pA Scattering: What We Have Learned?

In 1978, I became a postdoc at SLAC, and become interested in heavy ion collisions. I began talking with Miklos Gyulassy who was then a young fellow at LBL, began talking with Bj, but most important I read two very important papers:

REVIEW OF EXPERIMENTAL DATA ON HADRON-NUCLEUS COLLISIONS AT HIGH ENERGIES*,**

BY W. BUSZA

Department of Physics and Laboratory for Nuclear Science
Massachusetts Institute of Technology, Cambridge***

(Received December 15, 1976)

In this review an attempt is made to summarize briefly all that is presently known experimentally about hadron-nucleus collisions at high energies. Comparisons with theoretical models are kept to a minimum. However, an outline of some theoretical ideas that have been put forward in interpreting the data is included.

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(T/E)

HADRON FINAL STATES IN DEEP INELASTIC PROCESSES*

J. D. Bjorken

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

(Lectures given at the International Summer Institute in Theoretical Physics, Current Induced Reactions, DESY, Hamburg, September 15-26, 1975.)

I also read a number of papers by Anzdrej Bialas, and had the pleasure of discussing with Bj about his idea concerning the space-time picture of hadronic scattering

I wanted to understand if one could develop a space-time picture of heavy ion collisions which would let one figure out whether or not one could deposit enough energy in space-time region which would live long enough so that one could make a QGP.

Bj's work taught me two very important ideas:

The correlation between momentum and coordinate generated by Lorentz time dilation
and
The inside-outside cascade

This is done in Bj's style of minimal math and maximal physical intuition

The correlation between momentum and coordinate:

A high momentum hadron can be thought of in terms of constituents. Their position relative to the center of a hadron is of order 1/p, where p is their longitudinal momentum

When soft (low transverse momentum) particles are produced, in their rest frame there is a characteristic time scale, t of order 1 Fm/c. If the soft particle which is produced is relativistic, (has a big longitudinal momentum), the time is increased by a Lorentz gamma factor

$$t \sim \gamma t_o$$

For particle production in high energy collisions, particles are produced at longitudinal coordinates,

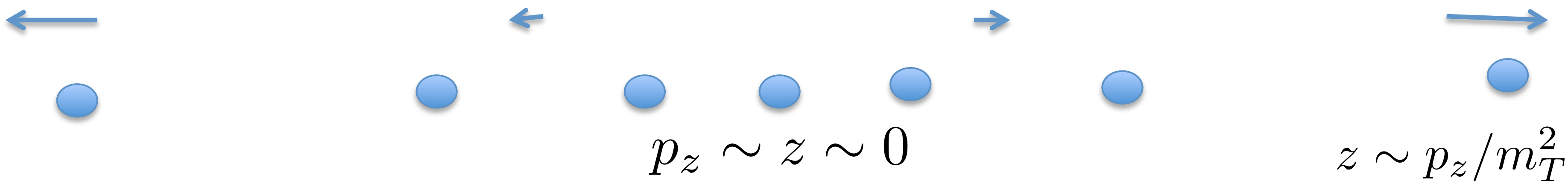
$$z \sim \gamma t_0$$

The rapidity variable

$$y = \frac{1}{2} ln \left(\frac{E + p_z}{E - p_z} \right)$$

Is shifted by a constant under a longitudinal Lorentz boost, so that dN/dy = const is a boost invariant distribution, which is also a fair approximation to what is seen in experiment

This observation is profound since it means that in any frame matter is produced expanding, with a local density which is constant (1+1 d Hubble expansion)

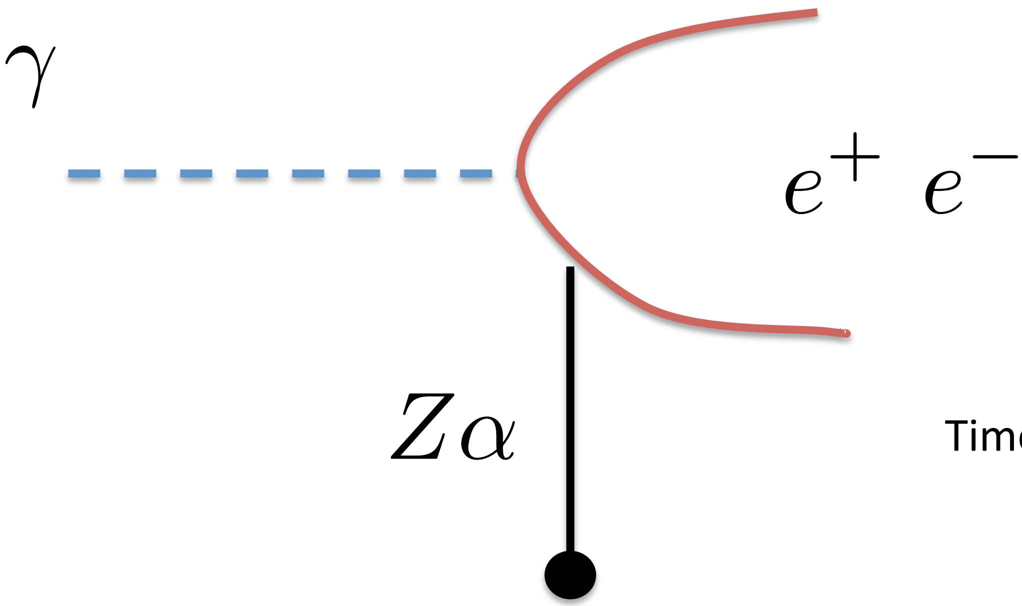


This is called the inside-outside cascade, and describes hadron production in high energy collisions, and particle production along a jet axis. The leading particles in jets are produced by hard processes at a time of order 1/p_t, which is very small, but the particle produced by the jets make an inside outside cascade.

This picture leads to a simple description of the initial energy deposition in heavy ion collisions, and with Anishetty and Koehler, I applied it to compute the energy deposition in the fragmentation region of ultra-relativistic heavy ion collisions. The central region had ambiguities associated with at that time poorly understood dependence on the multiplicity of pA collisions. Bj later replaced that problem with an for the energy density in the central region which could be determined by experiment. He also formulated initial 1+1 d hydrodynamics.

Bj's ideas had however not entirely arisen from the vacuum of pure thought:

Bj had thought hard about cosmic rays and understood the Landau-Pomeranchuk Migdal effect in electromagnetic cascades



Time to form the pair in the rest frame of the pair is

$$t_0 \sim \frac{1}{Z\alpha m}$$

Time in nuclear target rest frame is

$$t_0 \sim \frac{\gamma}{Z\alpha m}$$

The highest energy detected cosmic rays have their formation distance extended to scales of tens of meters!

I learned from Busza's articles what was known, what was fantasy, and what needed to be learned:

"Total hadron-nucleus cross sections at high energies show no surprises---to within experimental and theoretical uncertainties can be derived by hadron-nucleon cross sections using the Glauber model"

"If coherent production of multi-particle states is analyzed in terms of the Glauber model, one observes an apparent transparency of nuclear matter to newly produced states"

Color transparency?

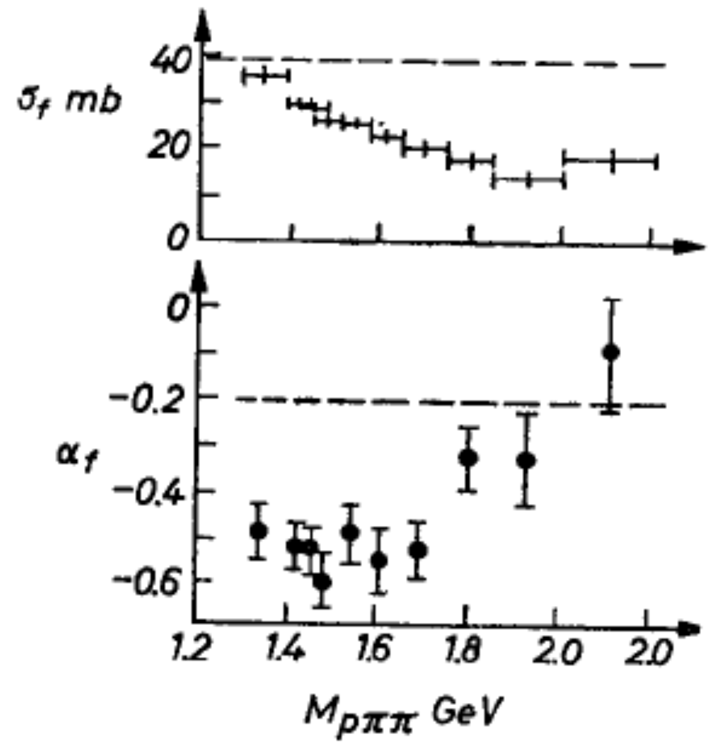
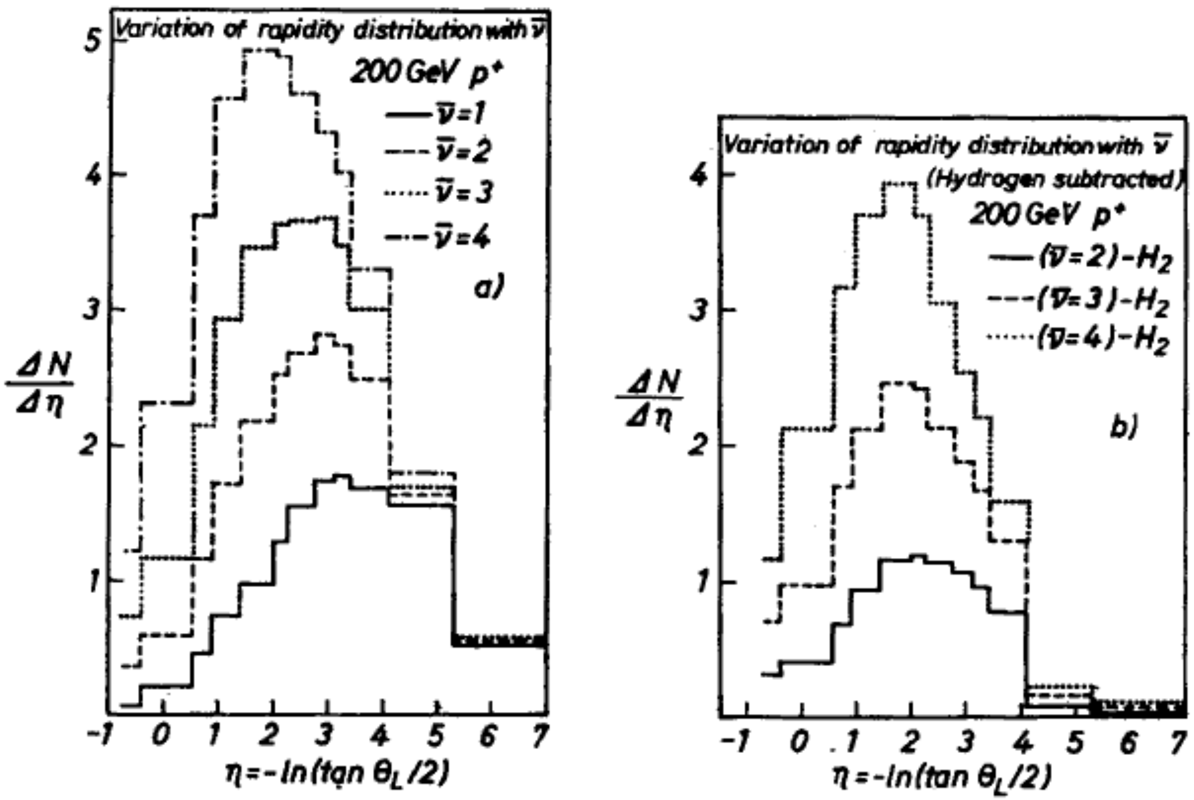


Fig. 2. Example of apparent transparency of nuclear matter to a coherently produced multihadron state. σ_f is the extracted total $(p\pi^+\pi^-)$-nucleon cross section from a Glauber analysis of $p+A \to p\pi^+\pi^- + A$ data at 22.5 GeV. α_f is the extracted value of the ratio of the real to the imaginary parts of the forward scattering amplitude. The data are from Ref. [10]

“The most striking feature of multi-particle production in hadron-nucleus collisions is its weak A dependence. There is little if any evidence of the buildup of an intra-nuclear cascade”



Inside-Outside Cascade

Foundation for the wounded nucleon model

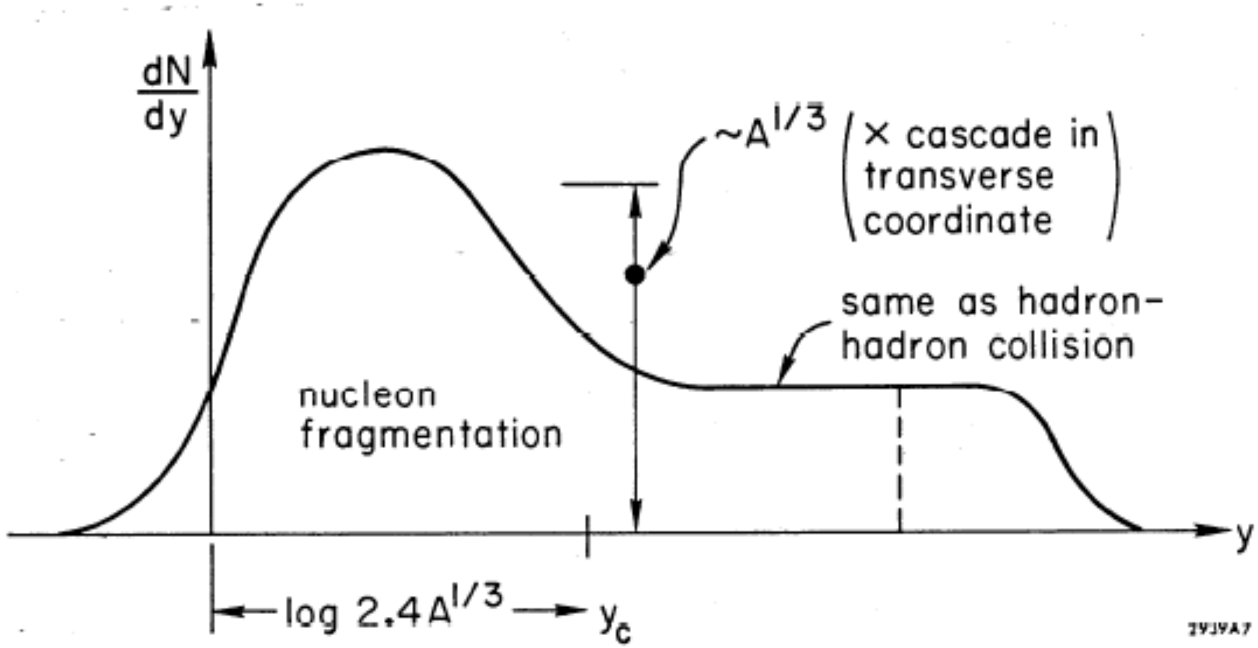
Fig. 3a, b). Example of the variation of pseudo-rapidity distributions with size of nuclear target. Data are from Busza et al. [35] $\bar{\nu}$ is a measure of the average thickness of the nucleus in units of the mean free path of protons in nuclear matter. N is the average number of charged relativistic particles produced in an inelastic collision. It includes both pions and fast recoil protons. For definitions see Appendix II

"Another totally unexpected result in hadron-nucleus collisions is the A dependence of the inclusive particle production spectra at large transverse momentum"

"It is possible that the interpretation of these data is uninteresting"

Cronin Effect, R_{pA}

An issue not resolved at that time, nor in my opinion completely resolved today, is how does the central region multiplicity in depend upon A at very high energy. In Bj's summer school notes, it was assume that the multiplicity went like the nuclear thickness in the central region and was independent of it outside this region



Modern theoretical arguments suggest that at asymptotic energies it is like Bj, but that even at LHC energies is not asymptotic, and more like

$$A^{1/3}$$

The multiplicity in the central region was an impediment to making a good prediction for the energy density in the central region in ultrarelativistic heavy ion collisions. Bj later turned this problem around and argued that a measurement of this multiplicity would give a measurement of the energy density. This was when he formulated the hydrodynamic description of heavy ion collisions. Shuryak had also formulated the problem is this way, and considered a hydrodynamic description in pp collisions

The Phobos experiment was the first to measure the multiplicity in the central region of ultra-relativistic heavy ion collisions, and implies that the energy density in such collisions is indeed high enough to make a Quark Gluon Plasma

Charged particle multiplicity near mid-rapidity in central Au+Au collisions at $\sqrt{s} = 56$ and 130 AGeV

B.B.Back[1], M.D.Baker[2], D.S.Barton[2], S.Basilev[5], R.Baum[8],R.R.Betts[1,7], A.Białas[4], R.Bindel[8], W.Bogucki[3], A.Budzanowski[3], W.Busza[5], A.Carroll[2], M. Ceglia[2], Y.-H.Chang[6], A.E.Chen[6], T.Coghen[3], C. Conner[7], W.Czyż[4], B.Dąbrowski[3], M.P.Decowski[5], M.Despet[3], P.Fita[5], J.Fitch[5], M.Friedl[5], K.Gałuszka[3], R.Ganz[7], E.Garcia-Solis[8], N.George[1], J.Godlewski[3], C.Gomes[5], E.Griesmayer[5], K.Gulbrandsen[5], S.Gushue[2], J.Halik[3], C.Halliwell[7], P.Haridas[5], A.Hayes[9], G.A.Heintzelman[2], C.Henderson[5], R.Hollis[7], R.Hołyński[3], B.Holzman[7], E.Johnson[9], J.Kane[5], J.Katzy[5,7], W.Kita[3], J.Kotuła[3], H.Kraner[2], W.Kucewicz[7], P.Kulinich[5], C.Law[5], M.Lemler[3], J.Ligocki[3], W.T.Lin[6], S.Manly[9,10], D.McLeod[7], J.Michałowski[3], A.Mignerey[8], J.Mülmenstädt[5], M.Neal[5], R.Nouicer[7], A.Olszewski[2,3], R.Pak[2], I.C.Park[9], M.Patel[5], H.Pernegger[5], M.Plesko[5], C.Reed[5], L.P.Remsberg[2], M.Reuter[7], C.Roland[5], G.Roland[5], D.Ross[5], L.Rosenberg[5], J.Ryan[5], A.Sanzgiri[10], P.Sarin[5], P.Sawicki[3], J.Scaduto[2], J.Shea[8], J.Sinacore[2], W.Skulski[9], S.G.Steadman[5], G.S.F.Stephans[5], P.Steinberg[2], A.Strączek[3], M.Stodulski[3], M.Stręk[3], Z.Stopa[3], A.Sukhanov[2], K.Surowiecka[5], J.-L.Tang[6], R.Teng[9], A.Trzupek[3], C.Vale[5], G.J.van Nieuwenhuizen[5], R.Verdier[5], B.Wadsworth[5], F.L.H.Wolfs[9], B.Wosiek[3], K.Woźniak[3], A.H.Wuosmaa[1], B.Wysłouch[5], K.Zalewski[4], P.Żychowski[3]
(PHOBOS collaboration)

These ideas were advocated and were the subject of intense research in Poland, where both Wit and Bj had close ties with Andzrej Bialas. My own interest in the high energy limit and the initial state of such collisions stems from a Krakow School of Physics meeting where both the data which showed rising gluon distributions were shown 2 and the possibilities of ultra-relativistic nuclear collisions were discussed (as were many other things). Such a cotemporaneous conversation was rare at the time and remains so. The mystery was that if the multiplicity becomes very high, one should be able to use a weak coupling approach.

Where are we now:

Various type of proposed matter at very high energy density:

Color Glass Condensate:

Very high energy density gluons in wavefunction of hadrons important for high energy scattering

Strongly Interacting Quark Gluon Plasma

Glasma:

Highly coherent gluons weakly coupled but strongly interacting gluons important for the early stages collisions

Thermalized sQGP

A strongly coupled ensemble of quark and gluons which is to a good approximation equilibrated

In the remainder of this talk, I will discuss issue related to the above which are being addressed in studies of pp, pA and dA collisions:

We need some rudimentary results from the theory of the CGC and Glasma:

The sources of particles are color charges of quarks and gluons distributed in the transverse plane

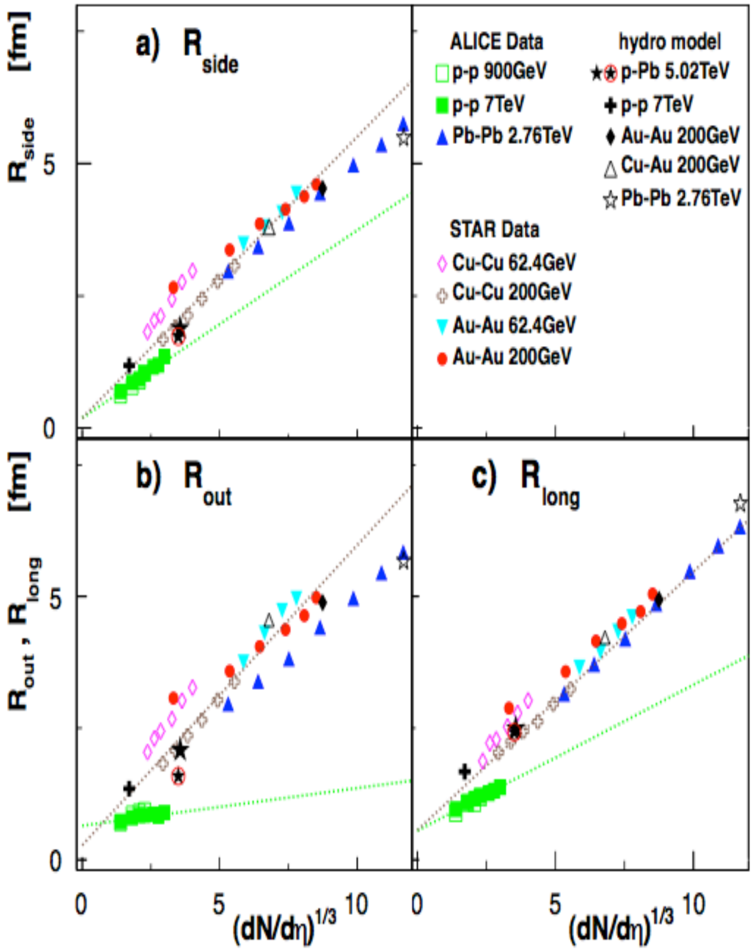
There is a transverse density scale which is the saturation momentum:

$$Q^2_{sat} = \rho_T$$

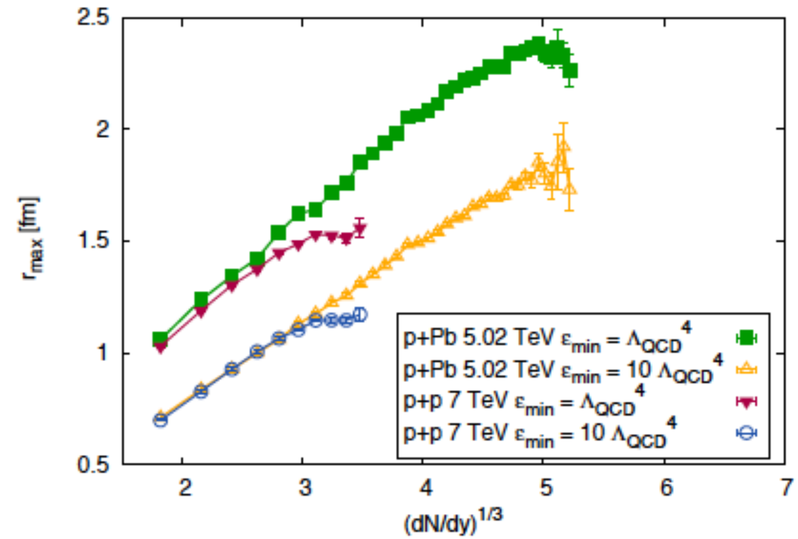
Fields with momenta much larger than this scale may be treated incoherently, and below this scale are highly coherent and may be described classically

The saturation momentum may have a dependence on transverse coordinate, and a computable dependence on nuclear and the rapidity scale at which it is measured

Particle production arises from string like longitudinal color electric and magnetic fields with a typical transverse size scale of the inverse saturation momenta



Do we know the transverse size scale characteristic of the interaction region in pp and pA interactions?



In pp collisions, it is smaller than would be predicted by hydrodynamic expansion, and characteristically different from AA

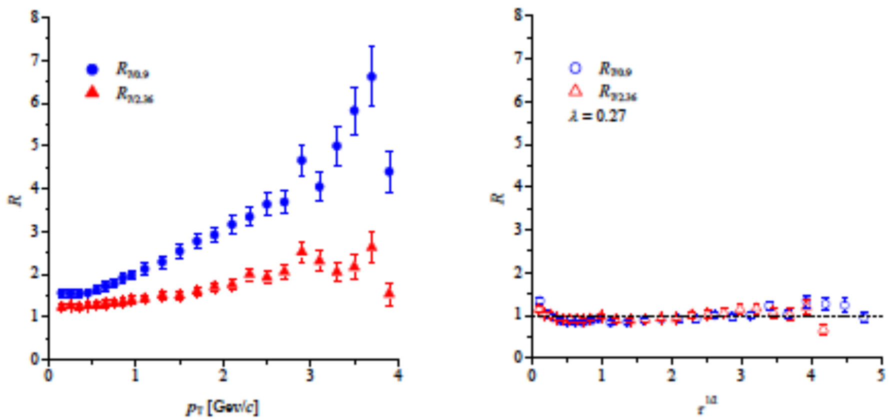
Theory conjecture:

CGC without final state interaction would be the same.

Glauber computation or hydro effect would give significantly larger value.

Bzdak, Schenke, Tribeddy and Venugopalan

Does the saturation momentum affect particle distributions?



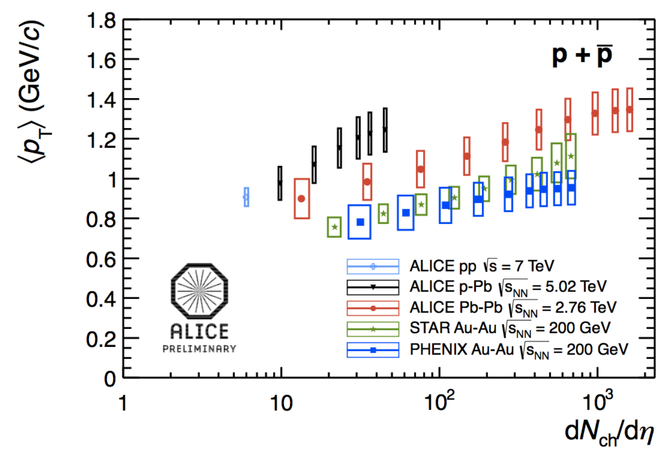
$$\left.\frac{dN}{dy d^2 p_T}\right|_{y \simeq 0} = \frac{1}{Q_0^2} F(\tau)$$

$$\tau = p_T^2 / Q_s^2(x) = p_T^2 / Q_0^2 \,\left(p_T / (x_0 \sqrt{s})\right)^{\lambda}$$

M. Praszaolwicz and LM

Fig. 2. Ratios of CMS p_T spectra [13] at 7 TeV to 0.9 (blue circles) and 2.36 TeV (red triangles) plotted as functions of p_T (left) and scaling variable $\sqrt{\tau}$ (right) for $\lambda = 0.27$.

Distributions as function of centrality?

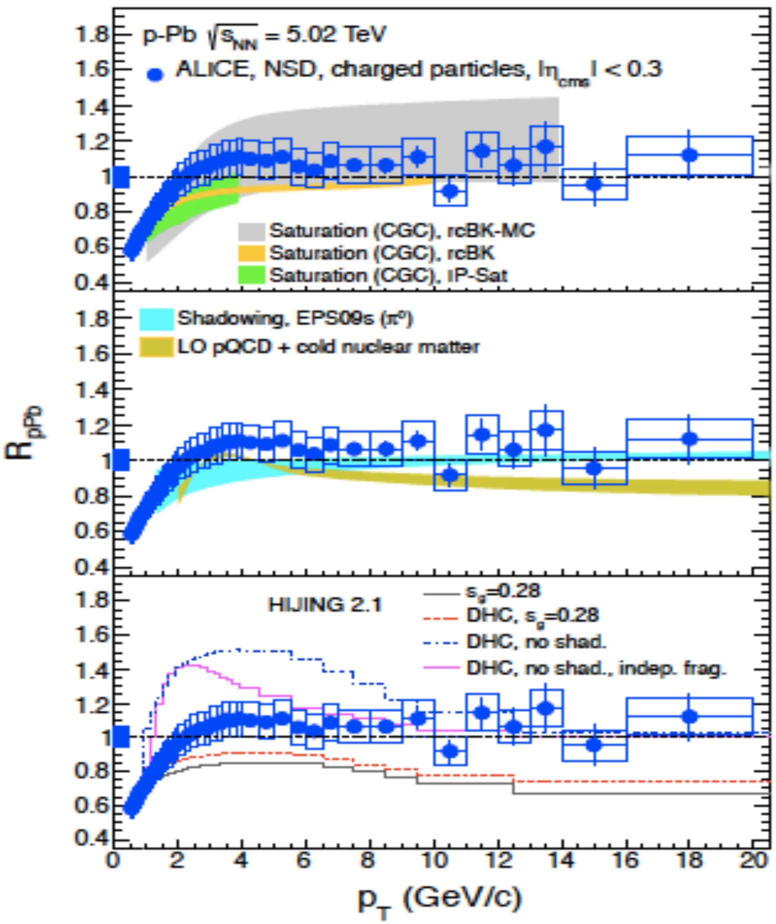


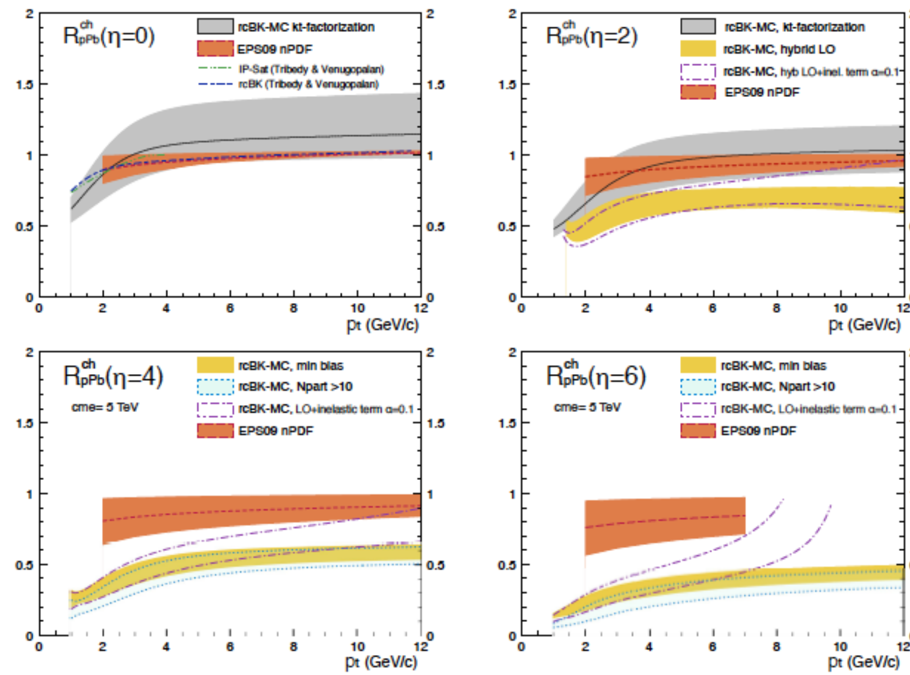
What about identified particle distributions? M_T scaling in low p_T region ? Geometric scaling?

Sikler

Or does it arise from hydrodynamic flow?

Is the issue for pA is more subtle and requires more detailed computation?

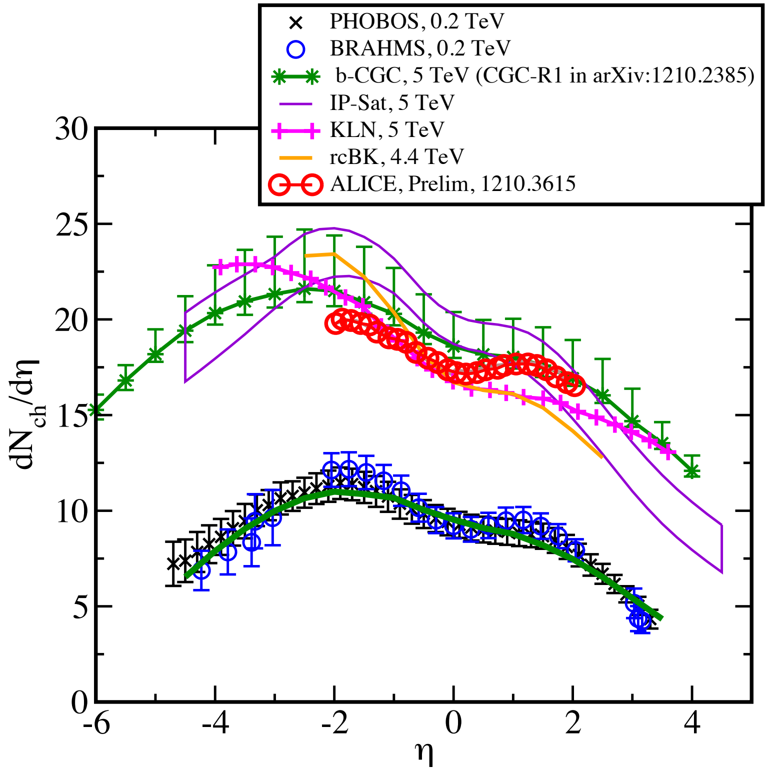


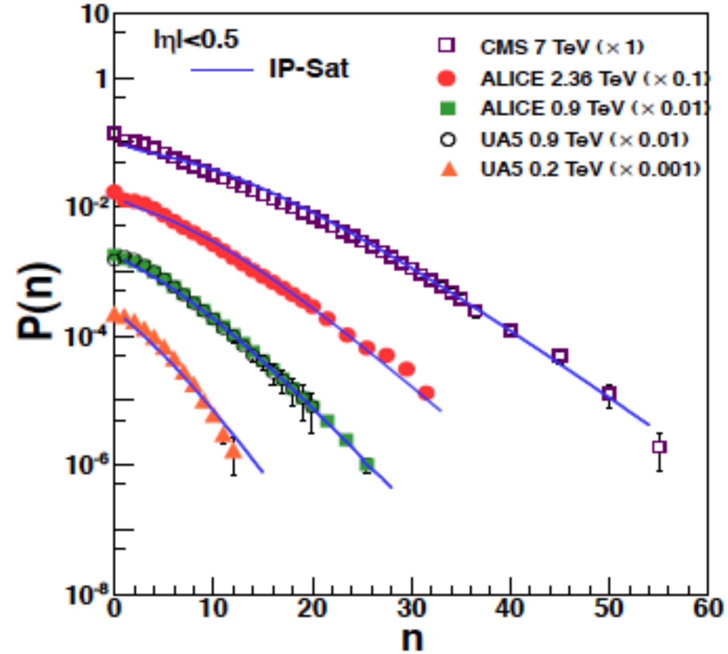


Albacete and Dumitru

How do we determine the underlying parton distributions from QCD?

Gross Features of Particle Production:

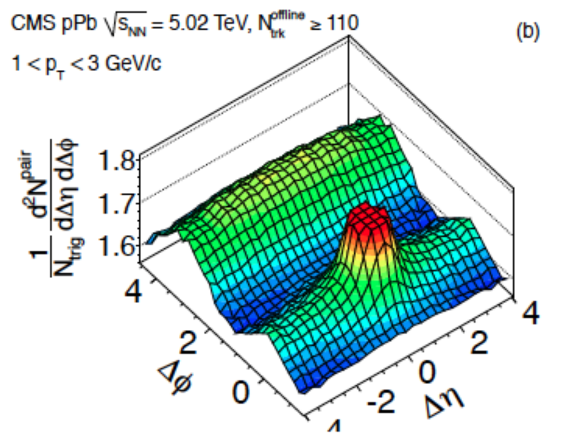


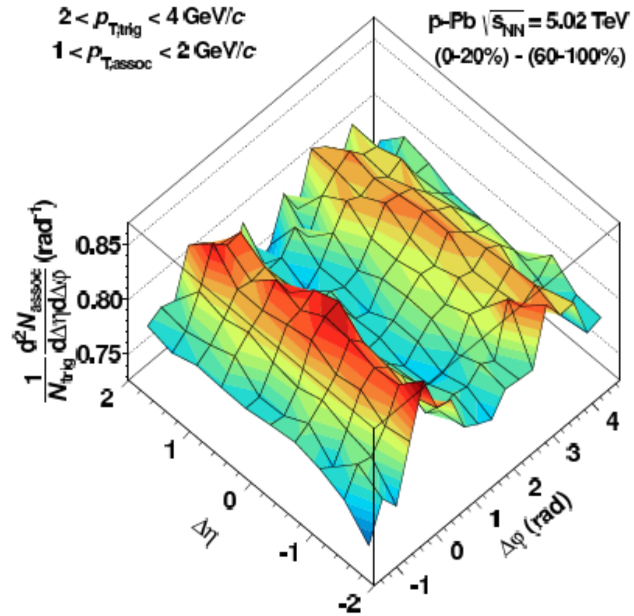


Multiplicity dependence on energy roughly correct in many different computations.

Multiplicity fluctuations are negative binomial in pp collisions and agree with CGC predictions. Multiplicity fluctuations must be properly included in pA and AA Monte-Carlos

p+Pb @ 5.02TeV





Much stated with great conviction, but little really known for sure.

The Ridge:

Existence of ridge in pp requires at least some source of the ridge that is sub-nucleonic and involves quarks and gluons.

(AA collisions: Glauber or CGC?)

Requires the formation at very early time of Long range rapidity structure on sub-nucleonic size scale. CGC provides a theory

How does the structure at very early time get translated into the structure seen at late times in multi-particle correlations?

Is it final state interactions? Are these interactions strong enough so that hydro is justified?

Is it largely initial state correlations from the decay of the flux line?

Coome ce, Comme ca?

The study of pp, pA and dA at RHIC and LHC energies much more exciting than anyone envisaged.

The issues being discussed are perhaps framed differently than 35 years ago, but they are equally important for our understanding of the fundamental properties of matter.
The questions being formulated are largely answerable, and they are simple questions.
It is quite surprising that the answers are not known and the conjectures so hotly disputed.
The answers to these questions I believe are of fundamental importance.

I think also it is important to think hard about how we formulate the questions we ask, and how we proceed to answer them.