

Probing dark matter and CMSSM with same-sign dilepton searches at the LHC

M. Cannoni,¹ O. Panella,² M. Pioppi,³ and M. Santoni⁴

¹*Departamento de Física Aplicada, Facultad de Ciencias Experimentales, Universidad de Huelva, 21071 Huelva, Spain*

²*Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Via Alessandro Pascoli, 06123, Perugia, Italy*

³*Imperial College, South Kensington Campus, London SW7 2AZ, United Kingdom*

⁴*Dipartimento di Fisica, Università di Perugia, Via Alessandro Pascoli, 06123, Perugia, Italy*

We introduce new observables for the study of the inclusive same sign dileptons production at LHC which are built out of ratios of the observed number of same-sign dileptons, both with same $N(\ell, \ell)$ and different flavor $N(\ell, \ell')$. As a case study we apply them to the stau coannihilation region of the constrained minimal supersymmetric standard model. We show that the new variables depend rather mildly on the center of mass energy and how these can be used to constraint the parameter space in the $(m_{1/2}, \tan \beta)$ plane.

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Introduction. The starting of the LHC era will allow us to finally shed light into the last missing piece of the standard model (SM), the Higgs boson, and hopefully to probe the supersymmetric (SUSY) extension of the SM that represents the most popular solution to the hierarchy problem, gauge coupling unification and the nature of dark matter. In the minimal supersymmetric standard model (MSSM) with R-parity conservation and in the mSUGRA inspired constrained version (CMSSM), the lightest neutralino is the lightest SUSY particle (LSP), neutral and stable and one of the favored dark matter (DM) candidates [1].

In the framework of the SM, events in proton-proton (pp) collisions with two isolated same-sign leptons in the final state, or same-sign dileptons (SSD), are very rare. They may come from double gauge boson production WZ , WW and decays, double parton scattering or ttW , the last processes yet to be observed in proton-proton collisions. This makes this signature very natural to look for new physics. Isolated SSD represent also a standard search channel for SUSY models [2]. The main processes that lead to inclusive final states SSD in proton-proton collisions are gluino pair production $pp \rightarrow \tilde{g}\tilde{g}$, gluino-squark associate production $pp \rightarrow \tilde{g}\tilde{q}$ and squark pair production $pp \rightarrow \tilde{q}\tilde{q}'$. Cascade decays from these pairs produce easily $\chi_1^\pm \chi_1^\pm$, $\chi_1^\pm \chi_2^0$, $\chi_2^0 \chi_2^0$ that decay and eventually lead to SSD that can be of the same flavor (SFSSD) $e^\pm e^\pm$, $\mu^\pm \mu^\pm$, $\tau^\pm \tau^\pm$ or of different flavor (DFSSD), $e^\pm \mu^\pm$, $\mu^\pm \tau^\pm$, $e^\pm \tau^\pm$. The signal was searched for by CDF at Tevatron [3] and both the CMS [4] and ATLAS [5, 6] collaborations have already performed searches for these particular class of events in the data sample of the final 2011 run with the LHC working at the center of mass energy $\sqrt{s} = 7$ TeV and a total integrated luminosity of about 5 fb^{-1} . No evidence for new physics was found and upper bounds on the number of SSD were used to set constraints on the parameter space of the CMSSM.

In this brief report we show that by simply counting the number of SSD pairs $N(ee)$, $N(\mu\mu)$, $N(\tau\tau)$, $N(e\mu)$, $N(e, \tau)$, $N(\mu\tau)$ it is possible to obtain direct information on fundamental CMSSM parameters like, for example, $m_{1/2}$ and $\tan \beta$. The proposed variables, that are build

from the number of SSD, may give preliminary informations on the fundamental parameters of the underlying theory. Once these are known, one has a guide to which decay chain are likely to show up in the data yields and thus measure the masses of the SUSY particles. As a practical example we study the SSD signature in connection with the so-called stau co-annihilation region ($\tilde{\tau}_{\text{CR}}$) of the CMSSM parameter space that is of interest for dark matter searches.

Observables for the SSD signal. Let us consider gluino pair production. The gluino is a Majorana particle and decays with equal branching fractions (\mathcal{B}) to particles and antiparticles; this property allows to have two same sign charginos from the decay chains of the pair of sparticles produced in the pp collisions. The two same-sign charginos lead to final states with SSD, neutrinos and LSP. Under this assumption, we introduce the new observables as follows. The cross section can be approximated by $\sigma(pp \rightarrow 2\chi_1^\pm + X) \simeq \sigma(pp \rightarrow \tilde{g}\tilde{g}) \times \mathcal{B}(\tilde{g} \rightarrow q\tilde{q})^2 \times \mathcal{B}(\tilde{q} \rightarrow q'\chi_1^\pm)^2$. We synthetically call this cross section $\sigma_{\chi\chi}^{\tilde{g}\tilde{g}}$ and the branching ratios corresponding to the various chargino's decay chains leading to a lepton plus undetected particles (neutrinos and LSP) plus hadronic jets, $\chi_1^\pm \rightarrow \ell + X$ with $\mathcal{B}_{i,\ell}$, $\ell = e, \mu, \tau$. For a given integrated luminosity, the number of SFSSD is estimated as $N(\ell\ell) \propto \sigma_{\chi\chi}^{\tilde{g}\tilde{g}} \times (\sum_i \mathcal{B}_{i,\ell})^2$, while the number of DFSSD is instead $N(\ell\ell') \propto 2\sigma_{\chi\chi}^{\tilde{g}\tilde{g}} (\sum_i \mathcal{B}_{i,\ell}) \times (\sum_i \mathcal{B}_{i,\ell'})$. The factor 2 takes into account the fact that the leptons come from two identical charginos. In reason of the expected similar behavior of the first two lepton generations and the peculiar role held by the leptons and sleptons of the third family, we consider the ratios:

$$\frac{N(l\tau)}{N(\tau\tau)} = 2R, \quad \frac{N(ll)}{N(\tau\tau)} = R^2 \quad (1)$$

with $l = e, \mu$ and

$$R = \frac{\sum_i \mathcal{B}_{i,l}}{\sum_i \mathcal{B}_{i,\tau}}. \quad (2)$$

We remark that when all contributing mechanisms are considered the total cross section ($\sigma_{\chi\chi} = \sigma_{\chi\chi}^{\tilde{g}\tilde{g}} + \sigma_{\chi\chi}^{\tilde{q}\tilde{q}'} +$

$\sigma_{\chi\chi}^{\tilde{q}\tilde{q}} \dots$) drops out exactly. Considering the relations (1), we finally define the variables:

$$N_1 = \frac{1}{2} \frac{N(e\tau) + N(\mu\tau)}{N(\tau\tau)} \approx 2R, \quad (3)$$

$$N_2 = \frac{1}{4} \frac{N(ee) + N(\mu\mu) + N(e\mu)}{N(\tau\tau)} \approx R^2. \quad (4)$$

We choose the normalization factors 1/2 and 1/4 in such a way that N_1 and N_2 are average quantities that should take values similar to the basic ratios in Eq. (1). By definition, these variables should depend very mildly on the production cross section and on the center of mass energy of the machine. If we relax the assumption that the SSD are produced through a pair of charginos $\chi_1^\pm \chi_1^\pm$ the above Eq. (3) and Eq. (4) are still valid to a very good degree of approximation although the cancellation of the cross section does not apply any longer.

Dark matter and the CMSSM. The CMSSM is specified by assigning the value of the common gauginos mass $m_{1/2}$, the common scalars mass m_0 , the common trilinear scalar coupling A_0 at a certain unification energy scale. The other fundamental parameter is $\tan\beta$, the ratio of the two vacuum expectation values of the Higgs doublet. Further we assume the Higgs mixing parameter μ to be positive. The $\tilde{\tau}_{\text{CR}}$ is one of the regions [7] of the parameter space in which the relic density of the neutralino as main dark matter component is compatible with the WMAP [8] measurement of the cosmic microwave background anisotropies, $0.096 < \Omega h^2 < 0.128$ at 3σ . In the $\tilde{\tau}_{\text{CR}}$ [9], the neutralino relic density is controlled by co-annihilation before the freeze-out between the LSP and the lightest stau, $\tilde{\tau}_1$, which is the next LSP with a mass splitting $\Delta m = m_{\tilde{\tau}_1} - m_{\chi_0^0}$ of few GeVs.

In literature there exist theoretical studies discussing signatures of the $\tilde{\tau}_{\text{CR}}$ at LHC. In Refs. [10] the authors show that with the reconstruction of the decays $\chi_2^0 \rightarrow \tilde{\tau}_1 \tau \rightarrow \tau\tau\chi_1^0$ at the end of the gluinos and squarks cascade, it is in principle possible to measure the masses of the relevant particles and infer the values of the CMSSM parameters. In Ref. [11] it is argued that the measurement of the tau polarization in the $\tilde{\tau}_1 \rightarrow \tau\chi_1^0$ can be useful to measure the mass difference Δm . The smallness of Δm is an important quantity for the phenomenology at LHC [10], as it sets the scale of the transverse momentum of the leptons at the end of the cascade decays, but also for indirect detection signals in astrophysical searches with gamma ray, as it is responsible for spectral features at the endpoint of the gamma spectrum [12] and for the large cross section for the annihilation into a $\tilde{\tau}_1$ pair at the galactic center [13].

We consider the parameter space with fixed trilinear scalar coupling $A_0 = 0$, which is used as benchmark for supersymmetric studies at the LHC. The stau-coannihilation strips shown in Figure 1 are obtained with microOMEGAs [14] using SoftSusy [15] as supersymmetric mass spectrum calculator, imposing WMAP constraints on the relic density accelerator constraints on the lightest Higgs, $m_h > 114.4$ GeV, chargino mass

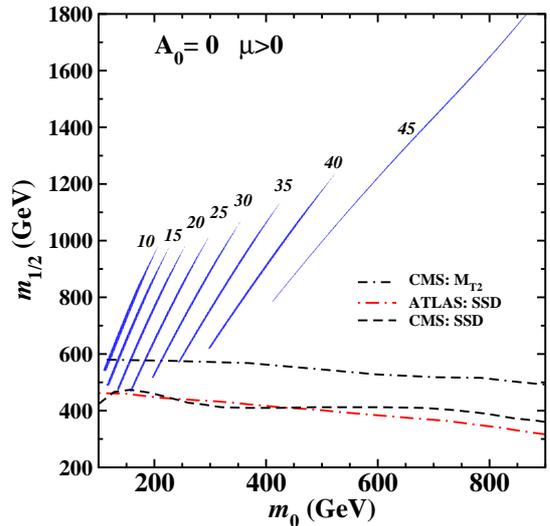


Figure 1. Regions of the CMSSM parameter space in the $(m_0, m_{1/2})$ plane which satisfy the WMAP constraint on the relic density $0.096 < \Omega h^2 < 0.128$ for different values of $\tan\beta$ that is given by the numbers above the strips. The dashed, dot-double-dashed and dot-dashed lines are respectively the 95% CL exclusion curves obtained by CMS [4] and ATLAS [5, 6] with the SSD search and the CMS SUSY search with hadronic final states [16].

$m_{\chi_1^+} > 103.5$ GeV and the flavor physics constraint from bottom mesons decays $B_s \rightarrow X\gamma$ and $B_s \rightarrow \mu^+\mu^-$. In Figure 1 we also report the 95% CL exclusion curves obtained by CMS [4] and ATLAS [5, 6] with the SSD search and the CMS SUSY search with hadronic final states [16]. As can be seen the first two years of operation of the LHC could only marginally exclude the parameter space of interest in this work.

Analysis. To check the validity of the new observables we make a preliminary simulation selecting points along the strips with $\tan\beta = 10$ and $\tan\beta = 40$. The theoretical ratio R defined in Eq. (2) is calculated in each point using SusyHIT [17] to compute the branching fractions. All informations of the selected models are then passed to Pythia 8.1 [18] to generate events in p-p collisions at $\sqrt{s} = 14$ TeV. We have generated 4×10^6 events for each CMSSM point requiring that in the final state there are same-sign leptons, jets and missing energy. We find that Eqs. (3) and (4) are well satisfied, the number of SSD coming from two same-sign χ_1^\pm is correctly predicted in terms of the theoretical ratio of the chargino's branching ratios R . When all production mechanisms are allowed, and especially at large $\tan\beta$, the number of taus SSD is contaminated by the decay chain involving the second neutralino, $\chi_1^\pm \chi_2^0$ and $\chi_2^0 \chi_2^0$ thus, depending on the point of the parameter space, deviations up to 50% are observed.

We now want to relate $N_{1,2}$ to $m_{1/2}$ and $\tan\beta$, the two CMSSM parameters that are the more interesting from the dark matter phenomenology point of view. In fact in

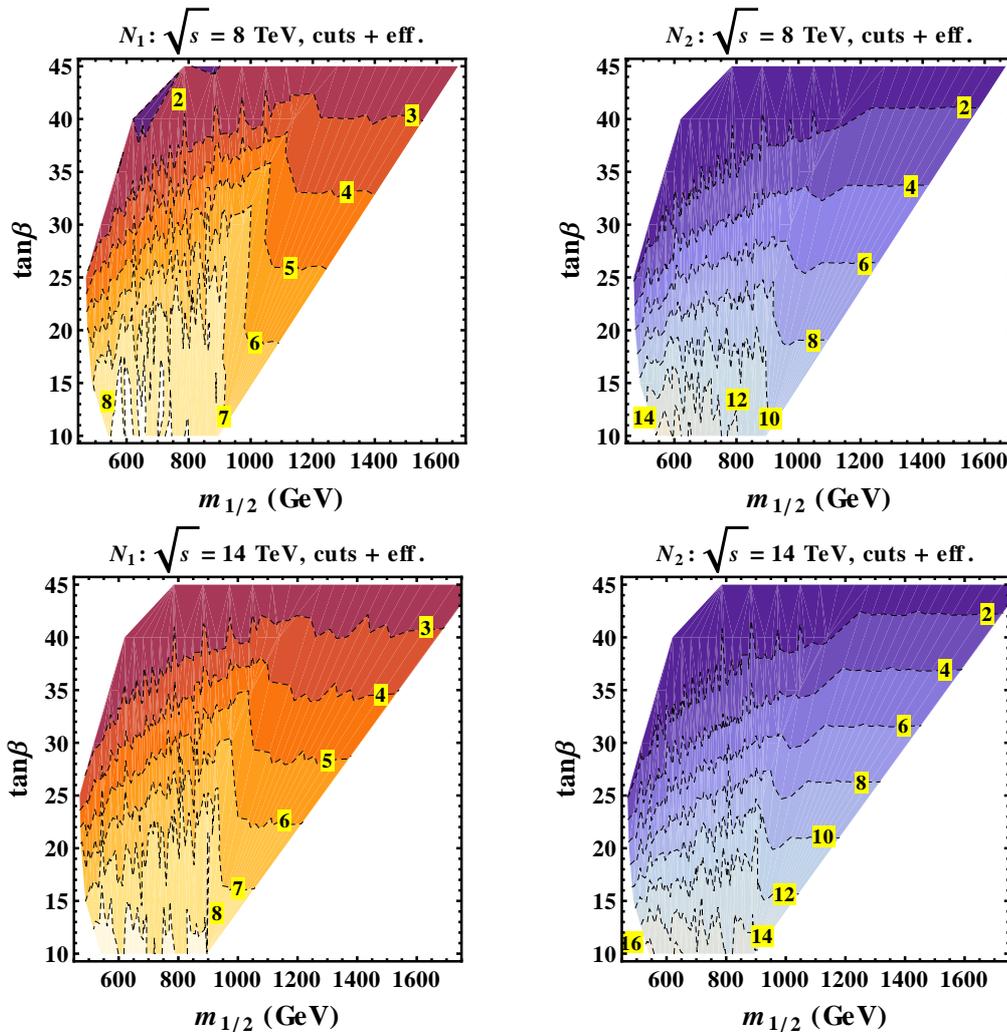


Figure 2. Contour maps in the plane $(m_{1/2}, \tan\beta)$ of the observables N_1 (left column) and N_2 (right column) as defined in respectively in Eq. (3) and Eq. (4). Top plots are obtained with a simulation with $\sqrt{s} = 8$ TeV, the bottom plots with $\sqrt{s} = 14$ TeV. The cuts and efficiencies are discussed in the text.

Ref. [20] it was found that the neutralino mass along the strips of Fig. 1 is roughly given by $m_\chi = 0.44 \times m_{1/2} - 16$ GeV for all the values of $\tan\beta$. Furthermore the spin-independent neutralino-nucleon cross section, and hence direct detection rates, strongly depend on $\tan\beta$.

In order to cover the full parameter space we took 20 equally spaced points (in $m_{1/2}$) along each strip of Fig. 1 and the corresponding value of m_0 is chosen to be the center value of the strip width along the m_0 direction. We carry out the simulation with 4×10^6 events for each model point. For realistic results we employ the efficiency model for the SSD signal developed by the CMS collaboration that allows to obtain realistic results at the generator level bypassing the full detector simulation [4, 19]. Tau leptons are identified by their hadronic decays, τ_h . We imposed all the observed leptons e, μ, τ_h to have a transverse momentum larger than 15 GeV, and to be within the acceptance of the ATLAS and CMS detectors ($|\eta| < 2.4$). The search region to detect experimentally

SSD events is defined by two additional variables: the transverse hadronic energy $H_T = \sum_{jet} p_{T,jet}$, determined by all the quarks and gluons with $p_T > 40$ GeV within the detector acceptance and E_T^{miss} , the missing transverse energy determined by all the undetectable particles (neutrinos and LSP) in the event and the visible particles outside the detector acceptance. On top of the lepton selection we require $H_T > 450$ GeV and $E_T^{miss} > 120$ GeV. The SSD detection efficiency is simulated using the formulas given in [4, 19], where the probability for an event to pass the selection cuts is given as a function of the H_T , E_T^{miss} and the p_T of the two same sign leptons. Events with three or more selected leptons are discarded. Some of the SSD events may even originate from a multi-lepton final state, typically with 3 or 4 leptons, where only two of them satisfy the selection criteria. The introduction of the kinematic cuts (especially those on p_T) lessen the accuracy of the approximations in Eqs. (3) (4), which have however been verified to hold when no cuts are ap-

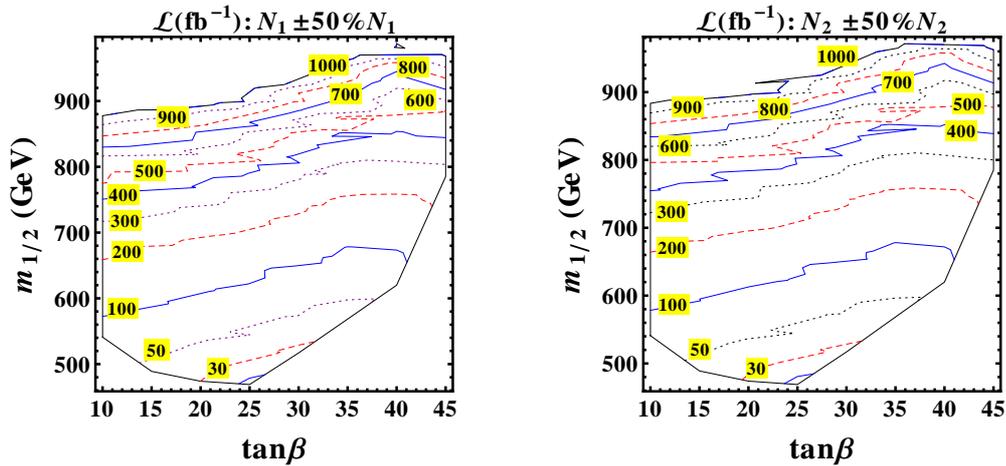


Figure 3. Curves in the $(m_{1/2}, \tan\beta)$ plane showing the luminosity in fb^{-1} (boxed values) necessary to measure the observables N_1 (left panel) and N_2 (right panel) with $\pm 50\%$ at the $\sqrt{s} = 14$ TeV run, given the CMS acceptance cuts and efficiency model discussed in the text.

plied. We emphasize that the results of the simulation presented here are obtained considering all the production mechanisms and without imposing any selection on the decay chain that lead to SSD.

We thus build the contour maps of N_1 and N_2 in the $(m_{1/2}, \tan\beta)$ plane that are shown in left panels of Fig. 2, $\sqrt{s} = 8$ TeV, and right panels, $\sqrt{s} = 14$ TeV. Fig. 3 shows the luminosity necessary to achieve an accuracy of 50% in the measurement of the observables N_1 (left panel) of N_2 (right panel) at $\sqrt{s} = 14$ TeV. We consider here only the statistical error. Systematic errors can be neglected because $N_{1,2}$ are ratios of observed yields measured using the same selection criteria and obtained in the same experimental conditions. With the $\sqrt{s} = 14$ TeV run that will follow after the LHC upgrade, with the possibility of accumulating up to 100 - 1000 fb^{-1} of luminosity, will offer the possibility to probe large portions of the parameter space in the plane $(m_{1/2}, \tan\beta)$ up to values of $m_{1/2} \approx 900$ GeV. We do not show the corresponding of Fig. 3 for $\sqrt{s} = 8$ TeV because the production cross sections are smaller and the planned 20 fb^{-1} are not enough to get $N_{1,2}$ with the same accuracy. The rather small differences that can be seen in Fig. 2 in the values that $N_{1,2}$ take at the two center of mass energies and in Fig. 3 in luminosity curves, confirm our expectation that to a first approximation the observables $N_{1,2}$ are independent of the center of mass energy of the collider.

Comments and summary. Both the CMS and ATLAS collaborations have released results that hint for a possible evidence of a Higgs with mass around 124-126 GeV in the first $\sim 5 \text{fb}^{-1}$ of data obtained with $\sqrt{s} = 7$ TeV [21, 22]. The light Higgs mass in the MSSM receives a large contribution from radiative corrections thus represents a crucial quantity to test any SUSY model. Updated analysis of the CMSSM parameter space including the new Higgs data [23] show that $A_0 \neq 0$, large $\tan\beta$ and heavy SUSY spectrum are now generally preferred.

In the case of the confirmation of the discovery it would be interesting to make detailed study of the SSD yield expected from the smaller parameter space, compared to the one explored here, compatible with that Higgs mass.

In our analysis we have excluded those model points found in the right edge of the strips at high $m_{1/2}$ in which the mass difference between the $\tilde{\tau}_1$ and the LSP ($\tilde{\chi}_1^0$) is less than the mass of the tau lepton ($m_\tau \approx 1.7$ GeV). In this case the two-body decay $\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \tau$ is forbidden. The $\tilde{\tau}_1$ decays only into suppressed three body final states and is a long lived charged particle that have been proposed as a solution to the lithium problem [24]. Once produced they can decay outside the detector [25]. The sudden reduction of the number of tau SSD $N(\tau\tau)$ is reflected in much higher numerical values of N_1 and N_2 (in particular those of N_2). For a recent study connecting long-lived staus and SSD in models with the gravitino as the dark matter candidate see Ref. [26].

In summary, we have shown that if an excess of SSD relative to the SM yield is observed then a measurement of the proposed observables $N_{1,2}$ within a given accuracy will allow to pin down a given portion of the stau co-annihilation region ($\tilde{\tau}_{\text{CR}}$) of the CMSSM parameter space in the $(m_{1/2}, \tan\beta)$ plane. This will in turn also give access to other informations. For example if we restrict the possible values of $m_{1/2}$ to a certain range then this will of course also restrict the possible values of m_0 since these two parameters are related according to the WMAP strips of Fig. 1. The proposed method can evidently be extended to all SUSY models predicting events with final states containing SSD or to different extensions of the standard model that contain Majorana particles such as models with weak scale heavy Majorana neutrinos [27].

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Note added. After submitting this paper for publication both the ATLAS and CMS experiments have reported new evidence at 5σ level for a scalar particle of mass around 125 GeV compatible with the Higgs boson [28]. As already discussed above, and in view of the newly reported experimental evidence on the Higgs

mass, the choice of the trilinear scalar parameter $A_0 = 0$ is not allowed any longer since the radiative corrections needed to achieve $m_h = 125$ GeV are driven by the couplings of the third generation sfermions and especially so the Higgs-stop-stop trilinear coupling A_t must be large, implying large and negative values for A_0 . The allowed parameter space of the CMSSM in light of the Higgs discovery is being still more severely constrained and according to some authors this model is already disfavored by the data, while others authors do not agree with this conclusion. We refer the reader to Refs. [23, 29] for a list of recent studies showing these different points of view.

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