Constituent quark number scaling: PHENIX transverse energy, multiplicity and flow results

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Workshop on Bulk Properties
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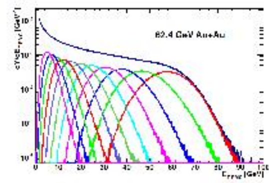
Based on PRC 89(2014)044905 (E_T)
+new preliminary results($\sqrt{s}$ dependence, E_T, multiplicity)
higher flow moments
Thanks to: M. Tannenbaum, J. Mitchell, S Esumi, T. Todoroki

Aplogies if I have missed some references to theory and other experiments.

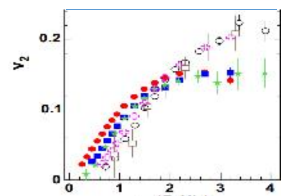
Outline:

Number of constituent quark (N_{cq}) scaling and two rather different topics
- o Flow: A final, or near final state process
- o Transverse Energy, and Multiplicity distributions: viewpoint is that of an initial state process

- Introduction to E_T, and N_{ch} distributions
  - Properties



- Flow and N_{cq} scaling and recombination
  - Higher moments



- Back to E_T and N_{ch}
  - Test 3 Extreme Independent Models
  - Calculating E_T and N_{ch}
  - Testing N_{cq} scaling, $\sqrt{s} = 200\ GeV, 2.76\ \mathrm{TeV}$
  - Lower energies

Global distributions: $dE_T/d\eta$ and $dN_{ch}/d\eta$

- Transverse Energy

$$E_T = \sum_i E_i \sin \bar{\ }_i$$

$$dE_T(\eta)/d\eta = \sin\theta(\eta)\, dE(\eta)/d\eta,$$

  - in the case of the ISR experiments, total EM energy E_T^0
- PHENIX – EMCAL
  - Corrected for inflow and outflow of energy
  - hadronic response is corrected using HIJING and adjusted to measured particle yield and p_T spectra
  - Limited η range at mid-rapidity

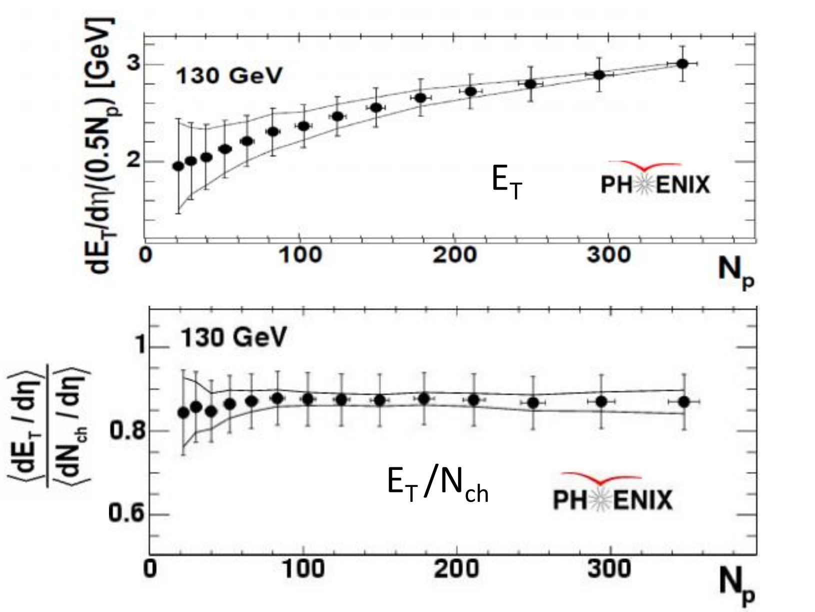
- Multiplicity (PHENIX)
  - Pad Chambers – combine hits in PC1 with PC3 (two pad chambers at r=2.5 and 5 m)
  - Zero field
  - Combinatorial background subtracted via mixed events
  - Corrections
    - Double hit resolution
    - decays

- Systematic errors
  - Transverse energy ~ 5-15%
  - Multiplicity 3-7% in/out flow
  - Trigger, and distribution of participants going into BBC

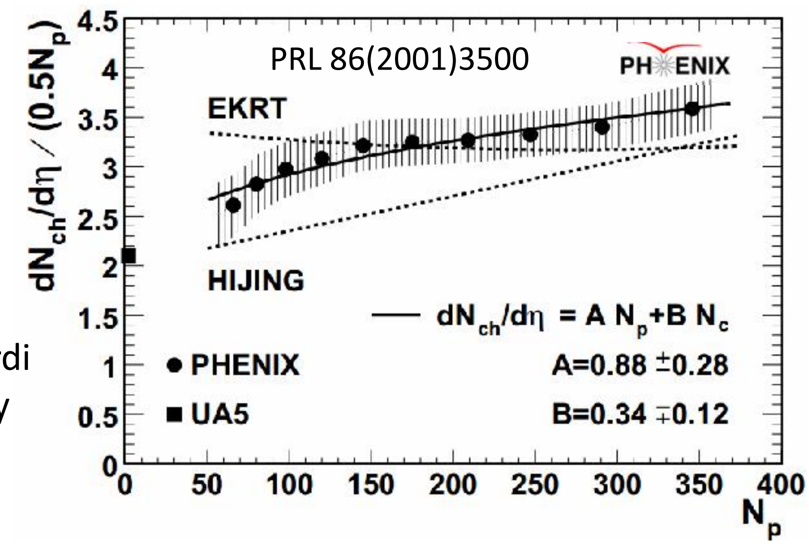
Reference acceptance

$\Delta\eta=1 \quad \Delta\phi=2\pi$

Mean values, soft+hard?



Kharzzeev, Nardi
Wang, Gyullasy



- N_{part} scaling doesn't work vs centrality
- $dN_{ch}/d\eta$ and $dE_T/d\eta$ behave similarly

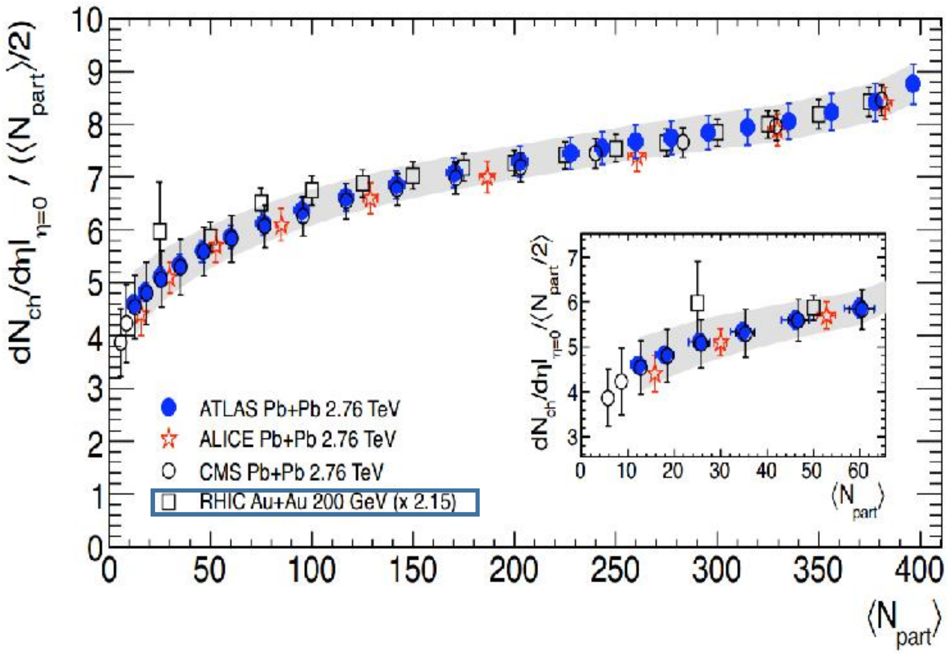
One early idea: Hard and Soft

$$\frac{d\{n, E_T\}}{d\eta} = \frac{d\{n, E_T\}_{pp}}{d\eta}\left[(1-x)\frac{\langle N_{part}\rangle}{2} + x\langle N_{coll}\rangle\right]$$

Works!

LHC: more hard scattering – N_{coll} large ⇨ steeper?

LHC compared to RHIC



ALICE PRL 106(2011)032301

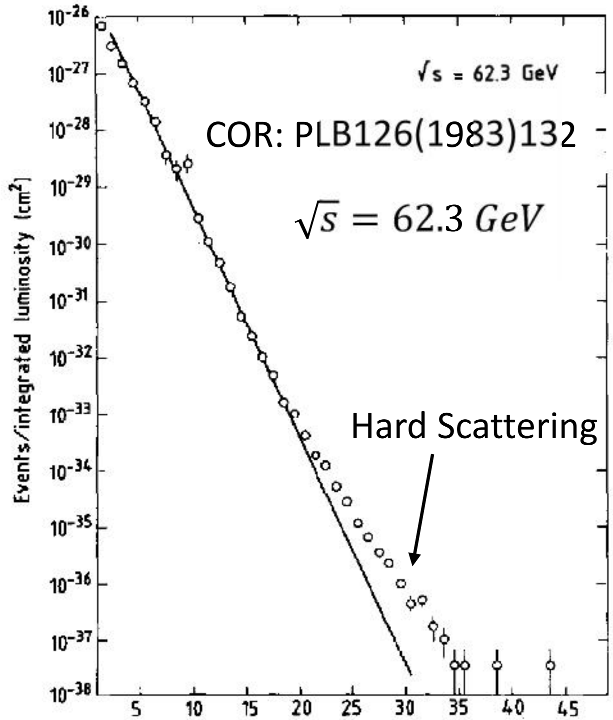
- RHIC and LHC have same shape
  - Surprising since
  - $<N_{coll}>$ at the LHC is 1.6 time larger than at RHIC

  - Argues against a hard scattering component
  - E_T
    - Dictated by soft physics
    - dependent on Nuclear geometry

  - Does not mean there is no Hard scattering! It just means it is not relevant for E_T and N_{ch} distributions

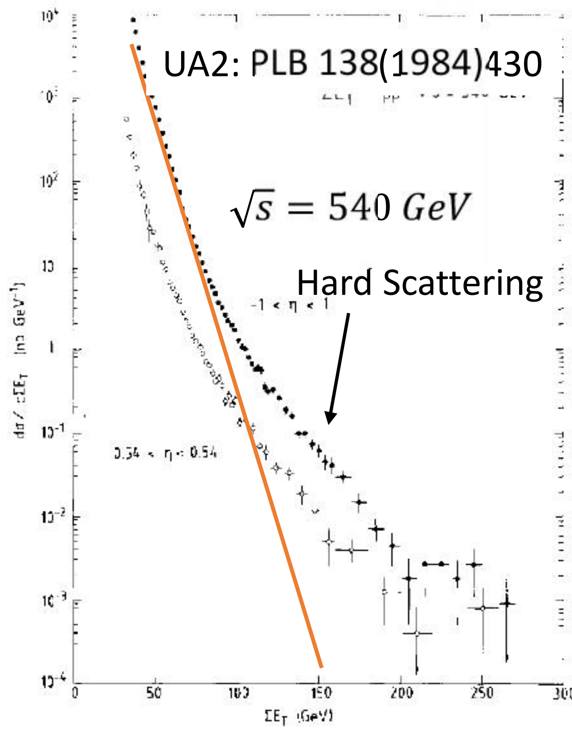
Some history: E_T distributions, Jets in pp

Initially E_T was thought to be a way to find jets in pp or $\bar{p}p$ collisions



E_T^0 (GeV)

|Δη|<0.8 Δφ=2π



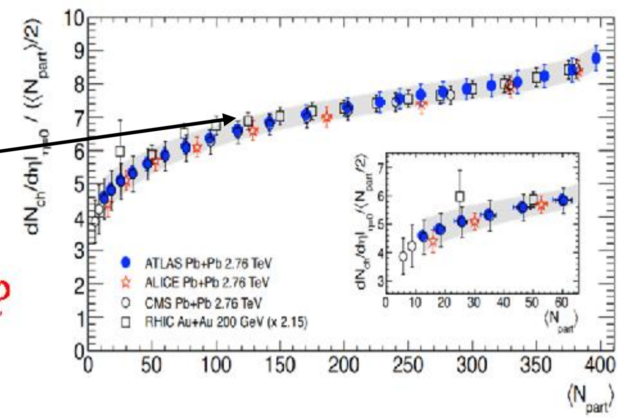
E_T(GeV)

|Δη|<1 Δφ=2π

- Hard scattering (jets) < 10^{-3} effect in E_T
- In p+p, soft physics dictates E_T distributions
  - $Q^2 < 2 GeV^2$
  - N_{coll} term absent in pp for E_T distributions

N_{cq} Scaling

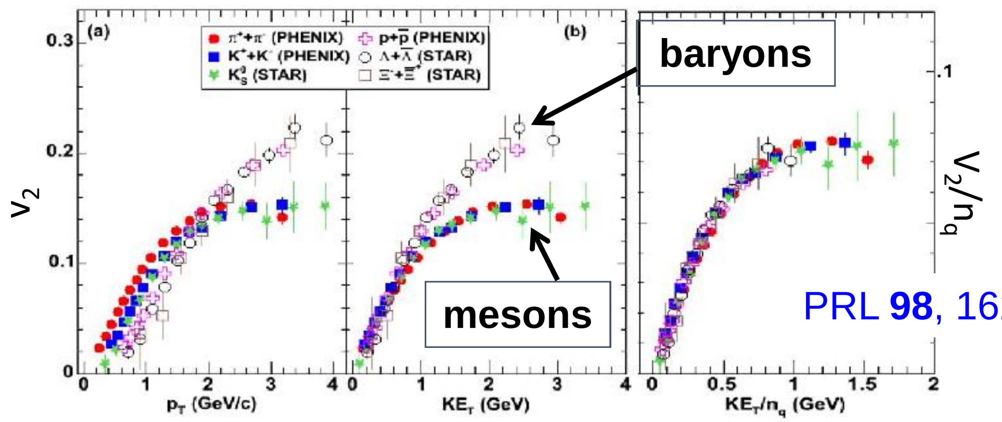
N_{part} scaling clearly doesn't work.



- Can we find some inspiration for another scaling variable?
  Yes → Flow results – N_{cq} scaling
- Original idea
  - Mesons N_{cq}=2
  - Baryons N_{cq}=3
  - recombination of constituent quarks → Final state hadron
- Hydrodynamic models, not invoking recombination
  - successful at reproducing flow
  - Cooper-Frye mechanism of final particle production from hydrodynamics
- For most models: three regions
  - p_T> 5 GeV – pQCD and jet quenching, hadronization via fragmentation functions
  - 1.5<p_T<5 GeV– N_{cq} scalling, hadrons via recombination
  - p_T<1.5 GeV – Hydrodynamics, hadrons via Cooper Frye
    - these sometime give results for flow moments, very close to predictions of N_{cq} scaling, particularly if you plot vs KE_T (e.g. Fries, PRC 82, 03907, 2010, and ref therein)

PID v_2/n_{cq} scaling

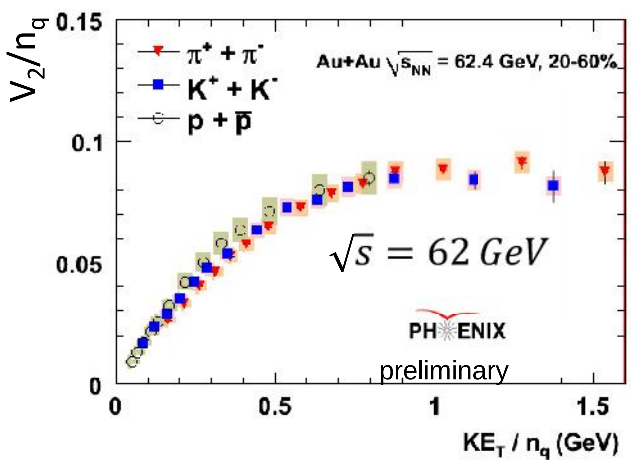
Min Bias Au+Au
$\sqrt{s} = 200\ \text{GeV}$

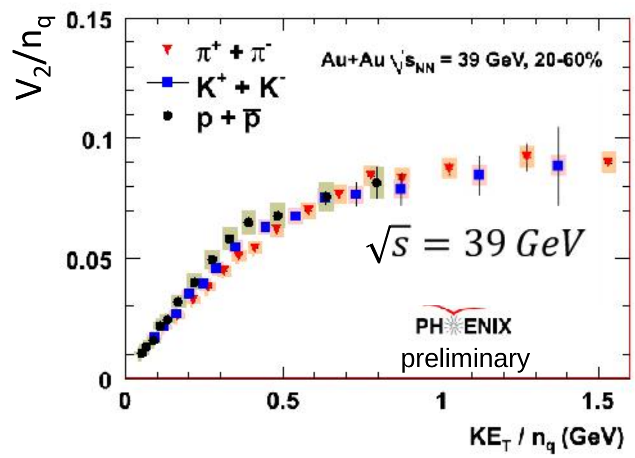


Note: Hydro models w/o recombination
can reproduce mass splitting e.g.1105.3226, 1108.5323
Also reproduced $dN_{ch}/d\eta$ via MC-KLN (CGC)

PRL **98**, 162301 (2007)

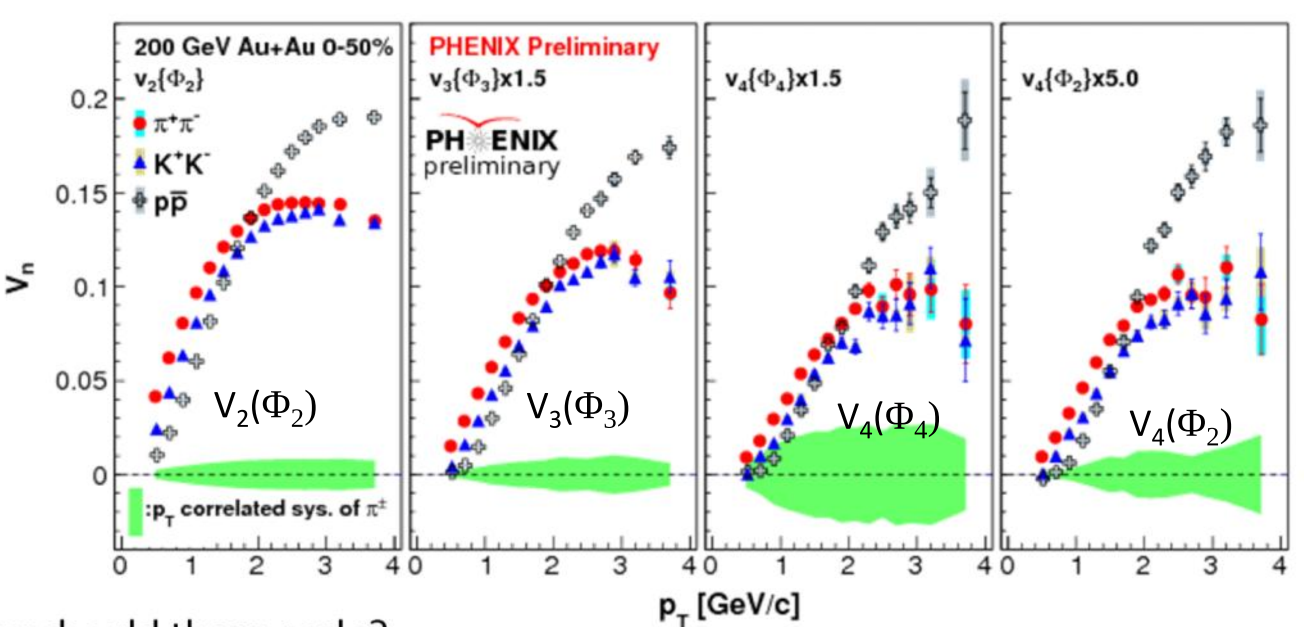
Lower Energies?





$KE_T=(p_T^2+m^2)^{1/2}-m$

What about higher harmonics?

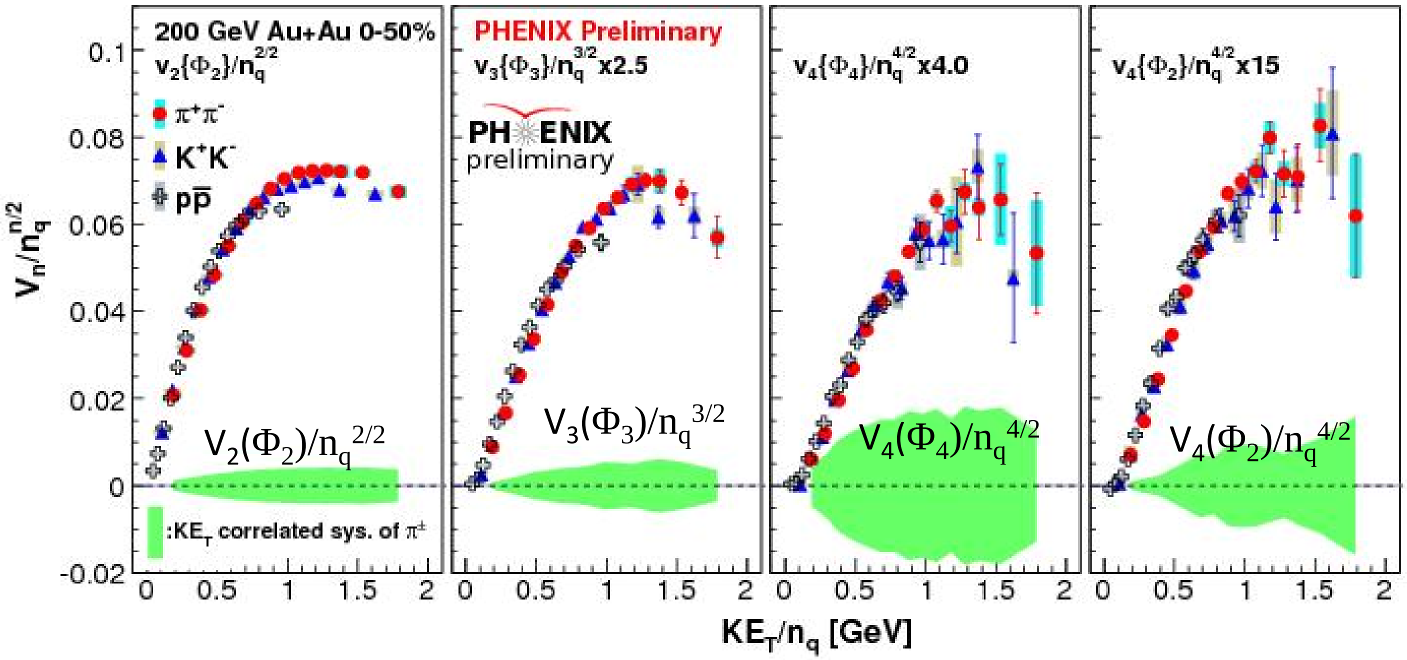


- How should these scale? ,
  - $(v_n)_q$ are the moments of a distribution of constituent quarks.
  - Mesons ~ (quark distribution)^2,
  - baryons ~ (quark distribution)^3
- ➡ v_n (hadrons) should scale like $v_n/n_q^{(n/2)}$

Kolb, PRC 69, 051901 (2004)

- Other more recent arguments
  - Start with N_{cq} scaling of v_2
  - Additional scaling $v_n \sim v_2^{n/2}$
    - From Hydro models
    - Acoustic scaling arguments [e.g. 1105.3782(Lacy et al)]
- ➡ v_n (hadrons) should scale like $v_n/n_q^{(n/2)}$

PID v_r scaling with Number of constituent quarks: N_{cq}

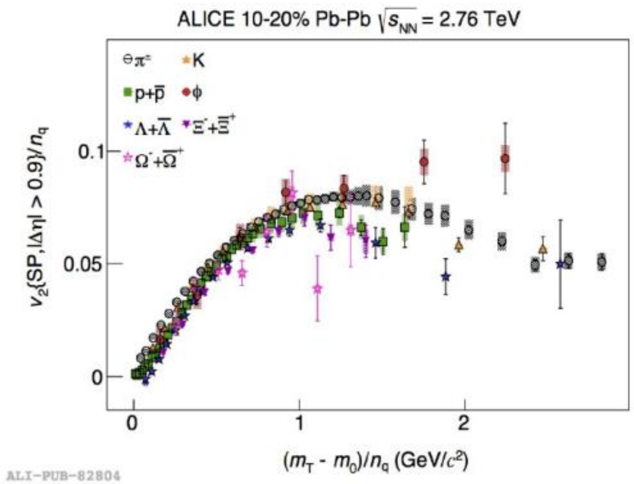


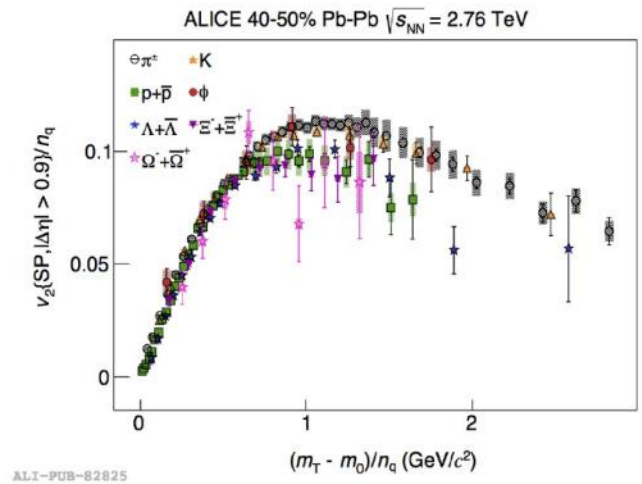
✓ N_{cq} scaling works down to 39 GeV for both v_2 and higher moments

Indicates partonic collective flow? Some would argue that v_2 has N_{cq} scaling and that the scaling of higher moments is from a picture of sound propogation in the plasma

It does provide a motivation to check if N_{cq} is a good scaling variable for dN/dη and dEt/dη

A caveat in the flow results: LHC





A. Dobrin
QM 2014

Hydro model, (MC-KLN, η/s=0.16), hadronization via Cooper-Frye, coupled to hadronic cascade, can qualitatively describe these results

- For KE_T/n_q<0.6-0.8 GeV/c^2: significant deviations from NCQ scaling are seen in data
- For KE_T/n_q>0.8 GeV/c^2: NCQ scaling, if any, is only approximate

Does this mean that N_{cq} scaling is not a valuable tool for understanding the system?

In Dobrin's summary ⇨ Observe deviations from NCQ scaling at the level of ±20%

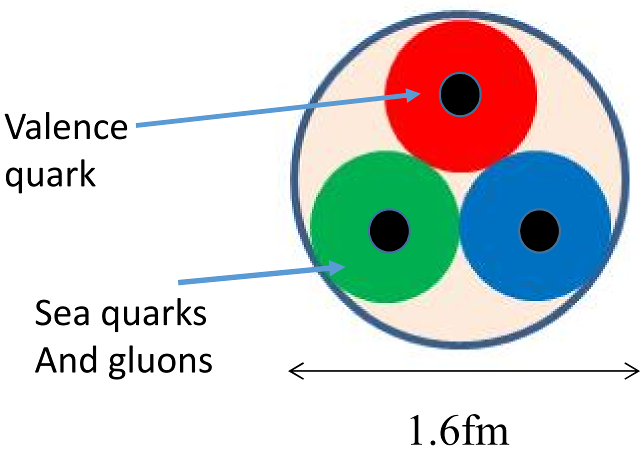
Hmm. How many things have such a large range of validity to 20%?

We can still an ask if N_{cq} is a good scaling variable for E_T and N_{ch}

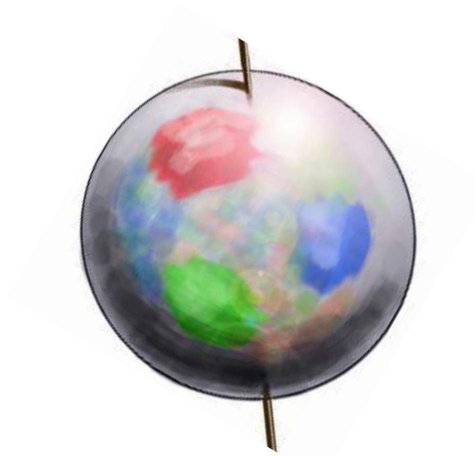
N_{cq}: What are Constituent Quarks?

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

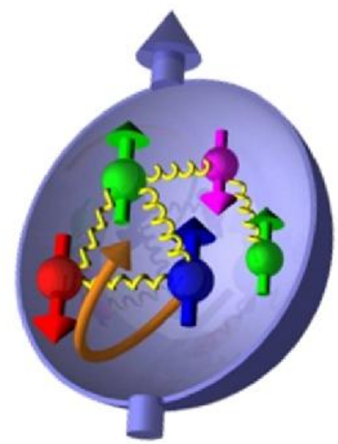
For hard-scattering, $p_T>2$ GeV/c, $Q^2=2p_T^2>8$ GeV^2, the partons (~massless current quarks, gluons and sea quarks) become visible



Resolution ~0.5fm



Resolution ~0.1fm



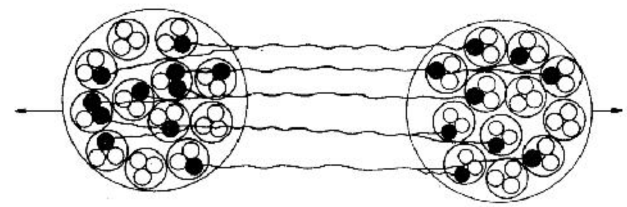
Resolution <0.07fm

Slide from M. J. Tannenbaum

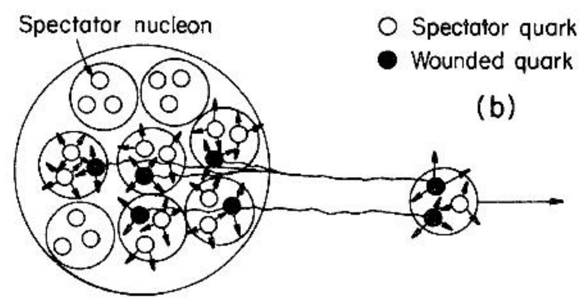
Three models (scaling variables)

- N_{part} (Wounded Nucleon Model)
  - Doesn't work
- AQM (Additive Quark Model)
  - Color strings – can only connect to one constituent quark
- N_{cq} (constituent quarks)

AQM vs N_{cq}



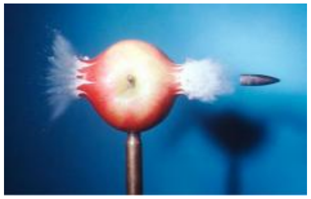
For symmetric systems AQM and N_{cq} are the same



d+Au can resolve this degeneracy

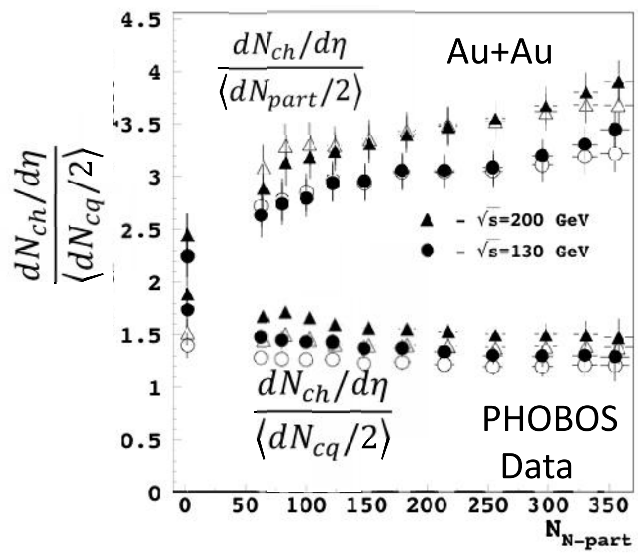
- AQM – only constituent quarks in the projectile
- N_{cq} model will count both projectile and target constituent quarks

Some history (~1970)



- In “high energy” p+A collisions, each incoming projectile can interact, but emerges out of the Nucleus before fragmenting.
  - Led to the “Wounded Nucleon model. (WNM) We know is as N_{part} scaling
    - Bialas et al (e.g. PLB 51, 179 (1974)
    - Seemed to work in p+p, α + α, p+ A below $\sqrt{s} = 20 \text{ GeV}$ (where it was first seen)
  - The WNM (N_{part} scaling), as well as others (wounded projectile-nucleon model, AQM, and the N_{cq}) are examples of Extreme Independent Models (EIM)
  - Distributions (e.g. $dE_T/ d\eta$, $dN_{ch} /d\eta$) can be derived from two things
    - Nuclear geometry under the assumptions of one of the EIM models (usually Glauber model)
    - Measurements of elementy collisions – usually p+p
- Most models we know are not EIM: e.g. CGC, Hydro, cascade, HIJING, combination models

N_{cq} scaling: not a new idea



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

See also

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

De, Bhattacharyya
PRC 71 024903 (2005)

N_{cq} works in Au+Au but could have been the AQM

How do we get the distributions?

First thing we need: N_{cq} and quark-quark inelastic cross section

- N_{cq} – Modified Glauber model
  - Nucleons distributed according to Woods-Saxon
  - Quarks located around nucleon centers with distribution:

$$\rho(r) = \rho_0^{proton} e^{-ar} \qquad a = 4.3\, fm^{-1}$$

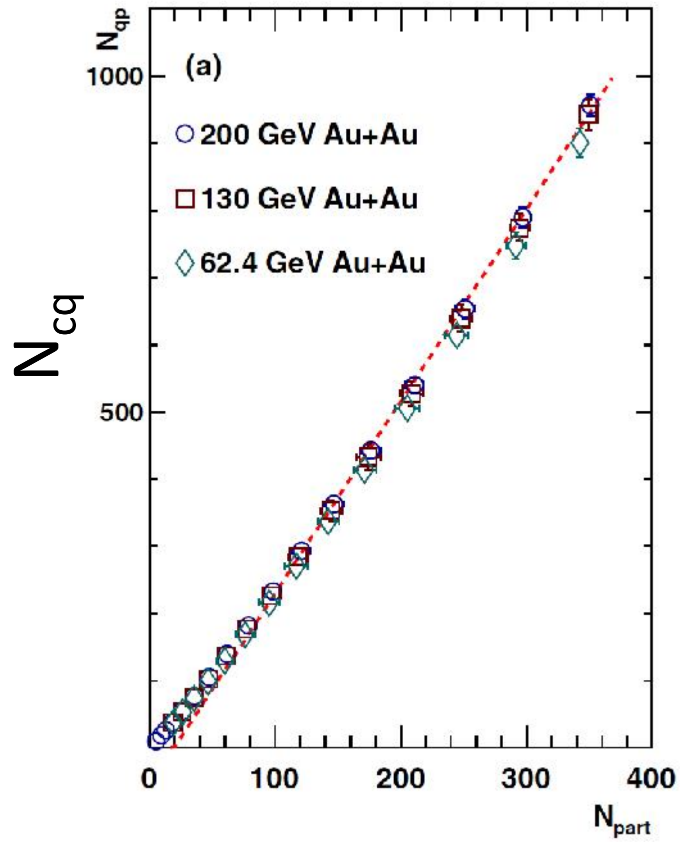
  - Quarks interact when

$$d < \sqrt{\frac{\sigma_{qq}^{inel}}{\pi}}$$

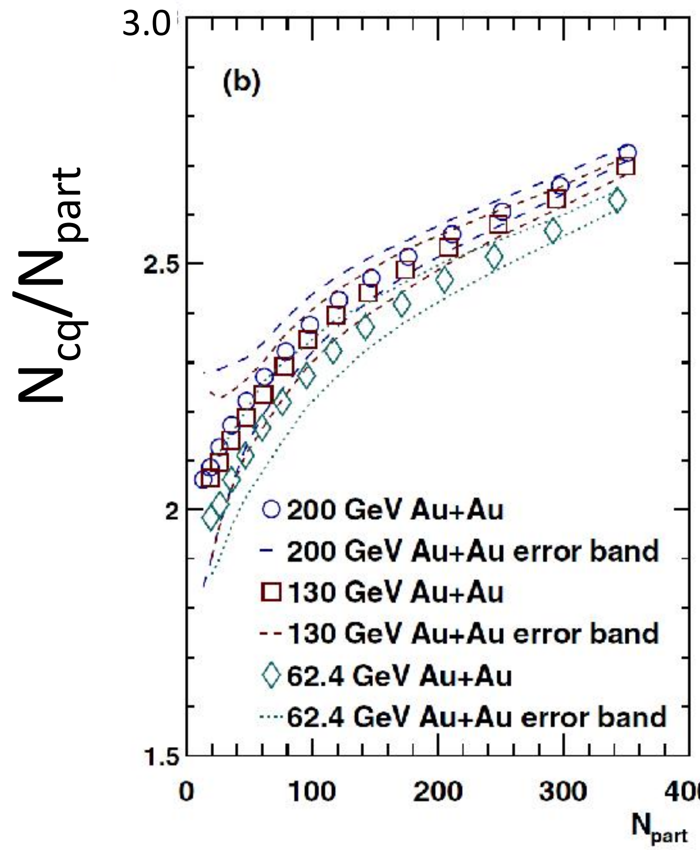
- Quark-quark inelastic cross section is estimated by reproducing the nucleon-nucleon inelastic cross section
- E_T distributions fit to Γ distribution
  - Shown to work over large range of energies

BCMOR PL 168B (1986), 158

N_{cq} vs N_{part}

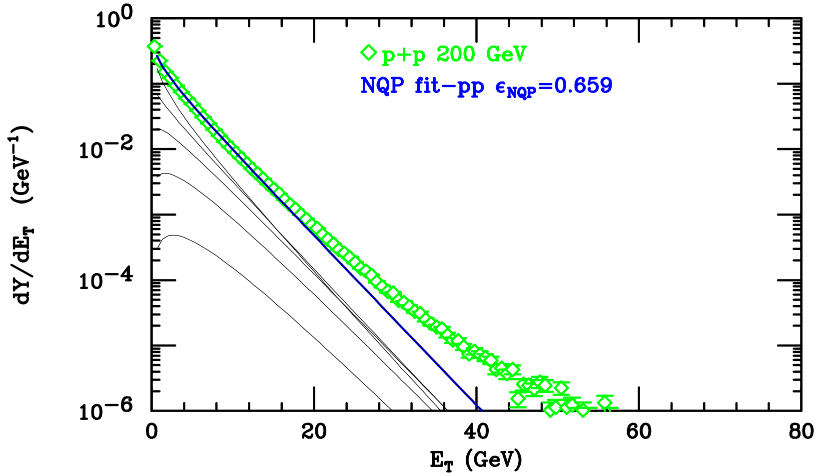


N_cq
N_qp
(a)
200 GeV Au+Au
130 GeV Au+Au
62.4 GeV Au+Au
1000
500
0
100
200
300
400
N_part



N_cq/N_part
(b)
3.0
2.5
2
1.5
200 GeV Au+Au
200 GeV Au+Au error band
130 GeV Au+Au
130 GeV Au+Au error band
62.4 GeV Au+Au
62.4 GeV Au+Au error band
0
100
200
300
400
N_part

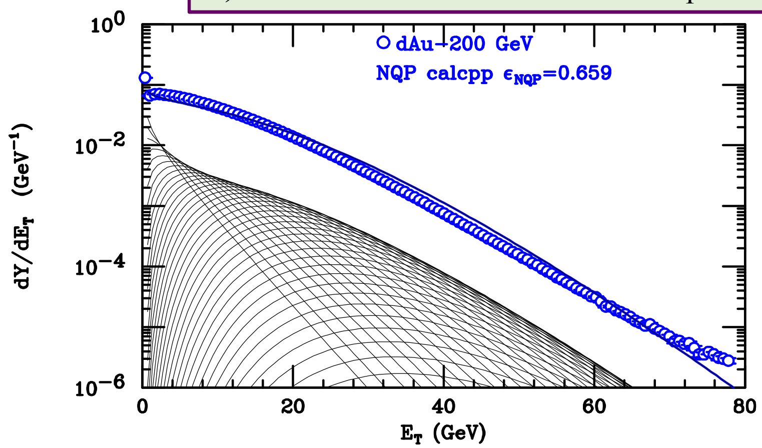
PHENIX N_{cq} model: Data driven pp→ dAu, AuAu

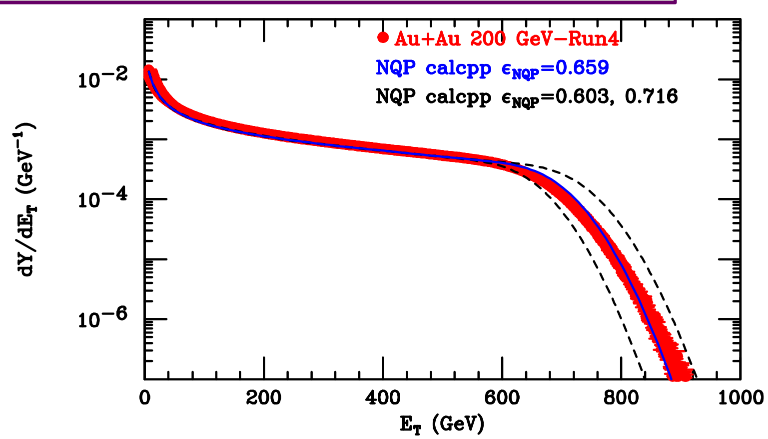


1) We now have N_{cq}, and the qq cross section

2) Deconvolute p-p E_T distribution to the sum constituent quark participant (CQP) E_T distributions taken as Γ distributions

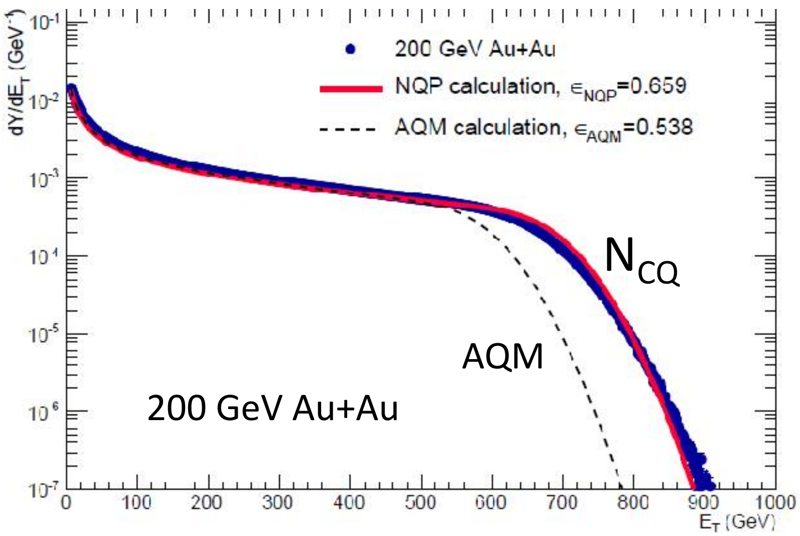
3) Calculate dAu and AuAu E_T distributions as sum of CQP E_T distributions

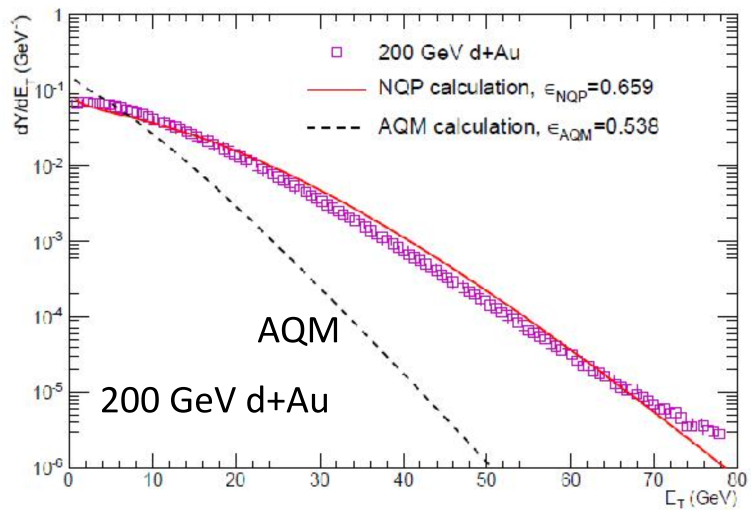




Slide modified from M Tannenbaum

Now let's compare the AQM with N_{CQ} model

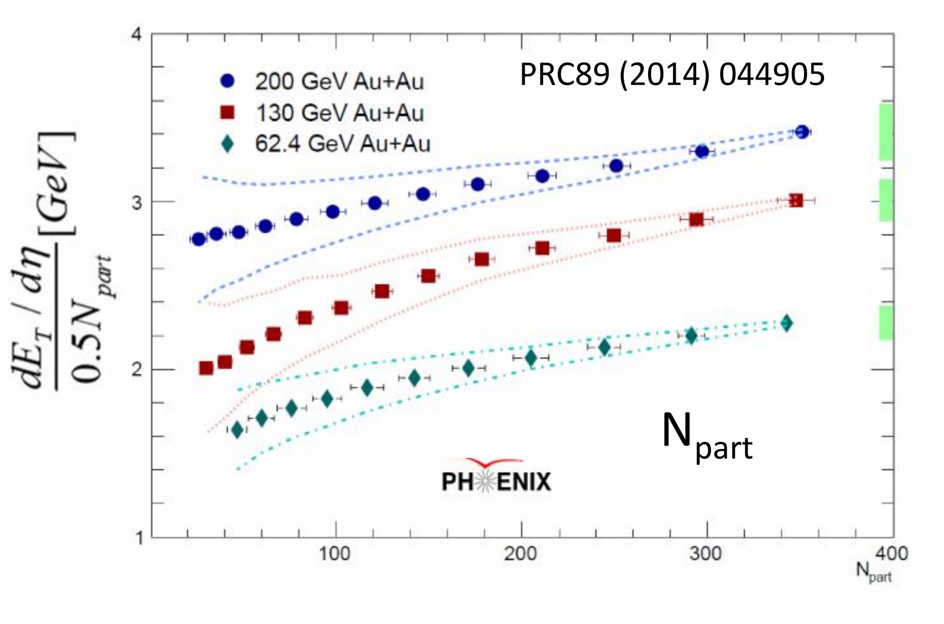


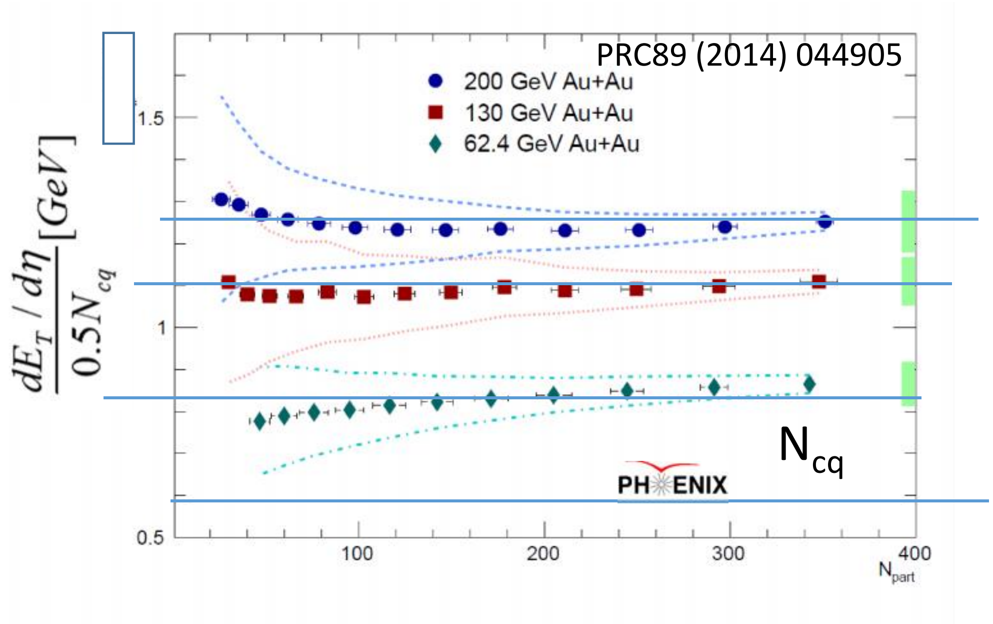


✓dAu shows clearly that AQM fails
N_{cq} model is able to get the right distributions

Test N_{cq} scaling : for E_T

,



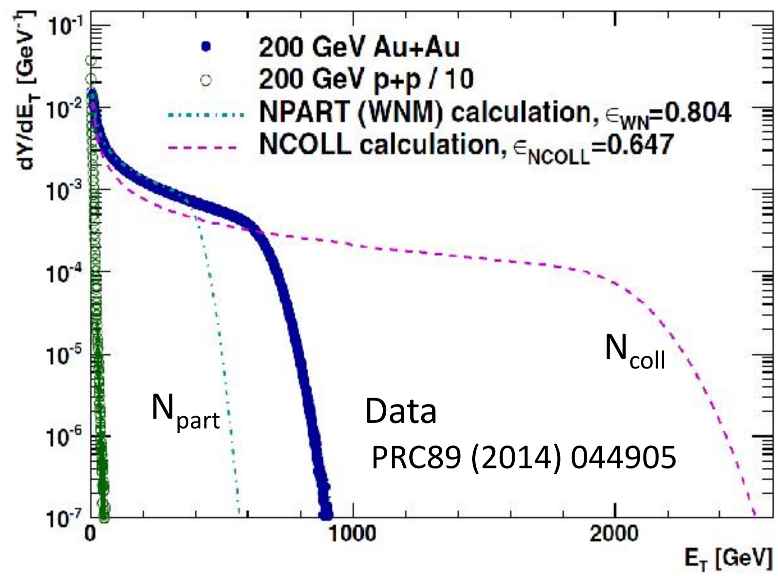


✓Looks like N_{cq} is a good scaling variable!

We will see dN/dη later

Look again at the Hard + Soft model

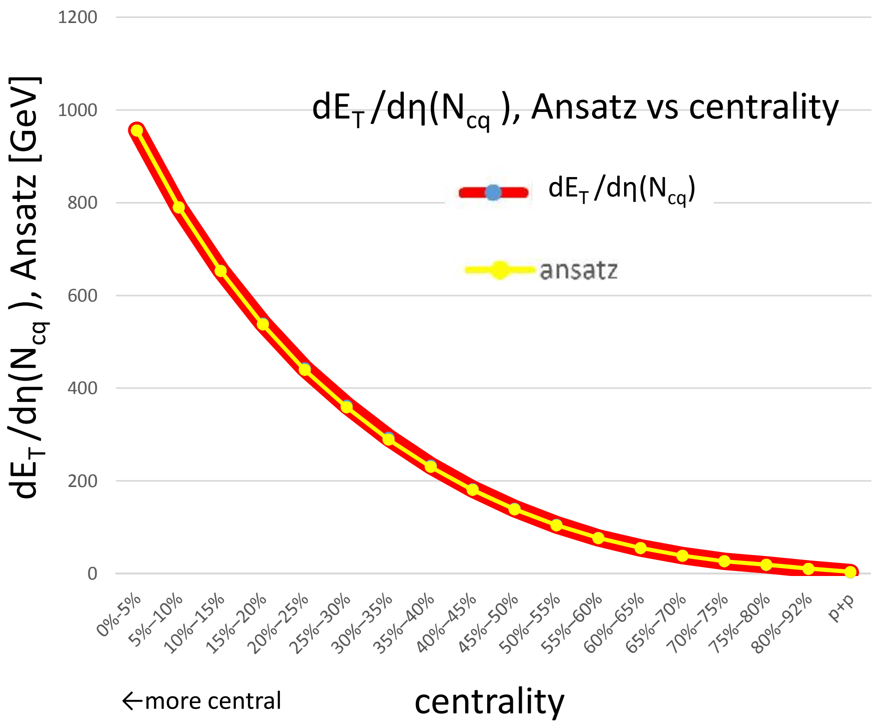
- From E_T baseline convolute to get
  - Distribution when N_{part} is the relevant variable. i.e. soft
  - Distributions when N_{coll} is relevant variable i.e. hard
- Ansatz cannot get Au+Au distribution as a combination of soft and hard distribution
- Ansatz OK for the average values

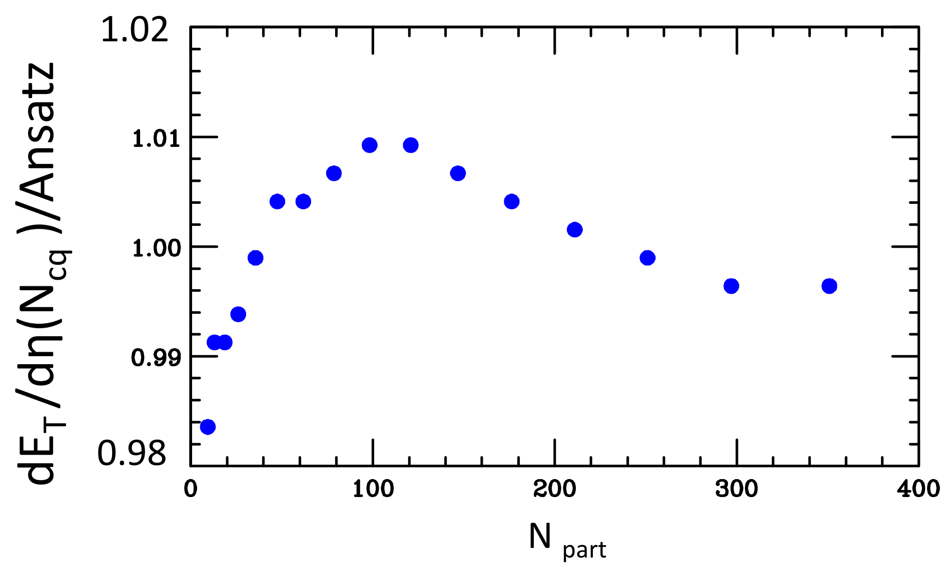


$$\frac{d\{n,\mathrm{E}_T\}}{d¦} = \frac{d\{n,\mathrm{E}_T\}_{pp}}{d¦}\left[(1-x)\frac{\langle N_{part}\rangle}{2} + x\langle N_{coll}\rangle\right]$$

Ansatz

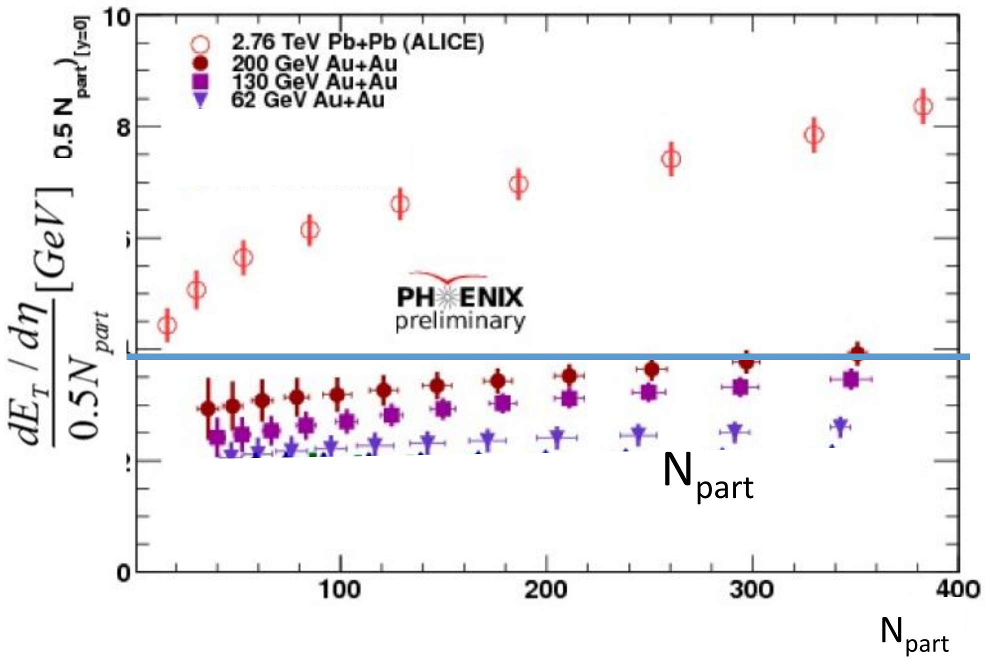
Hence we can thinkg of
Soft+hard calculation is an empirical proxy for N_{cq}

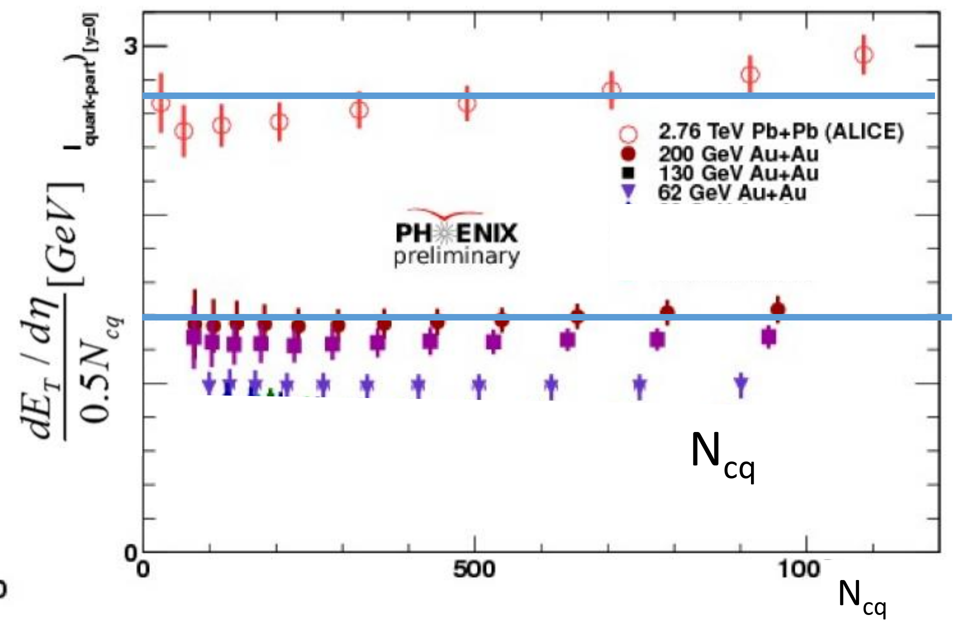




PRC89 (2014) 044905

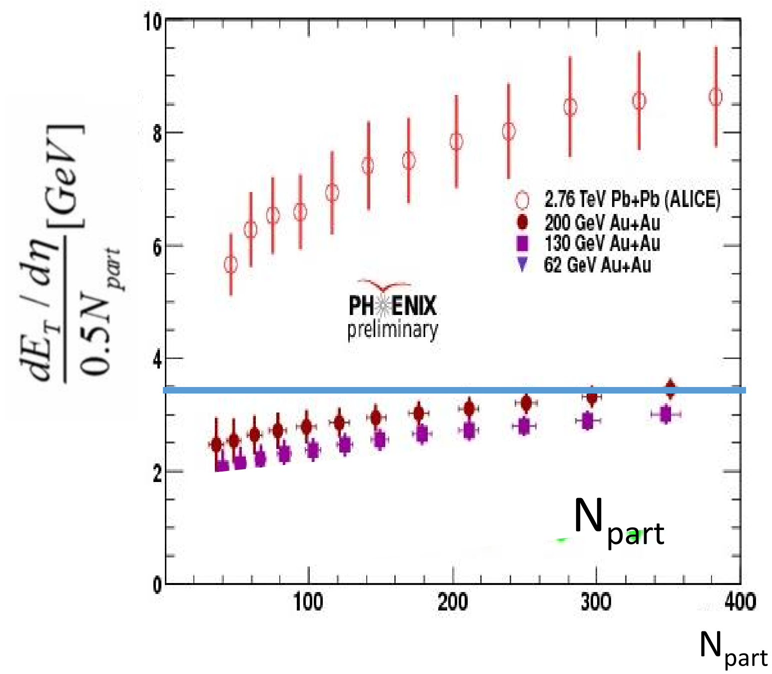
Now lets look at the $\sqrt{s}$ dependence for dN/dη including ALICE

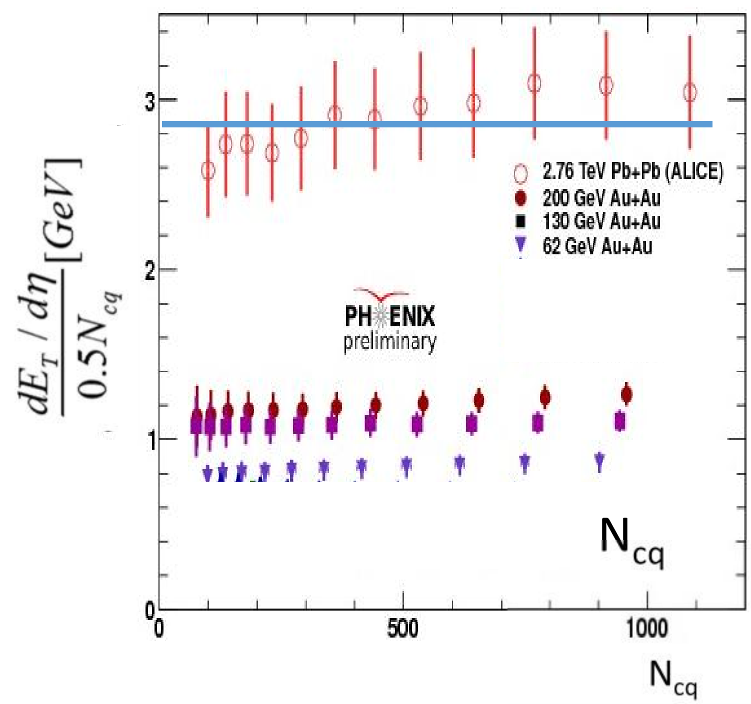




WORKS!

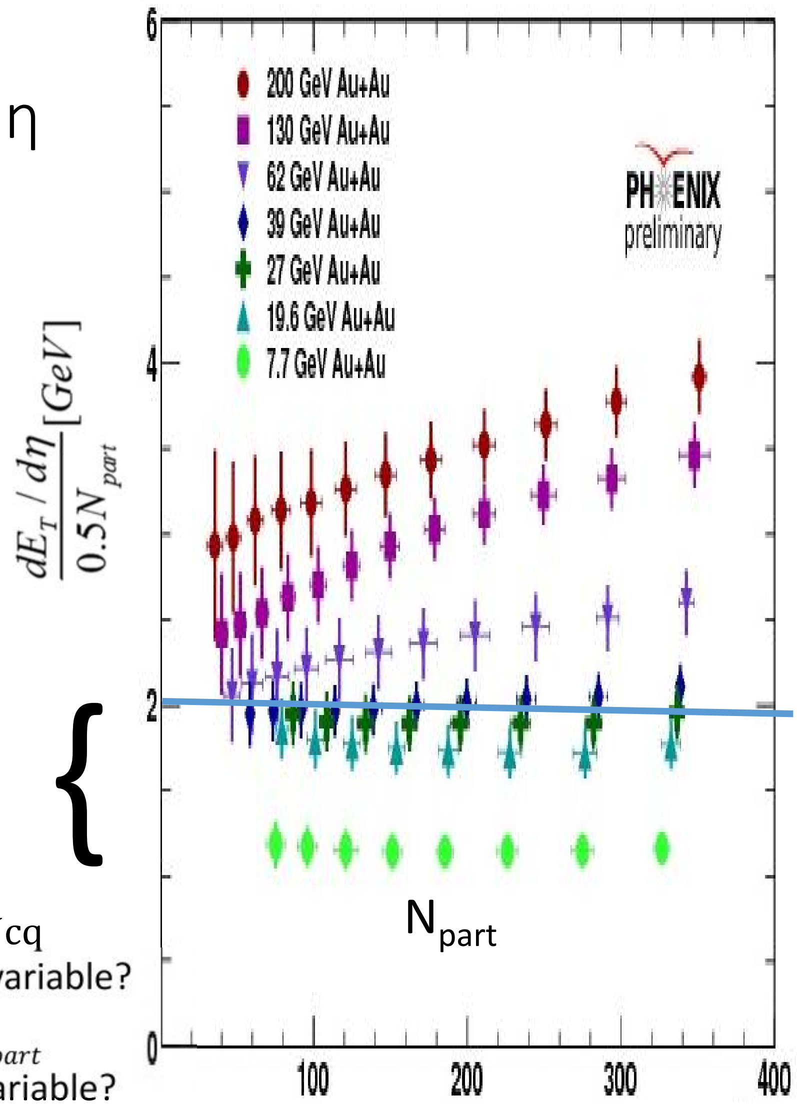
Now check $\sqrt{s}$ dependence for dE$_T$/dη including ALICE





✓N$_{cq}$ is a good scaling variable for dE$_T$/dη and dN/dη from $\sqrt{s} = 62\ to\ 2.8\ TeV$!

Scaling of $dN_{ch}/d\eta$ at lower energies

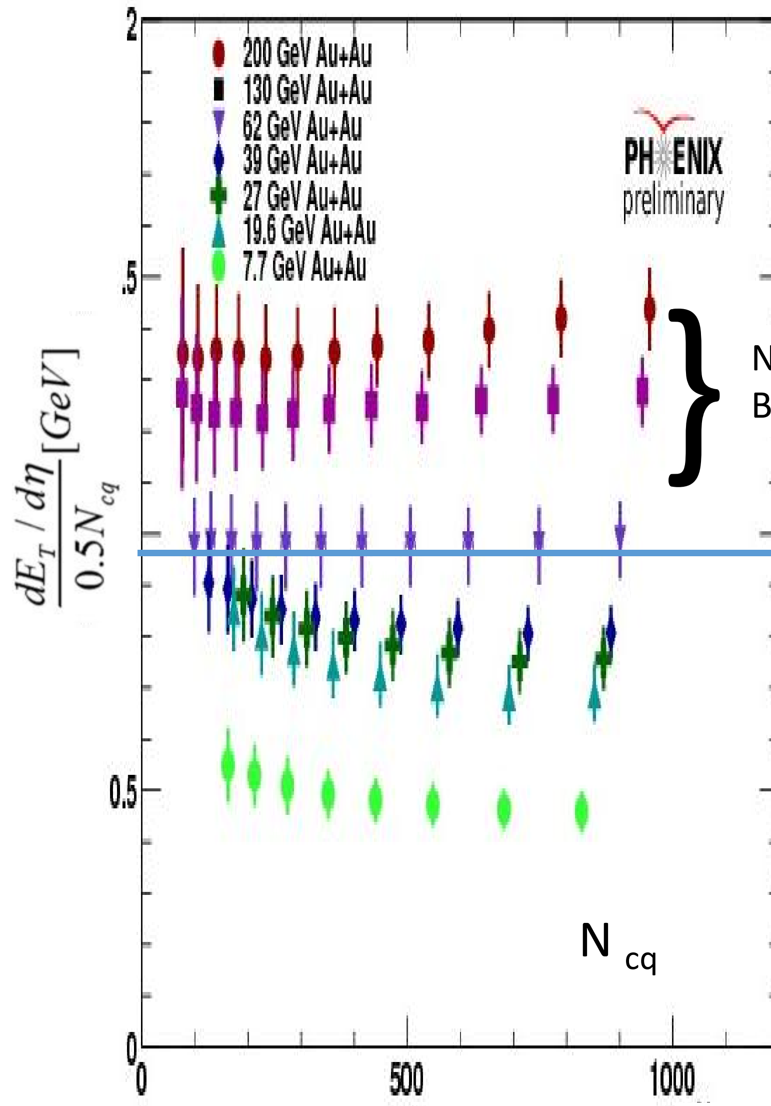


N_{part}

N_{part} Better?

$\sqrt{s}\geq 39$ GeV: Ncq better scaling variable?

$\sqrt{s}\leq 27$ GeV: N_{part} better scaling variable?

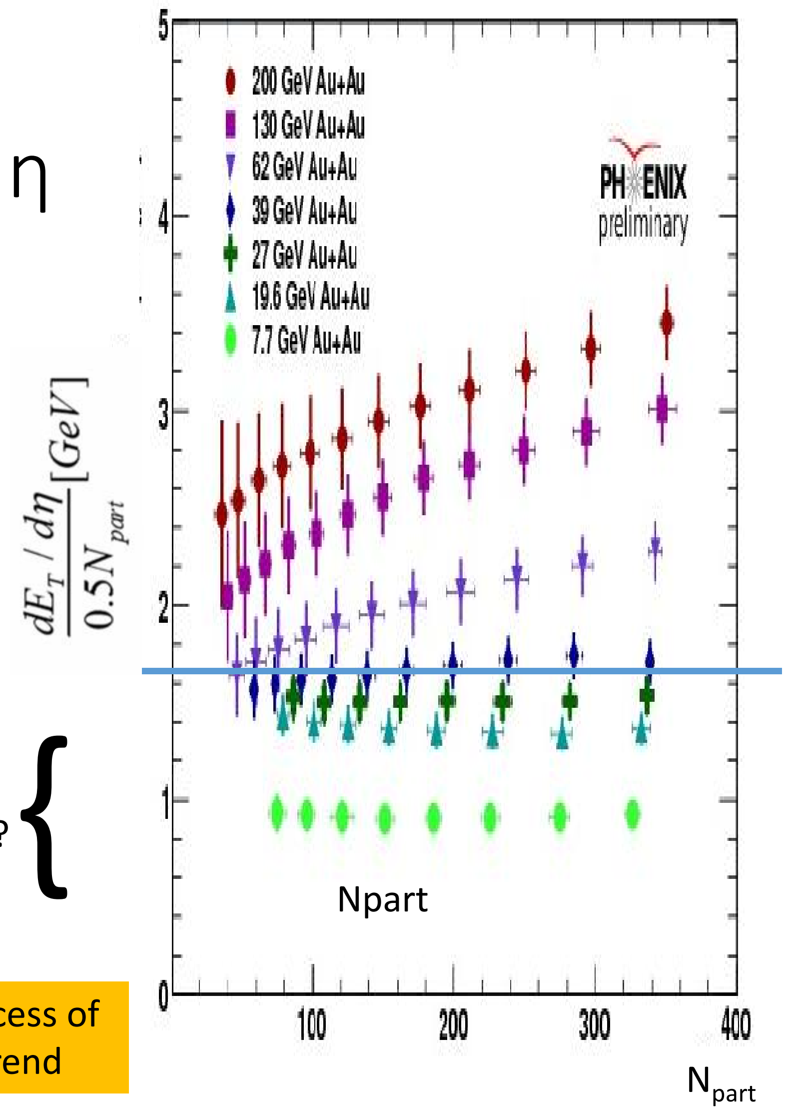


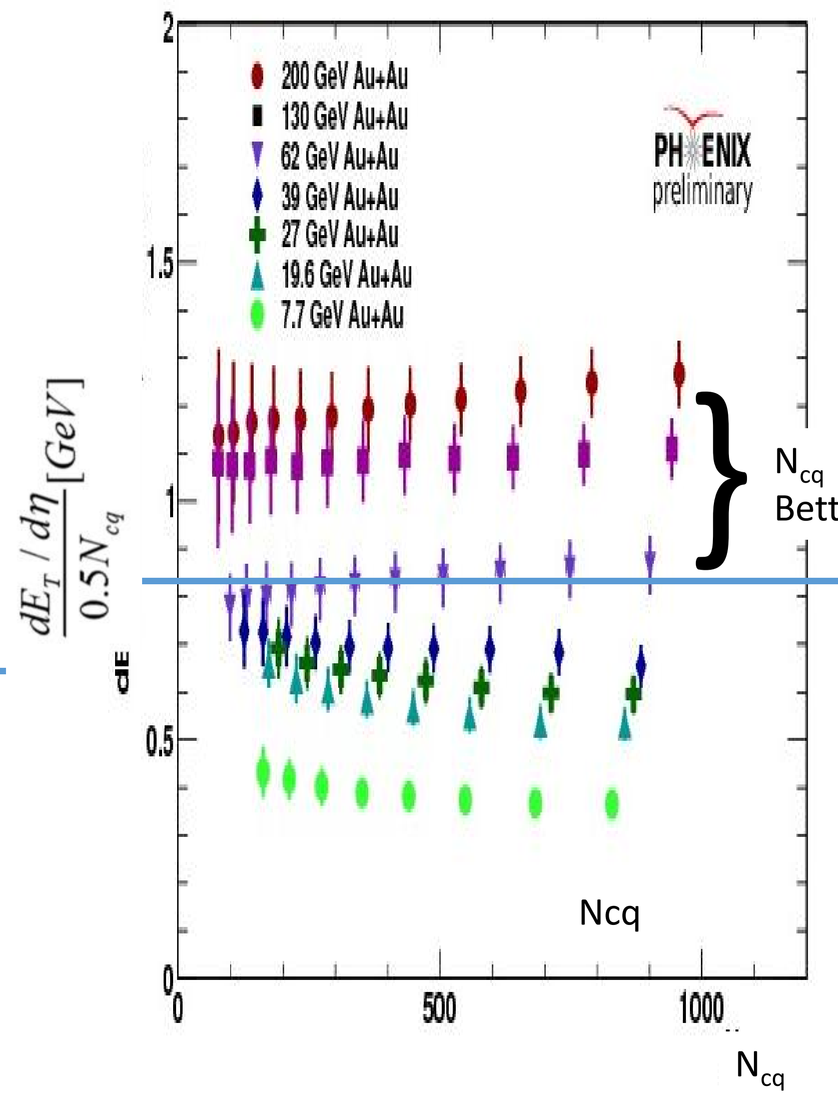
N_{cq}

N_{cp} Better?

Scaling of $dE_T/d\eta$ at lower energies

N_{part} Better?

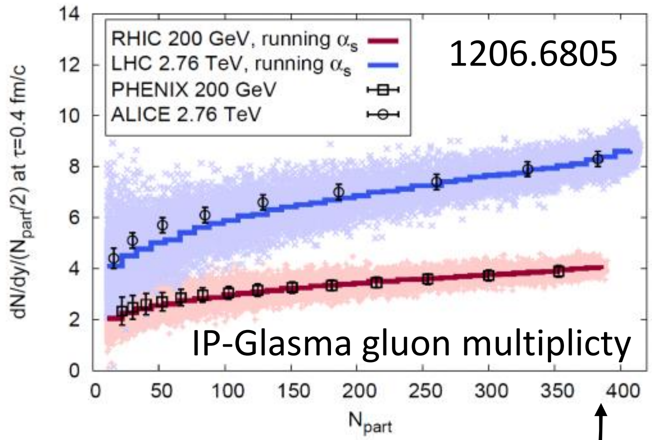




N_{cq} Better?.

We are in the process of Quantifying this trend

Some perspectives



- EIM models
  - need only geometry and fundamental particle (p+p or q+q) dynamics from experiment to calculate distributions
  - Assumes final heavy ion result is a convolution of pp or qq distributions (which in general is not true)

BUT

E_T Distributions?

- Scaling laws –have simplicity - may get at some of the important variables , especially if there is something fundamental - e.g. a quantum number conservation
  - We may learn something from the breaking of the scaling law
- models – may tell us something about the DOF (not quasiparticles) – in some basis (ala quantum mechanics) e.g. constituent quarks. (another example is sound waves) Lots of people have tried to connect these to QCD
- fundamental theory – QCD, but in a regime which is not easy to calculate

- All contribute to understanding – we know that QCD is the right theory. But we need to know a lot more about the collective many body phenomena before we start to understand. Can the model get the scaling laws?

Conclusions

- ✓Flow: Constituent quark scaling holds for higher moments and for a large range of energies
- ✓N_{cq} scaling holds for Transverse energy and multiplicity at the higher RHIC energies
- ✓Ambiguity between N_{cq} model and the AQM resolved in favor of N_{cq} model
- ✓First look at Ncq scaling 39 GeV and below (a hint of the breaking of N_{cq} scaling? Needs careful quantification)

backups

The method for the calculation of the E_T distribution from an A+B reaction in a given detector is illustrated for the $N_{\rm coll}$ or number of binary N+N collision model. The E_T distribution is equal to the sum:

$$\left(\frac{d\sigma}{d\mathrm{E}_T}\right)_{N_{\rm coll}} = \sigma_{BA} \sum_{n=1}^{\mathrm{N}_{\rm max}} w_n\, P_n(\mathrm{E}_T) \qquad (7)$$

where σ_{BA} is the measured A+B cross section in the detector, w_n is the relative probability for n N+N collisions in the A+B reaction with maximum value $n = \mathrm{N}_{\rm max}$, and $P_n(\mathrm{E}_T)$ is the calculated E_T distribution on the detector for n independent N+N collisions. If $f_1(\mathrm{E}_T)$ is the mea-

where $\delta(\mathrm{E}_T)$ is the Dirac delta function an $\int f_1(\mathrm{E}_T)\, d\mathrm{E}_T = 1$. $P_n(\mathrm{E}_T)$ (including the p_0 e fect) is obtained by convoluting $P_1(\mathrm{E}_T)$ with itself $n -$ times

$$P_n(\mathrm{E}_T) = \sum_{i=0}^{n} \frac{n!}{(n-i)!\; i!}\, p_0^{n-i} (1-p_0)^i f_i(\mathrm{E}_T) \qquad (9$$

where $f_0(\mathrm{E}_T) \equiv \delta(\mathrm{E}_T)$ and $f_i(\mathrm{E}_T)$ is the i-th convolutio of $f_1(\mathrm{E}_T)$:

$$f_i(x) = \int_0^x dy\, f_1(y)\, f_{i-1}(x-y) \quad . \qquad (10$$

Substituting Eq. 9 into Eq. 7 and reversing the indice gives a form that is less physically transparent, but co

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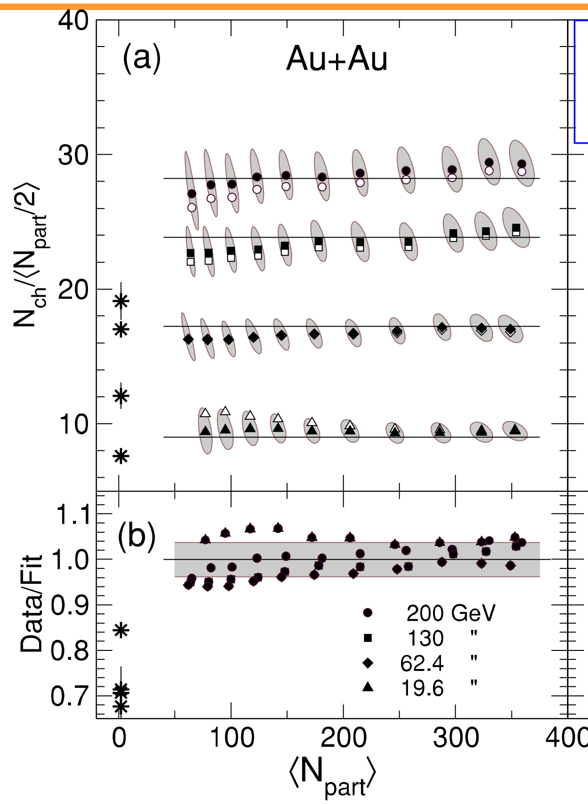

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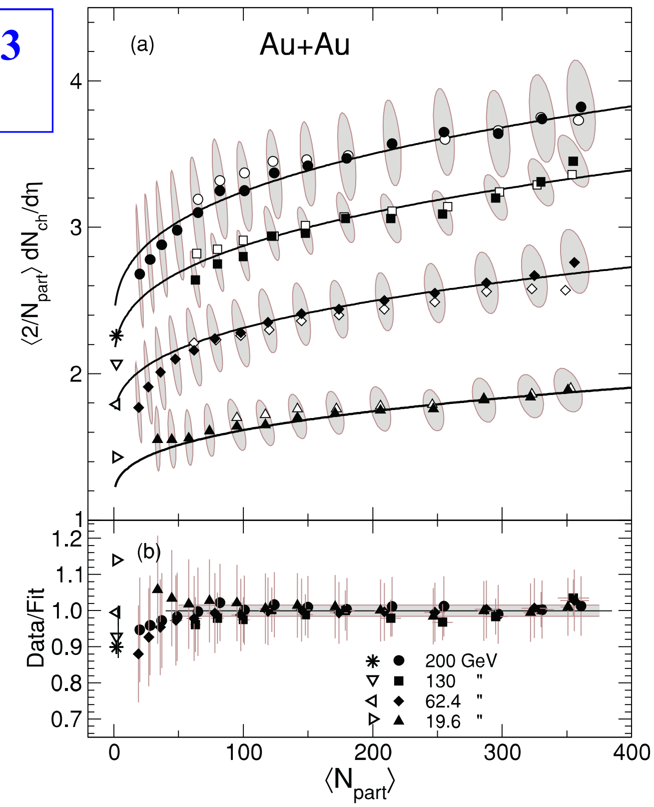
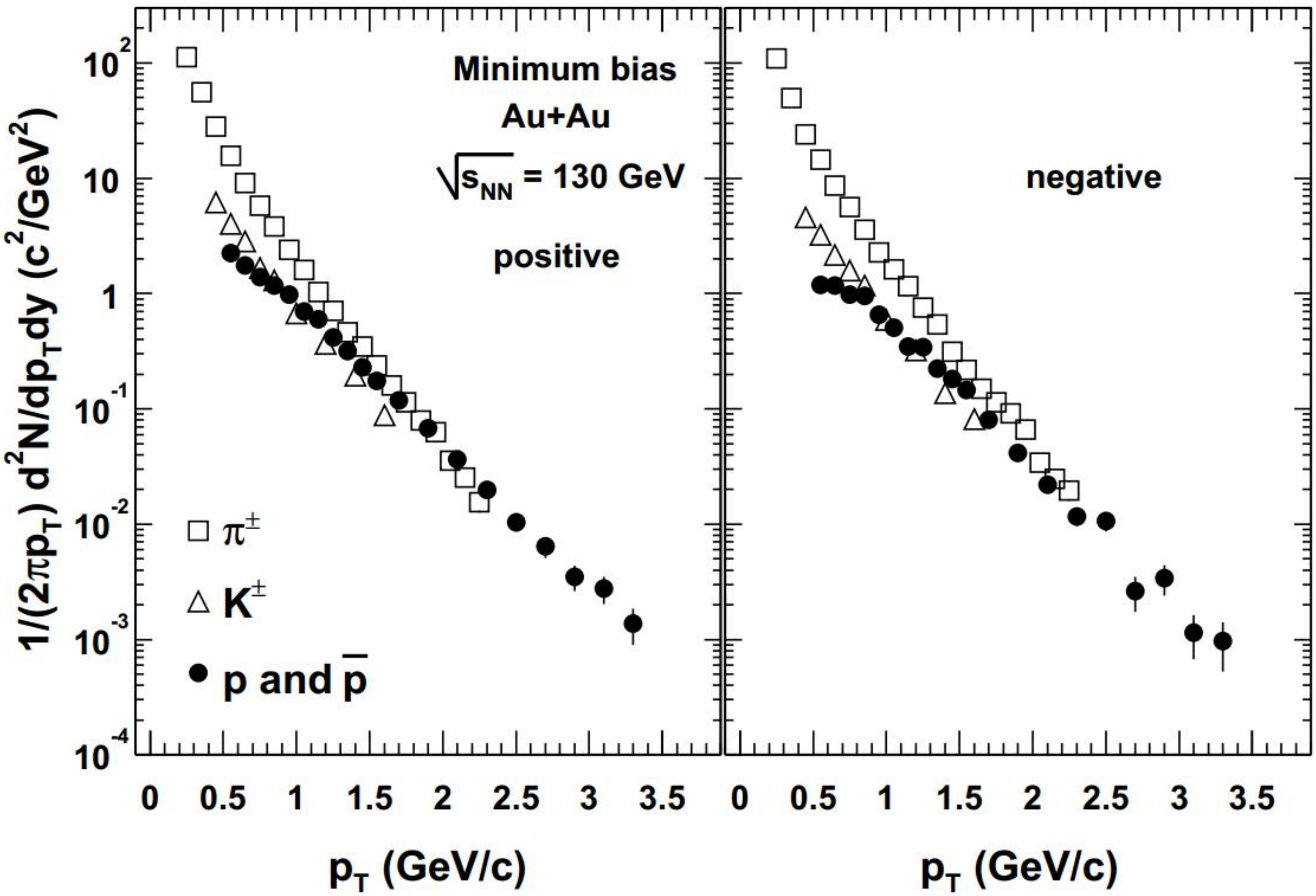
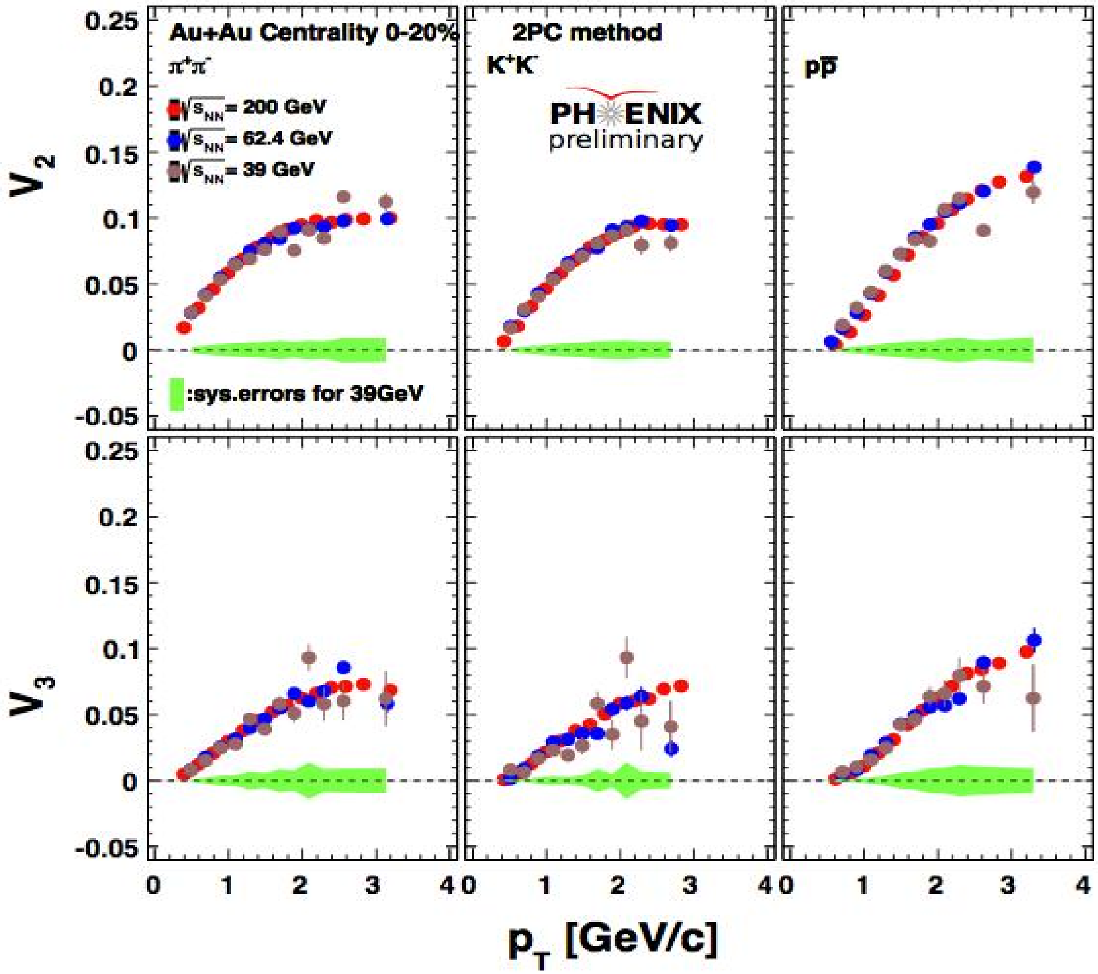


Using full rapidity range, total $N_{ch}/(0.5N_{part})$ does follow WNM (in AA only) but mid-rapidity $dN_{ch}/d\eta/(0.5N_{part})$ shows different but apparently universal dependence first seen by PHENIX and recently at LHC.


Minimum bias
Au+Au
$\sqrt{s_{NN}}$ = 130 GeV
positive
negative
$\pi^{\pm}$
$K^{\pm}$
p and $\bar{p}$
$1/(2\pi p_T)\ d^2N/dp_T dy\ (c^2/GeV^2)$
p_T (GeV/c)
p_T (GeV/c)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.5
1
1.5
2
2.5
3
3.5

Energy dependence of PIDed v_2 , v_3 at 39 – 200 GeV



- New measurements of particle identified v_3 from 2010 low energies runs
- No sizeable beam energy dependence observed for v_2 and v_3 for each particle species
- Implies flow saturates for 39-200 GeV

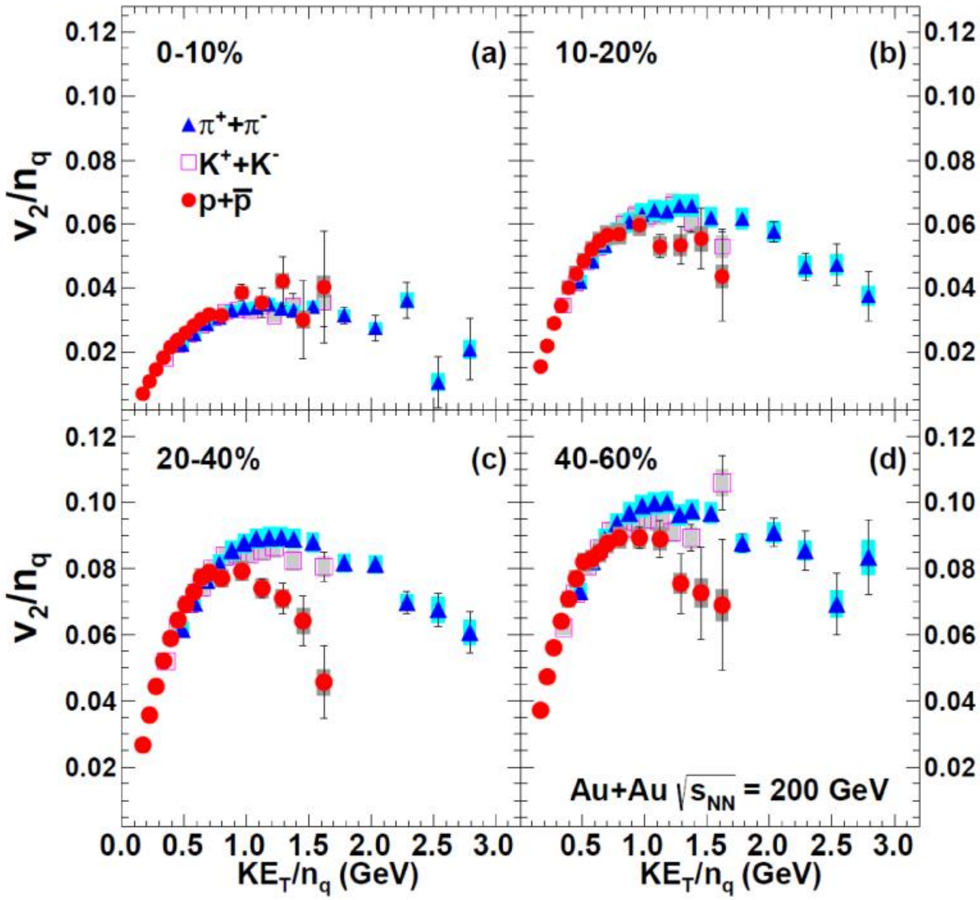


FIG. 9: (color online) The quark-number-scaled v_2 (v_2/n_q) of identified hadrons are shown as a function of the kinetic energy per quark, KE_T/n_q in 0–10% centrality (panel (a)), 10–20% (panel (b)), 20–40% (panel (c)), and 40–60% centrality (panel (d)) in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The error bars (shaded boxes) represent the statistical (systematic) uncertainties. The systematic uncertainties shown are type A and B only.

We have presented a high-statistics study of baryon and meson azimuthal anisotropy v_2 measured up to p_T of 6 GeV/c as a function of centrality in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions. The n_q scaling is found to exhibit strong dependence on the collision centrality. Significant deviations from n_q scaling are found in noncentral collisions, starting from the 10–20% centrality class, as $\mathrm{KE}_T/n_q > 0.7$ GeV. These results indicate that parton fragmentation and the associated energy loss may play an important role in generating the azimuthal anisotropy of particle emission. Conversely, in central collisions, such as the 0–10% centrality class, the universal n_q scaling appears to hold to $\mathrm{KE}_T/n_q = 1.5$ GeV, supporting parton recombination as the dominant mode of particle production at intermediate transverse momentum in central Au+Au collisions at top RHIC energy.

Energy dependence from STAR

- Need to quantify
  - How well the scaling's hold
  - Possibly the scaling is showing a general feature and there are additional features that break it

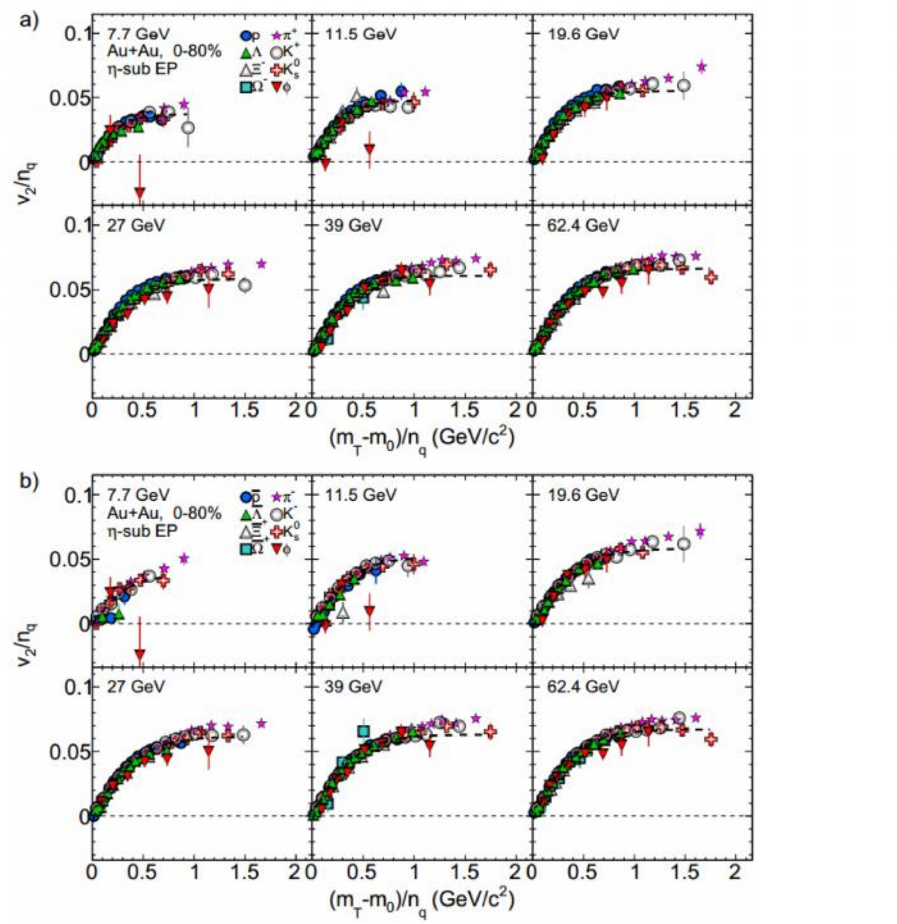
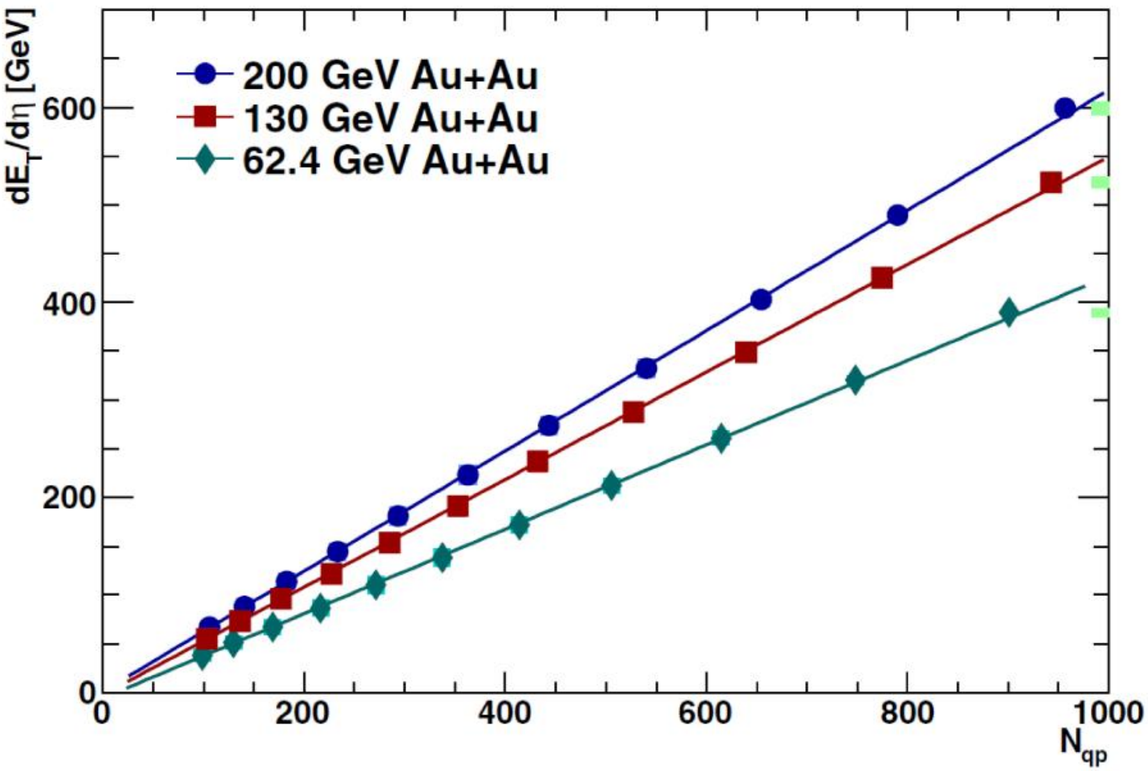


FIG. 19. (Color online) The Number-of-Constituent Quark (NCQ) scaled elliptic flow, v_2/n_q versus $(m_T - m_0)/n_q$, for 0–80% central Au+Au collisions for selected particles a) and corresponding anti-particles b). The dashed lines show the results of simultaneous fits with Eq. (17) to all particles except the pions.

Fit to dET/deta=a*Nqp+b



$\sqrt{s_{NN}}$ (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

dET/eta linear with Nqp