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Symmetric cumulants as a probe of the proton substructure

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The paper

Symmetric cumulants as a probe of the proton substructure at LHC energies

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We present a systematic study of the normalized symmetric cumulants, NSC(n,m), at the eccentricity level in proton-proton interactions at $\sqrt{s} = 13$ TeV within a wounded hot spot approach. We focus our attention on the influence of spatial correlations between the proton constituents, in our case gluonic hot spots, on this observable. We notice that the presence of short-range repulsive correlations between the hot spots systematically decreases the values of NSC(2,3) and NSC(2,4) in mid- to ultra-central collisions while increases them in peripheral interactions. In the case of NSC(2,3) we find that, as suggested by data, an anti-correlation of ε_2 and ε_3 in ultra-central collisions, i.e. NSC(2,3) < 0, is possible within the correlated scenario while it never occurs without correlations when the number of gluonic hot spots is set to three. We attribute this fact to the decisive role of correlations on enlarging the probability of interaction topologies that reduce the value of NSC(2,3) and, eventually, make it negative. Further, we explore the dependence of our conclusions on the number of hot spots, the values of the hot spot radius and the repulsive core distance. Our results add evidence to the idea that considering spatial correlations between the subnucleonic degrees of freedom of the proton may have a strong impact on the initial state properties of proton-proton interactions [1].

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Motivation

be positive. However, it turns out to be negative for very high multiplicities, $N_{trk}^{offline} > 60$ in both p+Pb and Pb+Pb and $N_{trk}^{offline} \sim 100$ in p+p. Moreover, NSC(2,3) in

tematic uncertainties make it compatible with zero. Relating the negative sign of NSC(2,3) at very high multiplicities with the initial geometry of the proton is the main goal of this work.

the color fields in the heavy nuclear target [21, 22]. Up to today we are unaware of any theoretical prediction for the values of SC(n,m) in p+p interactions at LHC energies, although results for RHIC energies were presented tween different flow harmonics v_n i.e. the symmetric cumulants defined as [2, 3]

$$\mathrm{SC(n,m)} = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle \qquad (1)$$

or in their normalized version

$$\mathrm{NSC(n,m)} = \frac{\langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle}{\langle v_n^2 \rangle \langle v_m^2 \rangle} \qquad (2)$$

Wounded hot spot model

parameter for the collision, we sample the transverse positions of the three hot spots in each proton $\{\vec{s}_i\}$ according to the distribution

$$D(\vec{s}_1, \vec{s}_2, \vec{s}_3) = C \prod_{i=1}^{3} e^{-s_i^2/R^2} \delta^{(2)}(\vec{s}_1 + \vec{s}_2 + \vec{s}_3) \times \prod_{\substack{i<j \\ i,j=1}}^{3} \left(1 - e^{-\mu |\vec{s}_i - \vec{s}_j|^2 / R^2}\right). \quad (3)$$

model. The third term of Eq. 3 allows us to go beyond these approaches by implementing short range repulsive correlations among all pairs of hot spots that effec-

jectile, the next step in the Monte Carlo simulation is to decide which of them have been wounded [40, 41] i.e.

the hot spot-hot spot scattering amplitude ρ_{hs}. Thus, in each event, the maximum number of wounded hot spots N_w and collisions N_{coll} is 6 and 9 respectively. In

Correlation scenarios

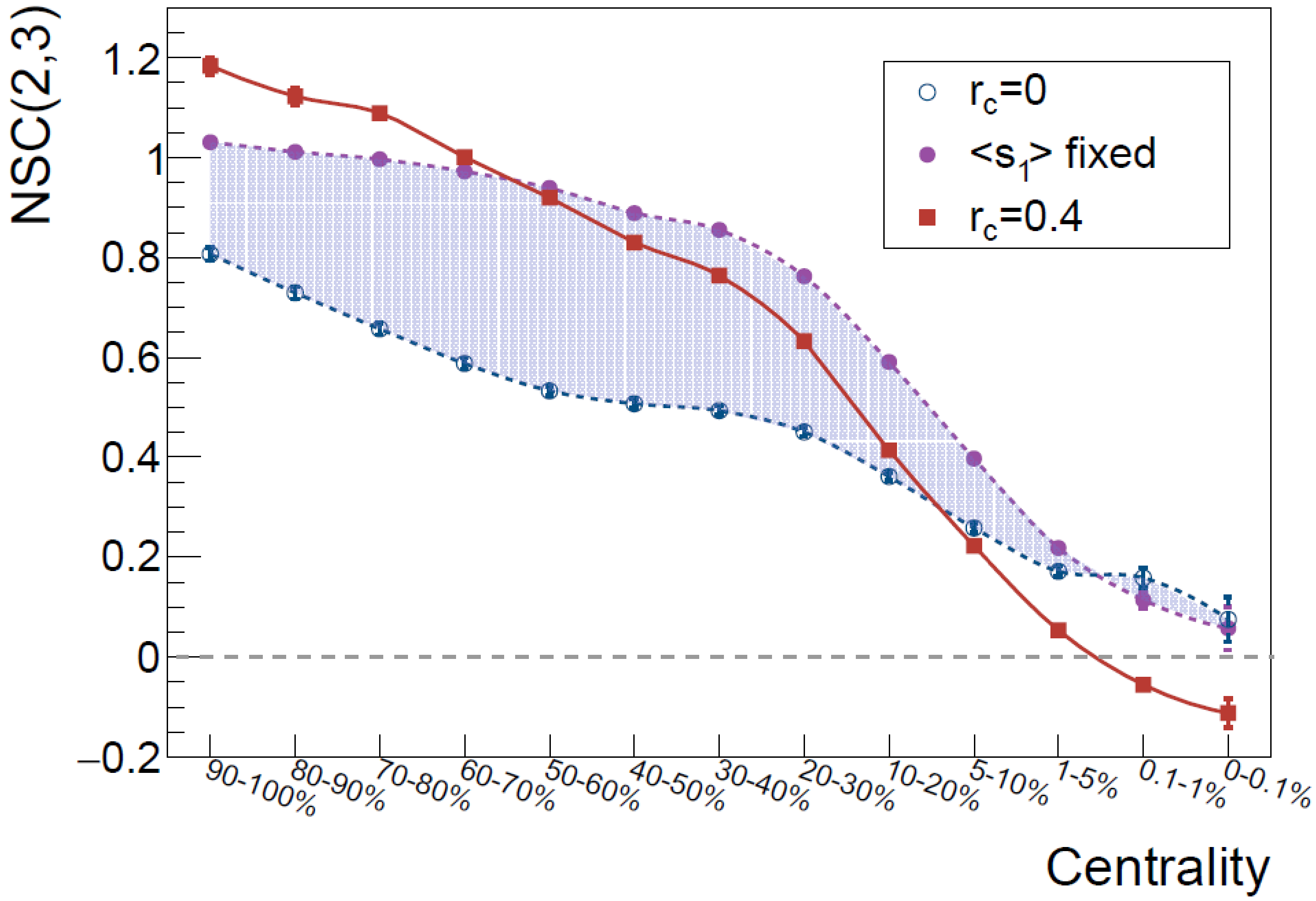
calculation to other regions of the parameter space. The three correlation scenarios under consideration in this work are the following: first, $r_c = 0.4$ refers to the correlated scenario with $\{R_{hs}, R, \rho_{hs}\}$ constrained to reproduce the extrapolated values of the total cross section and the ratio of real and imaginary parts of the scattering amplitude [42]. In the second case we impose the latter constraints to $\{R_{hs}, R, \rho_{hs}\}$ after setting $r_c = 0$. However, in order to do a more realistic comparison between

ence of repulsive correlations. The case labeled as "$\langle s_1 \rangle$ fixed" constitutes an attempt to perform this task by fixing the r.m.s of the spatial probability distribution given by Eq. 3 to be the same as in the $r_c = 0.4$ scenario. In the following plots the uncorrelated results will be exhibited as a band bounded by the $r_c = 0$ and $\langle s_1 \rangle$ fixed cases to display the different possibilities considered.

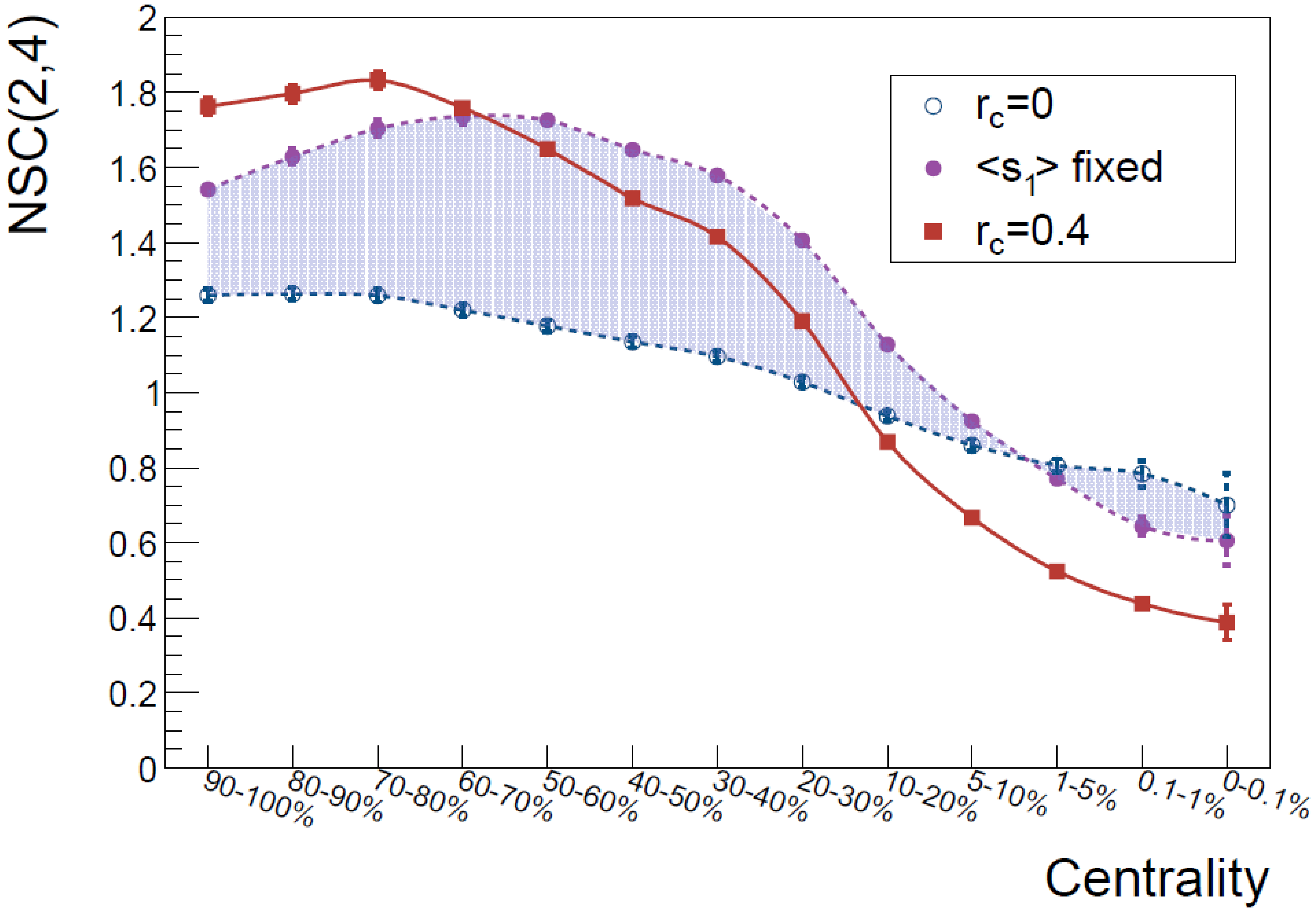
NSC(2,3) vs centrality

served in the ultra-central bins [0-0.1%] and [0.1-1%]: only in the $r_c = 0.4$ case there exists an anti-correlation of ε_2 and ε_3 as data dictates. Then, we conclude that the experimental evidence of NSC(2,3)<0 may back up the necessity to consider correlated proton constituents.

ticular mechanism i.e. the presence of spatial correlations inside the proton that builds up a negative value of NSC(2,3) in the highest centrality bin at the geometric level.



NSC(2,4) vs centrality

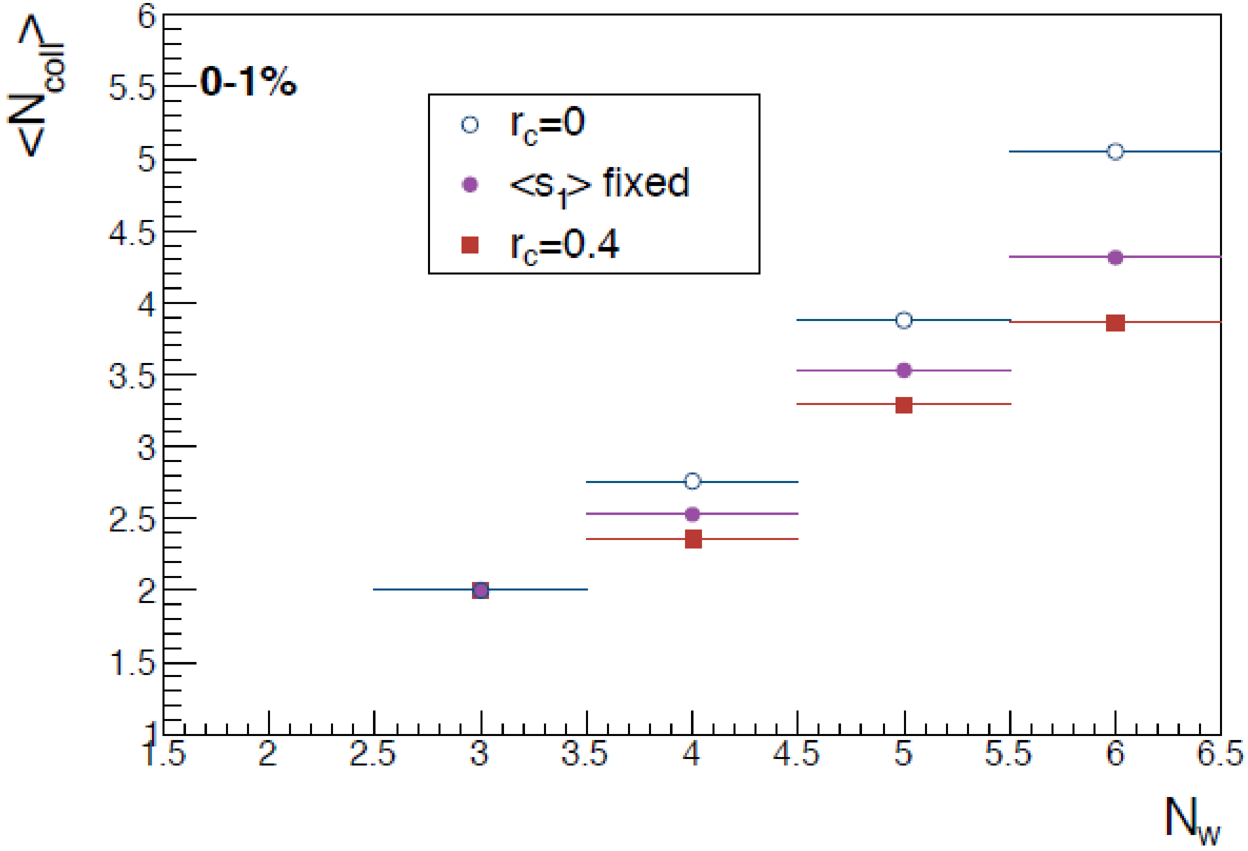


In the case of NSC(2,4), the role of the repulsive correlations is qualitatively the same as in the NSC(2,3) cal-

Ultra-central events

In order to capture the effect of the spatial correlations we characterize each proton-proton interaction by its number of wounded hot spots and the number of collisions (N_w, N_{coll}), the two basic quantities of any Monte-Carlo Glauber calculation. We dub each (N_w, N_{coll})-

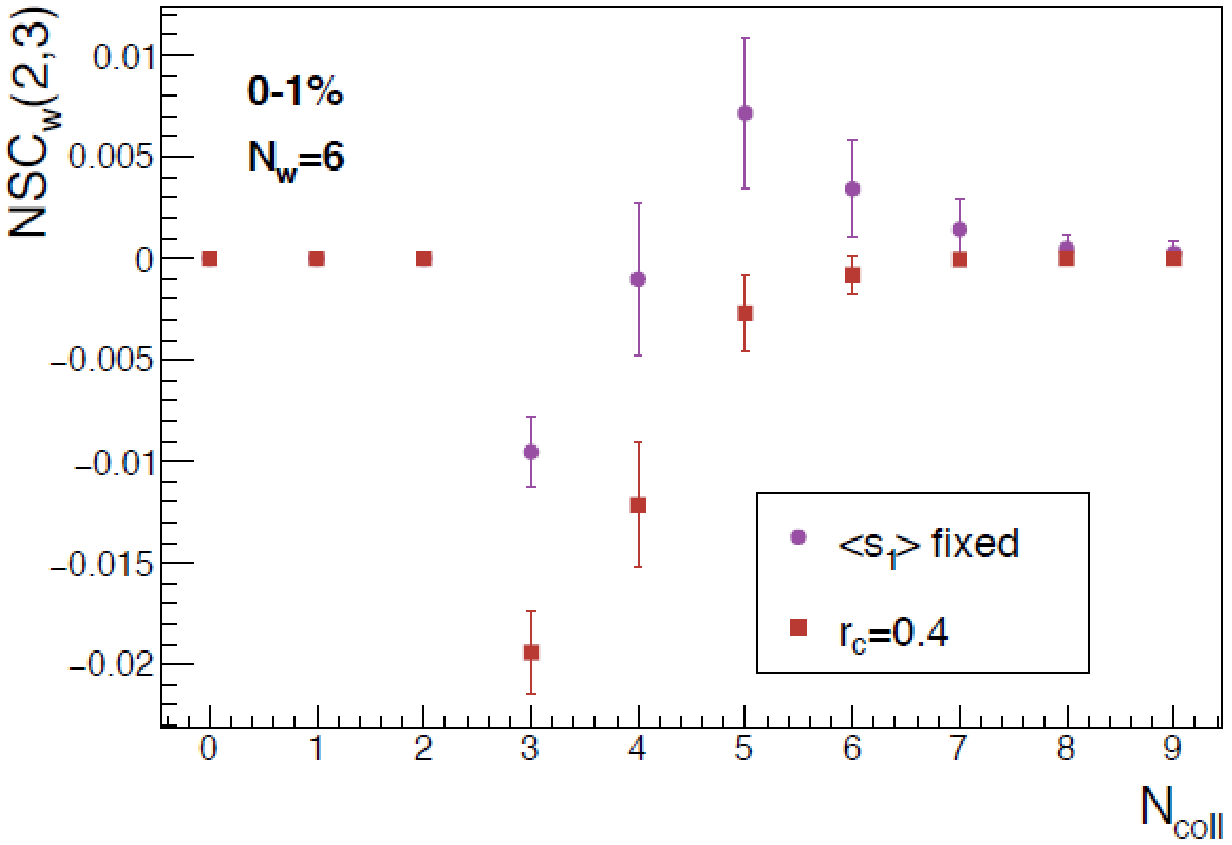
the only existing configuration. However, for $N_w > 3$ the average number of collisions starts to differ between the three different cases. We observe that $\langle N_{\text{coll}} \rangle$ is systematically reduced when including repulsive correlations with respect to the uncorrelated cases. This effect has a very straightforward interpretation: enlarging the mean transverse distance between the hot spots reduces the probability of having interaction topologies with a high number of collisions. In other words, the repulsive



$N_W = 6$

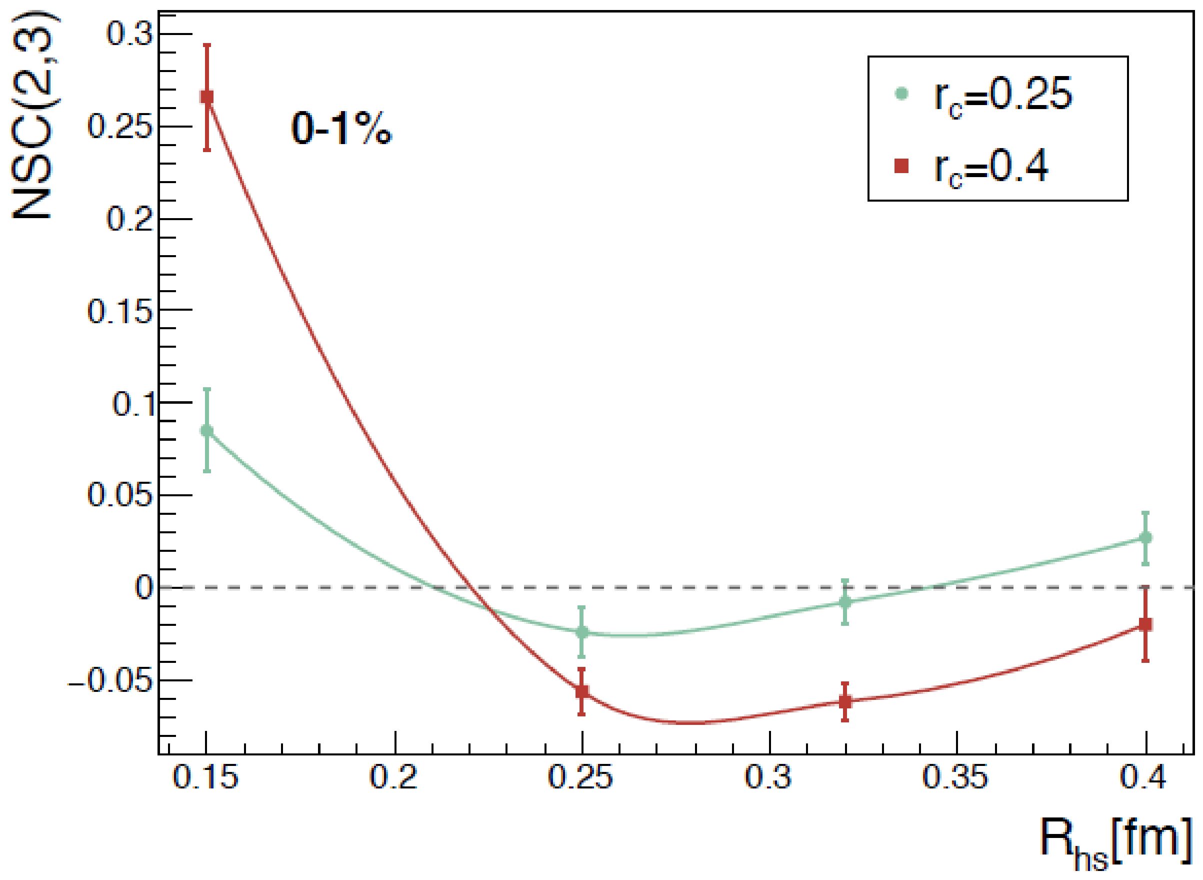
configurations with a large number of collisions, e.g. $N_{\text{coll}} > 6$, only occur in the uncorrelated case where the three hot spots are closer to each other or, equiva-

lently, clustered. Second, and more important, the value of $\text{NSC}_{\text{w}}(2,3)$ shows a clear dependence on N_{coll}: configurations with a smaller number of collisions reduce the value of NSC(2,3) and, eventually, contribute negatively.



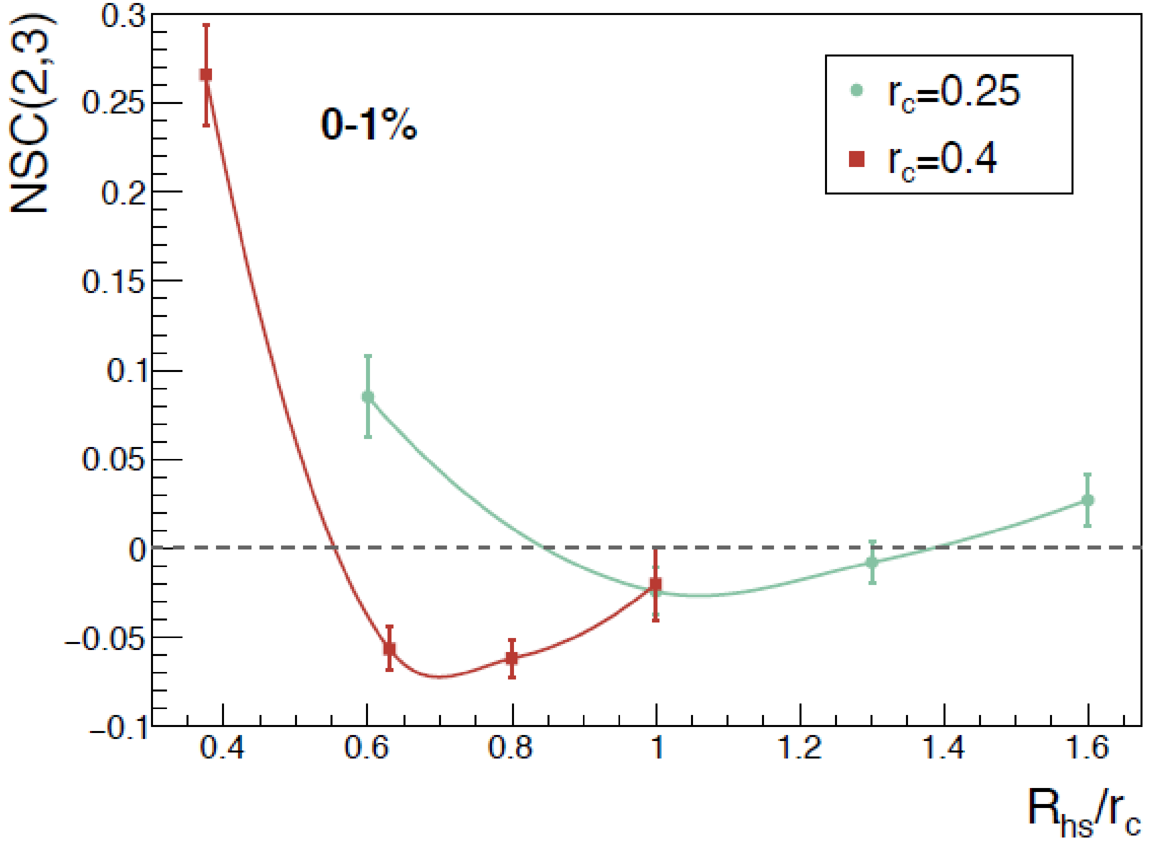
Parameter space scan

universal as it breaks down when $R_{hs} \lesssim 0.22$ fm. In this scenario of very small values of the radius of the hot spot, i.e. $R_{hs} \lesssim 0.22$ fm, ε_2 and ε_3 are positively correlated for both values of the repulsive core distance and the value of NSC(2,3) is larger in the $r_c = 0.4$ case. This result indicates that NSC(2,3) is not sensitive to R_{hs} and r_c independently but to the interplay of both scales. In other words, NSC(2,3) depends on a generic function of the radius of the hot spot and the repulsive core distance $f(R_{hs}, r_c)$.



R_{hs}/r_c dependence

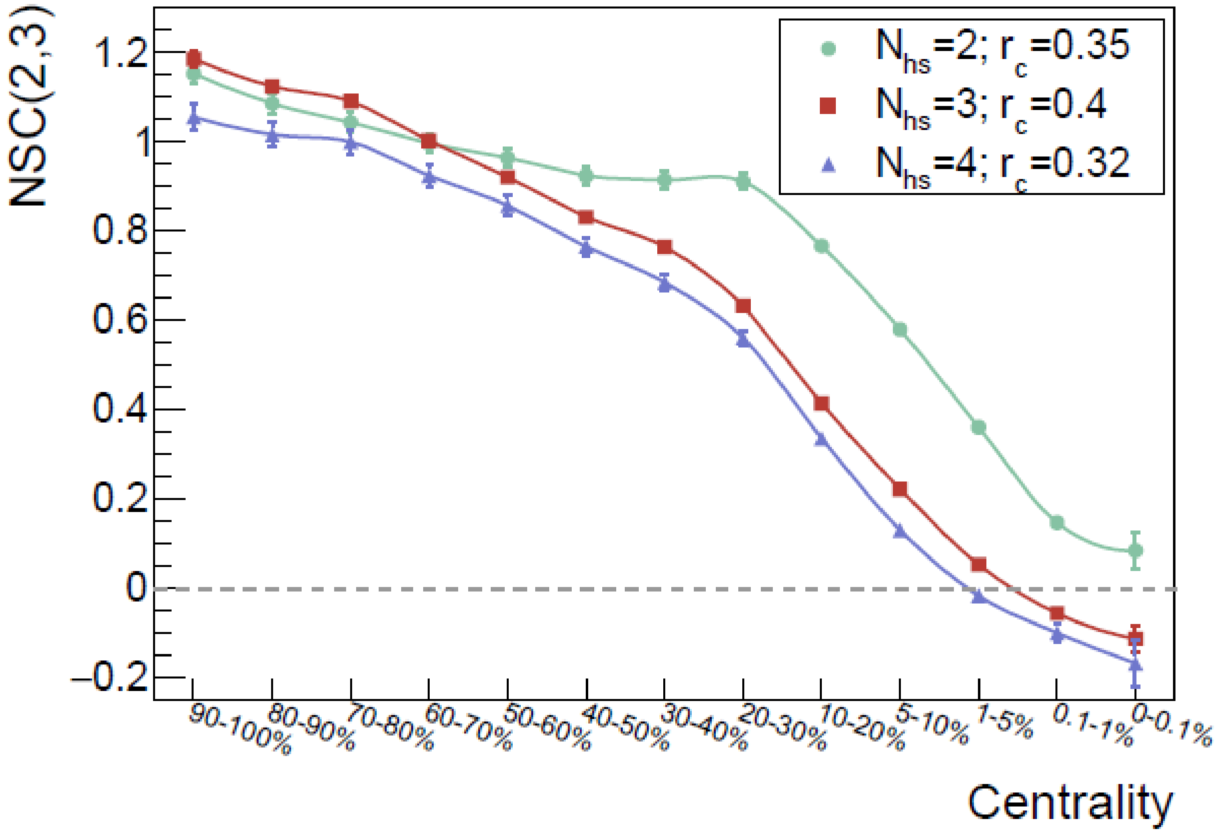
sult into a positive correlation between ε_2 and ε_3. Then, our study favors values of $0.6 \lesssim R_{hs}/r_c \lesssim 1.3$ in order to be compatible with the experimental observation of NSC(2,3)< 0 in the highest centrality bin. Unfortunately, this interval is large enough to be compatible with a picture of the proton in which the hot spots transverse separation is larger than in the uncorrelated case but still they can overlap ($R_{hs}/r_c \sim 1.3$) and with a much more dilute description in which the probability of two hot spots to overlap is highly supressed ($R_{hs}/r_c \sim 0.6$).



Sensitivity to number of hot-spots

ering the two more straight-forward extensions of our model: $N_{hs} = 2$ and $N_{hs} = 4$. In order to make a

ered. Specifically, the negative sign of NSC(2,3) in the high centrality bins is not achieved when $N_{hs} = 2$ even with correlations. Thus, we conclude that with the selected parameters the minimum number of hot spots to describe the onset of the anti-correlation between ε_2 and ε_3 is $N_{hs} = 3$. It should also be noted that the inclusion of an additional hot spot i.e. $N_{hs} = 4$ helps to make NSC(2,3) even more negative in the highest centrality bins although the effect is small when compared to the drastic impact of changing from $N_{hs} = 2$ to $N_{hs} = 3$.



Conclusion

tropy deposition as a proxy of particle production. We find that the inclusion of short-range repulsive correlations has a critical impact on the sign of NSC(2,3) in ultra central collisions. The net effect of the presence of corre-