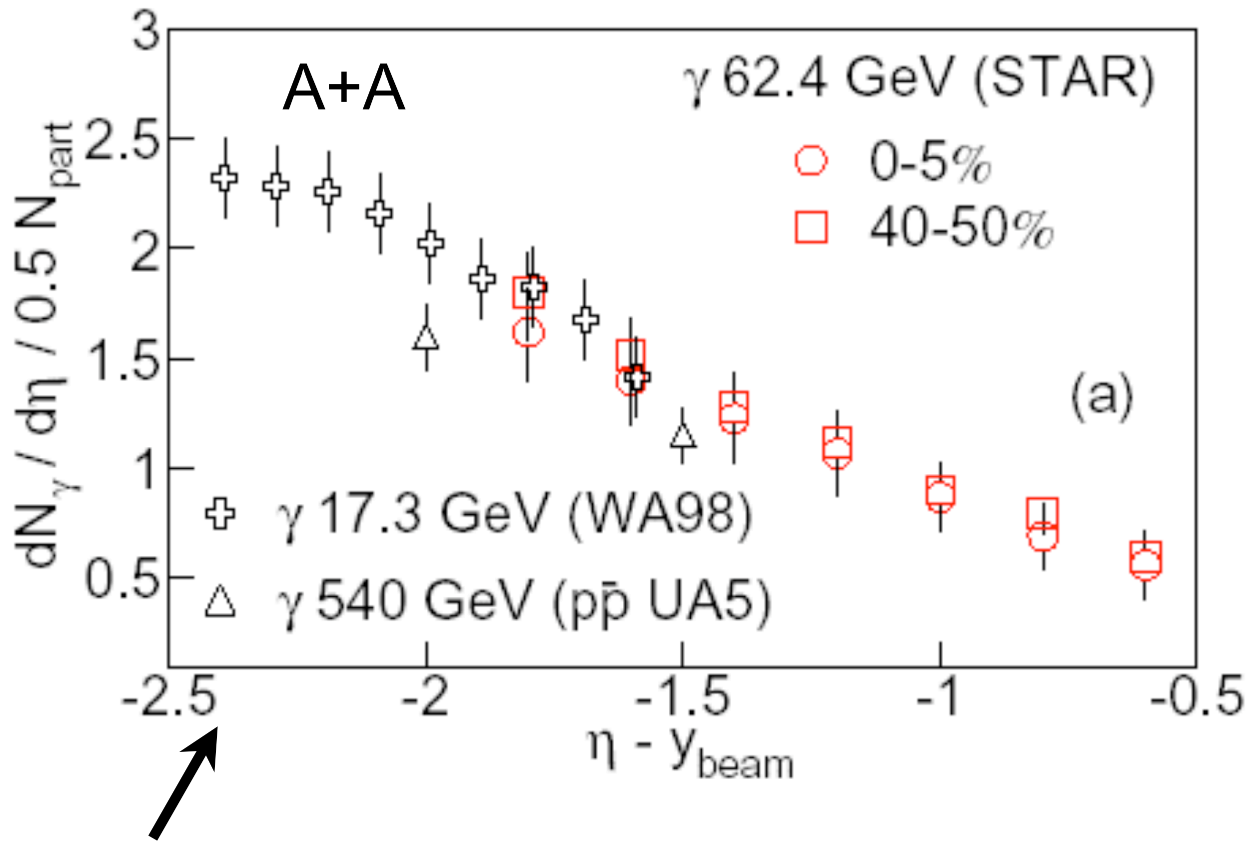
NA49, BRAHMS: "baryon stopping is larger in central p+A than in central A+A"

We found that baryons do not exhibit longitudinal scaling with changing collision energy, they are rather stopping in a complicated way which is energy and target dependent.

We found that inclusive charged particles and pions scale at high η to a remarkable precision.

Some more new measurements of scaling…⇒

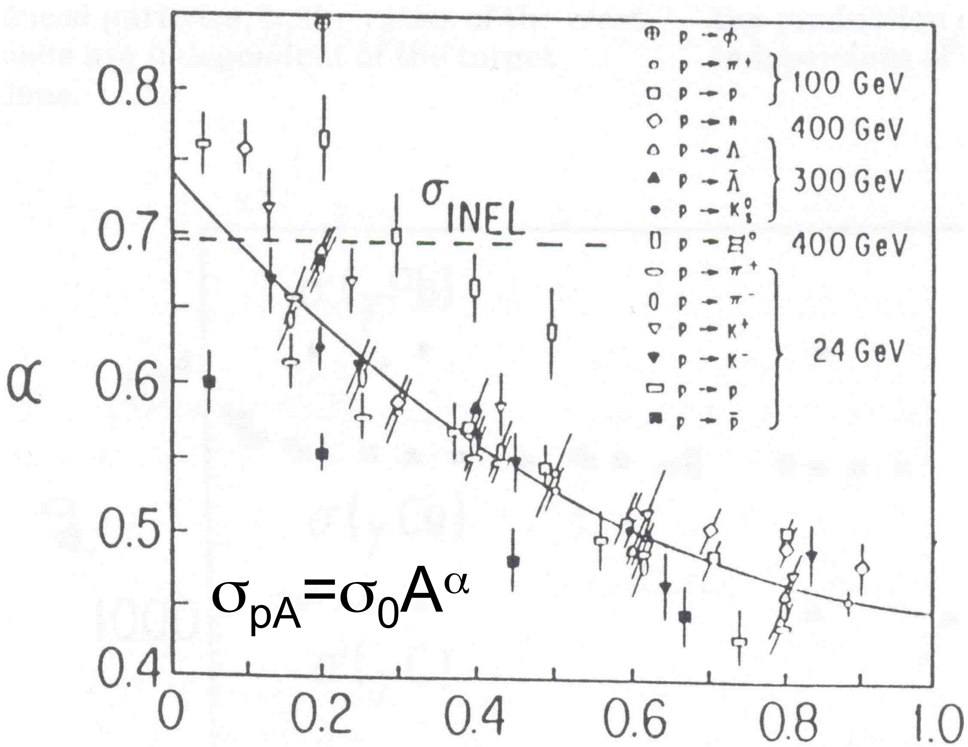
STAR: scaling photons ($\approx\pi^0$-s)



Photons scale with N_{part} and with energy (and even with centrality!?)

nucl-ex/0502008

p+A collisions



$\sigma_{pA}=\sigma_0 A^{\alpha}$

x_F

Various final states:
$\phi,\pi^+,\pi^-,p,\bar{p}$,
$n,\Lambda,\bar{\Lambda},K^0{}_s,\Xi$,
K^+,K^-

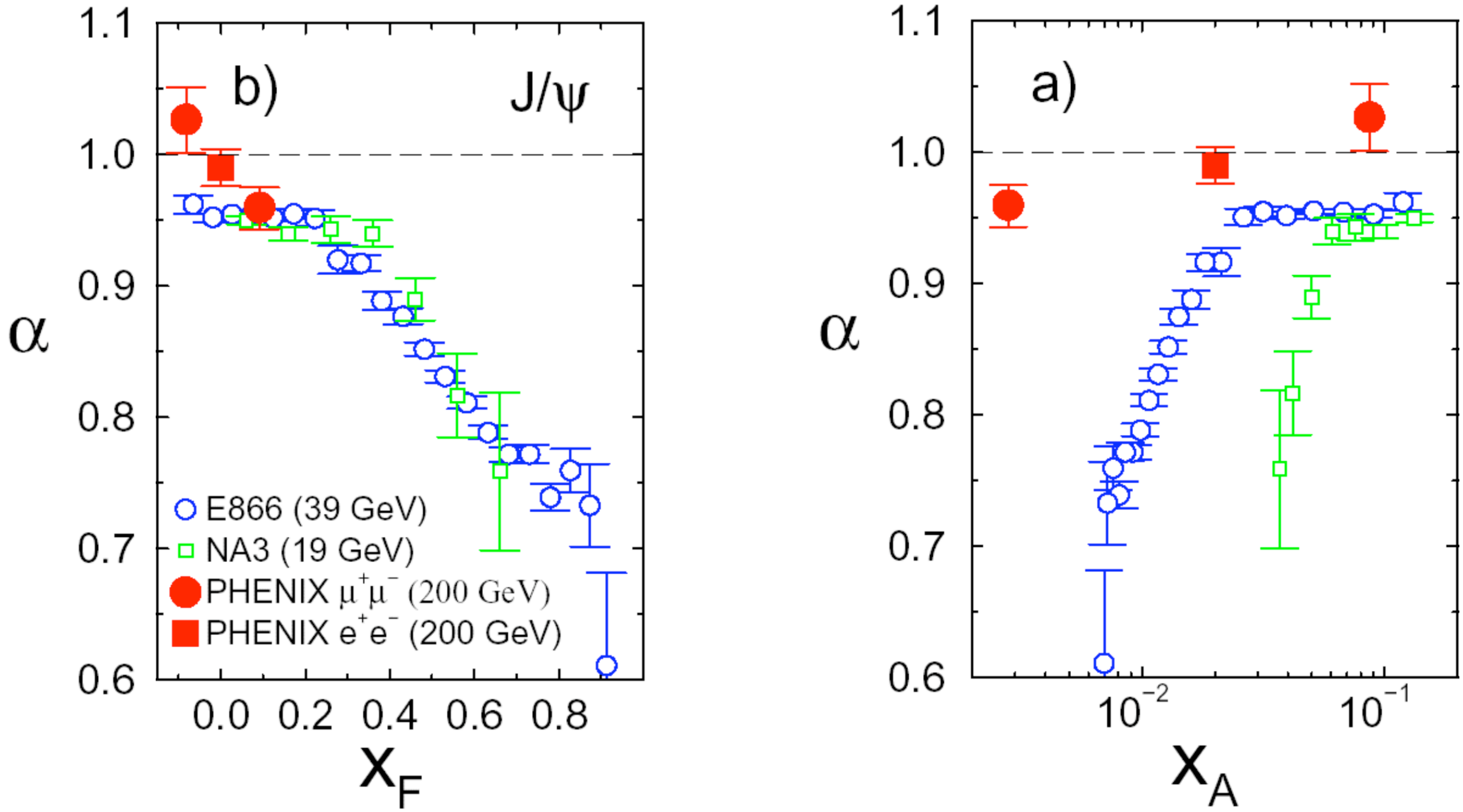
Various beam energies:
24, 100, 300, 400 GeV

Scaling still holds, for various energies and measured particles

Nucl. Phys. A544:49 (1992)

…do we have results on other mesons?

…J/Ψ x_F scaling in d+Au



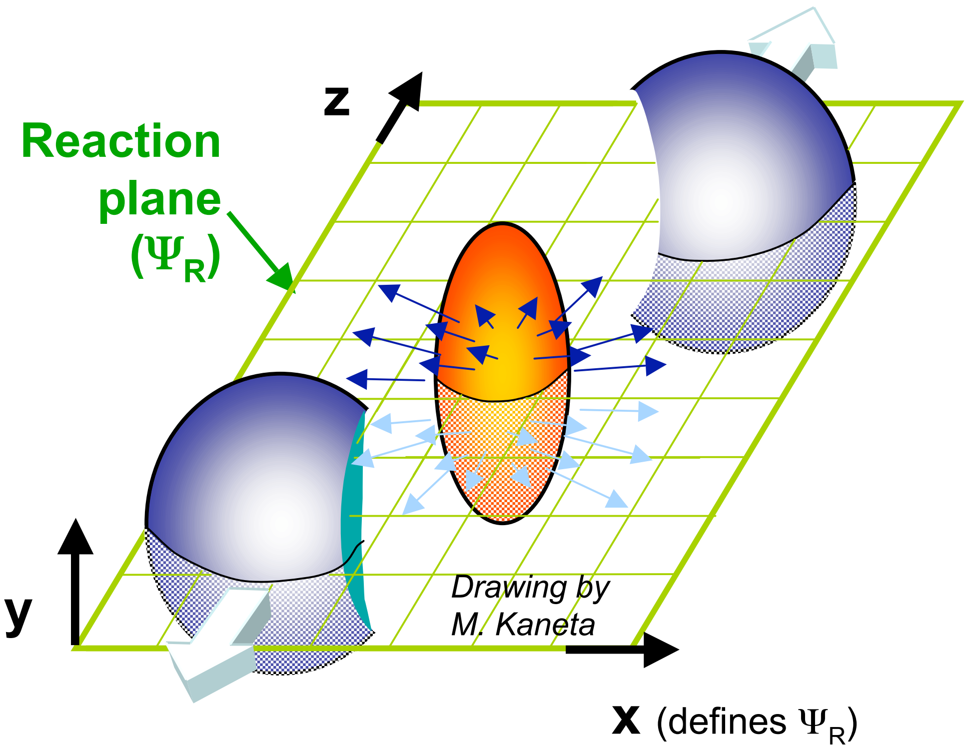
Scaling!

PHENIX, Submitted to PRL

However… the x probed in the Au does not seem to be the right scaling variable.

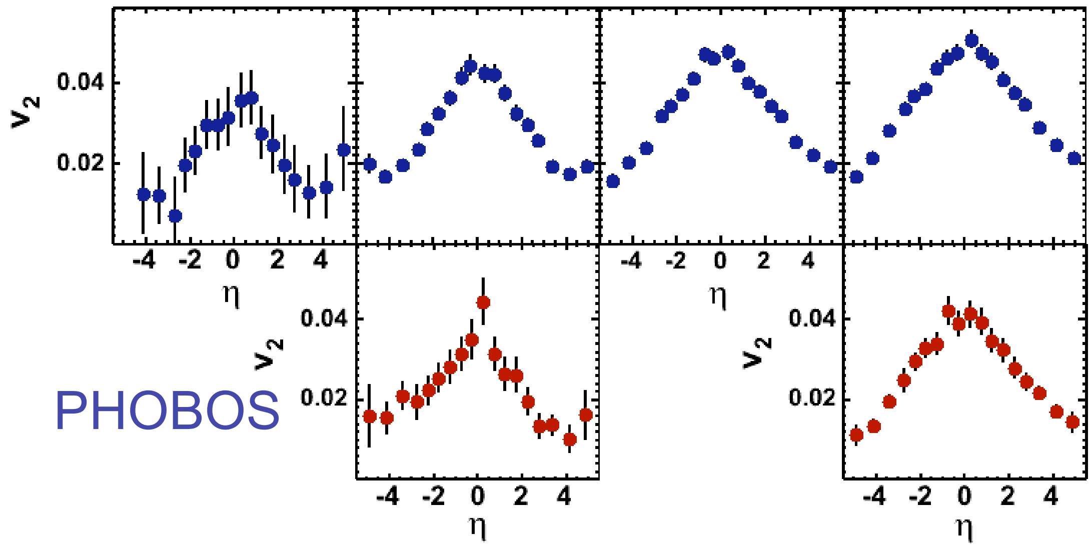
…Saturation and CGC is successful describing
bulk particle multiplicities (initial state effects+fragmentation), but…
other bulk features are out of the scope of an initial state model:

Anisotropy of bulk particle production



v_1 and v_2 are the first two Fourier-coefficients of the azimuthal distribution of particles

v_2 in A+A collisions at high η



Au+Au

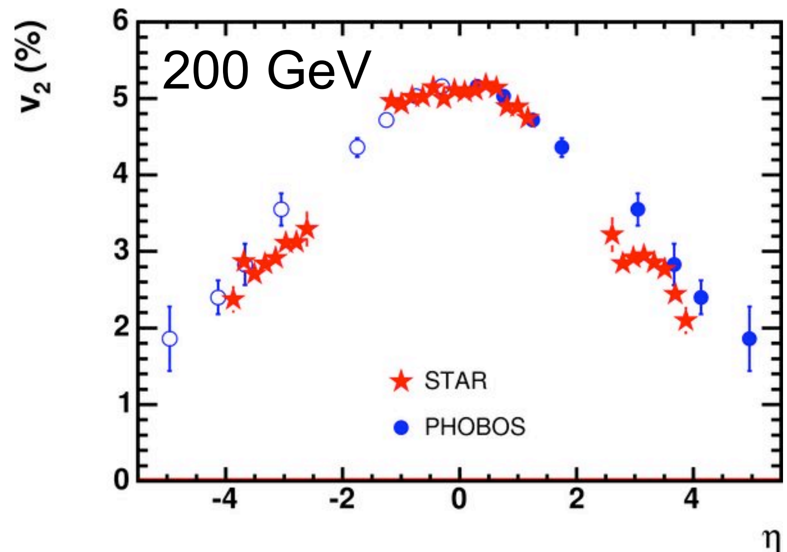
Cu+Cu (prelim.)

PHOBOS

19.6 62.4 130 200 GeV

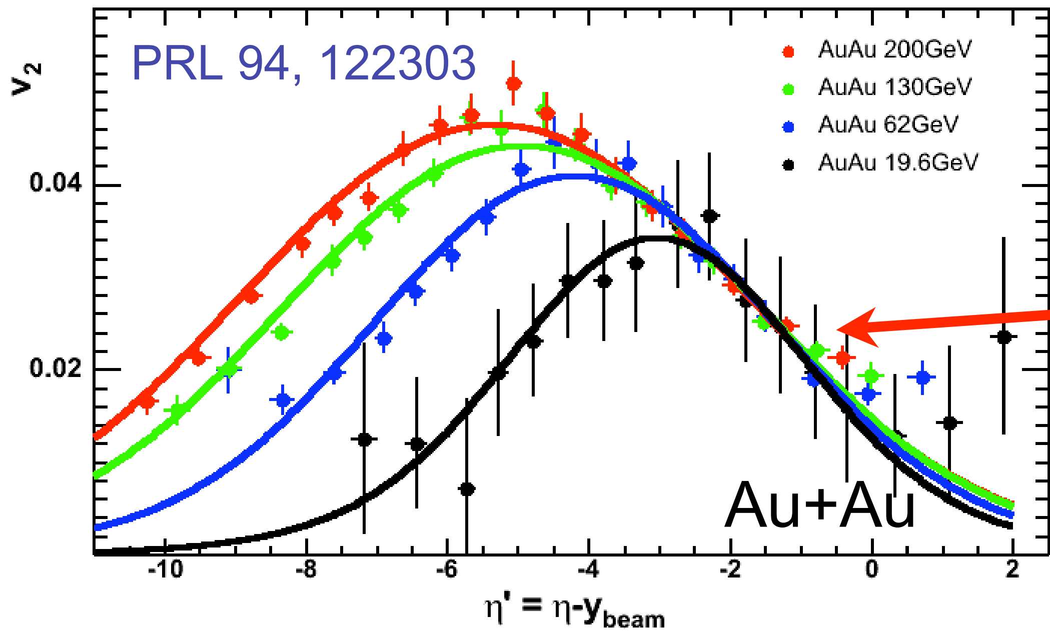
Nucl. Phys. A 757 28 (2005)

We know that the large anisotropy is a strong <u>*final state*</u> effect…
… but is is still simply scaling at high η?!



Phys. Rev. C 72 (2005) 014904

Extended longitudinal scaling: v_2

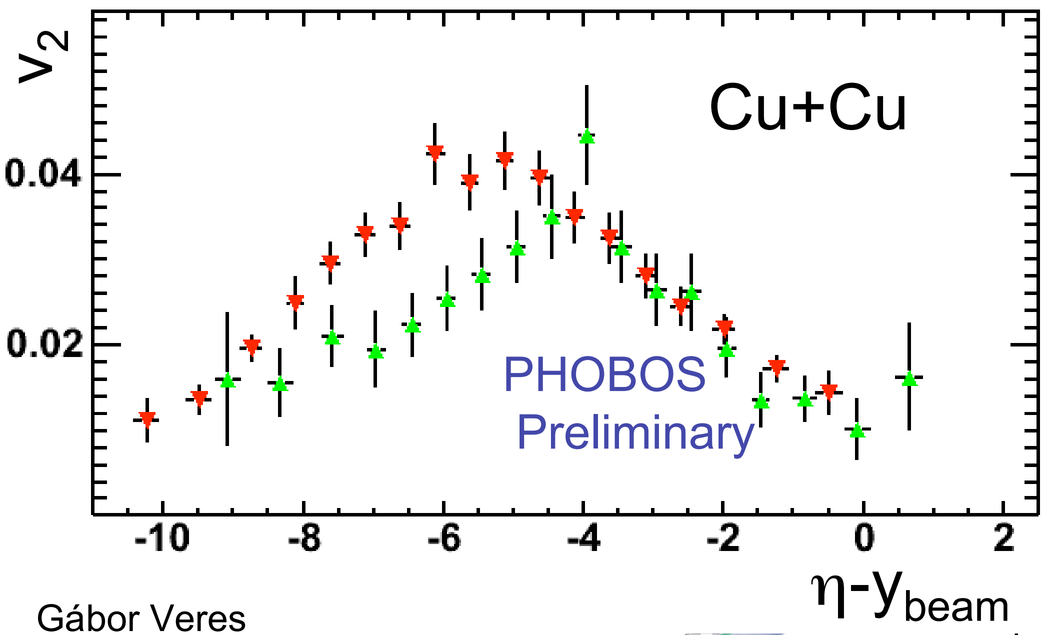


A surprising scaling!

Not an initial state effect

nucl-th/0505019

Scaling reproduced by the Buda-Lund parametrization of the emitting source. (Other hydro models: see parallel talks!)

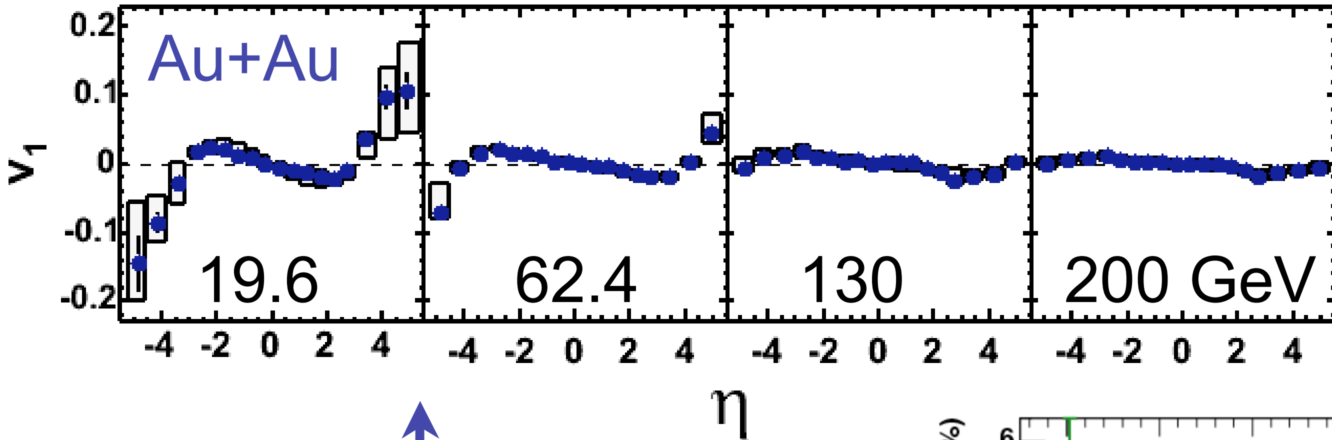


The same scaling is Observed in Cu+Cu!

BUT: BRAHMS observes Rather flat η depencence! (H. Ito, parallel session, Friday)

Gábor Veres

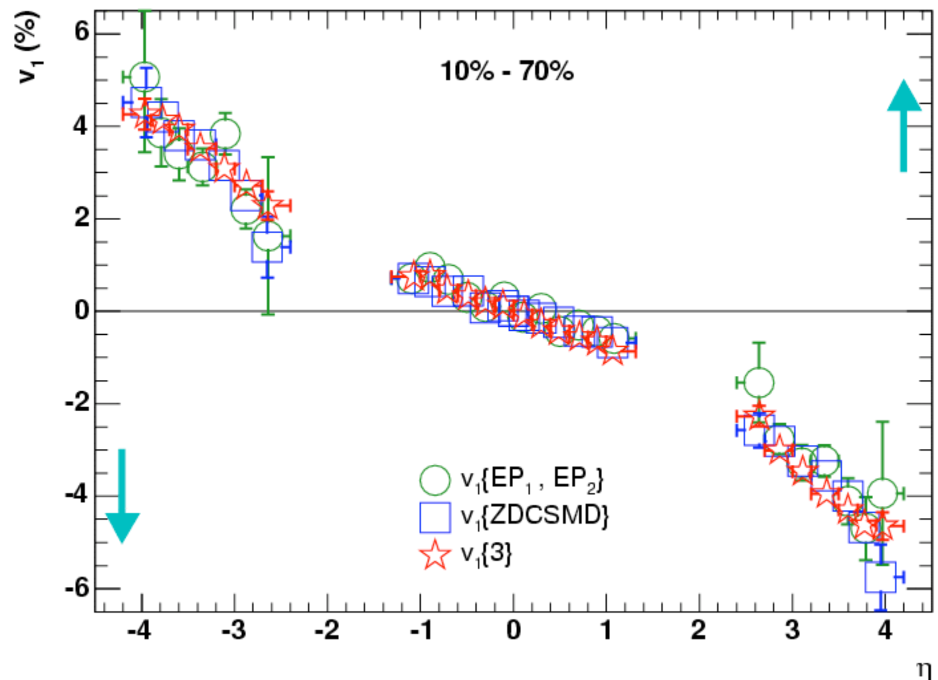
v_1 in A+A collisions at high η



PHOBOS preliminary
0-40% centrality

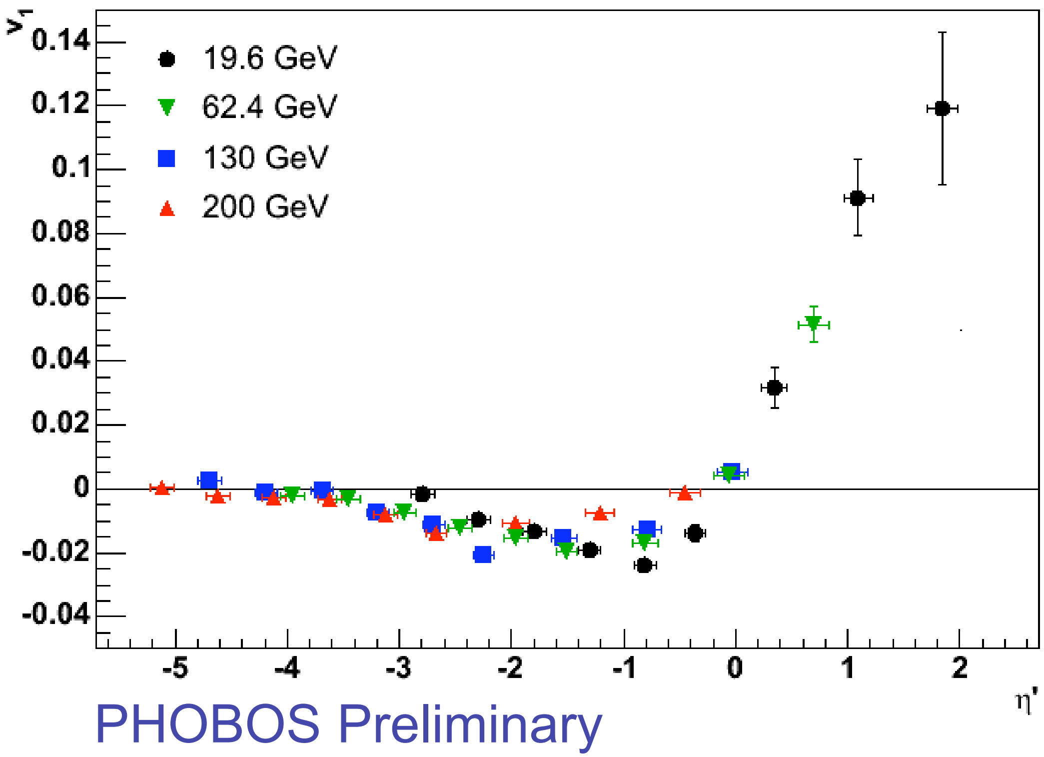
We see a sign change at low energies ⇒ role of baryons?

… is there scaling in v_1?



STAR preliminary

Extended longitudinal scaling: v_1



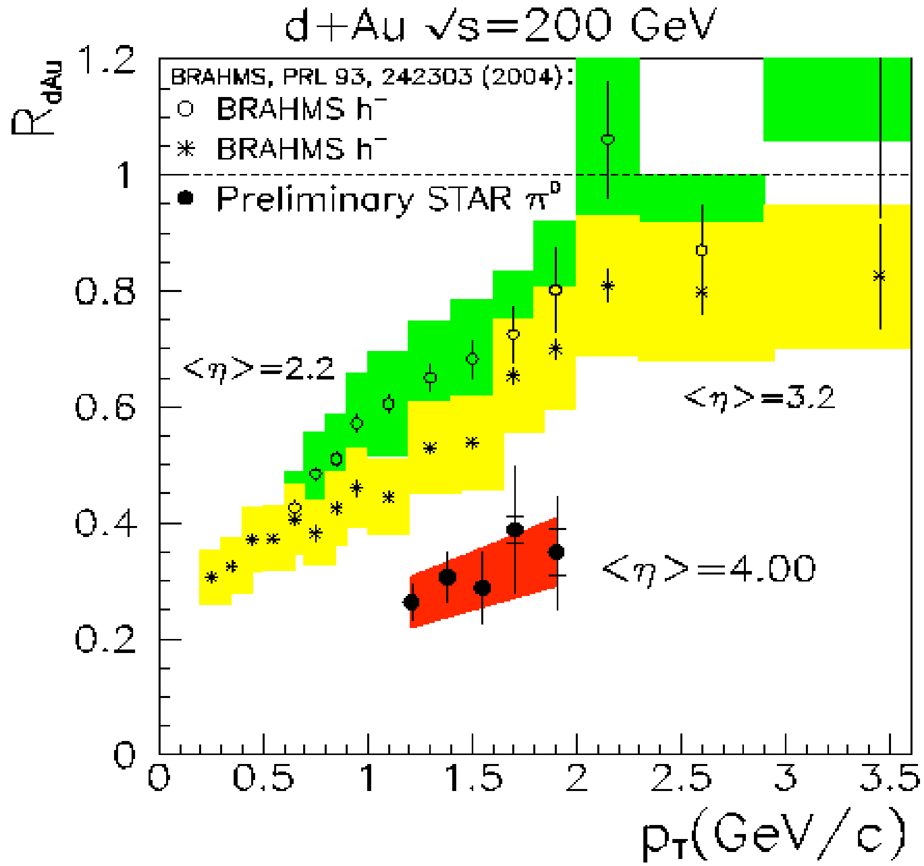
⇒ These scaling features of the bulk hadron production at high η are unexplained by initial state models alone.

Summary: do we understand particle production at high η?

- two random examples -

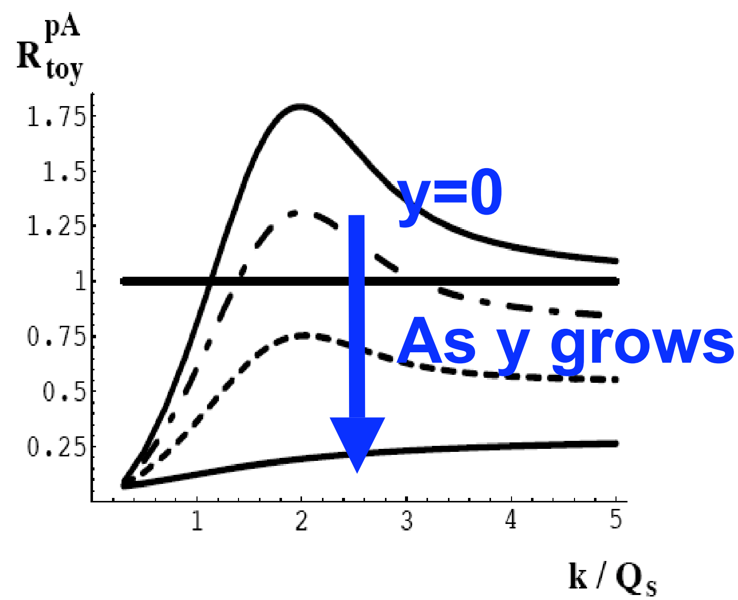
d+Au results from BRAHMS and STAR

$$R_{dAu} = \frac{\sigma_{pp}^{inelastic}}{\langle N_{binary}\rangle \sigma_{dAu}^{inelastic}} \frac{Ed^3\sigma / dp^3 \big|_{dAu}}{Ed^3\sigma / dp^3 \big|_{pp}}$$



G. Rakness: Moriond - QCD (2005)

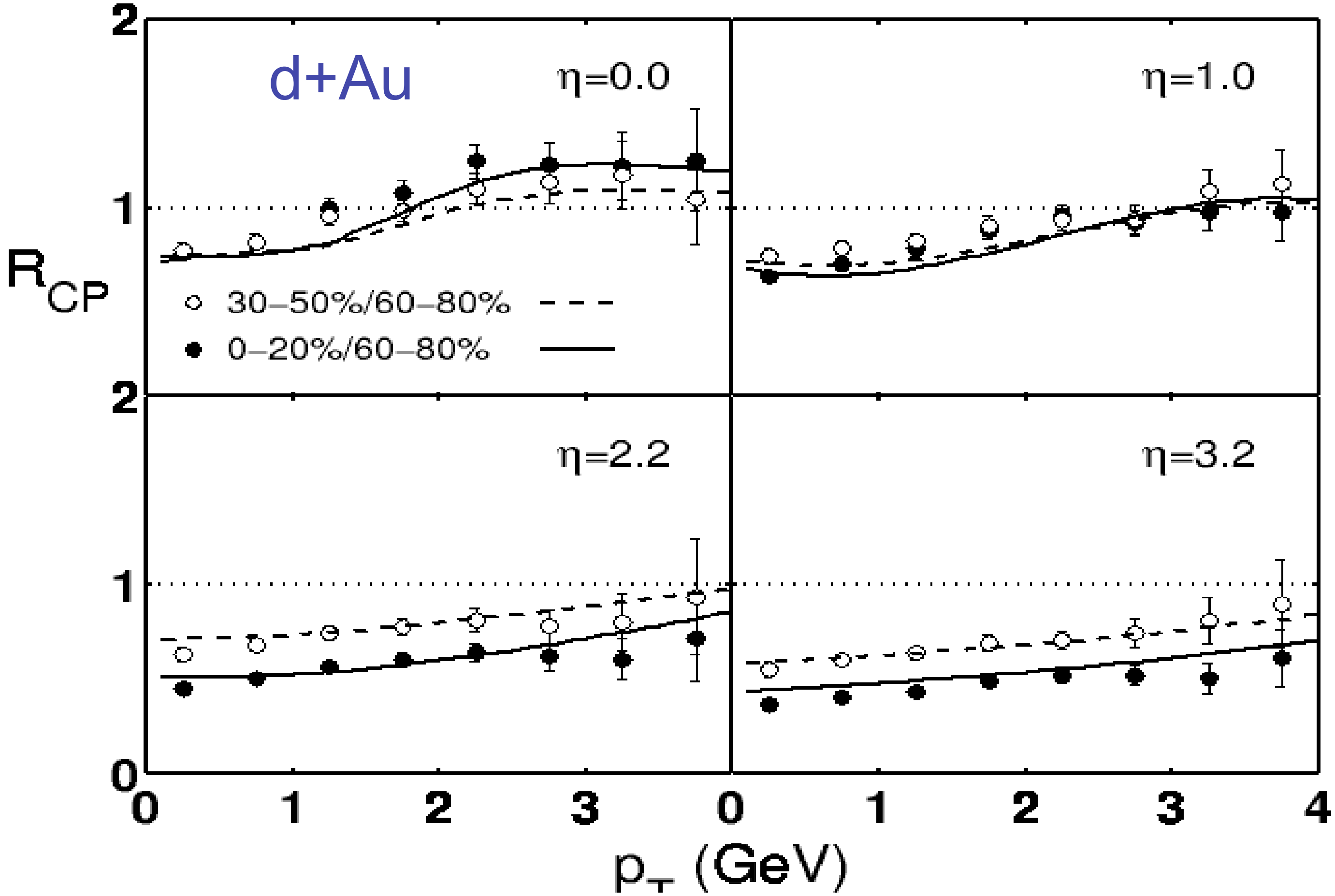
Saturation tells us that the Cronin-peak disappears at high η:



Phys. Rev. D 68 , 094013 (2003)

Nucl. Phys. A739, 319 (2004)

Recombination model works at high η



with only the **recombination** of soft and shower partons: <u>no multiple scattering</u>, and <u>no gluon saturation</u> put in explicitly

PRL 93 242303 (2004)

Phys.Rev.C 71 024902 (2005)

Future: eRHIC, LHC

Opens up phase space for saturation physics:
<u>low-x at high Q^2 is more easily accessible</u> (compared to RHIC).

Effect of the saturated gluon-distributions will show up in the particle production more cleanly.

But: only limited experimental capabilities at high η

All this is much more difficult kinematically and experimentally at RHIC $\Rightarrow$ uncertainties in predictions for LHC.

Looking forward to successful e+A, p+A, A+A programs!

Summary

- Lots of data available at high rapidities at all energies
- Longitudinal scaling of yields:
  - pions and charged hadrons scale, baryons don't
  - gluon saturation describes data, but not uniquely
- Baryon transport and valence structure makes interpretation hard
  - depends on target and energy
  - does not depend on projectile
- Longitudinal scaling of azimuthal asymmetry:
  - longitudinal scaling seen over a large energy range
  - for both directed and elliptic flow
  - here, models with final state interactions needed
- Theoretical interpretation of the low-x regime rapidly progressing
- Future experiments or more differential measurements may clarify uncertainties

A non-inclusive list of

Parallel talks on high η

1b Friday:

R. H. Karabowicz: Nuclear modification factor for identified hadrons at forward rapidity in Au+Au reactions at 200 GeV (BRAHMS)

B. Mohanty: Particle production at forward rapidity in d+Au and Au+Au collisions with STAR experiment at RHIC

Eun-Joo Kim: System and rapidity dependence of baryon/meson ratios at RHIC (BRAHMS)

2b Friday:

H. Ito: Rapidity dependence of pion elliptic flow at RHIC (BRAMS)

S. L. Manly: System-size and energy dependence of elliptic flow (PHOBOS)

A. Ster: A description of the pseudo-rapidity dependence of the elliptic flow from $\sqrt{s_{NN}}$ = 19.7 to 200 GeV measured by PHOBOS (TH)

8a Monday:

J. Jalilian-Marian: Color Glass Condensate: from RHIC to LHC (TH)

G. G. Barnaföldi: Nuclear modification factor at large rapidities at RHIC (TH)