Proton stopping at low energies

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A. Bialas, AB, V. Koch, 1608.07041

AB, V. Koch, V. Skokov, 1612.05128

AB, V. Koch, N. Strodthoff , 1607.07375

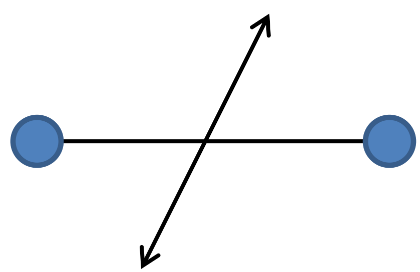
Outline

Proton stopping

Multi-proton correlations at STAR

At low A+A energies, e.g., $\sqrt{s} = 7$ GeV, most of the observed protons (neutrons) originate from stopping, namely they are transferred from the incoming nucleus.
There is no enough energy to produce proton-antiproton pairs.

At very low energies, $\sqrt{s} \sim 2$ GeV, protons simply undergo elastic scatterings. They can be easily transferred to $y = 0$ region.



At higher energies we expect that strings are formed which slow down the protons (neutrons) at a rate given by the string tension σ, typically $\sigma \sim 1$ GeV/fm.

The strings break (many times) and particles are produced (pions etc).

It takes some time and length to slow down protons. Thus we expect the stopped protons to be away from $z = 0$.

There is no infinite deceleration. It take some time and length to slow down or stop a proton.

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

E_i – initial energy $= \sqrt{s}/2$

z_c – collision point

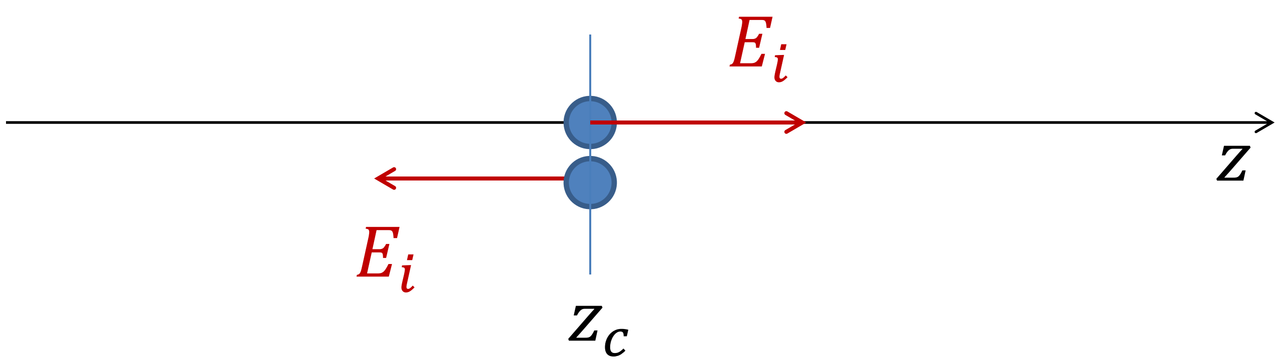
E_z – energy at a point z

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

y and M_t at a given z

$M_t^2 = M^2 + P_t^2$

σ – energy loss per unit length



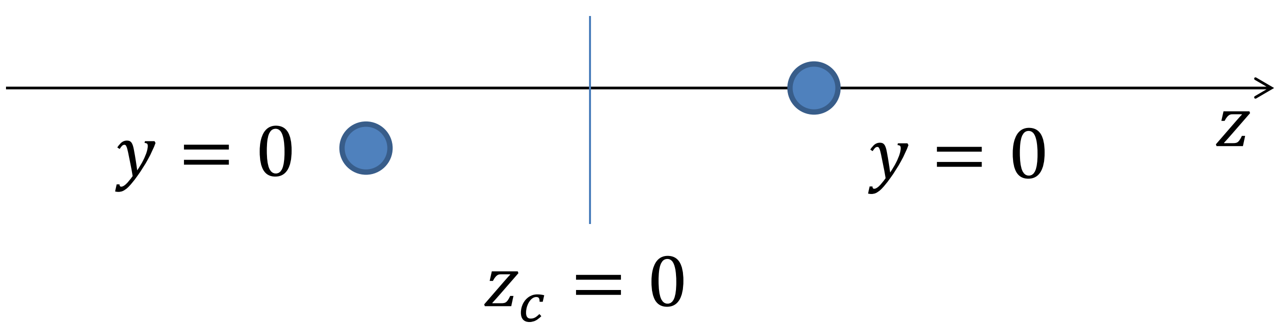
For example, when we look at protons with $y = 0$ and $z_c = 0$ we have

$$E_i - M_t = \sigma \cdot z \qquad\qquad z = \frac{E_i - M_t}{\sigma}$$

E_i – initial energy $= \sqrt{s}/2$

σ – energy loss per unit length

For example: $E_i = 10$ GeV, $M_t = 2$ GeV, $\sigma = 1$ GeV/fm and we have $z = 8$ fm



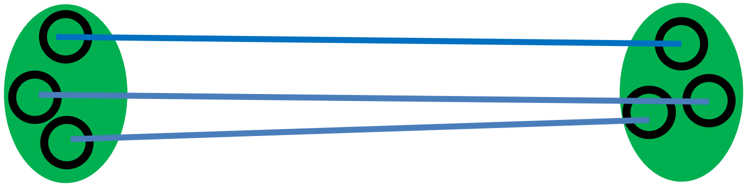
It is not clear if we can obtain large baryon density at $y \approx 0$.
Protons from the target and the projectile seem to be separated in z.

The separation depends on the initial energy, final transverse momentum and on σ.

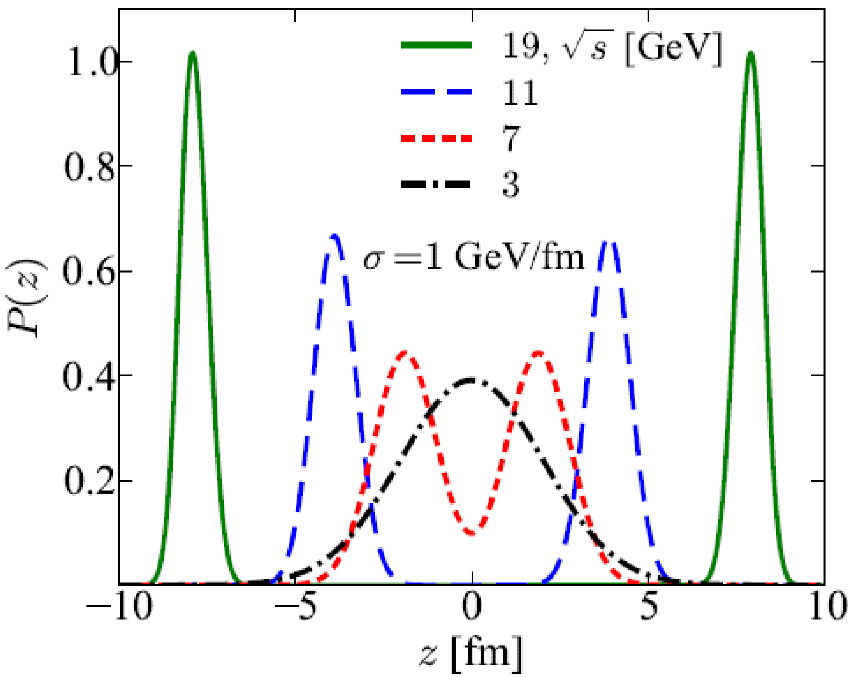
$$z = \frac{E_i - M_t}{\sigma} \qquad \text{protons at } y = 0$$

In the wounded nucleon model $\sigma \sim 1$ GeV/fm

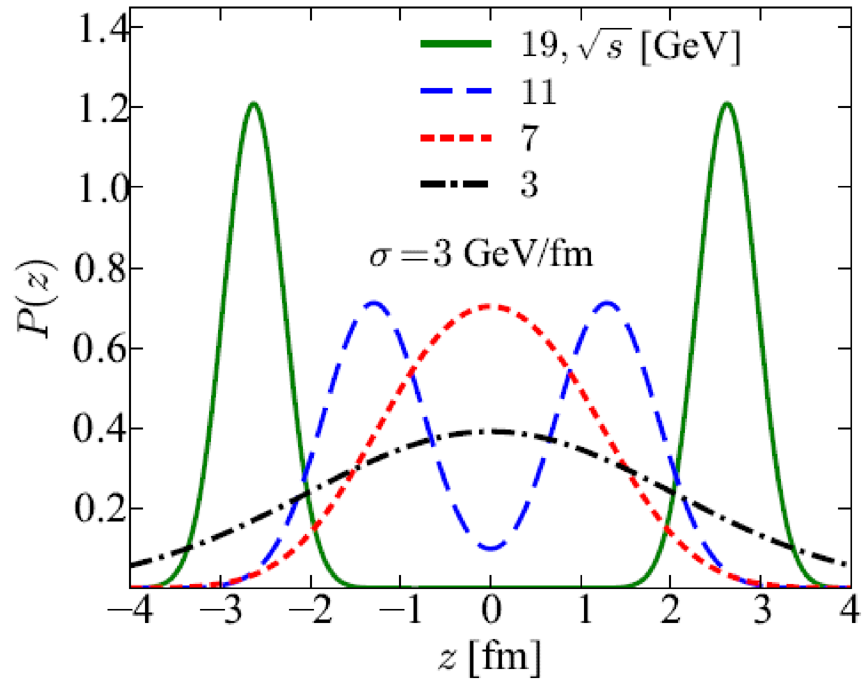
In the wounded quark model $\sigma \sim 3$ GeV/fm (three strings in central collisions)



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 like to see a uniform distribution in z.

We do not take into account resonances.

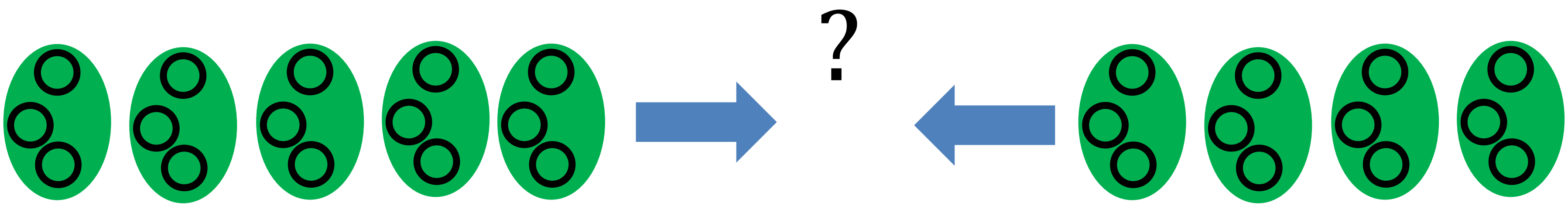
It is desired to make some real MC calculations but:

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.

How to properly model baryon stopping?

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

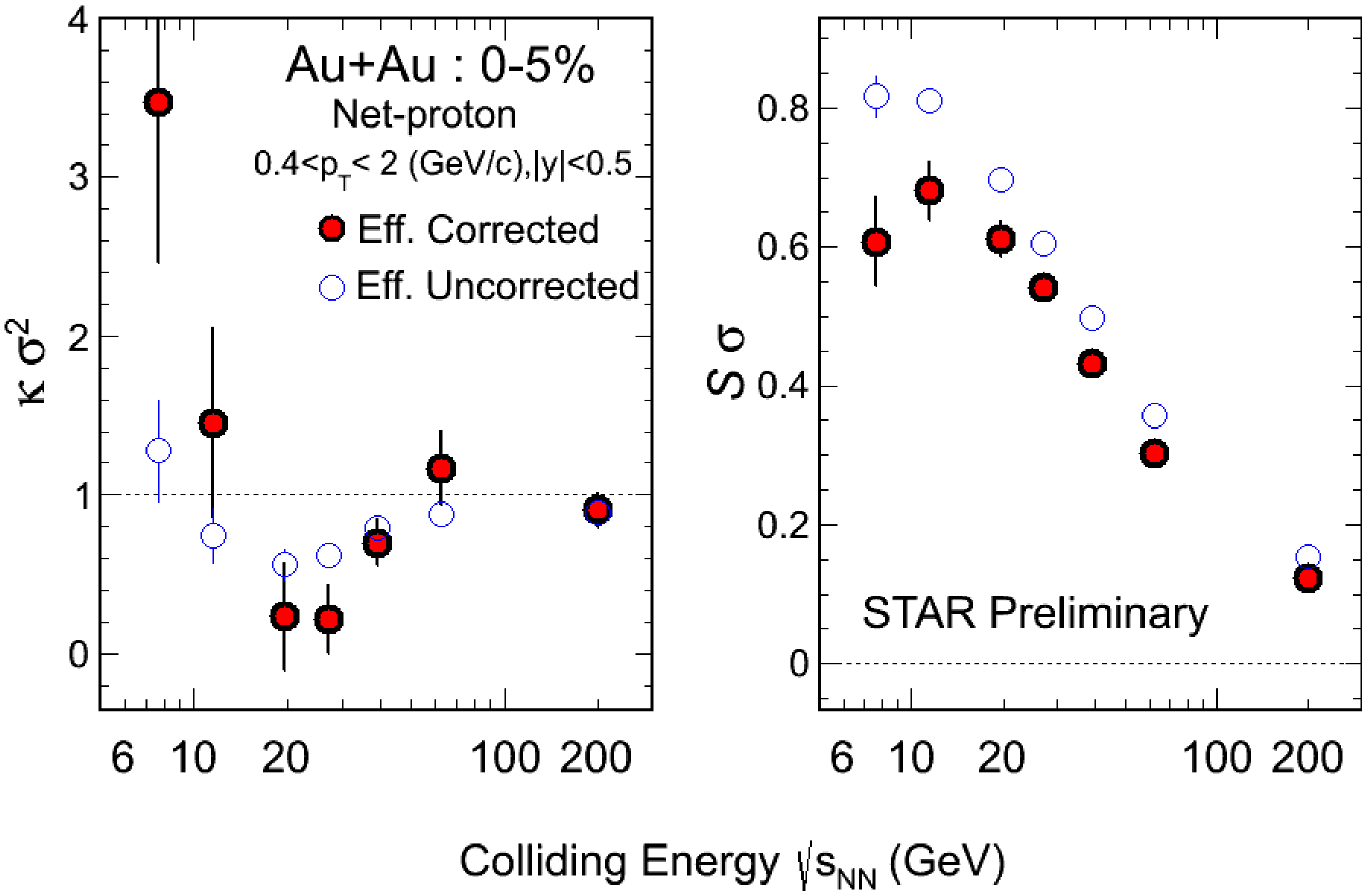


Important questions if we want to understand proton cumulants as measured by STAR at RHIC.

STAR sees some interesting multi-proton correlations at lower energies.

STAR data

$$K_2 = \langle (N - \langle N \rangle)^2 \rangle$$
$$K_3 = \langle (N - \langle N \rangle)^3 \rangle$$
$$K_4 = \langle (N - \langle N \rangle)^4 \rangle - 3\langle (N - \langle N \rangle)^2 \rangle^2$$



K_4/K_2 **my notation** K_3/K_2

Interesting signal at 7.7 GeV.

I will show that it is “unreasonably” large.

At this energy practically all protons come from stopping.

The critical point or some stopping correlations? (or something else)

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

correlation function

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

reduced correlation function

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

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

coupling

and the second order cumulant

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

Finally we obtain

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

$$\boldsymbol{C_2} = \int C_2(y_1,y_2)dy_1dy_2$$

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

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

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

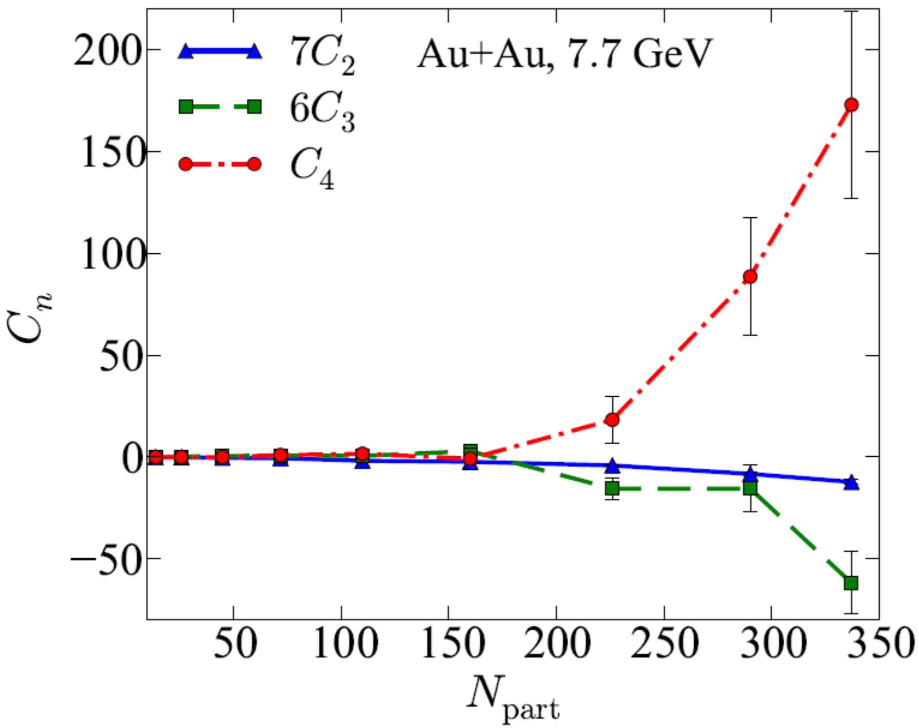
or, e.g.,

cumulants mix correlation functions

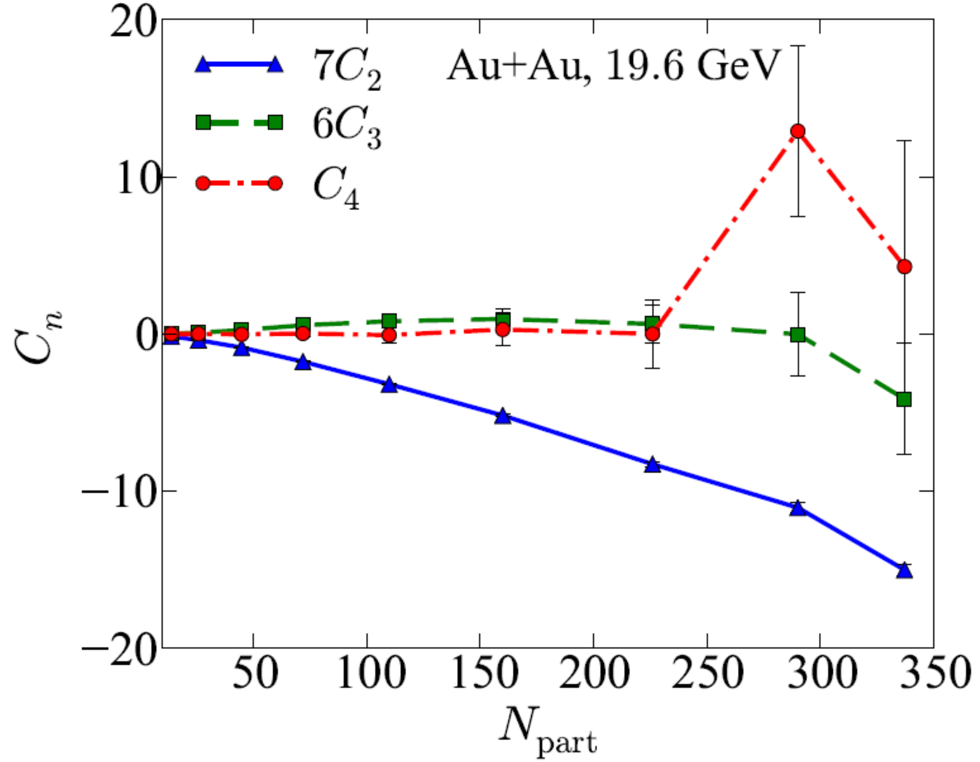
$$K_4 = \langle N\rangle + 7\boldsymbol{C_2} + 6\boldsymbol{C_3} + \boldsymbol{C_4}$$

results for C_n

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



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



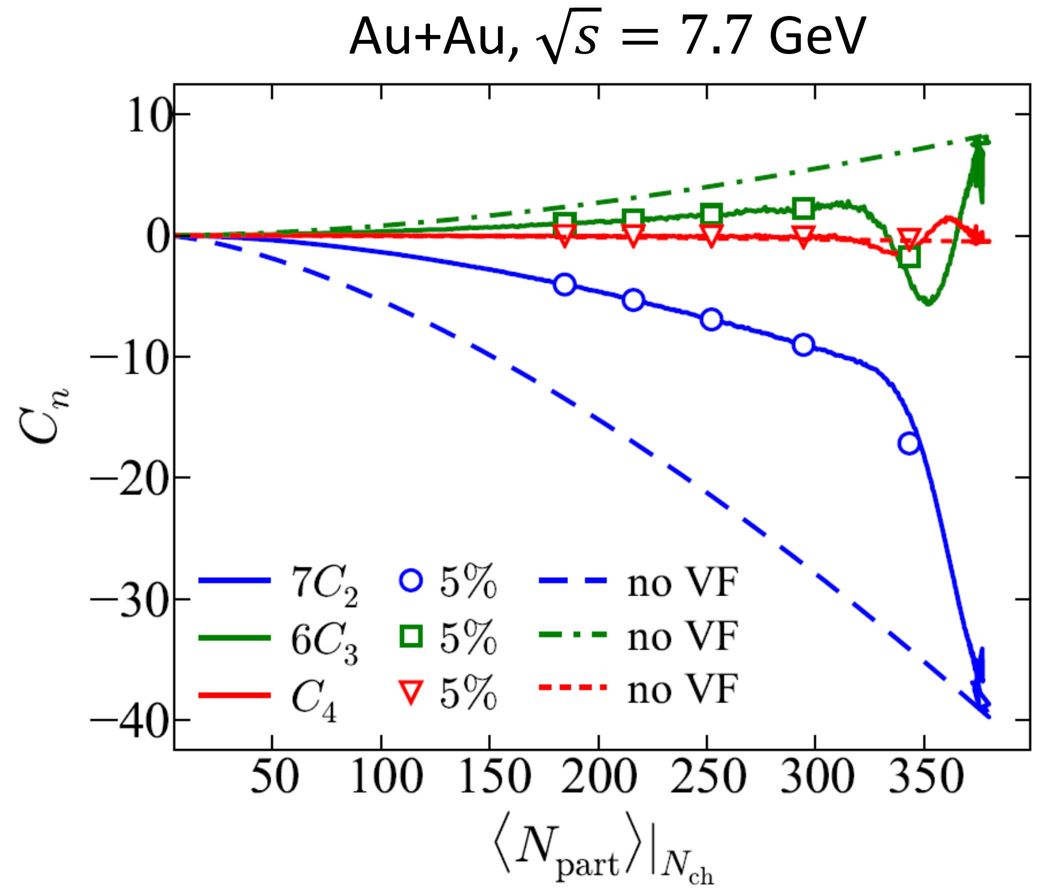
$$K_2 = \langle N \rangle + C_2$$

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

AB, V. Koch, N. Strodthoff, arXiv:1607.07375

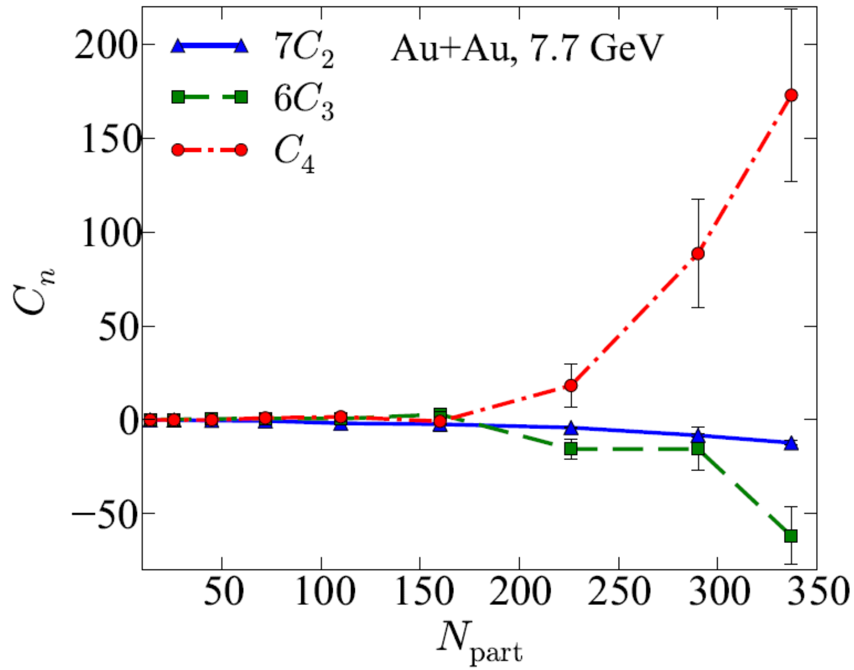
We constructed a simple model at low energies:

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

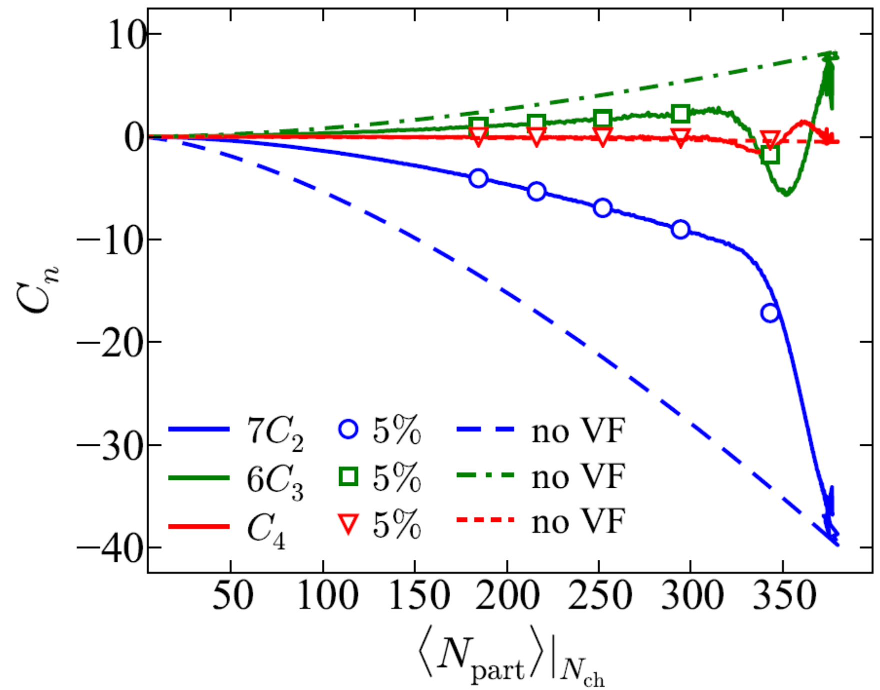


AB, V. Koch, V. Skokov, 1612.05128

STAR data



minimal model



wiggles in the right plot due to $N_{\rm part}$ fluctuations

STAR C_4 is larger by almost 3 orders of magnitude than the model with no non-trivial correlations between protons (except baryon conservation and volume fluctuation)

Let’s put the STAR number in perspective.

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

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

mean number
of clusters

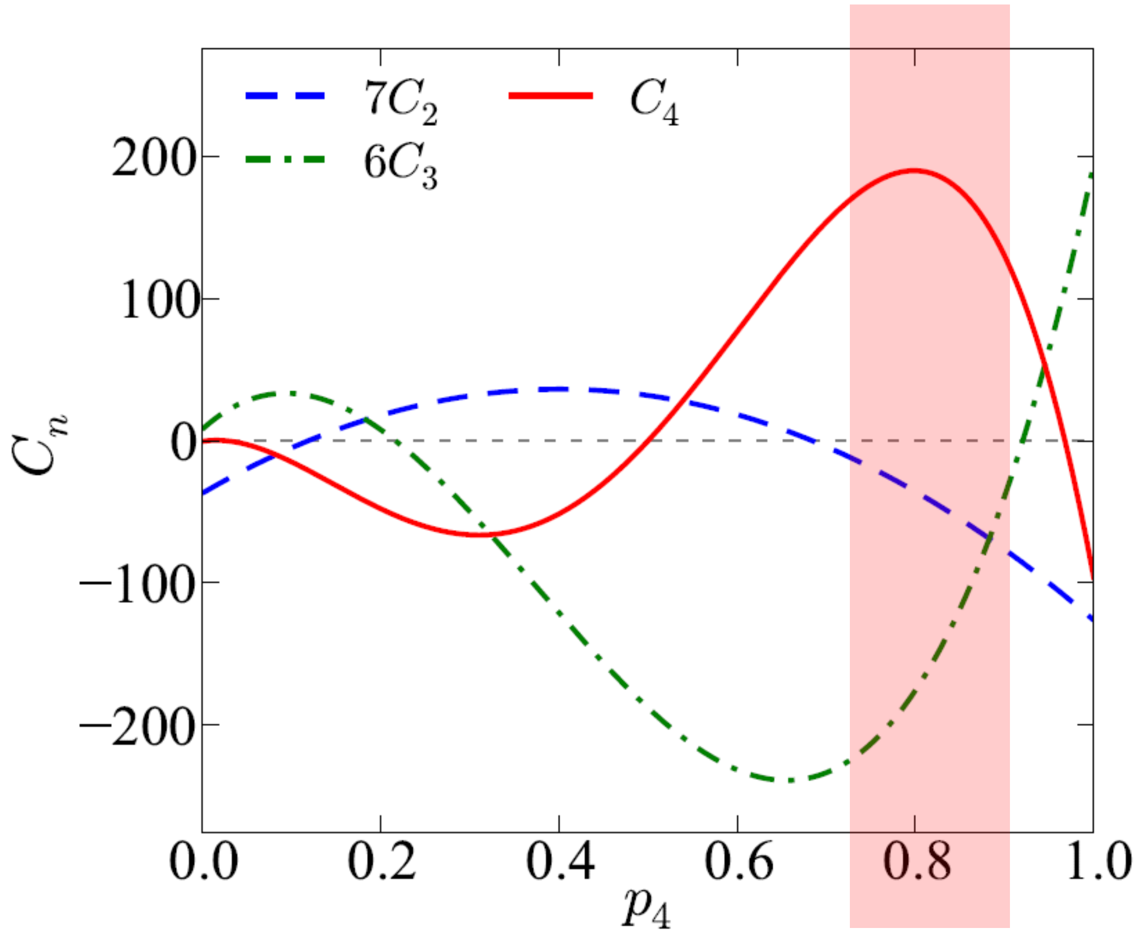
$$C_4 = \langle N_{\rm cl} \rangle \cdot 24$$

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

very strong 4-proton correlation

A toy model:

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



qualitatively consistent with STAR

AB, V. Koch, V. Skokov, 1612.05128

Conclusions

The configuration space distribution of the final protons (and other particles) requires careful study.

Possible separation in z between protons.

Multi-proton correlations from stopping?

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