Fluctuations, Correlations and the QCD Phase diagram

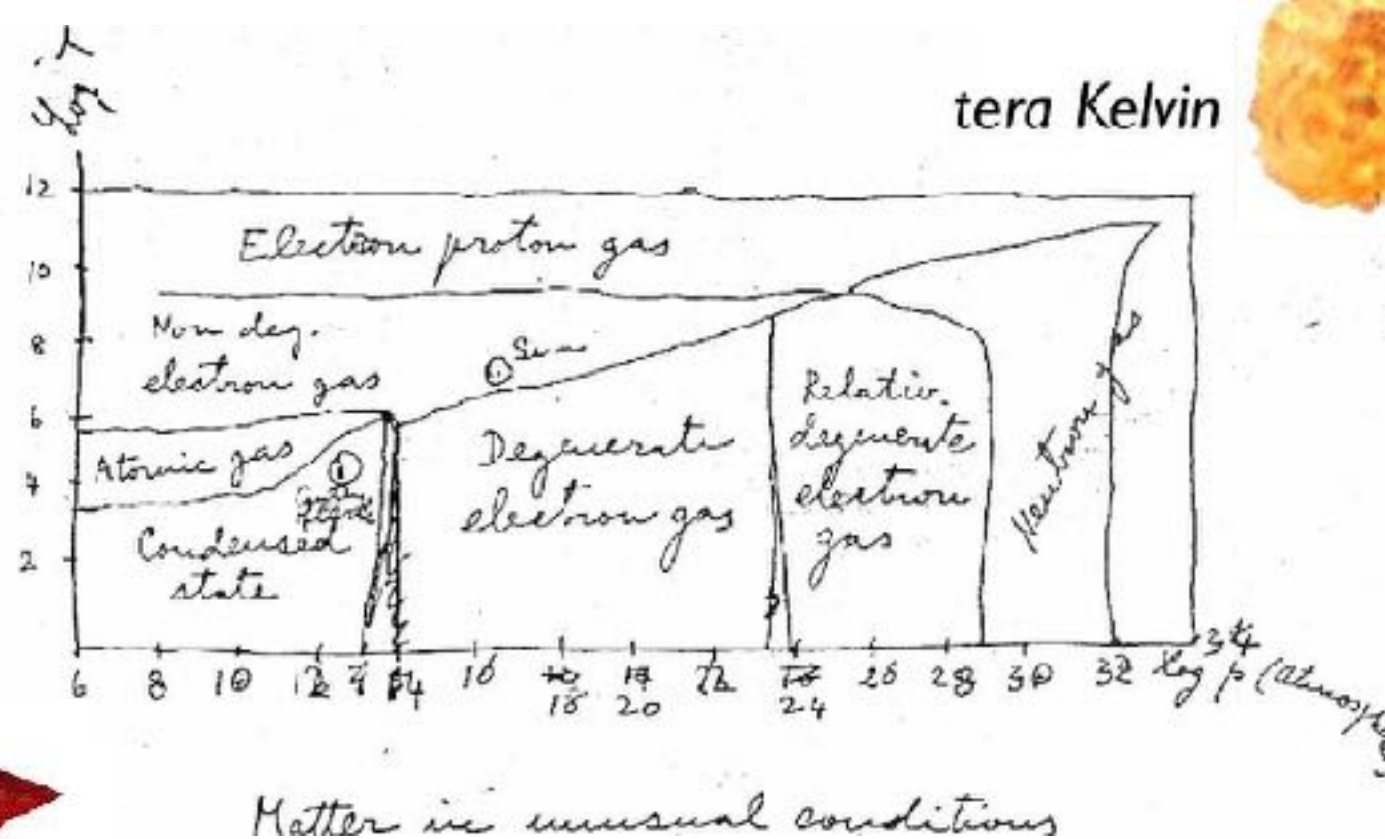
A. Bzdak, R. Holzmann, VK arXiv:1603.09057

A. Bzdak, VK, N. Strodthoff: arXiv:1607.07375

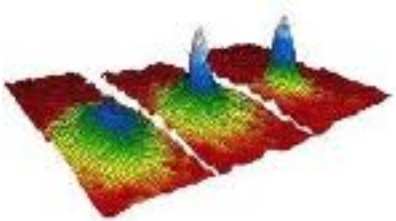
A. Bzdak, VK, V. Skokov: arXiv:1612.05128

An old question

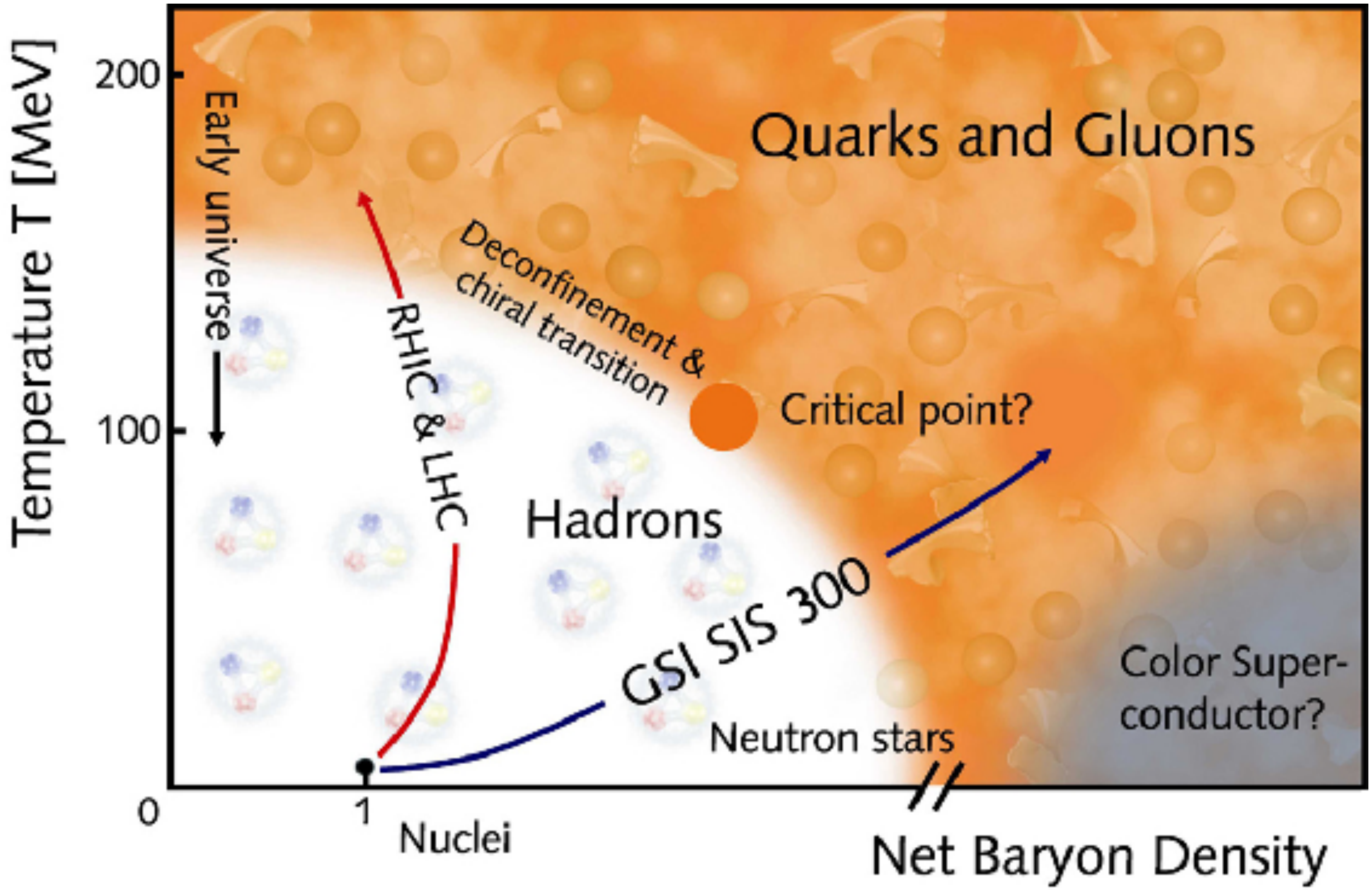
Fermi 1953



tera Kelvin

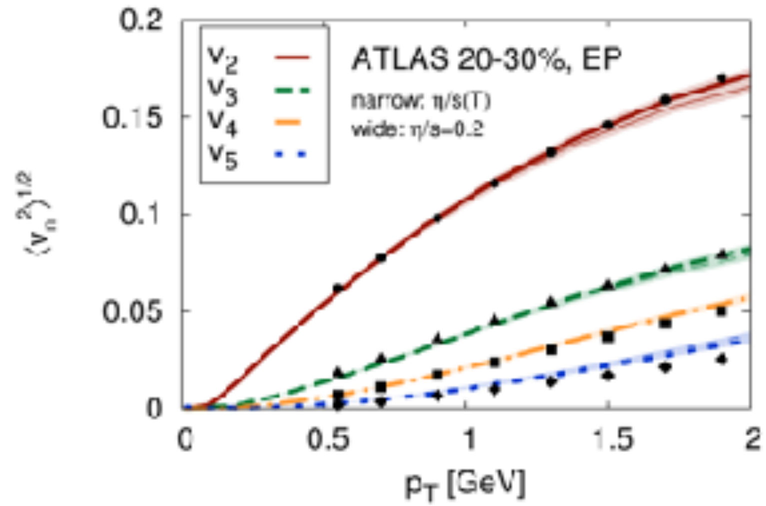


In a new context



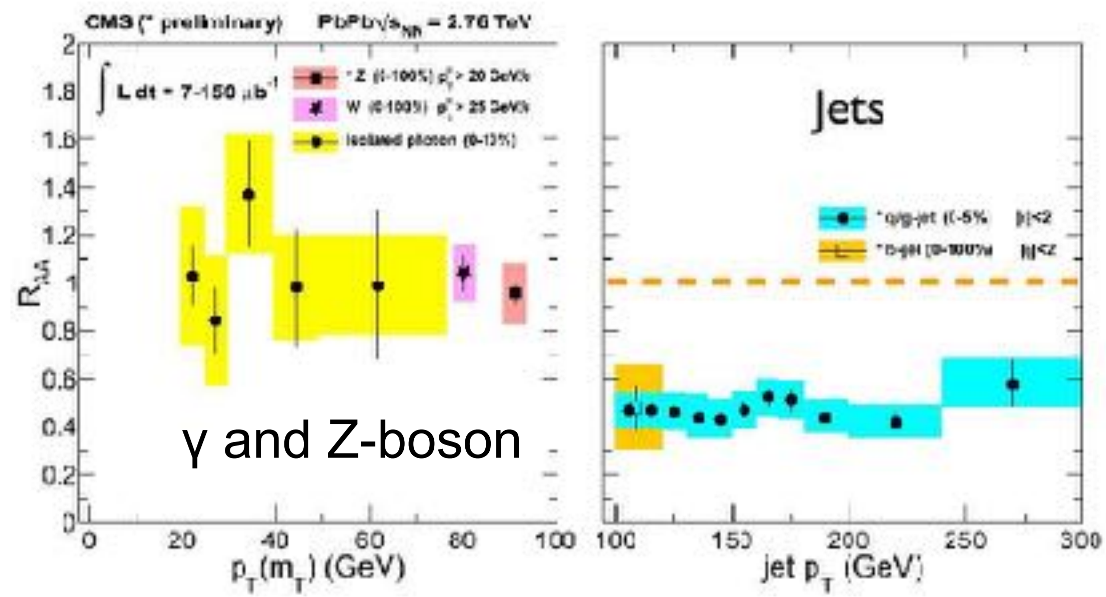
What have we learned

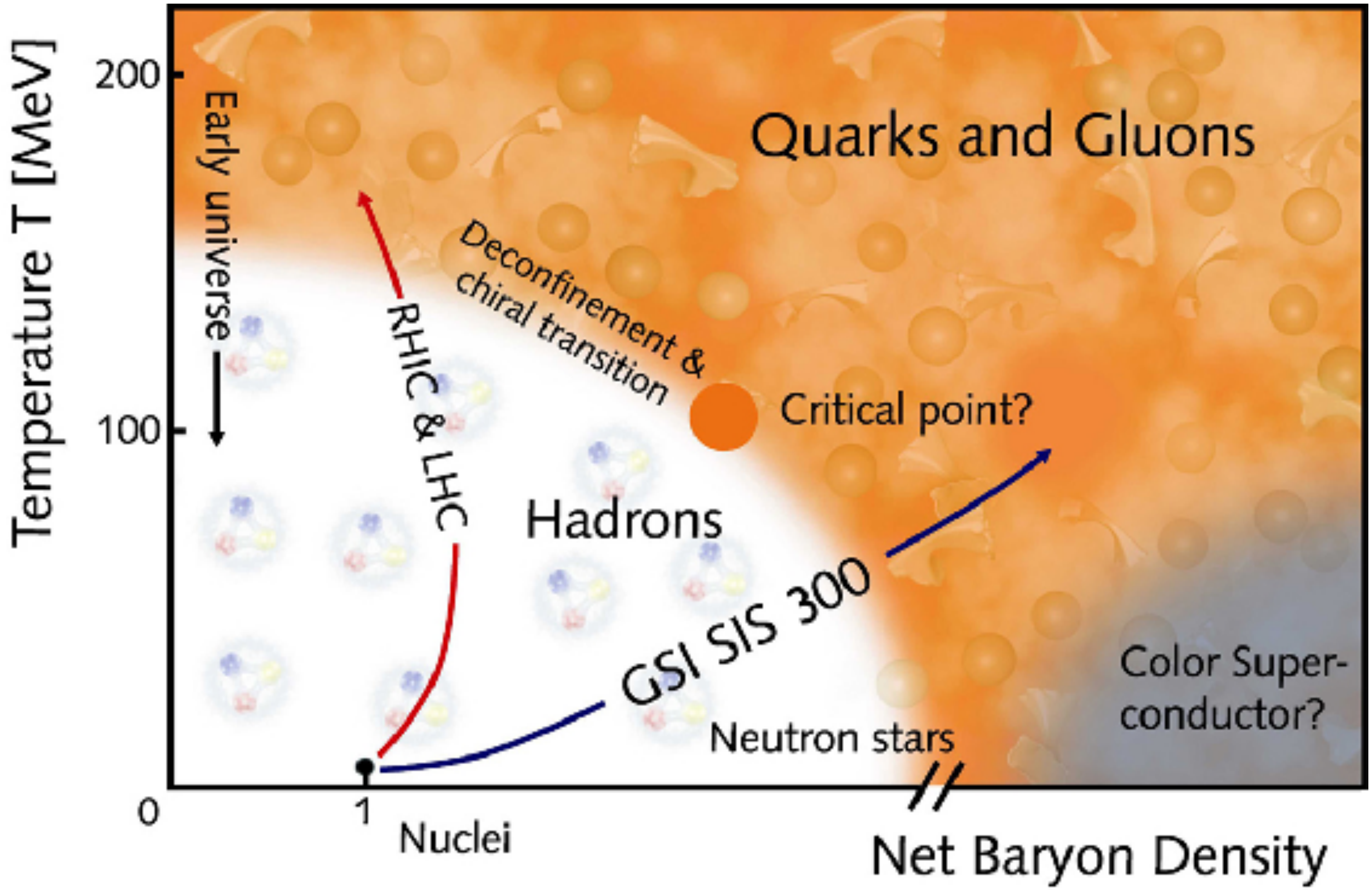
- Matter has rather small shear viscosity over entropy ratio
  - Similar phenomena also seen in p+p and p+A ??



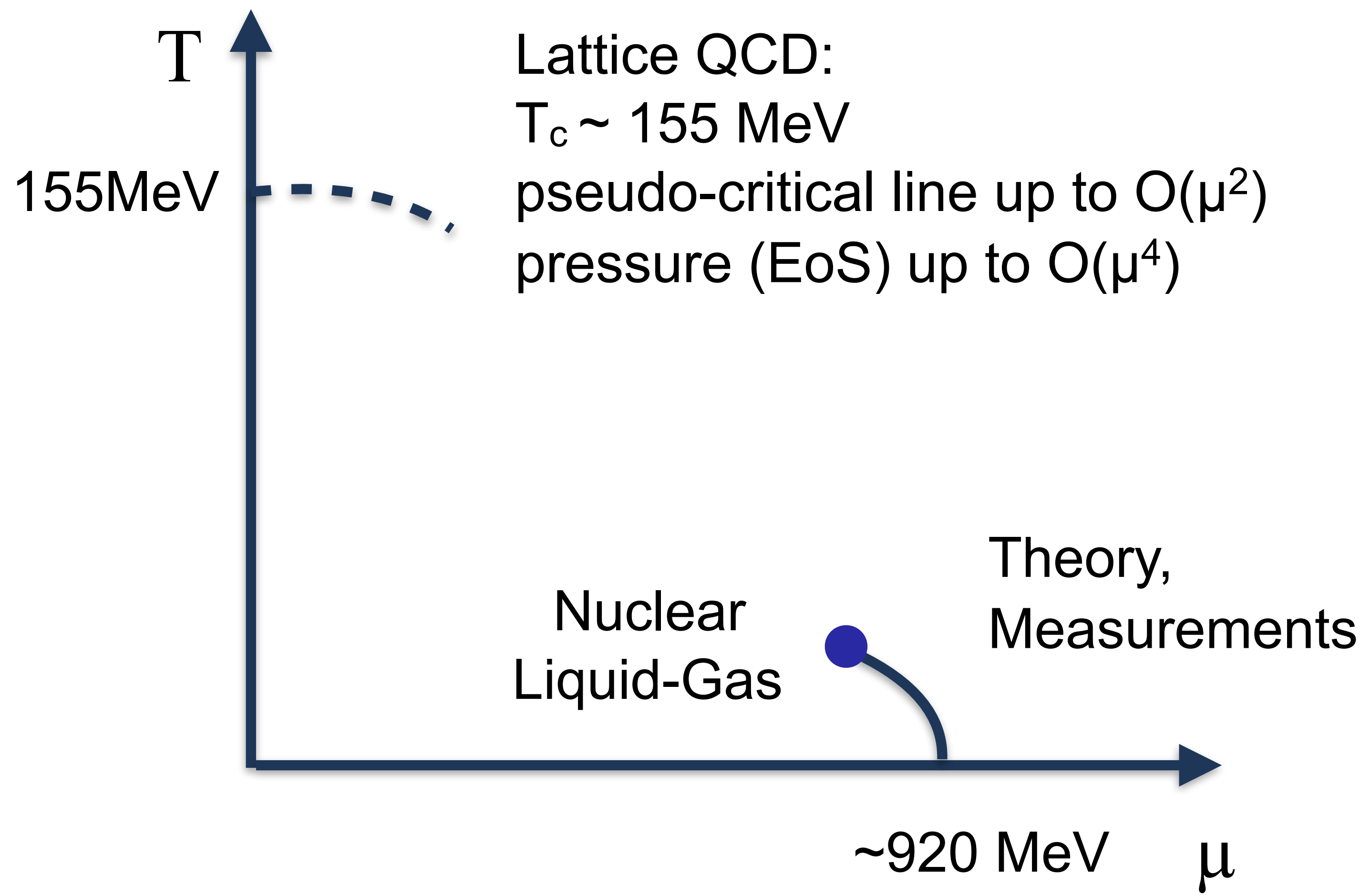
- Matter is rather opaque for high momentum particles and jets

- Heavy quarks seem to "flow" just as much as light quarks




Temperature T [MeV]
200
100
0
Early universe
Quarks and Gluons
Deconfinement &
chiral transition
RHIC & LHC
Critical point?
Hadrons
GSI SIS 300
Neutron stars
Color Super-
conductor?
1
Nuclei
Net Baryon Density

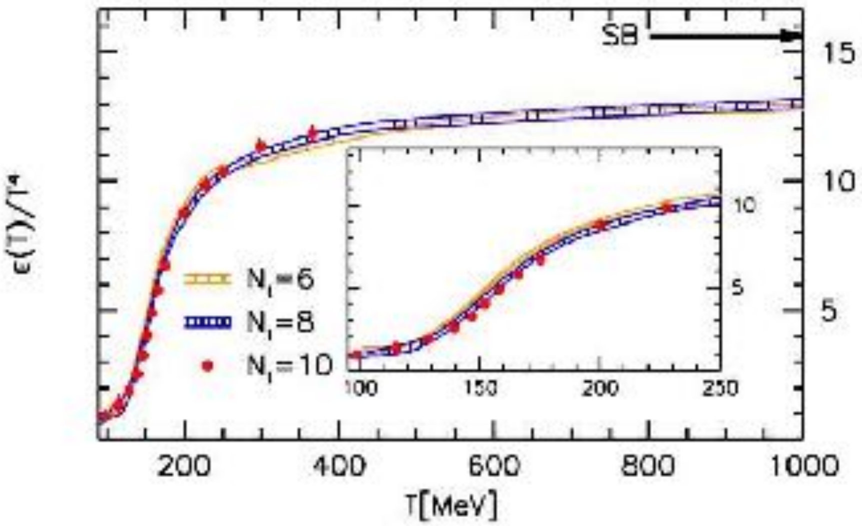
What we know about the Phase Diagram



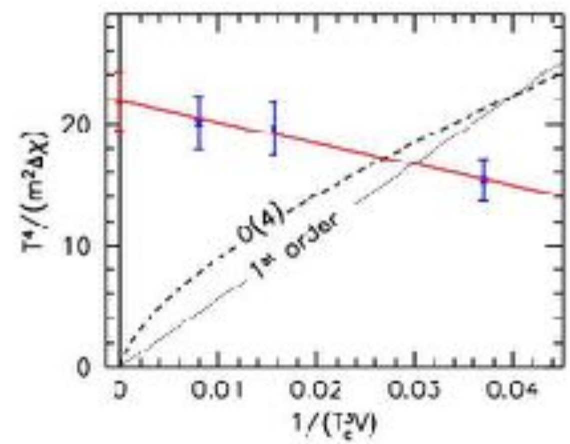
Lattice QCD

Equation of state

S. Borsanyi et al, JHEP 1011 (2010) 077

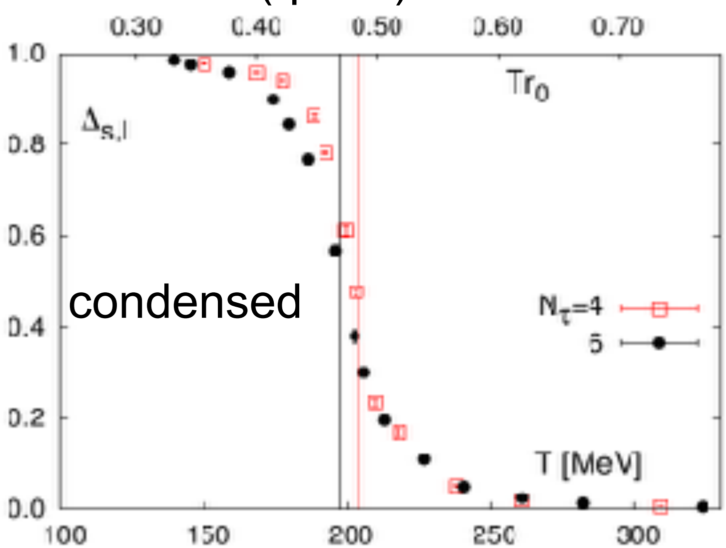


Cross over transition

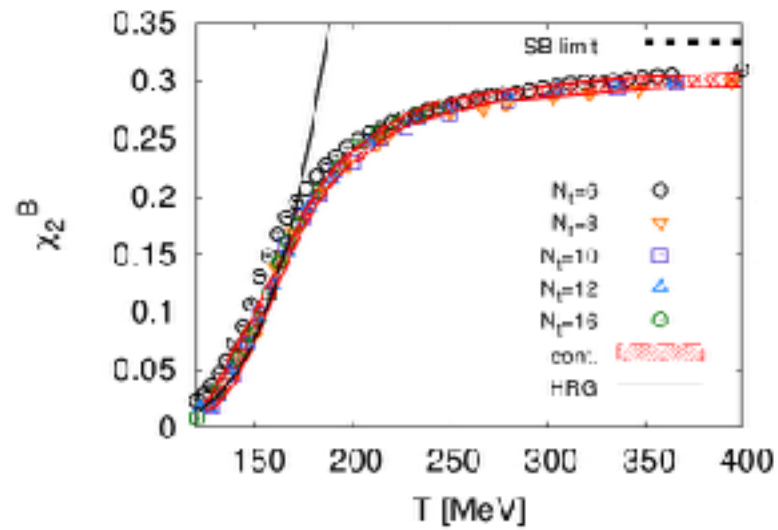


Aoki et al, Nature
443:675-678,2006

Chiral (quark) condensate



Susceptibilities



Hadron abundances

Assumption:

•Multiplicities are determined by statistical weights (chemical equilibrium)

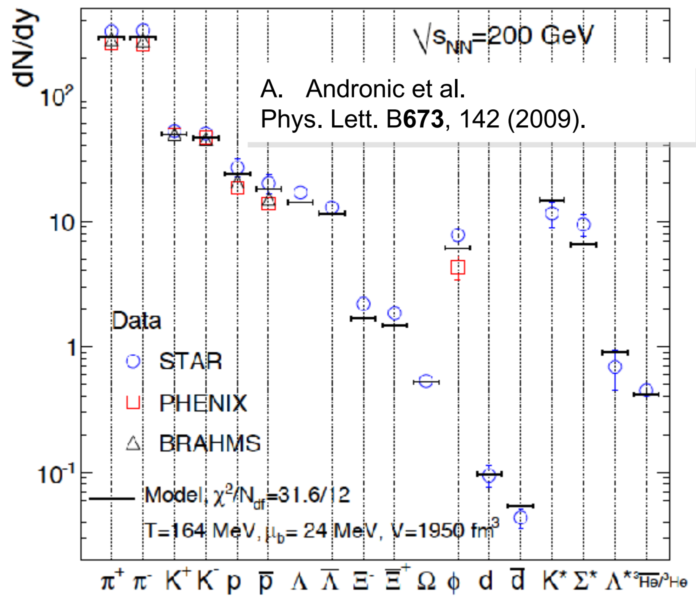
Grand-canonical partition function:

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

Parameters:

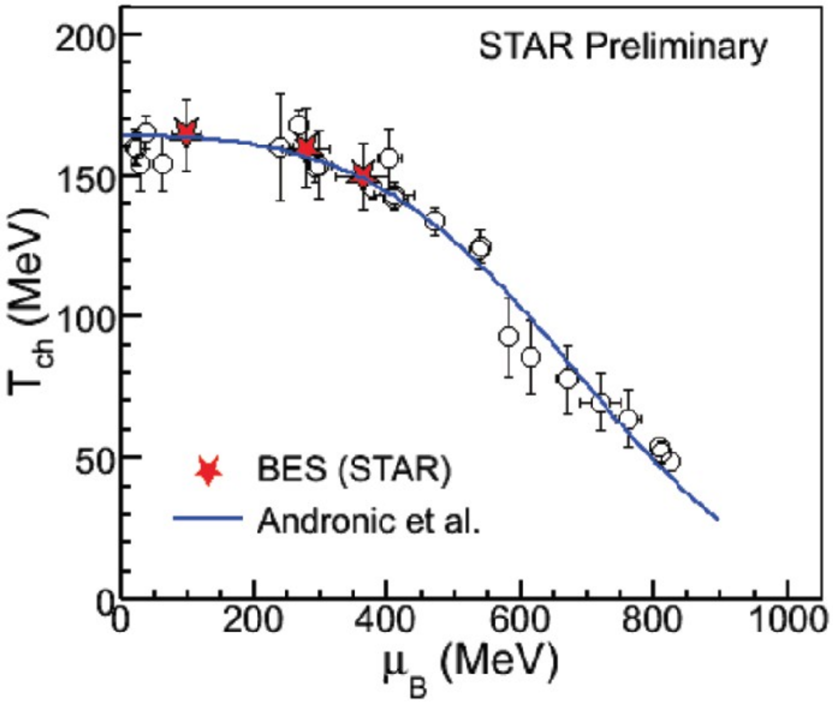
V, *T*, μ_B, (γ_s)

Allows in general excellent fits to measured multiplicities



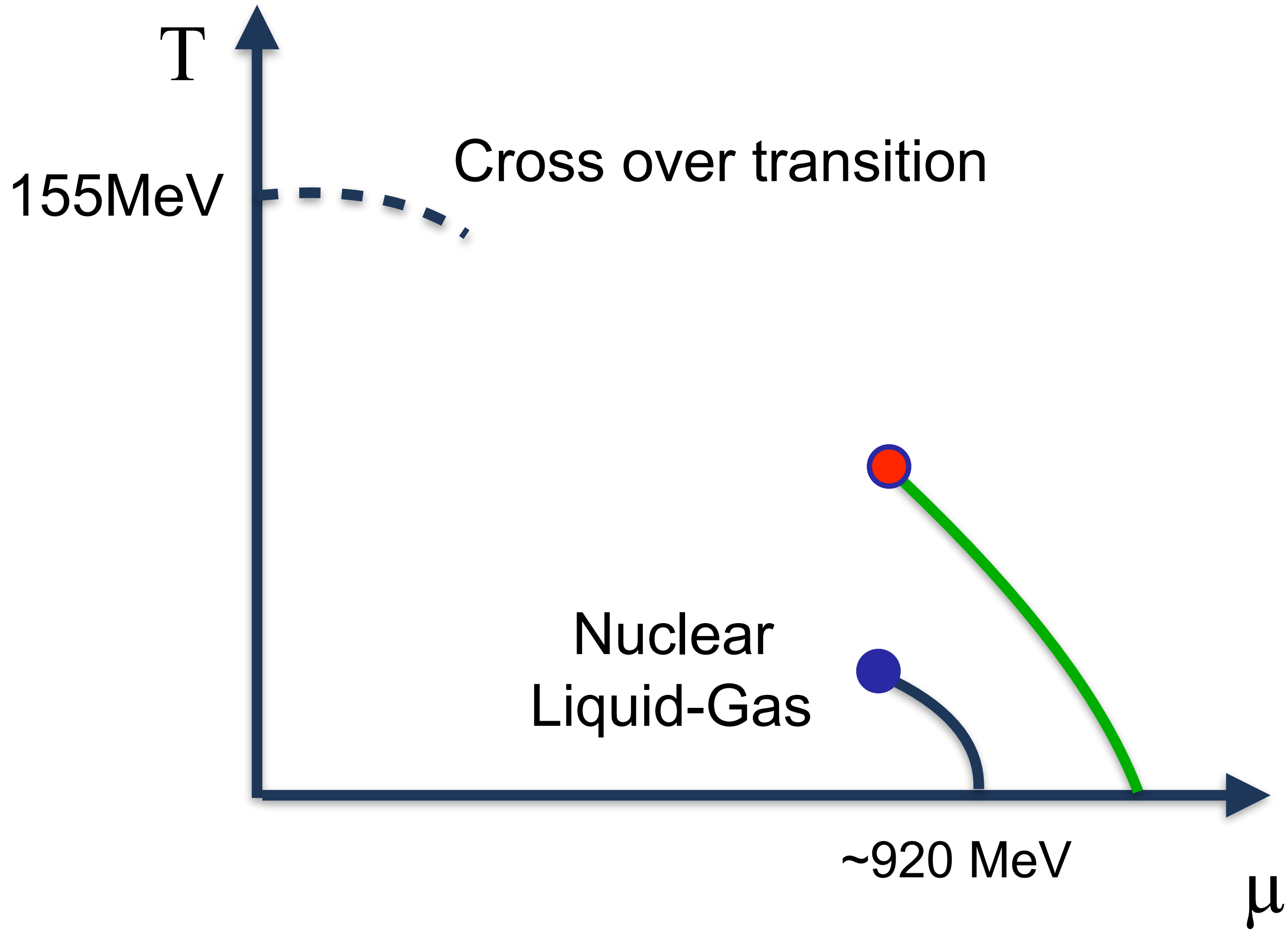
NB: works also for pp (phase space dominance, Fermi 1950)

Chemical freeze out systematics



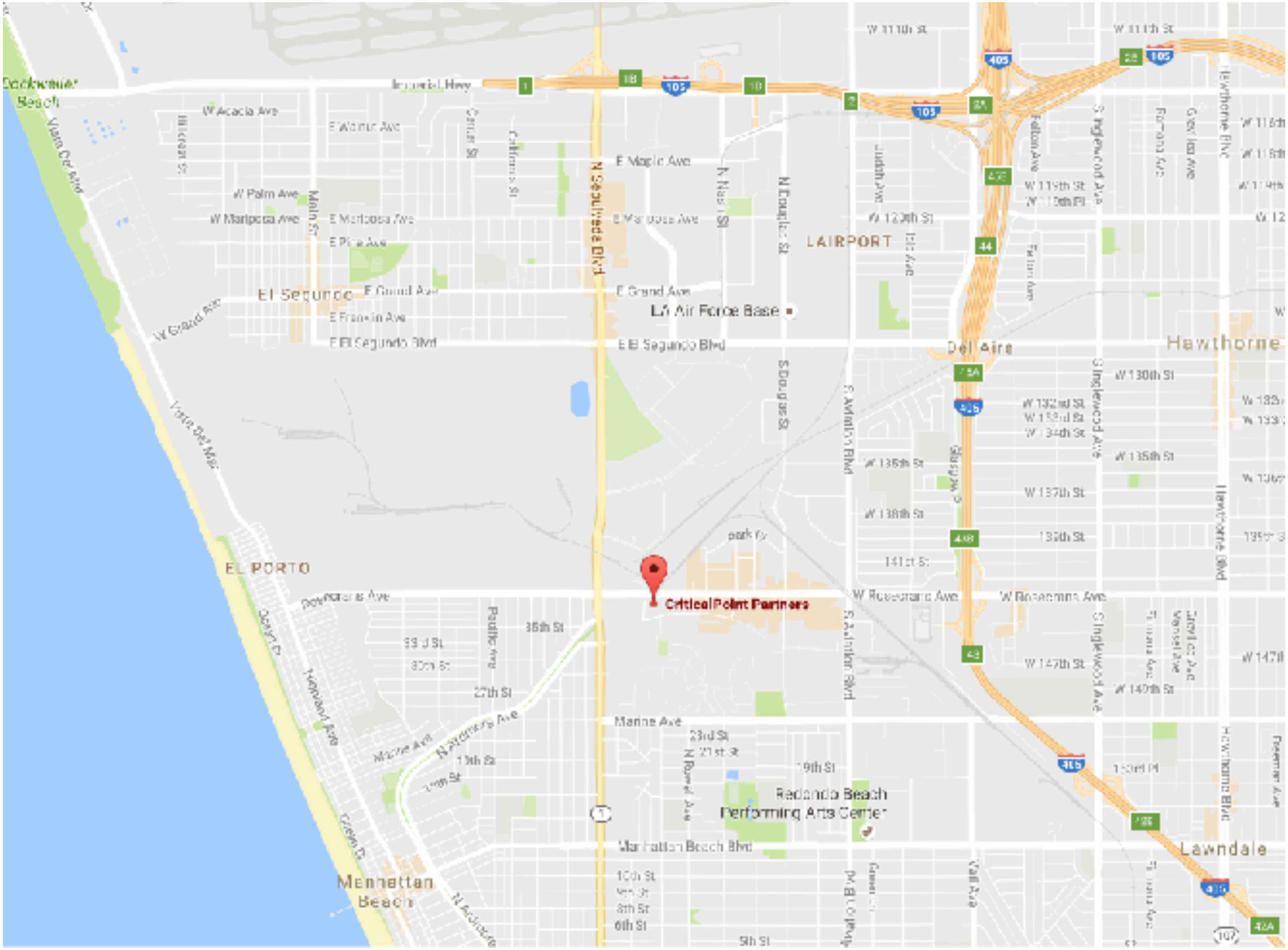
Provides rough idea which region in T, μ are probed

What we “hope” for

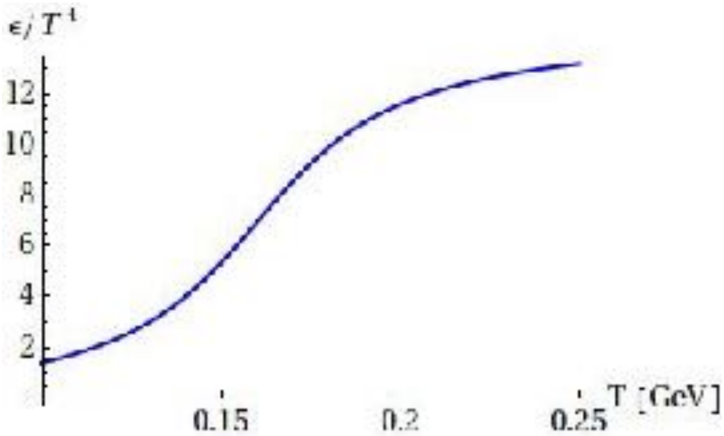


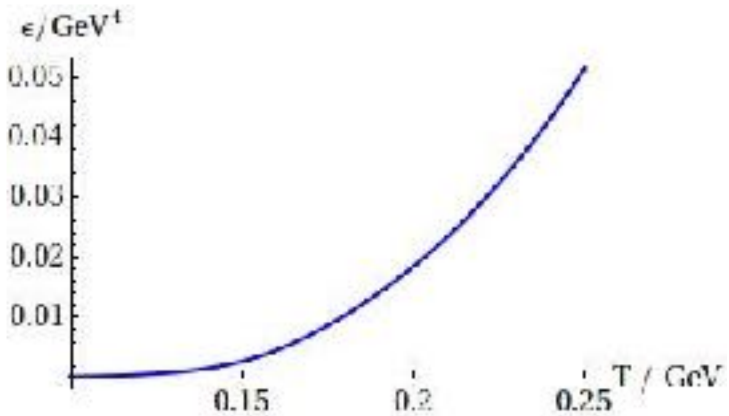
Is there a critical point?

Nothing you cannot find in LA…



Cumulants and phase structure



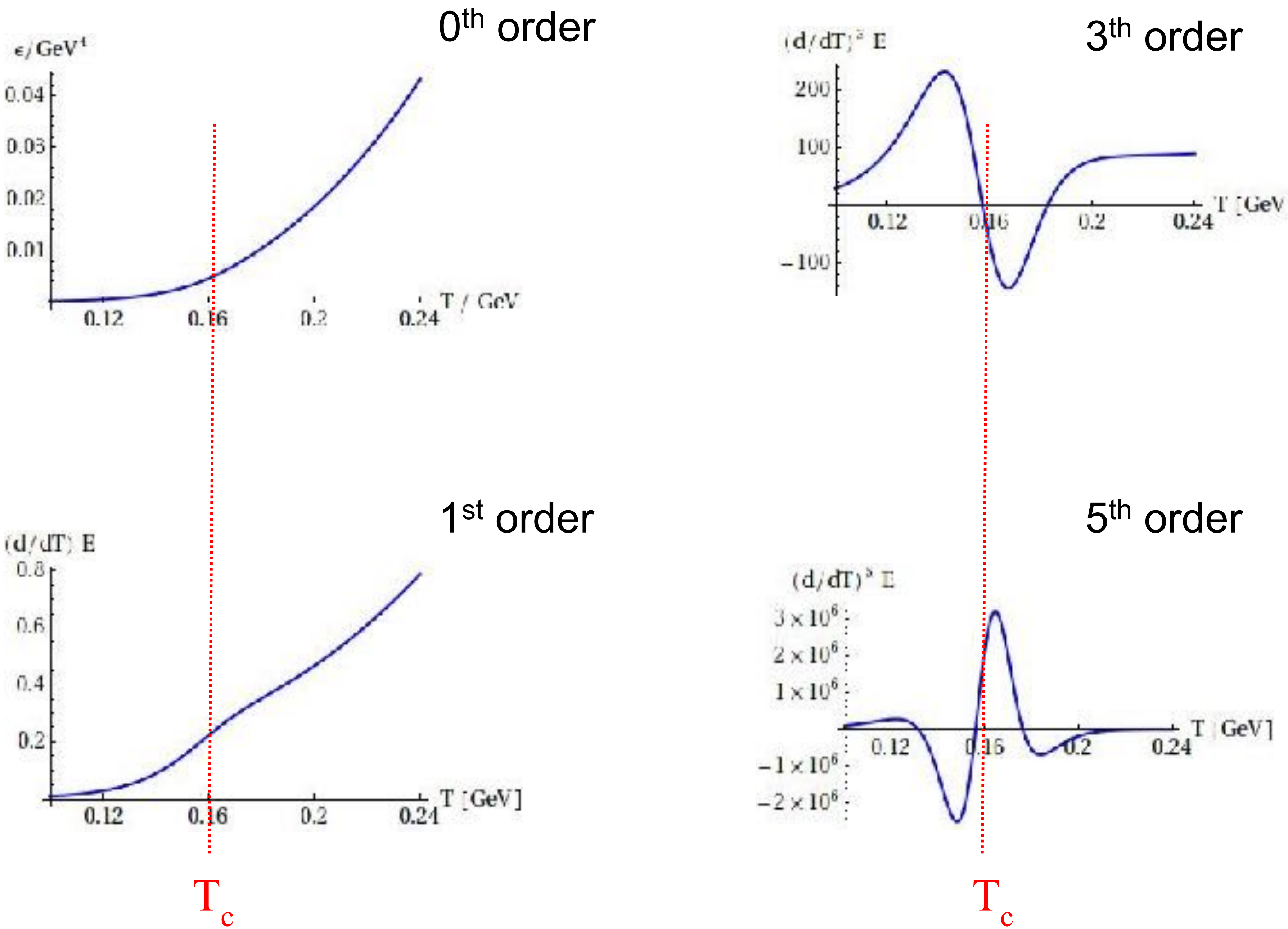


What we always see....

What it really means....

"T_c" ~ 160 MeV

Derivatives



How to measure derivatives

At μ = 0:

$$Z = tr\, e^{-\hat{E}/T + \mu/T \hat{N}_B}$$

$$\langle E \rangle = \frac{1}{Z}\, tr\, \hat{E}\, e^{-\hat{E}/T + \mu/T \hat{N}_B} = -\frac{\partial}{\partial 1/T} \ln(Z)$$

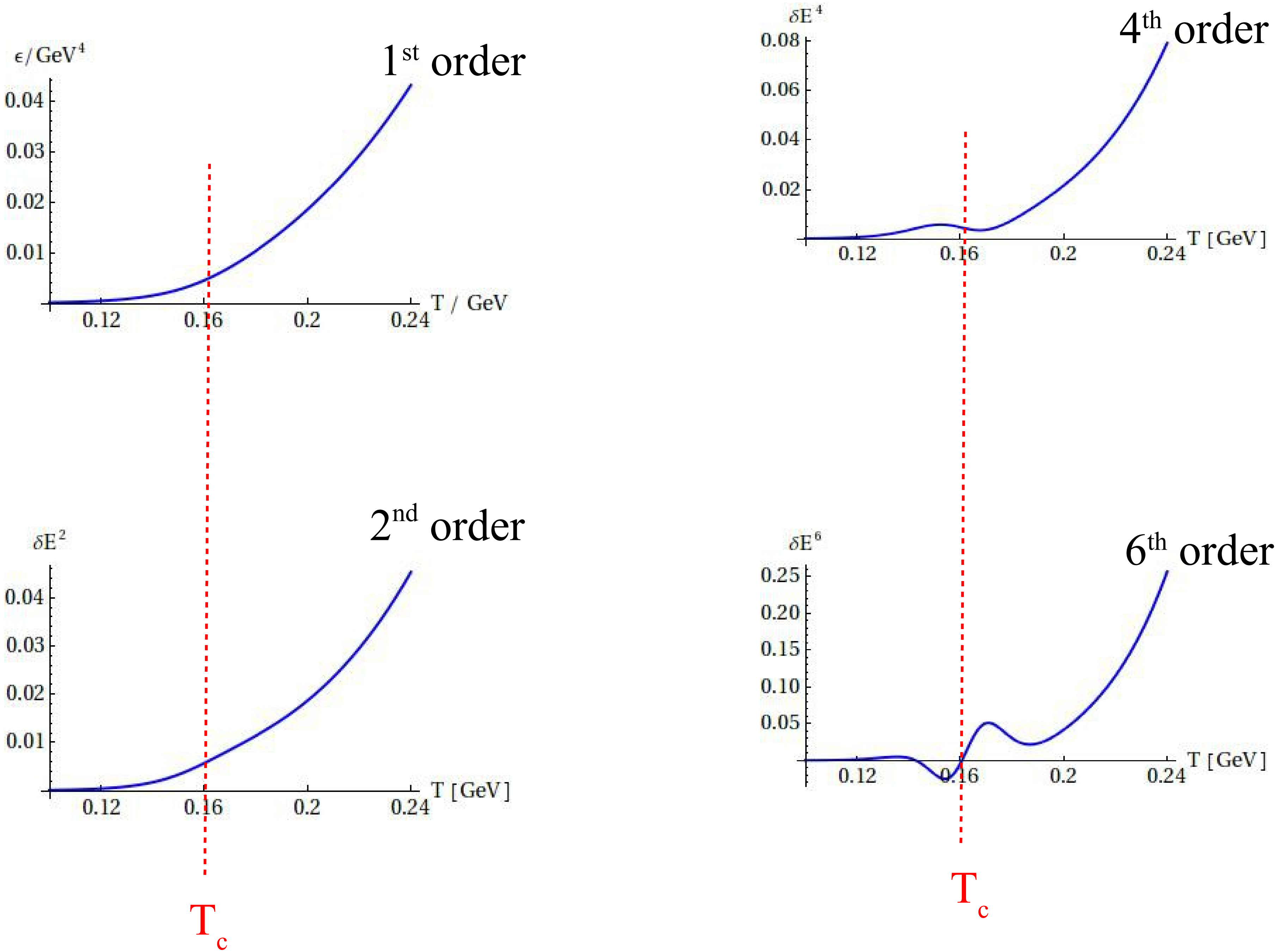
$$\langle (\delta E)^2 \rangle = \langle E^2 \rangle - \langle E \rangle^2 = \left(-\frac{\partial}{\partial 1/T}\right)^2 \ln(Z) = \left(-\frac{\partial}{\partial 1/T}\right) \langle E \rangle$$

$$\langle (\delta E)^n \rangle = \left(-\frac{\partial}{\partial 1/T}\right)^{n-1} \langle E \rangle$$

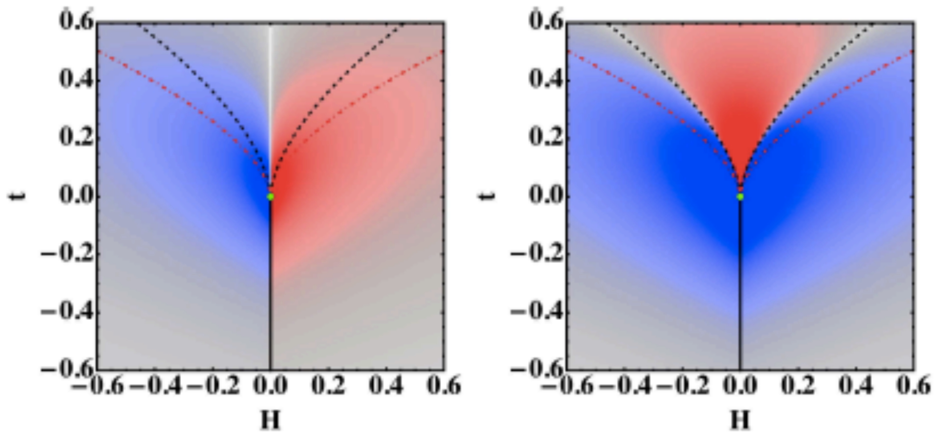
Cumulants of Energy measure the temperature derivatives of the EOS

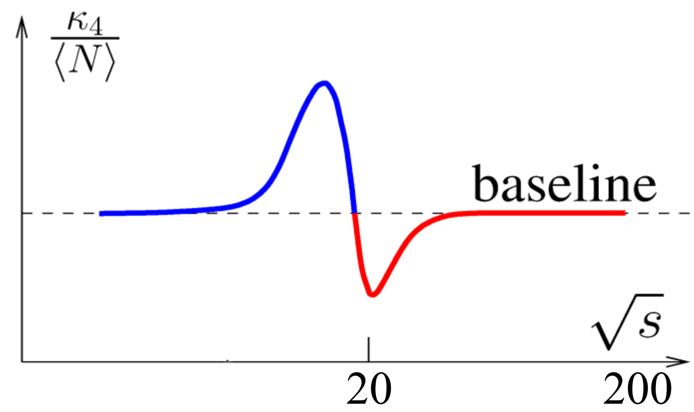
Cumulants of Baryon number measure the chem. pot. derivatives of the EOS

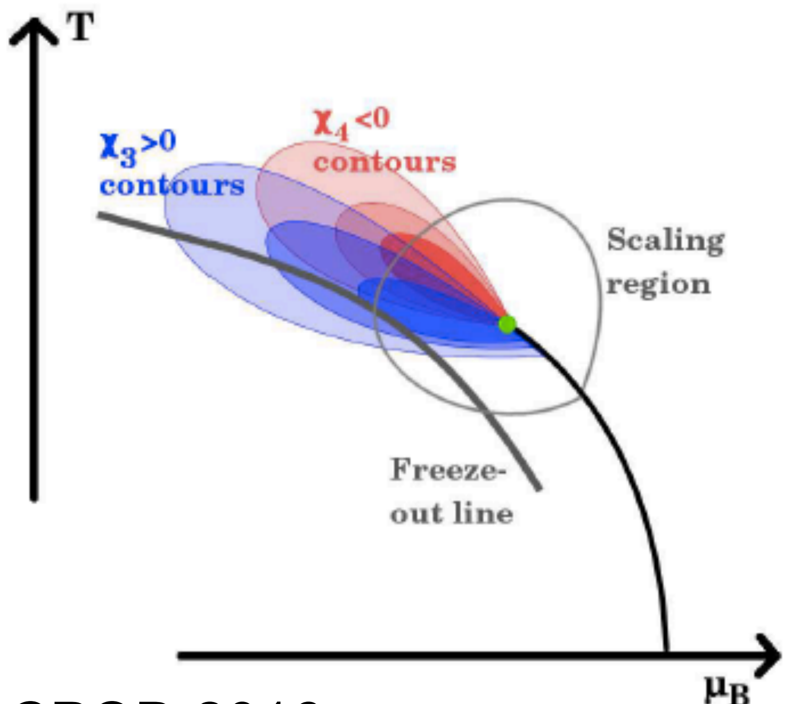
Fluctuations / Cumulants



Expectation from Calculations





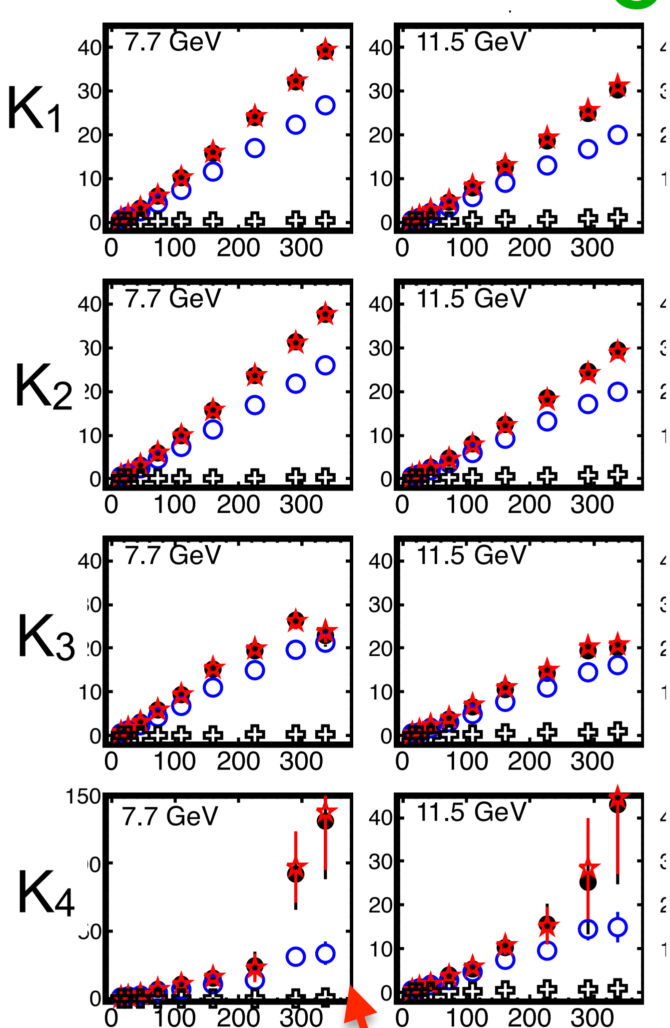


Characteristic "Oscillating pattern" is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP*

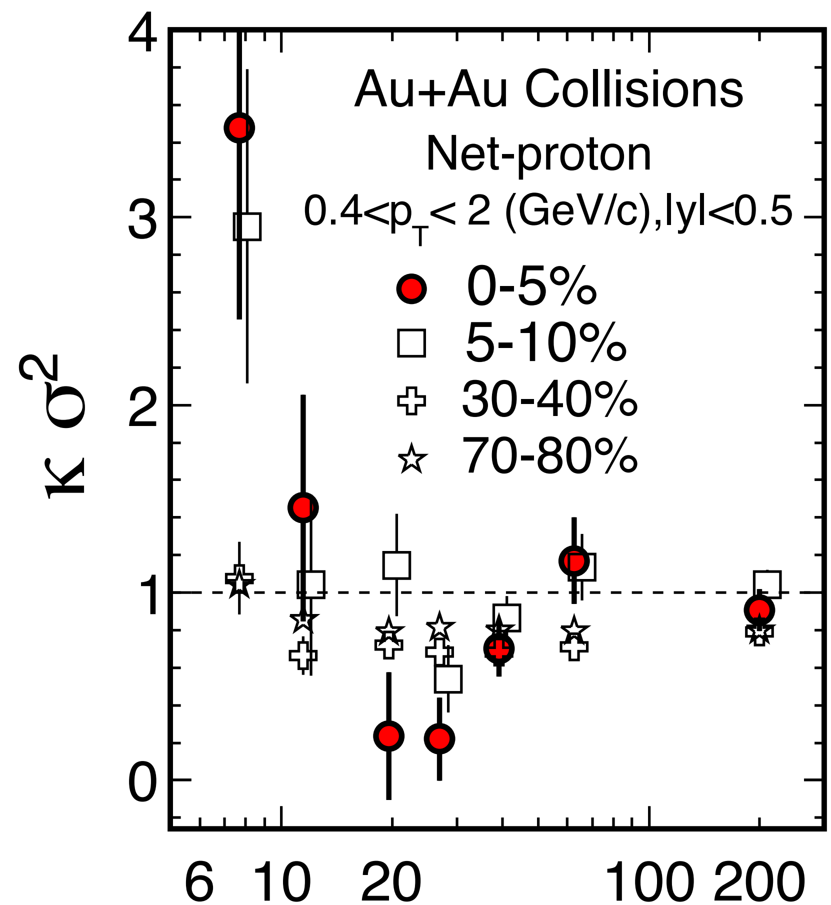
- M. Stephanov, ***PRL107***, 052301(2011)
- V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, arXiv: 1603.05198, Phys. Rev. **D93** (2016) 034037

N. Xu, CPOD 2016

Latest STAR result on net-proton cumulants



X. Luo, arXiv:1503.02558



Unfolding makes huge difference in new STAR data!

HADES sees similar behavior

(J. Stroth, INT, Oct 2016)

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Comparison to STAR

- HADES data from unfolding method

October 3-8, 2016

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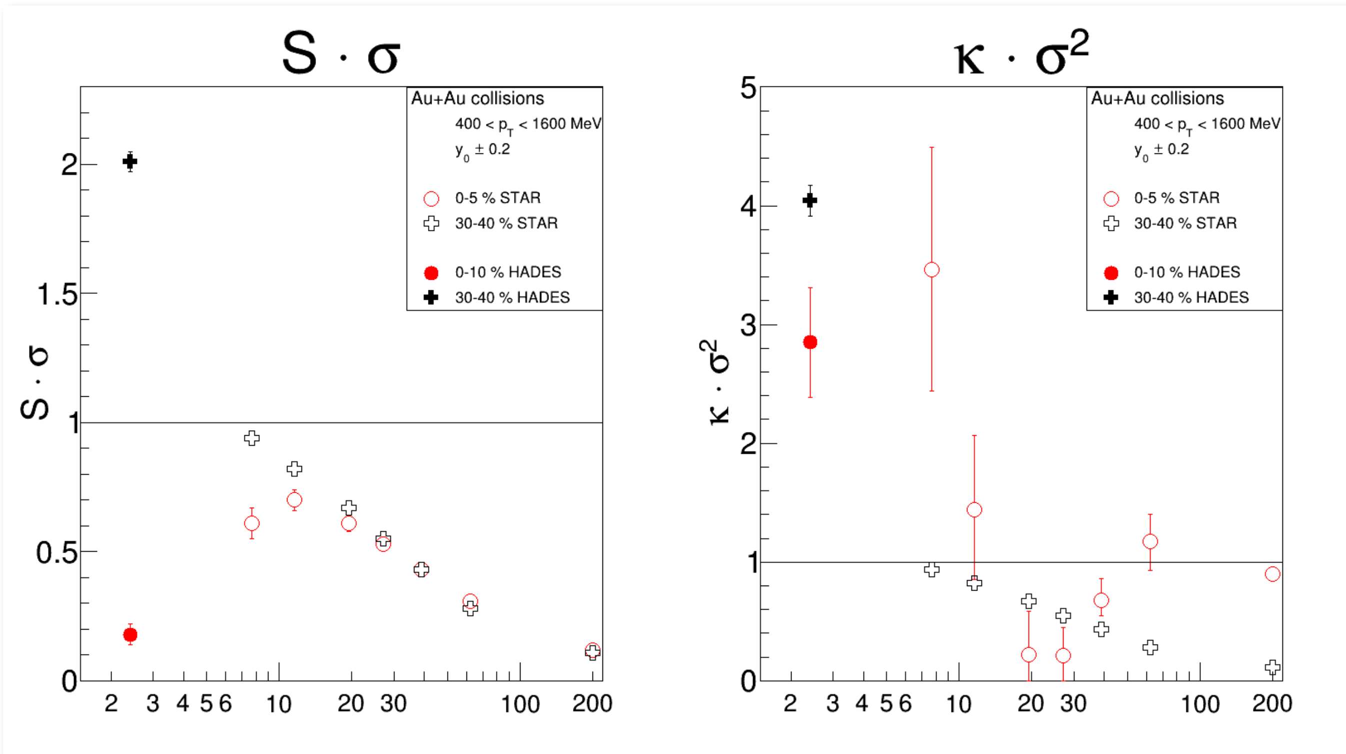


HADES, preliminary

Let's take the preliminary STAR data at face value

From Cumulants to Correlations

Cumulants $$K_n = \frac{\partial^n}{\partial \hat{\mu}^n} P/T^4$$

$$K_2 = \langle N - \langle N \rangle \rangle^2 = \langle (\delta N)^2 \rangle$$

$$\rho_2(p_1, p_2) = \rho_1(p_1)\rho_1(p_2) + C_2(p_1, p_2),$$

C_2: Correlation Function

$$K_3 = \langle (\delta N)^3 \rangle$$

$$\rho_3(p_1,p_2,p_3) = \rho_1(p_1)\rho_1(p_2)\rho_1(p_3) + \rho_1(p_1)\underline{C_2(p_2,p_3)} + \rho_1(p_2)\underline{C_2(p_1,p_3)} + \rho_1(p_3)\underline{C_2(p_1,p_2)} + \underline{C_3(p_1,p_2,p_3)}$$

From Cumulants to Correlations
(no anti-protons)

Defining integrated correlations function

$$C_n = \int dp_1 \ldots dp_n C_n(p_1, \ldots, p_n)$$

Simple Algebra leads to relation between correlations C_n and K_n

$$C_2 = -K_1 + K_2,$$
$$C_3 = 2K_1 - 3K_2 + K_3,$$
$$C_4 = -6K_1 + 11K_2 - 6K_3 + K_4, .$$

or vice versa

$$K_2 = \langle N \rangle + C_2$$
$$K_3 = \langle N \rangle + 3C_2 + C_3$$
$$K_4 = \langle N \rangle + 7C_2 + 6C_3 + C_4$$

Correlations near the critical point

M. Stephanov, 0809.3450, PRL 102

Scaling of Cumulants K_n with correlation length ξ

$$K_2 \sim \xi^2, \;\; K_3 \sim \xi^{4.5}, \;\; K_4 \sim \xi^7$$

Cumulants from Correlations

$$K_2 = \langle N \rangle + C_2$$
$$K_3 = \langle N \rangle + 3C_2 + C_3$$
$$K_4 = \langle N \rangle + 7C_2 + 6C_3 + C_4$$

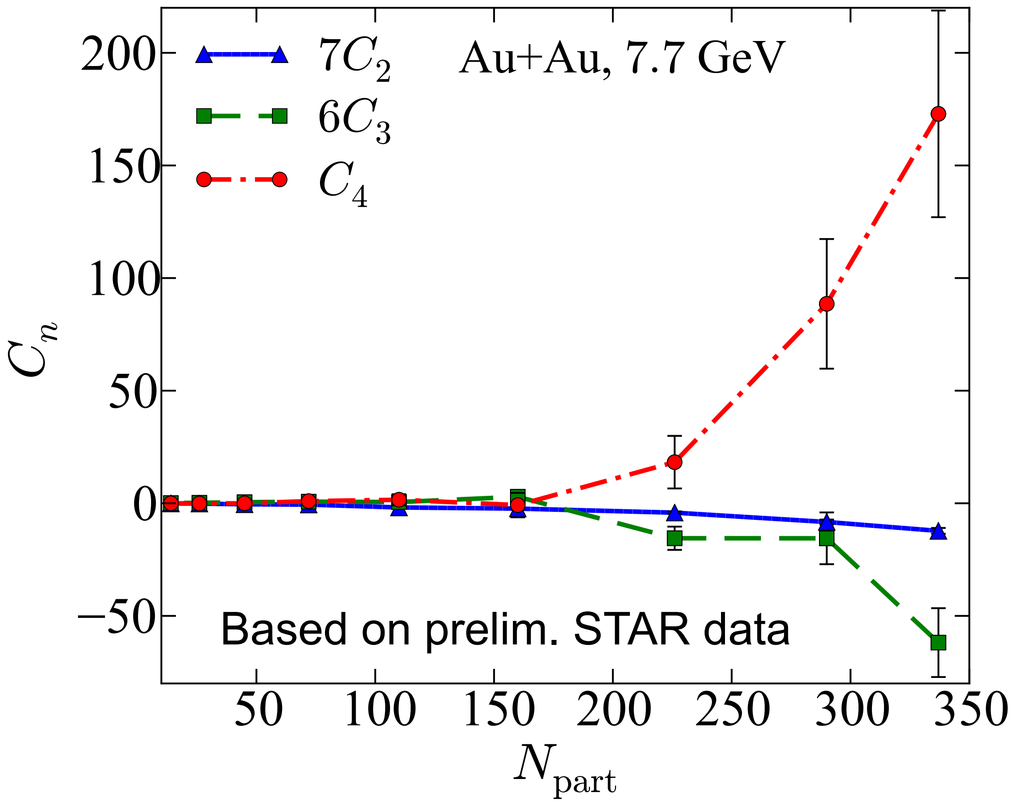
Consequently:

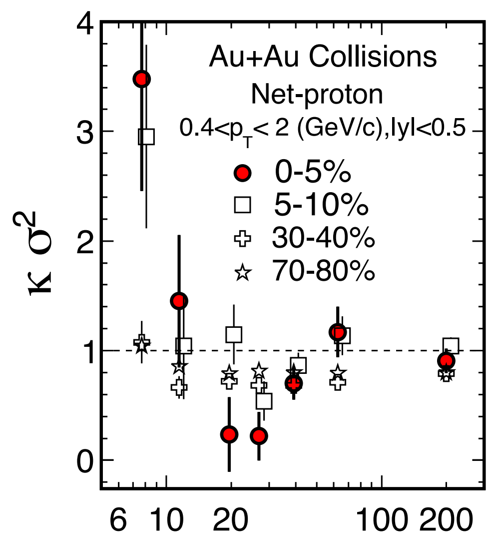
$$C_2 \sim \xi^2, \;\; C_3 \sim \xi^{4.5}, \;\; C_4 \sim \xi^7$$

Correlations C_n pick up the most divergent pieces of cumulants K_n!

Preliminary Star Data

(X. Luo, PoS Cpod 2014 (019))





Significant four particle correlations!

Four particle correlation dominate K_4 for central collisions at 7.7 GeV

$$K_2 = \langle N \rangle + C_2$$

$$K_3 = \langle N \rangle + 3C_2 + C_3$$

$$K_4 = \langle N \rangle + 7C_2 + 6C_3 + C_4$$

Hades see even stronger correlations

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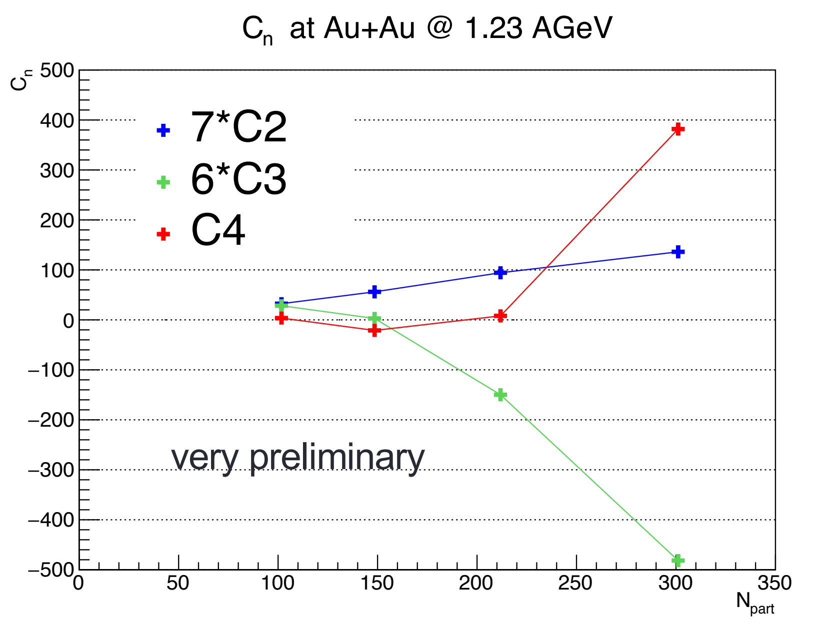
Particle Correlations

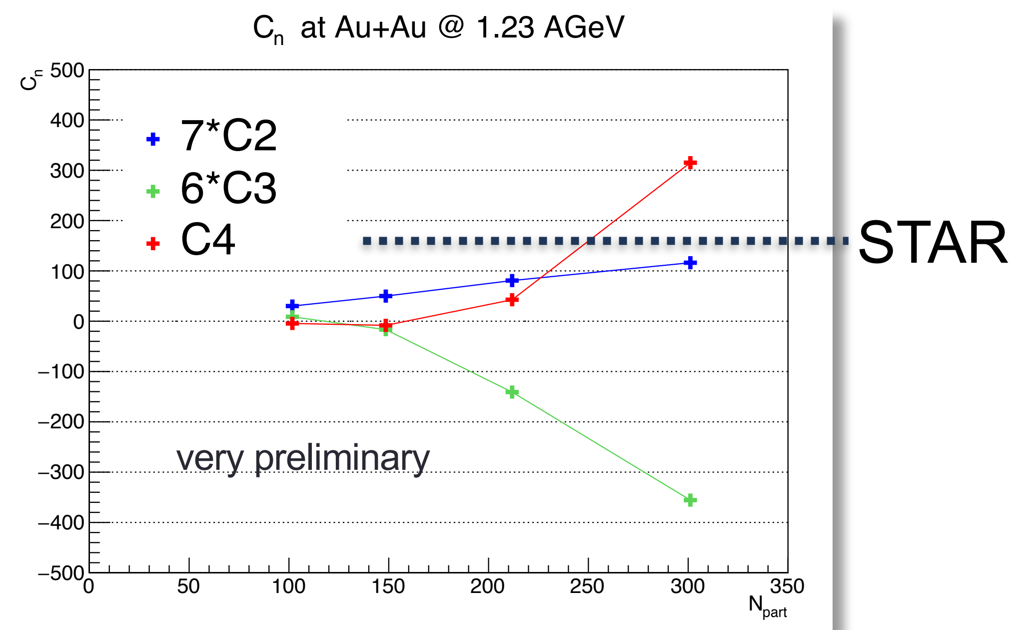
HADES

$$C_2 = -\langle N \rangle + K_2,$$
$$C_3 = 2\langle N \rangle - 3K_2 + K_3,$$
$$C_4 = -6\langle N \rangle + 11K_2 - 6K_3 + K_4.$$

○ CUMULANT



○ UNFOLDNG



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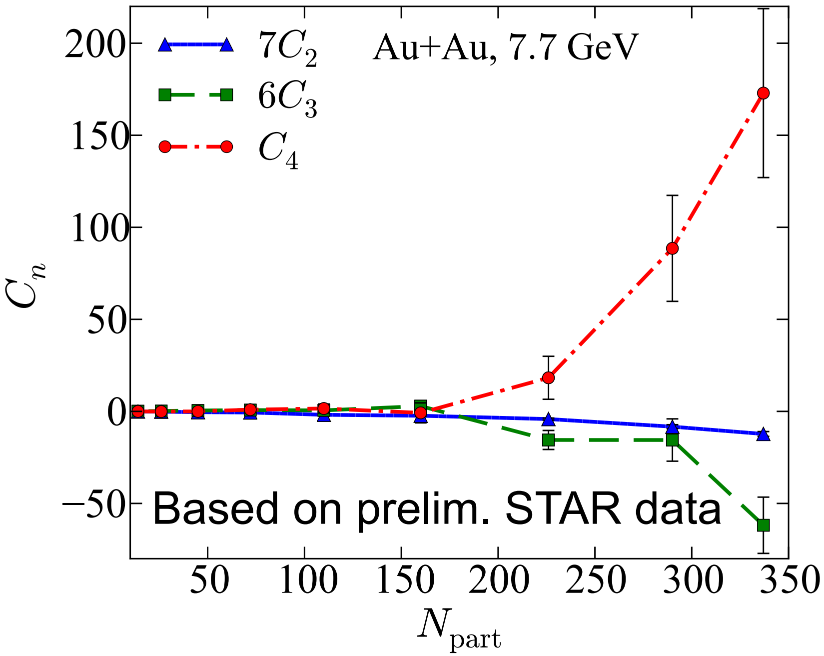
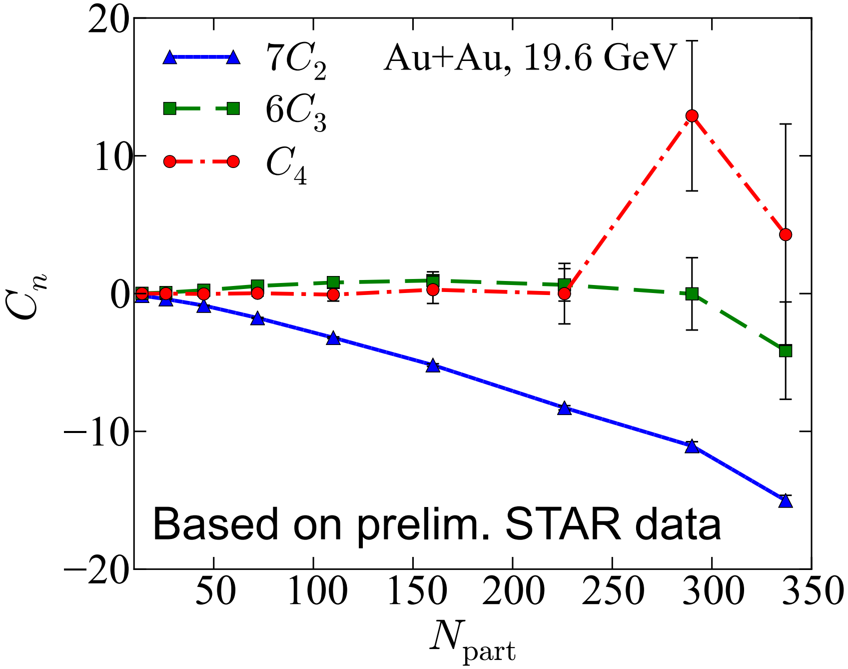
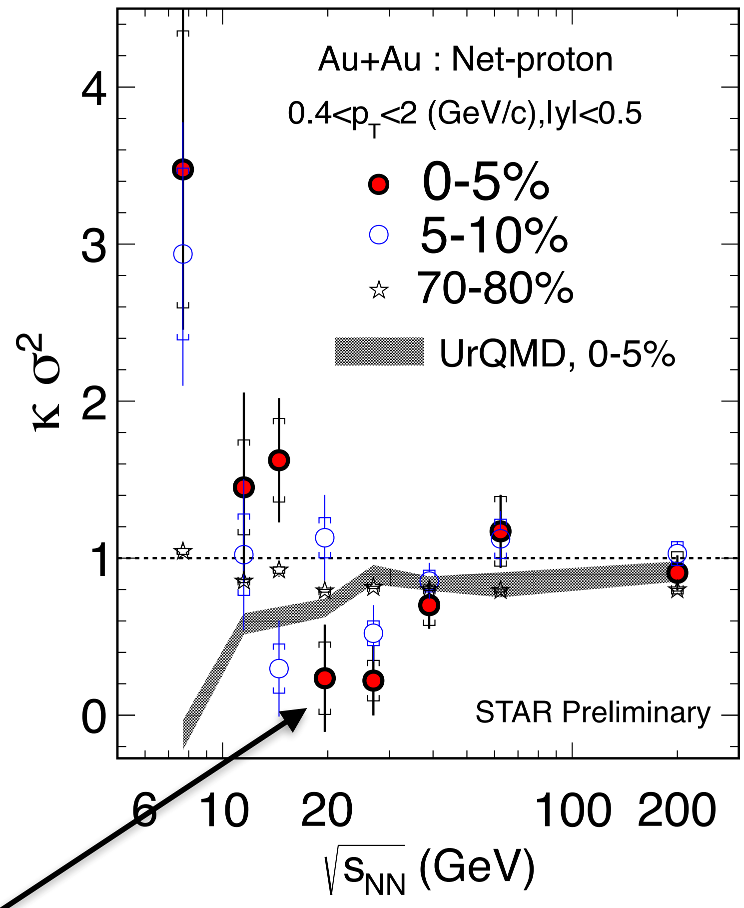
J. Stroth, INT, October 2016

Correlations







Dip at 19.6 GeV from NEGATIVE C_2 !

Reduced correlation function

Reduced correlation function

$$c_k = \frac{\int \rho_1(y_1) \cdots \rho_1(y_k)\, c_k(y_1, ..., y_k)\, dy_1 \cdots dy_k}{\int \rho_1(y_1) \cdots \rho_1(y_k)\, dy_1 \cdots dy_k} \qquad C_k = \langle N \rangle^k c_k$$

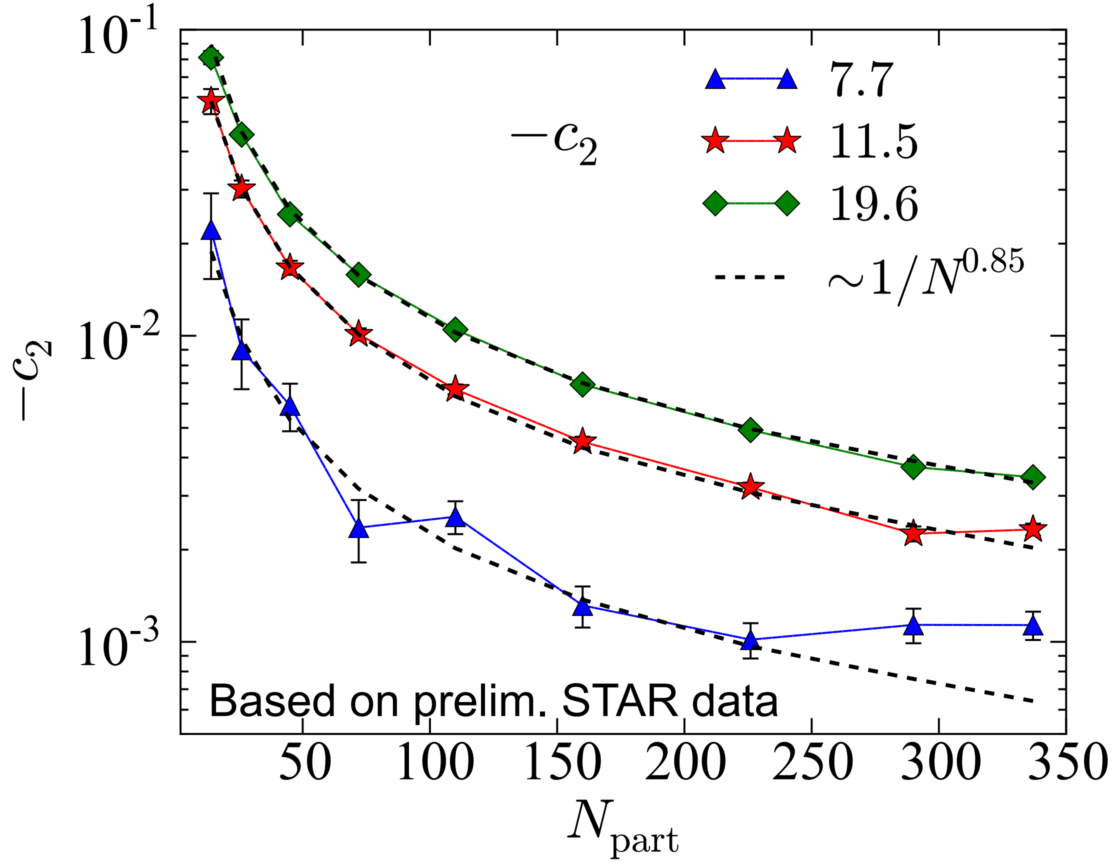
Independent sources such as resonances, cluster, p+p:

$$c_k \sim \frac{\langle N_s \rangle}{\langle N \rangle^k} \sim \frac{1}{\langle N \rangle^{k-1}}$$

For example two particle correlations:

$$c_2 \sim \frac{\text{Number of sources}}{\text{Number of all pairs}} = \frac{\text{Number of correlated pairs}}{\text{Number of all pairs}} = \frac{1}{\langle N \rangle}$$

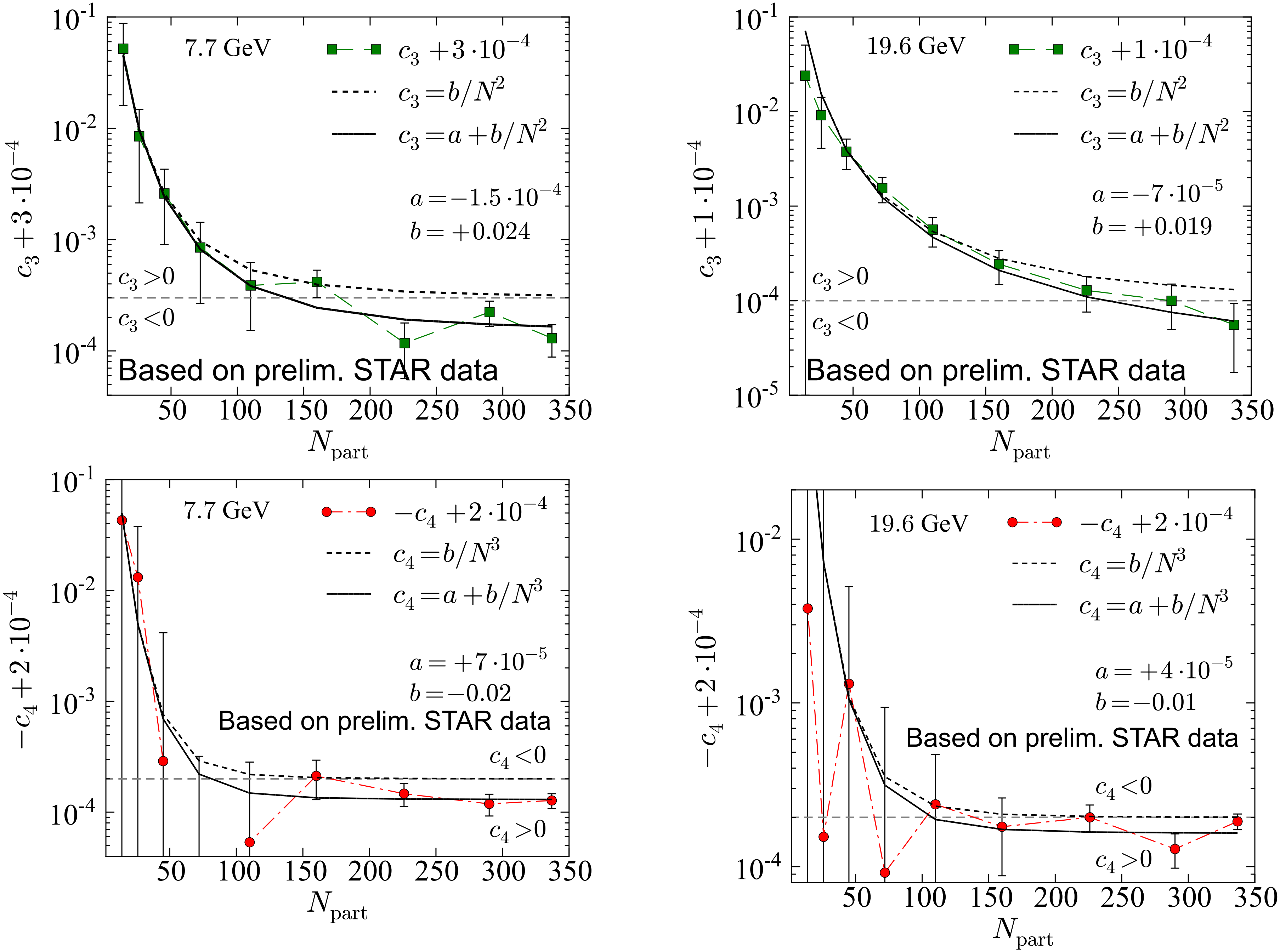
Centrality dependence



Centrality dependence

C_3

C_4



7.7 GeV — 19.6 GeV

Rapidity dependence

$$C_k(\Delta Y) = \int_{\Delta Y} dy_1 \ldots dy_k \rho_1(y_1) \ldots \rho_1(y_k) c_k(y_1, \ldots, y_k)$$

Assume: $\rho_1(y) \simeq const.$

short range correlations:

$$c_k(y_1, \ldots, y_k) \sim \delta(y_1 - y_2) \ldots \delta(y_{n-1} - y_k)$$

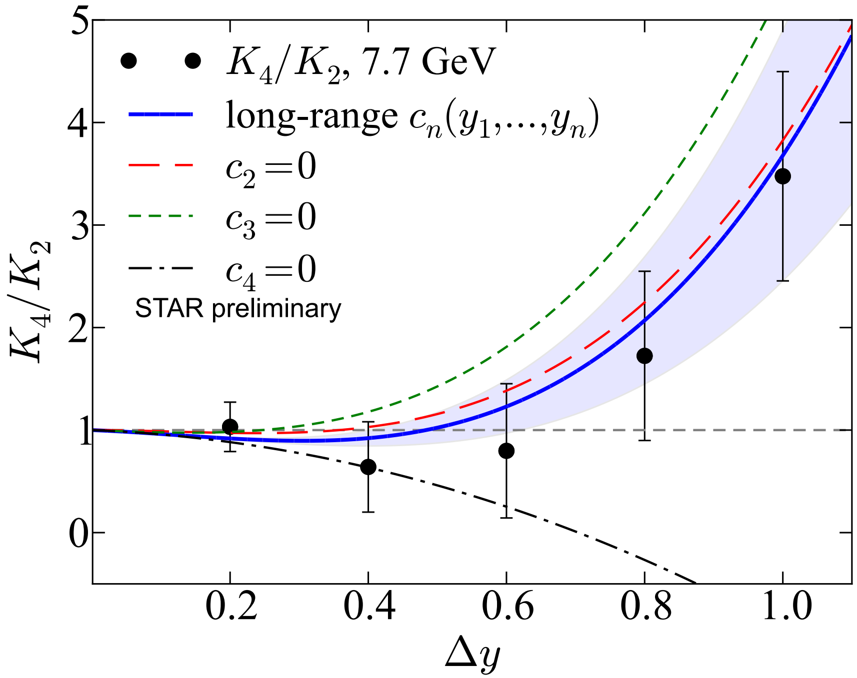
$$C_k(\Delta Y) \sim \Delta Y \rightarrow K_k \sim \Delta Y$$

Long range correlations:

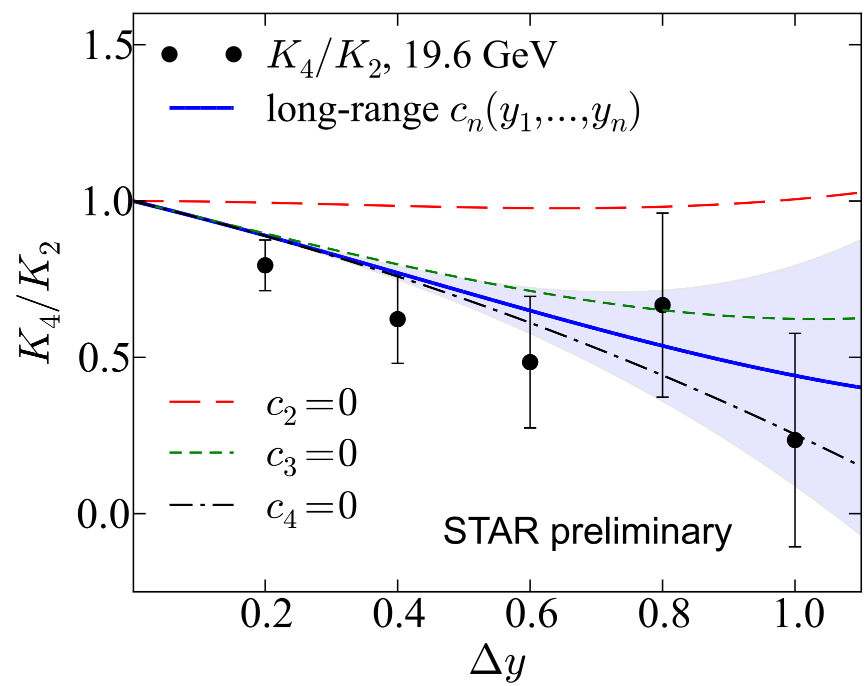
$$c_k(y_1, \ldots, y_k) = const.$$

$$C_k(\Delta Y) \sim (\Delta Y)^k$$

Preliminary Star data are consistent with long range rapidity correlations

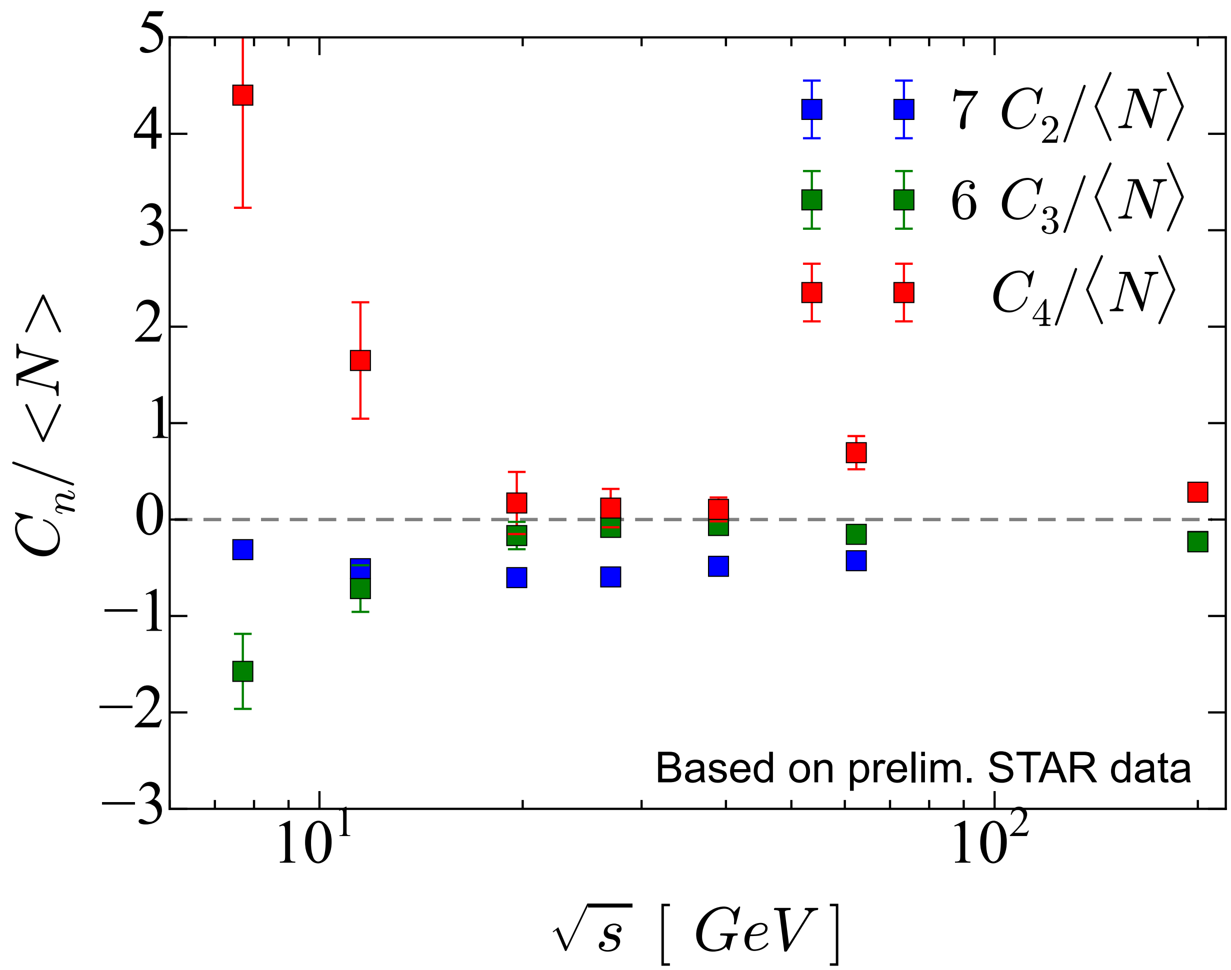


7.7 GeV
central



19.6 GeV
central

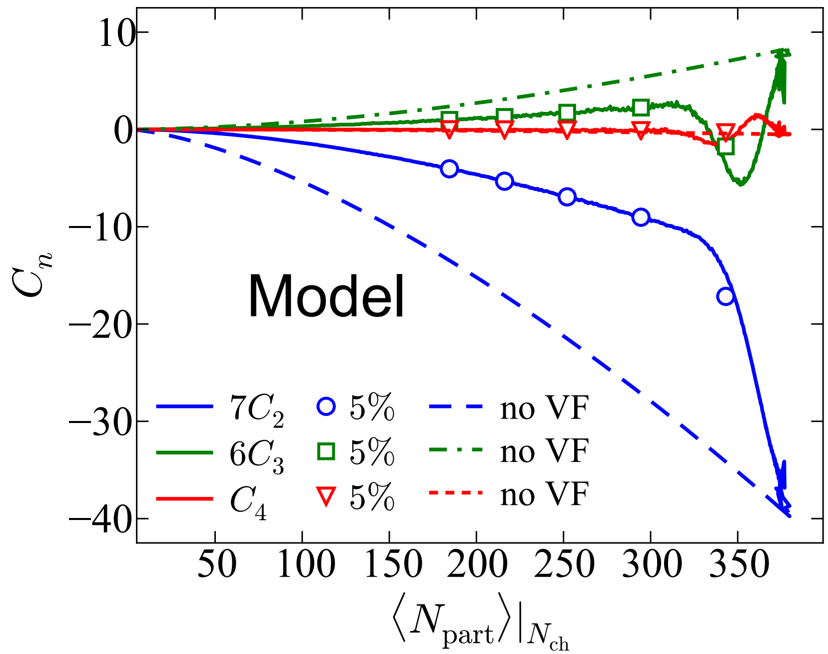
Energy dependence

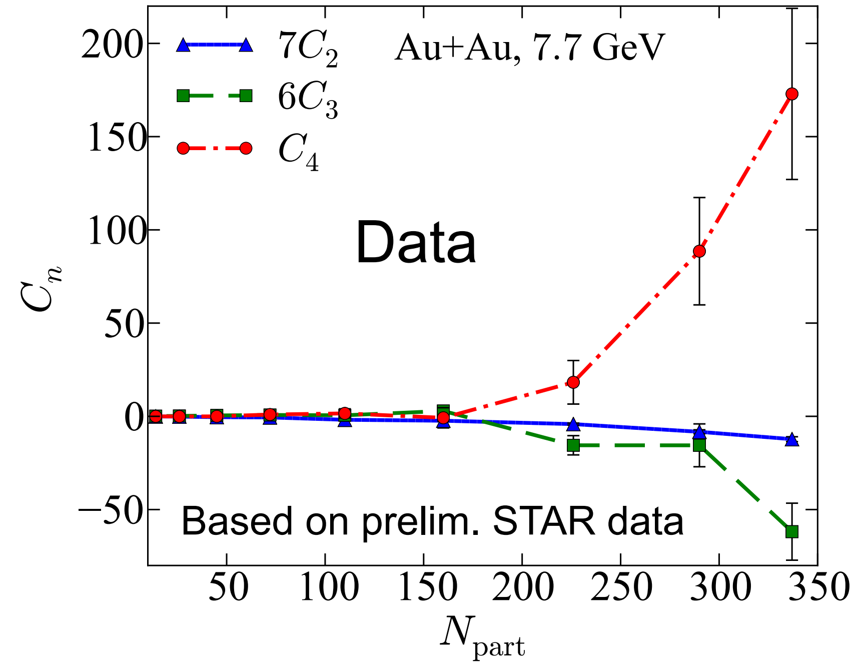


Note: anti-protons are non- negligible above 19.6 GeV

Can we understand these correlations?

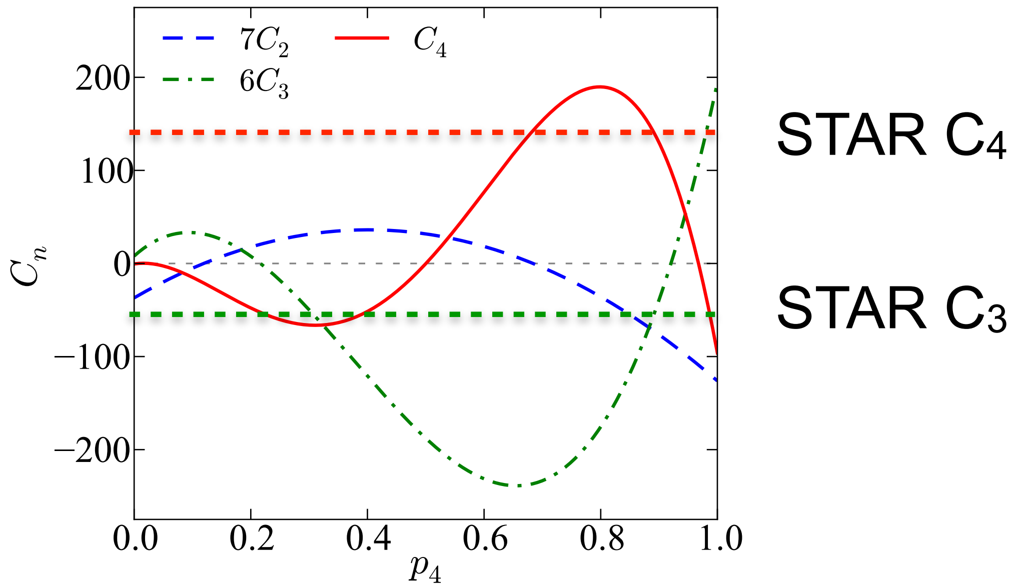
- Two particle correlations can be understood by simple Glauber model + Baryon number conservation
- No way to get even close to the data for four particle correlations!





Can we understand these correlations?

- Three and four particle correlations require lots of “fantasy”…
- For example, if about 40% of the nucleons come in 8-nucleon clusters one can get near the data…



Plenty of room for creative ideas!

Summary

- Fluctuations sensitive to phase structure:
  - measure “derivatives” of EOS
- Measurements are difficult
- Cumulants contain information about correlations
- Preliminary STAR data:
  - Significant four particle correlations at 7.7 and 11.5 GeV
  - Dip in K_4/K_2 at 19.6 GeV is due to negative two-particle correlations
  - Centrality dependence (at 7.7 GeV) indicates independent sources for $N_{part} < 150$ and “collective” correlations for $N_{part} > 200$.
  - At about the same centrality three- and four particle correlations change sign!
    - New dynamics?

Summary

- Preliminary STAR data continued:
  - For central 7.7 and 11.5 GeV two and three particle correlations are negative and four particle are positive.
    - This would rule out a large area around the critical point
- The STAR data are still preliminary!
- Other more mundane effects may contribute
  - Fluctuations of system size (N_{part})
    - May explain 2-particle correlations
    - Fail to reproduce the magnitude of 3- and 4- particle correlations
- Understanding 3- and 4 particle correlations requires "desperate measures"!

Thank You