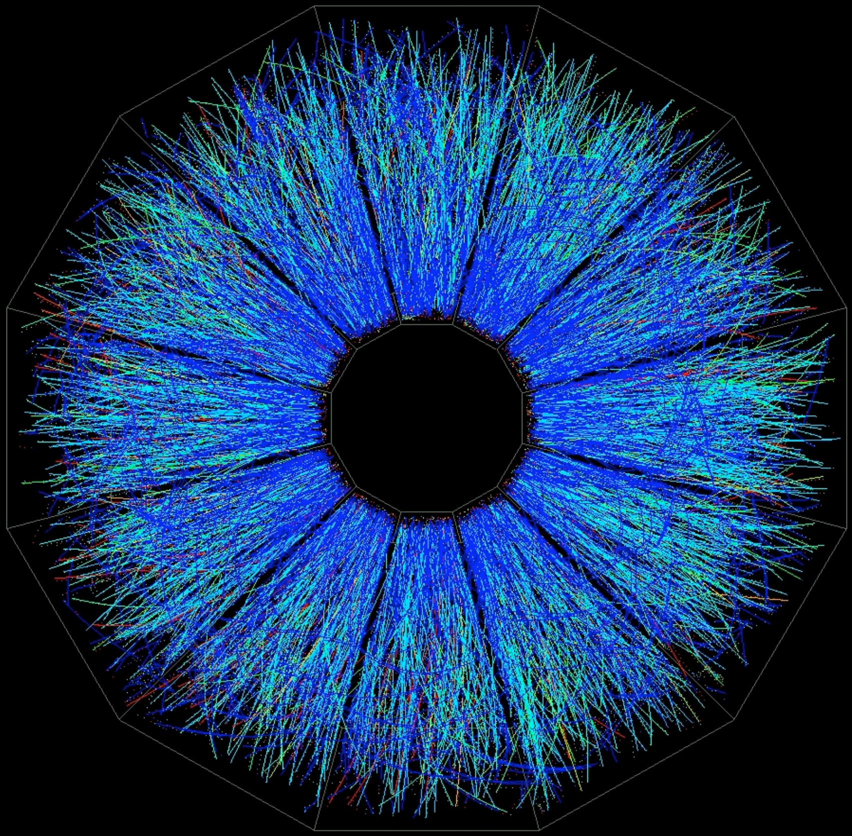
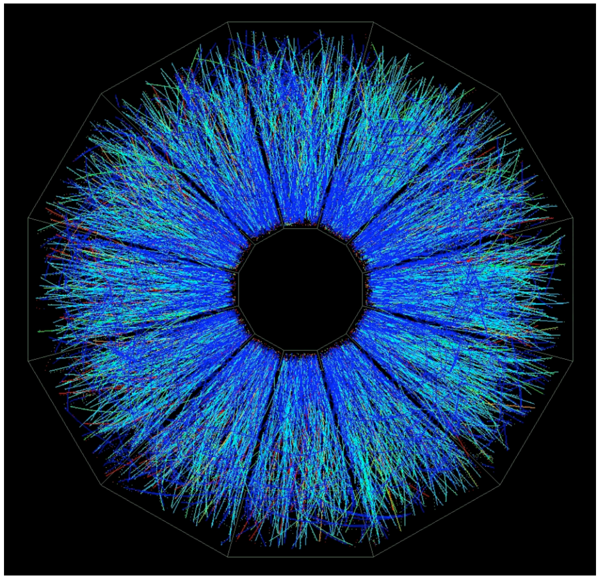
Bulk Particle Production
A Global View



Gunther Roland

Bulk Properties



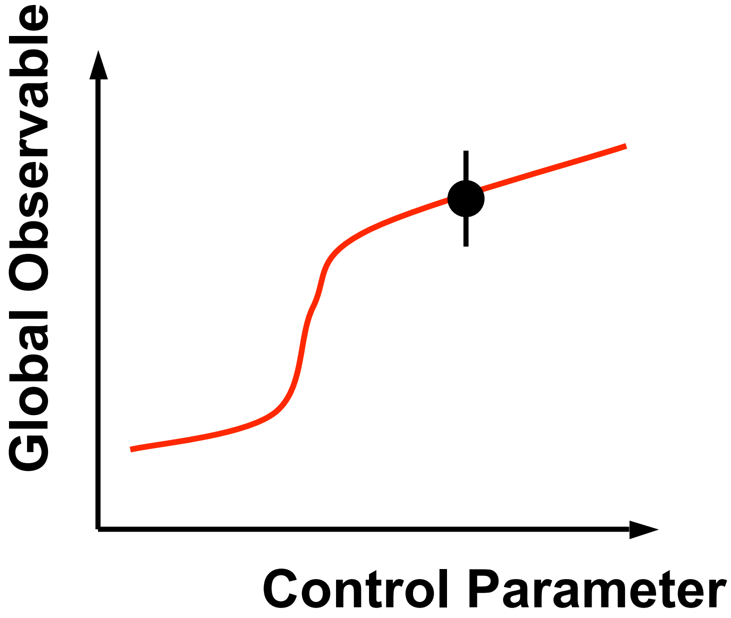
Single Au+Au Collision

O(10^4) 4-Vectors

How many $\left\{ \begin{array}{l} \text{Parameters} \\ \text{Concepts} \end{array} \right\}$ needed to describe *average* collision?

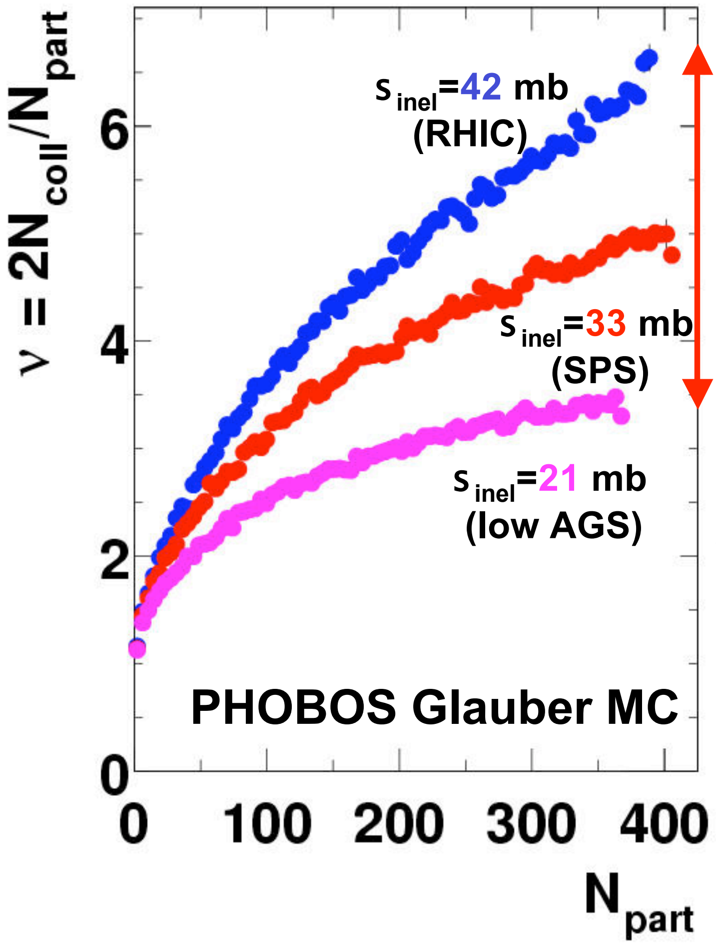
Provide background (5 - 15% accuracy) against which we can search for structure

Global Observables



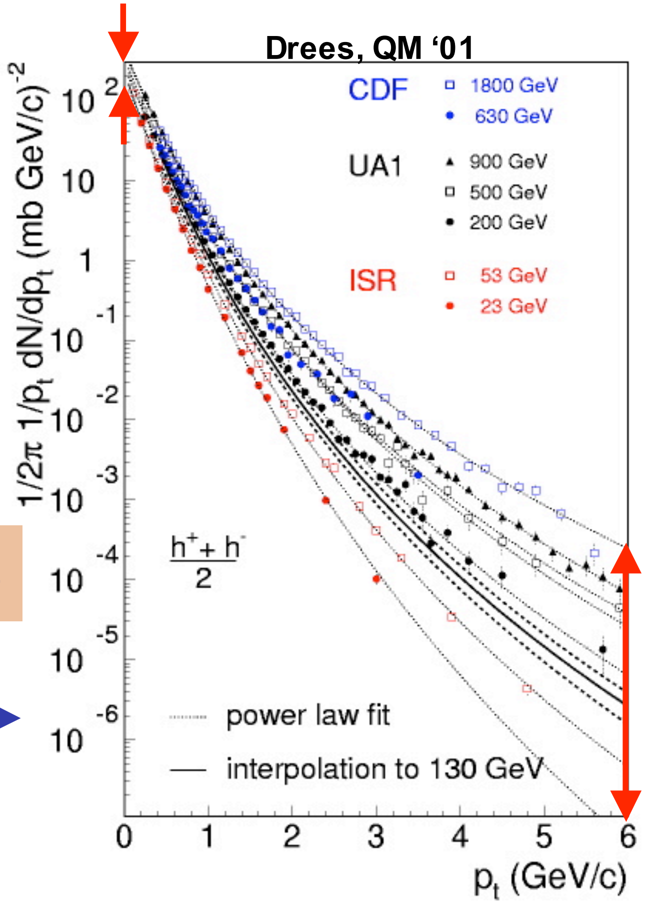
"Global Observables" need to be understood in context

Control Parameters



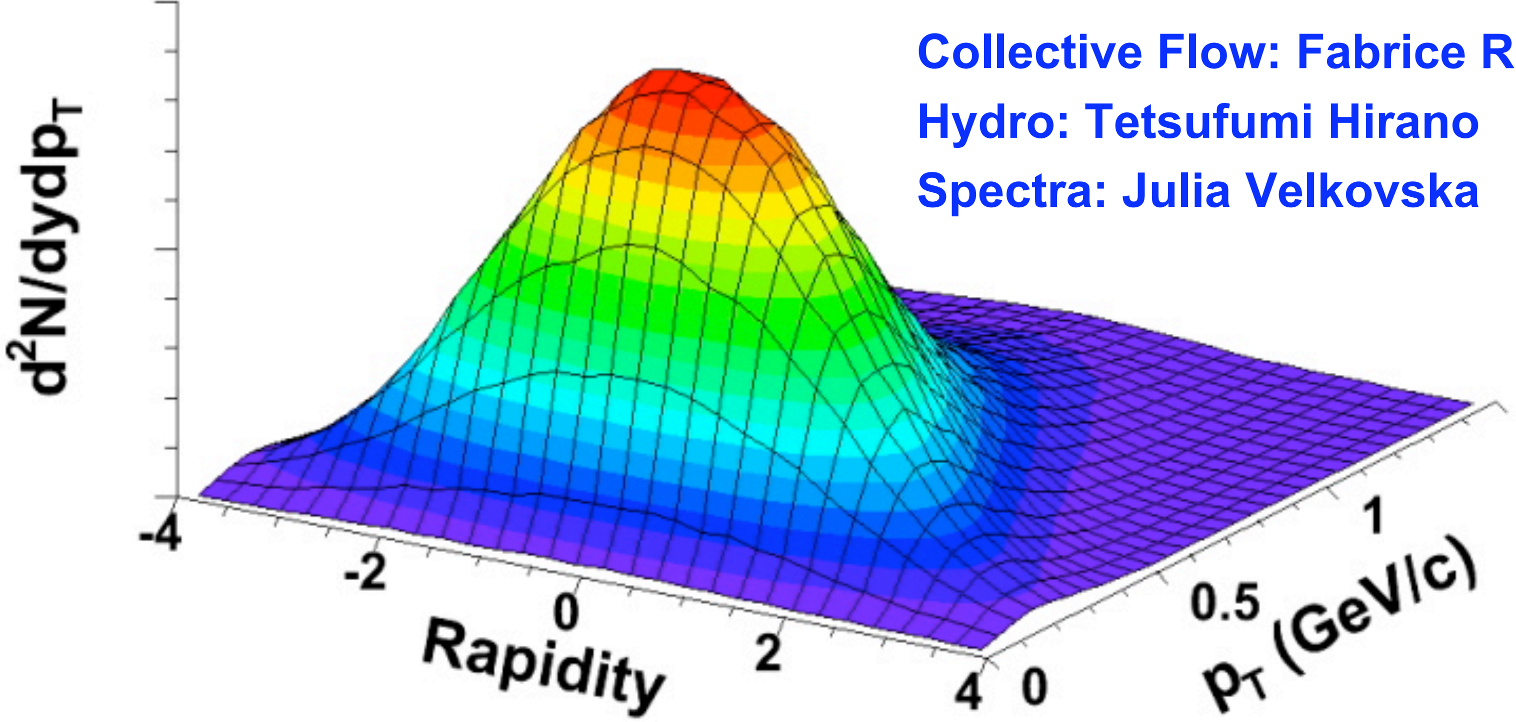
System-Size

Energy



Also: Different systems (different nuclei, pp, pA, e$^+$e$^-$)

Bulk Properties



Fluctuations: Jeff Mitchell

Collective Flow: Fabrice Retiere

Hydro: Tetsufumi Hirano

Spectra: Julia Velkovska

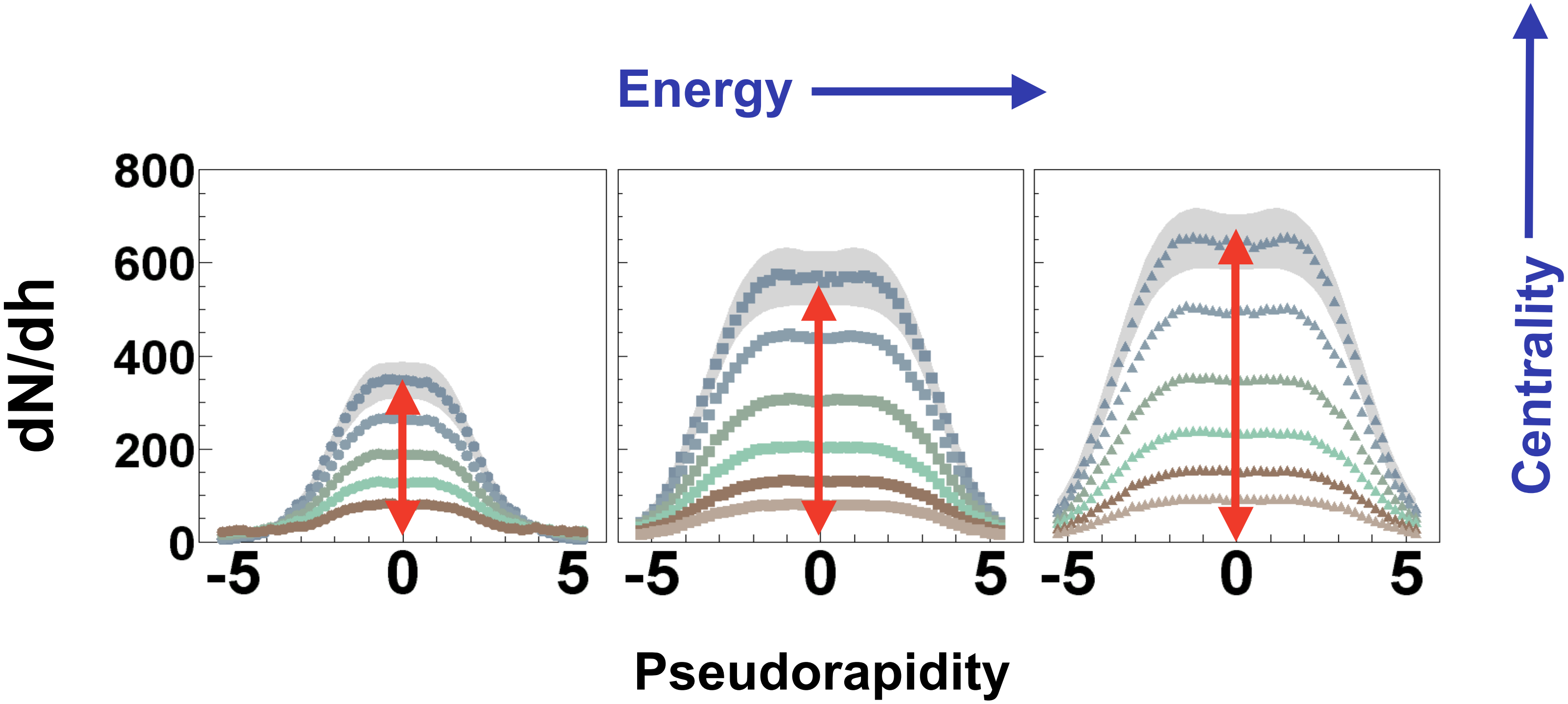
I. Mid-Rapidity Density

II. Total Multiplicity

III. Shape of dN/dh

IV. Hadron Mass Spectrum

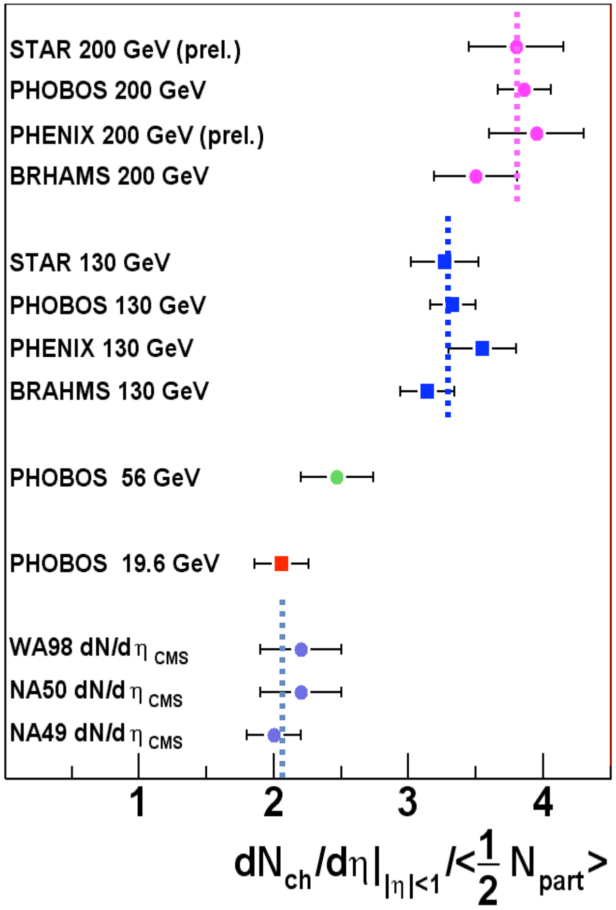
I. Particle Density near Mid-Rapidity



How does Density at 90^{o} change with Energy and Centrality?

Please, see poster by Sasha Milov !

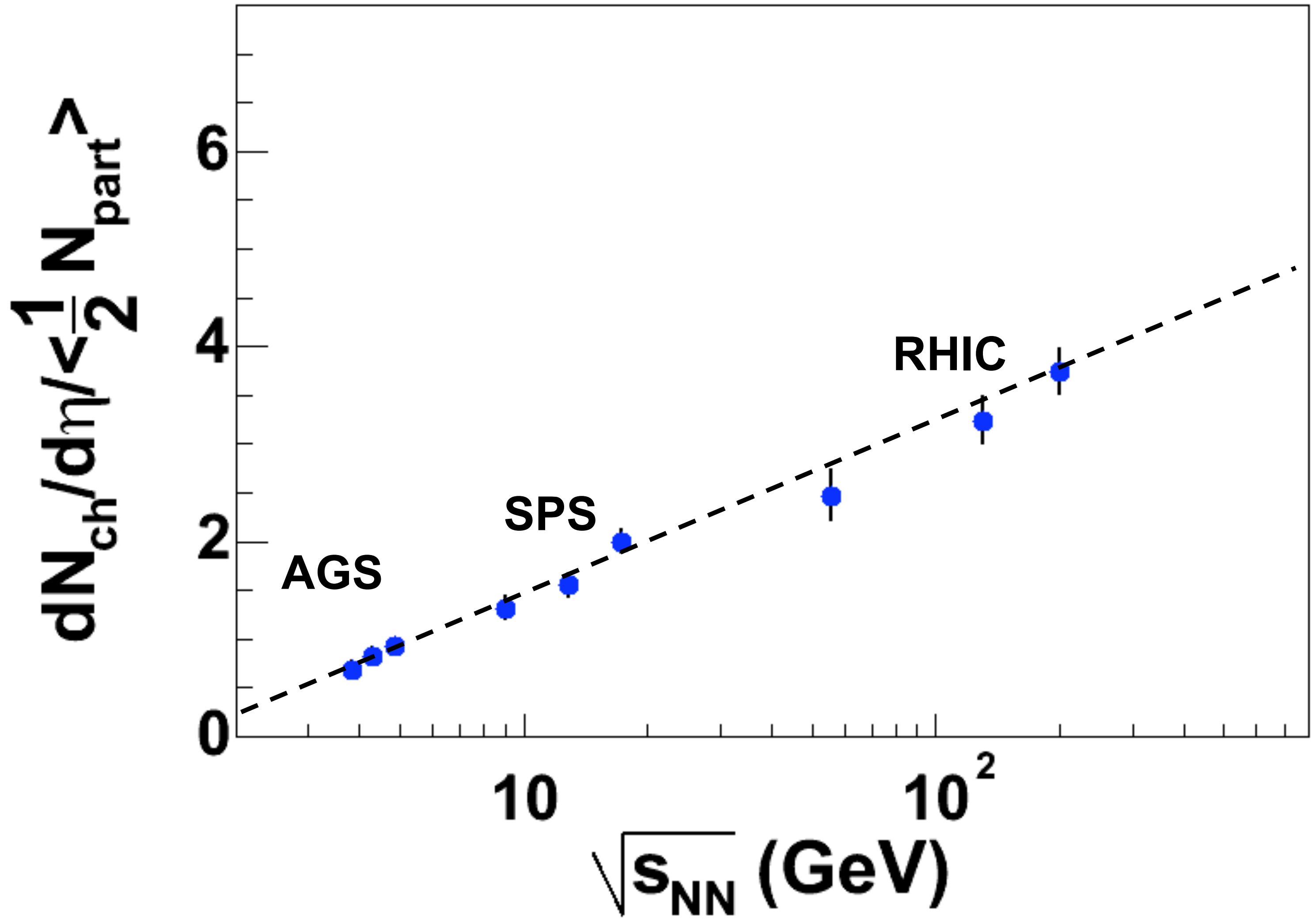
Particle Density near Mid-Rapidity



Beware of the Jacobian!

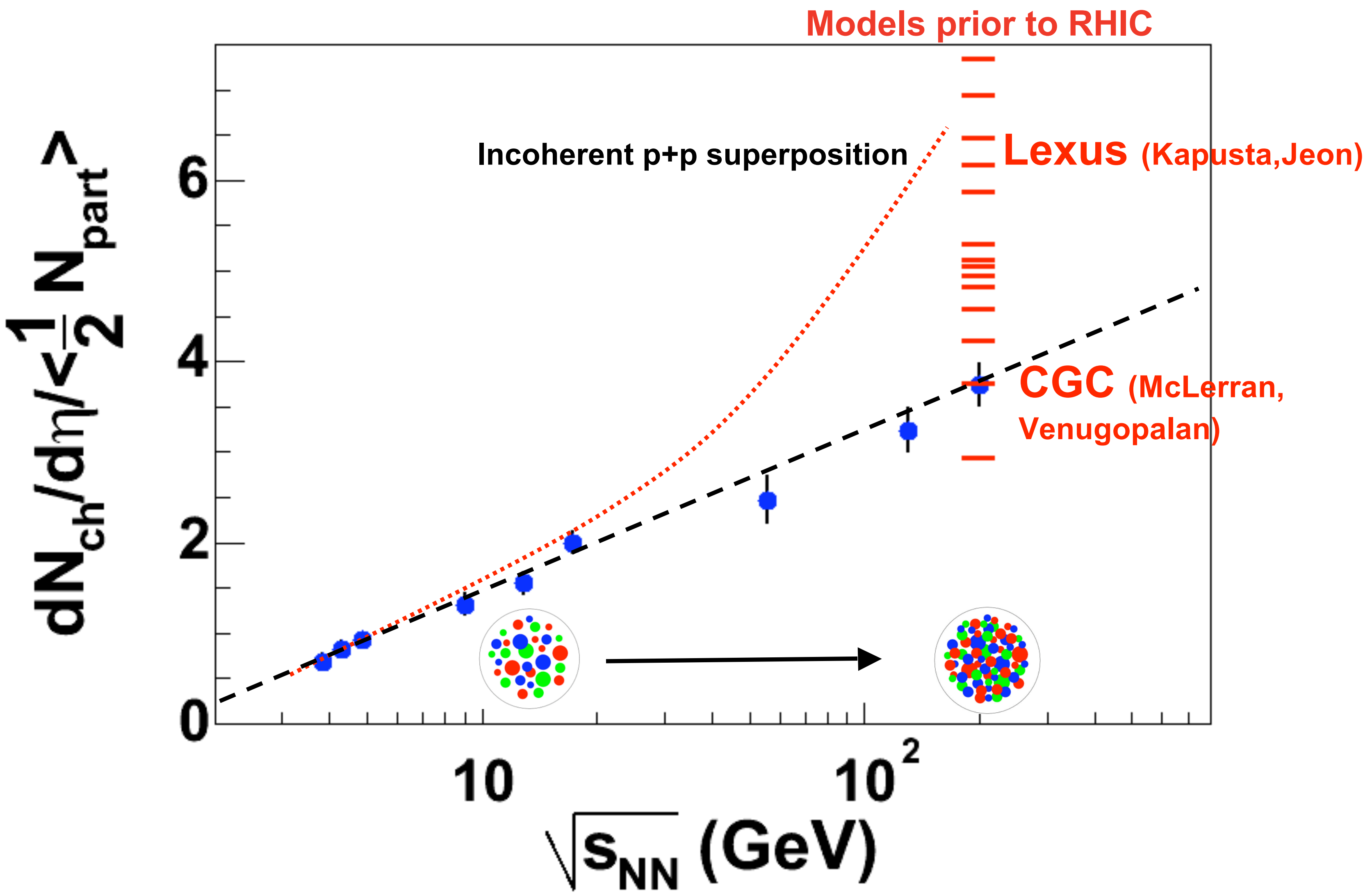
dN/dh = <b> dN/dy

Particle Density near Mid-Rapidity



Logarithmic rise with collision energy

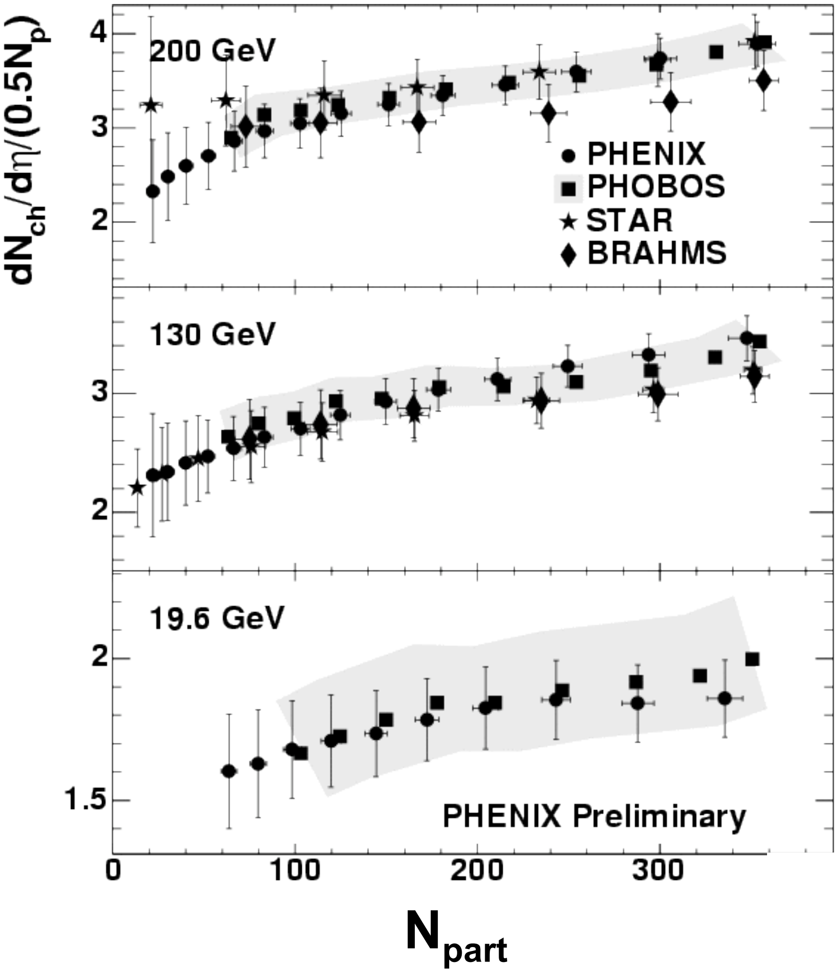
Particle Density near Mid-Rapidity

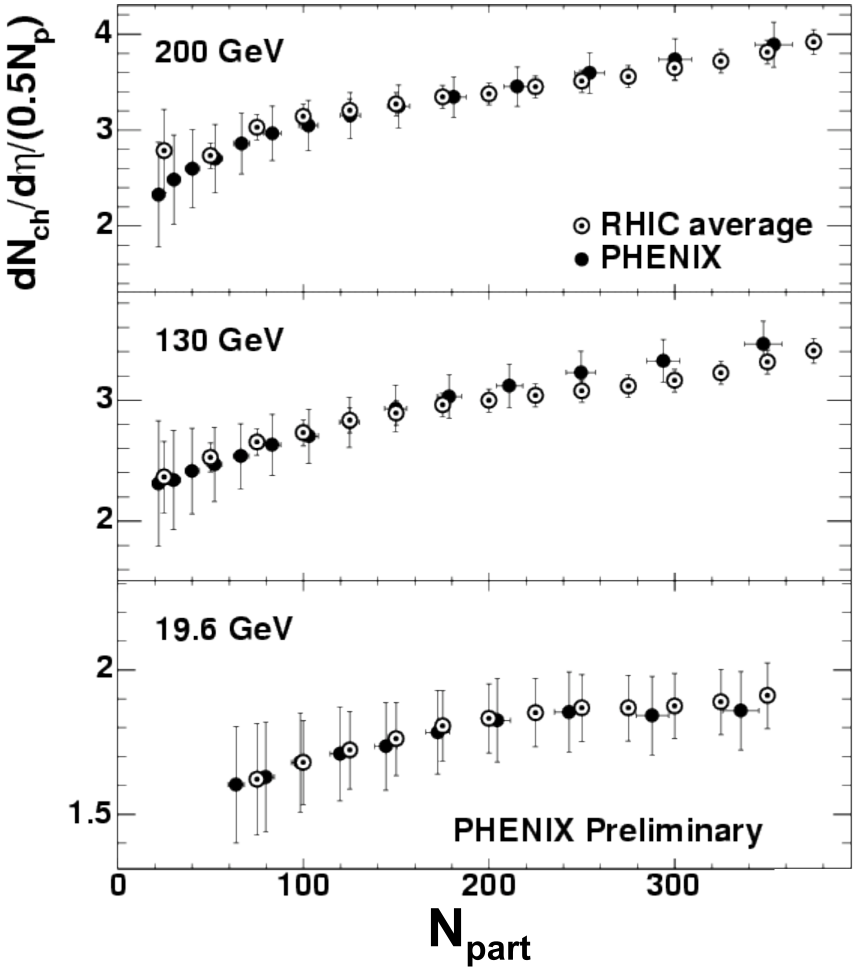


“Coherence” of hadron production

Centrality Dependence at |h| < 1

Compilation by Sasha Milow

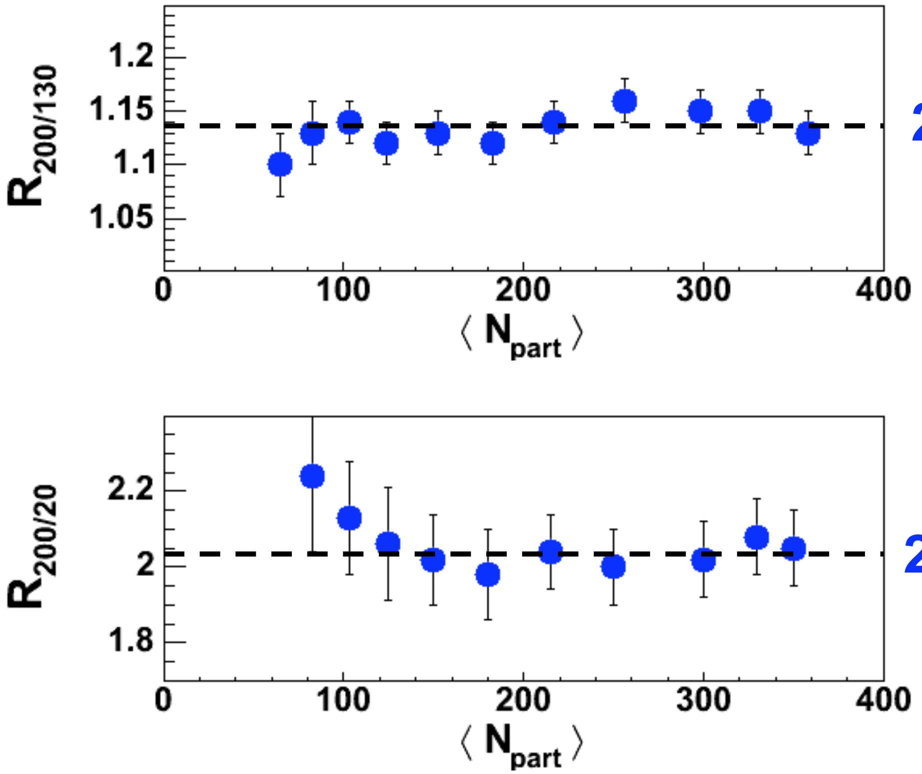




Consistent data set from all experiments

Centrality Dependence at |h| < 1

PHOBOS, QM’ 02, Aneta Iordanova

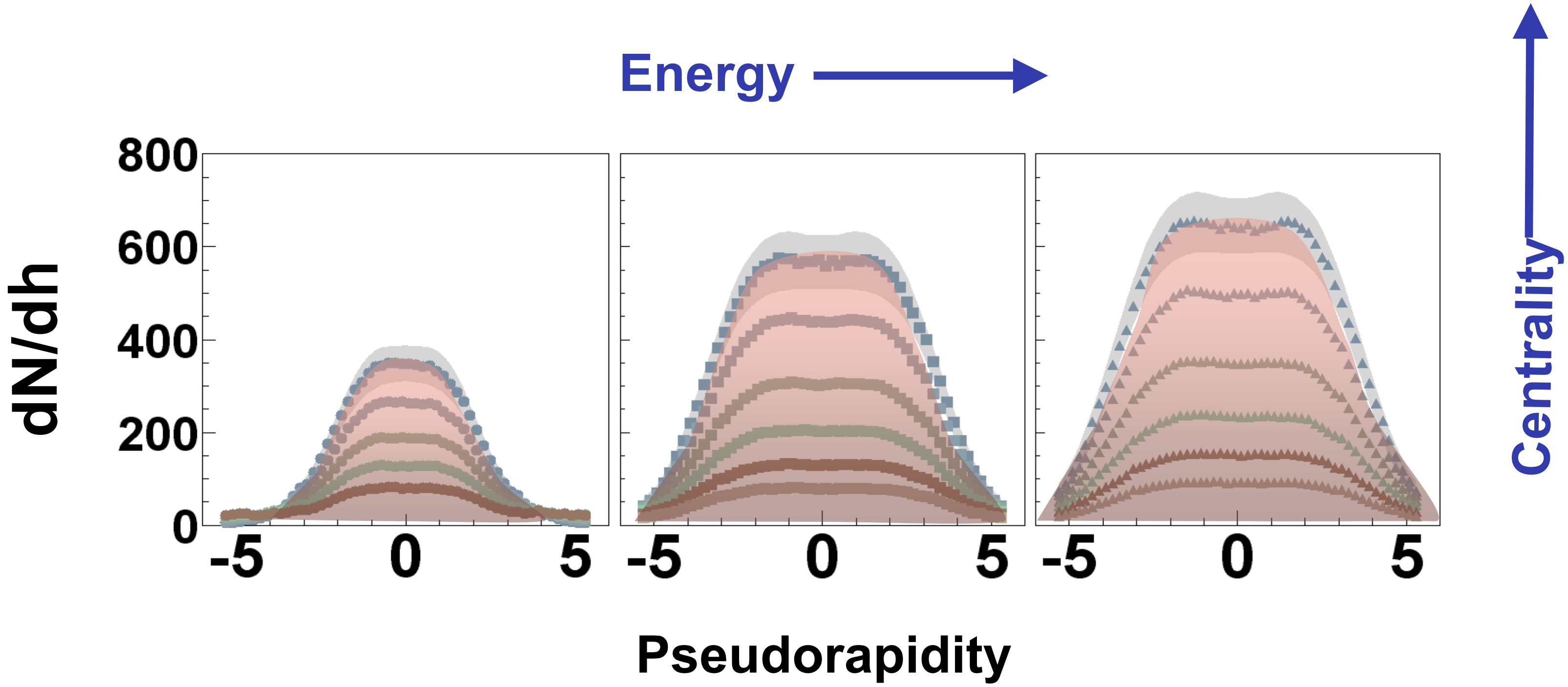


200 GeV / 130 GeV

200 GeV / 19.6 GeV

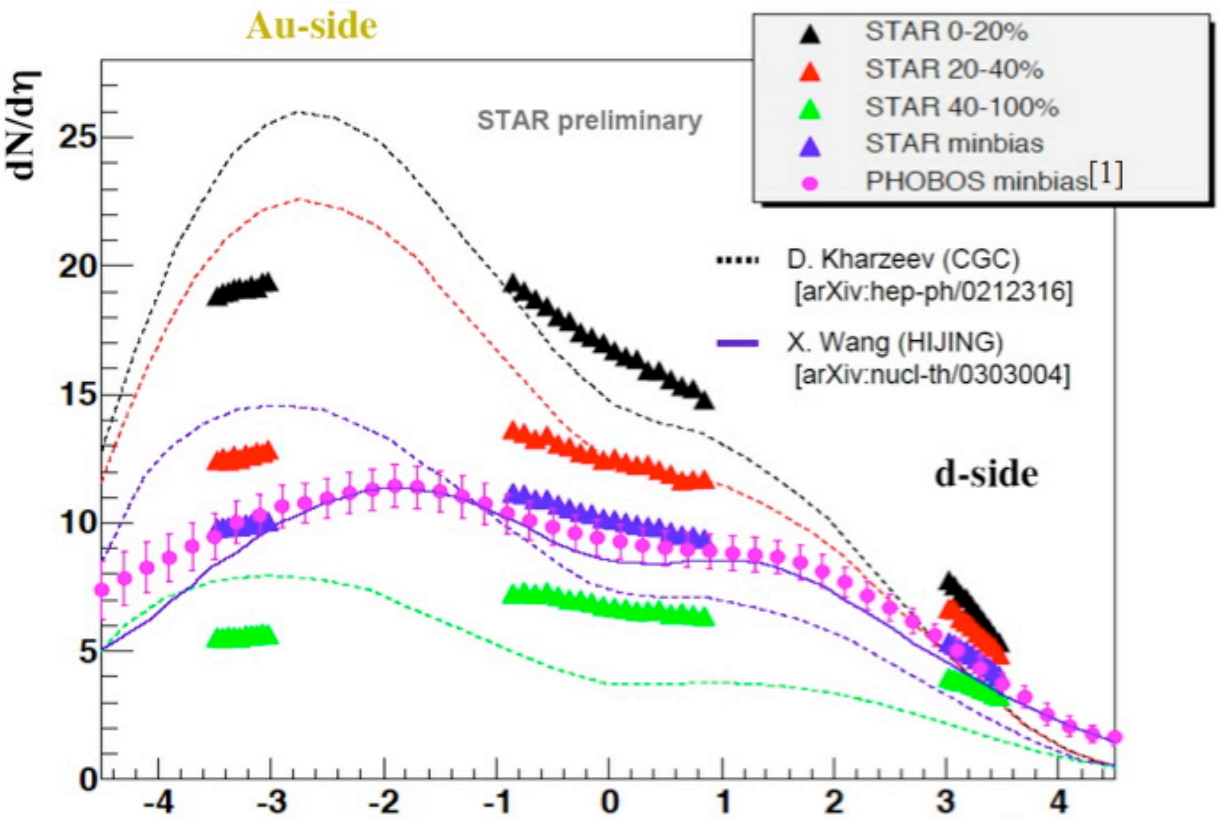
Surprising lack of energy dependence

II. 4-p Multiplicity $<N_{ch}>$



How does integral over 4-p, $<N_{ch}>$, change with Energy and Centrality?

$\langle N_{ch} \rangle$ vs N_{part} in d+Au

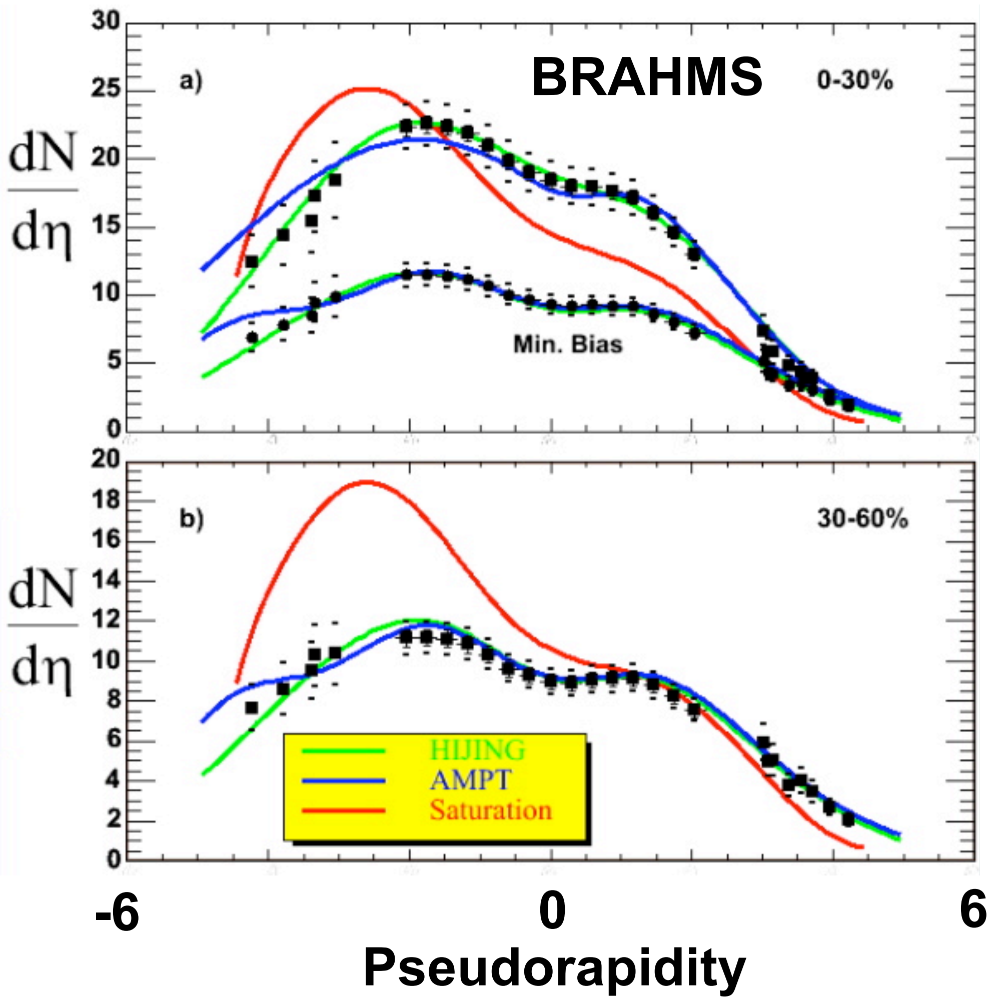


Pseudorapidity

Min bias confirms PHOBOS

Shape evolves with centrality

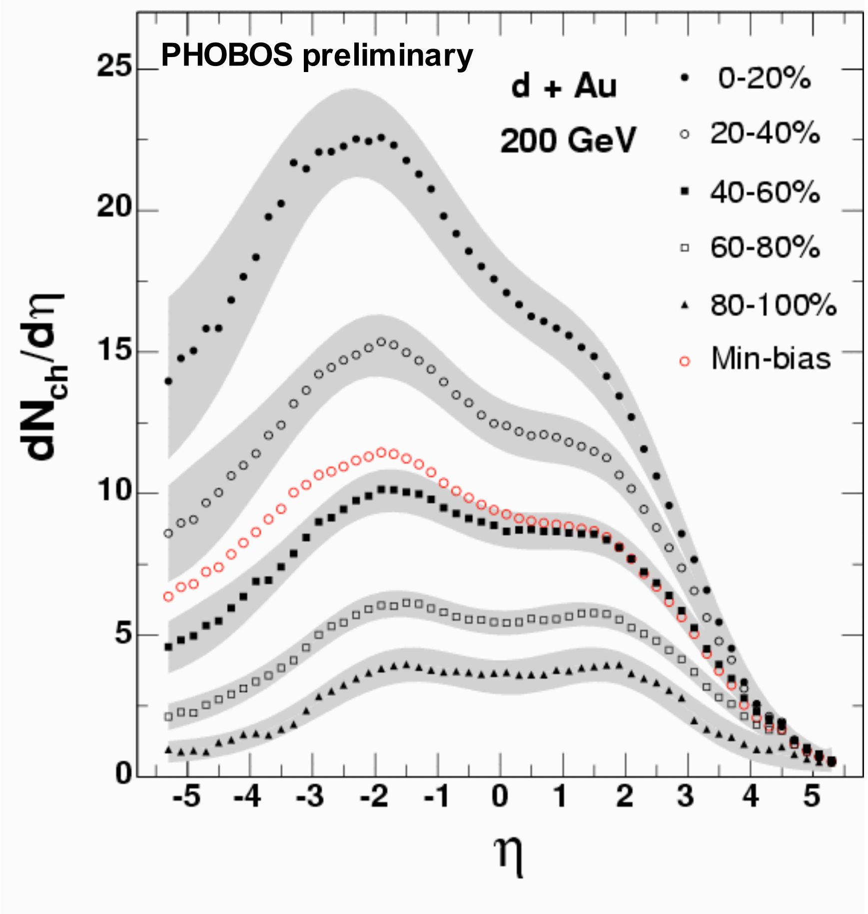
$\langle N_{ch} \rangle$ vs N_{part} in d+Au

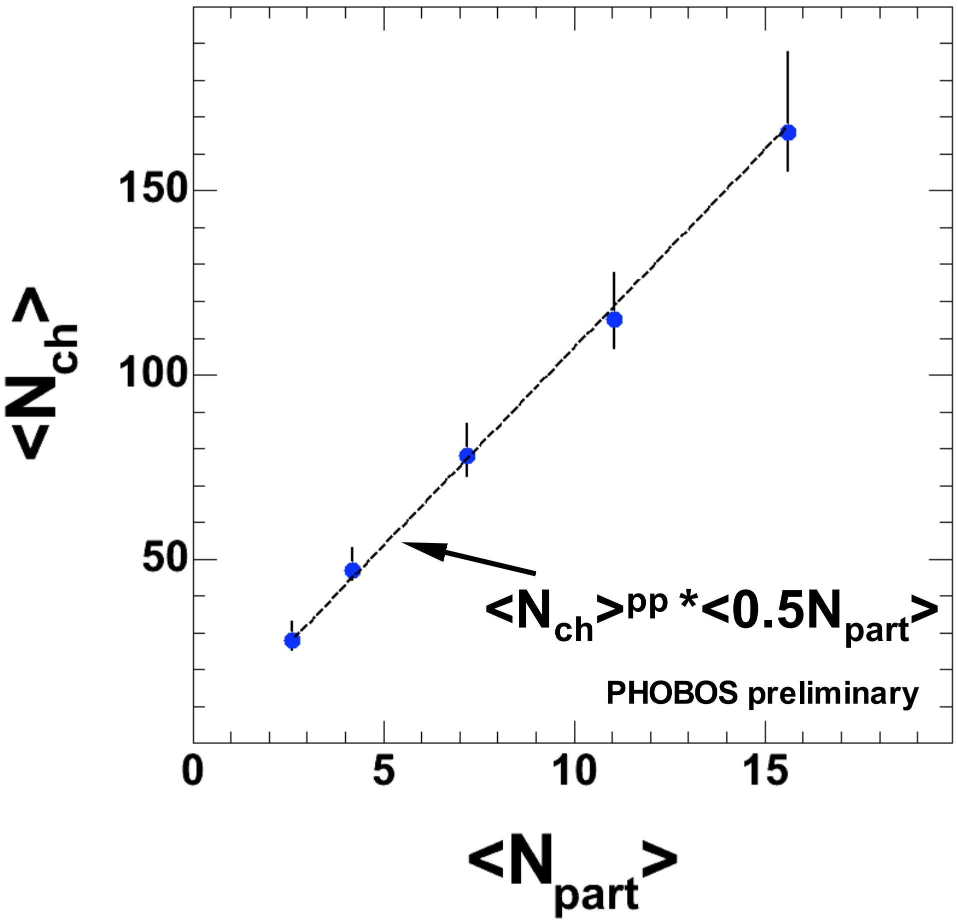


Again, evolution of shape with centrality

$\langle N_{ch} \rangle$ vs N_{part} in d+Au

see talk by Rachid Nouicer

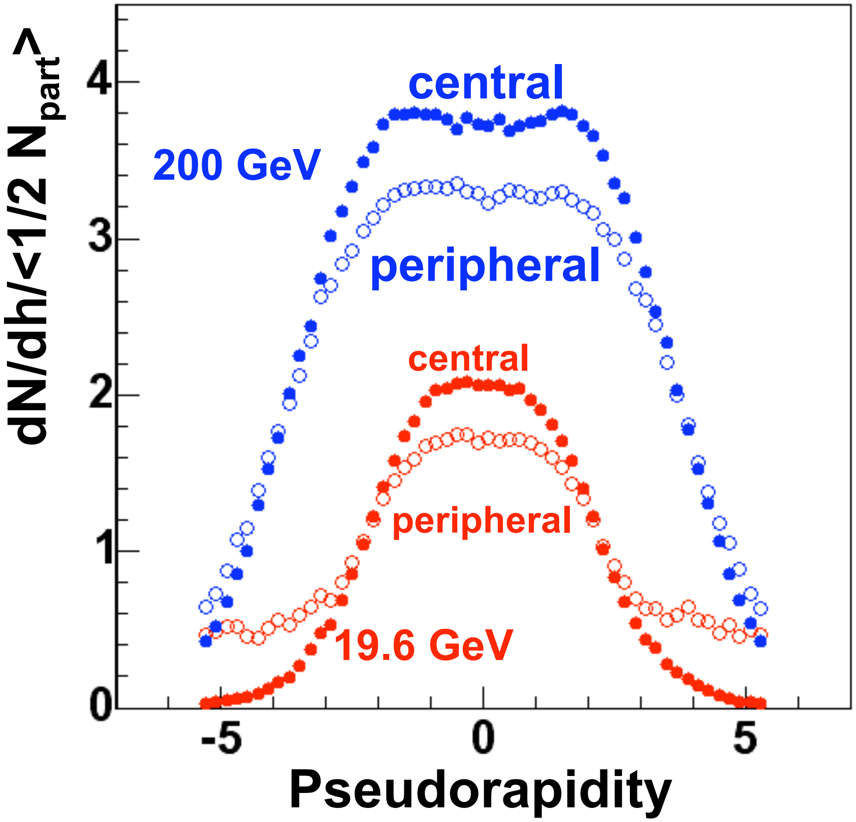




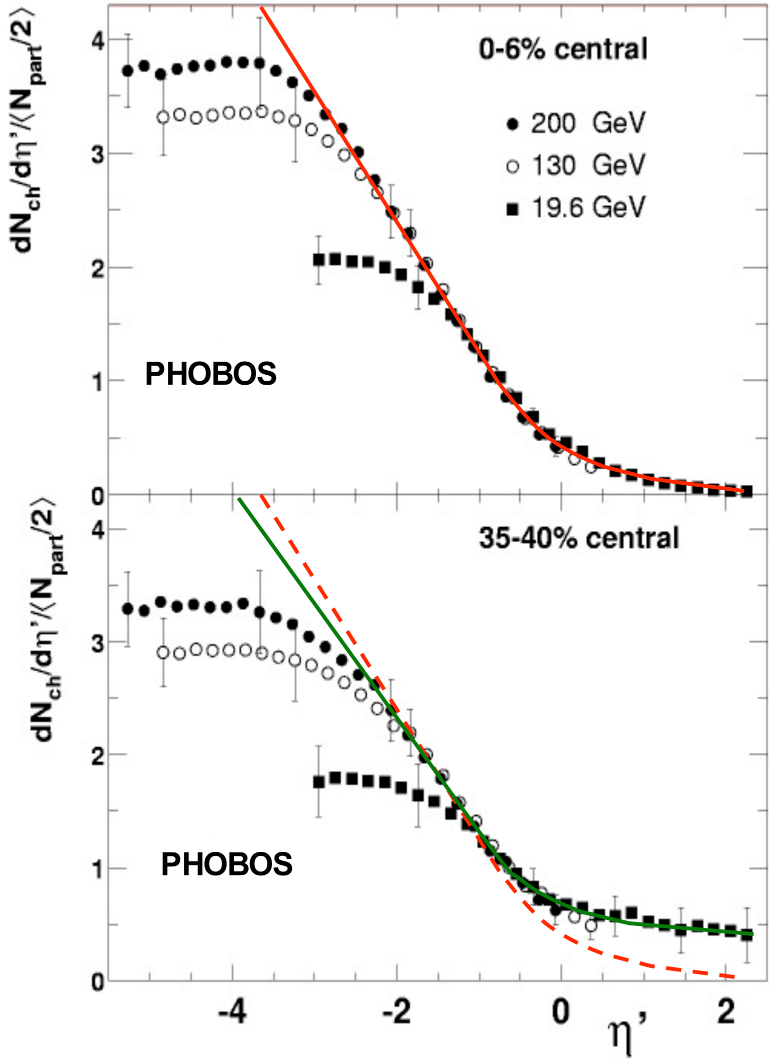
$<N_{ch}>$ in d+Au = $<N_{ch}>$ in p+p * 0.5 $<N_{part}>$

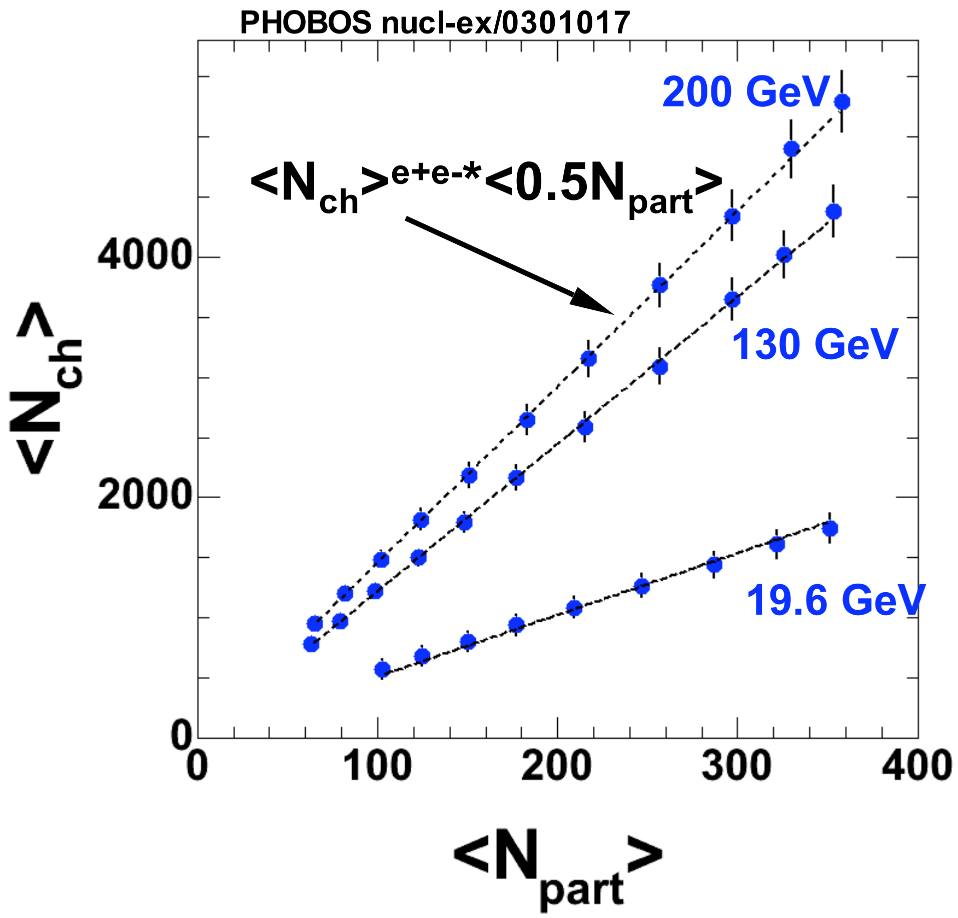
$\langle N_{ch} \rangle$ vs N_{part} in Au+Au

PHOBOS PRL91,052303 (2003)



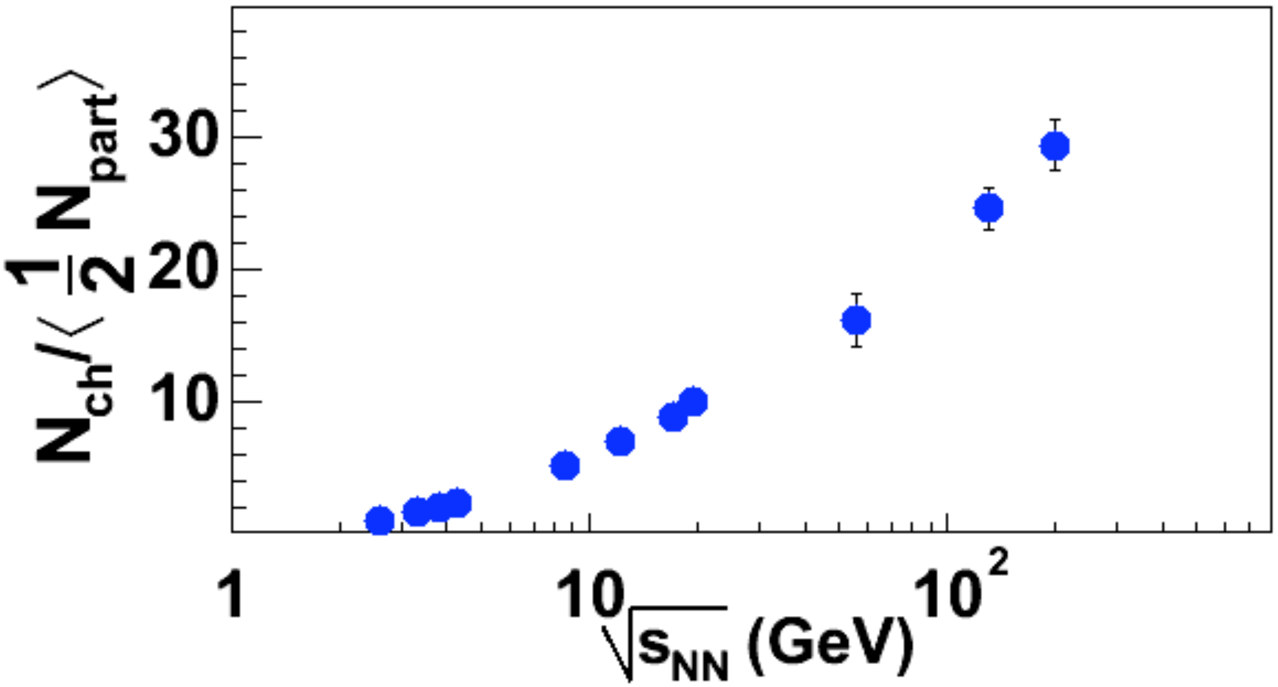
$\langle N_{ch}\rangle$ vs N_{part} in Au+Au





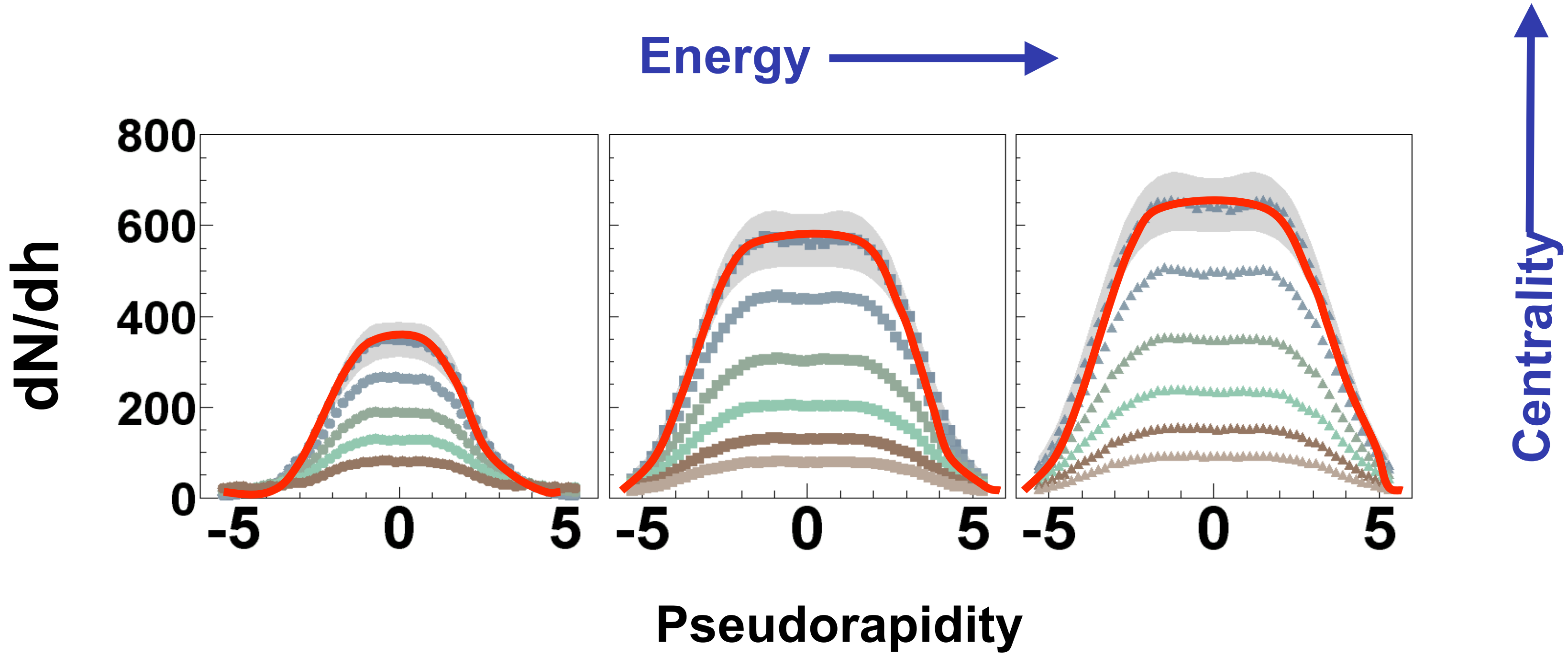
$<N_{ch}>$ in Au+Au proportional to N_{part}

<N_{ch}> vs sqrt(s)



Smooth Evolution of <N_{ch}> with sqrt(s)?

III. Shape of dN/dh Distributions

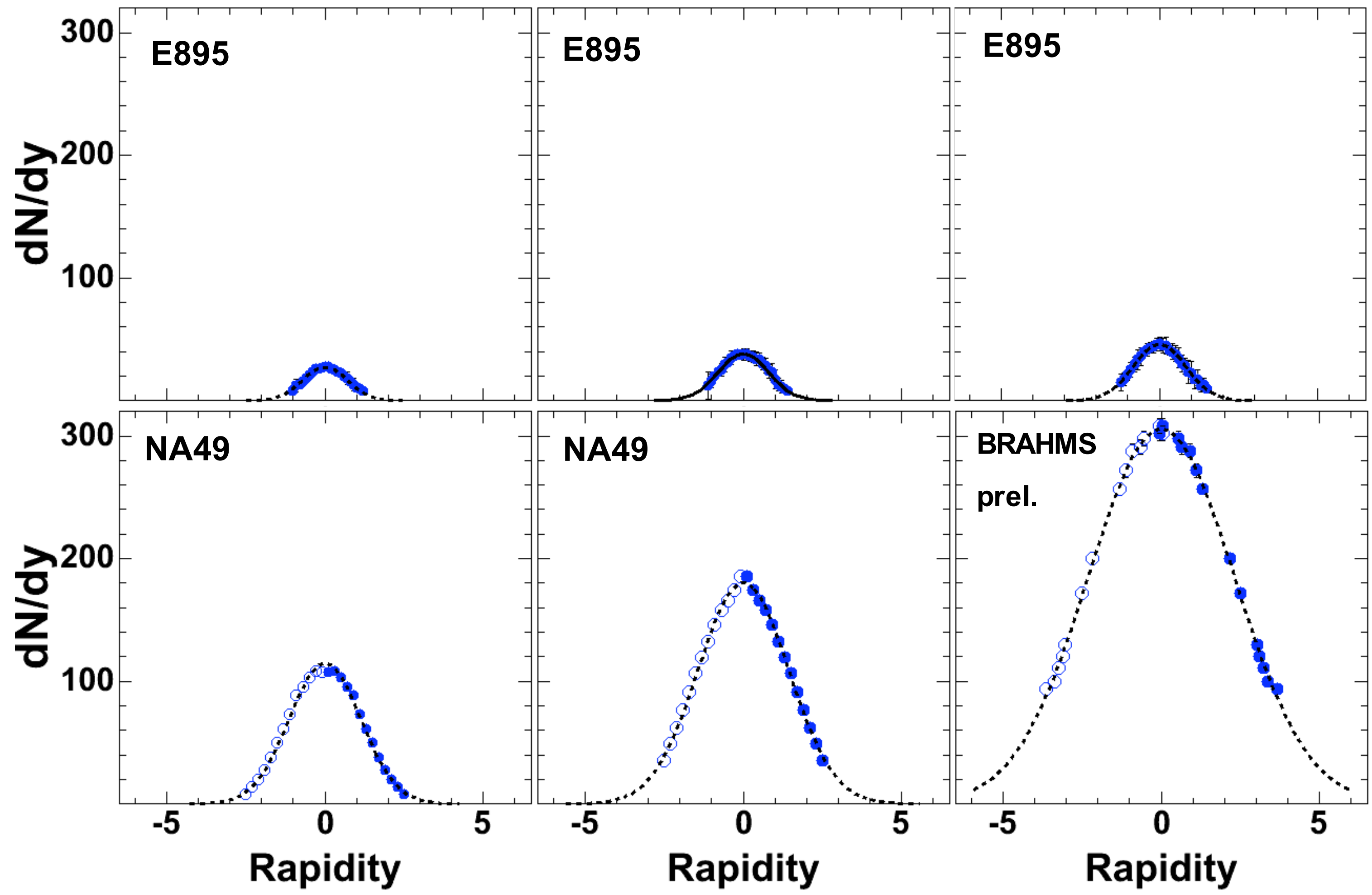


How does shape of dN/dh (dN/dy) change with Energy?

Reaching the central plateau?

Boost-invariance?

p^+ dN/dy spectra

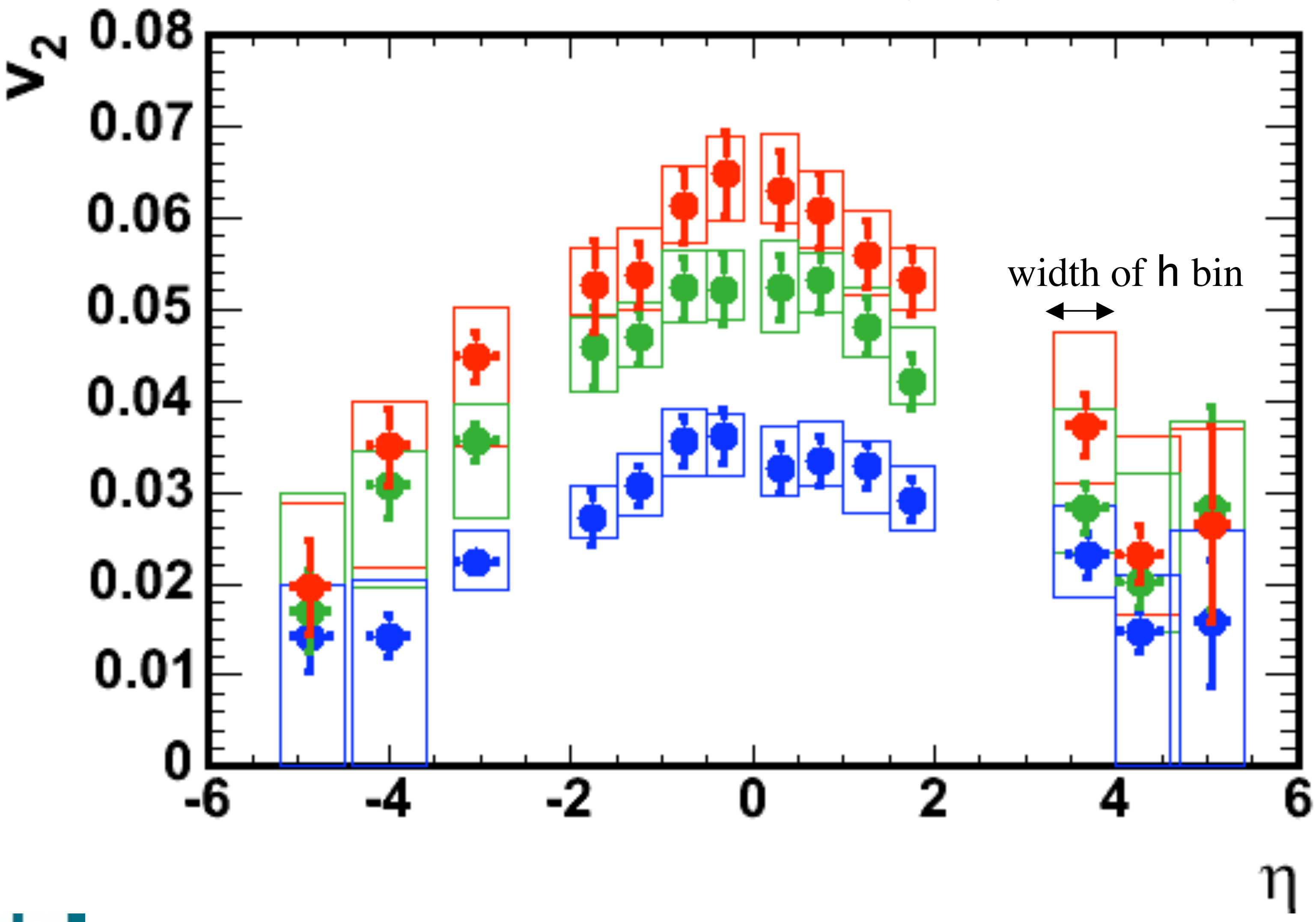


see talk by Djamel Ouerdane

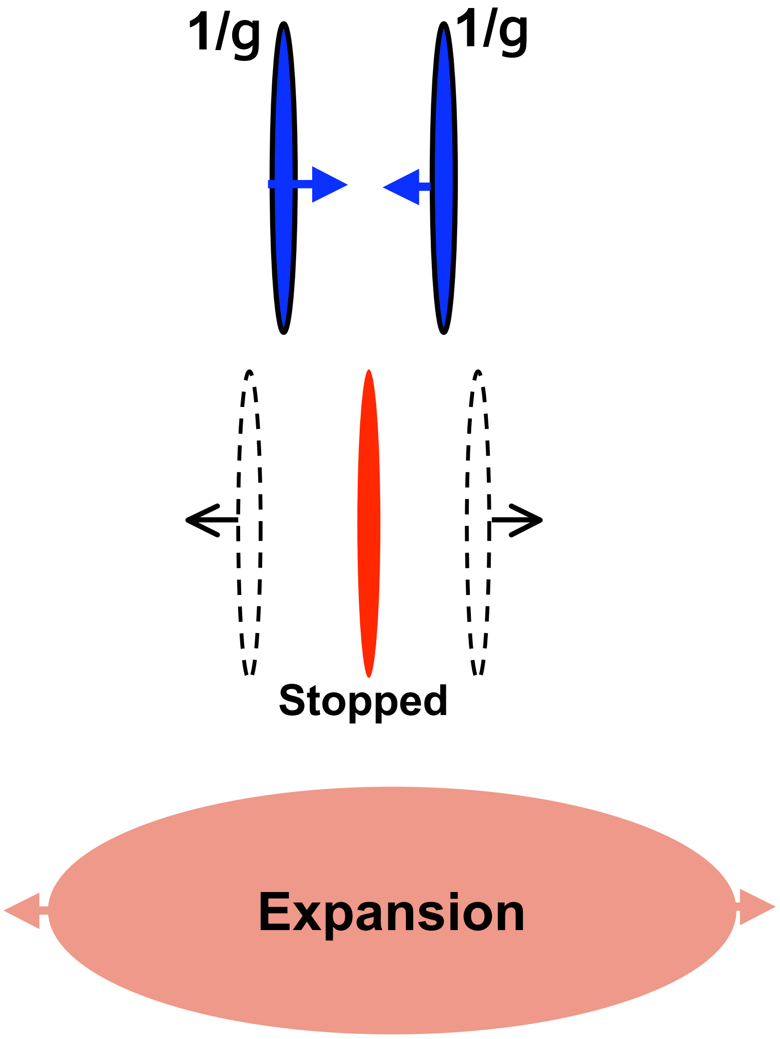
Single Gaussian <u>fits</u> from 2 to 200 GeV

Boost-Invariance?

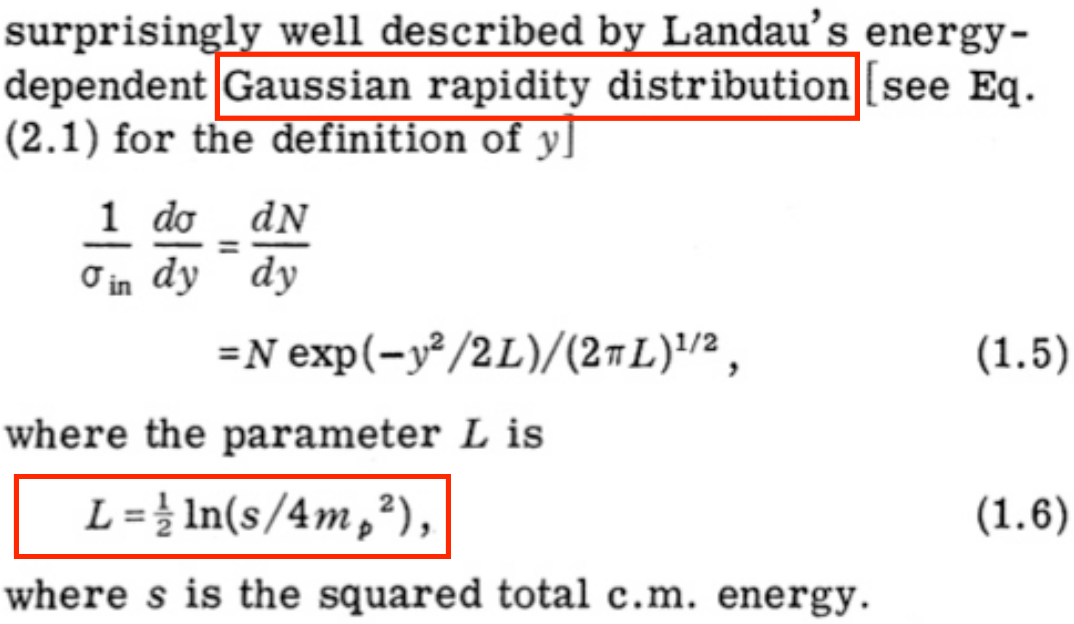
see talk by Marguerite Belt Tonjes



Landau Hydrodynamics



Carruthers, Duong-Van on pp data in 1973:



surprisingly well described by Landau's energy-dependent Gaussian rapidity distribution [see Eq. (2.1) for the definition of y]

$$\frac{1}{\sigma_{\text{in}}}\frac{d\sigma}{dy}=\frac{dN}{dy}$$

$$=N\exp(-y^2/2L)/(2\pi L)^{1/2}, \qquad (1.5)$$

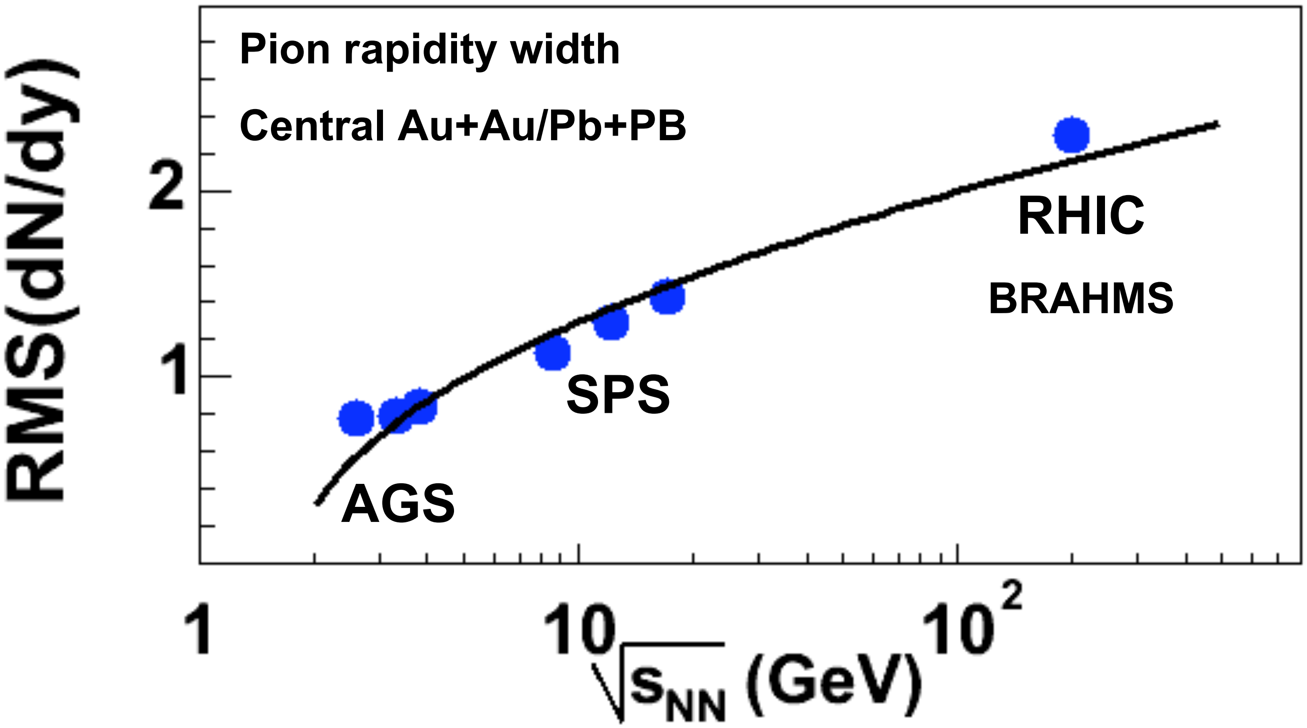
where the parameter L is

$$\boxed{L=\tfrac{1}{2}\ln(s/4m_p{}^2),} \qquad (1.6)$$

where s is the squared total c.m. energy.

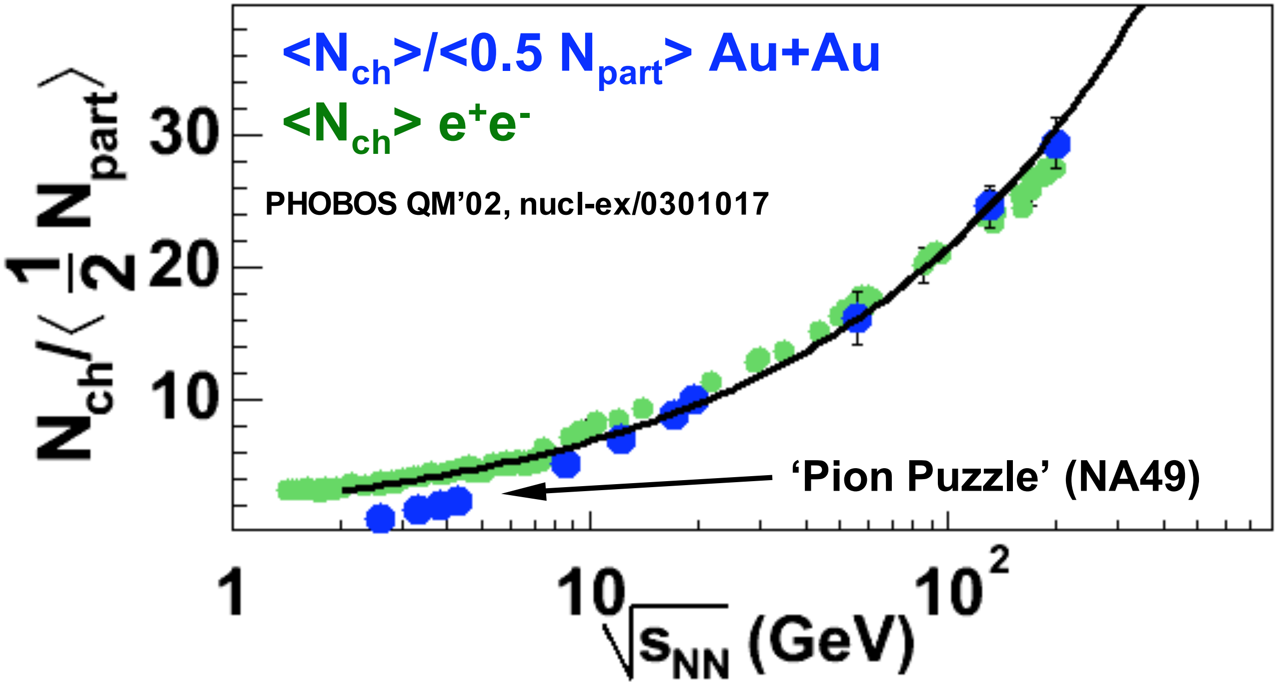
Landau Hydrodynamics

see Talk by Tetsufumi Hirano on Thursday, posters (e.g. Schlei, Csanad)



Reasonable agreement of prediction (1955) and data (2003)

$\langle N_{ch} \rangle$ vs sqrt(s) revisited

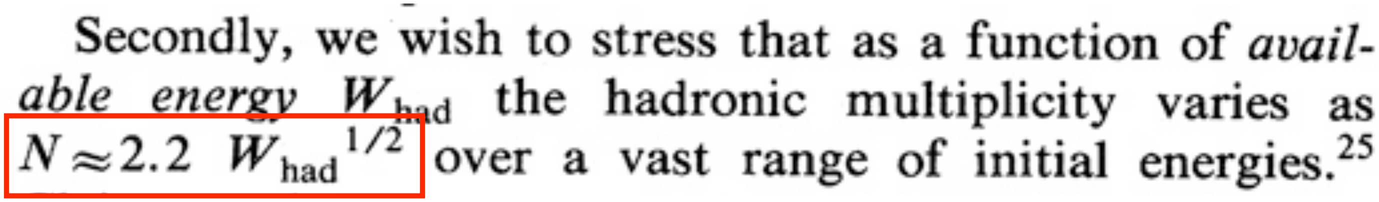


$\langle N_{ch} \rangle / \langle 0.5\ N_{part} \rangle$ Au+Au

$\langle N_{ch} \rangle$ e^+e^-

PHOBOS QM'02, nucl-ex/0301017

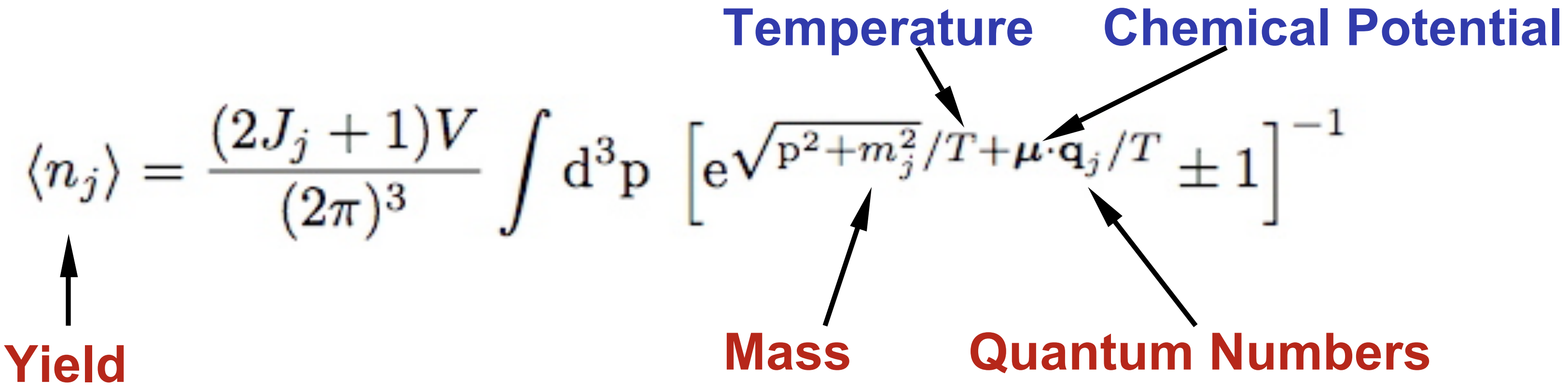
'Pion Puzzle' (NA49)



Secondly, we wish to stress that as a function of *available energy* W_{had} the hadronic multiplicity varies as $\boxed{N \approx 2.2\ W_{had}{}^{1/2}}$ over a vast range of initial energies.[25]

Carruthers, Duong-Van on pp and e^+e^- data in 1983

IV. Spectrum of Produced Hadrons



Temperature

Chemical Potential

$$\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^3} \int \mathrm{d}^3\mathrm{p} \left[\mathrm{e}^{\sqrt{\mathrm{p}^2+m_j^2}/T + \boldsymbol{\mu}\cdot\mathbf{q}_j/T} \pm 1 \right]^{-1}$$

Yield

Mass

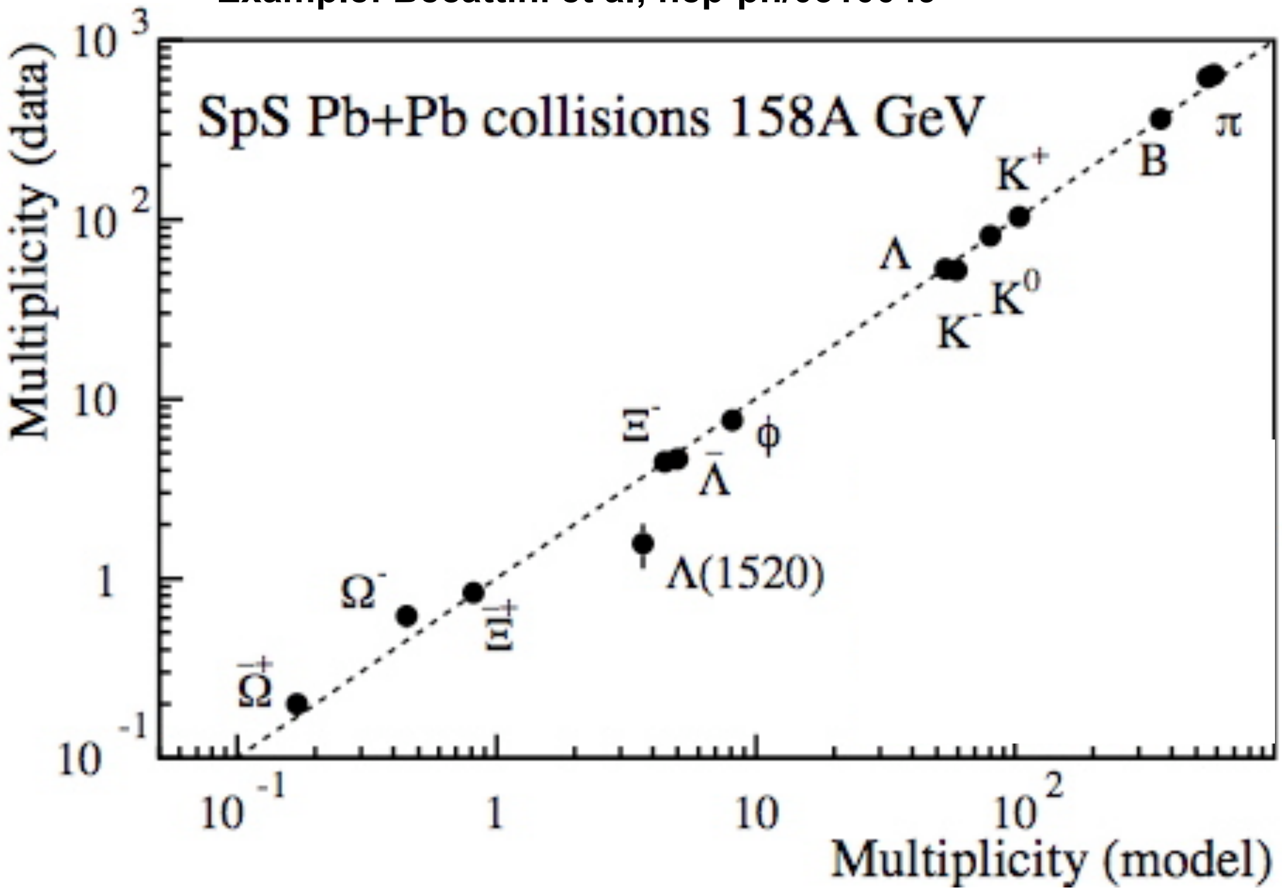
Quantum Numbers

- **Statistical *Description* of Observed Yields in Gibbs Grand-Canonical Ensemble**
  - Many Different Implementations
    - Mid-Rapidity vs 4-p yields
    - Non-Equilibrium (g_s, g_q)
    - Numerical Implementation
- **Here: Common Features of Different Approaches**

c.f. Hagedorn, Becattini, Braun-Munzinger, Cleymans, Heinz, Letessier,
Mekijan, Rafelski, Redlich, Sollfrank,Stachel, Tounsi + many others

Spectrum of Produced Hadrons

Example: Becattini et al; hep-ph/0310049



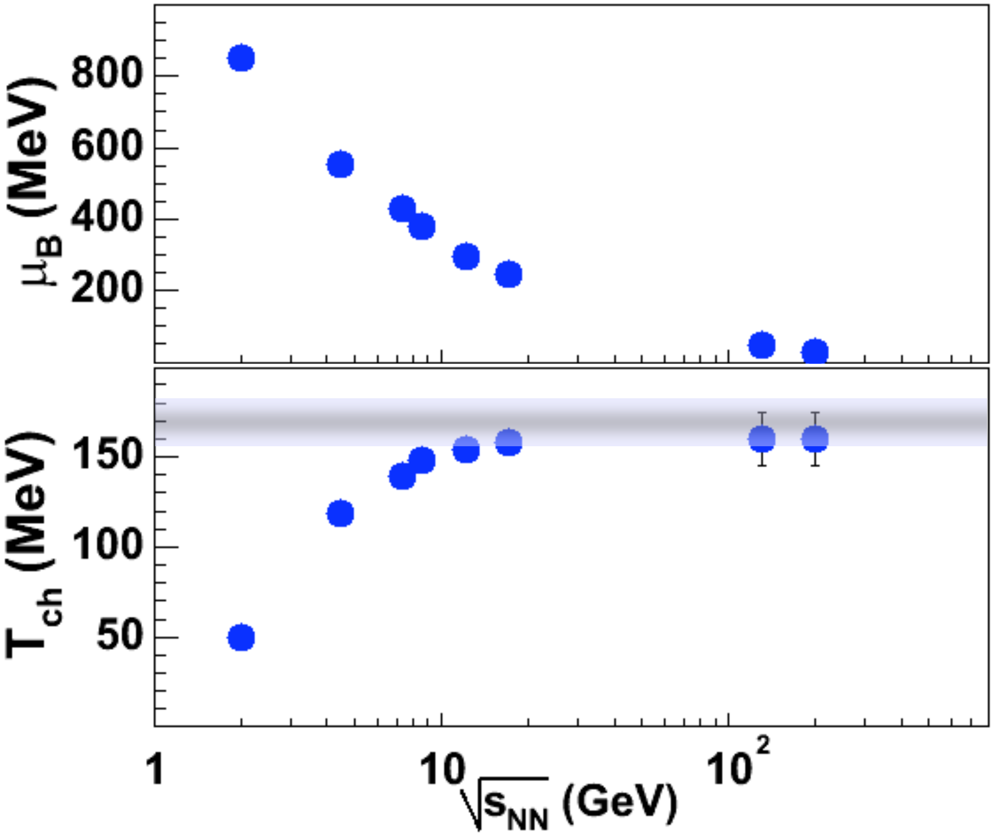
NA49 data,

4-p yields,

g_s ~ 0.85

“Thermal Fit” Parameters vs sqrt(s)

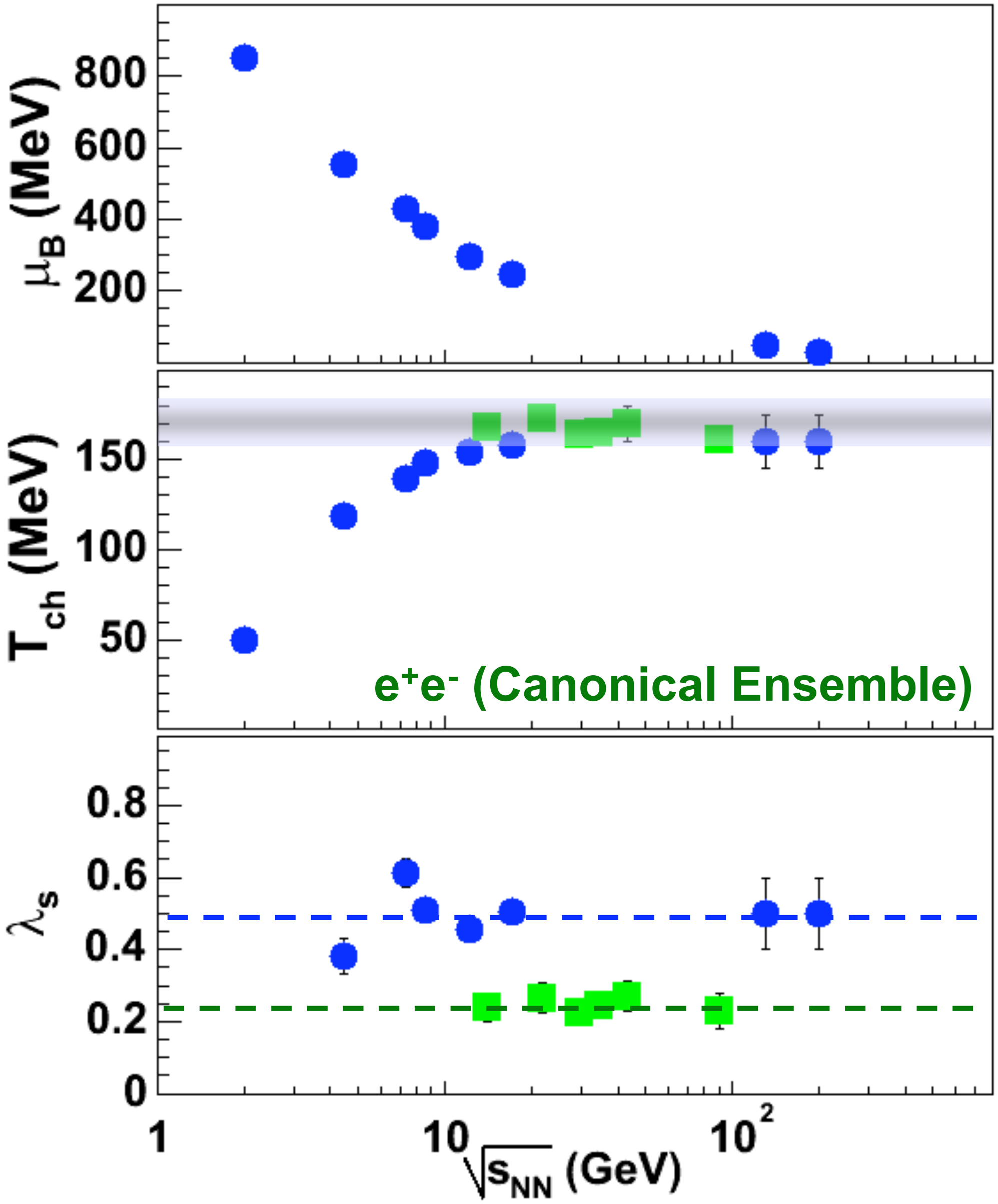
Calculations: Redlich et al, Becattini et al, Braun-Munzinger et al, Rafelski et al



m$_B$ drops with collision energy

T_{ch} approaches limiting value

“Thermal Fit” Parameters vs sqrt(s)



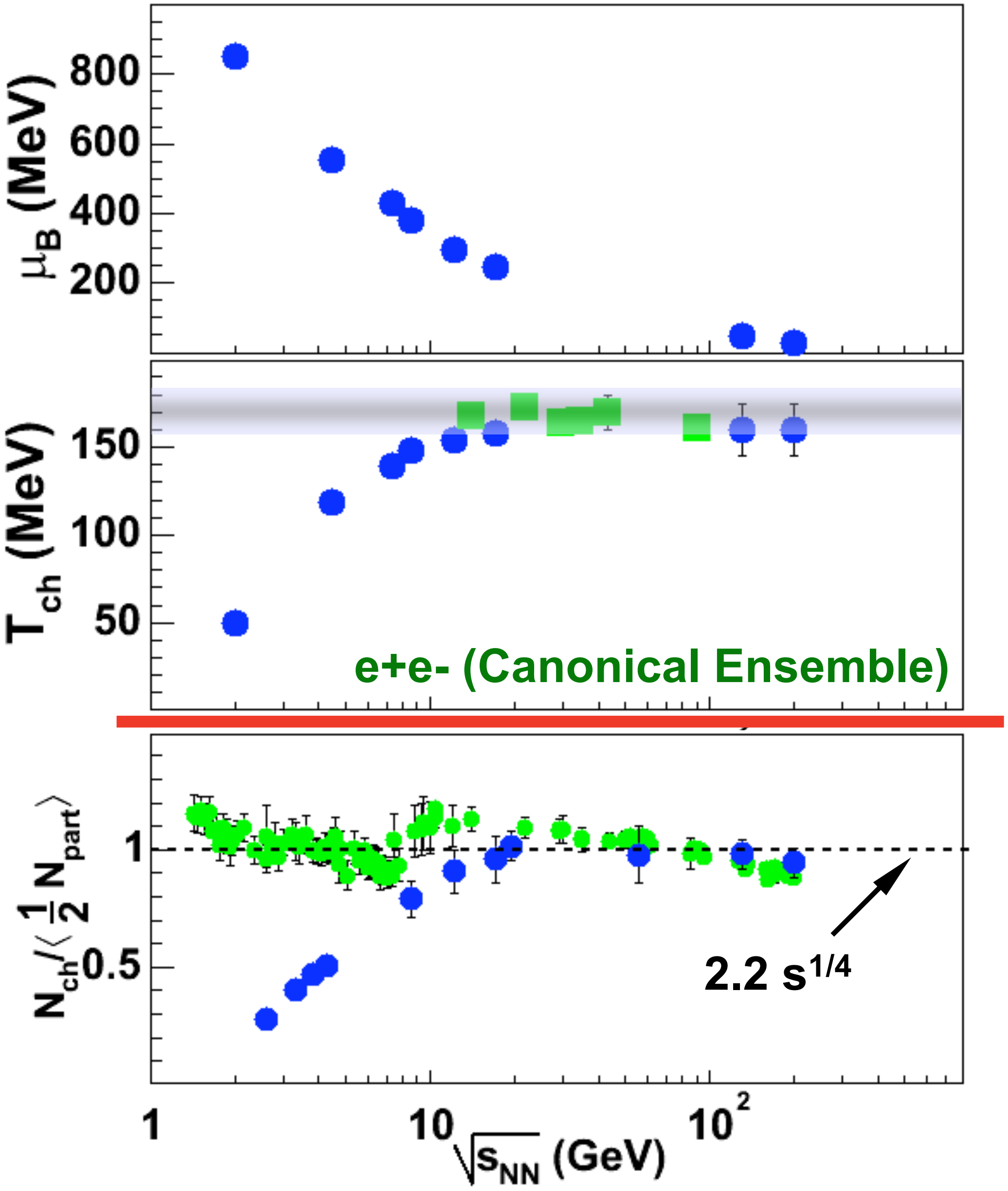
e^+e^- hadronizes at same T_{ch}

Are we looking at a *local* or *global* property?

Strangeness enhancement unique to AA

Global (or at least large correlation volume)

"Thermal Fit" Parameters and Multiplicity vs sqrt(s)



Summary

- **Data can indeed by reduced efficiently**
- **Total Multiplicity**
  - Proportional to N_{part}
  - Rises ~ $s^{1/4}$ from mid-SPS energy range
- **p dN/dy Distributions**
  - Single Gaussian with width $s^2 \sim 0.5 \ln(s/4m_p)$
  - Boost-invariance is not a dominant feature
- **Hadron Abundances**
  - Statistical Fits in Grand Canonical Ensemble
  - Systematic evolution, limiting temperature
  - Strangeness enhancement *unique* to AA

Challenges

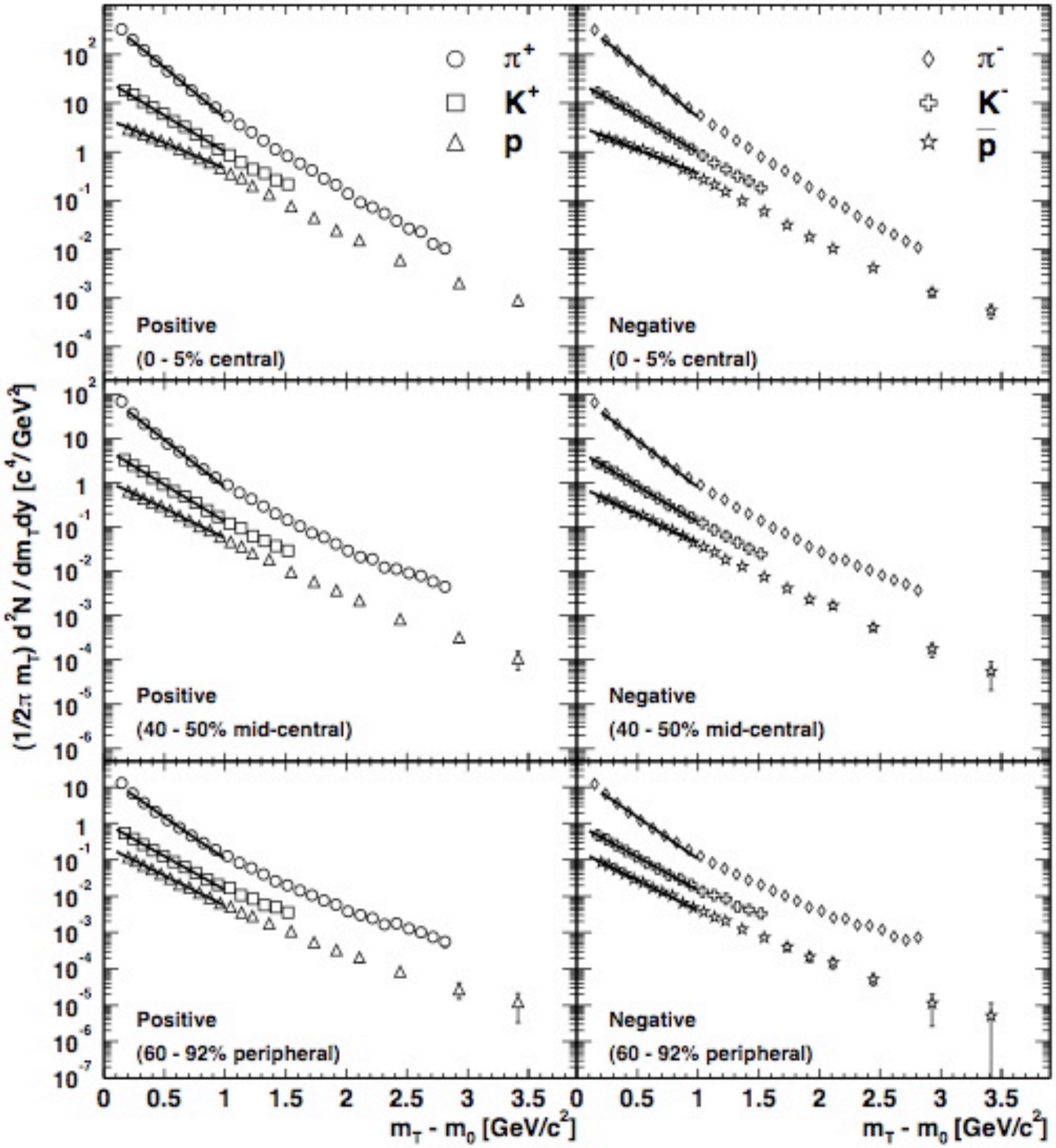
- **Correspondence with other ‘hadronic’ systems**
  - p+p, p+A, e^+e^-
- **“Max Entropy” evolution from sense initial state**
  - How is the initial state prepared?
    - Connection to parton saturation?
  - How can we understand “stopping” of
    - Baryon number?
    - Energy?

V. Transverse Dynamics

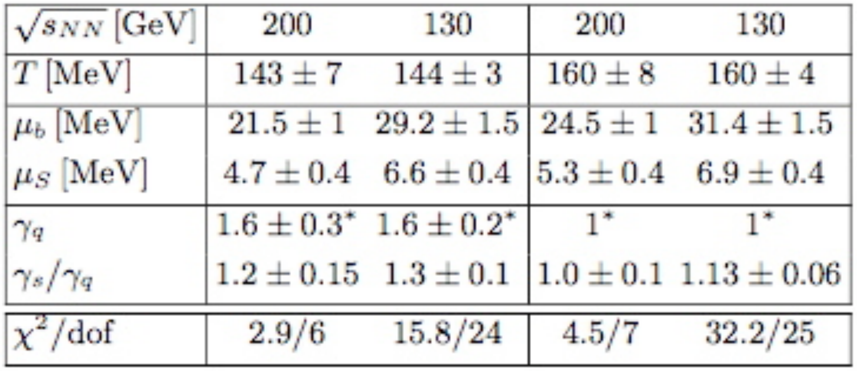
PHENIX

Au+Au 200 GeV

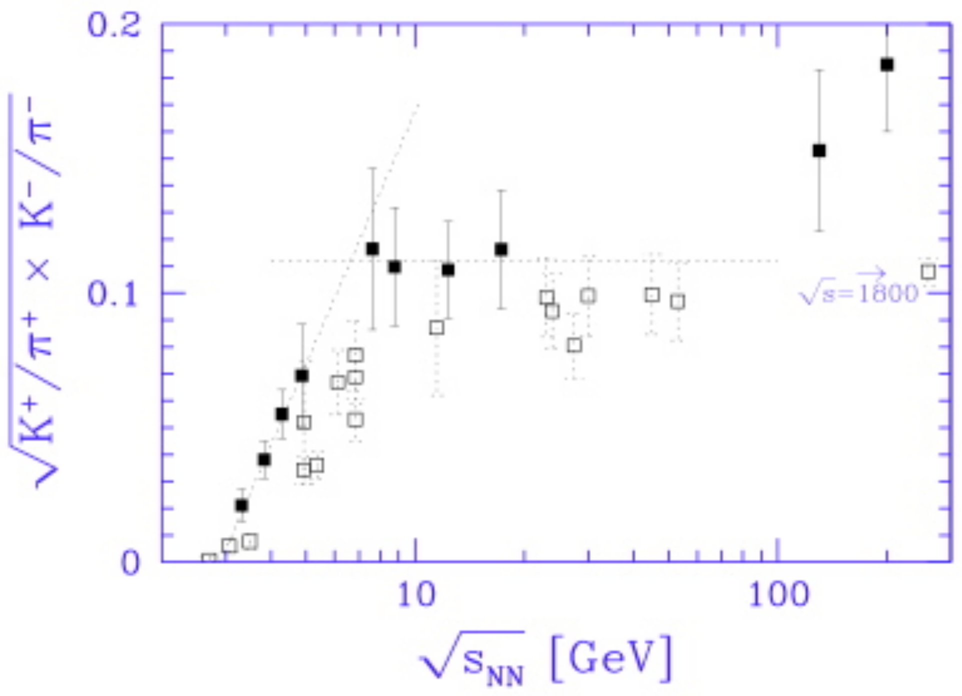
nucl-ex/0307022



Strangeness Excitation Function



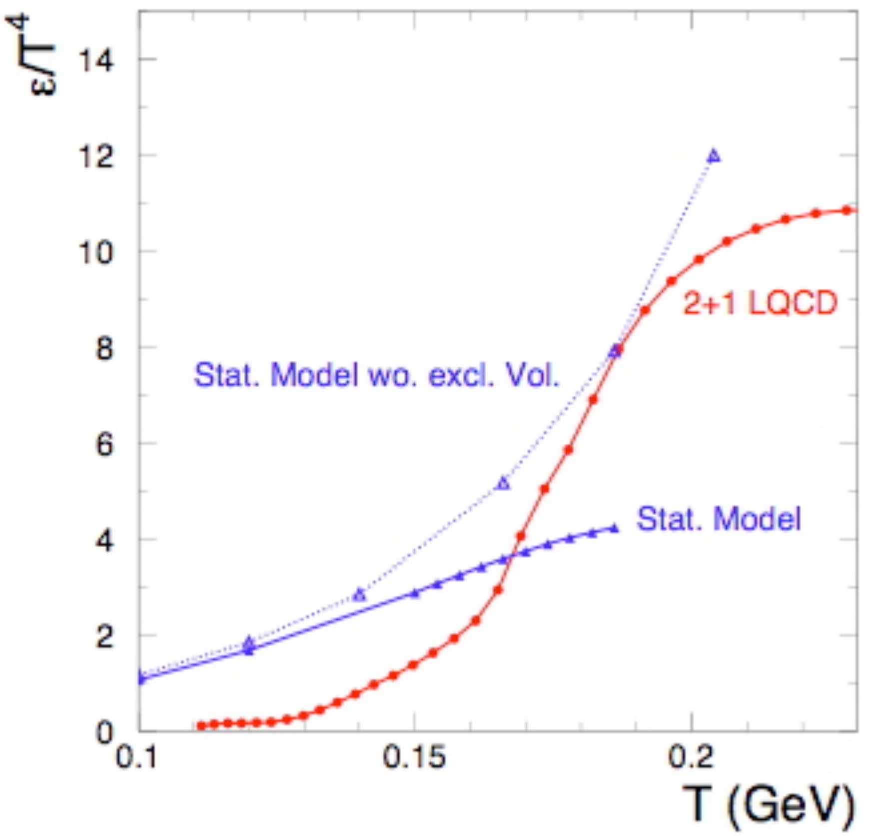
$\sqrt{s_{NN}}$ [GeV]	200	130	200	130
T [MeV]	143 ± 7	144 ± 3	160 ± 8	160 ± 4
μ_b [MeV]	21.5 ± 1	29.2 ± 1.5	24.5 ± 1	31.4 ± 1.5
μ_S [MeV]	4.7 ± 0.4	6.6 ± 0.4	5.3 ± 0.4	6.9 ± 0.4
γ_q	$1.6 \pm 0.3^*$	$1.6 \pm 0.2^*$	1^*	1^*
γ_s/γ_q	1.2 ± 0.15	1.3 ± 0.1	1.0 ± 0.1	1.13 ± 0.06
χ^2/dof	2.9/6	15.8/24	4.5/7	32.2/25



Rafelski/Letessier, hep-ph/0308154

T_{ch} and T_c

Braun-Munzinger, Stachel, Wetterich; nucl-th/0311005

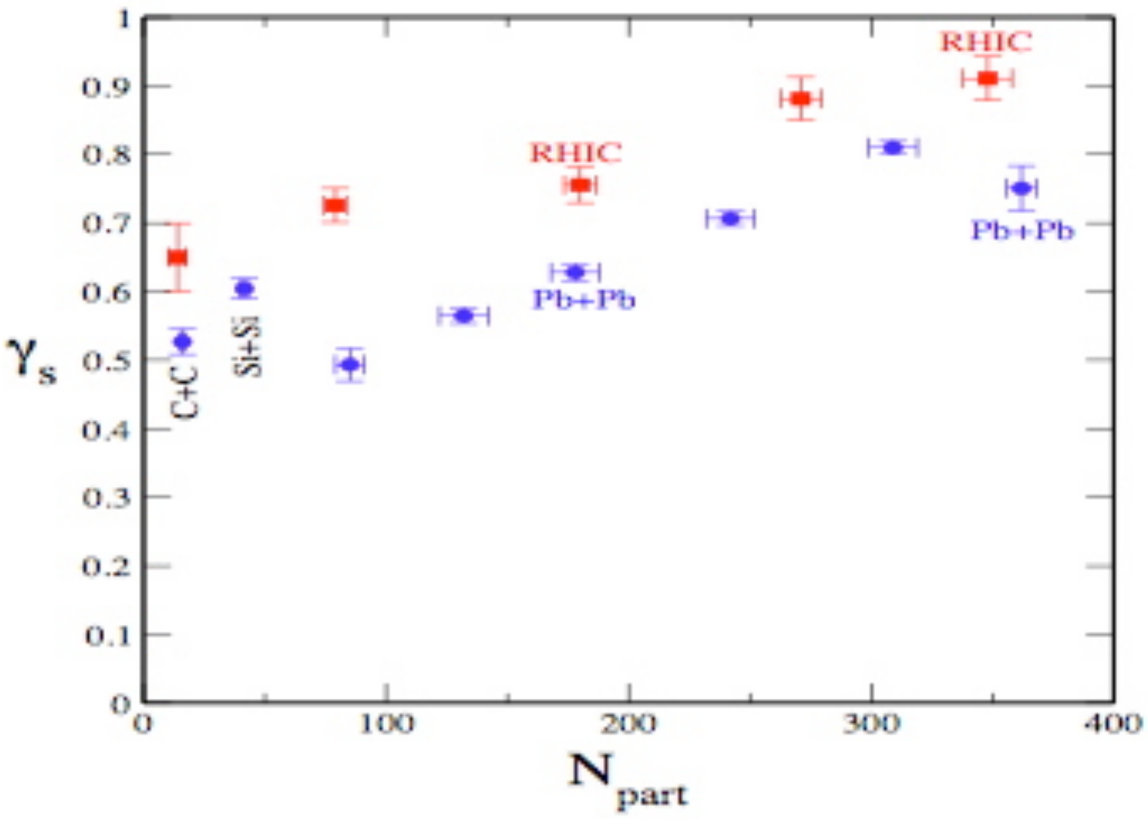


Freeze-out near T_c

Chemical Equilibrium sustained by multi-hadron interactions?

Statistical Fits vs N_{part}

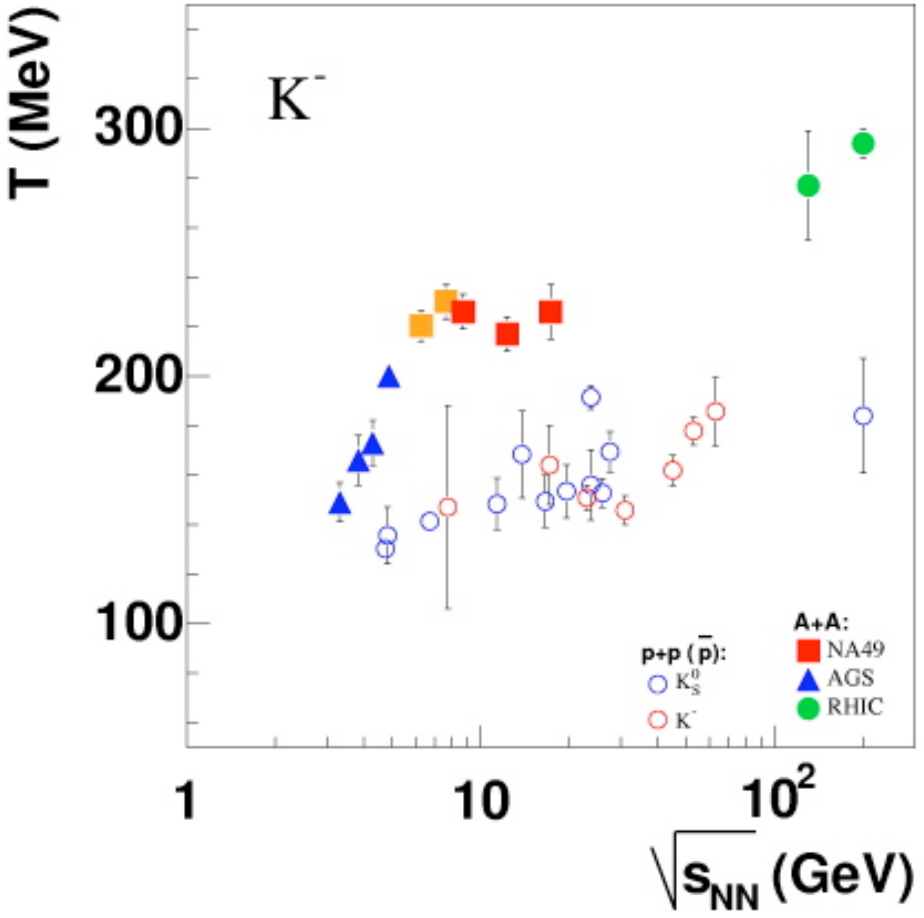
Cleymans et al, hep-ph/0311020

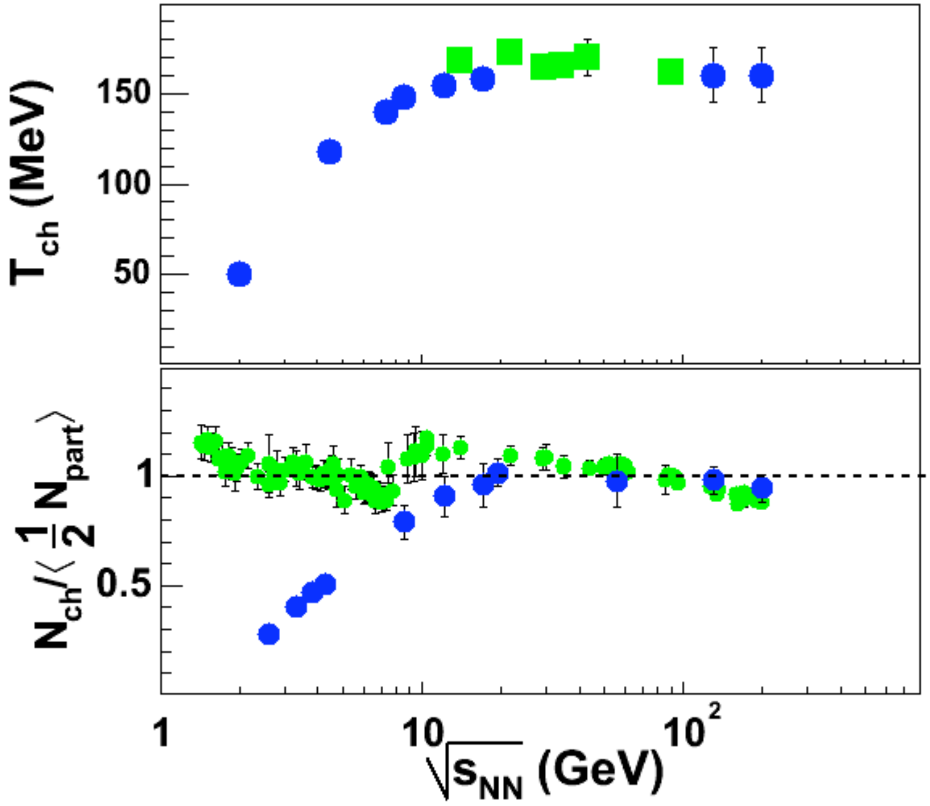


T_{ch} and m_B are (almost) constant

g_s N_{part} dependent

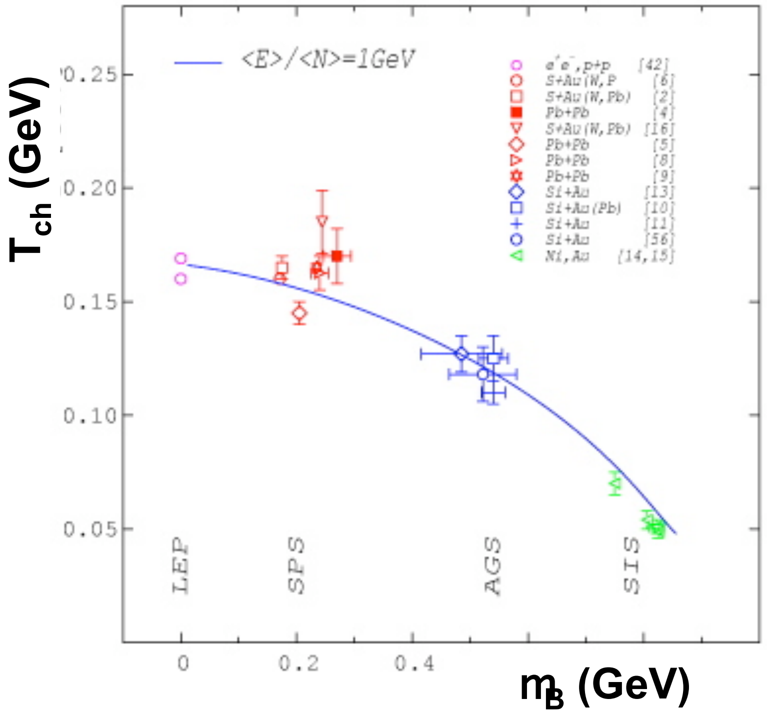
Structure in Inverse Slope vs sqrt(s)

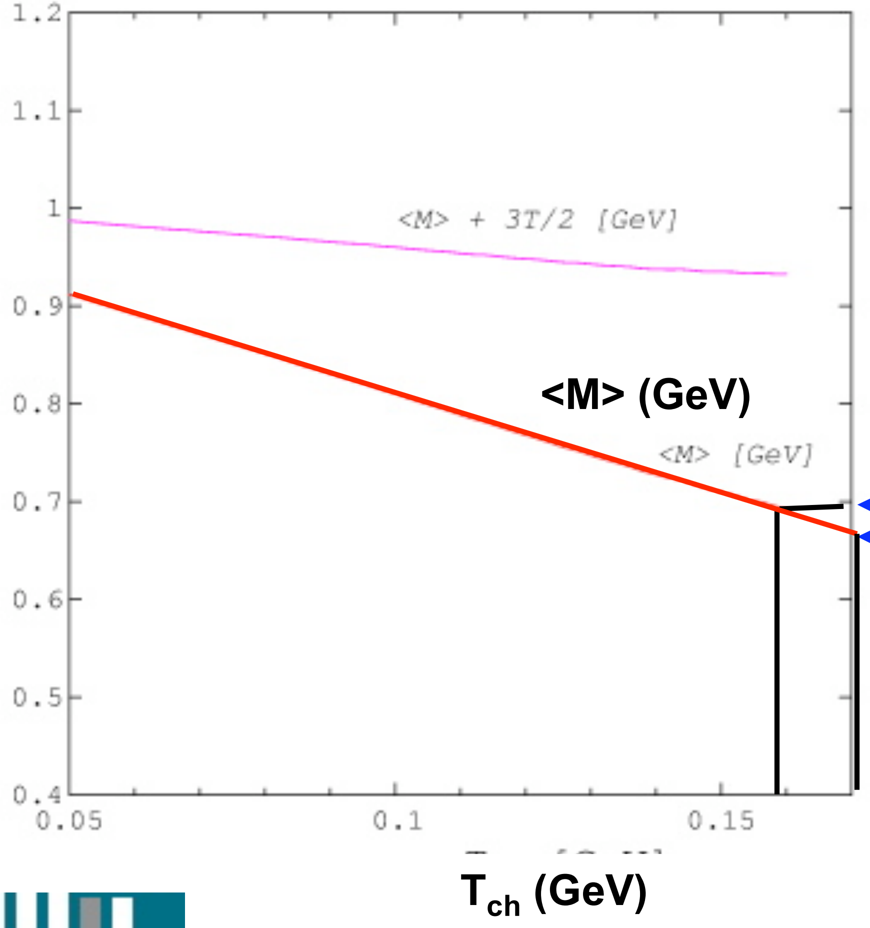




Energy in thermal model

Cleymans, Redlich nucl-th/9903063



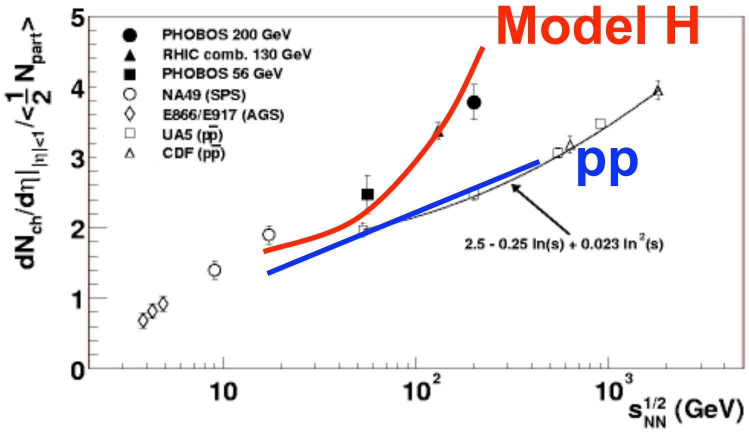


SPS

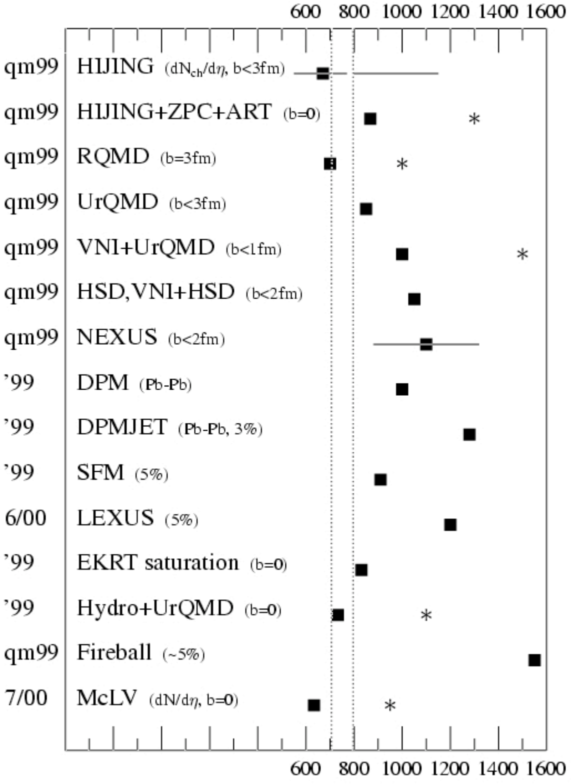
RHIC

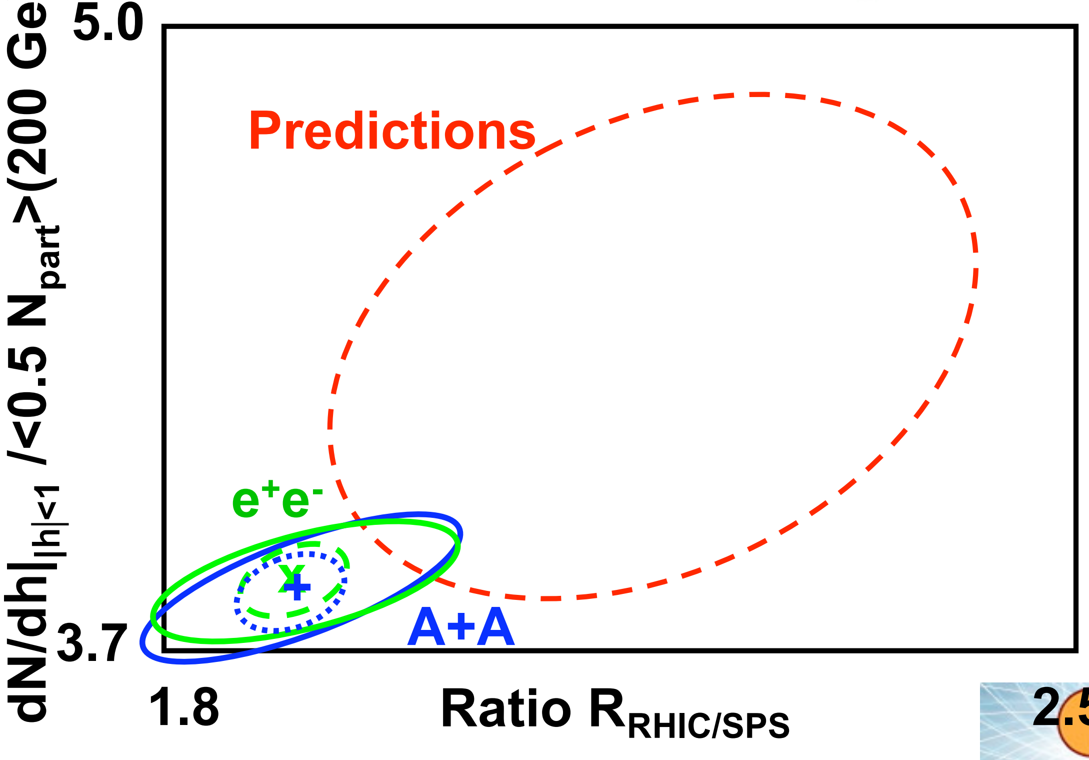
Coincidence?

This is a cartoon! (so far)



N_{min} - N_{max}

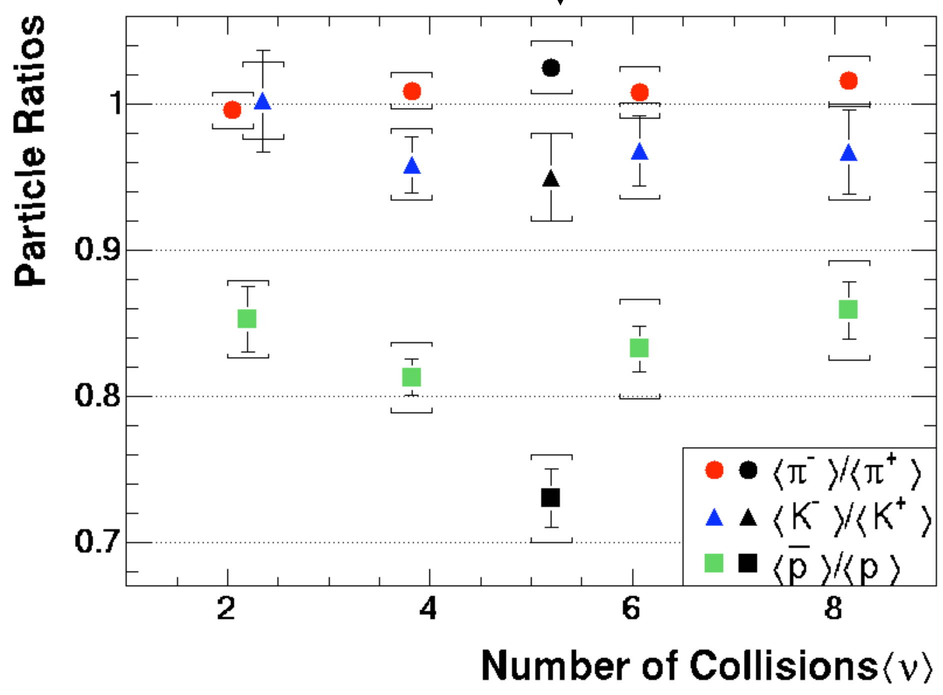




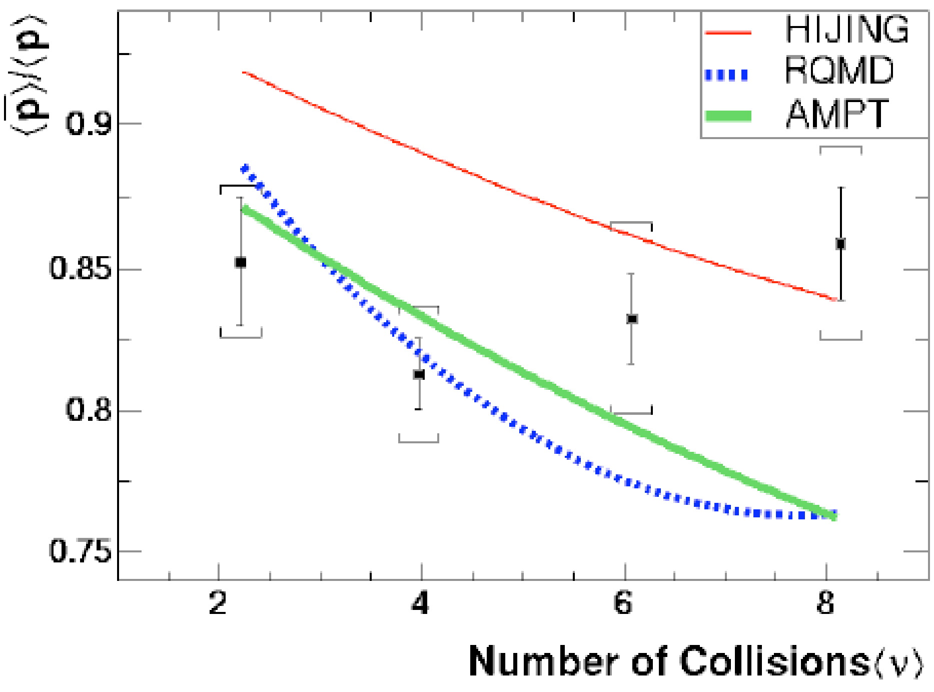
Particle Ratios in d+Au: $\bar{p}$/p vs Centrality

Au+Au

Phys. Rev. C 67, 021901R (2003)



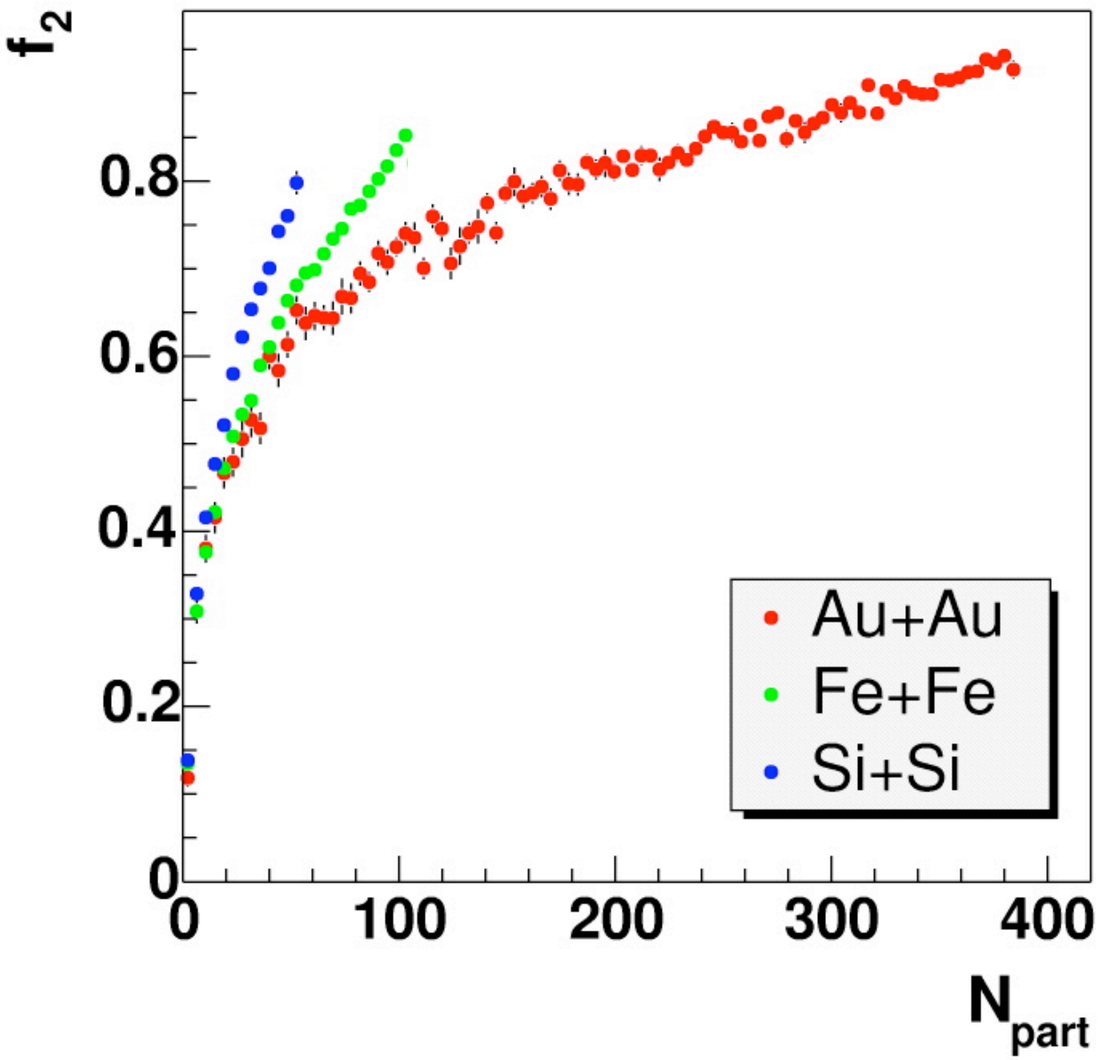
nucl-ex/0309013 - submitted to PRC



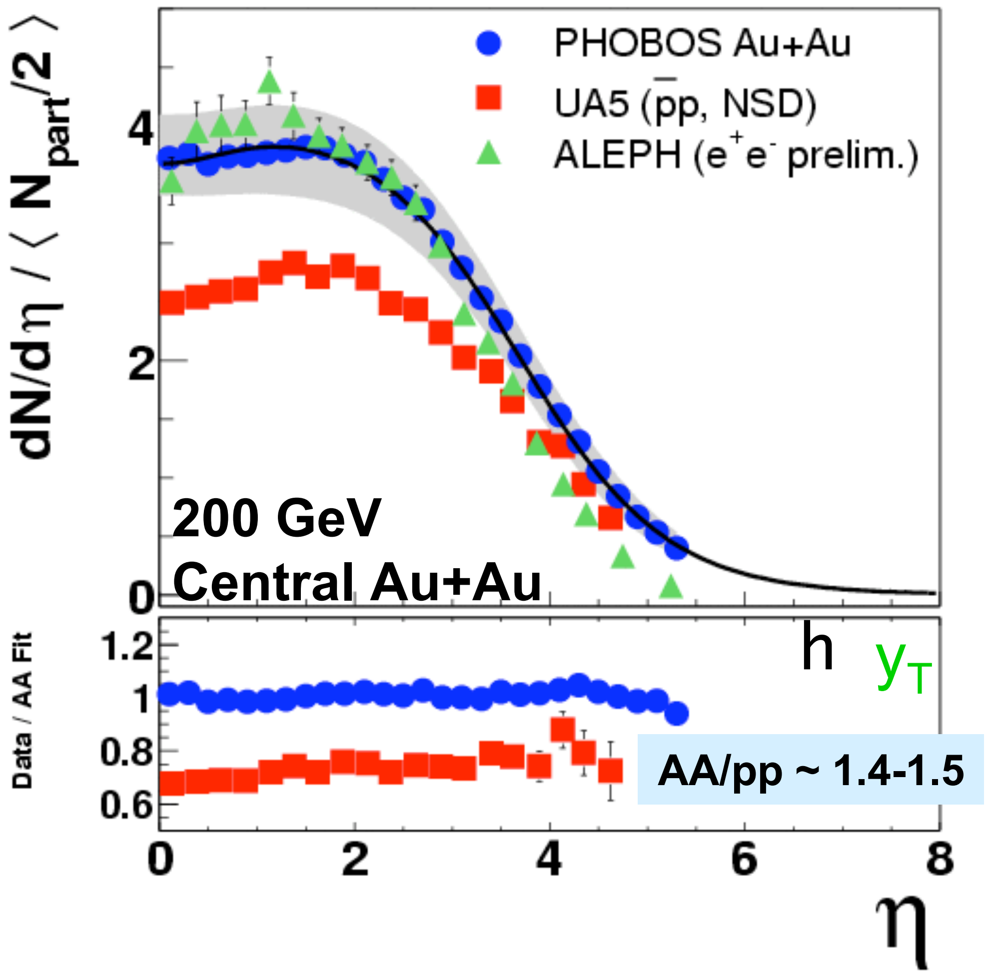
Constant $\bar{p}$/p ratio vs centrality

Disagreement with expectations/models

N_{part} scaling?

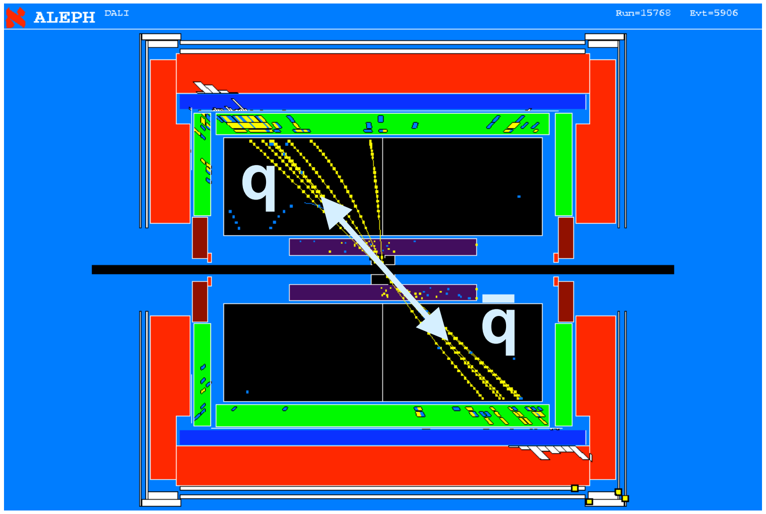


Rapidity Distributions at 200 GeV



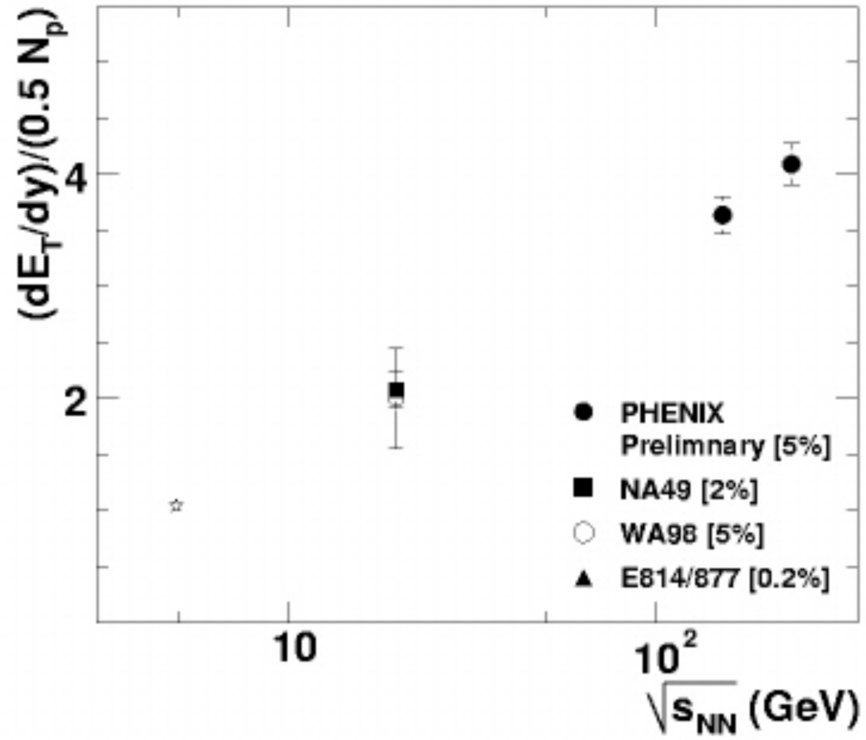
AA/pp ~ 1.4-1.5

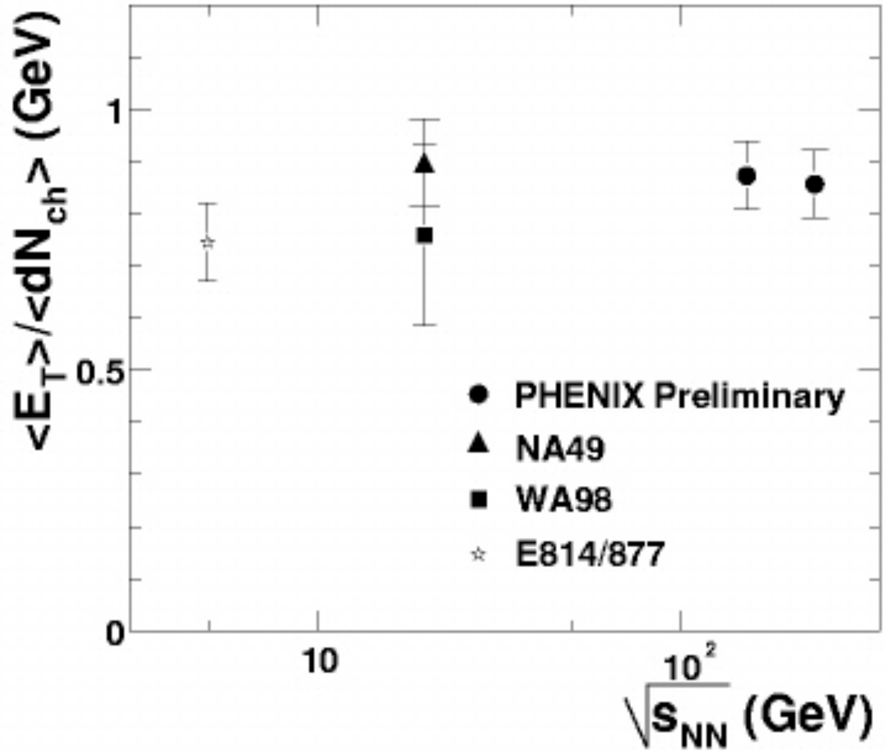
PHOBOS QM'02, Steinberg



e^+e^- measures dN/dy_T (rapidity relative to "thrust" axis)

Transverse Energy near h=0

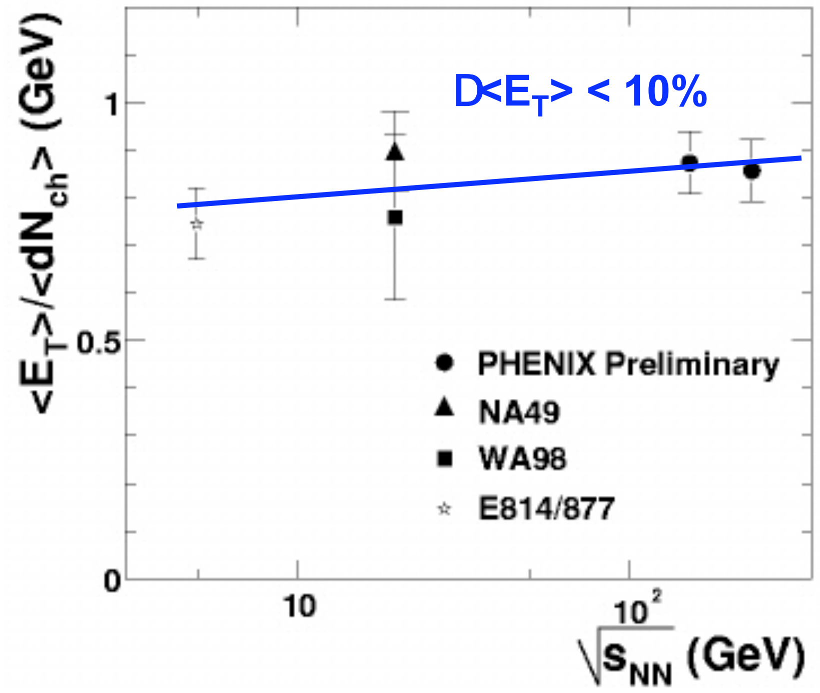

PHENIX QM '02 nucl-ex/0209025


PHENIX QM '02 nucl-ex/0209025

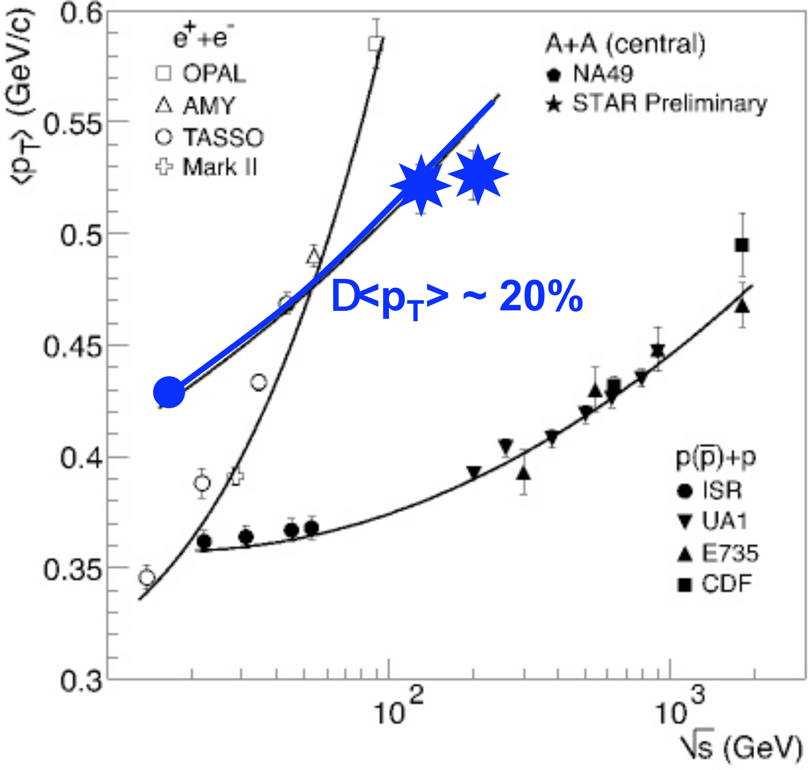
- dE_T/dh exhibits smooth rise vs sqrt(s)
- Surprisingly, $<E_T>$ per particle at h=0 constant
  - even though p+p spectra get much harder with sqrt(s)

Transverse Energy near h=0

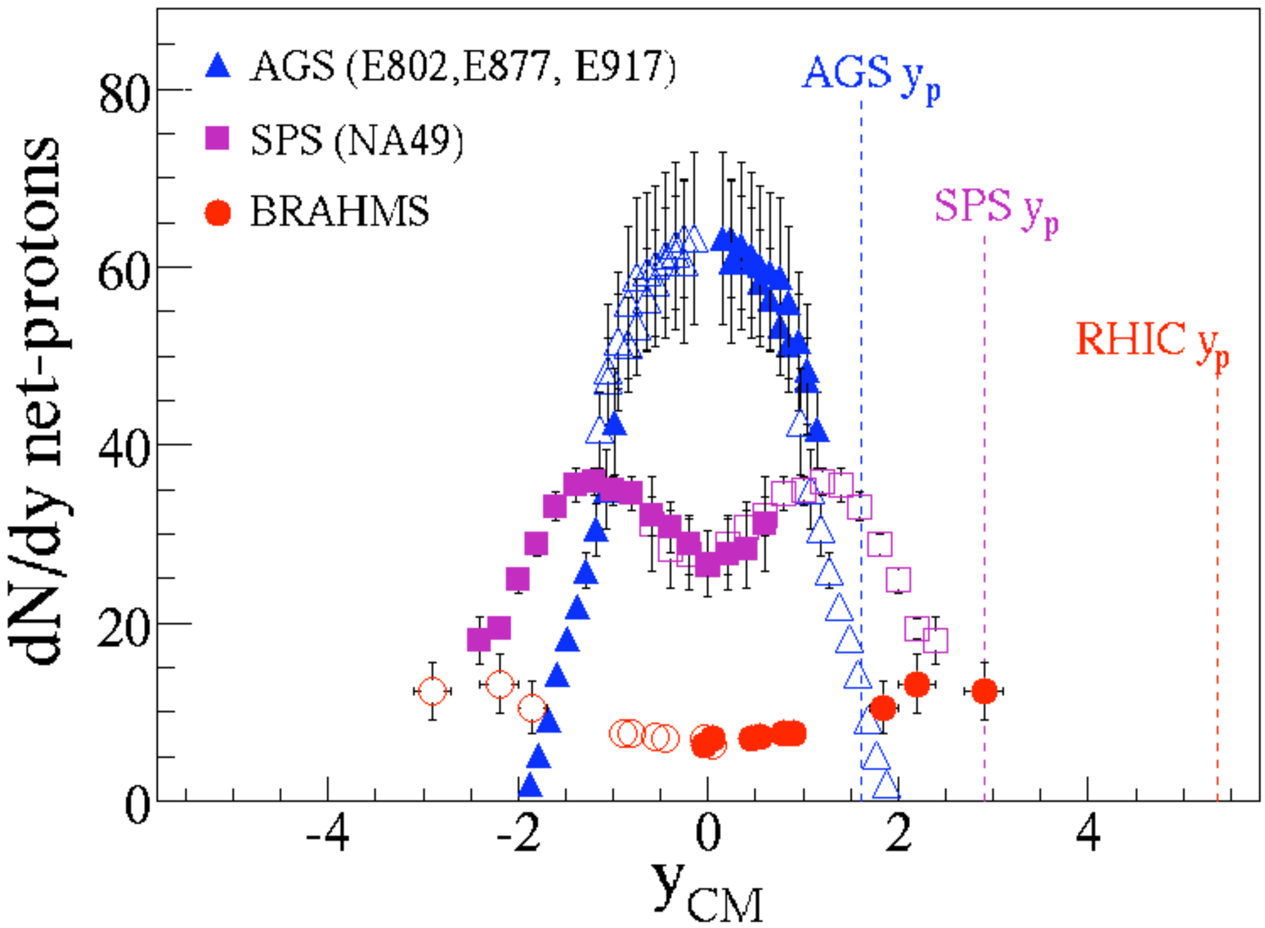
PHENIX QM '02 nucl-ex/0209025



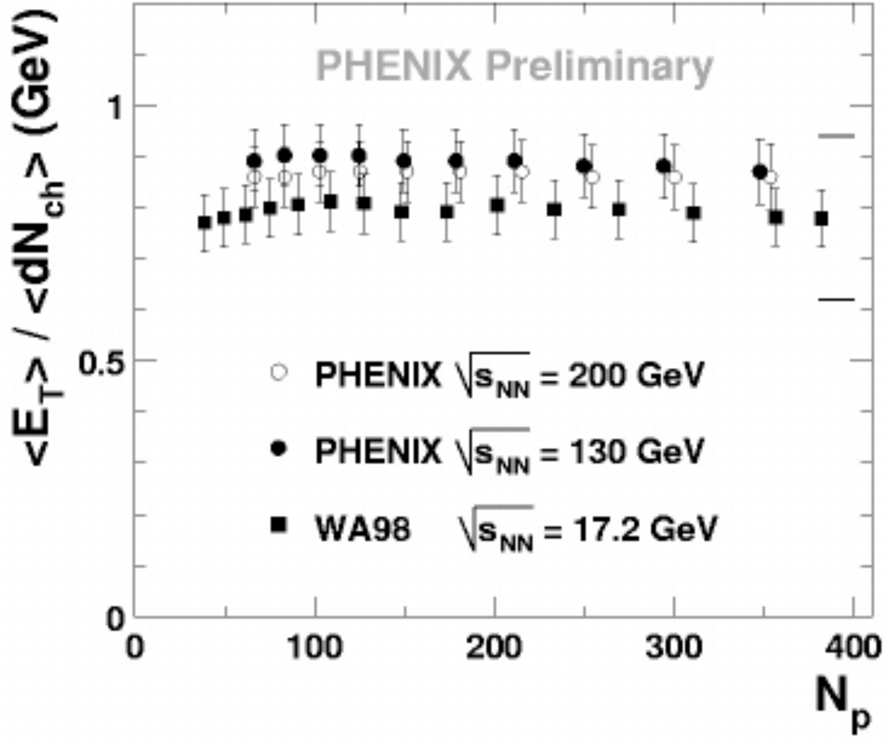
STAR QM '02 nucl-ex/02111021



Net Proton dN/dy



Transverse Energy vs N_{part}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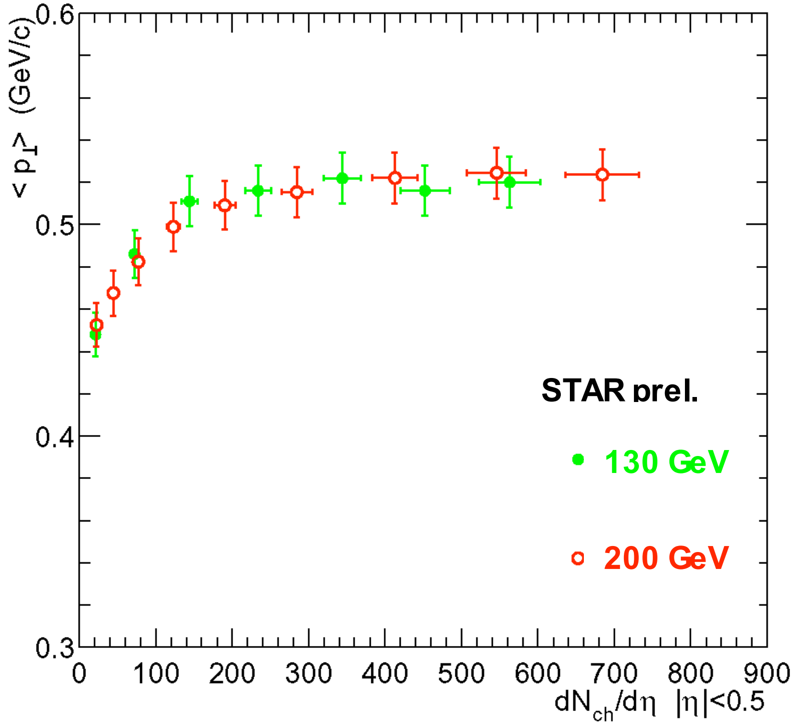
STAR QM '02 nucl-ex/0211021, poster M. Calderon

- dE_T/dh and <pT> independent of N_{part} above N_{part} ~50