Recent RHIC Beam Energy Scan Results

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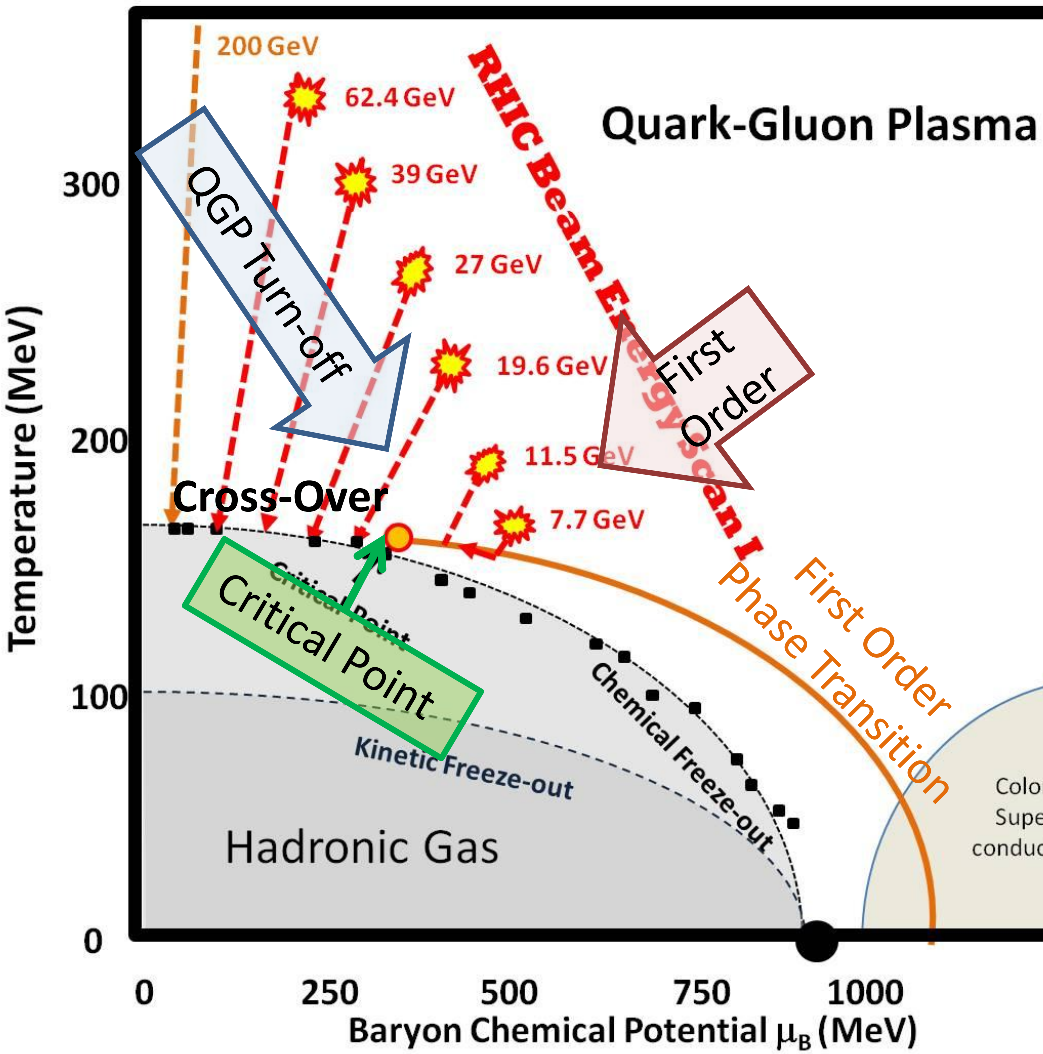
Phase Diagram of QCD Matter

- We built RHIC to find and to study the QGP.

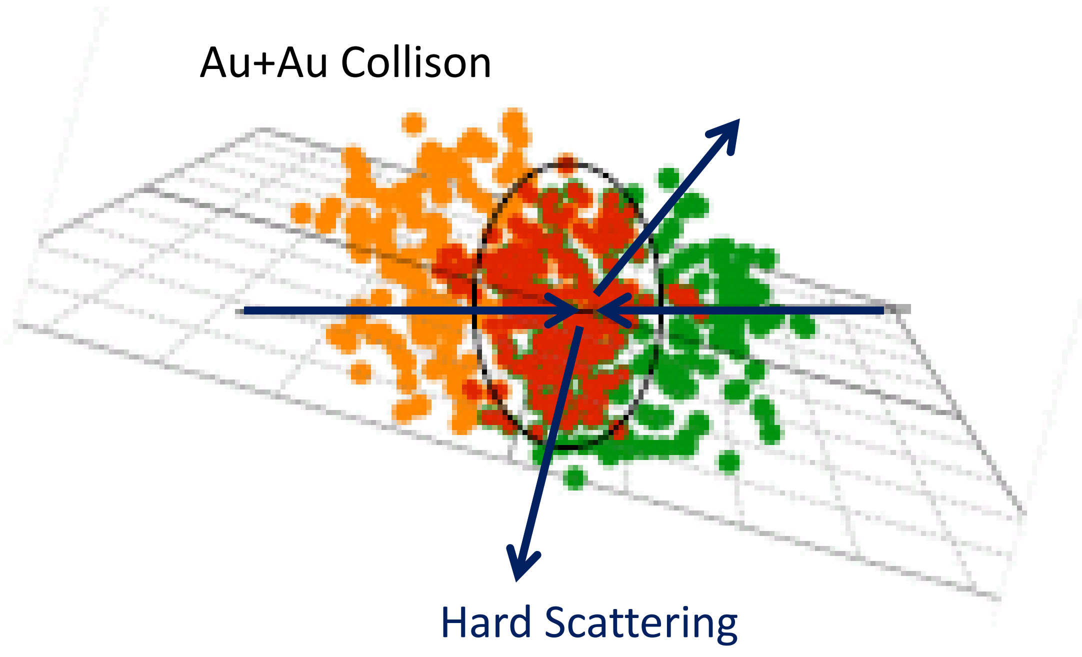
- But QGP is a new and complicated phase of matter. We have made huge progress in understanding its nature. At high energy, we expect a **cross-over** transition. At lower energy there should be a **first order** transition and a **critical point**.

- In order to better understand the phase s of QCD matter, RHIC has performed a Beam Energy Scan.



	Energy (GeV)	Chemical Potential μ_B
LHC	2760.0	2
RHIC	200.0	24
RHIC	130.0	36
RHIC	62.4	73
RHIC	39.0	112
RHIC	27.0	156
RHIC	19.6	206
RHIC	14.6	262
RHIC	11.5	316
RHIC	7.7	422
SPS	17.3	229
SPS	12.4	299
SPS	8.8	383
SPS	7.7	421
SPS	6.4	476
AGS	4.7	573
AGS	4.3	602
AGS	3.8	638
AGS	3.3	686
AGS	2.7	752
SIS	2.3	799

Disappearance of QPG Signatures



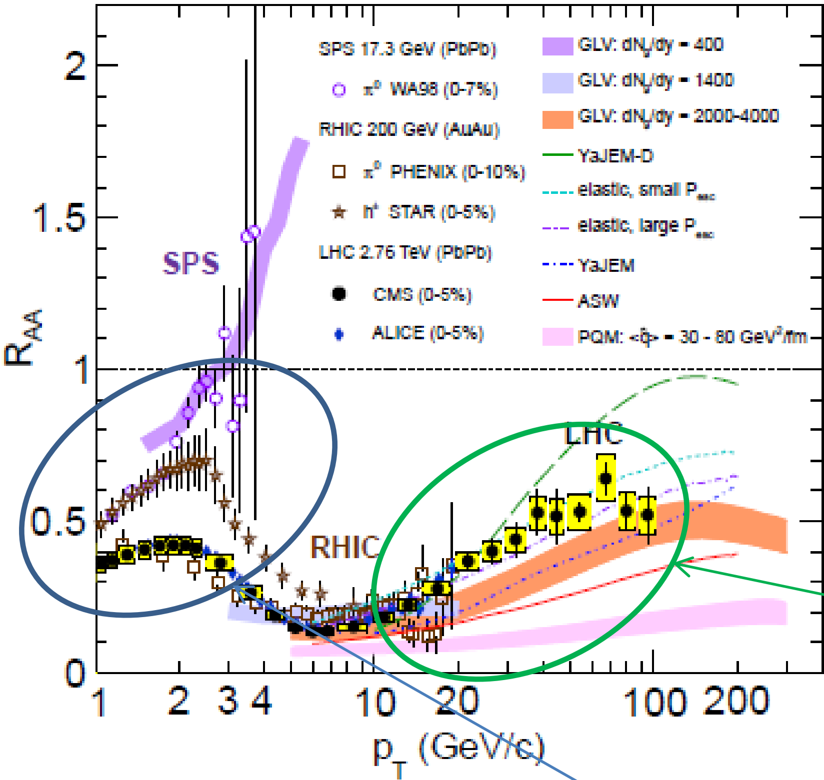
From the simple geometric Glauber model one can estimate the number of individual binary nucleon-nucleon collisions (N_{bin}) and the total number of participating nucleons (N_{part}) for a given impact parameter.

If there is no medium effect, then yields should follow binary scaling.

- Suppression at intermediate p_T depends on quark number
- Suppression at high p_T is an indication of opacity

High p_T Suppression: 2012

High p_T suppression has been seen as a clear manifestation of energy loss by color objects (quarks) in a color medium (QGP)



$$R_{AA} = \frac{\dfrac{d^2N}{dp_t dy}(Au + Au)}{\dfrac{d^2N}{dp_t dy}(p + p)}$$

Perturbative QCD and parton energy loss

Eur.Phys.J. C72 (2012) 1945

Thermal emission from a radially expanding source

High p_T Suppression: BES Results

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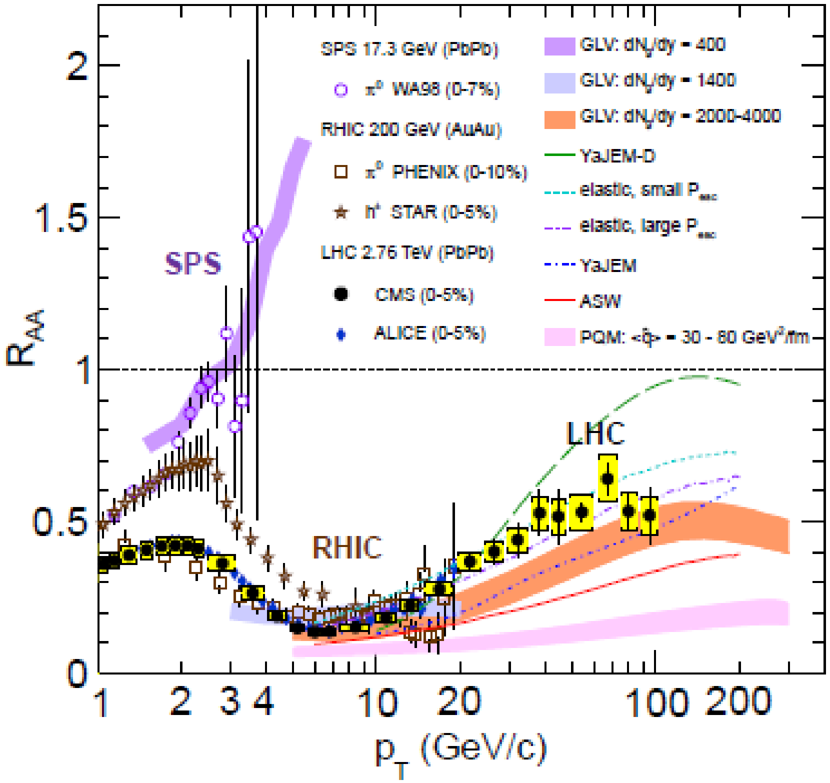
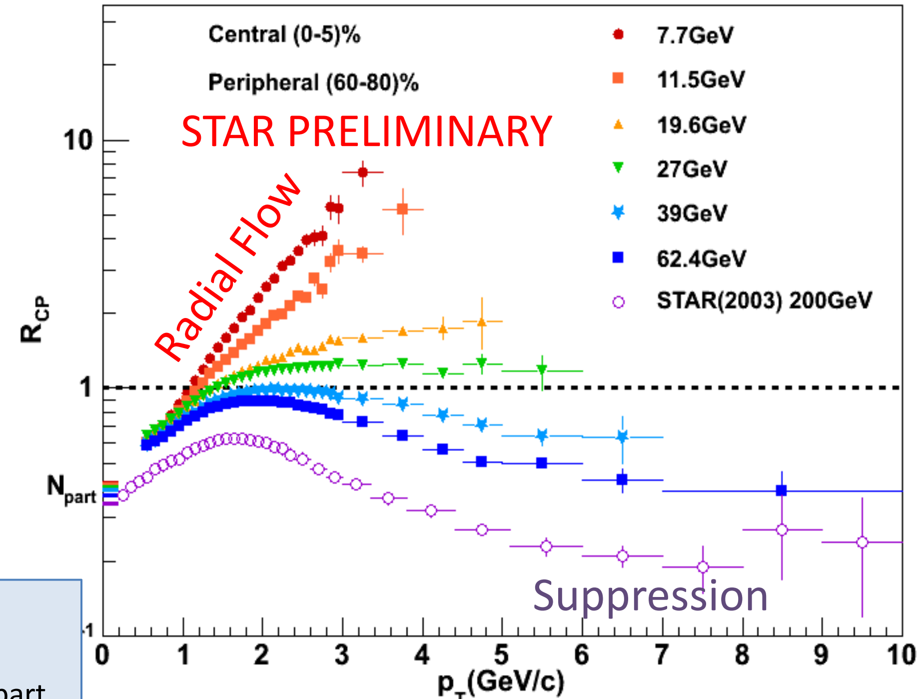


Eur.Phys.J. C72 (2012) 1945

- R_{cp} suppression NOT seen at lower energies!

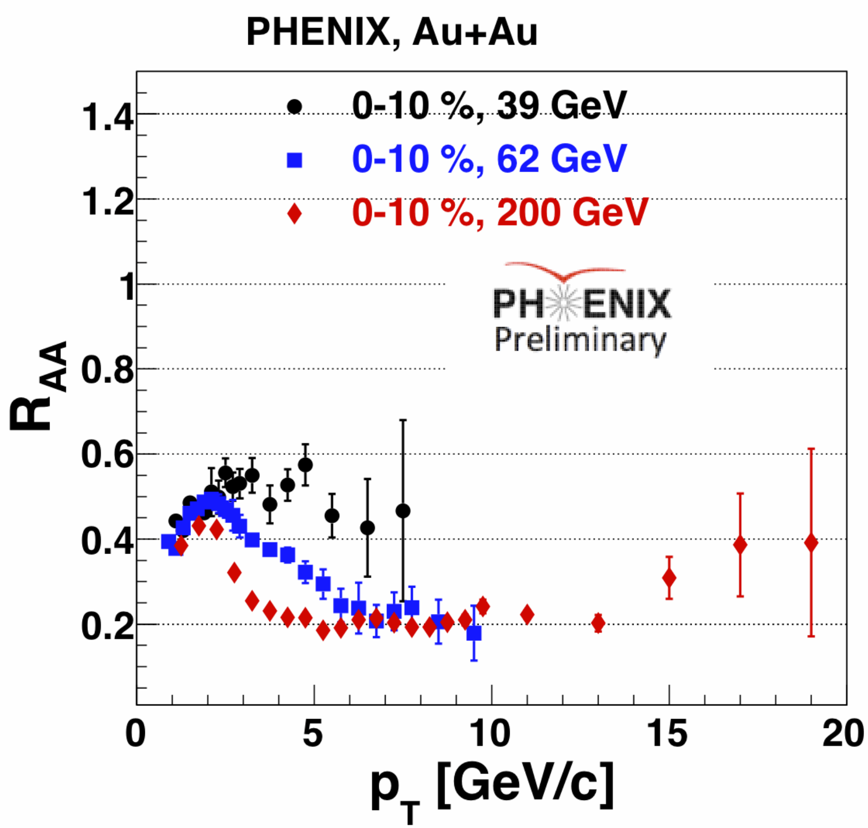
➔**The QGP signature is turned off.**

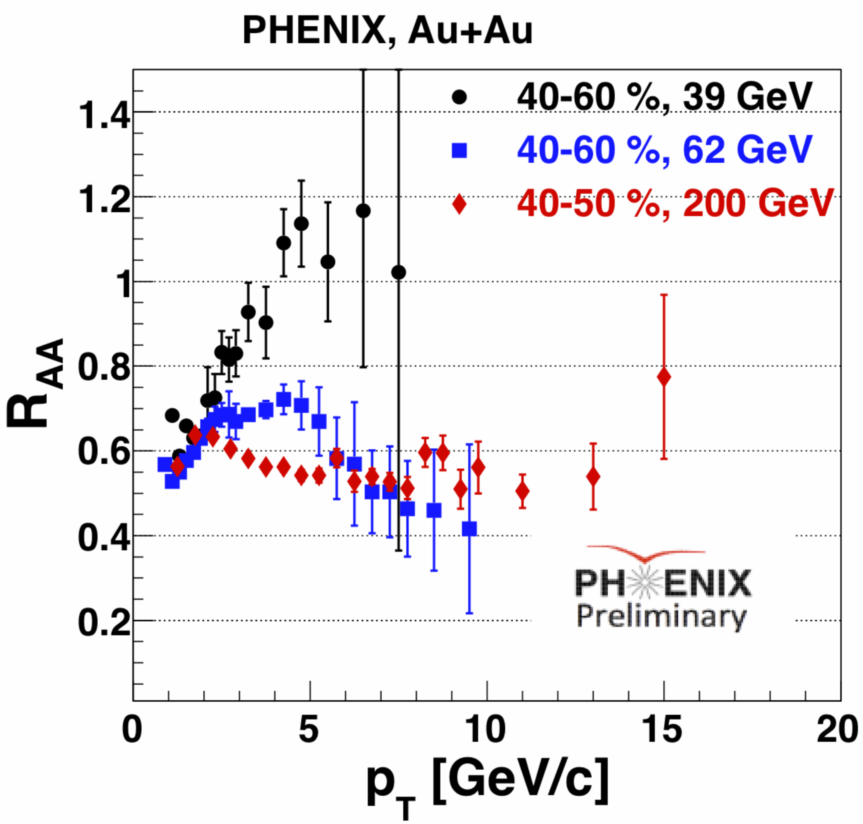


High pT yield is proportional to N_{bin}

Soft Yield (Underlying Event) is proportional to N_{part}

High p_T Suppression: PHENIX Results



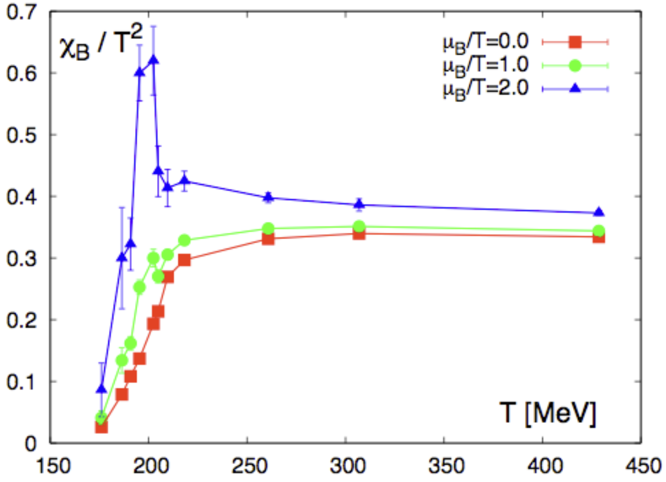


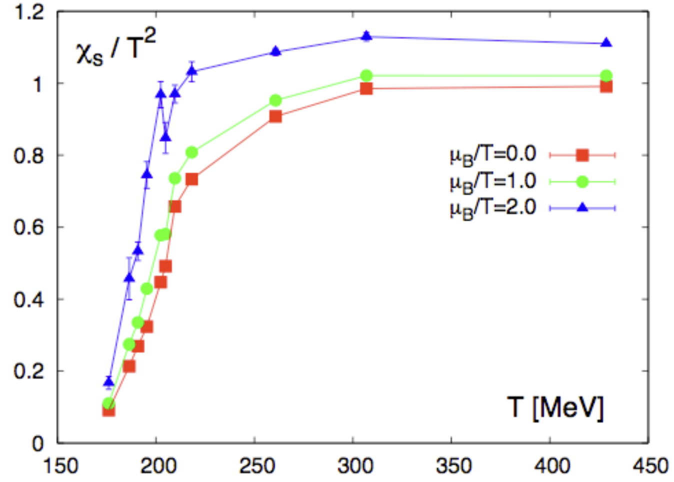
Suppression seen for central events for all three energies.
Note that the 40-60% bin for 39 GeV is not showing suppression. This supports the arguments for larger system size

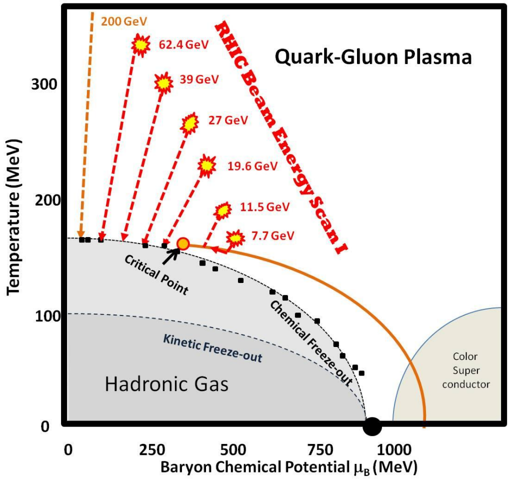
N. Novitsky QM2011

Search for 1st Order PhaseTransition

F. Karsch, PoS (CPOD07) 026, PoS (Lattice 2007) 015







Hadron Gas:

$$p^H = p_\pi + p_N + p_{\bar{N}} + p_w$$

$$p_\pi(T) = -g_\pi \int_{m_\pi}^{\infty} \frac{p\epsilon d\epsilon}{2\pi^2} \ln[1 - e^{-\beta\epsilon}]$$

$$p_N(T,\mu_0) = g_N \int_{m_N}^{\infty} \frac{p\epsilon d\epsilon}{2\pi^2} \ln[1 + e^{-\beta(\epsilon-\mu_0)}]$$

$$p_{\bar{N}}(T,\mu_0) = g_N \int_{m_N}^{\infty} \frac{p\epsilon d\epsilon}{2\pi^2} \ln[1 + e^{-\beta(\epsilon+\mu_0)}]$$

Quark-Gluon Plasma:

$$p^Q = p_g + p_q + p_{\bar{q}} - B$$

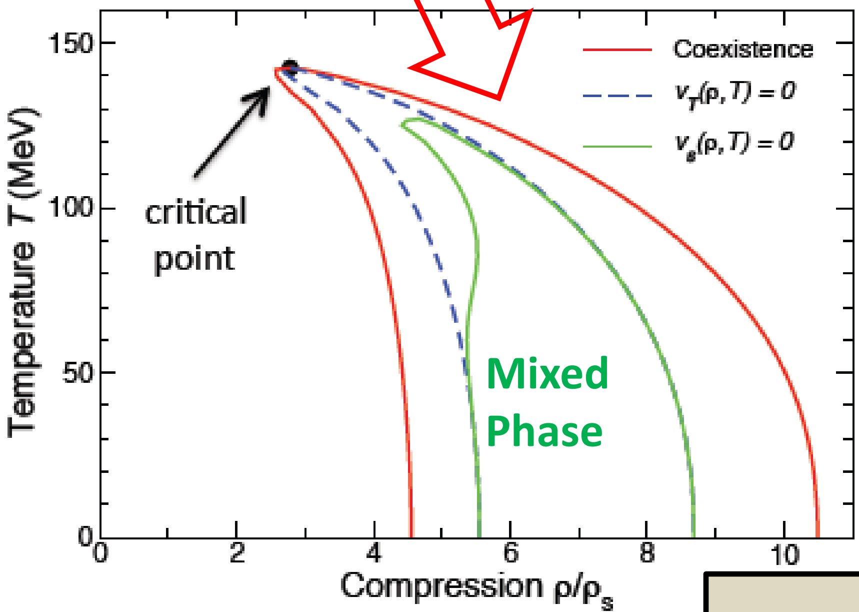
$$p_g = g_g \frac{\pi^2}{90} T^4$$

$$p_q + p_{\bar{q}} = g_q \left[\frac{7\pi^2}{360} T^4 + \frac{1}{12}\mu_q^2 T^2 + \frac{1}{24\pi^2}\mu_q^4 \right]$$

First order phase transition is characterized by unstable coexistence region. This spinodal region will have the lowest compressibility

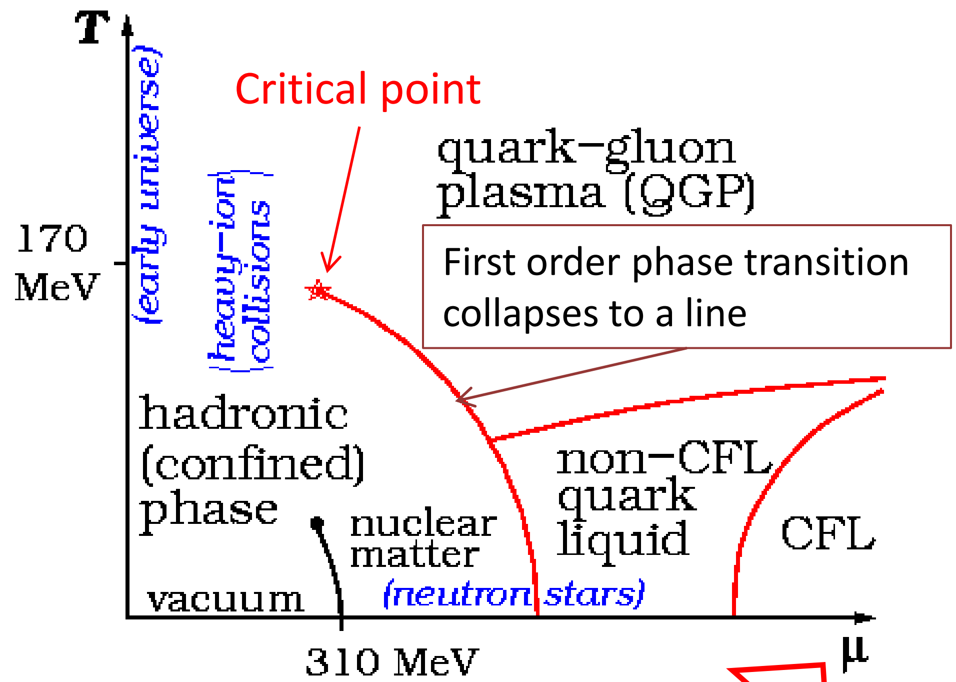
Compression versus Chemical Potential

A phase diagram might more intuitively be shown in Temperature versus density space.



$v_T = 0$: isothermal spinodal

$v_s = 0$: isentropic spinodal



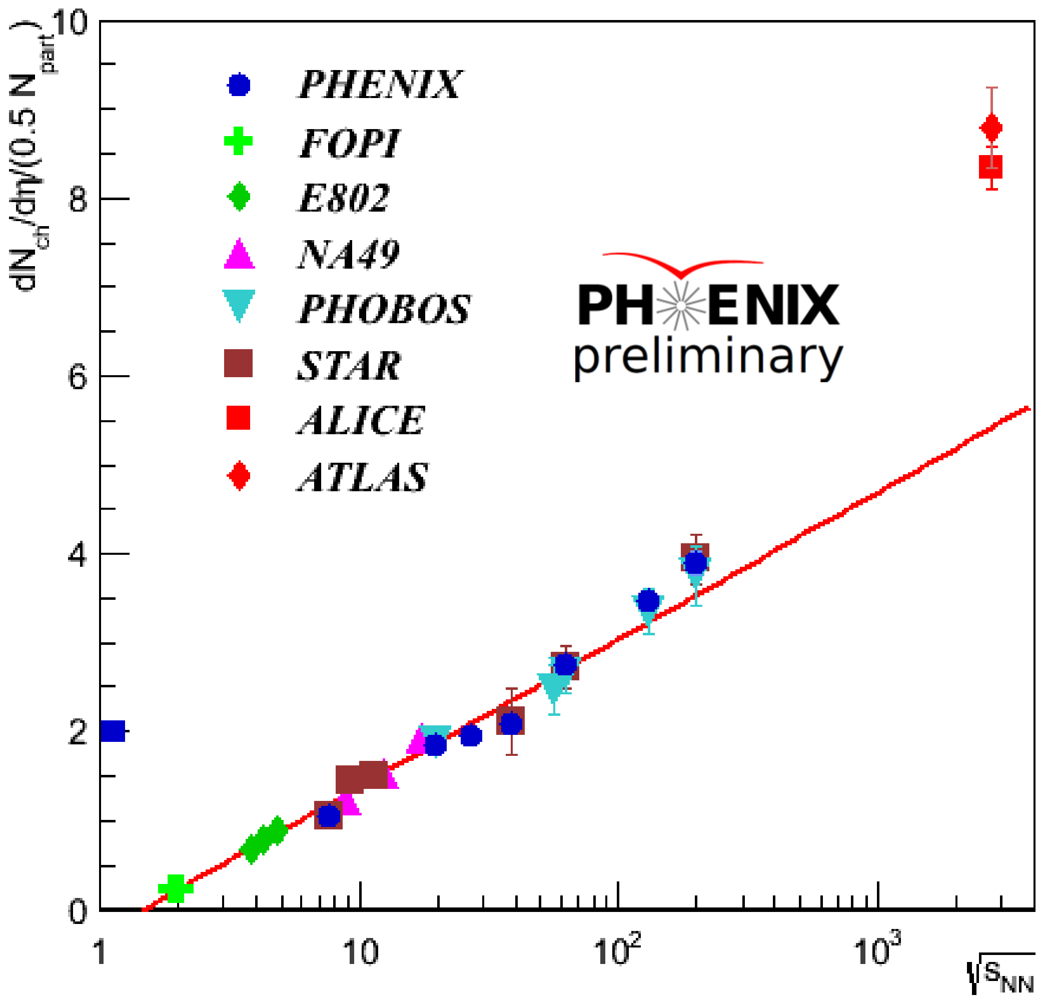
$$\frac{d^6N}{dx^3dp^3} = g \ln\left(\frac{1}{e^{\frac{E-\mu}{T}} \pm 1}\right)$$

We can not measure compression, volume, or density, so we instead use chemical potential, μ.

Particle Yields as Function of Beam Energy

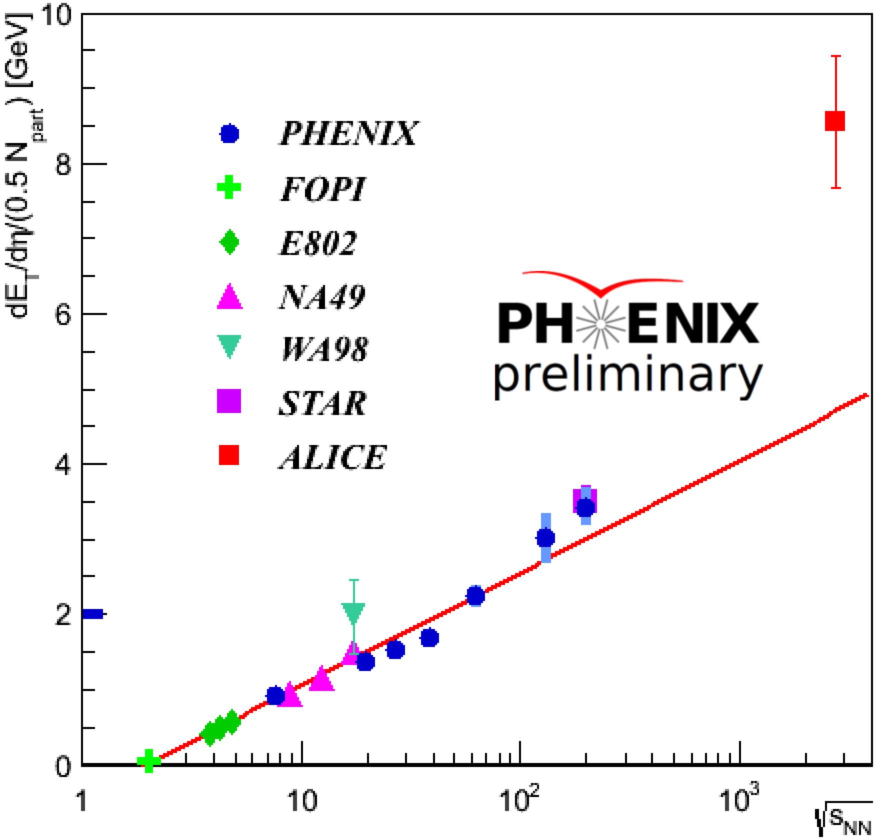
As the energy is increased, we should pass from a compressed hadronic matter state into the the partonic state (QGP). This opening of new degrees of freedom (partons) might effect the particle production and energy flow.

The particle yields for central heavy ion events show no significant features with beam energy.

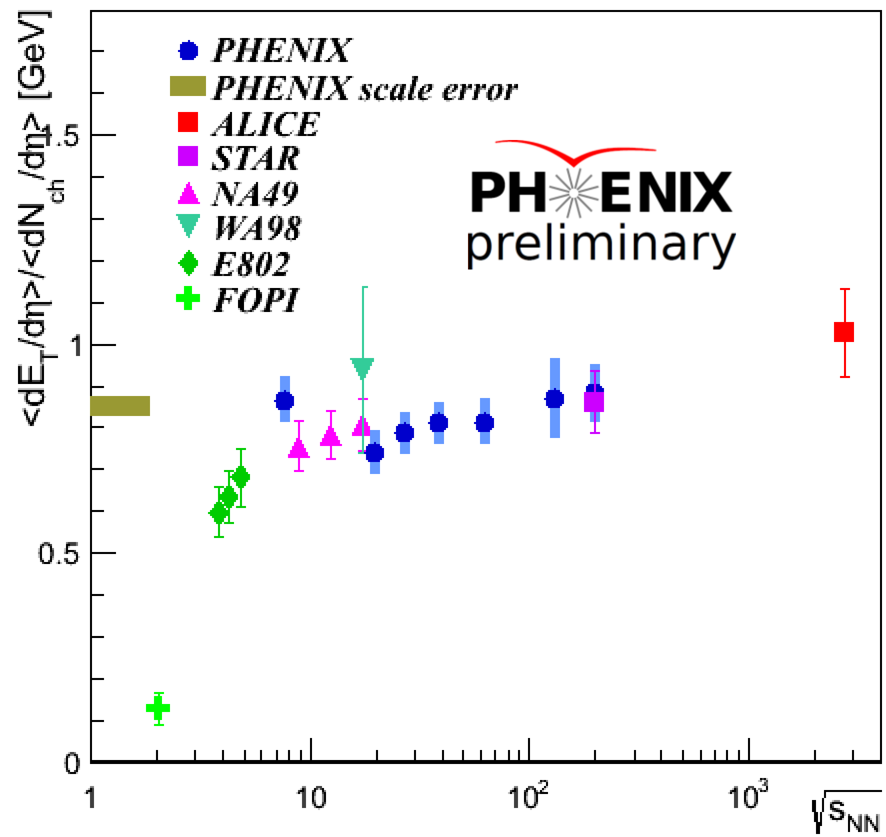


Transverse Energy

$dE_T/d\eta$ shows a monotonic increase, with an inflection point above 39 Gev



Charged particle pseudo-rapidity densities show a similar behavior.



E_T per particle flattens above 7.7 GeV

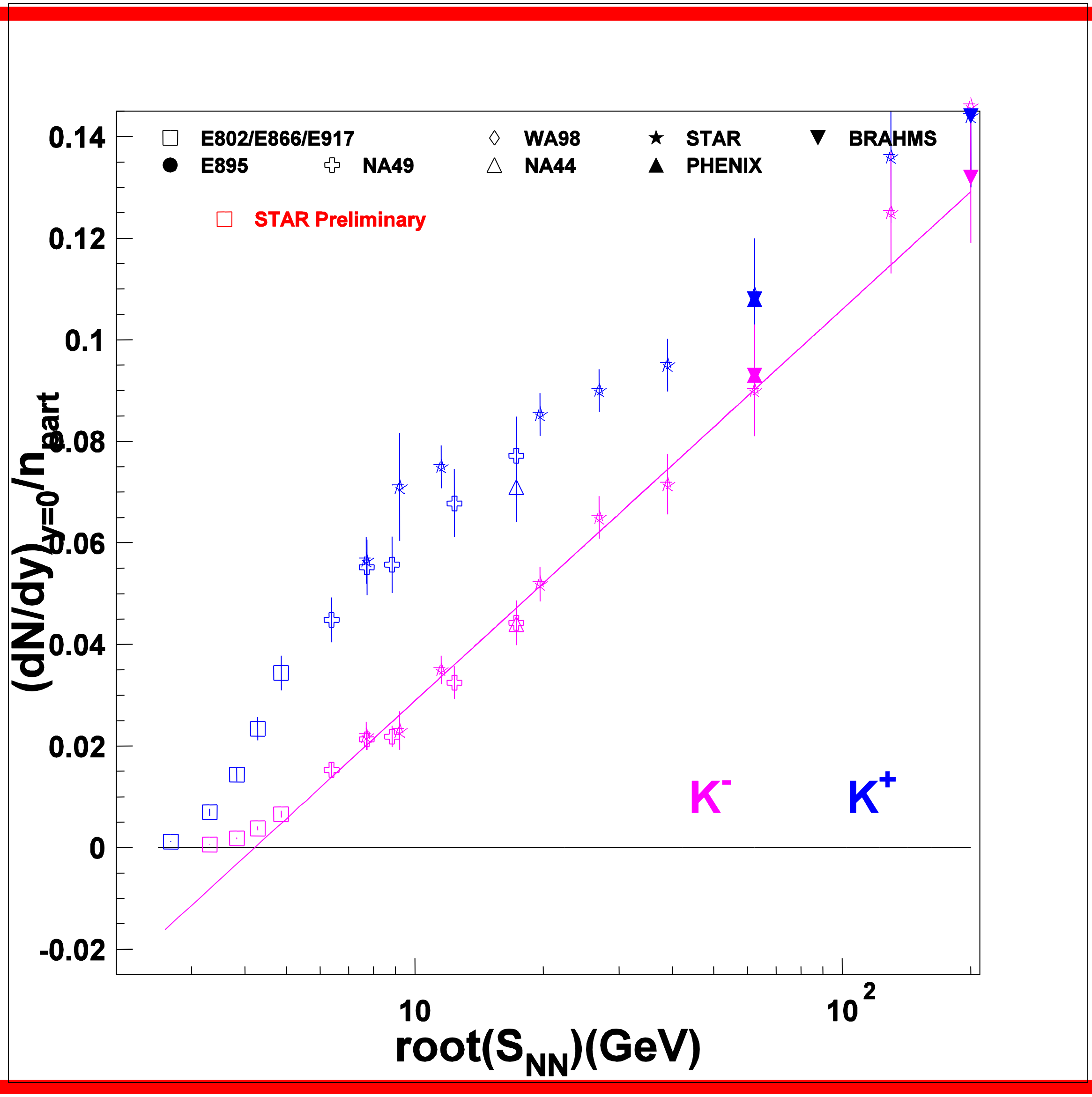
Kaon Yields Systematics

The positive kaons show a non-equilibrium enhancement.

This is consistent through a broad region of collision energies.

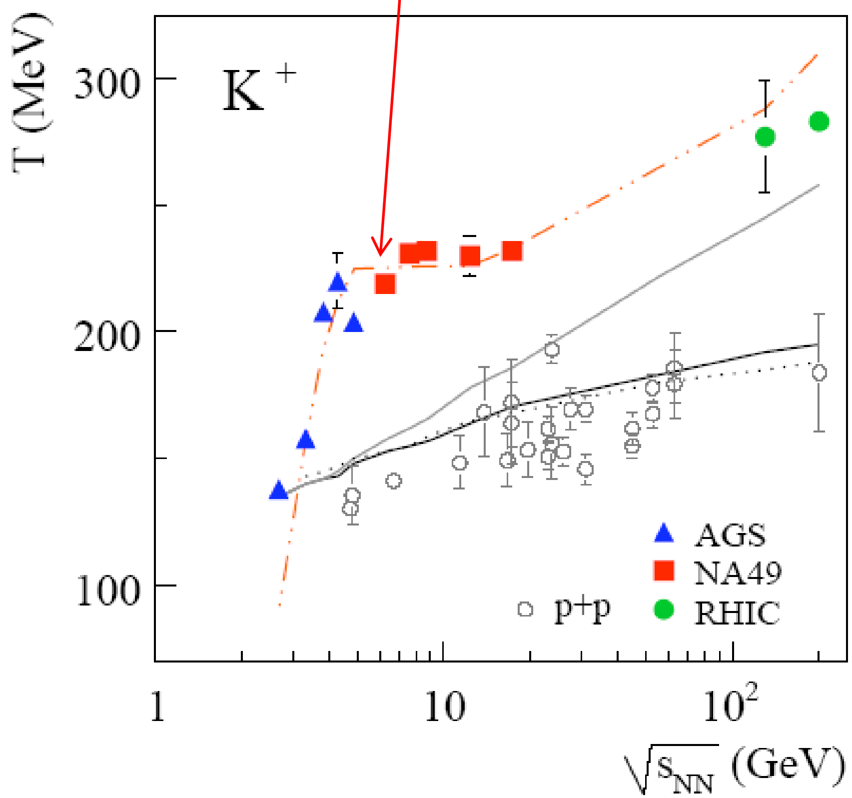
The K^+ carries and up and an anti-strange quark. At lower energies, it is produced primarily in association with a Λ baryon (uds).

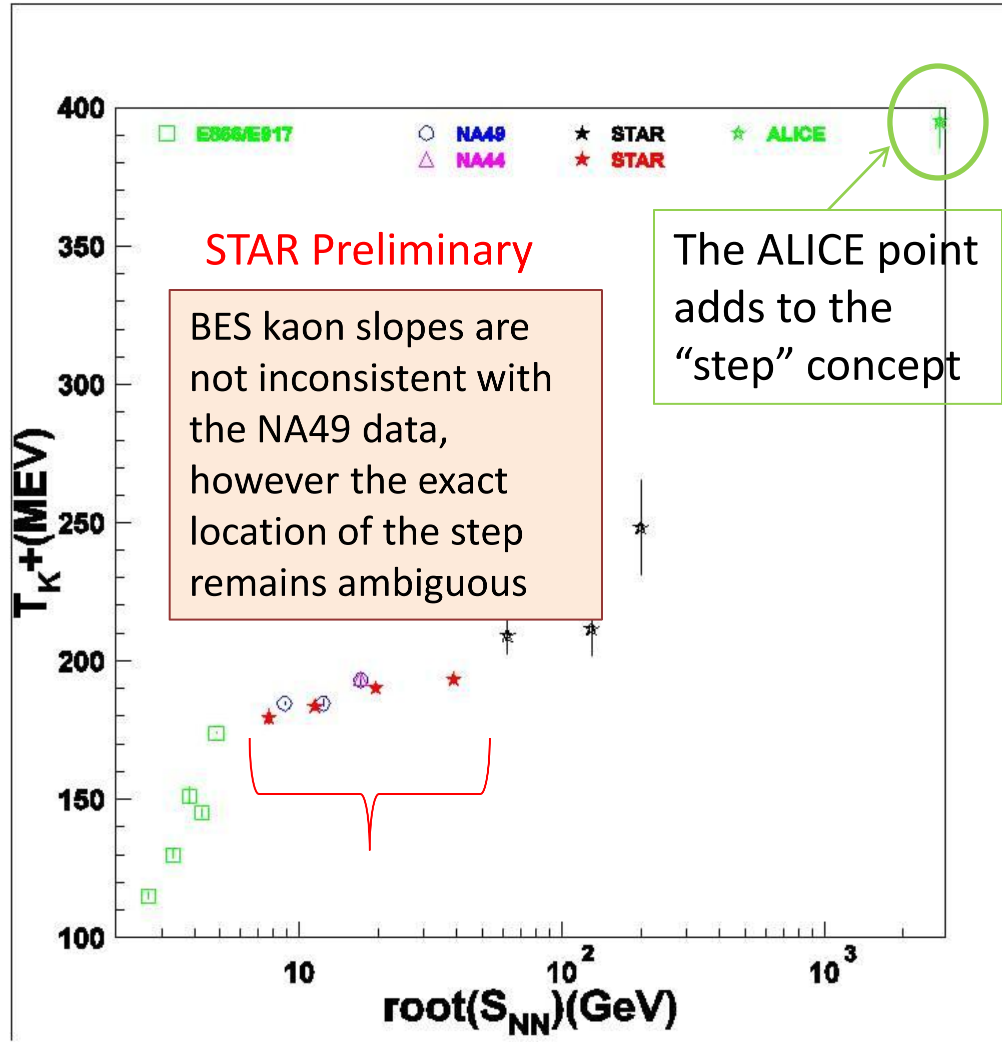
The K^- carries an anti-up and a strange quark. Neither are valence quarks of the projectiles



Slopes of the Kaon Spectra

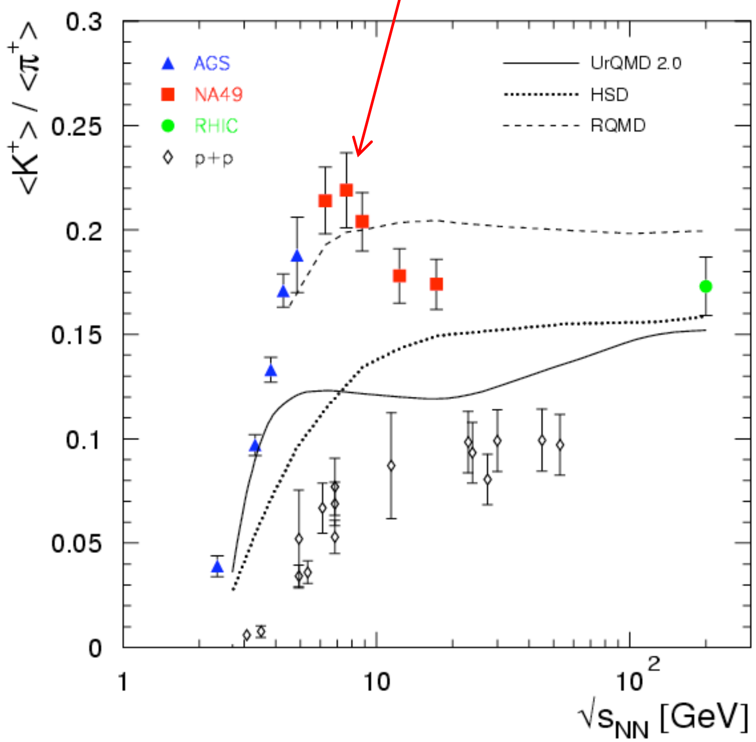
The step in the slope parameter is seen as evidence that energy is going into other channels.



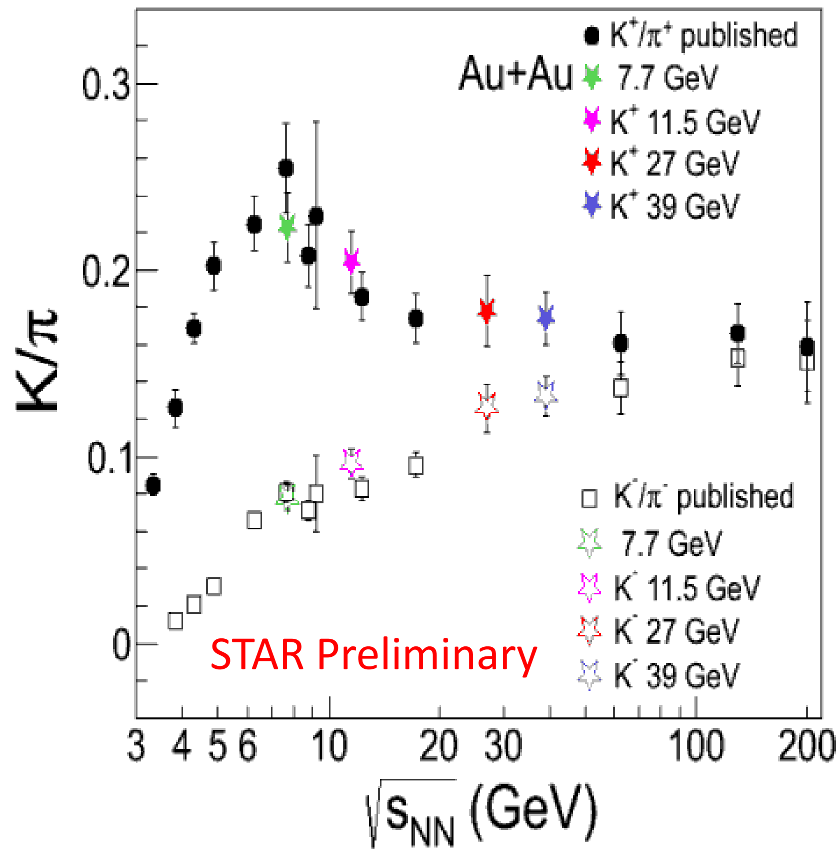


K/π Ratio

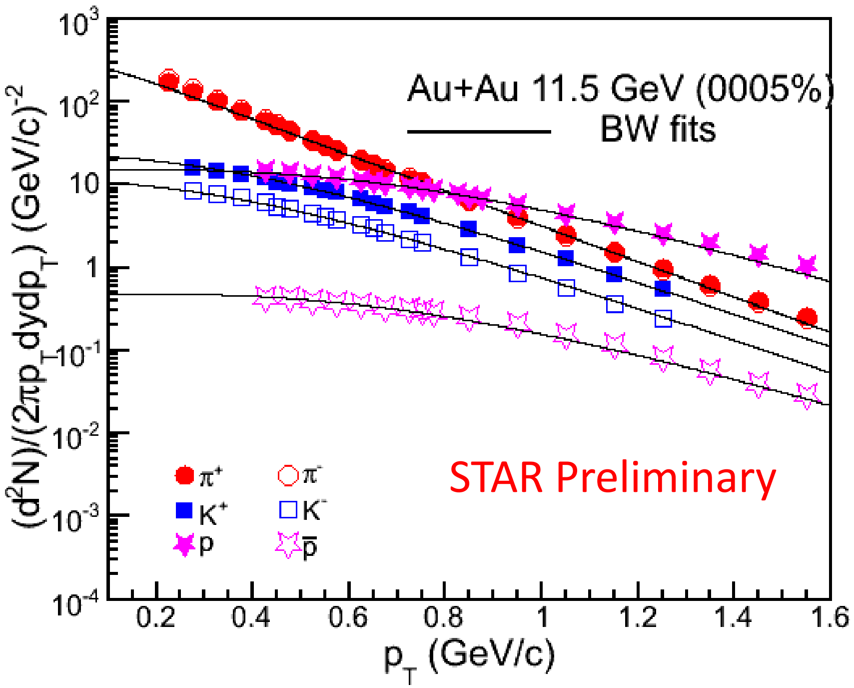
The peak in the K/π ratio is seen as evidence of the opening of the strangeness channel which may indicate the onset of deconfinement

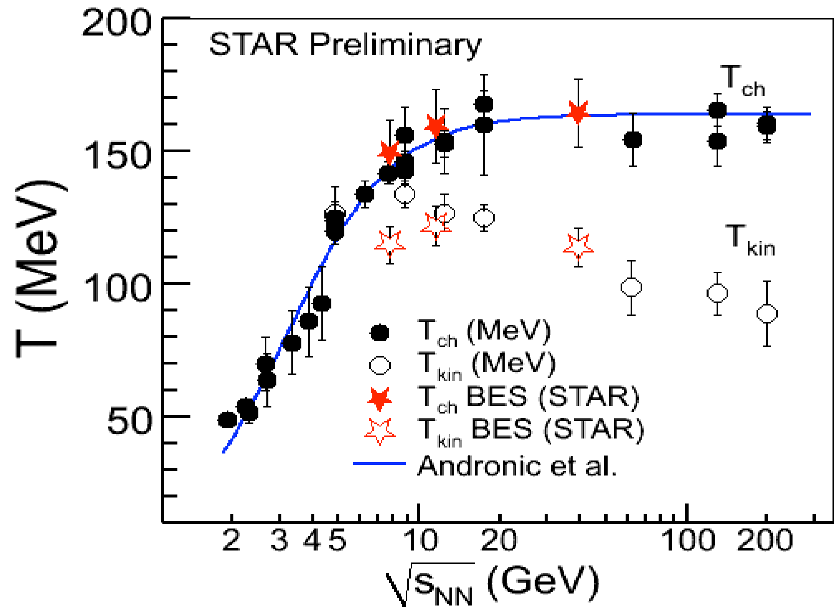


The RHIC data are consistent with NA49, however they do not suggest as sharp a peak in the "horn"



Kinetic Equilibrium





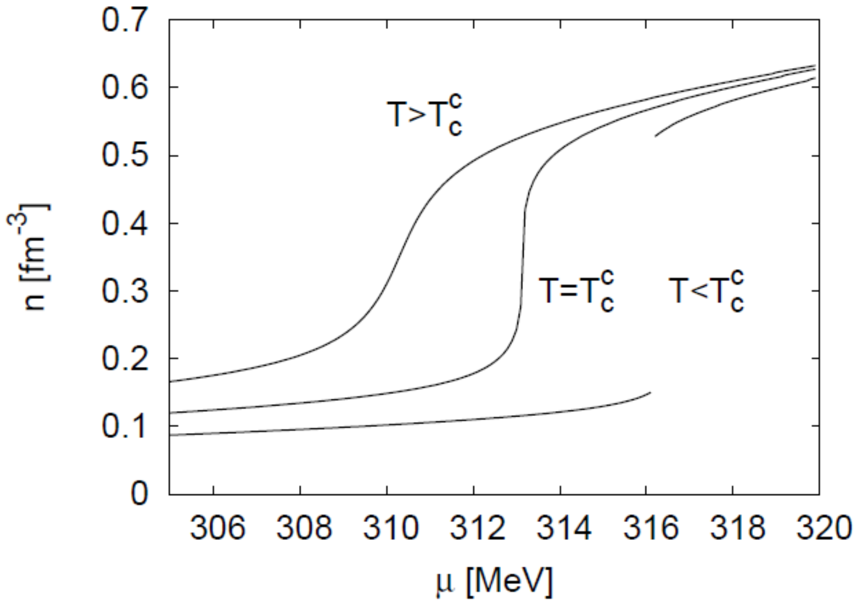
L Kumar QM2011

Using blast wave fits, we can explain the shape of the spectra and determine the location of the kinetic equilibrium.

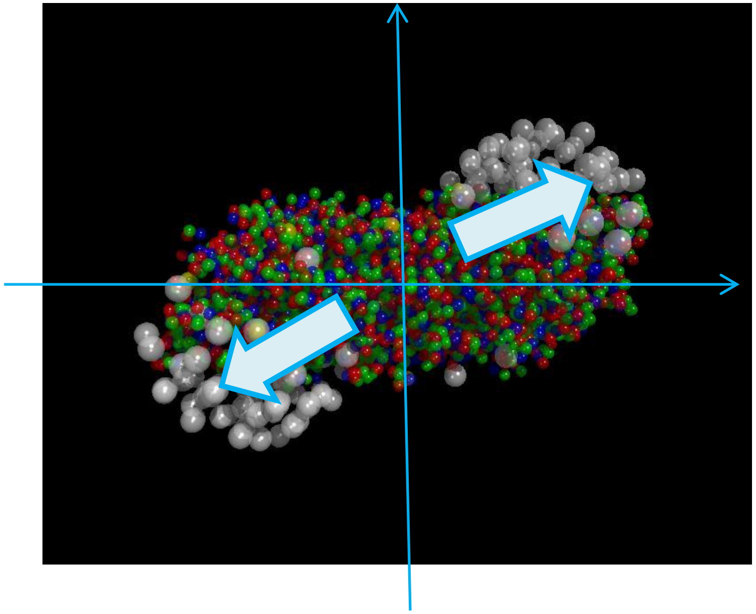
Kinetic temperatures diverge from chemical temperatures at BES energies.

Directed Flow -- BES

B. Schaefer and J. Wambach Phys.Rev. D75 (2007) 085015



Directed flow is a measure of the compressive recoil of the nucleons



•Lattice QCD calculations predict a first order phase transition seen, as a discontinuity in the density.
•First order phase transition is characterized by unstable coexistence region. This spinodal region will have the lowest compressibility
• v_1 is a manifestation of early pressure in the system

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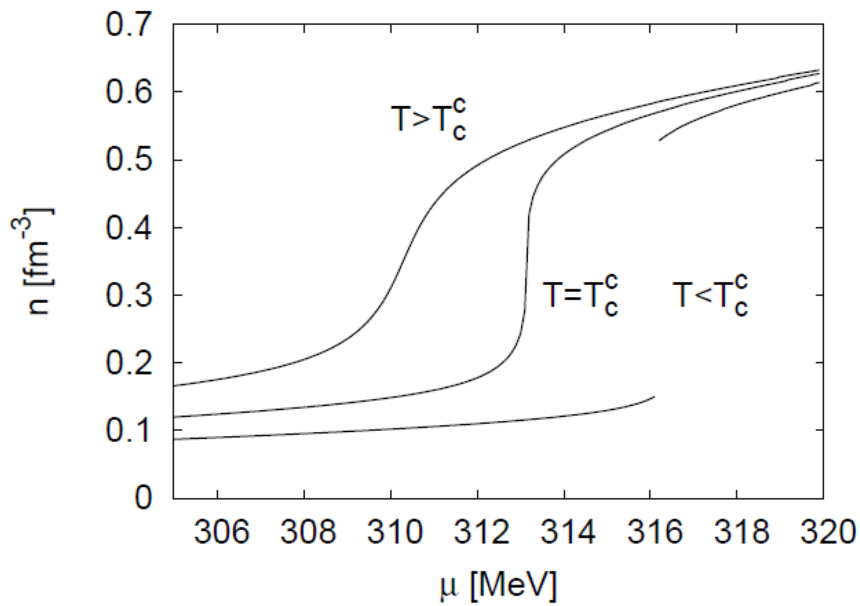
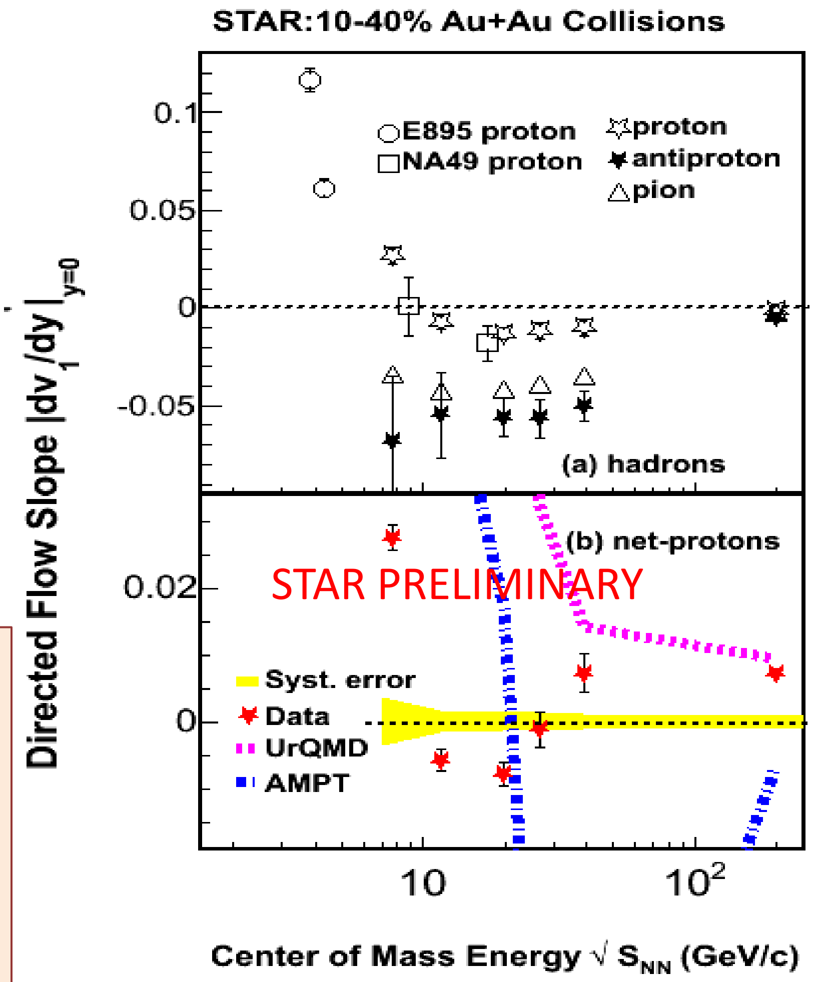




- Lattice QCD calculations predict a first order phase transition seen, as a discontinuity in the density.
- First order phase transition is characterized by unstable coexistence region. This spinodal region will have the lowest compressibility
- v_1 is a manifestation of early pressure in the system
- We see a minimum of the v_1 signal. ➔ ***Suggestive***

Search for the Critical Point

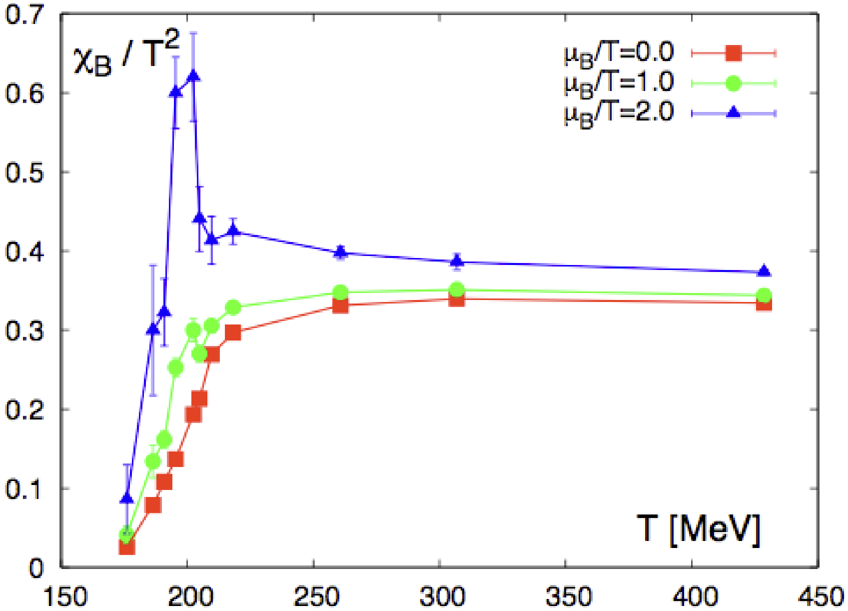
Volumes cancel

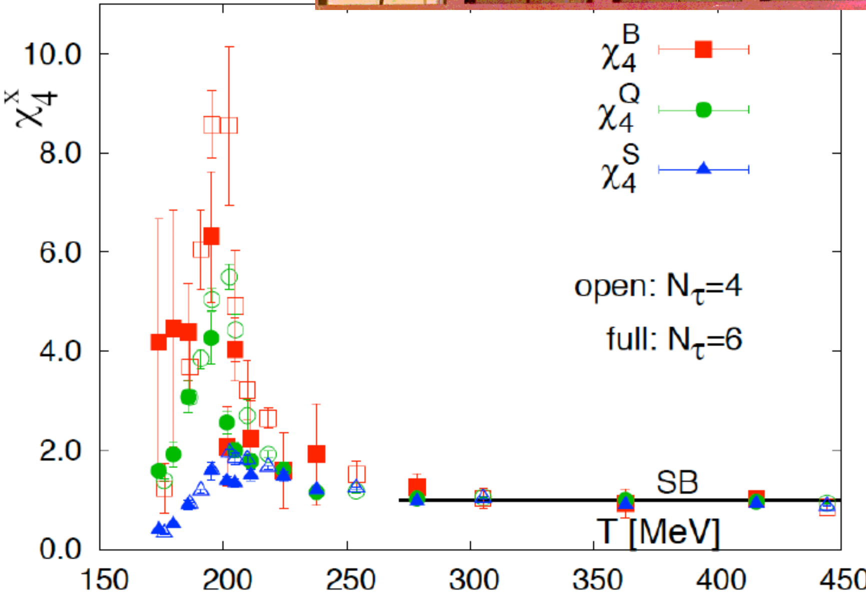
$$\chi_B^{(n)} = \left.\frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}\right|_T$$

$$\chi_B^{4} / \chi_B^{2} = (\kappa\sigma^2)_B$$
$$\chi_B^{3} / \chi_B^{2} = (S\sigma)_B$$

M. Cheng et al., Phys. Rev. D 79, 074505(2009)

F. Karsch, PoS (CPOD07) 026, PoS (Lattice 2007) 015





Higher Moments – Net Proton Skew/Kurtosis - BES

$$\chi_B^{(n)} = \left.\frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}\right|_T$$

Volumes cancel

$$\chi_B^4 / \chi_B^2 = (\kappa\sigma^2)_B$$
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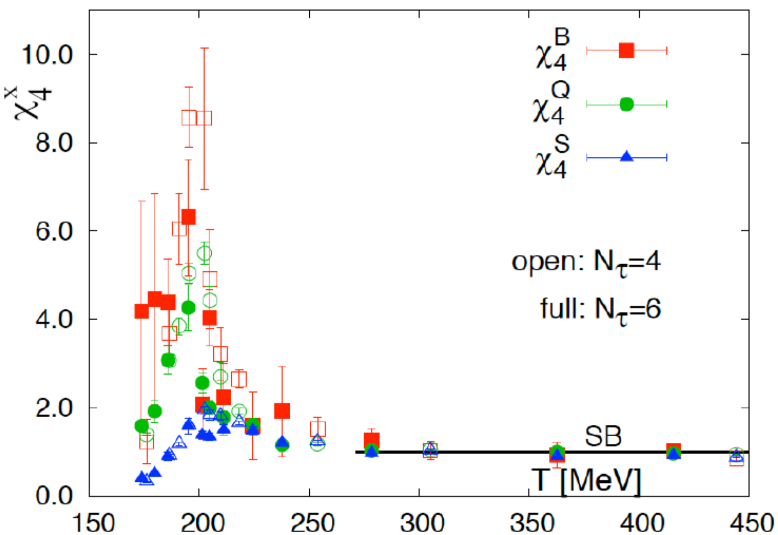
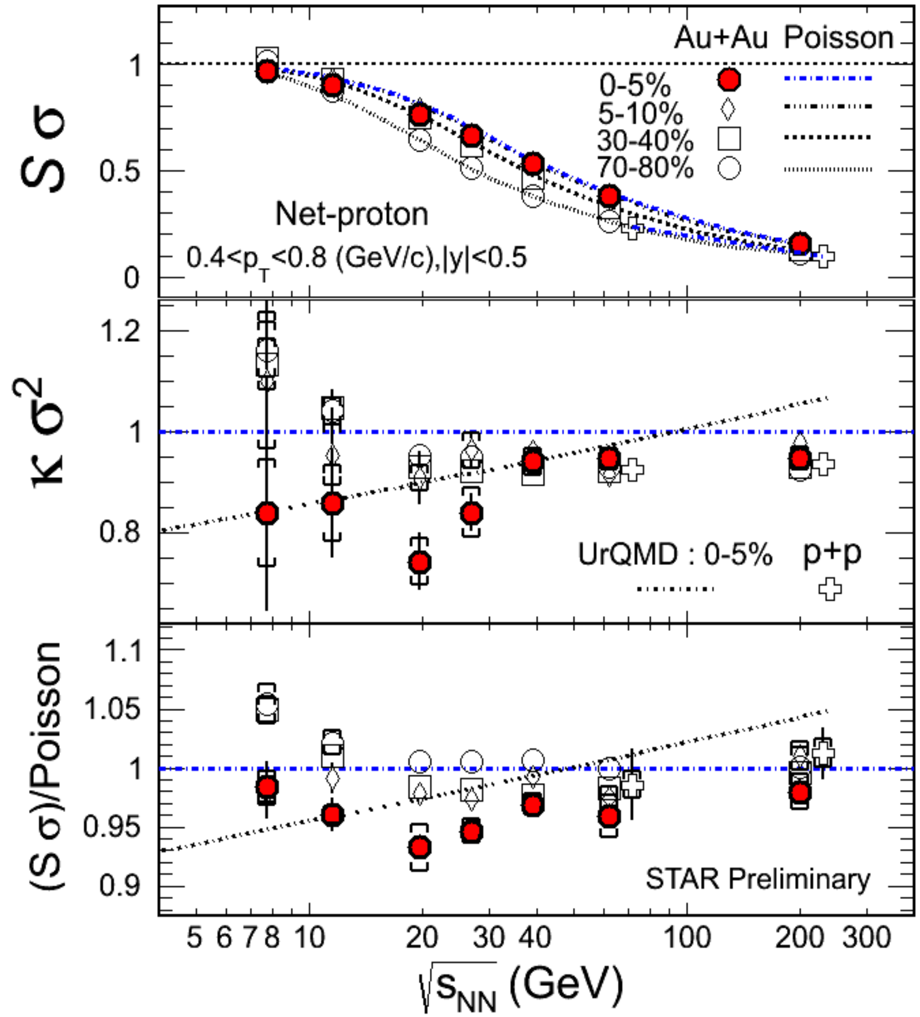
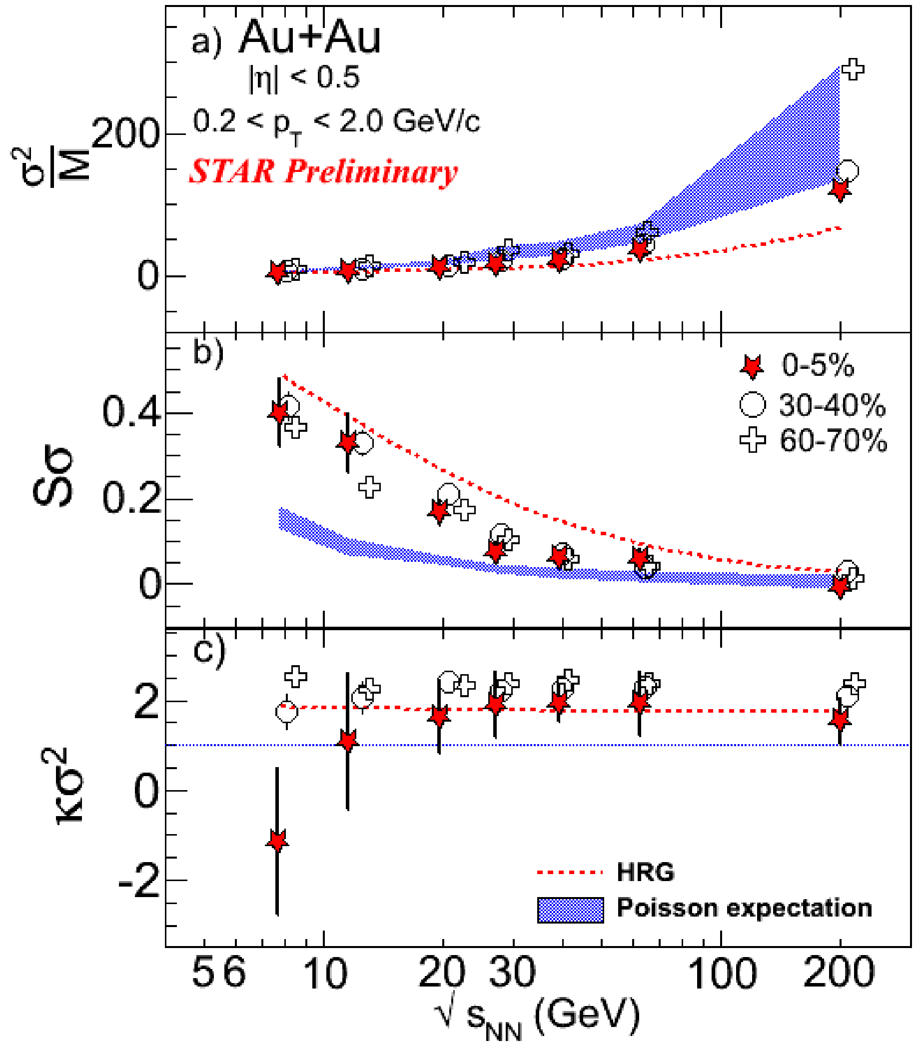




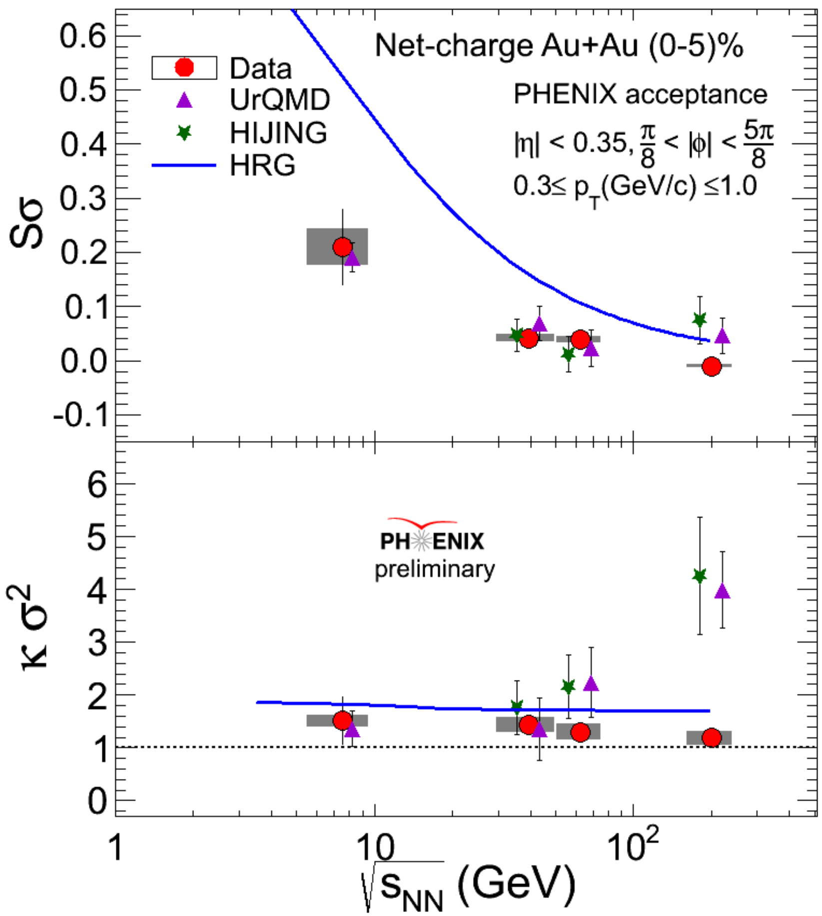
- Data are consistent Poisson baseline at high energy.
- Deviations from Poisson at low energy.
- Inconclusive ➔ **More data are needed**

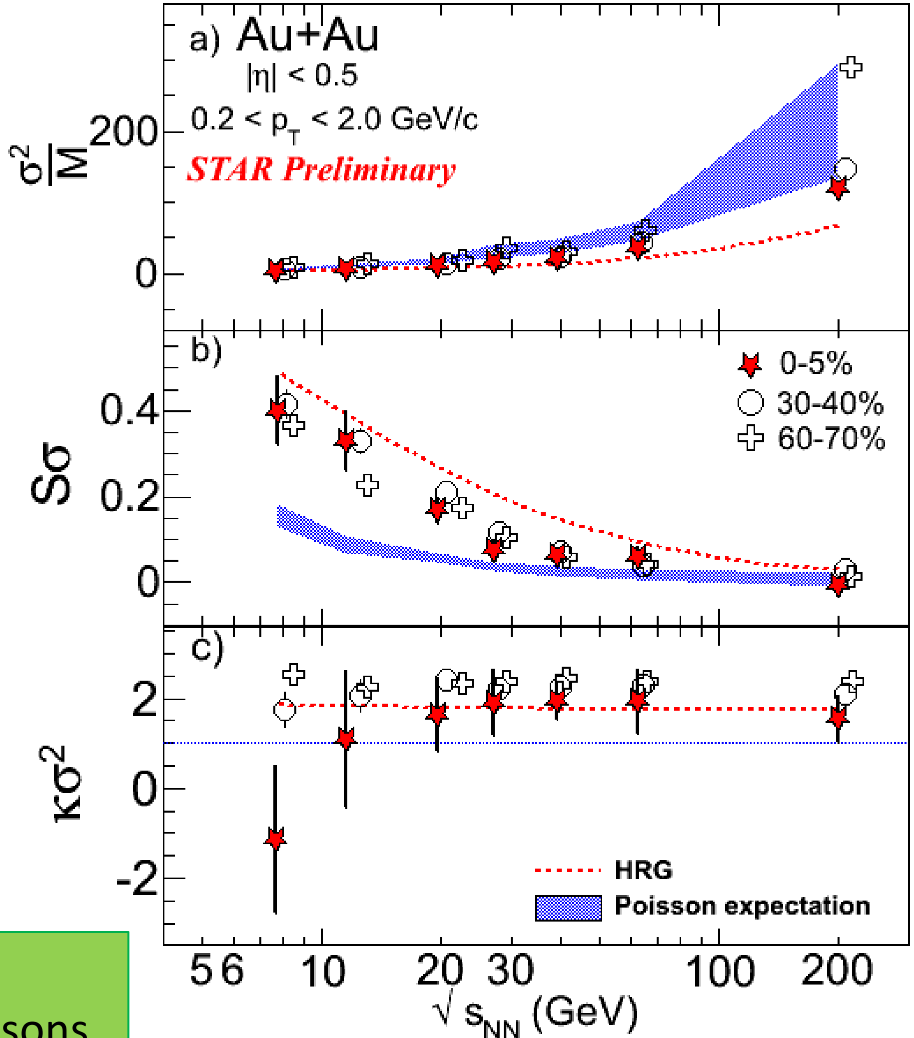
Higher Moments – Net Charge Skew/Kurtosis - BES

- Data are consistent Poisson baseline at highest energy.
- Deviations from Poisson at low energy.
- Inconclusive ➔ **More data are needed**



Higher Moments – PHENIX and STAR



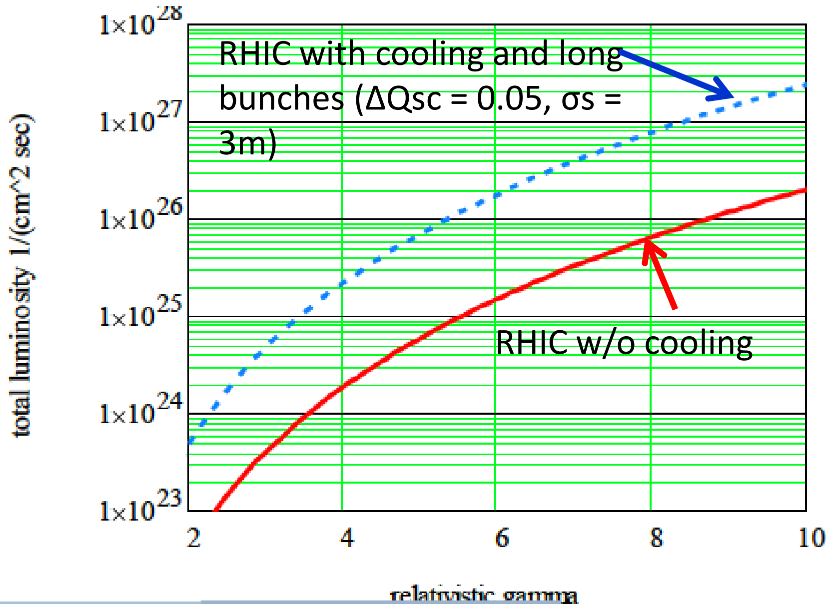


Acceptance and Efficiency correlations are needed before we can make direct comparisons.

Low Energy Electron Cooling at RHIC

Electron Cooling can raise the luminosity by a factor of 3-10 in the range from 3 – 10 GeV

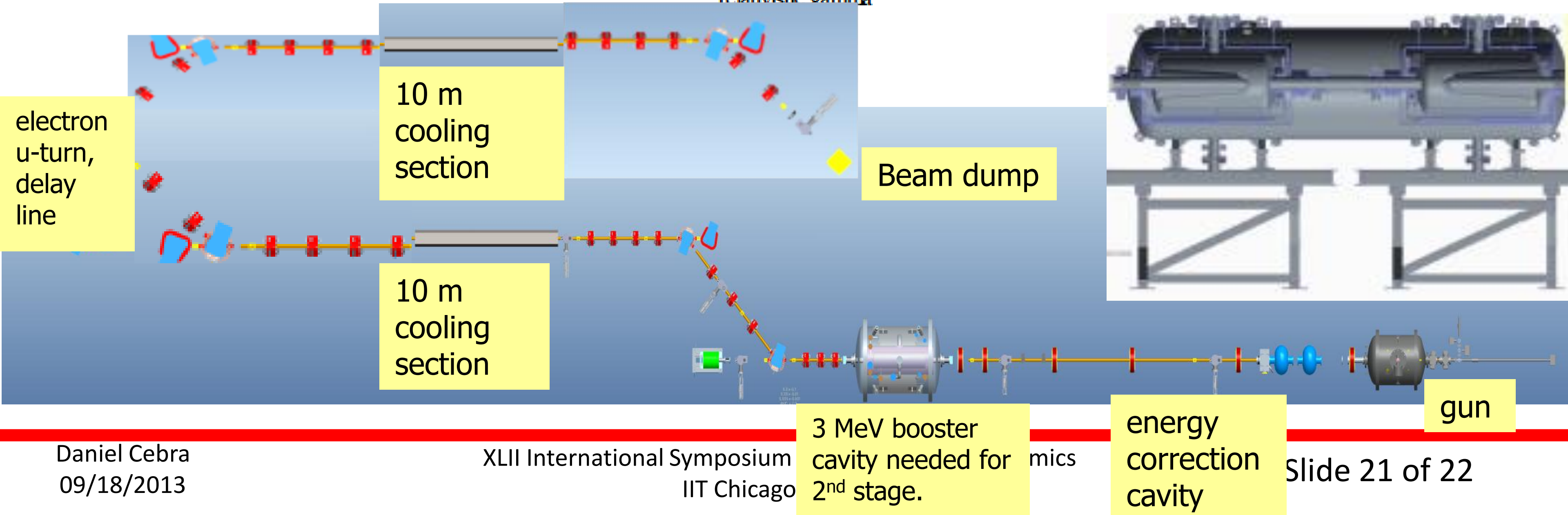
Long Bunches increase luminosity by factor of 2-5



Implimentation in phases:

Phase I (2018)
$\sqrt{s_{NN}}$ = 5-9 GeV

Phase II (2019+)
[additional 3 MeV booster cavity]
$\sqrt{s_{NN}}$ = 9-20 GeV



Conclusions

1. **Turn-off of QGP signatures:**
   - High p_t suppression not seen below 19.6 GeV

2. **Evidence of the first order phase transition.**
   - Saturation of Transverse Energy
   - Saturation of Kaon slope parameters
   - Peak in K^+/π^+ yields
   - Directed flow of protons show non-monotonic behavior.

3. **Search for the critical point.**
   - Higher moments of the net-proton and charge distributions, flat
   - Net Charge distributions also inconclusive

4. Future Beam Energy Scan phase II is planned for 2018-19