Nucleon generalized form factors with twisted mass fermions

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with

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European Twisted Mass Collaboration

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Outline

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   - Nucleon mass
   - Setting the scale
2. **High precision study of nucleon observables**
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   - Evaluation of disconnected quark loop contributions
   - Axial charge g_A
   - Momentum fraction $\langle x \rangle$
   - Scalar charge
3. **Results**
   - Axial charge
   - Momentum fraction and Nucleon spin
   - Scalar charge
4. **Conclusions**

Wilson twisted mass lattice QCD

- $N_f = 2$: $\psi = \begin{pmatrix} u \\ d \end{pmatrix}$

  Change of variables: $\psi = \frac{1}{\sqrt{2}}[\mathbf{1} + i\tau^3\gamma_5]\chi \qquad \bar{\psi} = \bar{\chi}\frac{1}{\sqrt{2}}[\mathbf{1} + i\tau^3\gamma_5]$

  $\Rightarrow$ mass term: $\bar{\psi} m \psi = \bar{\chi} i\gamma_5\tau^3 m\chi$

$$S = S_g + a^4 \sum_x \bar{\chi}(x)\left[\frac{1}{2}\gamma_\mu(\nabla_\mu + \nabla^*_\mu) - \frac{ar}{2}\nabla_\mu\nabla^*_\mu + m_{\rm crit} + i\gamma_5\tau^3\mu\right]\chi(x)$$

- $N_f = 2 + 1 + 1$

$$S_h = \sum_x \bar{\chi}_h(x)\left[D_W + m_{(0,h)} + i\gamma_5\tau^1\mu_\sigma + \tau^3\mu_\delta\right]\chi_h(x)$$

  S_g: Iwasaki action

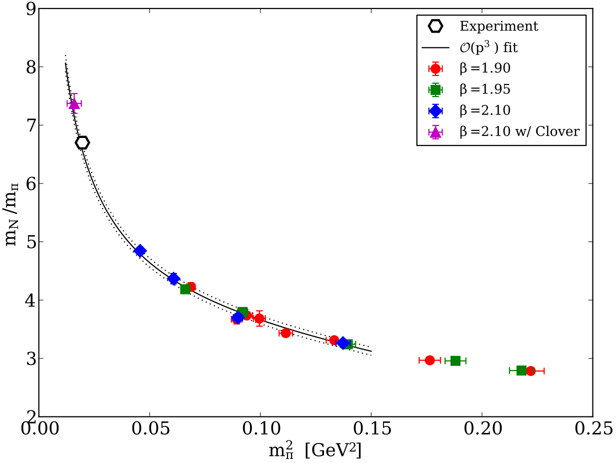
- $N_f = 2$ twisted mass plus clover and Iwasaki action $\rightarrow$ a good formulation for simulations at the physical point, talk by B. Kostrzewa, Monday, session 2G

  $\rightarrow$ preliminary results at physical point

Wilson tmQCD at maximal twist

- Automatic $O(a)$ improvement for a class of observables
- No operator improvement needed, renormalization simplified $\rightarrow$ important for nucleon structure

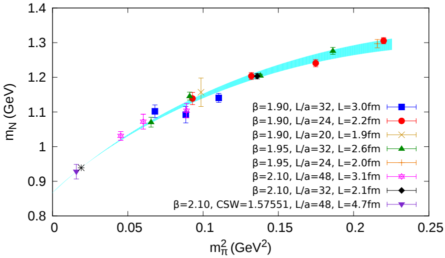
Nucleon mass



- Cut-off effects small for these lattice spacings
- Fit for $m_\pi < 375$ MeV
- New result at near physical pion gives complete agreement with experimental value

Setting the scale

- For baryon observables use nucleon mass at physical limit
- Extrapolate using lowest HBχPT result: $m_N = m_N^0 - 4c_1 m_\pi^2 - \frac{3g_A^2}{16\pi f_\pi^2} m_\pi^3$
- Estimate systematic error due to chiral extrapolation: i) using next order in HBχPT that includes explicit Δ-degrees of freedom; ii) varying the pion mass range for the fit; iii) allowing the coefficient of the m_π^3 to be a fit parameter
- Simultaneous fits to $\beta = 1.9$, $\beta = 1.95$ and $\beta = 2.1$ results
- Allows a cross-check with the determination using f_π



β	a (fm) $\mathcal{O}(p^3)$
1.90	0.0936(13)(32)
1.95	0.0823(11)(35)
2.10	0.0646(7)(25)
Preliminary	
2.10	0.0971(26)(3)

- σ-term from m_N using $\mathcal{O}(p^3)$ and $m_\pi \lesssim 300$ MeV: $\sigma_{\pi N} = 58(8)(7)$ MeV
- Using the nucleon mass we find $r_0 \sim 0.495(5)$ fm in the continuum limit

High precision study of nucleon observables

Dedicated high statistics study

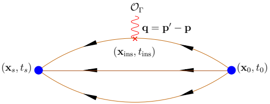
Choose one ensemble to perform a high statistics analysis for:

- excited state contributions
  - nucleon axial charge g_A - weak, S. Dinter, C.A., M. Constantinou, V. Drach, K. Jansen and D. Renner, arXiv: 1108.1076
  - momentum fraction $\langle x \rangle_{u-d}$ - intermediate
  - scalar charge (equivalently σ-terms) - severe, talk by V. Drach, Tuesday, session 4B
- disconnected contributions for all nucleon observables

$N_f = 2+1+1$ twisted mass, a = 0.082 fm, m_π = 373 MeV

Extracting nucleon matrix elements

Form ratio by dividing the three-point correlator by an appropriate combination of two-point functions:



- Plateau method:

$$R(t_s, t_{\rm ins}, t_0) \xrightarrow[(t_s - t_{\rm ins})\Delta \gg 1]{(t_{\rm ins} - t_0)\Delta \gg 1} \mathcal{M}[1 + \ldots e^{-\Delta(\mathbf{p})(t_{\rm ins} - t_0)} + \ldots e^{-\Delta(\mathbf{p}')(t_s - t_{\rm ins})}]$$

  - $\mathcal{M}$ the desired matrix element
  - t_s, $t_{\rm ins}$, t_0 the sink, insertion and source time-slices
  - $\Delta(\mathbf{p})$ the energy gap with the first excited state

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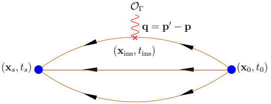

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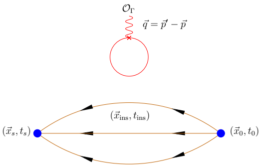
- Summation method: Summing over $t_{\rm ins}$:

$$\sum_{t_{\rm ins}=t_0}^{t_s} R(t_s, t_{\rm ins}, t_0) = \text{Const.} + \mathcal{M}[(t_s - t_0) + \mathcal{O}(e^{-\Delta(\mathbf{p})(t_s - t_0)}) + \mathcal{O}(e^{-\Delta(\mathbf{p}')(t_s - t_0)})].$$

  - Excited state contributions are suppressed by exponentials decaying with $t_s - t_0$, rather than $t_s - t_{\rm ins}$ and/or $t_{\rm ins} - t_0$
  - Also works if one does not include t_0 and t_s in the sum $\rightarrow$ used for the results shown here
  - However, one needs to fit the slope rather than to a constant or take differences and then fit to a constant

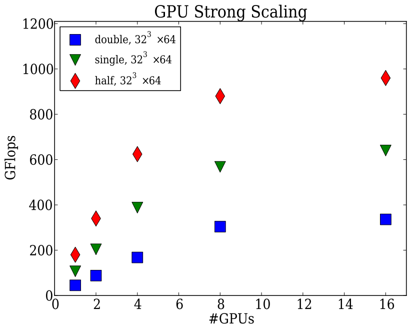
L. Maiani, G. Martinelli, M. L. Paciello, and B. Taglienti, Nucl. Phys. B293, 420 (1987); S. Capitani *et al.*, arXiv:1205.0180

Quark loop contributions



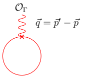
Notoriously difficult

- $L(x) = Tr\,[\Gamma G(x;x)]$ $\rightarrow$ need all-to-all propagator
- Large gauge noise $\rightarrow$ large statistics
- Use stochastic noise η $\rightarrow$ solve $Dv_r = \eta_r$, $r = 1, \ldots, N_r$ $\rightarrow$ $D^{-1} = \lim_{N_r \to \infty} \frac{1}{N_r} \sum_{j=1}^{N_r} |s_j\rangle\langle\eta_j|$
- Reduce noise by increasing statistics
  $\Longrightarrow$ Take advantage of graphics cards (GPUs) $\rightarrow$ CUDA programming language
  Special Session: Coding Efforts, Friday, 10G



C. A., M. Constantinou, S. Dinter, V. Drach, K. Hadjiyiannakou, K. Jansen, G. Koutsou, A. Strelchenko, A. Vaquero arXiv:1211.0126
C.A., K. Hadjiyiannakou, G. Koutsou, A. O'Cais, A. Strelchenko, arXiv:1108.2473

Quark loop contributions



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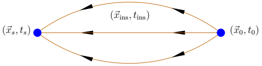

- Use stochastic noise η $\rightarrow$ solve $Dv_r = \eta_r$, $r = 1, \ldots, N_r$ $\rightarrow$ $D^{-1} = \lim_{N_r \to \infty} \frac{1}{N_r} \sum_{j=1}^{N_r} |s_j\rangle\langle\eta_j|$
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- For scalar charge (and σ-terms) a good signal is obtained with $N_r = 24$ in combination of using advantages of the twisted mass formulation
- For other disconnected contributions one has large stochastic noise $\rightarrow$ Reduce noise by increasing statistics at low cost $\rightarrow$ use low precision inversions and correct bias (truncated solver method (TSM)),
  G. Bali, S. Collins and A. Schäfer, PoSLat2007, 141; G. Bali *et al.*, arXiv:1111.1600

$$D^{-1} = \lim_{N_{HP} \to \infty} \frac{1}{N_{HP}} \sum_{j=1}^{N_{HP}} \left[|s_j >< \eta_j|_{HP} - |s_j >< \eta_j|_{LP}\right] + \frac{1}{N_{LP}} \sum_{j=N_{HP}+1}^{N_{HP}+N_{LP}} |s_j >< \eta_j|_{LP}$$

with $D|s_j >= |\eta_j >$

- Need to tune in addition to the high precision noise vectors $N_{\rm HP}$ and number of low precision vectors $N_{\rm LP}$
- Since the LP sources don't require an accurate inversion, we can take advantage of the half precision algorithms for GPUs - use the QUDA library
- To compute the isoscalar disconnected contribution to g_A, we use $N_{\rm HP} = 24$ and $N_{\rm LP} \geq 500$

Axial charge g_A

Axial-vector FFs: $A_\mu^3 = \bar{\psi}\gamma_\mu\gamma_5\frac{\tau^3}{2}\psi(x) \Longrightarrow \frac{1}{2}\bar{u}_N(\vec{p'})\left[\gamma_\mu\gamma_5 G_A(q^2) + \frac{q^\mu\gamma_5}{2m}G_p(q^2)\right]u_N(\vec{p})|_{q^2=0}$
$\rightarrow$ yields $G_A(0) \equiv g_A$: i) well known experimentally, & ii) no quark loop contributions

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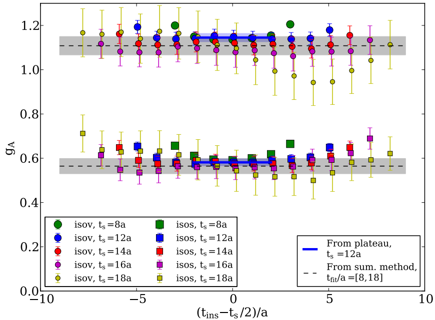
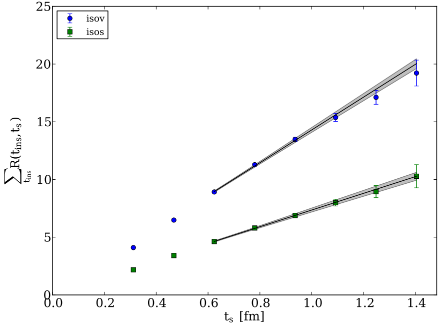
$N_f = 2+1+1$ twisted mass, a = 0.082 fm, m_π = 373 MeV, 1200 statistics



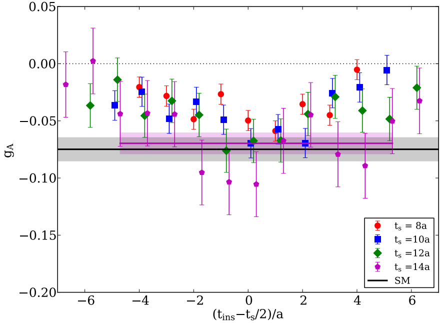


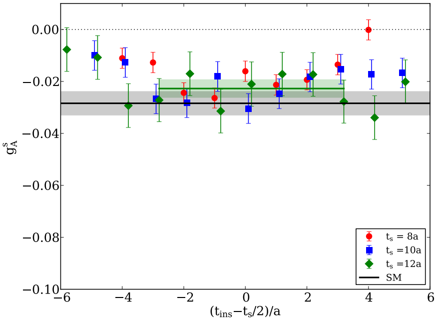
- Use of incremental eigCG algorithm, A. Stathopoulos and K. Orginos, arXiv:0707.0131
  - One sequential inversion for each t_s, obtain results for all operator insertions
  - $\sim 3\times$ cheaper
- Consistent results between summation and plateau methods

- No detectable excited states contamination, agrees with high precision study , S. Dinter *et al.*, arXiv:1108.1076 and C. Alexandrou *et al.*, arXiv:1112.2931
  - Same plateau for multiple t_ss
  - No curvature in summed ratio, consistent results for various fit-ranges

Isoscalar axial charge

Disconnected $N_f = 2 = 1 + 1$ TMF, $a = 0.082$ fm, $32^3 \times 64$, $m_\pi = 373$ MeV, 200000 statistics (on 4700 confs)





Disconnected isoscalar, agrees with Bali *et al.* (QCDSF), Phys.Rev.Lett. 108 (2012) 222001

Strange quark loop

- Renormalization currently under study

Perturbatively the difference between isovector and isoscalar at two-loop, shown to be small for the Wilson action, H. Panagoupoulos and A. Skouroupathis, arXiv:0811.4264

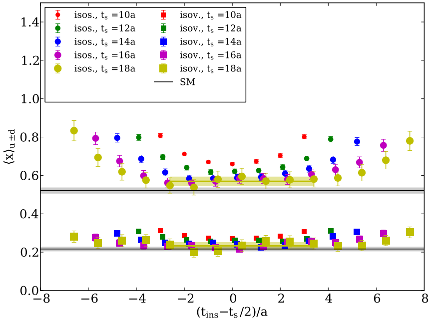
For now neglect the difference

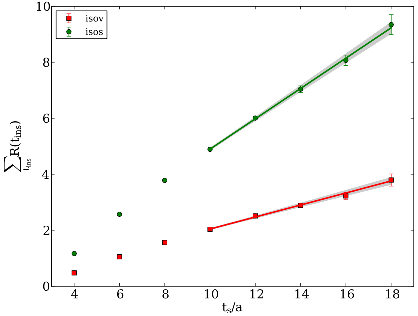
Momentum fraction

Isovector momentum fraction carried by quarks: Extracted from the nucleon matrix elements of $\mathcal{O}^{\mu_1\mu_2} = \bar{\psi}\gamma^{\{\mu_1} i \overleftrightarrow{D}^{\mu_2\}}\psi$ at $q^2 = 0$ with no disconnected contributions and known experimentally

$N_f = 2+1+1$ twisted mass, $a = 0.082$ fm, $m_\pi = 373$ MeV, 1200 statistics

Connected



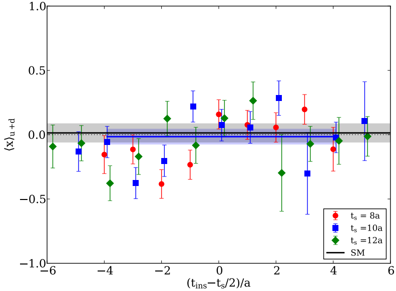


- Noticeable excited state contamination, especially for the iso-scalar
- For the plateau method one needs to show convergence by varying the sink-source time separation $\rightarrow$ also requires a number of sequential inversions $\Longrightarrow$ consistency of plateau and summation method gives confidence in the results

Momentum fraction

Twisted Mass, $a = 0.082$ fm, $32^3 \times 64$, $m_\pi = 373$ MeV, $\sim$200 0000 statistics (on 4700 confs)

Disconnected



- Can put bound on its value
- Including momentum in the sink/source improves statistical accuracy

- Renormalization currently under study

However, difference between isovector and isoscalar at two-loop, shown to be small for the Wilson action, H. Panagoupoulos and A. Skouroupathis, arXiv:0811.4264

For now neglect the difference

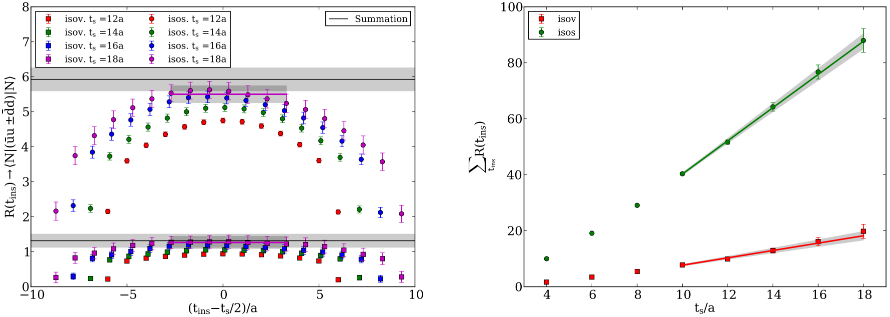
Scalar charge

The scalar charge g_s and the tensor charge g_T provide constrains for possible scalar and tensor interactions at the TeV scale. For g_T, talk by M. Constantinou in this session

- Isovector: $g_s = \langle N|\bar{u}u - \bar{d}d|N\rangle$
- Isoscalar: $g_s^{u+d} = \langle N|\bar{u}u + \bar{d}d|N\rangle \rightarrow$ analogous to the calculation of the nucleon sigma-terms, uses advantages for twisted mass fermions, talk by V. Drach, Tuesday, session 4B

$N_f = 2+1+1$ twisted mass, a = 0.082 fm, m_π = 373 MeV, 1200 statistics

Connected



- Severe contamination from excited states
- Agreement of summation, plateau and two-states fits give confidence to the correctness of the final result

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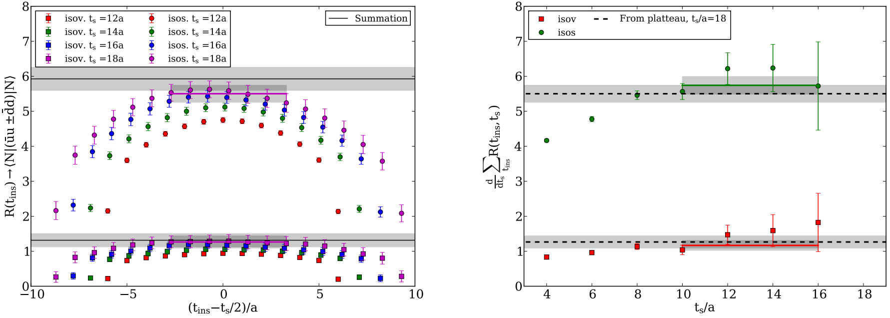

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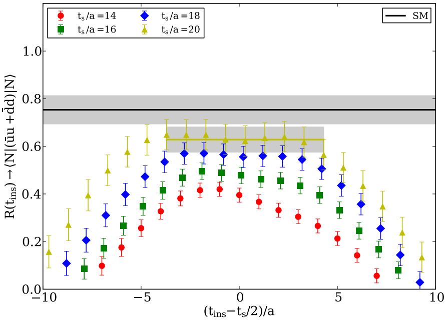
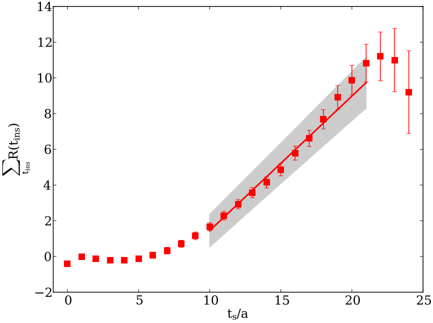
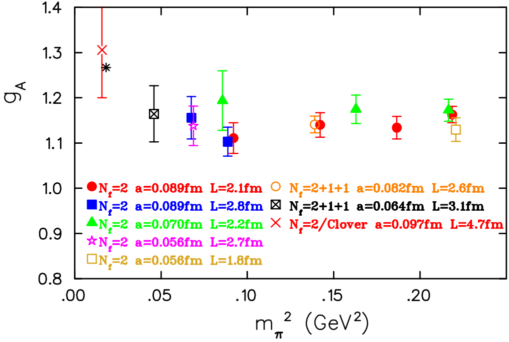
Disconnected





Results: I. Axial charge g_A



- Renormalized using non-perturbative Z_A
- High statistics analysis at $m_\pi = 373$ MeV reveal no excited states contamination for sink-source separation $\sim$1 fm
- Results using the plateau method and sink-source time separation (1-1.2) fm

C.A., M. Constantinou, S. Dinter, V. Drach, K. Jansen, C. Kallidonis, G. Koutsou, arXiv:1303.5979

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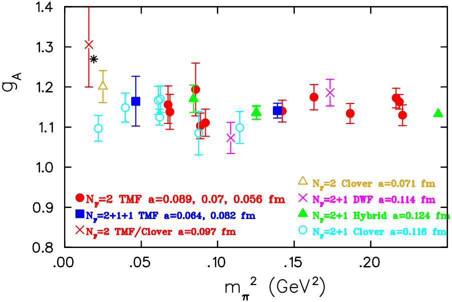
Comparison with other groups



Results obtained using the plateau method with sink-source time separation $\sim (1.0 - 1.2)$ fm

- Results at near physical pion mass are now becoming available $\rightarrow$ need dedicated study at physical point with high statistics and larger volumes
- A number of collaborations are engaging in systematic studies, e.g.
  - $N_f = 2 + 1$ Clover, J. R. Green *et al.*, arXiv:1209.1687
  - $N_f = 2$ Clover, R.Hosley *et al.*, arXiv:1302.2233
  - $N_f = 2$ Clover, S. Capitani *et al.* arXiv:1205.0180
  - $N_f = 2 + 1$ Clover, B. J. Owen *et al.*, arXiv:1212.4668
  - $N_f = 2 + 1 + 1$ Mixed action (HISQ/Clover), T. Bhattacharya *et al.*, arXiv:1306.5435
  - Also several talks in Lattice 2013 e.g. S. Ohta, M. Lin, Thursday, session 7B

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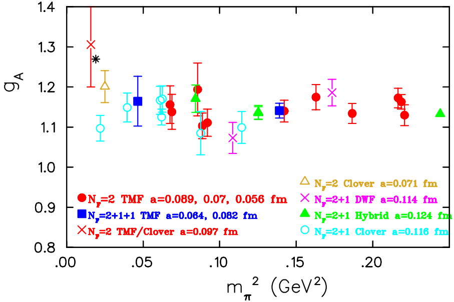

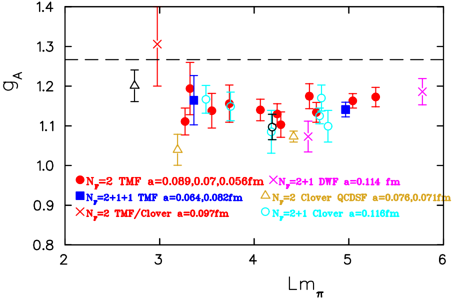

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- Volume effects may not be the full story if we compare the result by QCDSF ($Lm_\pi \sim 2.7$) and LHPC ($Lm_\pi \sim 4.2$) at near physical pion mass

C.A., M. Constantinou, S. Dinter, V. Drach, K. Jansen, C. Kallidonis, G. Koutsou, arXiv:1303.5979

Results: II. Momentum fraction and the nucleon spin

Total quark spin: $J^q = \frac{1}{2}(A^q_{20}(0) + B^q_{20}(0))$

$A_{20}(Q^2)$ and $B_{20}(Q^2)$ extracted from the nucleon matrix elements of $\mathcal{O}^{\mu_1\mu_2} = \bar{\psi}\gamma^{\{\mu_1} i \overleftrightarrow{D}^{\mu_2\}}\psi$
For $Q^2 = 0$: moments of parton distributions measured in DIS

$$A^q_{20}(0) \equiv \langle x \rangle_q = \int_0^1 dx\, x\, [q(x) + \bar{q}(x)]$$

Unpolarized quark distribution:	$q(x) = q(x)_\downarrow + q(x)_\uparrow$
Polarized quark distribution:	$\Delta q(x) = q(x)_\downarrow - q(x)_\uparrow$
Helicity quark distribution:	$\delta q = q_T + q_\perp$, talk by M. Constantinou, this session

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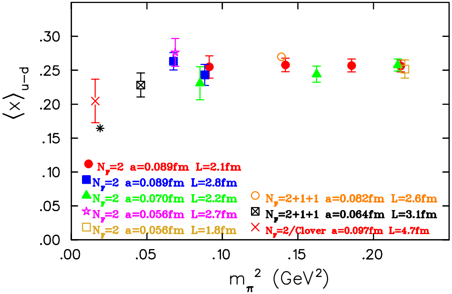
Results in the $\overline{MS}$ scheme at $\mu = 2$ GeV using non-perturbative renormalization, C. Alexandrou *et al.*, arXiv:1006.1920



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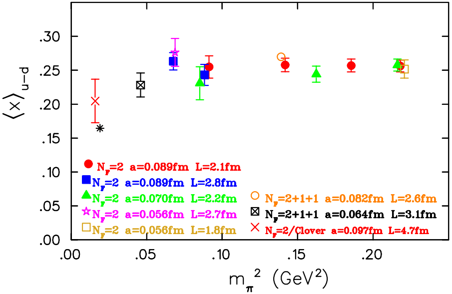
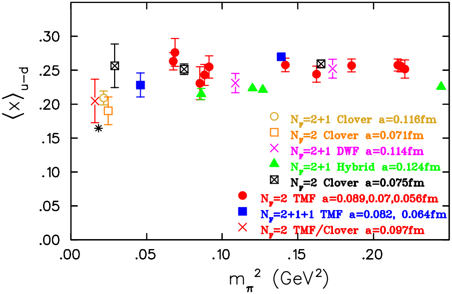
$$A^q_{20}(0) \equiv \langle x \rangle_q = \int_0^1 dx\, x\,[q(x) + \bar{q}(x)]$$

Unpolarized quark distribution: $q(x) = q(x)_\downarrow + q(x)_\uparrow$
Polarized quark distribution: $\Delta q(x) = q(x)_\downarrow - q(x)_\uparrow$
Helicity quark distribution: $\delta q = q_T + q_\perp$, talk by M. Constantinou, this session

Results in the $\overline{MS}$ scheme at $\mu = 2$ GeV using non-perturbative renormalization, C. Alexandrou *et al.*, arXiv:1006.1920





Results: II. Momentum fraction and the nucleon spin

Total quark spin: $J^q = \frac{1}{2}(A^q_{20}(0) + B^q_{20}(0))$

$A_{20}(Q^2)$ and $B_{20}(Q^2)$ extracted from the nucleon matrix elements of $\mathcal{O}^{\mu_1\mu_2} = \bar\psi\gamma^{\{\mu_1} i \overleftrightarrow{D}^{\mu_2\}}\psi$
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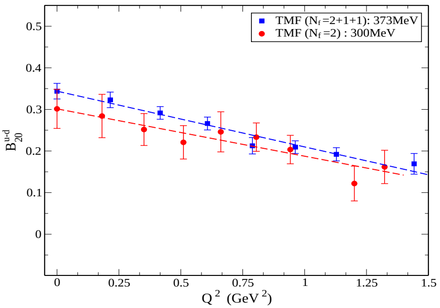
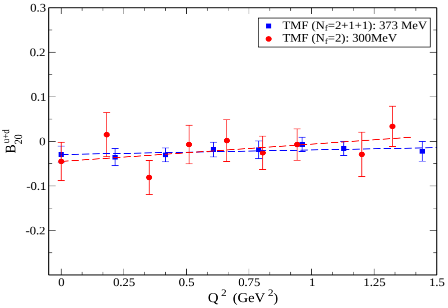
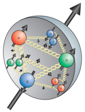
We also need $B^q_{20}(0)$



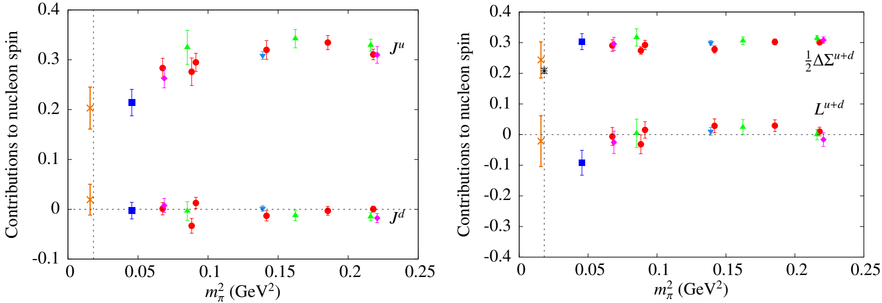


Where is the nucleon spin?

Spin sum: $\frac{1}{2} = \sum_q \left(\frac{1}{2}\Delta\Sigma^q + L^q\right) + J^G$



Connected contributions



$\Longrightarrow$ Total spin for u-quarks $J^u \lesssim 0.25$ and for d-quark $J^d \sim 0$

- $L^{u+d} \sim 0$ at physical point
- $\Delta\Sigma^{u+d}$ in agreement with experimental value at physical point
- The total spin $J^{u+d} \sim 0.25 \Longrightarrow$ Where is the other half?

However, more statistics and checks of systematics are needed for final results at the physical point

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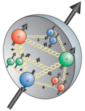
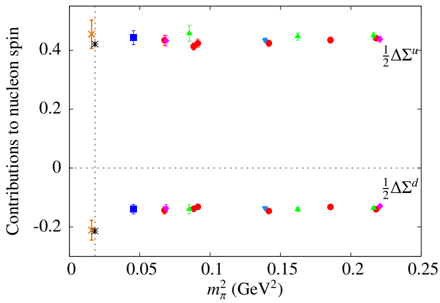
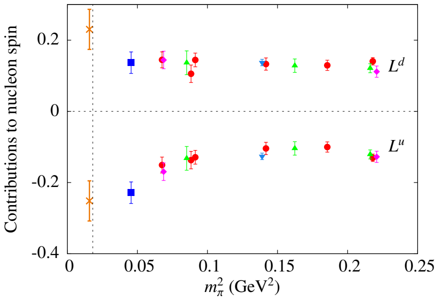


Connected contributions





- $\Delta\Sigma^{u,d}$ consistent with experimental values
- $L^d \sim -L^u$

However, more statistics and checks of systematics are needed for final results at the physical point

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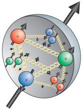
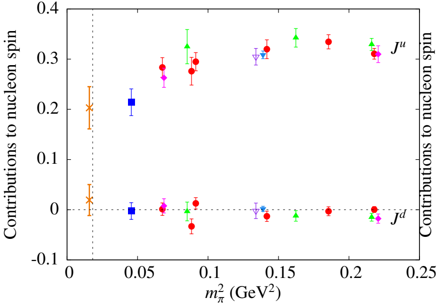
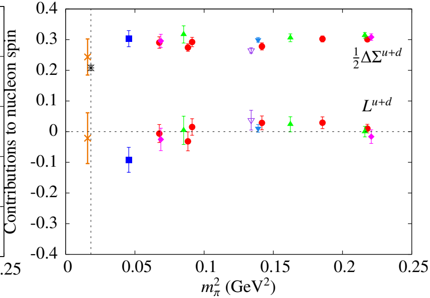


For one ensemble at $m_\pi = 373$ MeV we have the disconnected contribution $\rightarrow$ we can check the effect on the observables, $\mathcal{O}(200000)$ statistics





- Disconnected quark loop contributions non-zero for $\Delta\Sigma^{u,d,s}$
- Consistent with zero for $J^{u,d}$
- The total spin $J^{u+d} \sim 0.25 \implies$ Where is the other half?
- Quark loop contributions are small
- Contributions from J_g? $\rightarrow$ on-going efforts to compute them, K.-F. Liu *et al.* (χQCD), arXiv:1203.6388, talk by C. Wiese, this session

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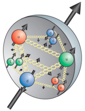

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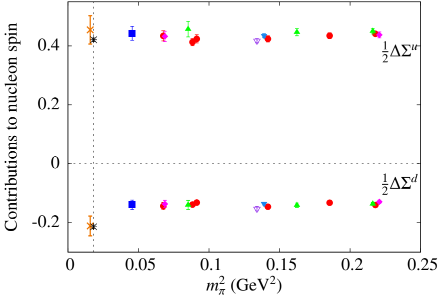

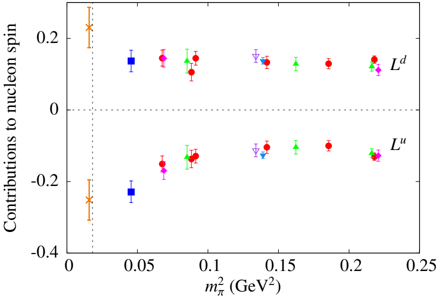

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Results: III. Scalar charge

The scalar charge g_s and the tensor charge g_T provide constrains for possible scalar and tensor interactions at the TeV scale. For g_T, talk by M. Constantinou in this session

- Isovector: $g_s = \langle N|\bar{u}u - \bar{d}d|N\rangle$
- Isoscalar: $g_s^{u+d} = \langle N|\bar{u}u + \bar{d}d|N\rangle \rightarrow$ analogous to the calculation of the nucleon sigma-terms, uses advantages for twisted mass fermions, talk by V. Drach, Tuesday, session 4B

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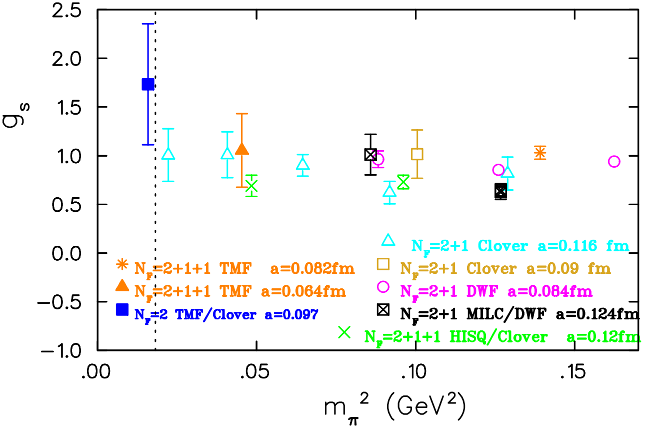

Connected isoscalar taking sink-source time separation $\sim (1.0 - 1.2)$ fm

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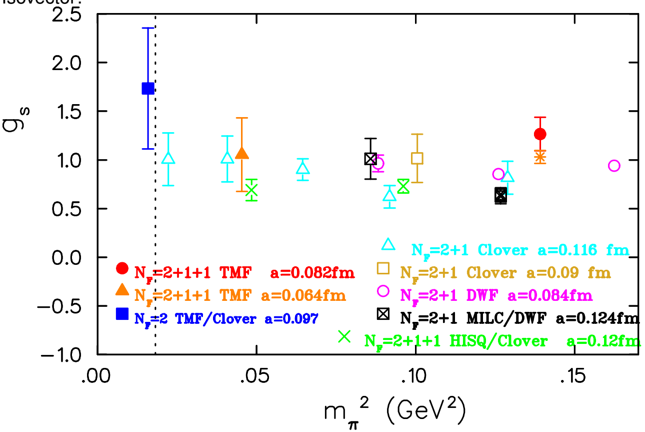
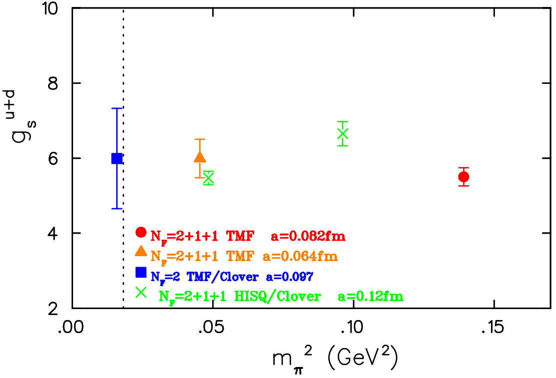


Increasing the sink-source time separation ~ 1.5 fm for one TMF ensemble

Isoscalar scalar charge

Besides the connected contribution it has a disconnected part



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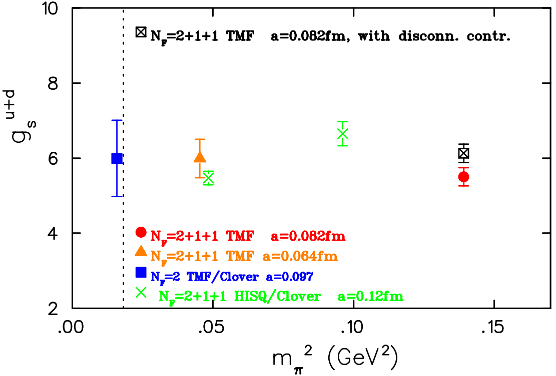

Conclusions

- Simulations at the physical point $\rightarrow$ that's where we always wanted to be!
  $\Longrightarrow$ Physical results on g_A, $\langle x \rangle_{u-d}$ etc are now directly accessible
  But will need high statistics and careful cross-checks $\rightarrow$ noise reduction techniques are crucial e.g. AMA, TSM, smearing etc
- Evaluation of quark loop diagrams has become feasible
- Predictions for other hadron observables are emerging e.g. axial charge of hyperons and charmed baryons
- Confirmation of experimentally known quantities such as g_A will enable reliable predictions of others $\rightarrow$ provide insight into the structure of hadrons and input that is crucial for new physics such as the nucleon σ-terms, g_s and g_T

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Thank you for your attention

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STRUCTURAL FUNDS
of the European Union in Cyprus
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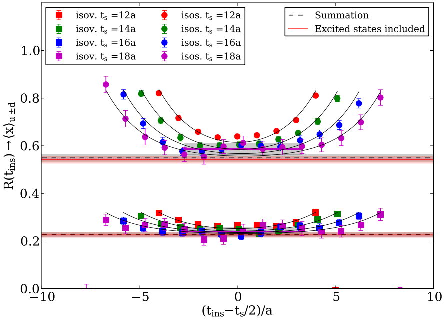
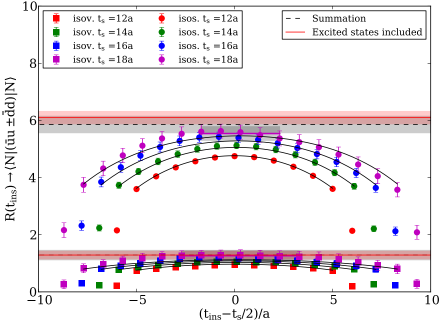
Backup slides

Two-state fits

Fitting the ratio to two-states simultaneous for several sink-source separations works for the scalar charge and momentum fraction. As stressed g_A does not pick up contributions from excited states.





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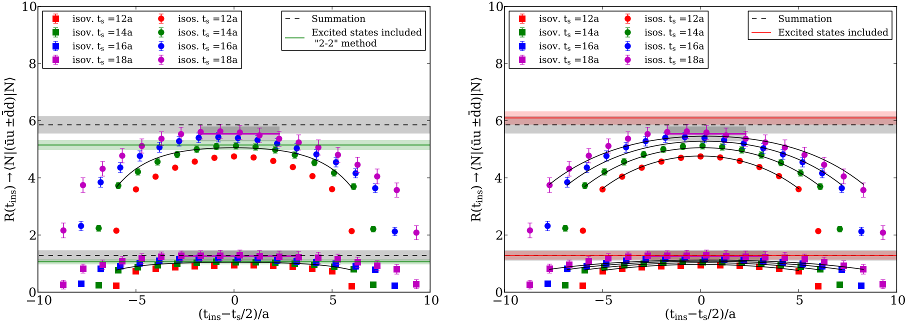

Not useful for predicting the large time dependence