Publishable Summary Report

During the 30 months of the grant the work of the researcher has been concerned with:

1) the computation of nucleon form factors (FFs) and moments of parton distribution functions (PDFs). Codes to compute these quantities have been developed and tested and simulations for the relevant correlation functions have been performed. In order to perform the continuum limit extrapolation, we have used the configurations generated by the European Twisted Mass Collaboration (ETMC) with $N_f = 2$ dynamical light quarks at three different values of the lattice spacing, namely $a \approx 0.089$ fm, $a \approx 0.070$ fm and $a \approx 0.051$ fm. The physical volume of the lattices is in the range $L \approx [2.1 - 2.4]$ fm with an additional larger volume $L \approx 2.8$ fm for $a \approx 0.089$ fm used to study final size effects. In order to keep fixed the physical volume, the smallest lattice spacing $a \approx 0.051$ fm requires a very large number of lattice points ($48^3 \times 96$) and thus the generation of gauge configurations, the inversion of quark propagators and the calculation of correlation functions become computationally very expensive. This lattice spacing is probably the smallest one available amongst all the present simulations of nucleon FFs and PDFs.

In the first place we have obtained accurate results for the axial $G_A(Q^2)$ and pseudo-scalar $G_p(Q^2)$ nucleon form factors as a function of the squared momentum transfer Q^2 for pion masses in the range of about 260-470 MeV (see Ref. [2]). The general feature is a dependence on Q^2 flatter than experiment (see Fig. 1.a) Finite volume

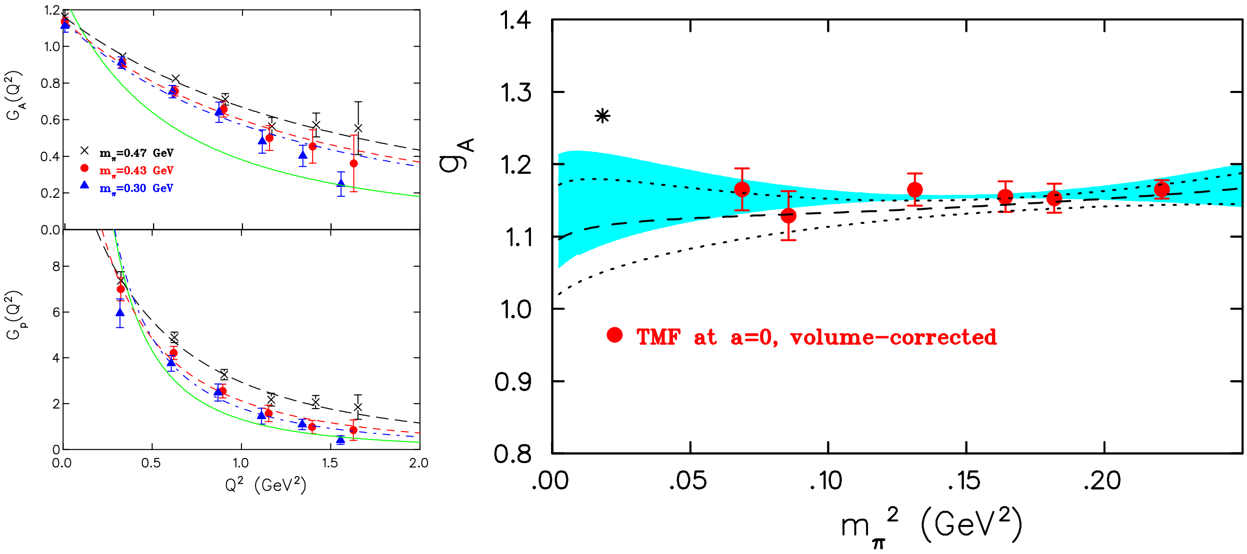

Figure 1: a) The nucleon axial form factors $G_A(Q^2)$ and $G_p(Q^2)$ at $\beta = 3.9$ for $m_\pi \approx 470$ MeV (crosses), $m_\pi \approx 430$ MeV (filled red circles) and $m_\pi \approx 300$ MeV (filled blue triangles) versus Q^2. The dashed lines are the result of a dipole fit and the solid line is the dipole parametrization of experimental data. b) The nucleon axial charge obtained by taking the continuum limit of the volume corrected data. The shaded area shows the best chiral fit with the error band.

effects are found to be small on G_A. Our results are in agreement with recent results obtained using other lattice discretizations such as dynamical $N_F = 2+1$ domain wall fermions. Having results at three lattice spacings enables us to take the continuum limit. We find that cut-off effects are small for the values of the lattice spacings used in this work. Performing a chiral extrapolation of our continuum results for the nucleon axial charge, we find at the physical point the value $g_A = 1.12(8)$. This is one standard deviation lower than the physical value. The large error associated with our determination of g_A is mostly due to the chiral extrapolation. Therefore it is crucial to perform an analysis having a pion mass closer to its physical value (see Fig. 1.b).

We then have computed the isovector electromagnetic nucleon form factors $G_E^{p-n}(Q^2)$ and $G_M^{p-n}(Q^2)$ (see Ref. [3]). As shown in Fig. 2.a, even for our lightest pion mass of 260 MeV the form factors decrease slower with increasing momentum transfer squared than form factors obtained from experiments. In Ref. [3] we examine both volume and cut-off effects to identify the source of this discrepancy. We also examine the pion mass dependence of the form factors as well as of the quantities derived by fitting the Q^2-dependence of these form factors.

By comparing results at two different volumes we find that for $Lm_\pi \gtrsim 3.3$ any volume effects are within our statistical accuracy for the magnetic form factor. A small volume dependence is seen in the case of the electric form factor that indicates an increase in the slope as the volume increases. By considering the continuum limit using results at three lattice spacings we also show that cut-off effects are small for lattice spacings less than about 0.1 fm. The pion mass dependence is examined using Heavy Baryon χPT with explicit Δ-degrees of freedom. Fitting the isovector Dirac and Pauli form factors at low Q^2 we show that the chiral extrapolated data agree with experiment (see Fig. 2.b).

Finally we have computed the lowest moments of nucleon generalized parton distributions (see Ref. [4]). In this work we have performed an analysis on the generalized form factors, $A_{20}(Q^2)$, $B_{20}(Q^2)$, $C_{20}(Q^2)$, $\tilde{A}_{20}(Q^2)$, $\tilde{B}_{20}(Q^2)$, extracted from the nucleon matrix elements of the one-derivative vector and axial-vector operators. Our main conclusion regarding cut-off effects is that they are small within the current accuracy of about 5-10% and for lattice spacings smaller than 0.1 fm. Similarly, no systematic volume effects are seen. Given the small cut-off effects

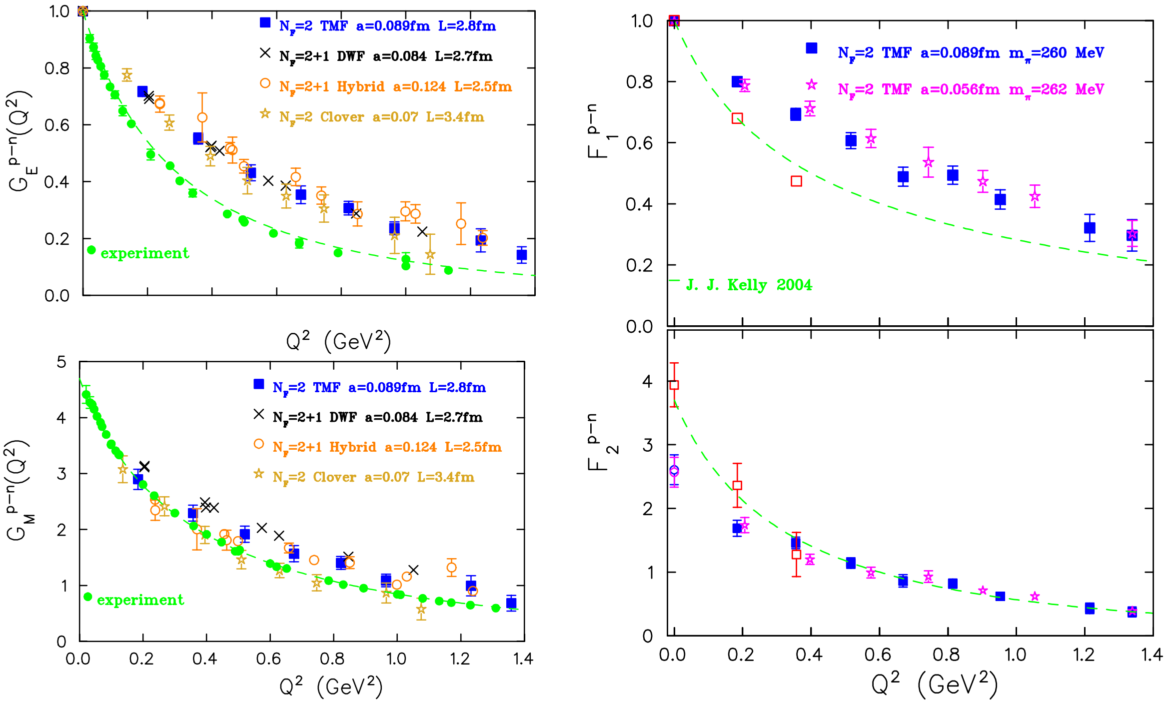

Figure 2: a) Isovector electric and magnetic form factors $G_E^{p-n}(Q^2)$ and $G_M^{p-n}(Q^2)$ as a function of Q^2. Our results at $m_\pi = 298$ MeV are shown with filled squares and compared with results obtained from other collaborations (crosses, open orange circles and yellow stars). Filled green circles are experimental data accompanied with Kelly's parametrization shown with the dashed line. b) Pauli and Dirac form factors F_1 and F_2 for the coarser and finer lattices at pion mass of about 260 MeV. The dashed line is Kelly's parametrization to the experimental data. The open squares show the values of F_1 and F_2 after chiral extrapolation to the physical point.

one can compare lattice results directly using different discretization schemes ($N_F = 2$ clover fermions, $N_F = 2+1$ domain wall fermions, $N_F = 2+1$ domain wall valence on staggered sea) and the comparison shows substantial agreement amongst all these discretizations.

Our results at three values of the lattice spacing allow for a continuum extrapolation. We consider both isovector (for which only connected contributions are needed) and isoscalar quantities. Amongst the latter, the spin content of the nucleon is of particular interest. The disconnected contributions to the isoscalar quantities are however not included. We find that the spin carried by the d-quark is almost zero whereas the u-quarks carry about 50% of the nucleon's spin. This result is consistent with other lattice calculations.

For the chiral extrapolations of these quantities we use HBχPT and Covariant Baryon χPT theory. In both cases, our results on the momentum fraction and helicity moment at the physical point are higher than their experimental value. Such discrepancies are also observed in the case of the nucleon axial charge and they need to be further investigated.

A report on the intermediate state of the project for all the different FFs and PDFs can be found in Ref. [8] while a summary of the final results can be found in Ref. [13].

2) the mass spectrum of strange and charmed baryons. Lattice artefacts for observables containing the charm quark can be quite large and thus dangerous for the continuum limit extrapolation. For dimensional reasons they are in fact of the form $O(m_c a)$ and being $m_c \simeq 1.3$ fm $\simeq 6.5$ fm^{-1}, $m_c a \sim 1$ for $a \sim 0.1$ fm. A very fine lattice spacing of ~ 0.5 fm can prove to be crucial in order to get well inside the scaling region. We have thus performed a detailed computation of the mass spectrum of strange and charmed ground state baryons (i.e. baryons made of light and strange and/or charm quarks) in a partially quenched setup where up and down quarks are dynamical (the same $N_f = 2$ configurations of the previous point have been used) while strange and charm quarks are only present in the valence (see Ref. [5], submitted to Phys. Rev. D).

The bare strange and charm valence quark mass is tuned by requiring that the physical values of the mass of the kaon and D-meson are reproduced after the lattice results are extrapolated at the physical value of the pion mass. We find that cut-off effects are small even in case of the charm baryons. This is a somewhat surprising result given that the Compton wave length of the D-meson mass is of the same order of magnitude as the lattice spacing. Using simulations on two different volumes we obtained results that are consistent showing that volume effects are smaller than our statistical accuracy.

Another artifact of our lattice formulation is isospin breaking at finite lattice spacing. We have found that isospin breaking decreases with the lattice spacing and it is consistent with zero for $a = 0.056$ fm confirming the expected restoration of isospin symmetry.

Our results on the strange quark sector are consistent with recent results using Clover improved fermions and DW fermions on a staggered sea(see Fig. 4 left). There is an overall agreement also in thee case of charm sector where we compare our results to other studies that used staggered sea quarks. The overall consistence among lattice

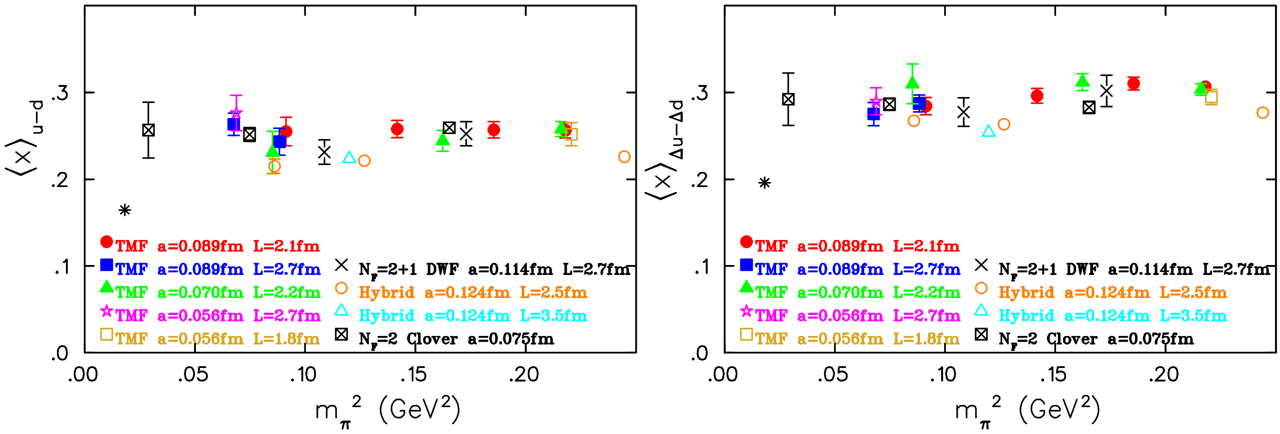

Figure 3: Our lattice data for $\langle x \rangle_{u-d}$ and $\langle x \rangle_{\Delta u - \Delta d}$ as function of the pion mass squared. Results using other lattice actions are also plotted. The physical point is shown by the asterisk.

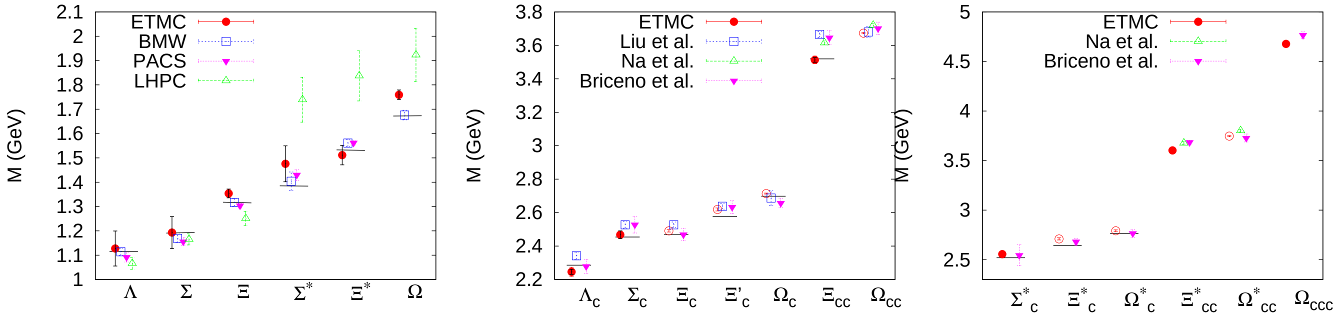

Figure 4: Masses for strange baryons (left), charm baryons with spin 1/2 (center) and spin 3/2 (right). The experimental values are shown by the horizontal lines. Our results (denoted by "ETMC") for the strange baryons and for Λ_c, Σ_c, Ξ_{cc}, Σ_c^*, Ξ_{cc}^*, Ω_{ccc} are extrapolated to the physical pion mass (shown with the red filled circles) whereas for the rest we give the results obtained at $m_\pi = 260$ MeV and $\beta = 4.2$ (shown with open red circles).

results, despite the different discretizations used, provides a strong validation of lattice QCD computations. Our results on the charm baryons reproduce the experimentally known values and provide a prediction for the mass of the Ω_{cc}, Ξ_{cc}^*, Ω_{cc}^* and Ω_{ccc} (see Fig. 4 center and right).

A preliminary analysis was presented at the International Symposium on Lattice Field Theory (Lattice 2010) and in an **invited talk** at the International Conference QCD-Montpellier (QCD 2010) and has been reported in two conference proceedings Ref. [7,9].

Having at our disposal also the newly generated ETMC configurations with $N_f = 2+1+1$ dynamical quarks (2 degenerate light quarks plus strange and charm quarks with approximate physical value of the mass), we have started the computation of the (low lying) strange baryon mass spectrum in which we plan to include the complete $SU(3)$ octet and decuplet. The main scope of this study is to see whether the inclusion of the strange (and the charm) quark in the sea changes significantly results obtained with $N_f = 2$ dynamical flavors. Preliminary results have been reported at the International Symposium on Lattice Field Theory (Lattice 2010) and in the proceedings Ref. [11].

3) Using $N_F = 2$ dynamical twisted mass fermions (a discretization which simplify the mixing pattern of four-fermion operators with respect to the standard Wilson discretization), we have computed the value of the strong interaction parameter, $\hat{B}_{\rm K}$, which controls the $K^0 - \bar{K}^0$ oscillations. Renormalization is carried out non-perturbatively in the RI-MOM scheme. Using data at three lattice spacings (in the interval [0.07, 0.1] fm) and a number of pseudoscalar masses in the interval 280 MeV $< m_{\rm PS} <$ 550 MeV, we get in the continuum limit and at the physical value of the pion and kaon mass, the value of the RGI "bag parameter" $B_K^{\rm RGI} = 0.729 \pm 0.030$ (see Ref. [1]). Our determination is quite accurate, with a $\sim 4\%$ total error (with statistical and total systematic errors added in quadrature), and agrees rather well with other existing values. In particular, from the comparison of our result for $B_{\rm K}$ with the results from $N_f = 2+1$ dynamical simulations it may be inferred that the quenching of the strange quark leads to an error which is smaller at present than other systematic uncertainties affecting current $B_{\rm K}$ estimates. If taken at face value, our result confirms the tension between the lattice determination and the preferred value of recent phenomenological, Standard Model based analyses.

Using $N_F = 2$ dynamical twisted mass fermions we have also performed the first unquenched lattice QCD determination in the continuum limit of the B_i-parameters of the full $\Delta S = 2$ four-fermion operator basis (see Ref. [6], submitted to JHEP). Using the same setup just mentioned, we get the most accurate estimates to date of $\Delta S = 2$ effective weak Hamiltonian matrix elements. The total error on the bag parameters B_i is between 4% and 12%. Our results for B_i (in $\overline{\rm MS}$ at 2 GeV) are shown in table 1. Preliminary results of this calculation have been reported at the International Symposium on Lattice Field Theory (Lattice 2010) and in the proceedings Ref. [10].

In Ref. [6], as an interesting phenomenological application of the calculation we have carried out a new Unitarity Triangle (UT) analysis. Thanks to the improved accuracy of the present determination of the $\Delta S = 2$ B-parameters, we could substantially strengthen the existing upper bounds on the Wilson coefficients of the operators of the non-standard sector of the effective weak Hamiltonian, and consequently increase the lower bound on the New Physics scale.

$\overline{\text{MS}}$ (2 GeV)				
B_1	B_2	B_3	B_4	B_5
0.52(02)	0.54(03)	0.94(08)	0.82(05)	0.63(07)

Table 1: Continuum limit results for B_i, renormalized in the $\overline{\text{MS}}$ scheme at 2 GeV.

Having at our disposal also the newly generated ETMC configurations with $N_f = 2+1+1$ dynamical flavours, we have started the computation of the Kaon B-parameter B_K on these configurations. Preliminary results for this study have been presented at the International Symposium on Lattice Field Theory (Lattice 2011) and in the conference proceedings Ref. [12].

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