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Strangeness of the nucleon from Lattice Quantum Chromodynamics

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Abstract

We present a non-perturbative calculation of the strangeness of the nucleon y_N within the framework of lattice QCD. This observable is known to be an important cornerstone to interpret results from direct dark matter detection experiments. We perform a lattice computation for y_N with an analysis of systematic effects originating from discretization, finite size, chiral extrapolation and excited state effects leading to the value of $y_N = 0.173(50)$. The rather large uncertainty of this value of y_N is dominated by systematic uncertainties which we were able to quantify in this work.

I. INTRODUCTION

The question of the exact composition of the nucleon, i.e. what are the different quark contents of the proton and neutron, is a long standing problem (see for instance [1]) which can be addressed only through non perturbative methods. In this paper, we will resort to lattice QCD techniques to address the calculation of the strange quark content of the nucleon which is important to know not only for addressing the fundamental question of the nucleon composition, but also, because it plays a most important role in the search for dark matter, as will be discussed in more detail below.

A very useful measure for the strange quark content is the y_N -parameter,

$$y_N \equiv \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle}, \quad (1)$$

where u, d and s denote respectively the up, down and strange quark fields. We will refer to y_N as the *strangeness of the nucleon* in the following.

As mentioned above, the y_N parameter plays an important role in the context of dark matter searches. Experiments which aim at a direct detection of dark matter [2–6] are based on measuring the recoil energy of a nucleon hit by a dark matter candidate. Even if in these processes a dark matter particle would not be detected directly, such experiments allow to provide bounds on the nucleon dark matter cross section which can in turn be translated into constraints on models of New Physics. In many supersymmetric scenarios [7] and in some Kaluza-Klein extensions of the standard model[8, 9] the dark matter nucleon interaction is mediated through a Higgs boson. In such a case the theoretical expression of the spin independent scattering amplitude at zero momentum transfer involves the y_N -parameter. In fact, even rather small changes of the poorly known value of y_N can be responsible for a variation of one order of magnitude of the nucleon dark matter cross section. Having a better determination of the y_N parameter would thus provide better estimates on the size of the cross-section or more reliable constraints on dark matter models.

The y_N -parameter is related to the ratio of the pion-nucleon ($\sigma_{\pi N}$) and the flavour non-singlet (σ_0) σ -terms, defined as

$$\sigma_{\pi N} \equiv m_l \langle N|\bar{u}u + \bar{d}d|N\rangle, \quad \sigma_s \equiv m_s \langle N|\bar{s}s|N\rangle \quad (2)$$

$$\sigma_0 \equiv m_l \langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle \quad (3)$$

where m_l denotes the average up and down quark mass, and m_s the strange quark mass and where we also introduced the strange σ -term σ_s . The σ -terms, $\sigma_{\pi N}$ and σ_0 can be estimated within the framework of chiral effective field theories and using the relation

$$y_N = 1 - \frac{\sigma_0}{\sigma_{\pi N}} \quad (4)$$

also estimates of y_N can be provided.

To be more specific, the value of $\sigma_{\pi N}$ can be extracted from the pion nucleon cross section data at an unphysical kinematics, known as the Cheng-Dashen point. Values for $\sigma_{\pi N}$ extracted in this way read $\sigma_{\pi N} = 45 \pm 8$ MeV from ref. [10] (GLS) and $\sigma_{\pi N} = 64 \pm 7$ MeV from ref. [11] (GWU). A more recent result has been obtained in ref. [12] (AMO) which gives $\sigma_{\pi N} = 59 \pm 7$ MeV[12]. The value of σ_0 can be computed analyzing the breaking of $SU(3)$ in the spectrum of the octet of baryons. Following this strategy an estimate for this quantity is given e.g. in [13] and reads $\sigma_0^I = 36 \pm 7$ MeV. A more recent calculation using an improved method based on Lorentz covariant chiral perturbation theory with explicit decuplet-baryon resonance fields suggests $\sigma_0^{II} = 58 \pm 8$ MeV[14].

Using the aforementioned values for $\sigma_{\pi N}$ and σ_0^I we obtain the following phenomenological estimates of the y_N parameter :

$$y_N^{I, \text{GLS}} = 0.20(21), \quad y_N^{I, \text{GWU}} = 0.44(13), \quad y_N^{I, \text{AMO}} = 0.39(14). \quad (5)$$

Using σ_0^{II} we obtain :

$$y_N^{II, \text{GLS}} = -0.29(29), \quad y_N^{II, \text{GWU}} = 0.09(16), \quad y_N^{II, \text{AMO}} = 0.02(17). \quad (6)$$

Note that these values from effective field theory (EFT) and phenomenology are affected by substantial errors leading to correspondingly large uncertainties for the cross-section for dark matter detection[15].

In this paper, we present a first principle computation of the strangeness of the nucleon using lattice QCD techniques. The difficulty of such a computation has been for a long time that, due to the appearance of dis-connected, singlet contributions, the error for y_N has been very large. Consequently, it has not been possible to obtain a precise enough value which can be used for calculating the cross-section reliably, see later in this manuscript for a discussion of various lattice computations.

In ref. [16] we were able to make a significant step forward by using a setup of maximally twisted mass fermions which avoids any mixing in the renormalization of the σ -terms and

hence y_N does not need to be renormalized. In addition, by employing special noise reduction techniques, amenable for our setup, we could achieve a significant improvement in the signal to noise ratio for y_N . The shortcoming of our result in ref. [16] has been that, being a feasibility study only, y_N was obtained at only one value of the lattice spacing, a single finite volume and only one quark mass.

Here we want to extend the calculation of ref. [16] by using different lattice spacings, finite volumes and quark masses such that we can probe effects of the discretization, the finite volume and non-physical quark masses. In addition, we now have available a high statistics analysis of excited state effects which, as we will see below, are potentially very dangerous for the computations of y_N . Being able to address the systematic uncertainties appearing in a lattice calculation of y_N , we believe that our computation can provide a reasonable estimate of the y_N parameter based on QCD alone and not resorting to effective field theories.

II. LATTICE QCD CALCULATION

In our computation of y_N we use gluon field configurations generated by the European Twisted Mass Collaboration (ETMC) [17] employing maximally twisted mass fermions. In particular, the setup used here includes a mass-degenerate light up and down quark doublet as well as a strange-charm quark pair, a situation which we refer to as the $N_f = 2 + 1 + 1$ setup. In our analysis we have used two values of the lattice spacing, $a = 0.082$ fm and $a = 0.064$ fm, to examine lattice cut-off effects. We have a number of light quark masses leading to pseudo scalar meson masses m_{PS} covering the range from 490 MeV to 220 MeV. This mass range allows us to perform the chiral limit with m_{PS} approaching the physical pion mass m_π . We finally remark that we use a mixed action setup with Osterwalder-Seiler quarks in the heavy quark sector which avoids any mixing due to the iso-spin violation otherwise occurring in the twisted mass sea quark action. This mixed action still enjoys the automatic $O(a)$ -improvement of twisted mass fermions.

The basic quantity needed for the evaluation of y_N is the ratio of correlation functions

$$R(t, t_s) \equiv \frac{\sum_{\mathbf{x}_s, \mathbf{x}} \langle \bar{J}(\mathbf{x}_s) (O_s(x) - \langle O_s(x) \rangle) J(0) \rangle}{\sum_{\mathbf{x}_s, \mathbf{x}} \langle \bar{J}(\mathbf{x}_s) (O_1 - \langle O_1(x) \rangle) J(0) \rangle}, \quad (7)$$

where J is an operator with quantum numbers of the nucleon and $O_1 = \bar{u}u + \bar{d}d$ and

$O_s = 2\bar{s}s$. The calculation of the ratio of eq. (7) is particularly challenging because of very noisy contributions originating from dis-connected diagrams. In Eq. (7), $x = (t, \mathbf{x})$ and $x_s = (t_s, \mathbf{x}_s)$ denote the Euclidean time and space coordinates. We will refer to t and t_s as the source-operator separation and the source-sink separation, respectively. We have shown in [16] that $R(t, t_s)$ does not need to be renormalized since no mixing in the renormalization pattern appears. The ratio $R(t, t_s)$ has the following asymptotic behaviour:

$$R(t, t_s) = y_N + \mathcal{O}(e^{-\Delta M t}) + \mathcal{O}(e^{-\Delta M(t_s - t)}) \quad (8)$$

where we have denoted with ΔM the mass gap between the ground state and the first excited state of the nucleon. Note that the two additional contributions to y_N are non-vanishing as long as t and t_s are finite. These two contributions are a systematic effect inherent to any lattice calculation and will be referred to as excited state contamination in the following.

More details on our setup and on the technique to evaluate Eq. (7) can be found in [16, 18] where we discuss in particular the crucial points of our improved variance reduction technique and of the non-perturbative renormalization.

III. CHIRAL EXTRAPOLATION

A crucial element in the determination of y_N is the extrapolation to the physical value of the pion mass. Ideally, to this end chiral perturbation theory should be used. Let us therefore shortly sketch, how the leading order chiral perturbation theory behaviour of y_N can be obtained.

Using the Feynman Hellman theorem, the sigma terms can be related to the derivative of the nucleon mass with respect to the light or strange quark masses:

$$\sigma_{\pi N} = m_l \frac{\partial m_N}{\partial m_l}, \quad \sigma_s = m_s \frac{\partial m_N}{\partial m_s}, \quad (9)$$

and the y_N parameter can be written as follows:

$$y_N = 2 \frac{\partial m_N}{\partial m_s} \left(\frac{\partial m_{\text{PS}}^2}{\partial m_l} \frac{\partial m_N}{\partial m_{\text{PS}}^2} \right)^{-1} \quad (10)$$

where we have neglected the strange quark mass dependence of m_{PS}^2 .

The nucleon mass dependence on the pion mass can be described by the leading one-loop result in $SU(2)$ heavy baryon chiral perturbation theory (HB χ PT) [19] which reads:

$$m_N(m_{\text{PS}}) = m_N^{(0)} - 4c^{(1)}m_{\text{PS}}^2 - \frac{3g_A^2}{32\pi f_\pi^2}m_{\text{PS}}^3 + \mathcal{O}(m_{\text{PS}}^4). \quad (11)$$

Here g_A is the axial coupling of the nucleon and f_π is the pion decay constant. We take the physical value $g_A = 1.2695$ and use the convention where the physical value of f_π is 92.4 MeV. Note that the leading order expansion of the the light sigma term reads $\sigma_{\pi N} = -4c^{(1)}m_{\text{PS}}^2$ and thus $c^{(1)}$ has to be strictly negative to give a positive value for $\sigma_{\pi N}$.

For the dependence of the nucleon strange sigma terms as a function of the pseudo-scalar meson mass, we use the following ansatz:

$$\langle N|\bar{s}s|N\rangle = d_0 + d_1m_{\text{PS}}^2 + \mathcal{O}(m_{\text{PS}}^3) \quad (12)$$

with d_0, d_1 as fit coefficients. Similar expressions can be derived also from EFT, see for instance [20].

Taking also the leading order chiral perturbation theory expression of the pseudo-scalar meson mass $m_{\text{PS}}^2 = 2Bm_l$ into account, the leading expression for the y_N parameter reads:

$$y_N = y_N^{(0)} + y_N^{(1)}m_{\text{PS}} + \mathcal{O}(m_{\text{PS}}^2) \quad (13)$$

where

$$y_N^{(0)} = \frac{d_0}{-4Bc^{(1)}}, \quad y_N^{(1)} = \frac{9d_0g_A^2}{2B\pi(4c^{(1)})^232f_\pi^2} \quad (14)$$

This simple leading order expression predicts that y_N is an increasing function of m_{PS} . As we will see in the following, this contradicts the behaviour of our data for y_N . An interpretation of this mismatch is that higher orders of chiral perturbation theory would be needed to describe our results. However, since this implies further free fit parameters more data points than we have presently would be necessary to be able to apply such higher order expressions. In addition the validity of such a chiral expansion is questionable for pion masses above 300 MeV (see e.g [21]) and thus cannot be applied to describe most of the lattice data presented here. This lack of being able to apply chiral perturbation theory led us to use simple linear and quadratic fit ansätze in the pseudo scalar mass, as will be discussed below.

IV. RESULTS AND SYSTEMATIC EFFECTS

Our results for y_N are shown in Fig. 1 as a function of m_{PS} . The chiral behaviour of the y_N parameter is a difficult issue and we are not aware of a direct computation for the quark mass dependence of y_N itself in the framework of EFT. As discussed above, our set of data points is insufficient to apply higher order chiral perturbation theory. It turned out that the number of fit parameters is too large to obtain reliable fits and, with our data set, it was not possible to disentangle different orders of the chiral expansion. We therefore follow here the approach to use simple polynomial fit ansätze for the pion mass dependence of y_N .

In the graph, we use different values of the lattice spacing a , the physical linear extent of the box L and the source-sink separation t_s . We perform an extrapolation to the physical pion mass employing a linear fit in m_{PS} (solid line) and a quadratic one (dashed line). Note that only the points marked by filled symbols are included in the fits and that only data for $m_{\text{PS}} < 400$ MeV are included in the linear fit. Open symbols are solely used to demonstrate systematic effects which will be discussed in more detail below. The vertical dotted line in Fig. 1 marks the physical value of the pion mass.

In our Osterwalder-Seiler setup the value of the valence strange quark mass has been tuned in order to match the Kaon mass obtained in the unitary setup. In principle, also other matching conditions could be used leading to different values of the valence strange quark mass. By computing y_N for valence strange quark masses varying them by about 40% we could not detect any significant change in y_N within our statistical error. Hence, below we will not consider the tuning of the valence strange quark mass as a source of systematic errors.

As mentioned above, the excited states contamination needs to be scrutinized carefully in order to obtain reliable results. This is particularly delicate in the case of nucleon matrix elements because the statistical error grows exponentially when t or t_s are increased. Determining the asymptotic regime in t and t_s where the two last terms of Eq. (8) can be safely neglected and a clear plateau behaviour appears is thus often difficult given the typical statistics of lattice calculations for nucleon observables. We therefore performed a detailed analysis of this effect on a single gauge ensemble increasing by more than one order of magnitude the statistics used.

We computed the ratio $R(t, t_s)$ for $t_s \sim 1.0$ fm (filled triangle in Fig. 1) and $t_s \sim 1.5$ fm

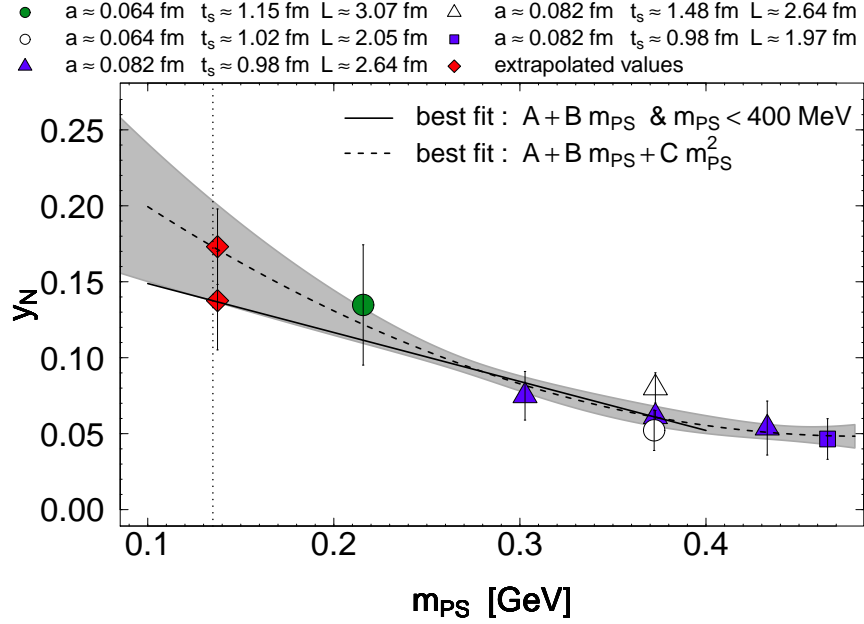


FIG. 1. Our results for y_N as a function of m_{PS} . The values of the lattice spacing a , the linear extent of the box L and the source-sink separation t_s used here are given in the legend. We extrapolate to the physical value of the pion mass (marked by the vertical dotted line) using linear (solid line) and quadratic (dashed line) fits in m_{PS} . For the quadratic fit, we also show the corresponding error band. Points represented by open symbols are only taken to estimate systematic effects and are not included in our final analysis.

(open triangle in Fig. 1) keeping the value of $a = 0.08$ fm and $L = 2.6$ fm fixed. We then performed several constant fits of the ratio $R(t, t_s)$ varying the fit interval $[t_{\text{min}}/a, t_{\text{max}}/a]$. We then chose the longest plateau such that the fit on a restricted range $[t_{\text{min}}/a - 1, t_{\text{max}}/a - 1]$ change marginally compared to the one obtained fitting on the range $[t_{\text{min}}/a, t_{\text{max}}]$. Since such a fitting window can be found we conclude that the systematic error introduced by the choice of a particular fitting range is negligible. We summarize the fitting range dependence for various source-sink separation in Table I. Note that the plateaux have a good quality because of a large cancellation of the t dependence of the numerator and denominator in the ratio $R(t, t_s)$. In particular, we find $y_N = 0.061(4)$ for $t_s = 1.0$ fm and $y_N = 0.080(10)$ for $t_s = 1.5$ fm which indicates a non-negligible excited states contamination of about $\sim 32\%$. Note that we also performed computations for intermediate source-sink separation of 1.14 and 1.31 fm. The results are summarized in Table I and as can be seen the latter source-sink separation is compatible with the result obtained for source-sink separation of ~ 1.5 fm. The

effect of different source-sink separations on our data is also exhibited in Fig. 2 where we show the ratio $R(t, t_s)$ for two source-sink separation of 0.98 fm and 1.31 fm. Note also that in [16] we obtained a result at $t_s = 1$ fm with a much lower statistic ($y_N = 0.082(16)$) which is fully compatible with the results quoted here. We thus consider as a conservative choice to use the difference between the two values for y_N obtained at $t_s = 1.0$ fm and $t_s = 1.5$ fm as an estimate of our systematic error originating from excited states contamination assuming that this systematic effect does not depend strongly on the pseudo scalar meson mass. As an additional check we performed global fits of the ratio R as a function of t and t_s for all the source-sink separations included in Table I. The asymptotic behaviour of the ratio R can be written as follows assuming that only one state contributes:

$$R(t, t_s) = y_N + Z(e^{-\delta m t} + e^{-\delta m(t_s - t)}) \quad (15)$$

for a range of time parametrized by $t \geq t_{\text{cut}}$ and $t_s - t \leq t_{\text{cut}}$ and where δm is the difference of the energy of the first excited state and the nucleon mass. The three coefficients ($y_N, Z, \delta m$) are treated as free parameters. The best fit values for $t_{\text{cut}}/a = 1$ reads

$$y_N = 0.091(7), \quad Z = 0.047(5), \quad \text{and} \quad \delta m = 0.203(30) \quad (16)$$

with $\chi^2/\text{ndof} = 23/53$. The corresponding curves are shown in Fig. 2 for $t_s/a = 12$ and $t_s/a = 16$. Estimating y_N in this way thus gives a result compatible within statistical errors with the value obtained for $t_s = 18a$ quoted in Table I. The best fit value for $\delta m \approx 490(70)\text{MeV}$ is larger than the mass of the pion on this ensemble, as expected for a nucleon-pion 2 particle state at non zero momentum. We conclude that the difference between the results obtained at $t_s/a = 18$ and $t_s/a = 12$ gives a reasonable estimate of the systematic error due to the excited state contamination.

Note that for the other gauge ensembles used in Fig. 1, we have used the same procedure to determine the fitting range $[t_{\text{min}}/a, t_{\text{max}}/a]$ of the ratio $R(t, t_s)$ and also found a marginal dependence of the results though with larger statistical errors.

We have computed y_N also at two different volumes (filled triangles and filled square in Fig. 1). However, we could not detect any significant finite volume effects within the statistical errors and thus finite volume effects can be safely neglected. We also show in Fig. 1 results for y_N for two different lattice spacings (filled triangle and empty circle in Fig. 1). The two points are clearly compatible, indicating that lattice discretization effects

t_s	$[t_{min}/a, t_{max}/a]$	y_N	$\chi^2/ndof$
$12a \approx 0.98$ fm	[3, 9]	0.061(4)	1.3/6
$12a \approx 0.98$ fm	[4, 8]	0.061(4)	0.4/4
$14a \approx 1.15$ fm	[3, 11]	0.063(5)	2.33/8
$14a \approx 1.15$ fm	[4, 10]	0.064(5)	1.38/6
$16a \approx 1.31$ fm	[6, 10]	0.070(7)	0.72/4
$16a \approx 1.31$ fm	[7, 9]	0.071(7)	0.17/2
$18a \approx 1.48$ fm	[5, 13]	0.080(10)	2.2/8
$18a \approx 1.48$ fm	[6, 12]	0.082(10)	1.01/6

TABLE I. Dependence on the fitting window of y_N for various source-sink separations. The fitting range and the $\chi^2/ndof$ are indicated.

are small. We took the difference between the values of these two data points as an estimate of the discretization errors.

In summary our final result reads:

$$y_N = 0.173(29)(36)(19)(9) \quad (17)$$

where the central value is given by the quadratic fit, the first error is statistical, and the last three errors are our estimates of systematic uncertainties, namely the chiral extrapolation, the excited states contamination and the discretization error, respectively. Note that the systematic errors are partly substantially larger than the statistical one and therefore dominate the total error. Adding all errors in quadrature, we find $y_N = 0.173(50)$.

V. DISCUSSION

There are a number of lattice works that concentrate on the determination of σ_s using direct and/or indirect computation (see for instance [22–25] for $N_f = 2 + 1$ results). Other lattice works for $N_f = 2 + 1$ provide indirect determinations of y_N [26–29] and our result for y_N is in agreement with these works. We stress, however, that in our work we were able to perform a comprehensive analysis of systematic uncertainties covering lattice spacing and finite volume effects and, in particular, a careful investigation of excited state contamination.

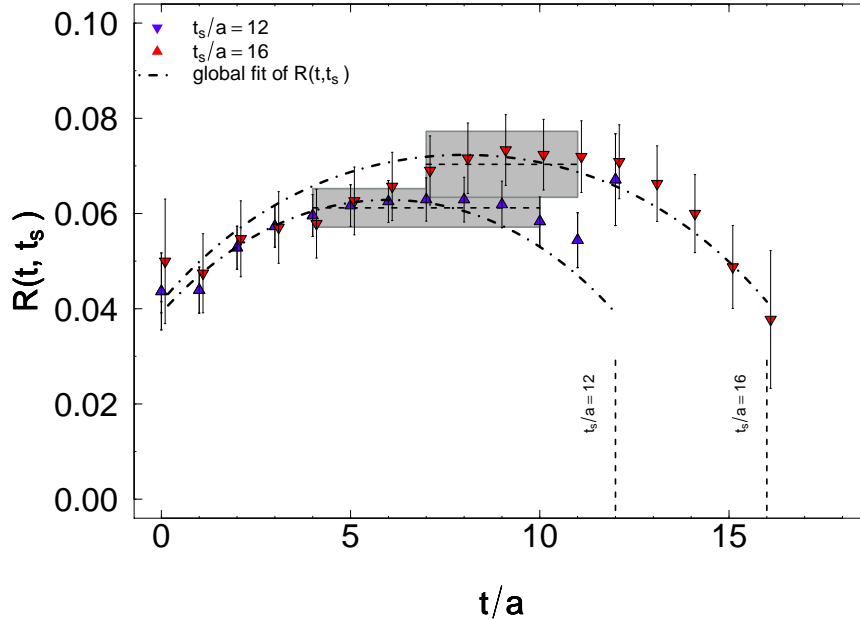


FIG. 2. $R(t, t_s)$ of Eq. (7) for two source-sink separations as a function of t/a . The source sink separations are indicated by vertical dotted lines. The best plateau fits together with their statistical error are represented by gray bands. The best fit curves of the global fit of $R(t, t_s)$ is shown by black dotted curves.

Furthermore computing directly the ratio of the matrix element y_N allows us to avoid any assumptions on the domain of validity of EFT relations which is based on $SU(2)$ or $SU(3)$ $HB\chi PT$ expansion and sometimes known only at leading order accuracy.

As in [30], we show in Fig. 3 the $(\sigma_{\pi N}, \sigma_s)$ plane together with vertical colored bands that represent the phenomenological determinations and the corresponding uncertainties of $\sigma_{\pi N}$ mentioned in the introduction. In order to put further constraints on σ_s , we use the following relations $\sigma_s = \frac{1}{2} \frac{m_s}{m_l} (\sigma_{\pi N} - \sigma_0) = y_N \frac{1}{2} \frac{m_s}{m_l} \sigma_{\pi N}$ together with the ratio of the quark masses taken from the FLAG group [31]. A first constraint derives from using the phenomenological determination of σ_0 (indicated by σ_0 in Fig. 3). The work performed here provide s a constraint through our direct computation of y_N (gray contour) which includes the estimate of both statistical and systematic errors. As can be seen the result constraints the strange σ -term and suggests an upper bound of ≈ 250 MeV for σ_s .

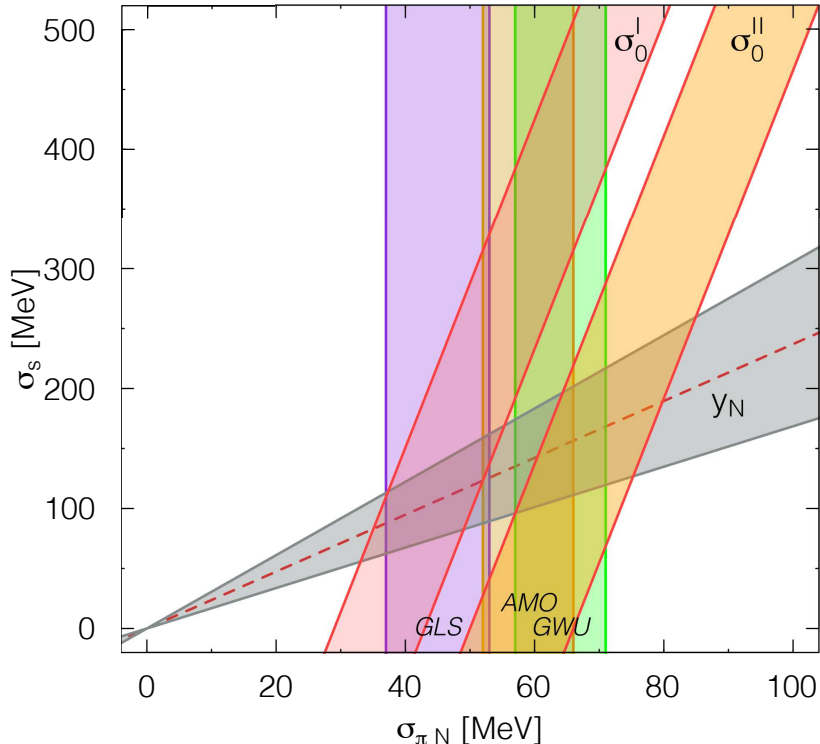


FIG. 3. Constraints on σ_s obtained from our determination of y_N . The phenomenological determination of $\sigma_{\pi N}$ are represented by colored band as obtained from [10] (GLS), [11] (GWU) and [12] (AMO). We also show the constraint provided by the estimates σ_0^I [13] and σ_0^{II} [14]. As can be seen the value of y_N can constrain the value of σ_s to be smaller than about 250 MeV.

VI. CONCLUSIONS AND OUTLOOK

In this work, we have performed a direct computation of the strangeness of the nucleon y_N , including light, strange and charm sea quarks with an emphasis on the study of systematic effects. Using maximally twisted mass fermions which allow for an efficient noise reduction technique and which avoids mixing under renormalization we have obtained $y_N = 0.173(50)$. Our result for y_N is compatible with previous determinations [26–29, 32] but includes an analysis of systematic errors originating from discretization, chiral extrapolation and excited states uncertainties. It is worth pointing out that we find a rather low value of the strange σ -term with corresponding consequences for the nucleon-dark matter cross section.

One important conclusion of our work is that the error we obtain for y_N is dominated by systematic uncertainties, in particular the chiral extrapolation and excited state contamination which cannot be neglected. While the error from the chiral extrapolation can be avoided in future calculations which are performed at or very close to the physical value of the pion mass, the excited state contamination must be carefully assessed. Thus, future lattice evaluation of the y_N parameter using the physical value of the light quark mass will avoid the systematic error due to the chiral extrapolation, but they will still have to address excited state contamination, as this study has demonstrated.

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