Physics at high baryon density

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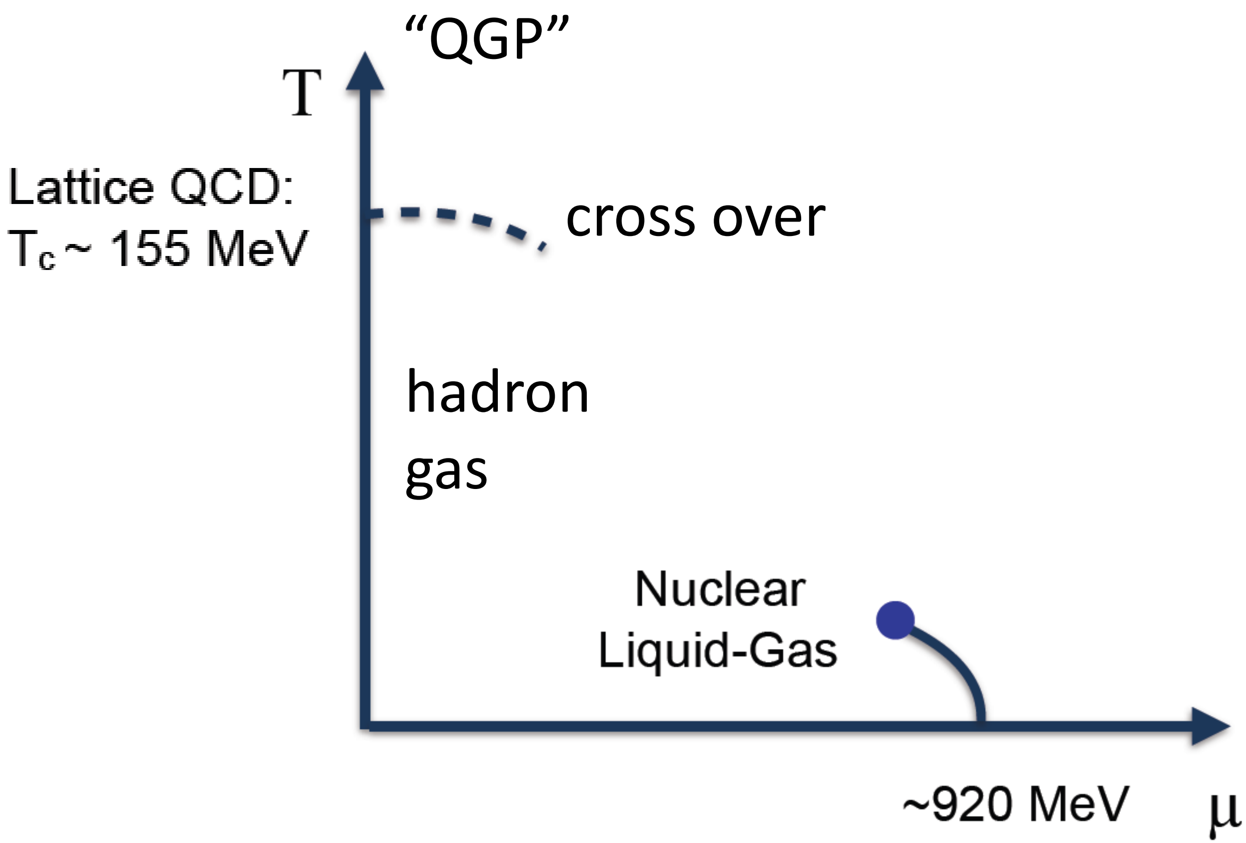
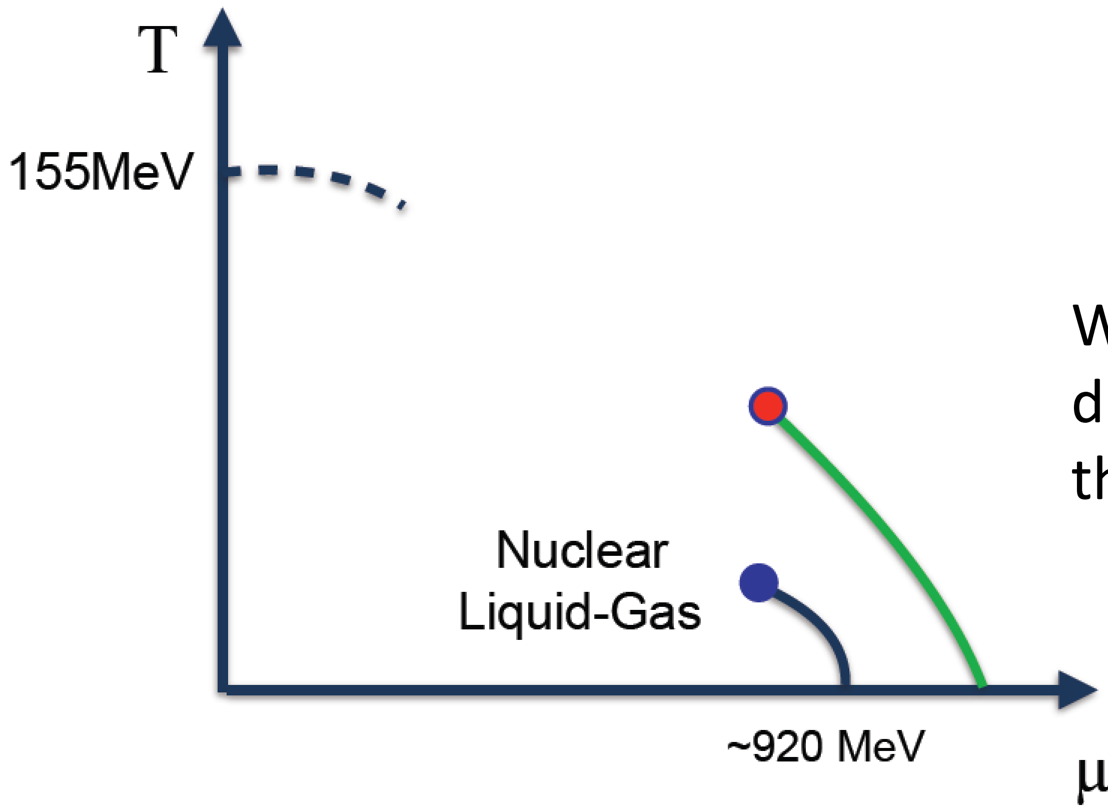
What we really know about the QCD phase diagram



The rest is everybody's guess.

Usual expectation based on various effective models



What **exactly** distinguishes the two phases?

Are these models good?

Usually (hopefully) Nature is more interesting than our guesses

Critical point: everybody's guess

M. Stephanov, hep-lat/0701002

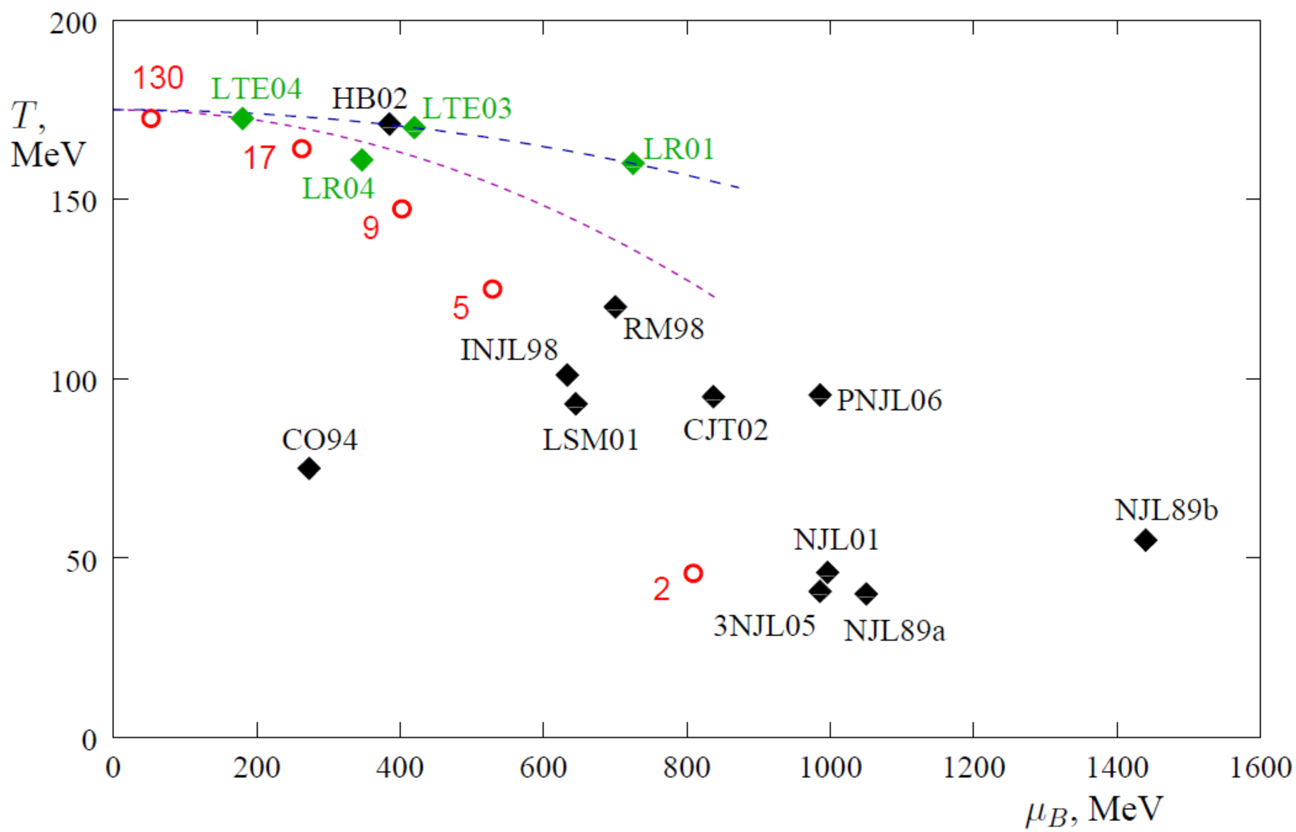


Figure 4: Comparison of predictions for the location of the QCD critical point on the phase diagram. Black points are model predictions: NJLa89, NJLb89 – [12], CO94 – [13, 14], INJL98 – [15], RM98 – [16], LSM01, NJL01 – [17], HB02 – [18], CJT02 – [19], 3NJL05 – [20], PNJL06 – [21]. Green points are lattice predictions: LR01, LR04 – [22], LTE03 – [23], LTE04 – [24]. The two dashed lines are parabolas with slopes corresponding to lattice predictions of the slope $dT/d\mu_B^2$ of the transition line at $\mu_B = 0$ [23, 25]. The red circles are locations of the freezeout points for heavy ion collisions at corresponding center of mass energies per nucleon (indicated by labels in GeV) – Section 5.

It is hard to expect any real theoretical progress (e.g., LQCD) in the near(est) future.

On the experimental side all we can do is to measure various fluctuation observables and hope to see some nontrivial energy or/and system-size dependence

see, e.g.,
Stephanov, Rajagopal, Shuryak, PRL (1998)
Stephanov, PRL (2009)
Skokov, Friman, Redlich, PRC (2011)

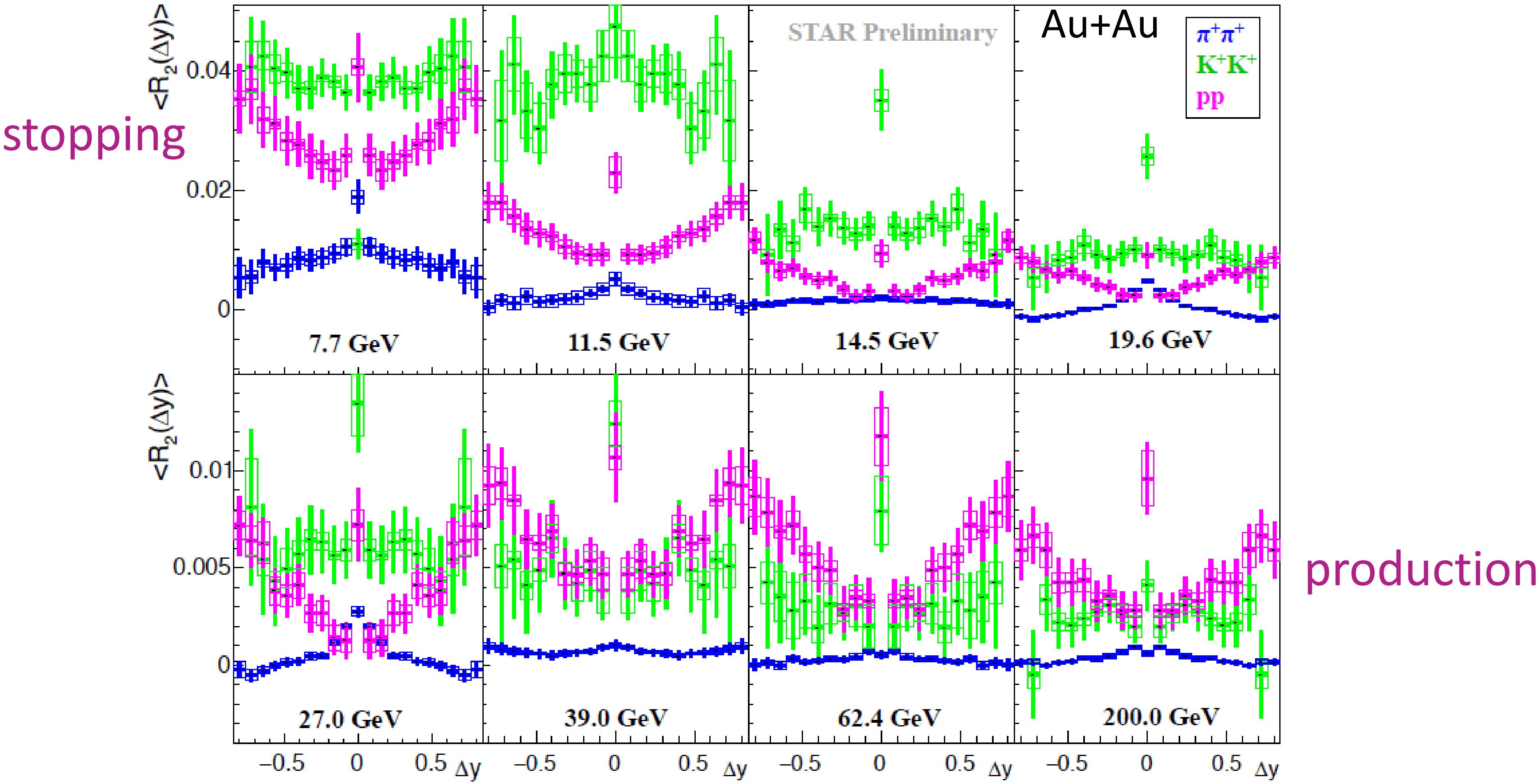
There are some intriguing results:

STAR, HADES	NA 49
Higher order net-proton cumulants	Intermittency in the transverse momentum phase space
Proton v_1 (STAR)	Strongly intensive variables

See, e.g., Eur. Phys. J. C75 (2015) 12, 587 (1208.5292)

We do not understand basic baryon physics.

S. Jowzaee,
QM2017



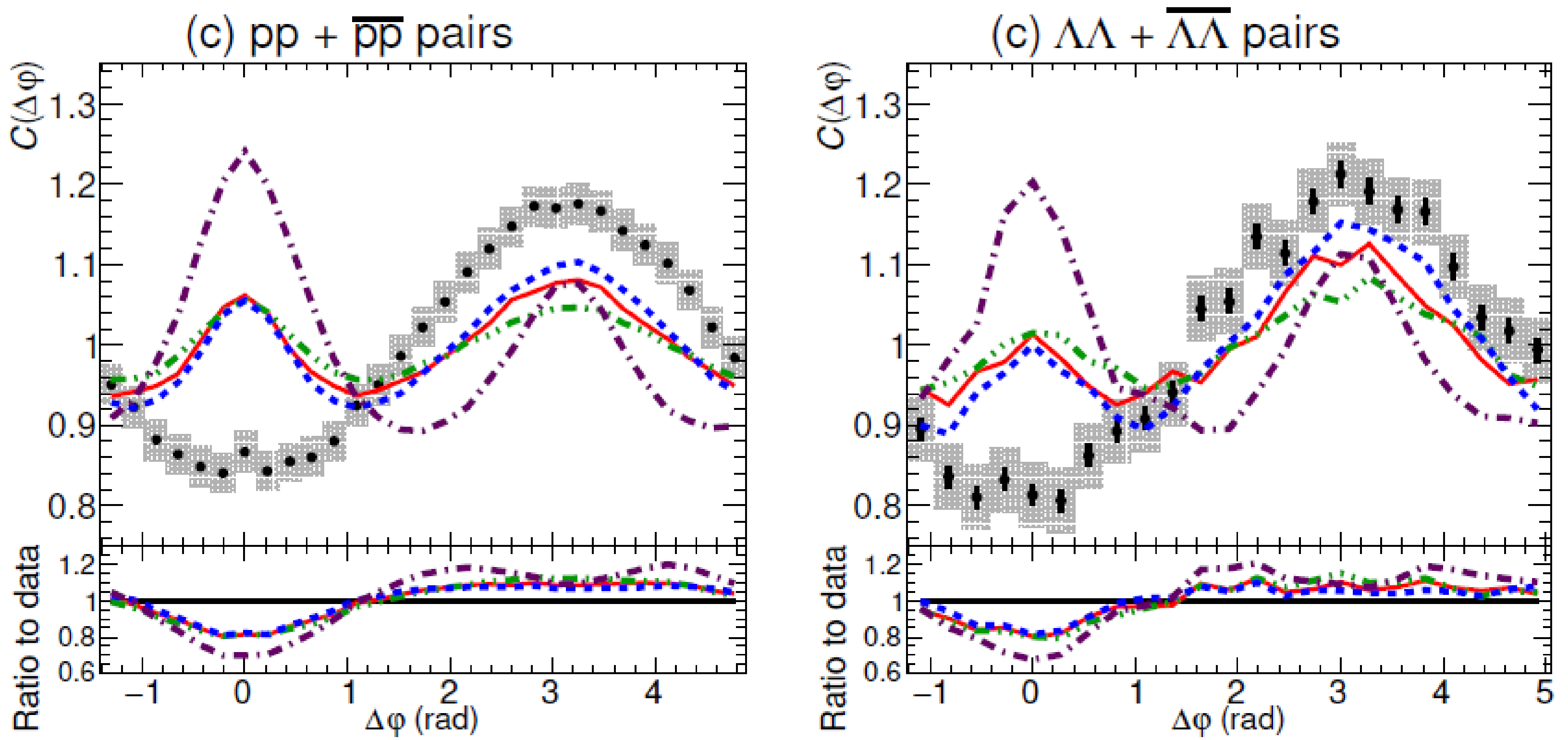
$$R_2(y_1, y_2) = -1 + \frac{\langle \rho_2(y_1, y_2) \rangle}{\langle \rho_1(y_1) \rangle \langle \rho_1(y_2) \rangle}$$

← Same event pair distributions

← Mixed event

and ALICE

ALICE, 1612.08975



- ALICE pp $\sqrt{s}$ = 7 TeV, $|\Delta\eta| < 1.3$
- PYTHIA6 Perugia-0
- PYTHIA6 Perugia-2011
- PYTHIA8 Monash
- PHOJET

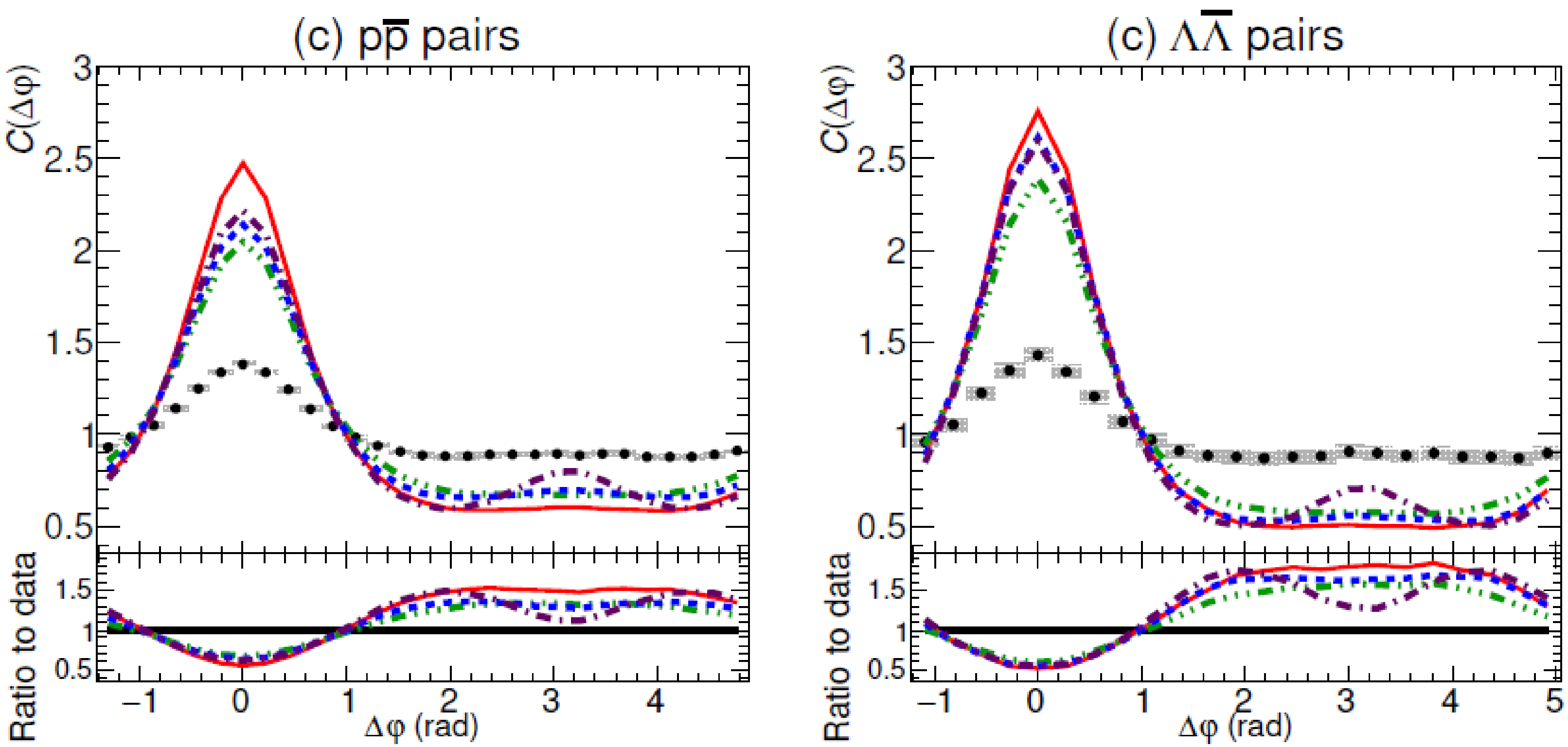
Baryons do not want to be close to each other in rapidity and azimuthal angle

And we want to create high baryon density

First seen by TPC/Two Gamma Collaboration in e+e- annihilation at 29-GeV, PRL 57, 3140 (1986).

ALICE, 1612.08975

No surprise for baryon-antibaryon correlation



Proton stopping – is it obvious that we produce high baryon density?

At low energy protons are not produced. They are transferred from incoming nucleus.

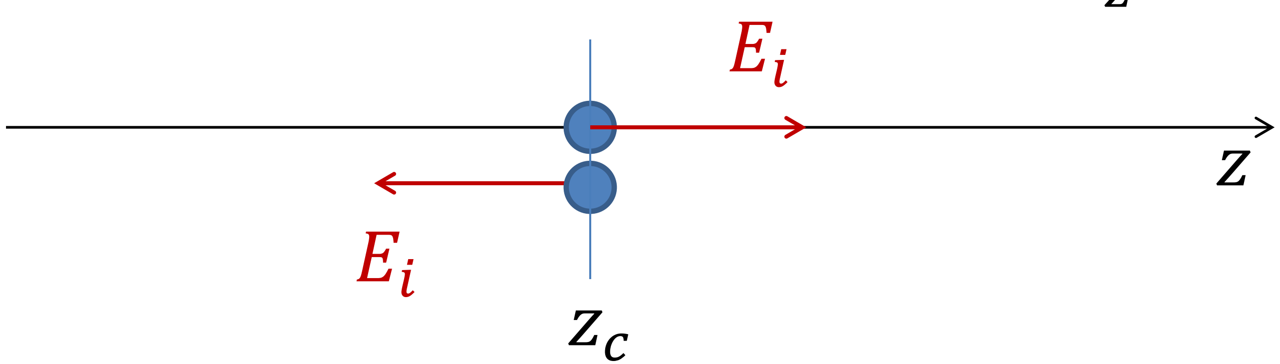
There is no infinite deceleration. It take some time and length to slow down or stop a proton. Thus we expect (?) the stopped protons to be away from $z = 0$.

$$E_z = E_i - \sigma(z - z_c)$$

E_i – initial energy; z_c – collision point; E_z – energy at a point z

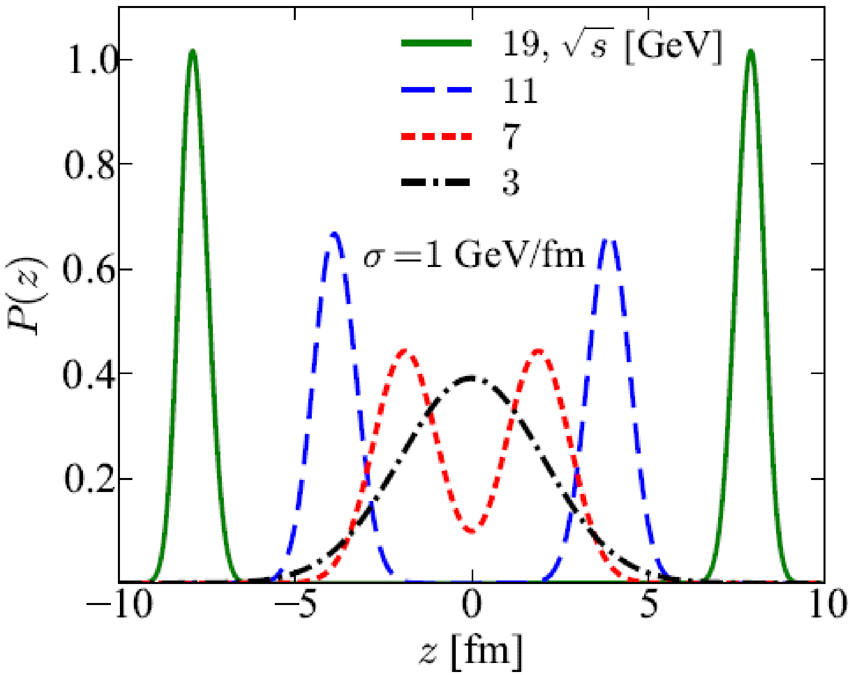
σ – energy loss per unit length

$$E_z \to M_t \cosh(y)$$

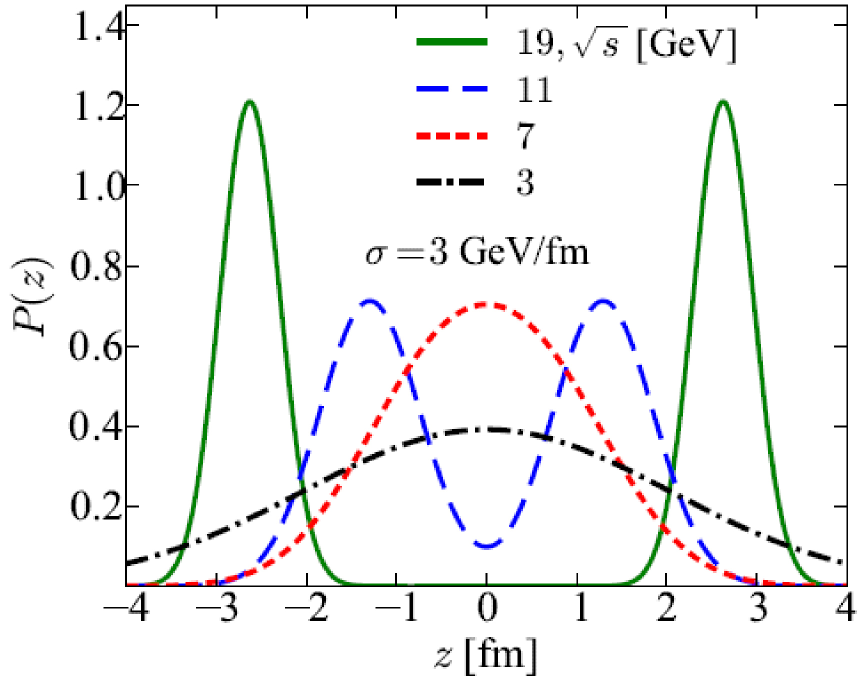


Now we need to average over the collision points z_c in A+A, and over the measured rapidity bin.

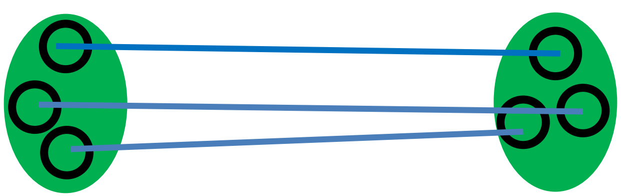
Here $|y| < 1$, $R_A = 6.5$ fm, $P_t = 1$ GeV. $M_t^2 = M^2 + P_t^2$



wounded nucleon model



wounded quark model



A.Bialas, AB, V.Koch, 1608.07041

One would prefer to see a more uniform distribution in z.

We do not take into account resonances.

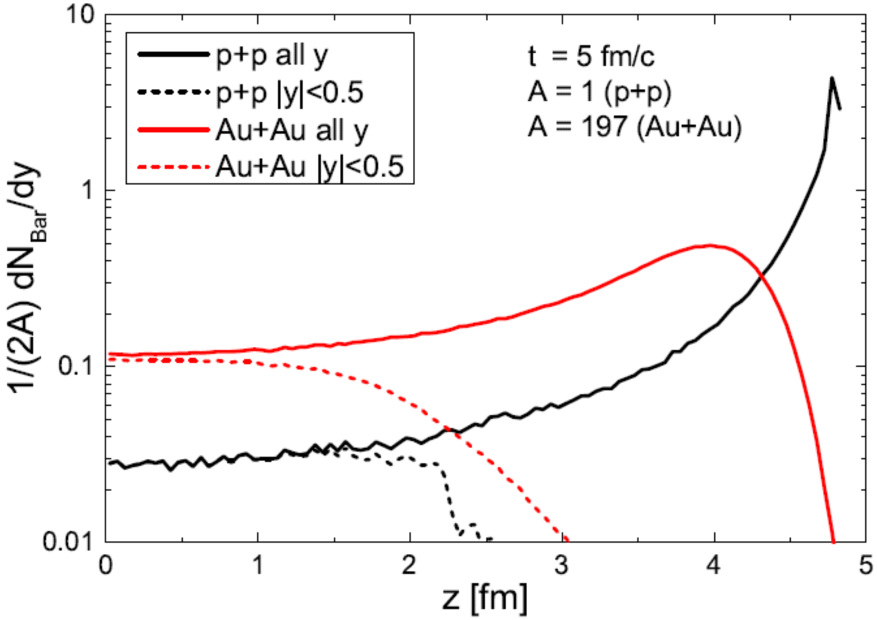
Real MC calculations are warranted but:

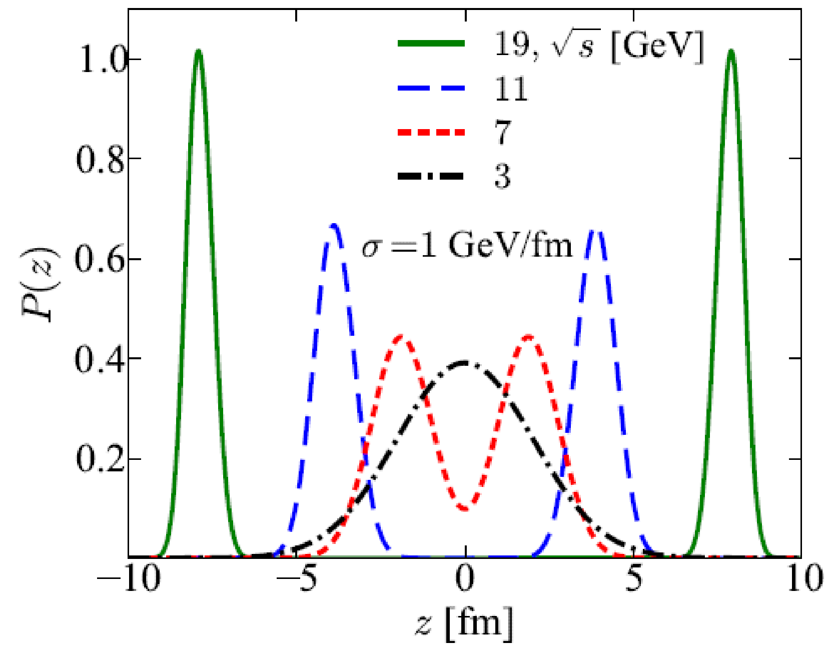
Y.Nara, H.Niemi, J.Steinheimer, H.Stoecker, 1611.08023

Also it has been pointed out that the usual description of baryon stopping in string models in a transport model assumes essentially an instant deceleration of the leading baryons because strings are immediately decay into hadrons with a formation time. In [59] it was argued that a constant deceleration would lead to a very different initial density profile in coordinate space, i.e. a smaller density at mid-rapidity, which may transform into a different time evolution of the particle flow.

UrQMD for example

J. Steinheimer, INT-16-3



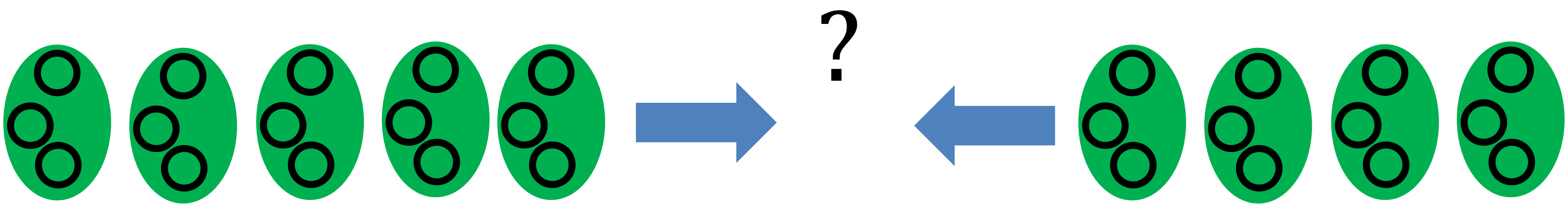


hopefully this is not right

Anyway, the question remains: what is the <u>realistic</u> z distribution of stopped protons? We need many baryons with similar y <u>and</u> z

How to properly model baryon stopping?

Do baryons stop independently or maybe we have some multi-baryon correlations?



Important questions if we want to understand proton cumulants as measured by STAR and HADES.

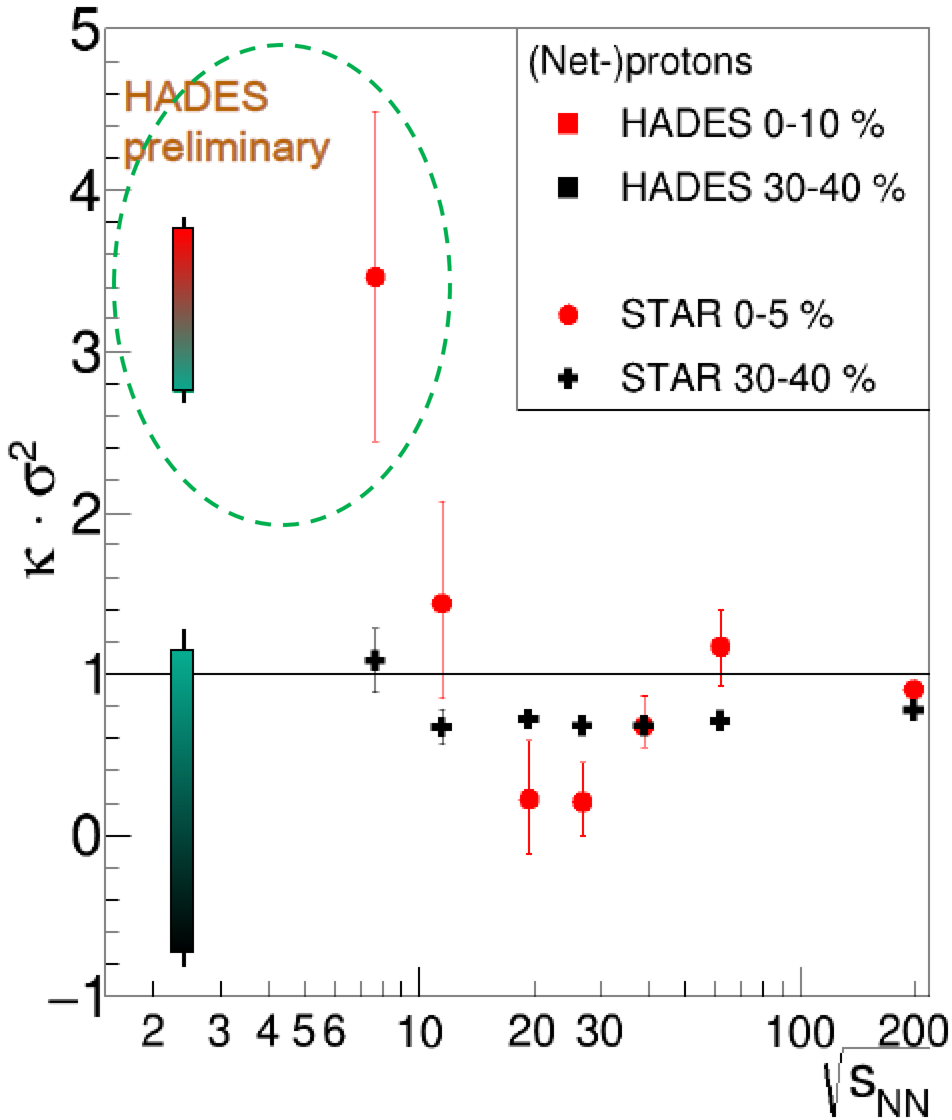
STAR and possibly HADES see rather exciting multi-proton correlations at lower energies.

Proton cumulants

X. Luo [STAR], 1503.02558
R. Holzmann, QM17

my notation

$$K_4/K_2$$



The signal at low (< 8 GeV) energy is surprisingly large

Cumulants are not the best choice

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

N – number of protons

we neglect anti-protons, good at low energies

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

$$K_4 = \langle (N - \langle N \rangle)^4 \rangle - 3\langle (N - \langle N \rangle)^2 \rangle^2$$

$$K_n = \langle N \rangle + physics[2, \ldots, n]$$

$physics$ = two-, three-, *n*-particle correlation functions

for Poisson $K_n = \langle N \rangle$, $(physics = 0)$

We have

$$K_2 = \langle N \rangle + \boldsymbol{C_2}$$

$$K_3 = \langle N \rangle + 3\boldsymbol{C_2} + \boldsymbol{C_3}$$

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

cumulants mix
correlation functions
of different orders

For example:

$$\rho_2(y_1, y_2) = \rho(y_1)\rho(y_2) + \boldsymbol{C_2}(y_1, y_2)$$

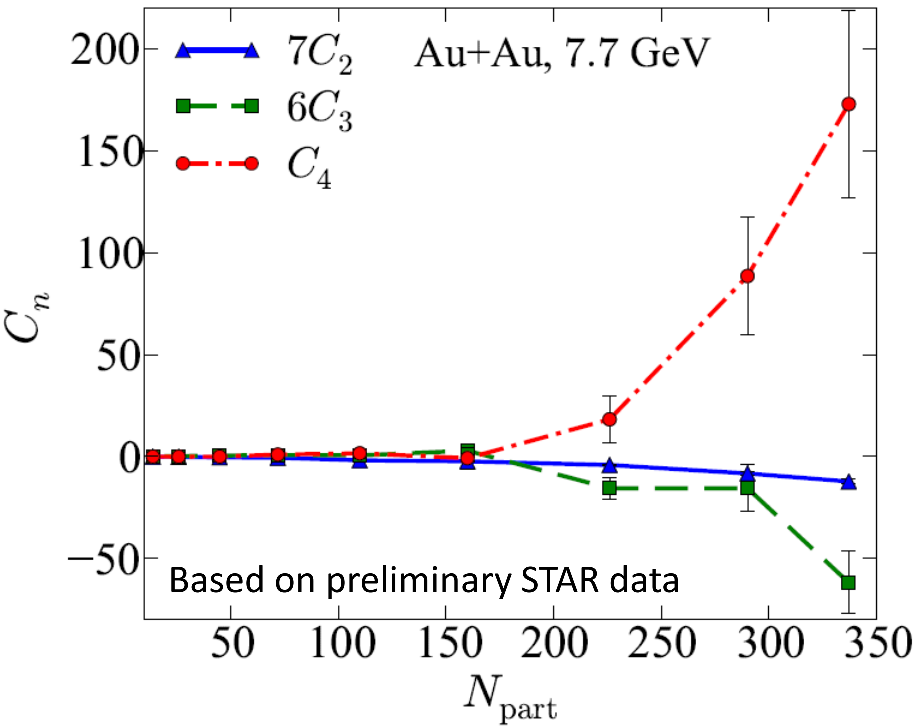
$$\boldsymbol{C_2} = \int \boldsymbol{C_2}(y_1, y_2)\, dy_1 dy_2 \qquad \boldsymbol{C_2} = \langle N \rangle^2 \boldsymbol{c_2}$$

we should
measure this

See, e.g.,
B. Ling, M. Stephanov, PRC 93 (2016) no.3, 034915
AB, V. Koch, N. Strodthoff , 1607.07375

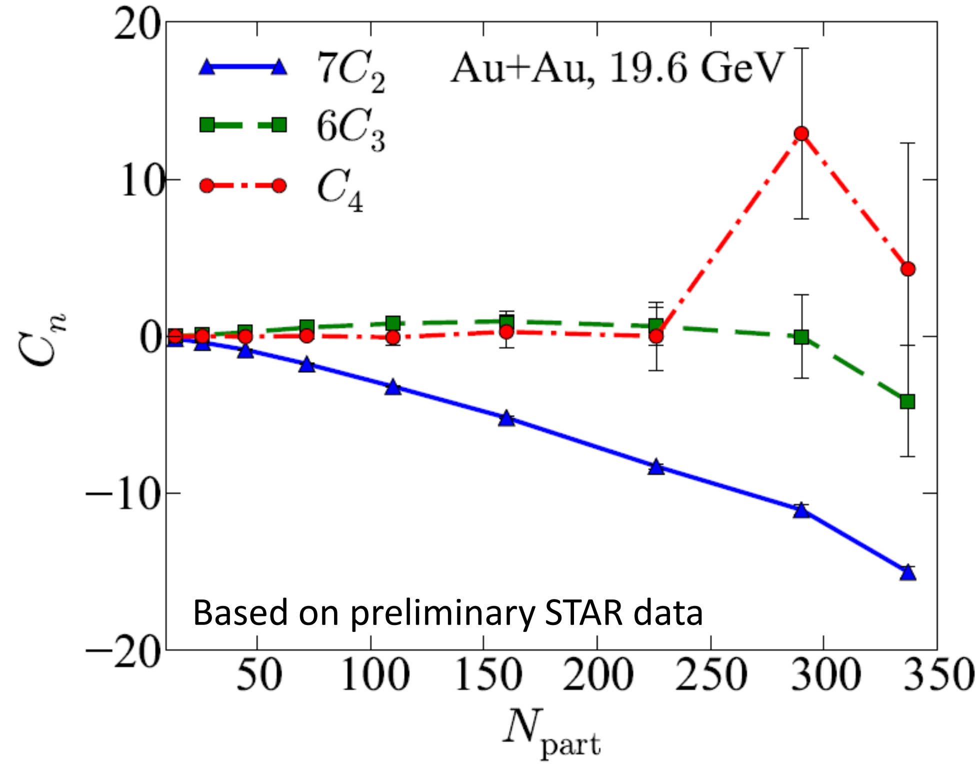
Using preliminary STAR data we obtain C_n

central signal at 7.7 GeV is driven by large 4-particle correlations



$$C_4(7.7)\ \sim \mathbf{170}$$

central signal at 19.6 GeV is driven by 2-particle correlations

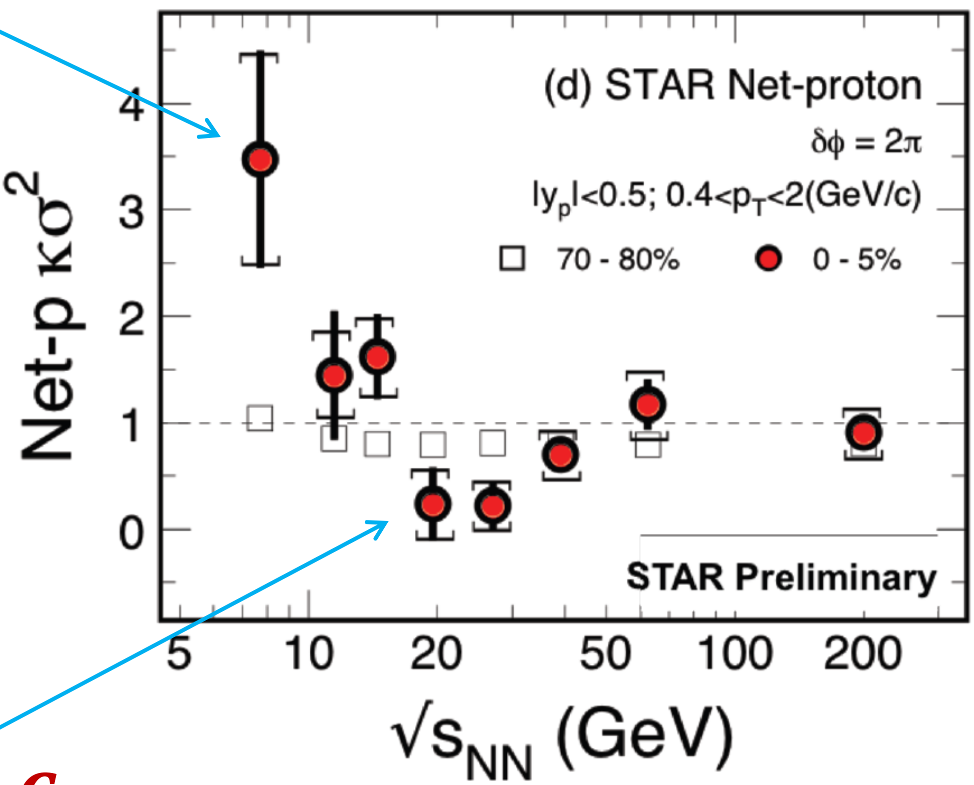


$\boldsymbol{C_4}$ and $\boldsymbol{6C_3}$ cancelation in most central coll.

AB, V. Koch, N. Strodthoff, 1607.07375

here we see $\boldsymbol{C_4}$

X.Luo, N.Xu, 1701.02105



and here $\boldsymbol{C_2}$

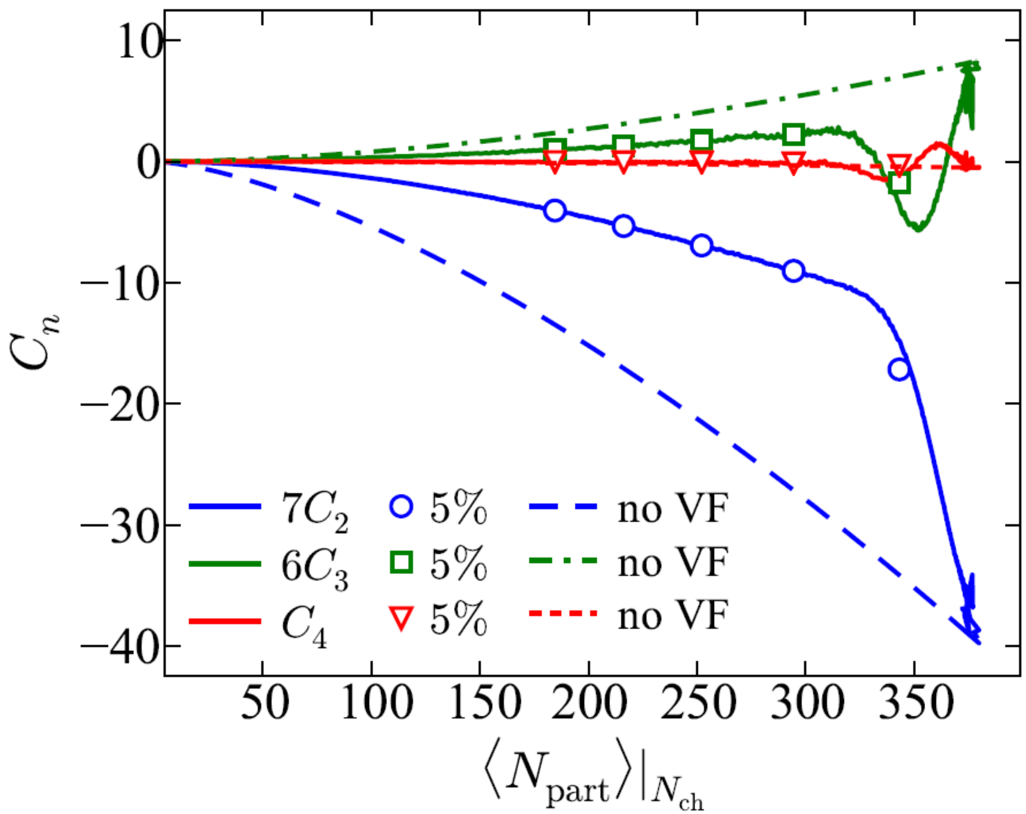
e.g., baryon conservation

what about HADES ?

Minimal model (MM) at low energies

- independent baryon stopping (baryon conservation by construction)
- N_{part} fluctuations (volume fluctuation - VF)

Au+Au, $\sqrt{s}$ = 7.7 GeV



STAR

$C_4 \sim 170$

$6C_3 \sim -60$

$7C_2 \sim -15$

we follow the STAR way (centrality etc.) as closely as possible

AB, V. Koch, V. Skokov, 1612.05128

See also: P. Braun-Munzinger, A. Rustamov, J. Stachel, NPA 960 (2017) 114

Let's put the STAR numbers in perspective.

Suppose that we have clusters (distributed according to Poisson) decaying always to 4 protons

$$\boldsymbol{C_k} = \langle N_{\mathrm{cl}} \rangle \cdot 4!/(4-k)!$$

mean number of clusters

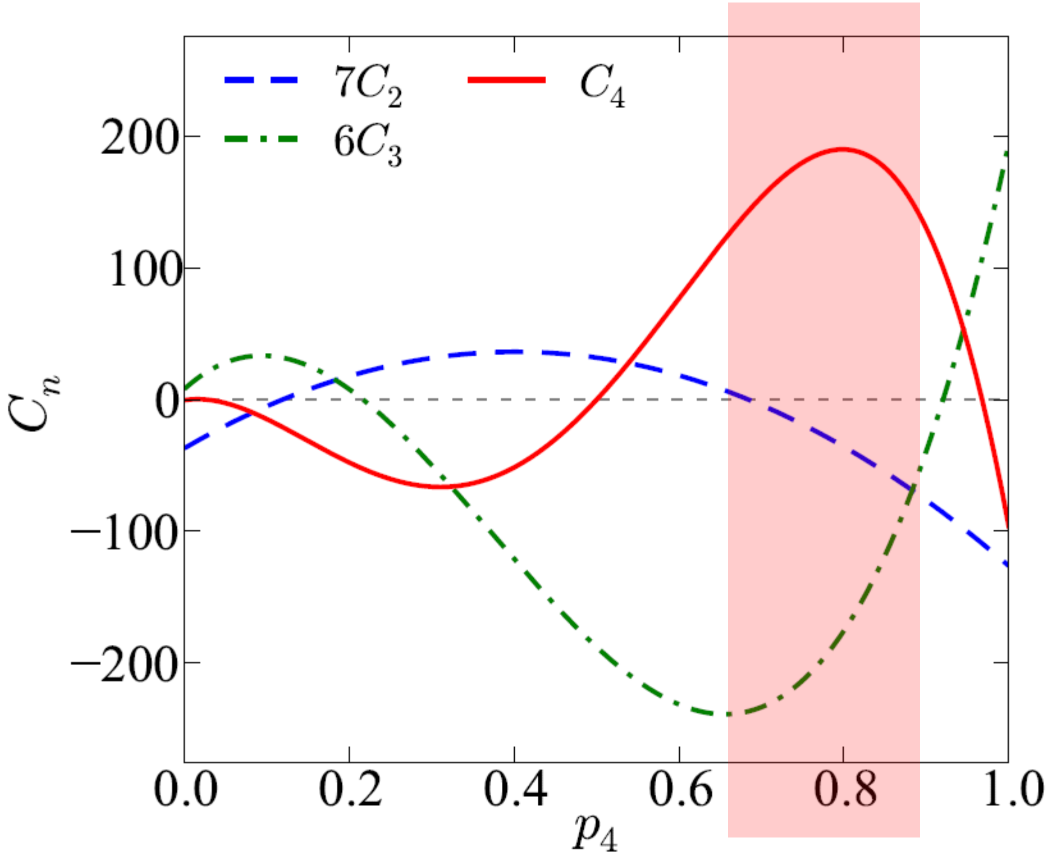
$$\boldsymbol{C_4} = \langle N_{\mathrm{cl}} \rangle \cdot 24$$

To obtain $C_4 \approx 170$ we need $\langle N_{\mathrm{cl}} \rangle \sim 7,$ it means 28 protons.
STAR sees on average 40 protons in central collisions.

In this model $C_2 > 0$ and $C_3 > 0$ contrary to the STAR data

Toy model:

- 16 protons stop in quartets with probability p_4
- remaining protons stop independently with some small probability $p_1 \sim 0.1$



qualitatively consistent with STAR

STAR

$C_4 \sim 170$

$6C_3 \sim -60$

$7C_2 \sim -15$

AB, V. Koch, V. Skokov, 1612.05128

Take-home message:

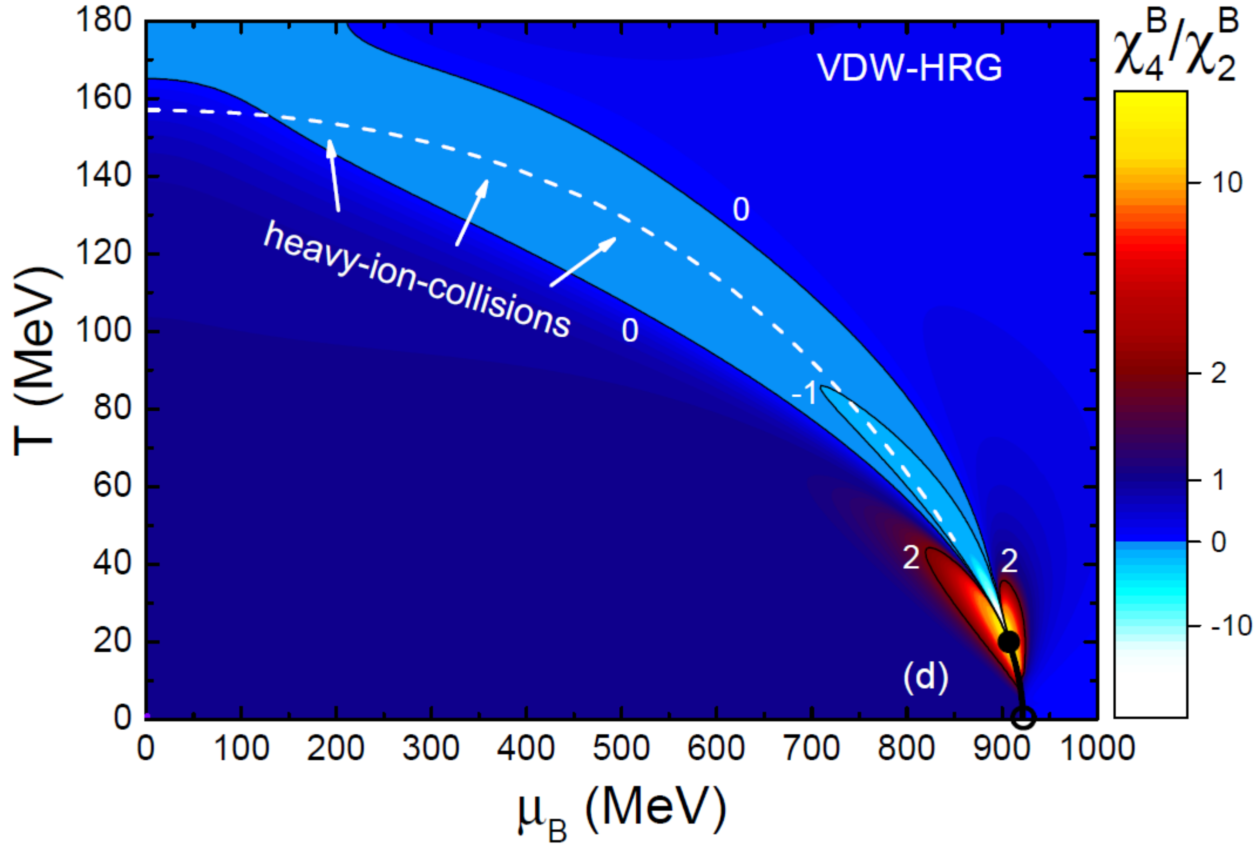
C_4 (four-proton correlation function) observed by STAR (and likely by HADES) is larger by almost **three orders of magnitude** than the minimal model.

To explain C_4 we need a strong source of multi-proton correlations.
Proton clusters? Phase transition?

Similar story with 3-proton correlation function.

One needs to be careful with interpretations, for example the liquid-gas phase transition shines across a broad range of T and μ

HRG with attractive and repulsive Van der Waals interactions between (anti)baryons



V. Vovchenko, M.I. Gorenstein, H. Stoecker, 1609.03975

Conclusions

We do not know much about the QCD phase diagram.
Real theoretical progress is not expected soon.

We need to make sure we produce high baryon density.
The configuration space distribution of the final baryons (and other particles) requires careful study.

Multi-proton correlations from stopping, critical point, phase transition?

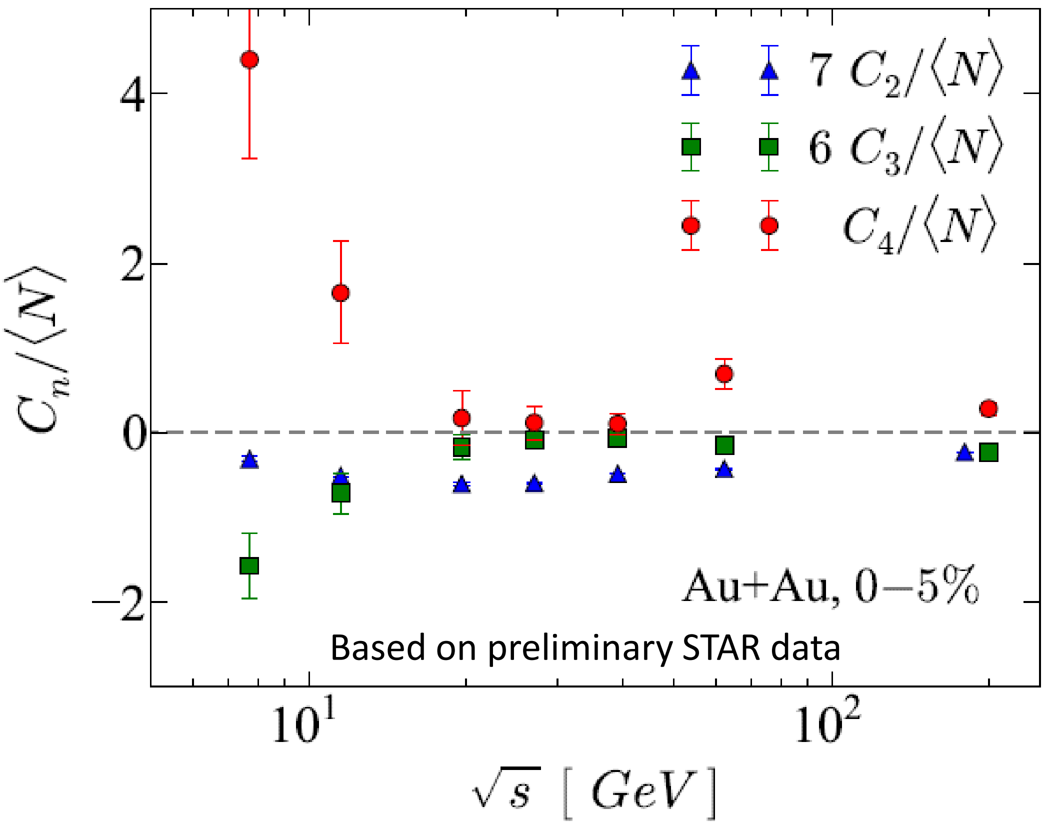
Very large 4-proton correlations at 7.7 GeV in central Au+Au collisions.

See backup: QCD exclusion plots, interesting centrality and rapidity dependence of the proton correlation functions

Backup

Exclusions plots

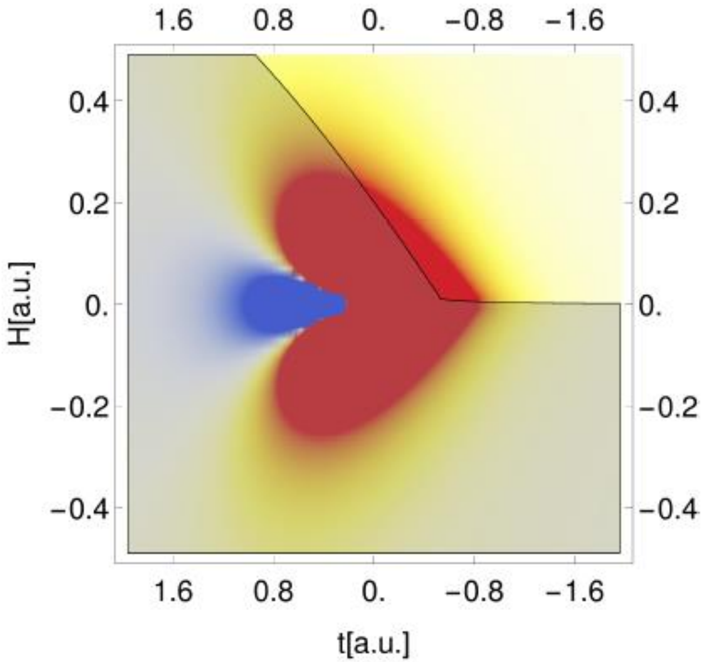
We propose to make the phase-diagram exclusion plots based on the **signs** of the correlation functions.



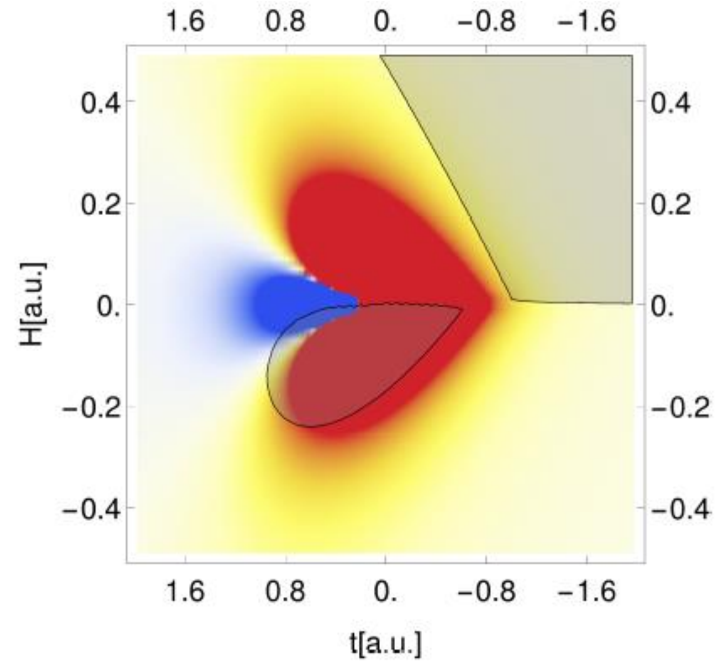
C_4 at 62 GeV !

$$\boldsymbol{C_4 > 0,\ C_3 < 0 \qquad C_2 < 0}$$

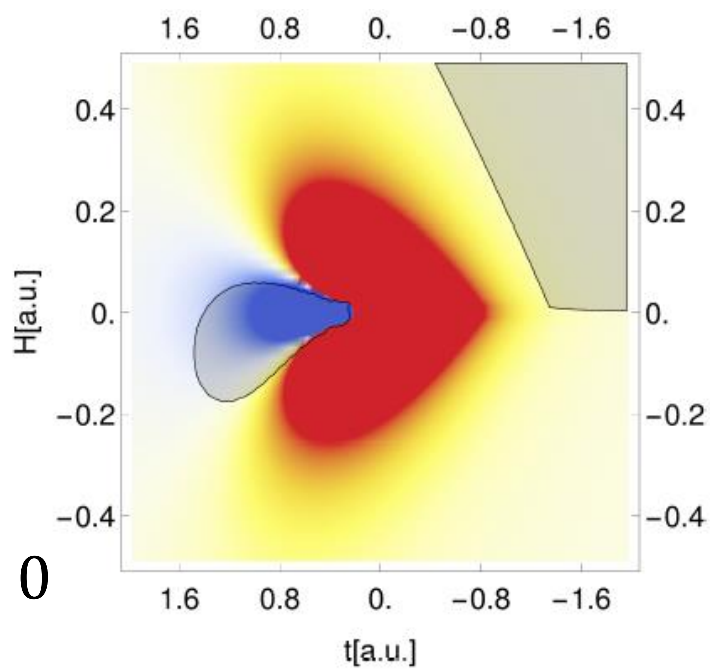
Exclusions plots based on the Ising model



$C_2 < 0$



$C_3 < 0$



$C_4 > 0$

Clearly we need to use more realistic model with various effects included

Observations

$$c_2 = \frac{\int \rho(y_1)\rho(y_2)c_2(y_1,y_2)dy_1dy_2}{\int \rho(y_1)\rho(y_2)dy_1dy_2}$$

$$K_2 = \langle N\rangle + \langle N\rangle^2 c_2$$

$$K_4 = \langle N\rangle + 7\langle N\rangle^2 c_2 + 6\langle N\rangle^3 c_3 + \langle N\rangle^4 c_4$$

Rapidity dependence:

short-range correlation

$$c_2(y_1,y_2) = c_2^0\delta(y_1 - y_2)$$

$$c_2 \sim 1/(\Delta y)$$

$$\boxed{K_n \sim \Delta y}$$

long-range correlation

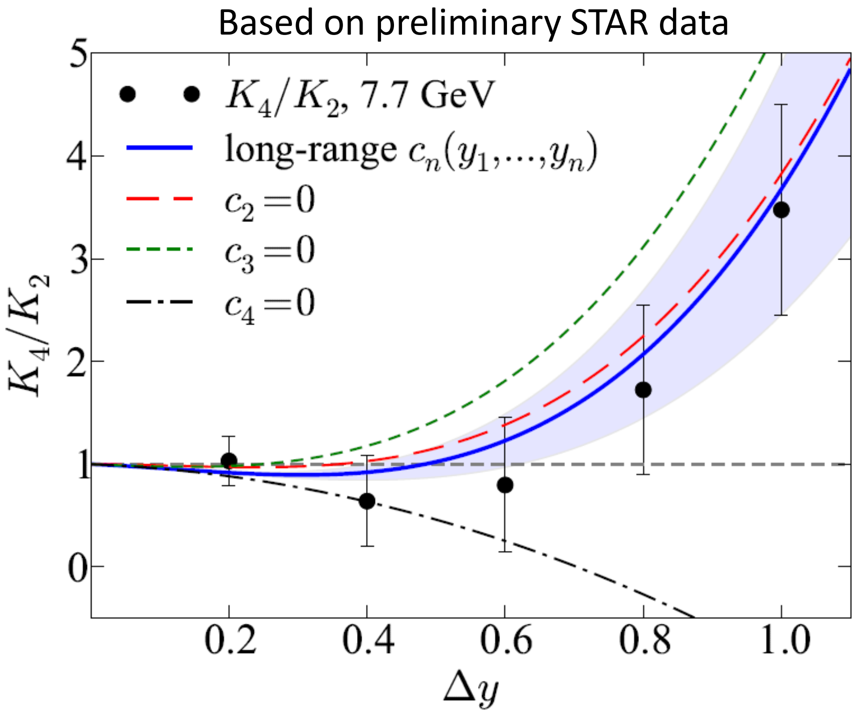
$$c_n(y_1,\dots,y_n) = c_n^0$$

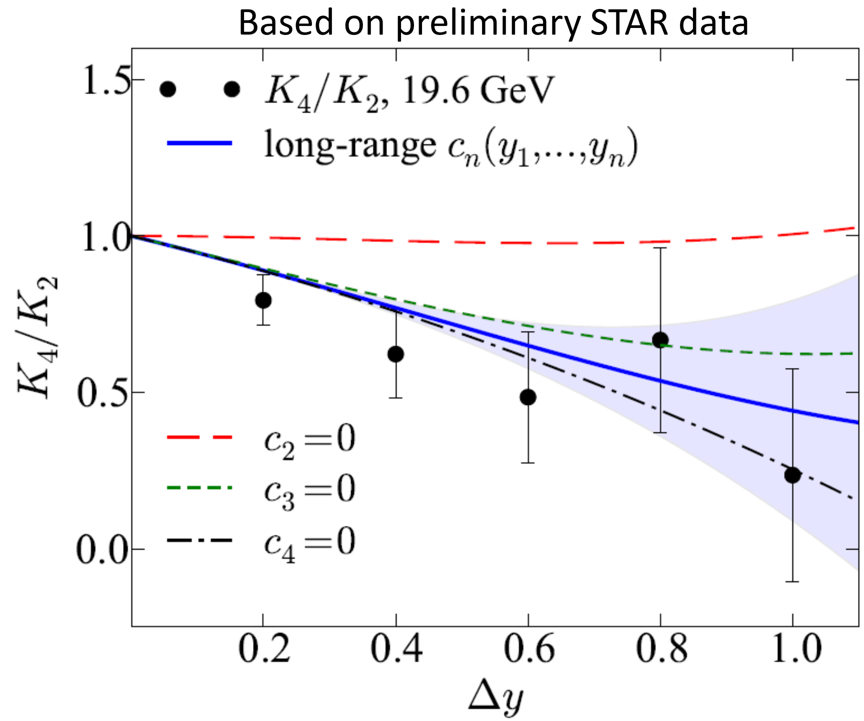
$$c_n = c_n^0$$

$$K_2 = \langle N\rangle + c_2^0\langle N\rangle^2, \qquad \langle N\rangle \sim \Delta y$$

$$\boxed{K_4 = \langle N\rangle + 7c_2^0\langle N\rangle^2 + 6c_3^0\langle N\rangle^3 + c_4^0\langle N\rangle^4}$$

Rapidity dependence consistent with long-range correlations





$|y| < 0.5$ is not particularly large

$$\rho_2(y_1, y_2) = \rho(y_1)\rho(y_2) + \boldsymbol{C_2}(y_1, y_2)$$

correlation function

$$\rho_2(y_1, y_2) = \rho(y_1)\rho(y_2)[1 + \boldsymbol{c_2}(y_1, y_2)]$$

reduced correlation function

$$\langle N(N-1)\rangle = \langle N\rangle^2 + \langle N\rangle^2 \boldsymbol{c_2}$$

$$\boldsymbol{c_2} = \frac{\int \rho(y_1)\rho(y_2)\boldsymbol{c_2}(y_1, y_2)dy_1 dy_2}{\int \rho(y_1)\rho(y_2)dy_1 dy_2}$$

and the second order cumulant

$$K_2 = \langle N\rangle + \underbrace{\langle N\rangle^2 \boldsymbol{c_2}}_{\boldsymbol{C_2}}$$

In the same way

$$\rho_3(y_1, y_2, y_3) = \rho(y_1)\rho(y_2)\rho(y_3)[1 + \boldsymbol{c_2}(y_1, y_2\ ) + \cdots + \boldsymbol{c_3}(y_1, y_2, y_3)]$$

$$F_3 = \langle N(N-1)(N-2)\rangle = \langle N\rangle^3 + 3\langle N\rangle^3 \boldsymbol{c_2} + \langle N\rangle^3 \boldsymbol{c_3}$$

$$\boldsymbol{c_3} = \frac{\int \rho(y_1)\rho(y_2)\rho(y_3)\boldsymbol{c_3}(y_1, y_2, y_3)dy_1dy_2dy_3}{\int \rho(y_1)\rho(y_2)\rho(y_3)dy_1dy_2dy_3}$$

and the third order cumulant

$$K_3 = \langle N\rangle + 3\langle N\rangle^2 \boldsymbol{c_2} + \langle N\rangle^3 \boldsymbol{c_3}$$

$$3\boldsymbol{C_2} \qquad \boldsymbol{C_3}$$

Centrality dependence

$$\boldsymbol{C}_2(y_1, y_2) = \rho(y_1)\rho(y_2)\boldsymbol{c}_2(y_1, y_2)$$

$$K_4 = \langle N \rangle + 7\boldsymbol{C}_2 + 6\boldsymbol{C}_3 + \boldsymbol{C}_4$$

$$\boldsymbol{C}_k = \langle N \rangle^k \boldsymbol{c}_k$$

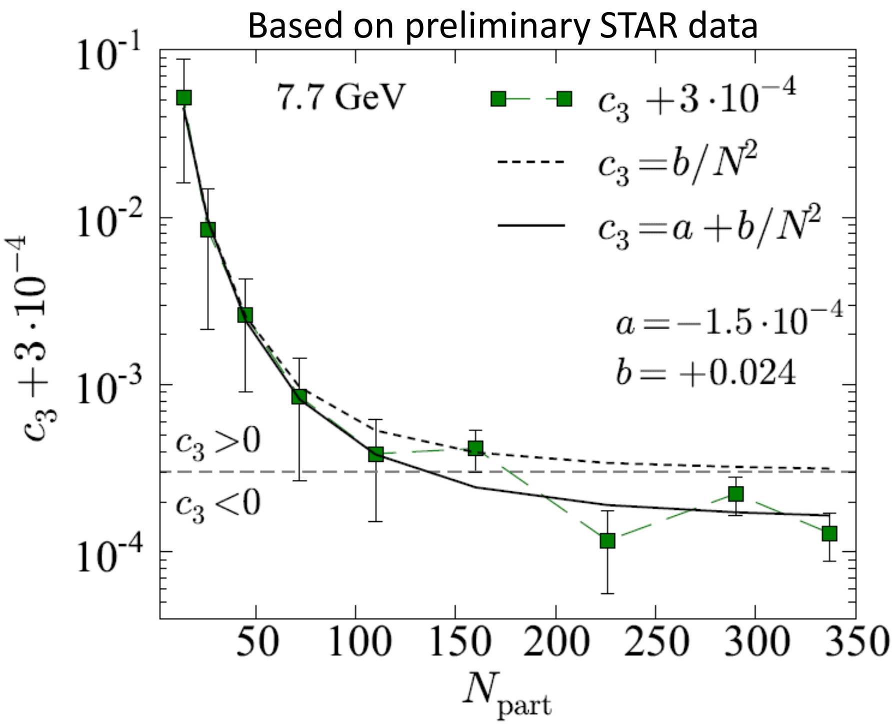
$$K_4 = \langle N \rangle + 7\langle N \rangle^2 \boldsymbol{c}_2 + 6\langle N \rangle^3 \boldsymbol{c}_3 + \langle N \rangle^4 \boldsymbol{c}_4$$

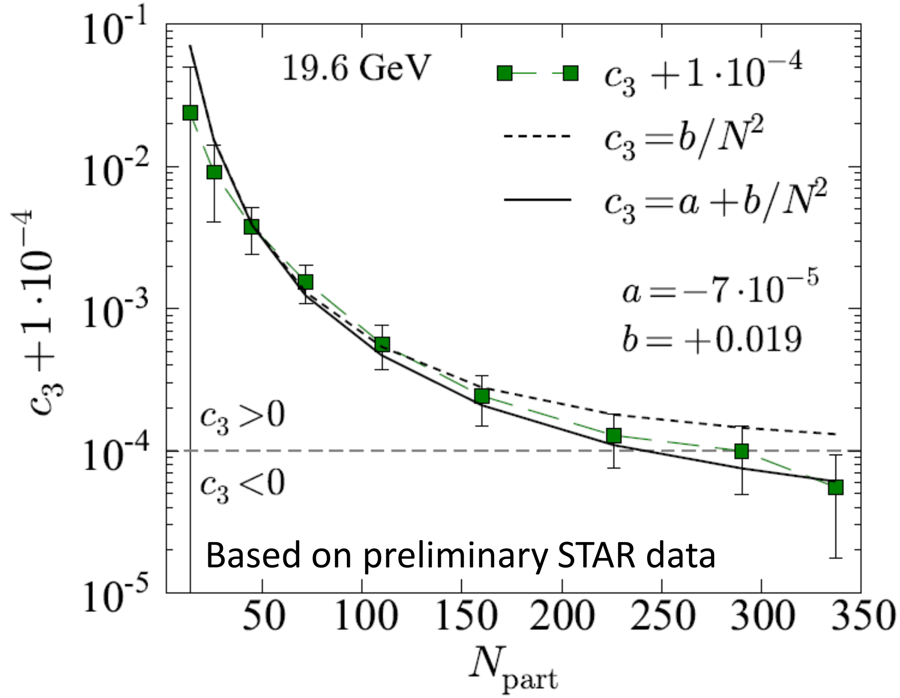
Suppose we have N_s **independent sources** of correlations (resonances, superposition of p+p etc.)

$$\boldsymbol{c}_k \sim \frac{N_s}{N^k} \sim \frac{1}{N^{k-1}}$$

Using preliminary STAR data we obtain c_3

AB, V. Koch, N. Strodthoff, 1607.07375

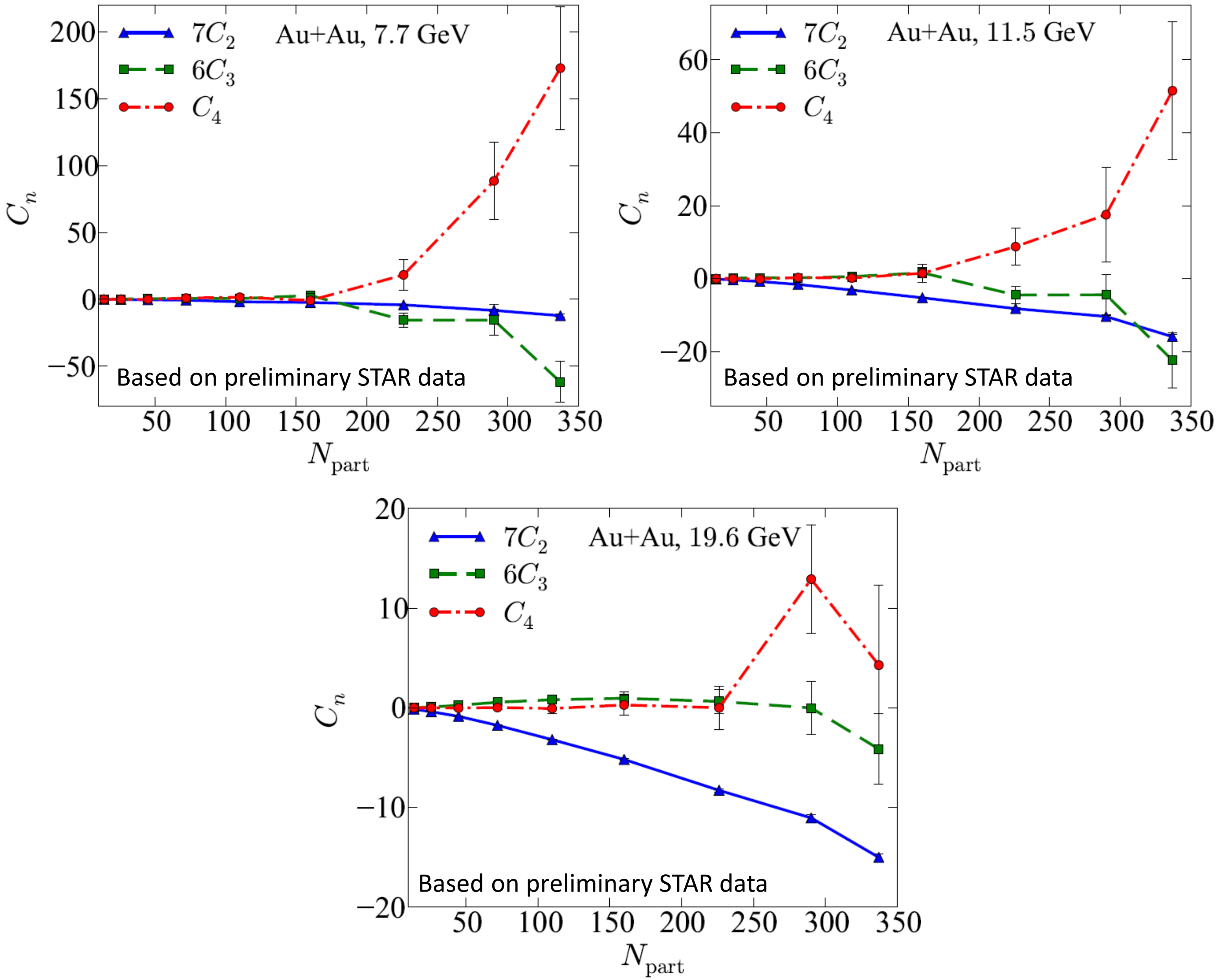




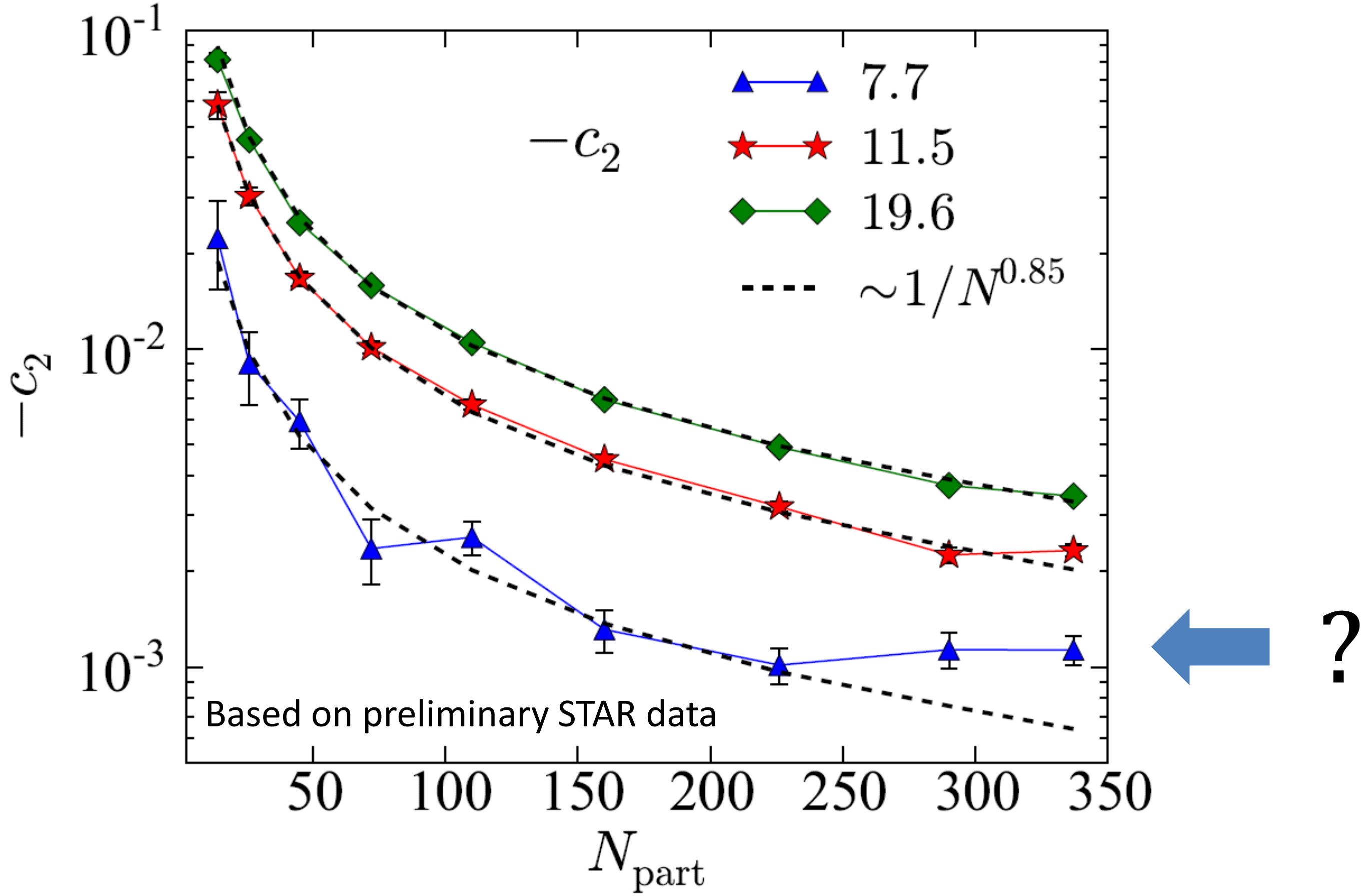
At 7.7 GeV we see $1/N^2$ for small N_{part} then c_3 **changes sign** and stays roughly constant…

Similar story for c_4

Comparison of 7.7, 11.5 and 19.6 GeV



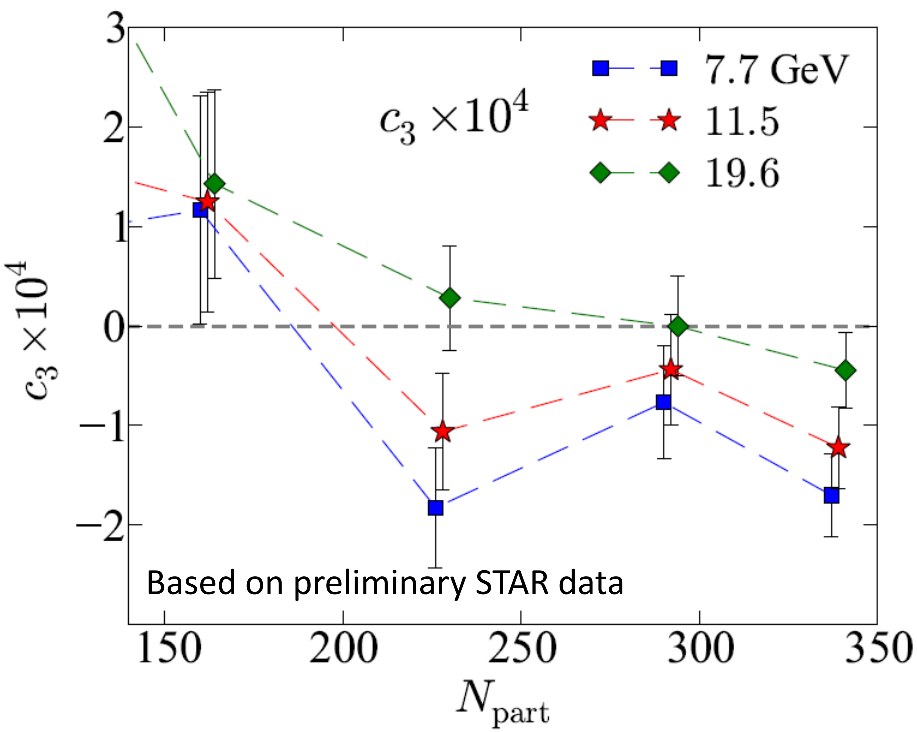
results for c_2

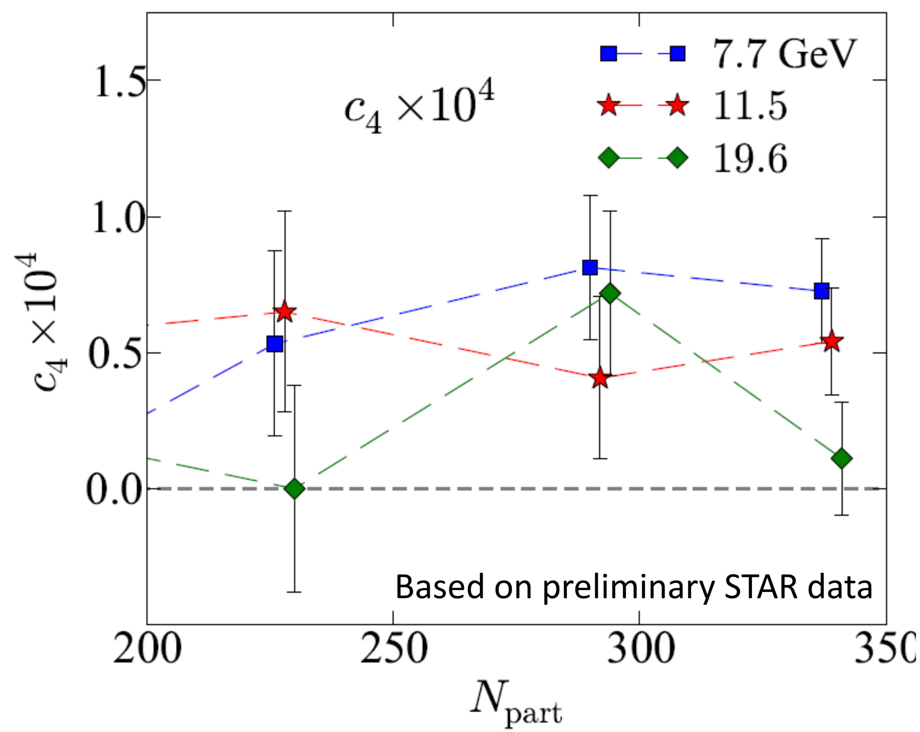


central 7 GeV points are somehow special

AB, V. Koch, N. Strodthoff , 1607.07375

results for central c_3 and c_4

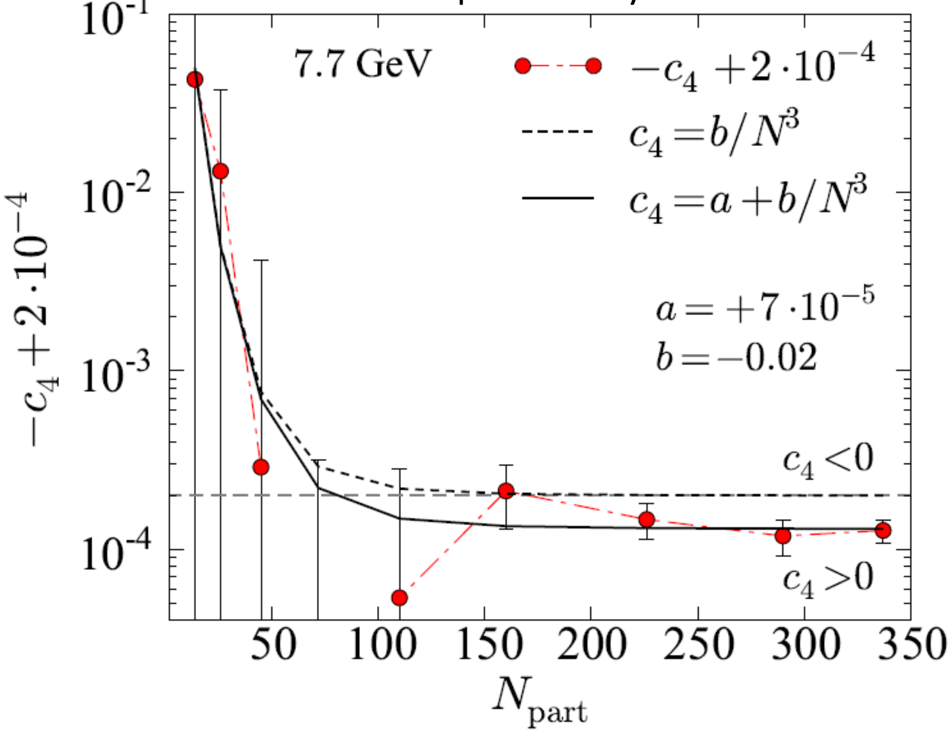




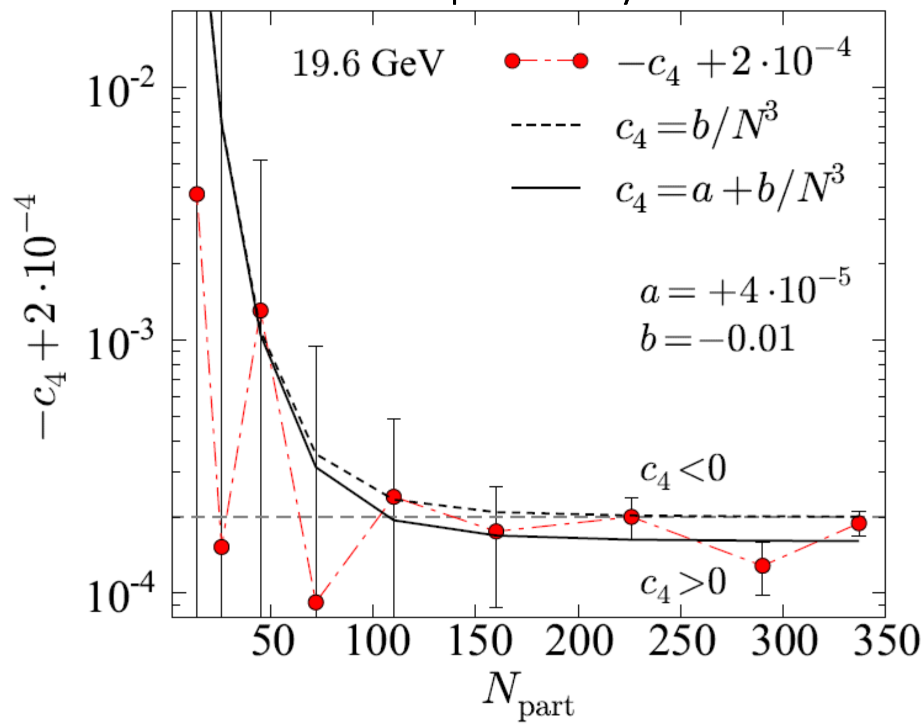
AB, V. Koch, N. Strodthoff , 1607.07375

results for c_4

Based on preliminary STAR data



Based on preliminary STAR data



AB, V. Koch, N. Strodthoff , 1607.07375