Spectator nucleons in ultracentral ^{208}Pb- ^{208}Pb collisions as a probe of nuclear periphery

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Introduction

In collisions of relativistic nuclei spectator matter consists of nucleons that do not interact with the collision partner. In contrast to the overlap domain of colliding nuclei, spectator matter remains relatively cold and propagate in forward direction. In ALICE experiment at the LHC spectator neutrons and protons are detected by Zero Degree Calorimeters (ZDCs)[1)]. In this work we show that the calculated cross sections of emission of given numbers of spectator neutrons and protons in ultracentral ^{208}Pb–^{208}Pb collisions are sensitive to the parameters of the density distributions of neutrons and protons at the periphery of ^{208}Pb, in particular to the thickness of the neutron skin (NS).

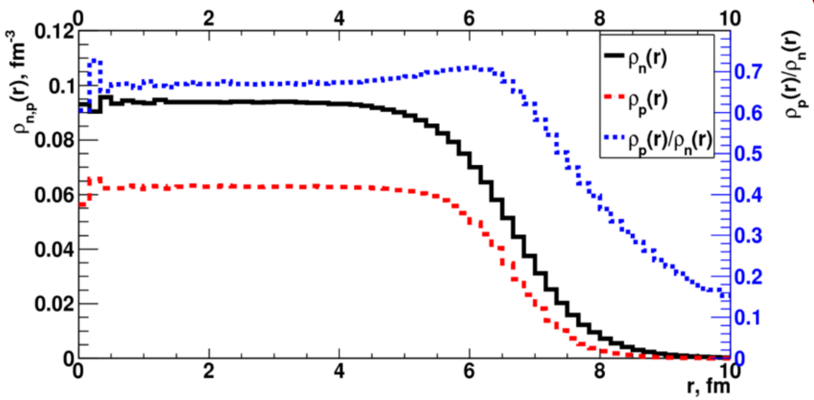

Fig. 1: Neutron and proton radial density distributions $\rho_n(r)$ and $\rho_p(r)$ in ^{208}Pb (left scale) and their ratio (right scale).

[1)] G. Puddu et al. Nucl. Instrum. Methods Phys. Res. A. **581** (2007), 397

At the periphery of heavy nuclei like ^{208}Pb, the neutron density is higher than the proton density, Fig. 1, and this phenomenon is known as NS. Its thickness is characterized by the difference between neutron and proton RMS-radii: $\Delta r_{np} = \sqrt{\overline{r_n^2}} - \sqrt{\overline{r_p^2}}$. It is very challenging to calculate Δr_{np} and also to measure it precisely. In case of ^{208}Pb calculated Δr_{np} ranges from 0.12 fm to 0.32 fm[2)]. A similar spread is observed in the experimental data for ^{208}Pb: the latest result of the PREX experiment[3)] and the result of the experiment on coherent pion photoproduction on ^{208}Pb[4)] differ by a factor of 2.

The precise determination of the parameters of the nuclear periphery enriched by neutrons is important for restricting the parameters in the equitation of state of nuclear matter, its symmetry energy, which define the properties of neutron stars[5)]. The effect of NS also defines the properties of nuclei at the border of stability[6)], and can be sensitive to physics beyond the Standard Model[7)]. All this motivates to search for new methods to restrict the parameters of NS. We argue that spectator nucleons produced in ultracentral relativistic heavy-ion collisions can be used to probe the neutron excess at the nuclear periphery. It can be expected, see Fig. 2, that in central collisions of equal heavy nuclei the nuclear periphery is peeled off, propagates forward and thus can be detected in ZDCs.

[2)] M. Centelles et al. Phys. Rev. C. **82** (2010), 054314
[3)] D. Adhikari et al. Phys. Rev. Lett. **126** (2021), 172502
[4)] C.M. Tarbert er al. Phys. Rev. Lett. **112** (2014), 242502
[5)] A.W. Steiner et al. Phys. Rep. **411** (2006), 325
[6)] J. Dobaczewski et al. Z. Phys. A. **354** (1996), 27
[7)] D.H. Wen et al. Phys. Rev. Lett.**103** (2009), 211102

The relative yields of spectator neutrons and protons reflect their ratio at the nuclear periphery which remains beyond the overlap of colliding nuclei. With the latest version of the Abrasion-Ablation Monte Carlo for Colliders model (AAMCC)[8)] we calculate the yields of spectator neutrons and protons in ^{208}Pb- ^{208}Pb collisions at the LHC and show their sensitivity to the parameters of NS.

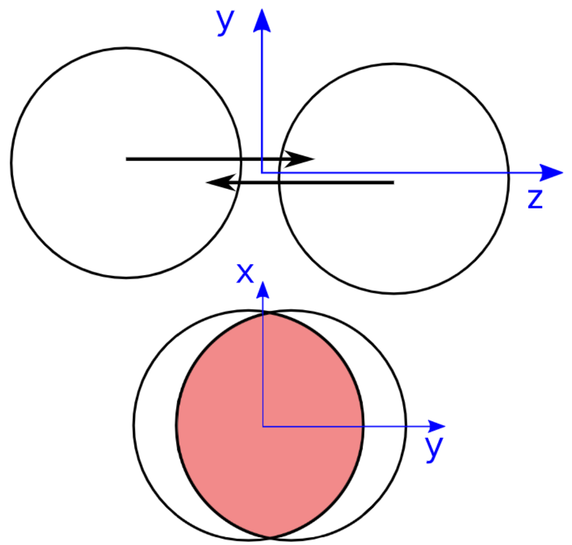

Fig. 2: General view (top) and beam-eye view (bottom) of central collisions of two equal spherical nuclei. The overlapping area is colored.

[8)] A. Svelticnhyi, I. Pshenichnov. Bull. Russ. Acad. Sci.: Phys. **84** (2020), 911

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AAMCC model

AAMCC is a model designed specifically for describing the properties of spectator matter, which includes unbound spectator neutrons and protons as well as spectator nuclear fragments. The modelling of each collision event consists of several stages.

1. Nucleus-nucleus collisions with Glauber Monte Carlo model. We use Glauber Monte Carlo[9] to model the initial collision geometry. Neutrons and protons are considered as spheres and sampled randomly in 3D space according to the respective density distributions, which were parametrized individually for neutrons and protons with two-parameter Fermi distribution:

$$\rho_{n,p}(r) = \frac{\rho_{0n,p}}{1+\exp(\frac{r-R_{n,p}}{a_{n,p}})}$$

where $\rho_{0n,p}$ are, respectively, the proton and neutron density in the center of the nucleus, $R_{n,p}$ are half-density radii and $a_{n,p}$ are diffuseness parameters. The collision of nuclei at the impact parameter b is simulated: it is assumed that two nucleons have collided if the distance between its centers in the X-Y plane is less than the nucleon effective diameter. Two spectator prefragments consisting of non-interacting nucleons from each of the initial nuclei are formed.

2. Calculation of Excitation energy. At the next stage the excitation energy ε^* of the spectator prefragment is calculated. We employ a hybrid approximation that combines Ericson's formula[10] and ALADIN approximation[11] to calculate ε^*.

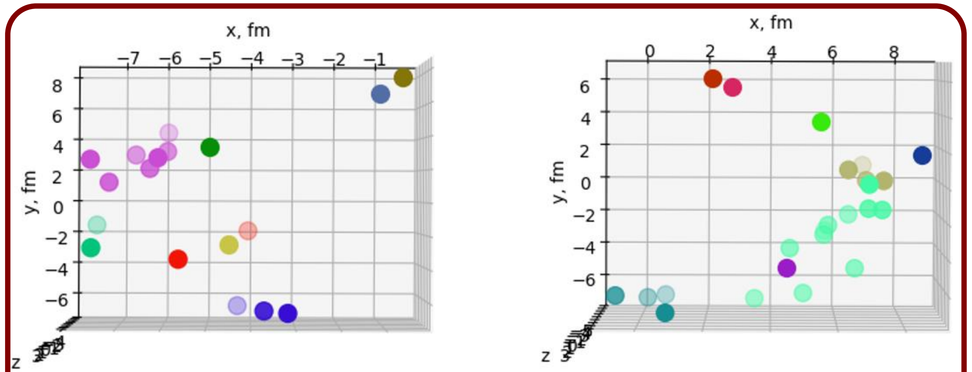

Fig. 3: Cluster representation of two spectator prefragments in central collision. Different colors represent different clusters.

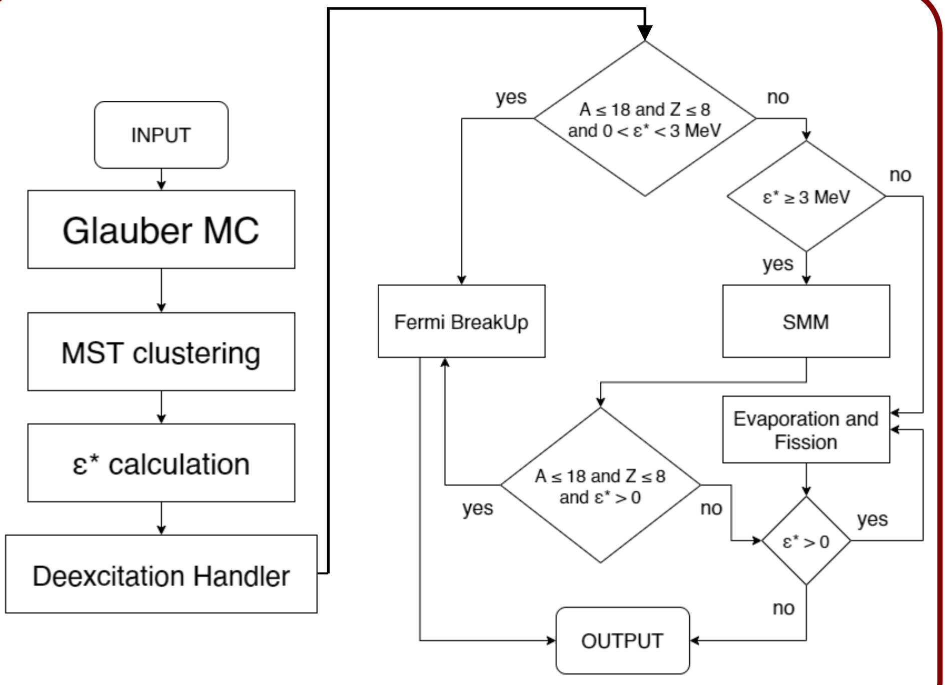

Fig. 4: AAMCC flowchart.

3. MST-clustering. In most versions of abrasion-ablation models the production of a single spectator prefragment as a remnant of the initial nucleus is assumed. However, this can be questioned in most central (ultracentral) collisions of nuclei, in which spectator matter has a characteristic shape of a narrow crescent and therefore its connectedness is lost. One can assume, that because of its specific configuration spectator matter is promptly split into several clusters well before the thermal equilibrium has been achieved. To allow for such pre-equilibrium percolation process we developed an algorithm for the prefragment clusterization based on the construction of a minimum spanning tree (MST)[12]. It uses a graph with nucleons in its vertices. The edge weights of the graph are equal to the modulus of the effective distance between the corresponding nucleons. The effective distance depends on the excitation energy of prefragment due to the effect of nuclear expansion with the increase of temperature[13]. The excitation energy is distributed between clusters proportionally to their masses.

4. Simulation of decays. Finally, the decays of clusters (Fig. 3) are modelled by means of the Evaporation model, Statistical Multifragmentation Model (SMM) and Fermi Break-up model from Geant4 toolkit. Each model is applied depending on the excitation energy and size of each cluster. A general scheme of the AAMCC modelling is shown in Fig. 4.

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10) T. Ericson. Adv. Phys. **9** (1960), 425
11) A.S. Botvina et al. Nucl. Phys. A. **584** (1995), 737
12) R.C. Prim. Bell Syst. Tech. J. **36** (1957), 1389
13) V.E. Viola et al. Phys. Rev. Lett. **93** (2004), 132701

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Calculation results

The cross sections $\sigma(N_n,N_p)$ of emission of given numbers of spectator spectator neutrons N_n and protons N_p were calculated for ^{208}Pb- ^{208}Pb collisions at 5.02 TeV for 0-5% centrality ($0 < b < 3.49$ fm), Fig.5. Four sets of calculations were performed for four different parametrizations (Table 1) of neutron density in ^{208}Pb. Pbpnrw follows the distribution adopted in Ref.[4] to describe the respective data, while the other three parametrizations correspond to the results of PREX collaboration[3]. However, PREX results provide only Δr_{np} value, leaving the exact values of a_n and R_n unknown. Therefore, in PREX1 and PREX2, respectively, we calculate a_n from R_n that is chosen as the lowest and the highest value from theory[2]. In PREX parametrization, R_n is chosen as the average value between «PREX1» and «PREX2» options.

Table 1: Parameters of 2pF neutron density distributions used in this work.

	Pbpnrw	PREX	PREX1	PREX2
R_n, fm	6.69	6.81	6.68	6.94
a_n, fm	0.56	0.60	0.66	0.53
Δr_{np}, fm	0.15	0.283	0.283	0.283

Pnpnrw vs PREX

The comparison of calculation results obtained with Pbpnrw and PREX answers the question of whether $\sigma(N_n,N_p)$ in ultracentral collisions are sensitive to Δr_{np}. As found, the replacement of Pnpnrw by PREX shifts $\sigma(N_n,N_p)$ shown in Fig. 5 towards higher N_n and lower N_p. Such changes are especially visible in Fig. 6 where $\sigma(N_n,N_p)$ are given for N_p=0,1,2,3.

Fig. 7 demonstrates the relative change of $\sigma(N_n,N_p)$ shown in Fig. 6: it is up to 100% for events with low N_n and high N_p and up to 50% for events with high N_n and low N_p. However, the statistical uncertainty of calculations is large for N_p =0 and high N_n despite the fact that 1M events were simulated with AAMCC for 0-5% centrality. One can conclude that accurate measurement of $\sigma(N_n,N_p)$ for N_p=0,1,2,3 will help to determine whether the NS in ^{208}Pb is consistent with Δr_{np}=0.15 fm or rather with Δr_{np}=0.283 fm.

2) M. Centelles et al. Phys. Rev. C. **82** (2010), 054314
3) D. Adhikari et al. Phys. Rev. Lett. **126** (2021), 172502
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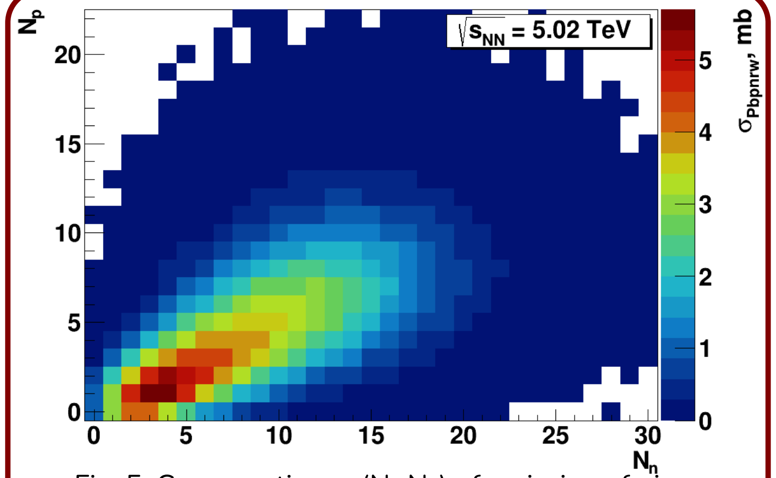

Fig. 5: Cross sections $\sigma(N_n,N_p)$ of emission of given numbers of spectator protons N_p and neutrons N_n obtained with Pbpnrw parametrization.

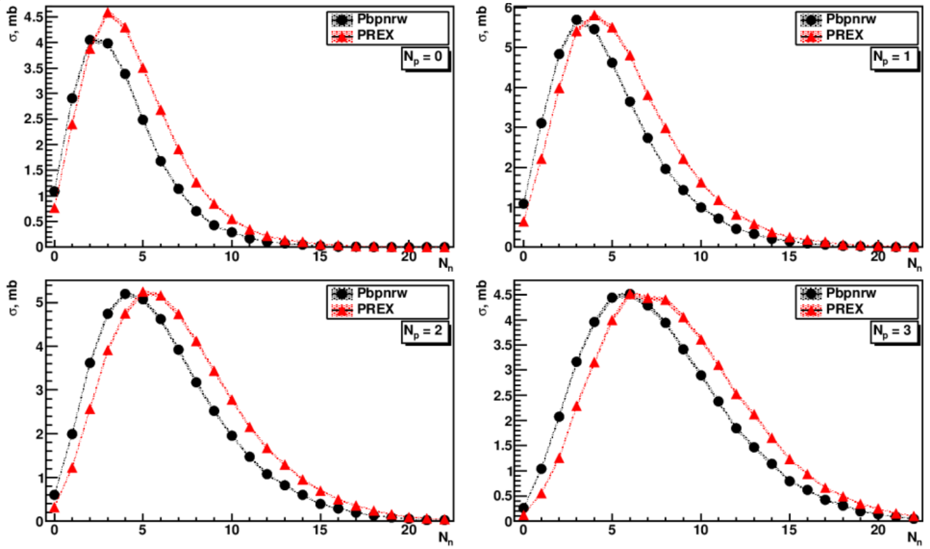

Fig. 6: $\sigma(N_n,N_p)$ for N_p=0,1,2,3 obtained with Pbpnrw and PREX parameterizations, see text for details.

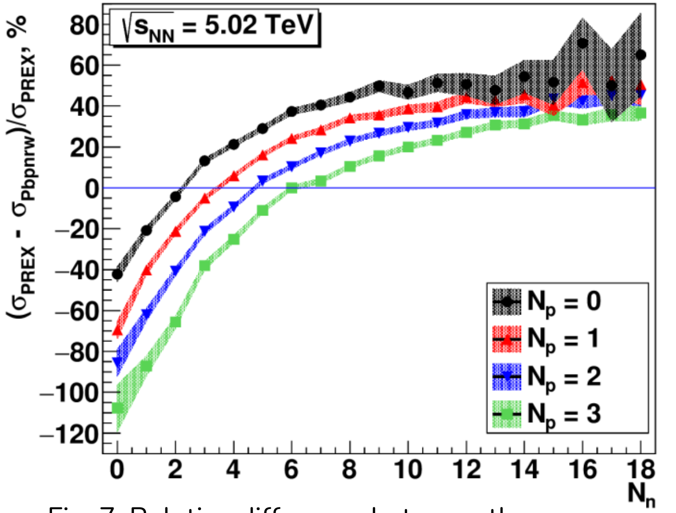

Fig. 7: Relative difference between the cross sections shown in Fig.6.

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PREX1 vs PREX2

As shown above, $\sigma(N_n,N_p)$ calculated for low N_p are quite sensitive to the value of Δr_{np}. Our calculations with AAMCC demonstrate that $\sigma(N_n,N_p)$ are also sensitive to more subtle details of neutron density distributions. In contrast to R_p and a_p which were accurately measured in several experiments, only $\langle r_n^2\rangle^{1/2}$ are usually measured for neutron distributions. Several pairs of R_n and a_n give the same $\langle r_n^2\rangle^{1/2}$ as, for example, PREX1 and PREX2 parametrizations, see Table 1. As seen from Fig.8, $\sigma(N_n,N_p)$ calculated with these two parametrizations differ. Therefore, the measurements of $\sigma(N_n,N_p)$ can help to disentangle different parametrizations even if their $\langle r_n^2\rangle^{1/2}$ are exactly the same. The largest difference is found for N_p=0, as can be seen in Fig. 9 presenting the relative difference between the cross sections shown in Fig. 8. The measurements of $\sigma(0,N_p)$ or $\sigma(N_n,0)$ in ultracentral ^{208}Pb–^{208}Pb collisions at the LHC can be proposed to find the most relevant parametrization of neutron density out of several parametrizations of the same $\langle r_n^2\rangle^{1/2}$ and, consequently, Δr_{np}.

Conclusion

On the basis of our calculations with AAMCC, we conclude that the measurements of the cross sections $\sigma(N_n,N_p)$ of emission of certain numbers of spectator neutrons N_n and protons N_p in ultracentral ^{208}Pb—^{208}Pb collisions at the LHC can be potentially used to restrict the exciting variety of neutron density distributions predicted by different groups of theorists[2] and also to refute or confirm Δr_{np} measured in experiments[3),4)]. The considered effects of NS in ^{208}Pb can be studied in the ALICE experiment at the LHC providing that the measurements of spectator neutrons and protons are properly corrected for the acceptance and efficiency of Zero Degree Calorimeters[14] and combined with the respective procedure for centrality determination[15].

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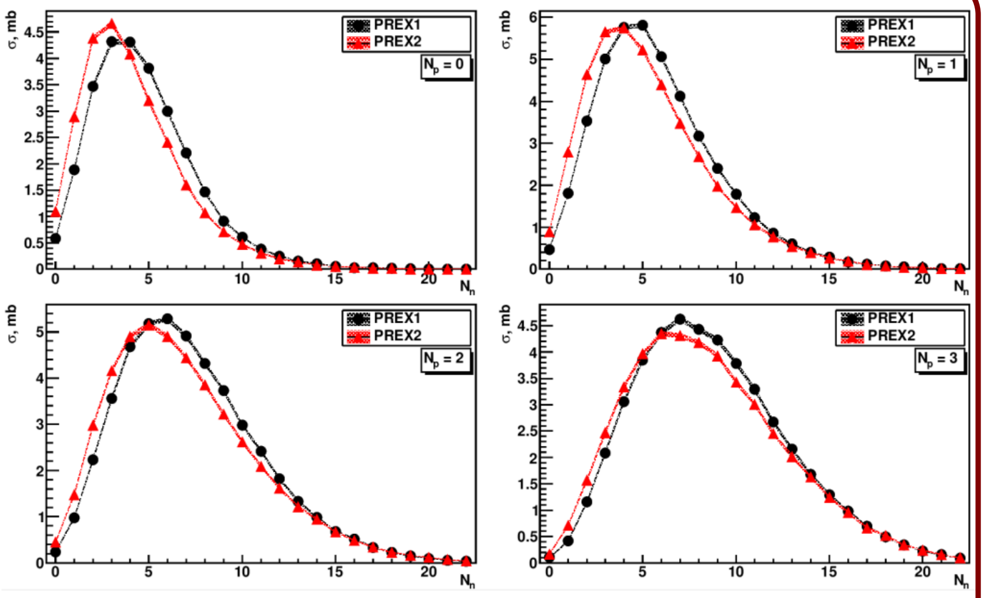

Fig. 8: Same as in Fig.6, but for PREX1 and PREX2 parametrizations.

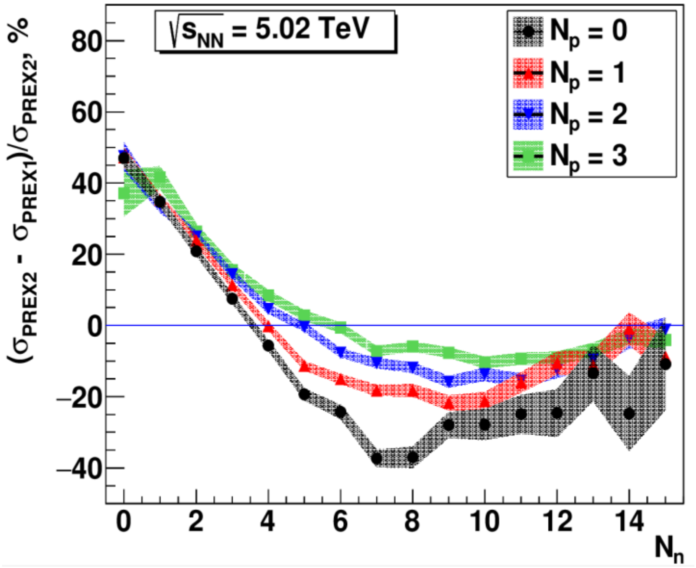

Fig. 9: Relative difference between the cross sections shown in Fig.8.

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4) C.M. Tarbert er al. Phys. Rev. Lett. **112** (2014), 242502

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