Constituent-quarks as the fundamental elements of the initial state at RHIC and LHC

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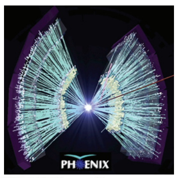

Nuclear Physics Seminar
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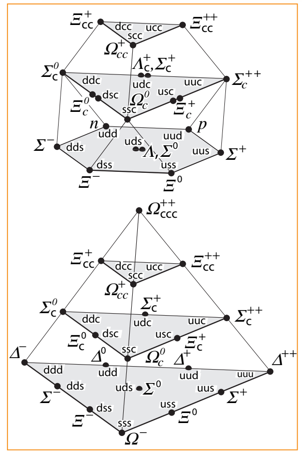
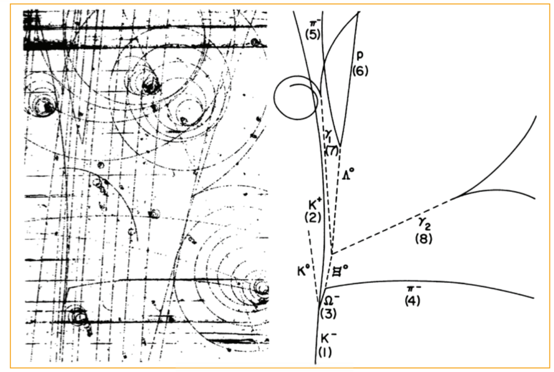
PHENIX E_T distributions from PRC**89** (2014) 044905

The massive constituent-quarks, which form mesons and nucleons (e.g. a proton=uud), are relevant for static properties and soft physics with $p_T < 2$ GeV/c. They are complex objects or quasiparticles made of the massless partons (valence quarks, gluons and sea quarks) of DIS such that the valence quarks acquire masses ≈ 1/3 the nucleon mass with radii ≈ 0.3 fm when bound in the nucleon. With smaller resolution one can see inside the bag to resolve the massless partons which can scatter at large angles according to QCD. At RHIC, hard-scattering is distinguishable from soft (exponential) particle production only for $p_T \geq 2$ GeV/c at mid- rapidity, where $Q^2 = 2p^2_T = 8$ (GeV/c)^2 which corresponds to a distance scale (resolution) < 0.07 fm.

Constituent quarks are Gell-Mann's quarks from Phys. Lett. **8** (1964)214, Zweig's Aces



Constituent quark model of Baryons



Ω^- (sss)

BNL-Barnes, Samios *et al.*, PRL**12**, 204 (1964)

For more on Constituent quarks in QCD see E. V. Shuryak, Nucl. Phys. B 203, 116 (1982).

Constituent Quarks cf. Partons

Constituent quarks are Gell-Mann's quarks from Phys. Lett. 8 (1964)214, proton=uud [Zweig's Aces].These are relevant for static properties and soft physics, low Q^2<2 GeV^2 ; resolution> 0.14fm

For hard-scattering, p_T>2 GeV/c, $Q^2=2p_T^2$>8 GeV^2, the partons (~massless current quarks, gluons and sea quarks) become visible

1.6fm

Resolution ~0.5fm

Resolution ~0.1fm

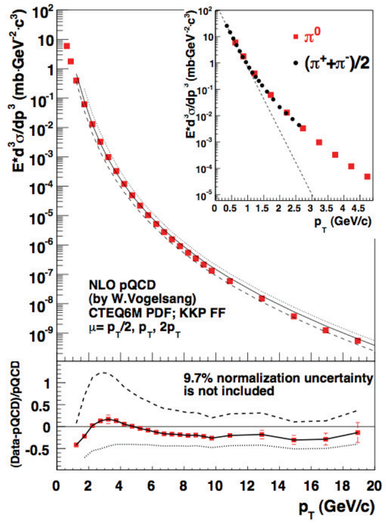
Resolution <0.07fm

π^0's in p+p $\sqrt{s}$=200 GeV: Data vs. pQCD

- All hadron spectra are exponential for p_T<2 GeV/c in both p-p and A+A collisons. Exponential does not mean thermal unless you think pp is thermal.
- Result from run2-a classic PRL91 (2003) 241803. Better result shown is PRD76 (2007) 051006(R)

NLO-pQCD describes data down even to $p_T \sim 1.5$ GeV/c

Inclusive invariant π^0 spectrum is a pure power law for $p_T \geq 3$ GeV/c, n=8.1±0.1, indicating hard scattering which is visible by the break from an exponential ~3 orders of magnitude down in cross section. Hard scattering more prominent in single particle p_T spectrum than E_T distribution



E_T distributions

η= pseudorapidity

- E_T is an event-by-event variable defined as:

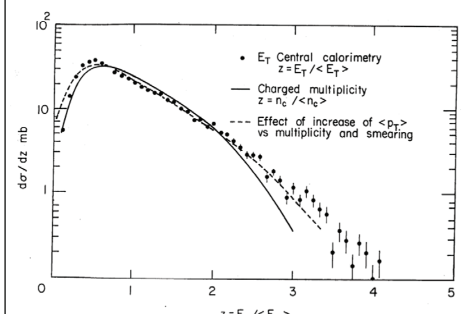
$$E_T = \sum_i E_i \sin\vartheta_i \quad \text{and} \quad dE_T(\eta)/d\eta = \sin\theta(\eta)dE(\eta)/d\eta$$

- The sum is over all particles emitted on an event into a fixed but large solid angle (which is different in every experiment)
- Measured in hadronic and electromagnetic calorimeters and even as the sum of charged particles $\Sigma_i\, |p_{Ti}|$
- Introduced by High Energy Physicists as an "improved" method to detect and study the Jets of hard-scattering. It didn't work as expected, E_T distributions are dominated by soft particles near $<p_T>$.
- The importance of E_T distributions in relativistic heavy ion (RHI) collisions is that they are largely dominated by the *nuclear geometry* of the reaction and so provide a measure of the overall character or *centrality* of individual RHI interactions.

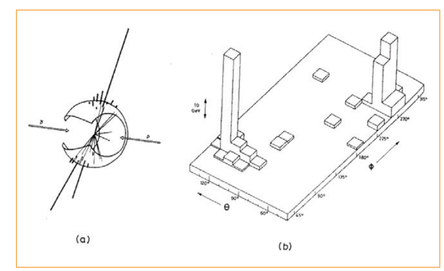
Snowmass 1982, ICHEP 1982, QM1983

- A Fermilab experiment using 2 back-to-back 1-2 steradian HCAL claimed to have discovered jets in PRL 38 (1977) 1447, which was clearly refuted at ICHEP 1980 by CERN experiment UA5
- At Snowmass 1982 to determine the future of HEP in the U.S. nobody believes in jets in hadron collisions. Bob Wilson proposes "Desertron" to replace ISABELLE (800 GeV) since FNAL finally gets magnets working to build Tevatron collider.
- at ICHEP 1982, UA1 explains why E_T distributions are soft, UA2 shows the first believable jet 5-6 orders of magnitude down in an E_T distribution.
- January 1983, Rubbia announces W discovery [at APS meeting in New York. MJT drives Carlo to BNL for seminar]. June 11, 1983, DOE terminates ISABELLE and on the same day NSAC votes to build RHI collider in ISABELLE tunnel.
- Quark Matter 1983 moved to BNL(Sept 26-30) by effort of Nick Samios and T. D. Lee. Because the ISR had run α-α and p+α collisions in the ISR in 1980 thanks to Martin Faessler, with exciting results, MJT who had worked for years at the ISR happened to have the only relevant measurement from BNL, from a second run in August 1983, presented by Sanki Tanaka (now deceased).

ICHEP 1982 contradictions (?)

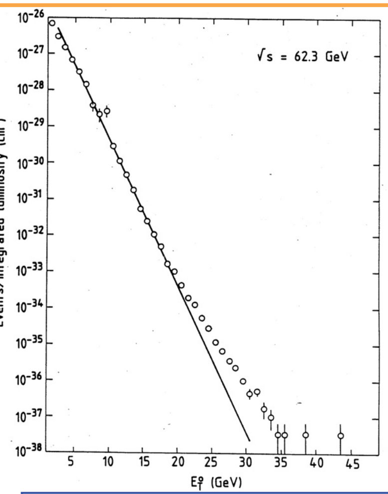


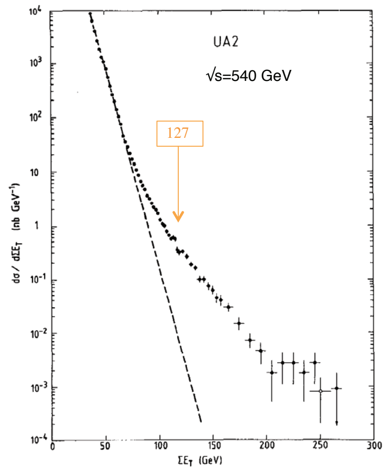
UA1-N_{ch} and E_T follow same KNO scaling



UA2-first dijet in hadron collisions E_T=127 GeV

Jets are a <<10^{-3} effect in p-p E_T distributions



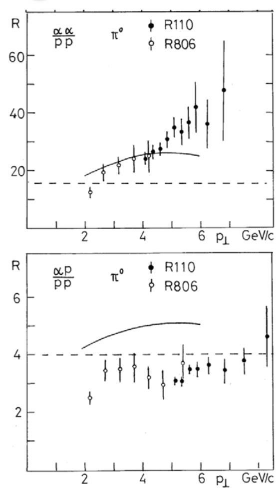


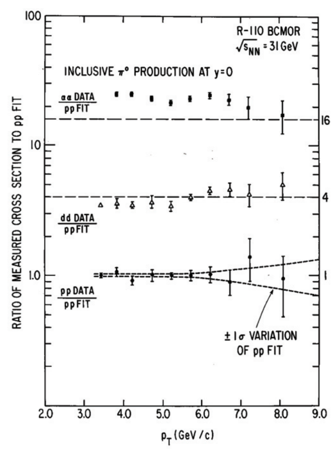
COR PLB**126**(1983)132 E_T in $\Delta\Phi=2\pi$, $|\eta|<0.8$ EMCal. Break above 20 GeV is due to jets. Also see NuclPhys B**244**(1984)1

UA2 PLB**138**(1984)430 (from DiLella) Break from jets ~5-6 orders of magnitude down for E_T in $\Delta\Phi=2\pi$, $|\eta|<1.0$

"Exciting" ISR Results from First A+A run

These Measurements are wrong due to incorrect estimate of p-p data—no comparison data; but made a huge impact. See book.

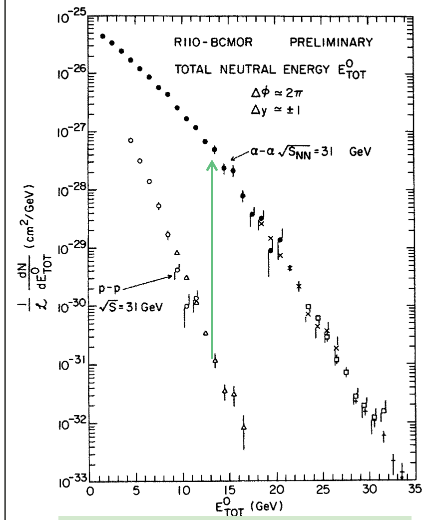




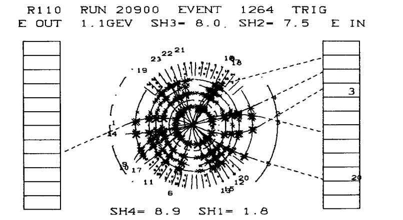
Correct measurements from 1983 run

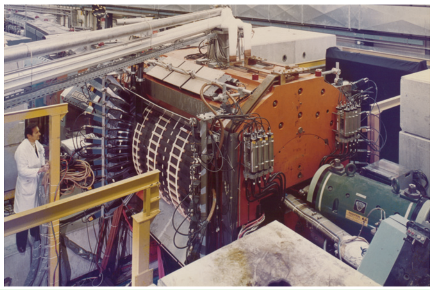
Fig. 14.1. a) (left) Ratio of cross sections in α–p and α–α interactions to the cross sections in p-p interactions as a function of pT : R[(αp → π0 + X)/(pp → π0 + X)] at √sNN =44GeV and R[(αα→π0+X)/(pp→π0+X)] at √sNN =31GeV, compiled by Faessler [692]. b) (right) BCMOR measurements [693] of the inclusive π0 cross sections in α – α, d – d and p-p collisions at √sNN = 31 GeV divided by a fit to the p-p data.

From Sanki Tanaka's presentation QM83



we were originally thinking that this large ratio, much larger than the Cronin effect was a big discovery, but then we learned the difference of E_T and p_T



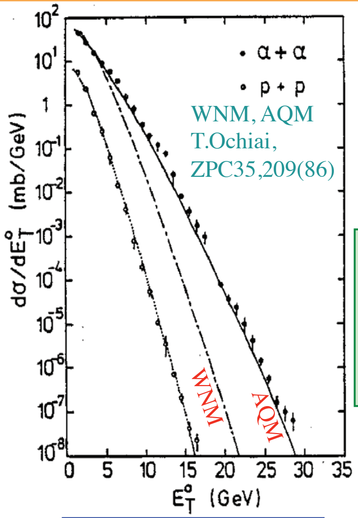


CCOR 1977 First thin coil superconducting solenoid detector at a collider r=70cm

Quark Matter 1984

The B in BCMOR collaboration was put together by the Physics department chair and Nuclear Physicist, Arthur Schwartzschild, because of the previous Exciting results and the switch to RHIC from ISABELLE. He offered me the following collaborators: Chellis Chasman, Peter Thieberger, John Olness and Peter Haustein (chemistry) in addition to Sanki for the 1983 run. Plus CCOR and CERN wanted Nuclear Physicist collaborators to help understand the data. By Quark Matter 1984 we had made great progress in understanding E_T distributions. I got to give the talk and there I first met Bill Zajc, Shoji Nagamiya, Larry McLerran, Richard Weiner, Vesa Ruuskanen, Pete Carruthers, . . .

From My First Quark Matter Talk 1984
ISR-BCMOR-αα $\sqrt{s_{NN}}$=31GeV: WNM FAILS! AQM works

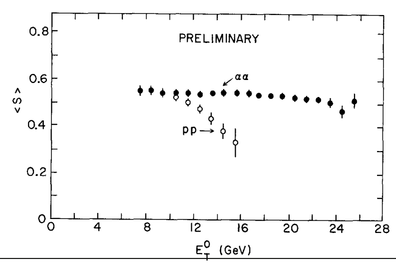


BCMOR PLB**168**(1986)158

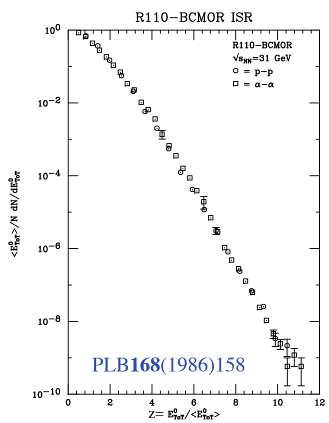
WNM agrees with αα data for 1 order of magnitude but disagrees for the other 10 orders of magnitude. AQM (Nqp) is in excellent agreement over the entire distribution. WNM Fails! AQM=Nqp works at 31 GeV

A youngster, Bill Zajc, and other Penn collaborators claimed that failure of WNM was due to jets. BUT, in pp collisions E^{o}_{T} is dominated by soft physics, jet effects are not visible until four orders of magnitude down in cross section. For α-α no jet effect in whole measured region [see CMOR Nucl.Phys B**244**(1984)1]

Other interesting results from this Data



From measured sphericity, E^{o}_{T} not jetty in pp for E^{o}_{T} <10 GeV, 4 orders of magnitude down in cross section. No jet effect in whole measured region in α-α. Thus claim of Zajc and other Penn collaborators at QM1984 that failure of WNM was due to jets was WRONG as acknowledged in their QM1984 Proceedings



PLB**168**(1986)158

Both p-p and alpha-alpha data are beautiful Γ-distributions with the same value of p=2.5 which means they scale in the mean over 10 orders of magnitude!!! This is a fluke, one of many in this field.

$$\langle E\rangle f_1(E) = \psi(z) = [p/\Gamma(p)](pz)^{p-1}\, e^{-pz}.$$

Extreme Independent Models in A+A

FNAL p+A measurements at $\sqrt{s_{NN}}$=20 GeV in 1972 inspired Wounded Nucleon Model

One of the more memorable of the proposals from my service on Bob Wilson's Program Advisory Committee at FNAL from 1972-75

NAL Proposal NO. 178
Correspondent:
Wit Busza
MIT: 24-510
Cambridge, Mass. 02139
617- 864-6900 X7586
June, 1972

A study of the average multiplicity and multiplicity distributions in hadron-nucleus collisions at high energies

W. Busza, J. I. Friedman, H. W. Kendall and L. Rosenson
Massachusetts Institute of Technology, Cambridge, Massachusetts

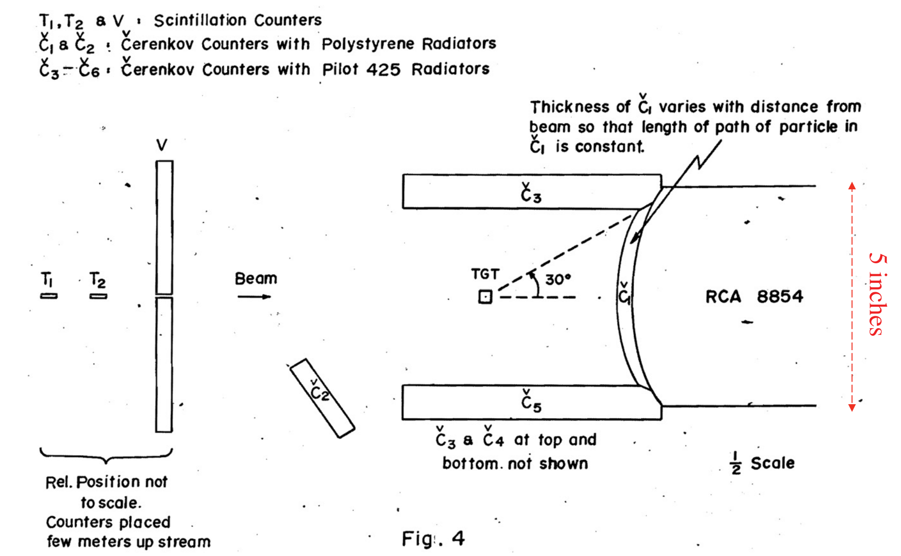
ABSTRACT

In a simple counter experiment requiring about 40 hours of data taking time we propose to study the detailed shape of the multiplicity distribution for larger values of n and the average charged particle multiplicity in hadron-nucleus collisions at 100 and 200 Gev.

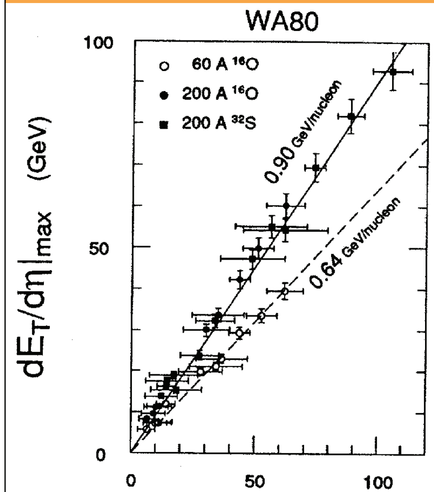
The results of the experiment should be a valuable input for comparison with theoretical models, in particular they should provide a sensitive test of whether multiparticle production in hadron-nucleon collisions proceeds through a one or two step process.

This was the first accelerator experiment specifically designed to study the charged multiplicity in high energy p+A collisions

Wit proposed ONE photomultiplier!



In 60, 200 A GeV fixed target p+A and A+A collisions N_{ch} and E_T scale with N_{part} not N_{coll}

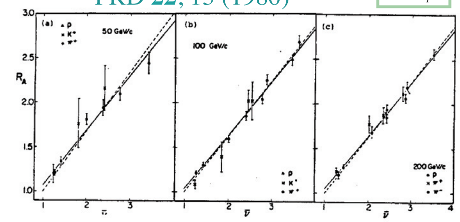


PRC **44**, 2736 (1991)

$\mathbf{W}$ = <Npart> from ZDC

Original Discovery by W. Busza, et al at FNAL $\langle n\rangle_{pA}$ vs $\langle\nu\rangle = (N_{coll})$ PRD **22**, 13 (1980)

$$\bar{\nu} = \frac{A\sigma_{pp}}{\sigma_{pA}}$$



$R_A = \langle n\rangle_{pA} / \langle n\rangle_{pp} = (1+\langle\nu\rangle)/2$

$\langle Npart\rangle_{pA}$

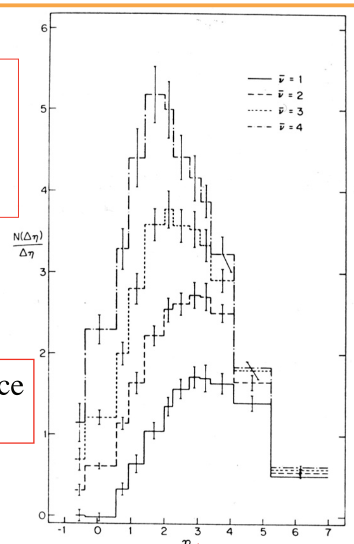
$\langle Npart\rangle_{pp}$

FNAL p+A data inspire Wounded Nucleon N_{part} Model

p+A where A is represented by average number of collisions $\bar{\nu}$

$$\bar{\nu} = \frac{A\sigma_{pp}}{\sigma_{pA}}$$

Strong dependence on rapidity



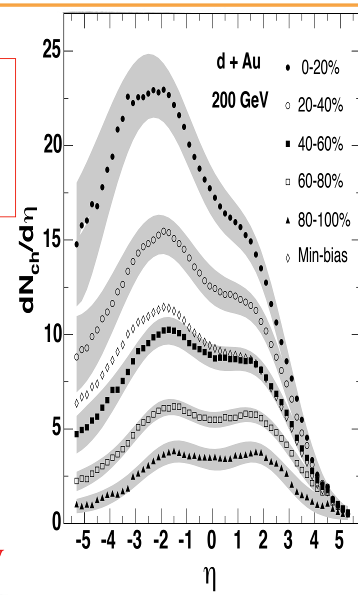
PRL **39**, 1499 (1977)

- NO CHANGE (η>5) Forward fragmentation proton passes through!!
- Tremendous Activity Target region (η<0.5)
- ★ Mid rapidity: dn/dη increases with A with small shift backwards with increasing A

200 GeV fixed target $y^{NN}_{cm}=3.0$ $\sqrt{s_{NN}}=19.4$ GeV

FNAL p+A data inspire Wounded Nucleon N_{part} Model

d+Au at RHIC looks the same vs **centrality** PHOBOS



PRC**72**,031901(2005)

- NO CHANGE (η>5) Forward fragmentation proton passes through!!
- Tremendous Activity Target region (η<0.5)
- ★ Mid rapidity: dn/dη increases with A with small shift backwards with increasing A

$\sqrt{s_{NN}}=200$ GeV

Physics of A+A collisions c. 1980. Quantum Mechanics and Relativity Very Important

•Immediately after a nucleon interacts with another nucleon in a nucleus the only thing consistent with relativity and quantum mechanics is for the nucleon to become an excited nucleon with roughly the same energy but reduced longitudinal momentum (rapidity), i.e. m $\longrightarrow$ m*, E*=E, p*<p

• The nucleus is transparent, incident protons pass through, make many successive collisions and come out the other side

• Uncertainty principle and time dilation prevent cascading of produced particles in relativistic collisions γ h/m_πc > 10fm even at AGS energies: particle production takes place outside the Nucleus in a p+A reaction.

With 2 additional assumptions:

• An excited nucleon interacts with the same cross section as an unexcited nucleon.

• Successive collisions of the excited nucleon do not affect the excited state or its eventual fragmentation products

The conclusion is that the elementary process for particle production in nuclear collisions is the excited nucleon and that the multiplicity is proportional to the number of excited nucleons **=Wounded Nucleon Model (Npart)**

Extreme Independent Models

- **Extreme-Independent models:** separate nuclear geometry and fundamental elements of particle production.
- Nuclear Geometry represented by the weights, the relative probability w_n per B+A interaction for a given number n of fundamental elements, which are assumed to emit particles independently.
- I will discuss models with 3 different fundamental elements:
  - ✓**Wounded Nucleon Model (WNM)** - number of participants N_{part}
  - ✓**Quark Part. Model (NQP),** -number of constituent-quark participants N_{qp}
  - ✓**Additive Quark Model (AQM),** color-strings between quark participants in projectile & target: constraint: one string per qp → **projectile quark participants**.
- AQM & NQP cannot be distinguished for symmetric collisions, since projectile and target have the same number of struck quarks. Need asymmetric collisions, *e.g*, d+Au,

See A. Bialas pp139-165 in Proc. Bielefeld Workshop 1982, Eds Jacob, Satz, World Scientific.

Implementation

• The dynamics of the fundamental elementary process is taken from the data: e.g. the measured E_T distribution for a p-p collision represents: 2 participants (WNM); a predictable convolution of constituent-quark-participants (Nqp); or projectile quark participants (AQM).

•The above bullet is why I like these models: a Glauber calculation of the weights, w_n, and a p-p measurement provide a prediction for B+A in the same detector.

• Use a Gamma distribution as the pdf for a fundamental element

$$f(x) = f_\Gamma(x,p,b) = \frac{b}{\Gamma(p)}(bx)^{p-1}e^{-bx}$$

• If E_T adds independently for n elements, i.e. participants, etc, the pdf is the n-fold convolution of $f(x)$: $p \rightarrow np$ $b \rightarrow b$

$$f_n(x) = \frac{b}{\Gamma(np)}(bx)^{np-1}e^{-bx} = f_\Gamma(x,np,b)$$

Summary of Wounded Nucleon Models at mid-rapidity c. 1991

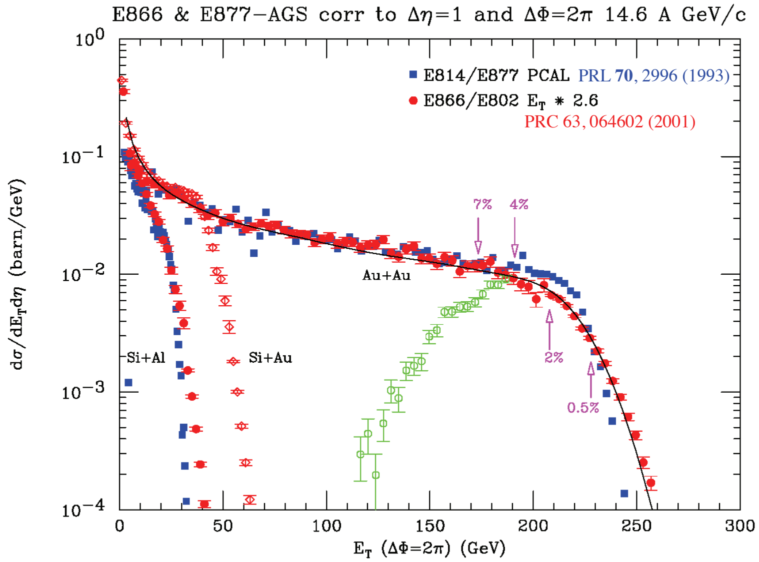
• The classical Wounded Nucleon (N_{part}) Model (WNM) of Bialas, Bleszynski and Czyz (NPB **111**, 461 (1976)) works at mid-rapidity only at CERN fixed target energies, $\sqrt{s_{NN}}$~20 GeV.

• WNM overpredicts at AGS energies $\sqrt{s_{NN}}$~ 5 GeV (WPNM works at mid-rapidity)--this is due to stopping, second collision gives only few particles which are far from mid-rapidity. E802

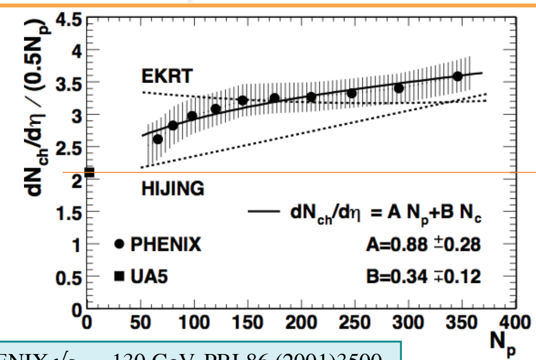
• WNM underpredicts for $\sqrt{s_{NN}} \geq$ 31 GeV---Additive Quark Model Works. BCMOR + Ochiai

• This is the explanation of the ‘famous’ kink, well known as p+A effect since QM87+QM84

E_T distributions in RHI collisions $\sqrt{s_{NN}}$=5.4 GeV



But first, evolution of mid-rapidity $dN_{ch}/d\eta/(0.5N_{part})$ with centrality, N_{part}



If WNM works, $dN_{ch}/d\eta/(0.5\ N_{part})$ should be constant at the p-p value, i.e. WNM fails!

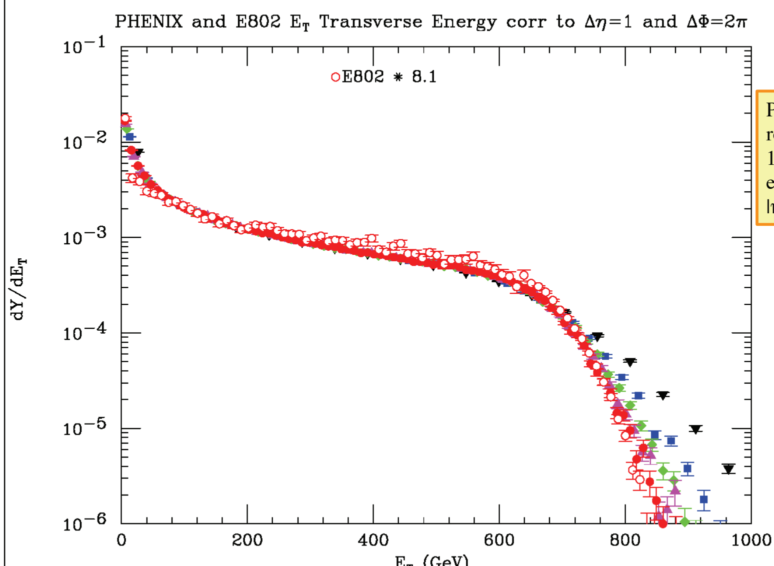
PHENIX $\sqrt{s_{NN}}$=130 GeV, PRL86 (2001)3500

Inspired by article in same issue [PRL86, 3496], PHENIX included the following fit:

$$dE_T{}^{AA}/d\eta = [(1-x)\ \langle N_{\rm part}\rangle\ dE_T{}^{pp}/d\eta/2 + x\ \langle N_{\rm coll}\rangle\ dE_T{}^{pp}/d\eta]$$

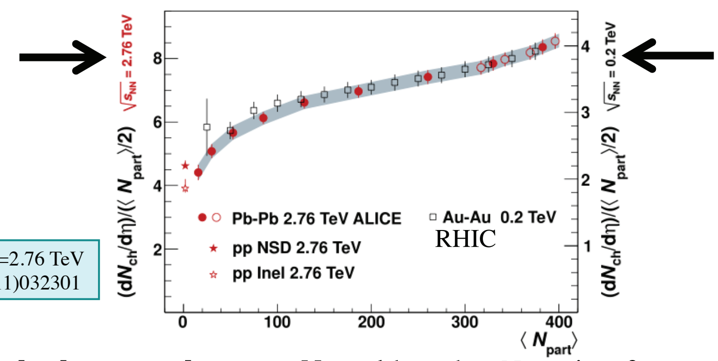
The N_{coll} term implied a hard-scattering component for E_T, known to be absent in p-p

Au+Au E_T spectra at AGS and RHIC are the same shape!!!



PHENIX E_T results in 1,2,3,4,5 sectors each with $|\eta|<0.38, \Delta\Phi=\pi/8$

Important Observation 2.76TeV cf. 200 GeV

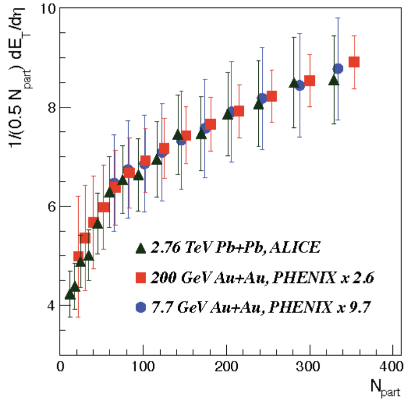


ALICE $\sqrt{s_{NN}}$=2.76 TeV PRL 106(2011)032301

- **Exactly the same shape vs. N_{part}** although $\langle N_{coll}\rangle$ is a factor of 1.6 larger and the hard-scattering cross section is considerably larger.
  - ✓ PHENIX (2001) $dN_{ch}/d\eta \sim N_{part}{}^{\alpha}$ with α=1.16±0.04 at $\sqrt{s_{NN}}$=130 GeV
  - ✓ WA97,98 (2000) $dN_{ch}/d\eta \sim N_{part}{}^{\alpha}$ with α=1.07±0.04 at $\sqrt{s_{NN}}$=17.2 GeV
  - ✓ ALICE (2013) $dN_{ch}/d\eta \sim N_{part}{}^{\alpha}$ with α=1.19±0.02 at $\sqrt{s_{NN}}$=2760 GeV
- Strongly argues against a hard-scattering component and for a Nuclear Geometrical Effect.

Identical shape of distributions indicates a nuclear-geometrical effect

New RHIC data for Au+Au at $\sqrt{s_{NN}}$ =0.0077 TeV show the same evolution with centrality



The geometry is the number of constituent quark participants/nucleon participant

Eremin&Voloshin, PRC 67, 064905(2003) ; De&Bhattacharyya PRC 71; Nouicer EPJC 49, 281 (2007)

Remember, constituent quarks also gave universal scaling for v_2/n_q vs KE_T/n_q

Constituent Quarks cf. Partons

Constituent quarks are Gell-Mann's quarks from Phys. Lett. 8 (1964)214, proton=uud [Zweig's Aces].These are relevant for static properties and soft physics, low Q^2<2 GeV^2 ; resolution> 0.14fm

For hard-scattering, p_T>2 GeV/c, $Q^2=2p_T^2$>8 GeV^2, the partons (~massless current quarks, gluons and sea quarks) become visible

1.6fm

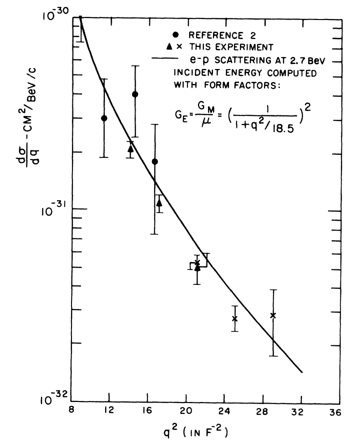
Resolution ~0.5fm

Resolution ~0.1fm

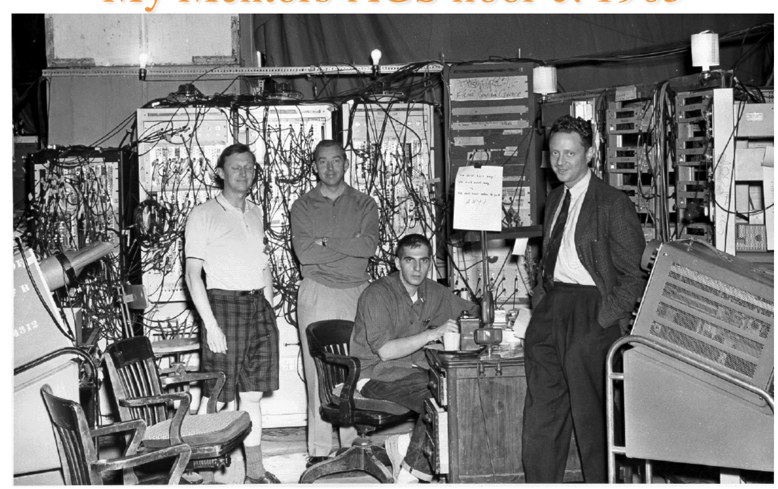
Resolution <0.07fm

To calculate the positions of the constituent quarks we need the charge distribution of the proton. The radius of the proton may be controversial to atomic physicists now but not to me because I measured it

R.L.Cool, A.Maschke, L.M.Lederman, M.Tannenbaum, R.Ellsworth, A.Melissinos, J.H.Tinlot and T. Yamanouchi PRL**14**, 724 (1965) *Muon-Proton Scattering at High Momentum Transfers*



My Mentors-AGS floor c. 1963



Tinlot, Cool (ALD), MJT, Lederman

My thesis experiment, muon-proton elastic scattering---``Why does the muon weigh heavy?" We still don't know! Next beam to left: first neutrino expt (Nobel Prize); over in inner Mongolia CP violation (Nobel Prize). Those were the days!

Details of NQP calculation

The NQP calculation for a B+A reaction

$$\left(\frac{d\sigma}{dE_T}\right)_{\rm NQP} = \sigma_{BA} \sum_{n=1}^{B} w_n P_n(E_T) \qquad (15)$$

- σ_{BA} is the measured B+A cross section in the detector aperture,
- w_n is the relative probability for n quark participants in the B+A reaction from a Glauber Monte Carlo.
- $P_n(E_T)$ is the calculated E_T distribution on the detector aperture for n **independently interacting** quark participants.
- If $f_1(E_T)$ is the measured E_T spectrum on the detector aperture for one quark participant, and p_0 is the probability for the elementary collision to produce no signal on the detector aperture, then, the correctly normalized E_T distribution for one quark participant is:

$$P_1(E_T) = (1-p_0) f_1(E_T) + p_0 \delta(E_T) \quad , \qquad (16)$$

where $\delta(E_T)$ is the Dirac delta function and $\int f_1(E_T)\, dE_T = 1$.

- $P_n(E_T)$ (including the p_0 effect) is obtained by convoluting $P_1(E_T)$ with itself $n-1$ times

$$P_n(E_T) = \sum_{i=0}^{n} \frac{n!}{(n-i)!\; i!} p_0^{n-i} (1-p_0)^i f_i(E_T) \qquad (17)$$

where $f_0(E_T) \equiv \delta(E_T)$ and $f_i(E_T)$ is the i-th convolution of $f_1(E_T)$:

$$f_i(x) = \int_0^x dy\, f(y)\, f_{i-1}(x-y) \quad . \qquad (18)$$

Apart from generating the positions of the 3 quarks per nucleon this is standard method for calculations of E_T distributions. See PHENIX PRC**89** (2014) 044905 for further details. Also see MJT PRC69(2004)064902

3 quarks are distributed about the center of each nucleon with a spatial distribution $\varrho(r)=\varrho(0)\exp(-ar)$ where $a=\sqrt{12}/r_m=4.27$ fm^{-1} and $r_m=0.81$ fm is the rms charge radius of the proton. Hofstadter RevModPhys 28(1956)214 The q-q inelastic scattering cross section is adjusted to 9.36 mb to reproduce the 42 mb N+N inelastic cross section at $\sqrt{s_{NN}}$=200 GeV

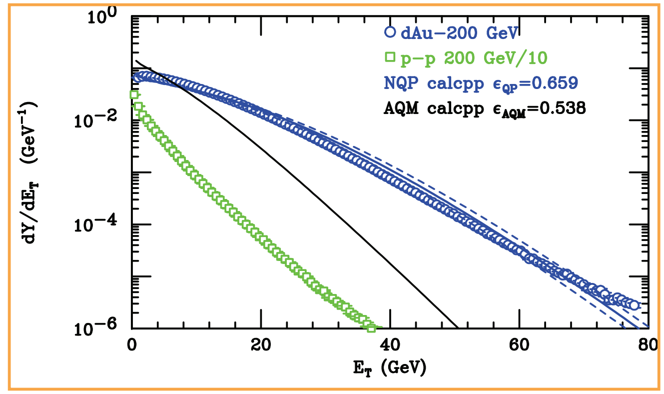
Gamma distribution is used because it fits and because n-th convolution is analytical

$$f(x) = \frac{b}{\Gamma(p)} (bx)^{p-1} e^{-bx}$$

$$f_n(x) = \frac{b}{\Gamma(np)} (bx)^{np-1} e^{-bx}$$

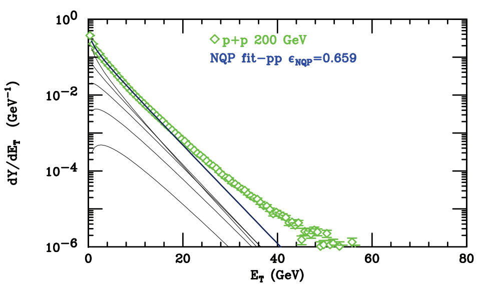
N_{qp} or AQM?

- Additive Quark Model (AQM) & NQP Identical for symmetric collision systems
- PHENIX asymmetric d+Au data resolves the degeneracy! It is NQP



The Additive Quark Model (AQM), Bialas and Bialas PRD20(1979)2854 and Bialas, Czyz and Lesniak PRD25(1982)2328,→ color string model. In the AQM model only one color string can be attached to a wounded quark. However for asymmetric systems such as d+Au it is a ``wounded projectile quark'' model since in this model, a maximum of 6 color strings are allowed from d to Au although the Au has many more quark participants. PHENIX data shows that all the quark participants are needed to reproduce d+Au data.

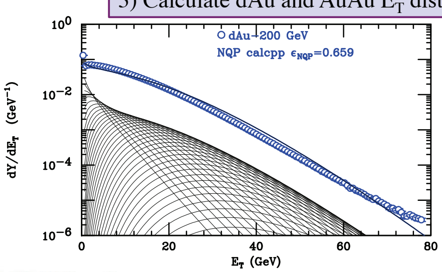
PHENIX NQP model: Data driven pp→ dAu, AuAu

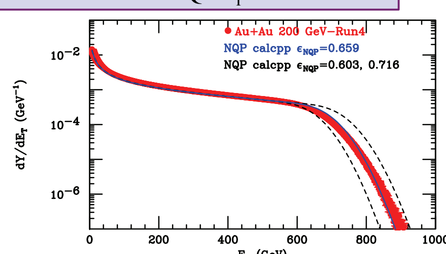


1) Generate 3 constituent quarks around nucleon position, distributed according to proton charge distribution for pp, dA, AA

2) Deconvolute p-p E_T distribution to the sum of 2—6 quark participant (QP) E_T distributions taken as Γ distributions

3) Calculate dAu and AuAu E_T distributions as sum of QP E_T distributions





Previous analyses have shown that Quark Participant Model works in Au+Au but could have been the AQM

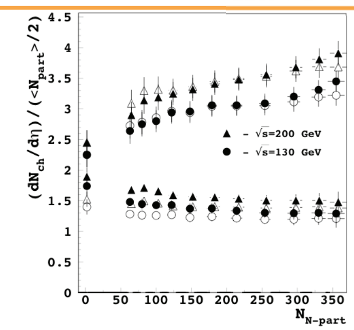
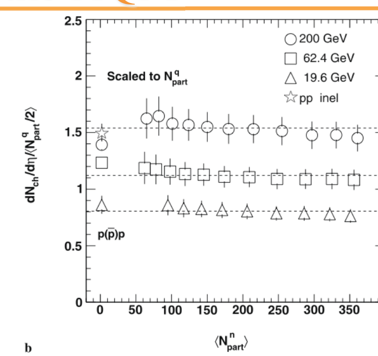


FIG. 3. (Color online) N_{ch} per nucleon and quark participant pair vs centrality. The results for quark participant pair are shown for σ_{qq}=4.56 mb (solid symbols) and σ_{qq}=6 mb (open symbols).

Eremin&Voloshin, PRC **67** (2003) 064905

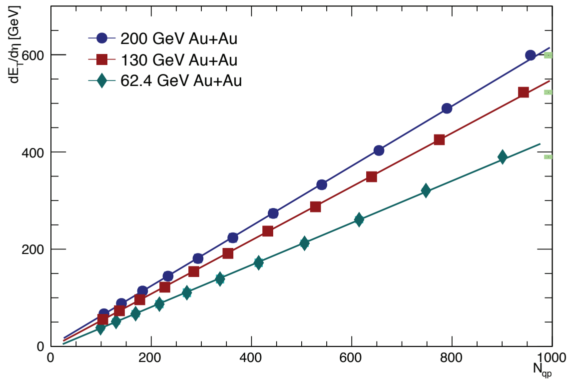


b

Nouicer, EPJC **49** (2007) 281

These analyses didn't do entire distributions but only centrality-cut averages. PHENIX has also done this and learned something VERY interesting.

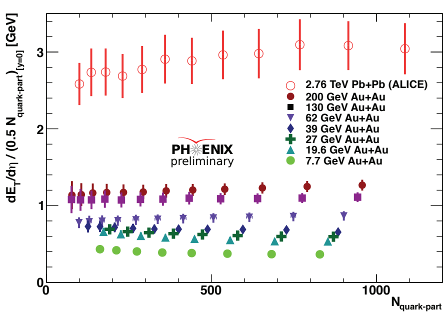
$dE_T/d\eta$ is "strictly proportional" to Nqp



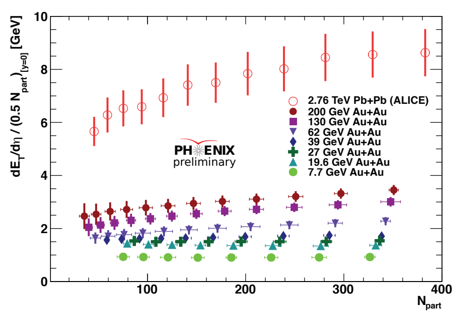
A fit of $dE_T/d\eta = a \times N_{qp} + b$ at each $\sqrt{s_{NN}}$ gives b=0 in all 3 cases which establishes the linearity of $dE_T/d\eta$ with N_{qp}

$\sqrt{s_{NN}}$ (GeV)	a (GeV)	b (GeV)
200	0.617 ± 0.023	1.2 ± 7.0
130	0.551 ± 0.020	-2.1 ± 6.5
62.4	0.432 ± 0.019	-5.4 ± 5.4

NQP Scaling works for $\sqrt{s_{NN}} \geq 31$ GeV



$dE_T/d\eta/(0.5\text{Nqp})$ vs Nqp constant for $\sqrt{s_{NN}}$>27 GeV



$dE_T/d\eta/(0.5\text{Npart})$ vs Npart constant near $\sqrt{s_{NN}}$=20 GeV

Jeff Mitchell has recently added Nqp analyses and new measurements from $\sqrt{s_{NN}}$ =7.7 to 39 GeV as well as the Nqp analysis for 2.76 TeV

How I learned to love the Ansatz-Autumn 2013

$$dE_T{}^{AA}/d\eta = [(1-x)\ \langle N_{\rm part}\rangle\ dE_T{}^{pp}/d\eta/2 + x\ \langle N_{\rm coll}\rangle\ dE_T{}^{pp}/d\eta]$$

The N_{coll} term implied a hard-scattering component for E_T, known to be absent in p-p!

However, both ATLAS [PLB707(2012)330] and ALICE [PRC 88 (2013)044909] computed this ansatz in an event-by-event MC Glauber Calculation which fit their forward E_T measurements used to define centrality in 2.76 TeV Pb+Pb collisions. ALICE realized that this combination represented the number of emitting sources of particles, which they named "ancestors".

But if the ansatz works as a nuclear geometry element and a constituent quark also works THEN said Bill Zajc [now very senior] "the success of the two component model is not because there are some contributions proportional to N_{part} and some going as N_{coll}, but because a particular linear combination of N_{part} and N_{coll} turns out to be an empirical proxy for the number of constituent quarks". We checked and it worked so we are very happy!

PHENIX Calculation vs Centrality Au+Au

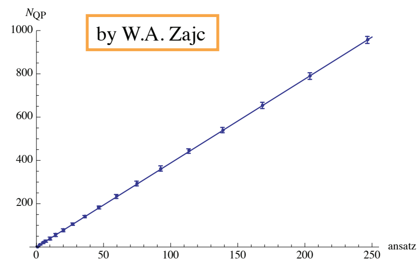
Et voilà, we checked and it worked: the ratio of $N_{qp}/[(1\text{-}x)N_{part}/2 + x\ N_{coll}]$=3.38 on the average and varies by less than 1% over the entire centrality range in 1% bins, except for the most peripheral bin where it is 5% low and for p-p collisions where it is 2.99

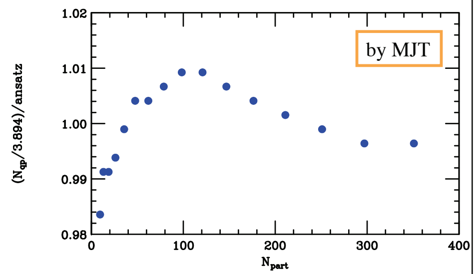
Centrality	$\langle N_{part}\rangle$	$\langle N_{qp}\rangle$	$\langle N_{\rm coll}\rangle$	ansatz	$\langle N_{\rm qp}\rangle$/ansatz
0-5%	350.9 ± 4.7	956.6 ± 16.2	1064.1 ± 110.0	246.5	3.88
5-10%	297.0 ± 6.6	789.8 ± 15.3	838.0 ± 87.2	203.7	3.88
10-15%	251.0 ± 7.3	654.2 ± 14.5	661.1 ± 68.5	168.3	3.89
15-20%	211.0 ± 7.3	540.2 ± 12.3	519.1 ± 53.7	138.6	3.90
20-25%	176.3 ± 7.0	443.3 ± 10.4	402.6 ± 39.5	113.3	3.91
25-30%	146.8 ± 7.1	362.8 ± 12.2	311.9 ± 31.8	92.5	3.92
30-35%	120.9 ± 7.0	293.3 ± 11.0	237.8 ± 24.2	74.6	3.93
35-40%	98.3 ± 6.8	233.5 ± 9.2	177.3 ± 18.3	59.4	3.93
40-45%	78.7 ± 6.1	182.7 ± 6.8	129.6 ± 12.6	46.6	3.92
45-50%	61.9 ± 5.2	140.5 ± 5.3	92.7 ± 9.0	35.9	3.91
50-55%	47.6 ± 4.9	105.7 ± 5.5	64.4 ± 8.1	27.0	3.91
55-60%	35.6 ± 5.1	77.3 ± 6.8	43.7 ± 7.6	19.9	3.89
60-65%	26.1 ± 4.7	55.5 ± 7.1	29.0 ± 6.5	14.3	3.87
65-70%	18.7 ± 4.0	39.0 ± 6.7	18.8 ± 5.3	10.1	3.86
70-75%	13.1 ± 3.2	27.0 ± 4.9	12.0 ± 3.6	7.0	3.86
75-80%	9.4 ± 2.1	19.0 ± 3.2	7.9 ± 2.2	5.0	3.83
80-92%	5.4 ± 1.2	10.3 ± 1.5	4.0 ± 1.0	2.8	3.67
p+p	2	2.99 ± 0.05	1	1	2.99

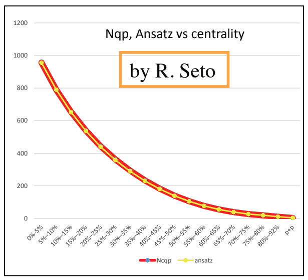
x=0.08

PHENIX Collab. S. S. Adler, *et al.*, PRC 89, 044905 (2014)

People who prefer plots are also happy







Conclusions

- The Constituent Quark Participant Model (N_{qp}) works at mid-rapidity for A+B collisions in the range (~30 GeV) 62.4 GeV< $\sqrt{s_{NN}}$< 2.76 TeV.
- The two component ansatz [(1-x)N_{part}/2+x N_{coll}] also works but does not imply a hard-scattering component in N_{ch} and E_T distributions. It is instead a proxy for N_{qp} as a function of centrality.
- Thus, ALICE's "ancestors" are constituent-quarks.
- Everybody's happy. (OK probably not everybody).

Edward Shuryak is Happy, (CGC types less so?)

arXiv:1404.1888

Collective interaction of QCD strings and early stages of high multiplicity pA collisions

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Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA
(Dated: April 8, 2014)

We study early stages of "central" *pA* and peripheral *AA* collisions. Several observables indicate that at the sufficiently large number of participant nucleons the system undergoes transition into a new "explosive" regime. By defining a string-string interaction and performing molecular dynamics simulation, we argue that one should expect a strong collective implosion of the multi-string "spaghetti" state, creating significant compression of the system in the transverse plane. Another consequence is collectivization of the "sigma clouds" of all strings into collective chorally symmetric fireball. We find that those effects happen provided the number of strings $N_s > 30$ or so, as only such number compensates small sigma-string coupling. Those finding should help to understand subsequent explosive behavior, observed for particle multiplicities roughly corresponding to this number of strings.

I. INTRODUCTION

A. The evolving views on the high energy collisions

Before we got into discussion of high multiplicity *pA* collisions, let us start by briefly reviewing the current views on the two extremes: the *AA* and the minimum bias pp collisions.

The "not-too-peripheral" *AA* we will define as those which have the number of participant nucleons $N_p > 40$, and the corresponding multiplicity of the order of few hundreds. (*Peripheral AA*, complementary to this definition, we will discuss in this paper, below in section IV B.) Central *AA* collisions produce many thousands of secondaries: the corresponding fireball has the

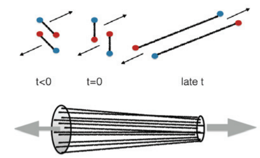
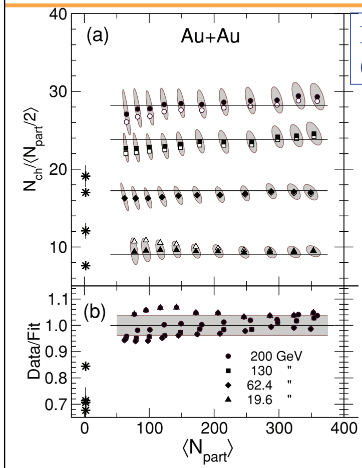


FIG. 1: The upper plot reminds the basic mechanism of two string production, resulting from color reconnection. The lower plot is a sketch of the simplest multi-string state, produced in pA collisions or very peripheral *AA* collisions, known as "spaghetti".

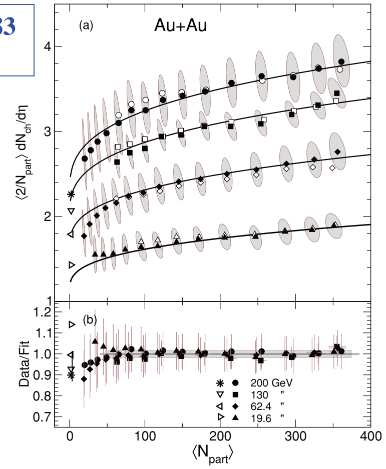
Confirmation: Solution to several puzzles

PHOBOS-Final Multiplicity Paper 2011

PHOBOS PRC **83** (2011) 024913



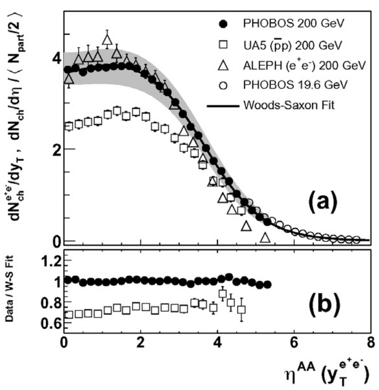
Using full rapidity range, total $N_{ch}/(0.5N_{part})$ does follow WNM (in AA only) but p-p Nch is a factor of ~1.5 lower than AuAu.



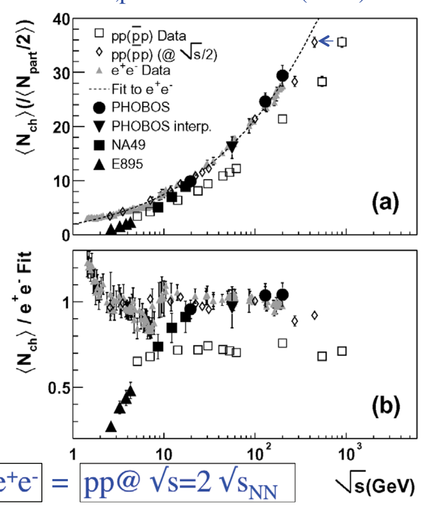
At mid-rapidity $dN_{ch}/d\eta/(0.5N_{part})$ shows the apparently universal dependence first seen by PHENIX and recently at LHC.

MJT-Erice 2003-For Nino PHOBOS dn/dη, N_{ch}

cf. M.Basile, A. Zichichi et al, PL **B92**, 367 (1980); **B95**, 311 (1980)



From 1993,published PRC74(2006)021902



$N_{ch}/\langle N_{part}/2\rangle$ Au+Au @ $\sqrt{s_{NN}}$ ~ e^+e^- = pp@ $\sqrt{s}=2\sqrt{s_{NN}}$

Leading particle effect-in pp--Zichichi—vanishes in AuAu

But this effect disagrees with the WNM because the basic assumption is that what matters is whether or not a nucleon was struck, not how many times it was struck. The good news is that the quark-participant model solves this problem because the multiplicity increases due to more constituent quarks/wounded nucleon being struck, from 1.5 in a p-p collision to 2.3-2.7 in central Au+Au

Hui Wang, BNL-STAR

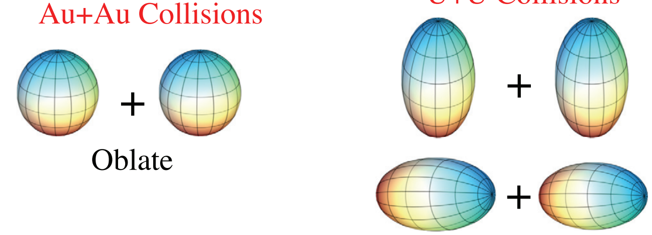
U+U Collisions-STAR Motivation

Allows us to manipulate the initial geometry and study:

- How multiplicity depends on N_{part} and N_{coll} They won't be happy
- Path-length dependence of jet quenching
- Particle production in heavy-ion collisions
- Other effects most importantly v_2 in central collisions

Au+Au Collisions

U+U Collisions



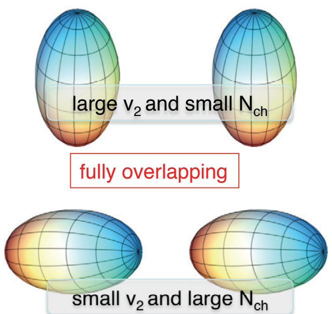
Oblate

Prolate

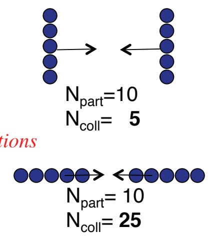
Can we see a difference between Au+Au and U+U and preferentially select body-body or tip-tip U+U collisions?

Selecting Body-body or Tip-tip

In two-component model, multiplicity depends on the N_{part} and N_{coll} and since v_2 is propotional to initial eccentricity



$$n_{AA} \propto n_{pp}[(1-x_{hard})\frac{N_{part}}{2} + x_{hard}N_{coll}]$$



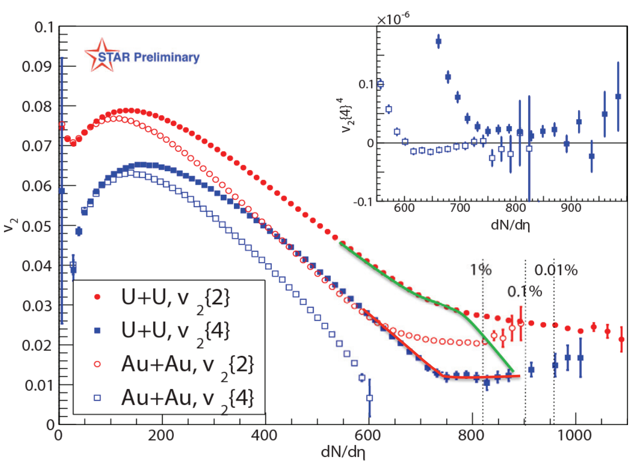
This is wrong they will be disappointed

If dN/dη depends on N_{coll}, large dN/dη should correlate with small v_2.

➪ *Central U+U collisions are ideal for testing particle production*

Strategy: select events with few spectators (fully over-lapping), then measure v_2 vs. multiplicity: **how strong is the correlation?**

Minimum-bias U+U and Au+Au



No evidence of knee structure for central U+U

- ✓Glauber plus 2-component model suggests knee structure at ~2% centrality
- ✓Knee washed out by additional multiplicity fluctuations?1
- ✓Other interpretations? Yes,Nqp!!!

[1]Maciej Rybczyński, et. al. Phys.Rev. C87 (2013) 044908

The U+U $v_2\{4\}$ results are non-zero in central

✓Result of intrinsic prolate shape of the Uranium nucleus

✓Au $v_2\{4\}$4 becomes consistent with zero

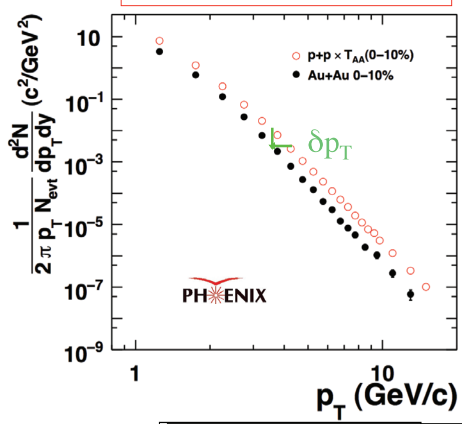
Dashed lines represent top centrality percentages for U+U collisions based on multiplicity, curves are used to guide the eye

$v_2\{4\}$ data: we see the prolate shape of the Uranium nucleus ✓

The lack of a knee indicates a weakness in Ncoll multiplicity models

A reminder RHIC π^0 pp vs AuAu

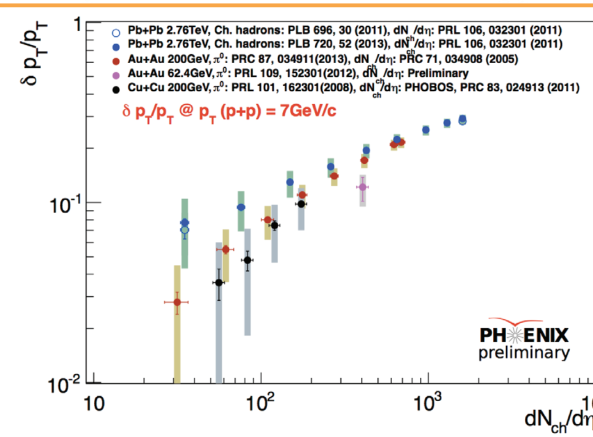
π^0 are suppressed in Au+Au eg 200 GeV



Shift in spectrum≈ energy loss

$$R_{AA}(p_T) \Rightarrow \delta p_T / p_T$$

dNch/dη determines the "energy loss" $\delta p_T/p_T$



Not quite universal $\delta p_T/p_T \approx (dN_{ch}/d\eta)^\alpha$, α≈0.35@ 2.76 TeV, α≈0.55 @200 GeV

200 GeV and 2.76 TeV curves may merge $(dN_{ch}d\eta)\geq300$

Thus

For centrality-cut data, the two-component ansatz $dE_T/d\eta \propto (1-x)N_{part}/2+xN_{coll}$ which has been used to explain E_T distributions is shown to be simply a proxy for Nqp, so that the Ncoll term does not represent a hard-scattering component in E_T distributions. The energy loss of hard-scattered initial state partons has been shown to be proportional to the charged-particle multiplicity dNch/dη at both RHIC and LHC which follows the same Nqp scaling as E_T distributions. Thus IMHO it is hard to avoid the conclusion that the relevant initial state for production of the QGP in A+A collisions at both RHIC and LHC is based on massive constituent-quarks rather than the massless current quarks and gluons that they contain which are observable at finer resolution as the initial state partons of hard-scattering which produce the jet and single particle probes at large p_T .

Everybody is still happy, Right?

Find p_0 in p-p collisions by measuring the E_T cross section with same method as for π^0

n.b. Tail is due to pileup. 0.9% of data for E_T>15 GeV $\langle E_T \rangle$ of fits and data differ by <0.6%

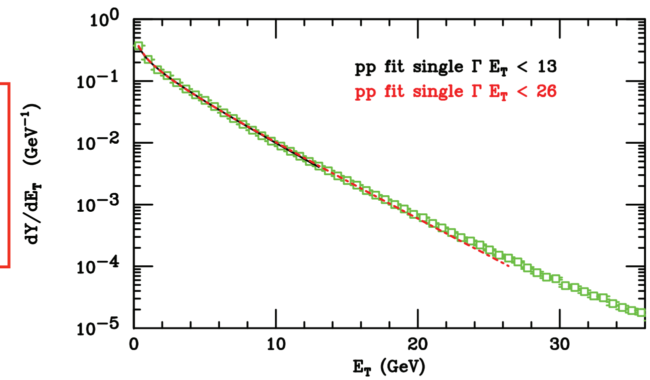
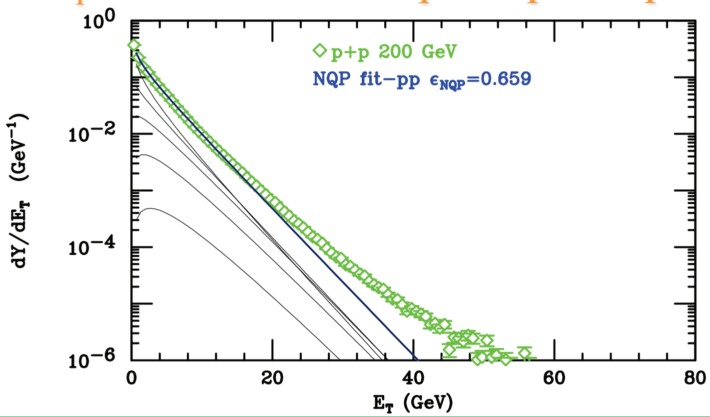


TABLE X: Fitted parameters Y_Γ^{pp} b, p of p+p data, and calculated $1-p_0$. Note that the standard errors on these parameters using $\chi^2=\chi^2_{\min}+1$ have been multiplied by $\sqrt{\chi^2_{\min}/\mathrm{dof}}$ in each case.

System	Y_Γ^{pp}	b (GeV)$^{-1}$	p	$\langle E_T\rangle^{ref}$ GeV	$\chi^2_{\min}$/dof	$1-p_0$
p+p $E_T<13.3$	0.933 ± 0.006	0.273 ± 0.003	0.724 ± 0.010	2.64	4866/17	0.647 ± 0.065
p+p $E_T<26.6$	0.952 ± 0.004	0.263 ± 0.003	0.692 ± 0.007	2.63	6715/37	0.660 ± 0.066

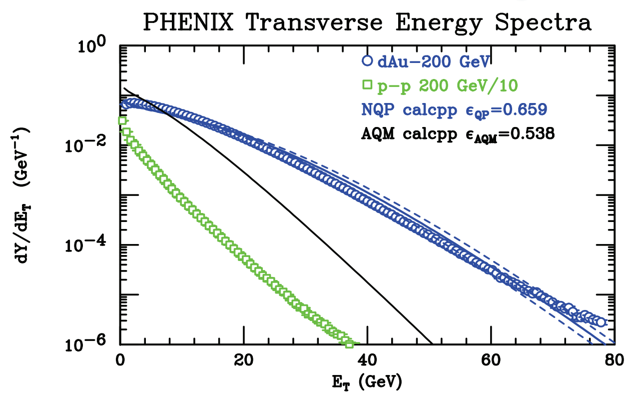
$$1-p_0=\frac{1}{\sigma_{\mathrm{INEL}}}\,\frac{23.0\,\mathrm{mb}\pm9.7\%}{0.79\pm0.02}\,Y_\Gamma^{pp}=0.693(\pm10\%)\,Y_\Gamma^{pp}$$

Deconvolute the p-p E_T distribution to find the E_T distribution of a quark-participant



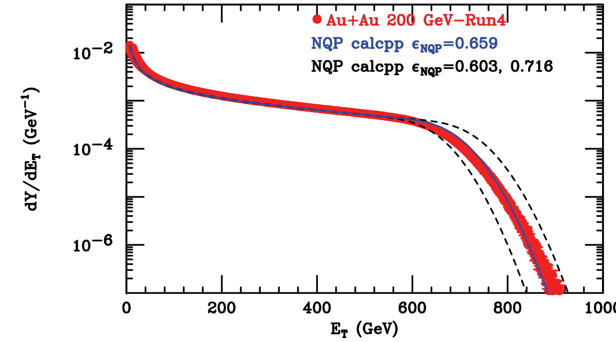
p-p E_T distribution fit to the sum (blue) of properly weighted E_T distributions of 2,3,4,5,6 constituent-quark-participants with constituent-quark $\varepsilon_{NQP}=1-p_0=0.659$ (black lines) [Γ distributions].

Calculate d+Au and Au+Au E_T distributions



The NQP calculation is in excellent agreement with the d+Au measurement in shape and in magnitude over a range of a factor of 1000 in cross section, while the AQM calculation disagrees both in shape and magnitude, with a factor of 1.7 less E_T emission than the measurement, clearly indicating the need for the emission from additional quark-participants in the target beyond those in the projectile deuteron.

Calculate d+Au and Au+Au E_T distributions



Both the shape and magnitude of the NQP calculation are in excellent agreement with the Au+Au measurement. The upper edge of the calculation using the central $\varepsilon_{NQP}=1-p_0=0.659$ is essentially on top of the measured E_T distribution, well within the systematic error shown. The systematic error is predominantly from the 10% uncertainty in p_0 calculated from the measured E_T cross section.

i.e. The kink is a p+A effect well known since 1987-seen at FNAL,ISR,AGS

Marek Gazdzicki
QM2004, QM 2001...
Pions per participant