Selected results on hadron structure

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The Cyprus Institute

Hadrons and Hadron Interactions in QCD
27th February 2015

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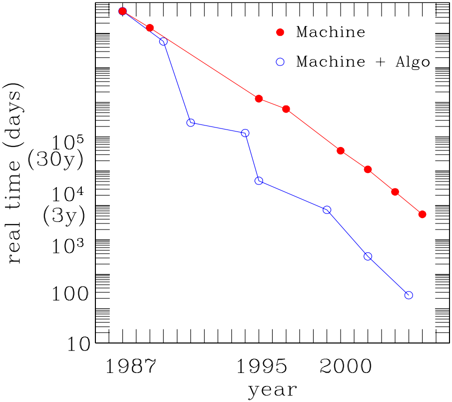
Outline

Computer and algorithmic development

Algorithm development has been decisive



Simulation on a $32^3 \times 64$ lattice, 5000 configurations

Fermion actions

Observables: $\langle \mathcal{O} \rangle = \frac{1}{Z} \sum_{\{U_\mu\}} O(D^{-1}, U_\mu)$

Several $\mathcal{O}(a)$-improved fermion actions, K. Jansen, Lattice 2008
$\langle O \rangle_{\rm cont} = \langle O \rangle_{\rm latt} + \mathcal{O}(a^2)$

Action	Advantages	Disadvantages
Clover improved Wilson	computationally fast	breaks chiral symmetry needs operator improvement
Twisted mass (TM)	computationally fast automatic improvement	breaks chiral symmetry violation of isospin
Staggered	computational fast	four doublers (fourth root issue) complicated contractions
Domain wall (DW)	improved chiral symmetry	computationally demanding needs tuning
Overlap	exact chiral symmetry	computationally expensive

Several collaborations:

Clover	QCDSF, BMW, ALPHA, CLS, PACS-CS, NPQCD
Twisted mass	ETMC
Staggered	MILC
Domain wall	RBC-UKQCD, JLQCD
Overlap	JLQCD

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

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

  Simulations by ETMC: Ph. Boucaud *et al.*, Comput.Phys.Commun. 179 (2008) 695; Phys.Lett. B650 (2007) 304

- $N_f = 2+1+1$

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

  Simulations by ETMC: R. Baron *et al.*, JHEP 1006(2010) 111

- $N_f = 2$ twisted mass plus clover with $c_{SW} = 1.57551$

  $\rightarrow$ a good formulation for simulations at the physical point„ (ETMC) A. Abdel-Rehim *et al.*, arXiv:1311.4522 and arXiv:1411.6842

  $\rightarrow$ results at physical point, (ETMC) C. Alexandrou *et al.*, PoS LATTICE2013 (2014) 292

Wilson tmQCD at maximal twist, R. Frezzotti, G. C. Rossi, JHEP 0408 (2004) 007

- Automatic $O(a)$ improvement
- No operator improvement needed, renormalization simplified → important for hadron structure

European Twisted Mass Collaboration

European Twisted Mass Collaboration (ETMC)

Cyprus (Univ. of Cyprus, Cyprus Inst.), France (Orsay, Grenoble), Germany (Berlin/Zeuthen, Bonn, Frankfurt, Hamburg, Münster), Italy (Rome I, II, III, Trento), Netherlands (Groningen), Poland (Poznan), Spain (Valencia), Switzerland (Bern), UK (Liverpool)

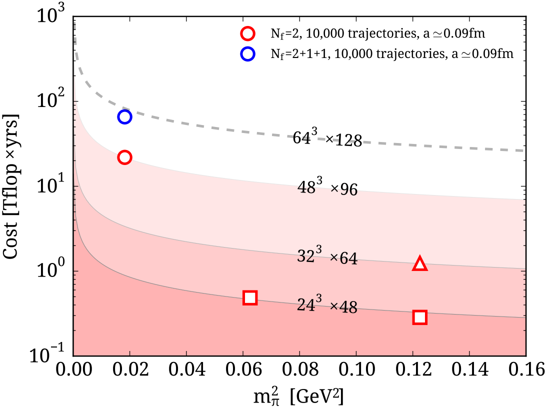
Collaborators:

A. Abdel-Rehim, K. Cichy, M. Constantinou, V. Drach, E. Garcia Ramos, K. Hadjiyiannakou, K.Jansen Ch. Kallidonis, G. Koutsou, K. Ottnad, M. Petschlies, F. Steffens, A. Strelchenko, A. Vaquero, C. Wiese

Simulations with physical quark masses

A number of collaborations are producing simulations with physical values of the quark mass: MILC, BMW, PACS-CS, ETMC

European Twisted Mass Collaboration (ETMC): $N_f = 2$ and $N_f = 2 + 1 + 1$ twisted mass Wilson fermions



Simulation cost: $C_{\rm sim} \propto \left(\frac{300{\rm MeV}}{m_\pi}\right)^{c_m} \left(\frac{L}{3{\rm fm}}\right)^{c_L} \left(\frac{0.1{\rm fm}}{a}\right)^{c_a}$
We find $c_L \sim 4.5$ and $c_m \sim 2$ for a fixed lattice spacing.

Thanks B. Kostrzewa and G. Koutsou

Simulations with physical quark masses

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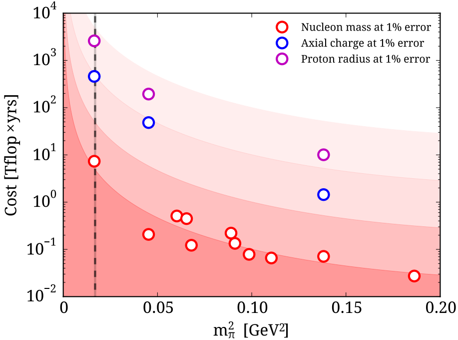
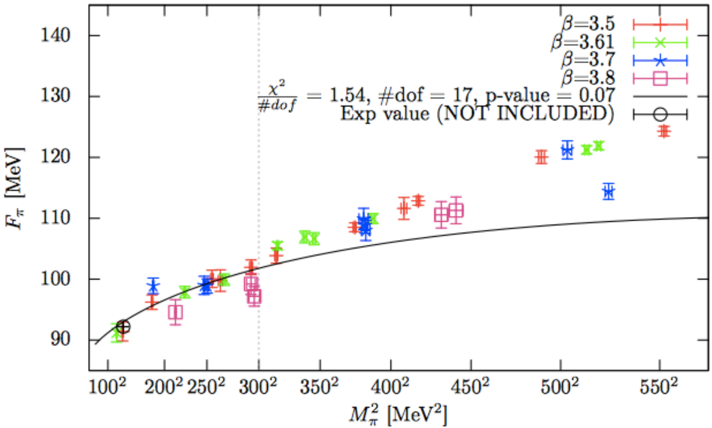


Inversion cost (for a lattice of 64^3x128, $Lm_\pi = 4$):$\sim e^{(m_p - \frac{3}{2}m_\pi)t_s}$

Deflation of lower eigenvalues essential for computations at the physical point → reduction of cost by ~ 20 times.

Pion decay constant by BMW

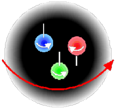
Budapest-Marseille-Wuppertal (BMW) Collaboration: $N_f = 2 + 1$ Clover improved Wilson fermions

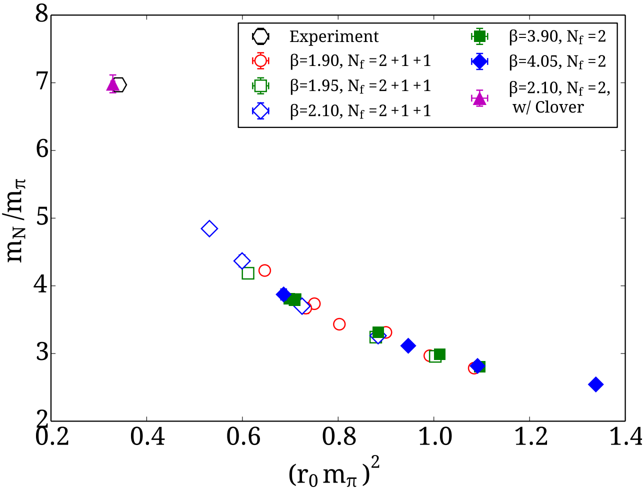


NLO SU(2) chiral perturbation theory for $m_\pi < 300$ MeV, S. Durr *et al.*, 1310.3626

Hadron masses

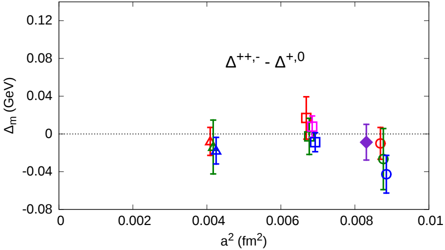
The nucleon



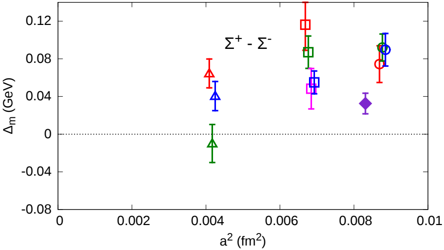


- Cut-off effects small for these lattice spacings
- LO fit with $m_\pi < 375$ MeV does not include the physical point
- Complete agreement with experimental value
- Determine lattice spacing using the $\mathcal{O}(p^3)$ result,
  $\rightarrow a = 0.094(2)(2)$ fm, $\sigma_{\pi N} = 65(2)(13)$ MeV and $r_0 \sim 0.499(2)$ fm

Isospin breaking



Mass splitting for the Δ for different types of actions.



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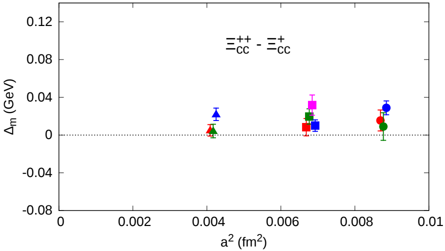
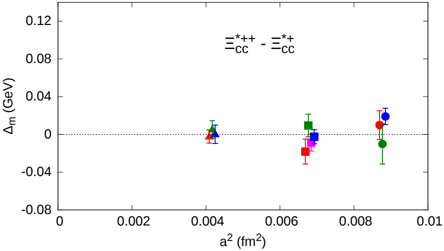


Mass splitting for the Ξ_{cc} for different types of actions.

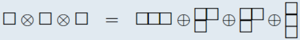


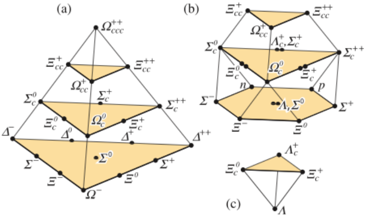
Mass splitting for the Ξ_{cc}^{*} for different types of actions.

Hyperons and Charmed baryons

SU(4) representations:

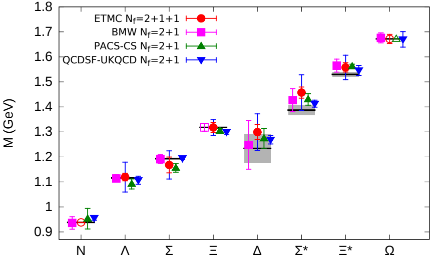
$$4 \otimes 4 \otimes 4 \;=\; 20 \oplus 20 \oplus 20 \oplus \bar{4}$$





First goal: reproduce the low-lying masses

Also $N_f = 2+1+1$ results: C.A., V. Drach, K. Jansen, Ch. Kallidonis, G. Koutsou, arXiv:1406.4310



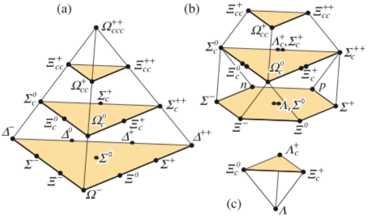
Chiral extrapolation using SU(2) to $\mathcal{O}(p^3)$ and $\mathcal{O}(p^4)$,
B. Tiburzi and A. Walker-Loud, arXiv:0808.0482

- continuum limit taken
- finite volume effects checked
- systematic error due to the chiral extrapolation estimated - biggest uncertainty

Hyperons and Charmed baryons

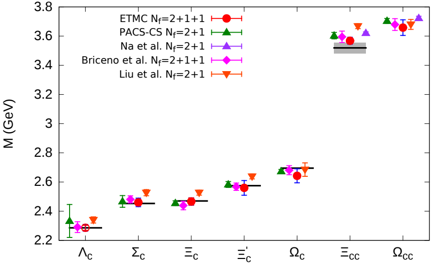
SU(4) representations:

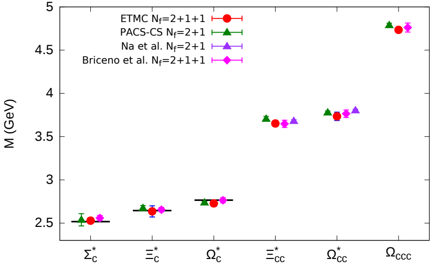
$$4 \otimes 4 \otimes 4 = 20 \oplus 20 \oplus 20 \oplus \bar{4}$$



First goal: reproduce the low-lying masses and make predictions

Also $N_f = 2 + 1 + 1$ results: C.A., V. Drach, K. Jansen, Ch. Kallidonis, G. Koutsou, arXiv:1406.4310





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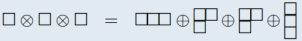
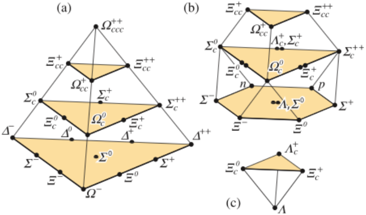
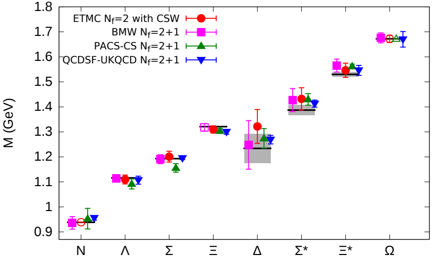




Results by ETM Collaboration using $N_f = 2$ simulations with physical pion mass for one lattice volume and lattice spacing $a = 0.094(2)(2)$ fm, C. A. arXiv:1411.3495



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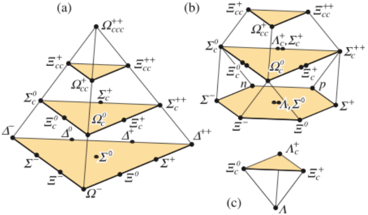

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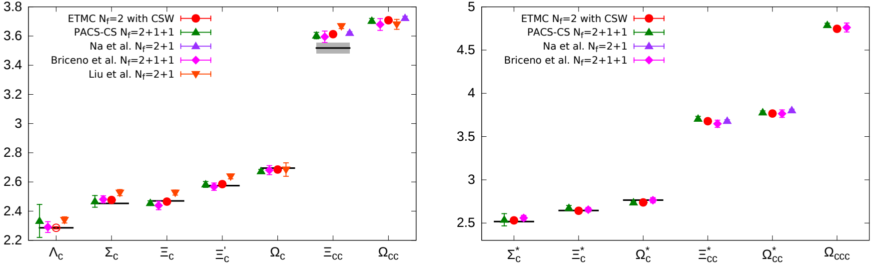
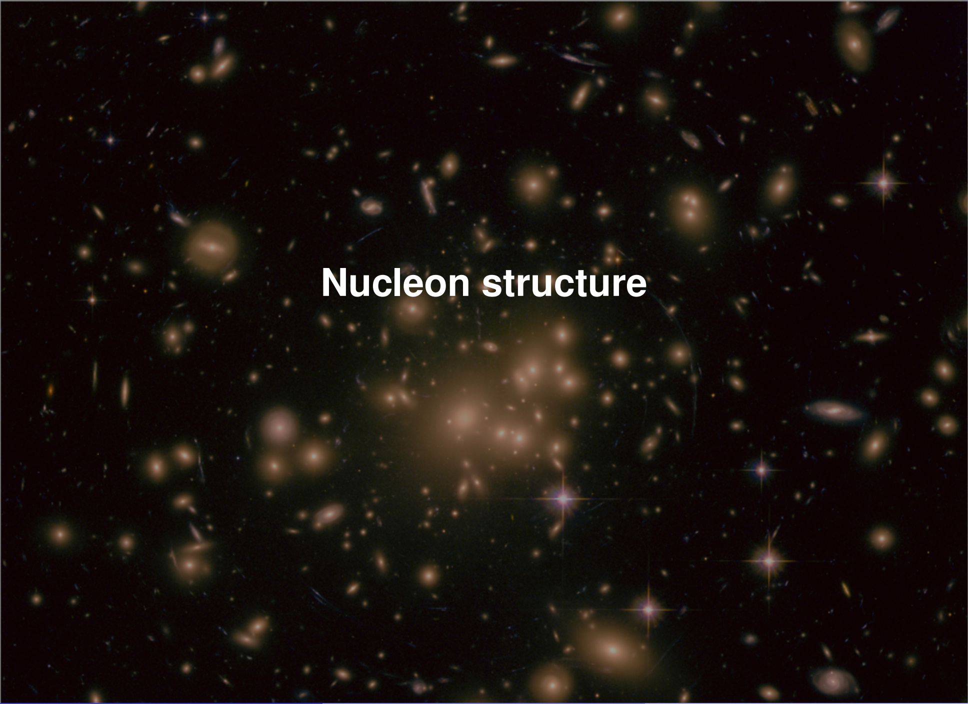




Nucleon structure

Nucleon structure

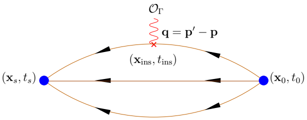
- $N_f = 2+1+1$ twisted mass, $32^3 \times 64$, a=0.082 fm, $m_\pi = 373$ MeV-high statistics analysis including disconnected contributions, 7 sink-source time separations ranging from 0.5 fm to 1.5 fm
- $N_f = 2$ twisted mass plus clover, $48^3 \times 96$, a = 0.094 fm, m_π = 130 MeV, ~ 1400 confs, 4 sink-source time separations ranging from 0.9 fm to 1.5 fm

- Ground state dominance
  - nucleon axial charge g_A, tensor charge - weak, S. Dinter, C.A., M. Constantinou, V. Drach, K. Jansen and D. Renner, arXiv: 1108.1076
  - momentum fraction $\langle x \rangle_{u-d}$, electromagnetic form factors - intermediate
  - nucleon scalar charge (equivalently σ-terms) - severe
- Disconnected contributions - computed only for pion mass down to about 300 MeV
  - nucleon scalar charge, axial charge - need to be taken into account C. Alexandrou *et al.*, arXiv:1309.2256; A. A. Rehim *et al.*, arXiv:1310.6339
  - small for EM form factors

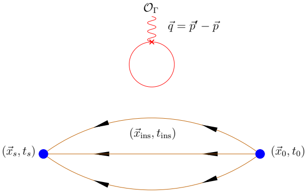
Nucleon structure

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

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



connected contribution



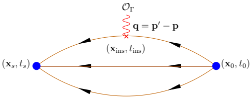
disconnected contribution

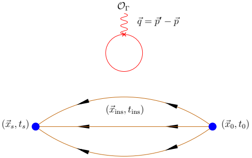
- $\mathcal{M}$ the desired matrix element; t_s, $t_{\rm ins}$, t_0 the sink, insertion and source time-slices; $\Delta(\mathbf{p})$ the energy gap with the first excited state
- Identification of hadron state of interest - dependent on $\mathcal{O}_\Gamma$ i.e. different for g_A, σ-terms, EM form factors
- Connect lattice results to measurements:
  $\mathcal{O}_{\overline{\rm MS}}(\mu)=Z(\mu,a)\mathcal{O}_{\rm latt}(a) \Longrightarrow$ evaluate $Z(\mu,a)$ non-perturbatively

Nucleon structure

Evaluation of three-point functions:

$$G^{\mu\nu}(\Gamma, \vec{q}, t_s, t_{\rm ins}) = \sum_{\vec{x}_s, \vec{x}_{\rm ins}} e^{i\vec{x}_{\rm ins}\cdot\vec{q}}\, \Gamma_{\beta\alpha} \langle J_\alpha(\vec{x}_s, t_s) \mathcal{O}^{\mu\nu}(\vec{x}_{\rm ins}, t_{\rm ins}) \overline{J}_\beta(\vec{x}_0, t_0)\rangle$$





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

- Plateau method:

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

- Summation method: Sum 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 → 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

- Fit $R(t_s, t_{\rm ins}, t_0)$ including the first excited state, T. Bhattacharya *et al.*, arXiv:1306.5435

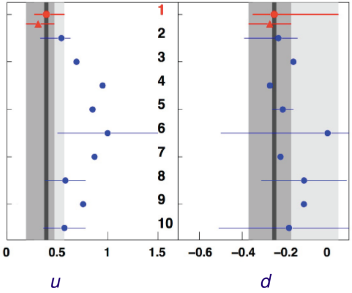
All should yield the same answer in the end of the day!

Nucleon charges

- axial-vector operator: $\mathcal{O}^a_A = \bar{\psi}(x)\gamma^\mu\gamma_5\frac{\tau^a}{2}\psi(x)$
- tensor operator: $\mathcal{O}^a_T = \bar{\psi}(x)\sigma^{\mu\nu}\frac{\tau^a}{2}\psi(x)$
- scalar operator: $\mathcal{O}^a_S = \bar{\psi}(x)\frac{\tau^a}{2}\psi(x)$

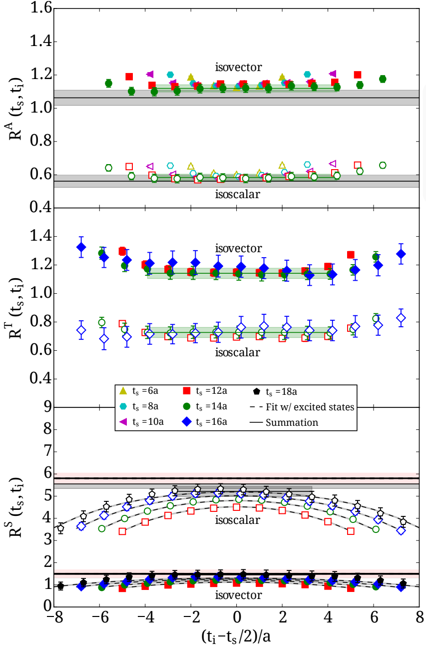
$\Longrightarrow \langle N(\vec{p'})\mathcal{O}_\Gamma N(\vec{p})\rangle|_{q^2=0}$ yeilds $g_s,\ g_A,\ g_T$
(i) isovector combination has no disconnect contributions; (ii) g_A well known experimentally, g_T to be measured

Planned experiment at JLab, SIDIS on ^{3}He/Proton at 11 GeV:



Experimental values: $g^u_T = 0.39^{+0.18}_{-0.12}$ and $g^d_T = -0.25^{+0.3}_{-0.1}$

Nucleon charges



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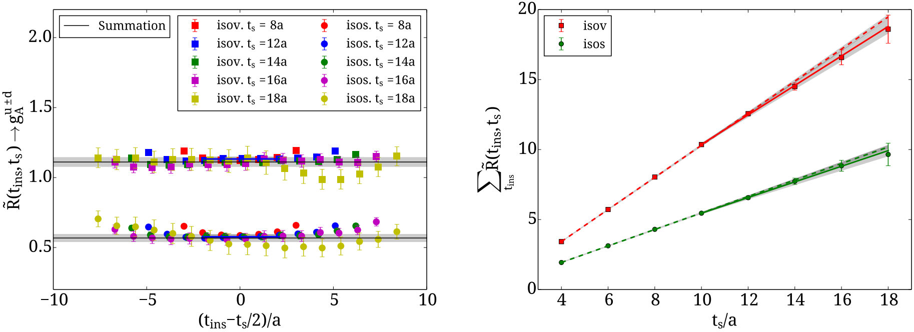
High-statistics study (1200 confs) for $N_f = 2+1+1$ twisted mass fermions at $m_\pi \sim 370$ MeV for the connected contributions.

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

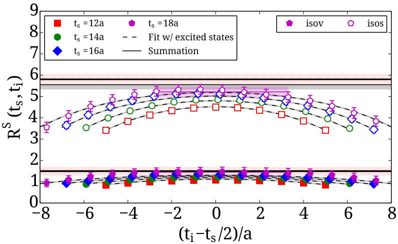
$N_f = 2+1+1$ twisted mass, a = 0.082 fm, m_π = 373 MeV, 1200 statistics



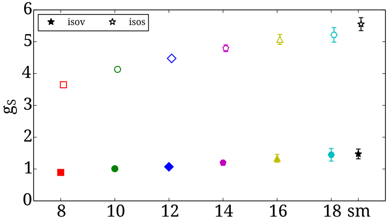
- No detectable excited states contamination
- Consistent results between summation and plateau methods

Scalar charge

- High statistics analysis with $N_f = 2 + 1 + 1$ TMF, $a = 0.082$ fm, $m_\pi = 373$ MeV
- Connected part with 1200 statistics

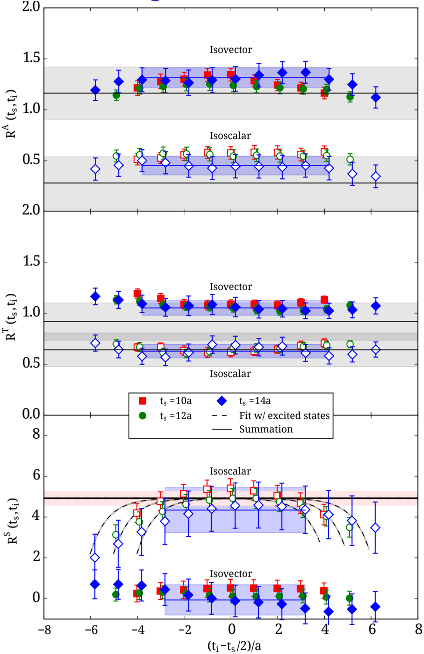


Agreement of summation, plateau and two-states fits give confidence to the correctness of the final result



- g_A: No detectable excited states
- g_T: similar to g_A
- g_s: severe contamination from excited states

Nucleon charges



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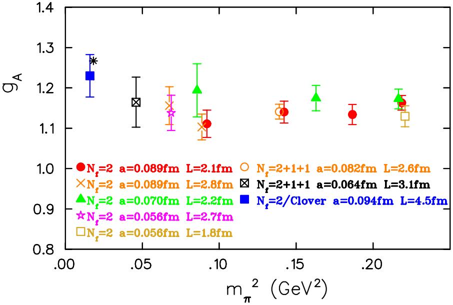
1400 confs for $N_f = 2$ twisted mass fermions at $m_\pi \sim 130$ MeV for the connected contributions → need more statistcs to reach the same accuracy as that at $m_\pi \sim 370$ MeV.

Axial charge g_A

The good news:

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

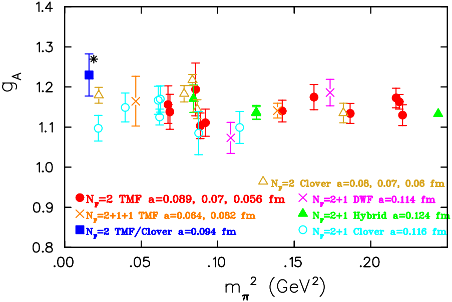


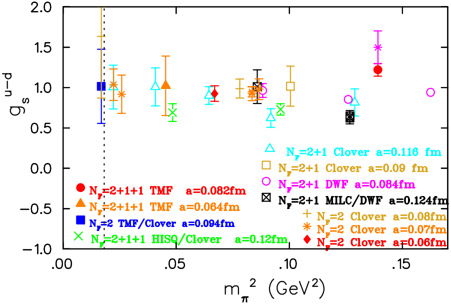
ETM Collaboration

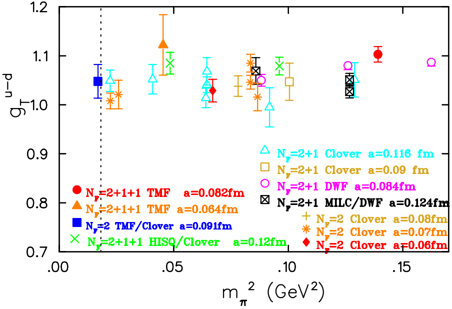
- g_A at the physical point mass indicates agreement with the physical value → important to reduce error
- many results from other collaborations e.g.
  - $N_f = 2 + 1$ Clover, LHPC, J. R. Green *et al.*, arXiv:1209.1687
  - $N_f = 2$ Clover, QCDSF, R.Hosley *et al.*, arXiv:1302.2233
  - $N_f = 2$ Clover, CLS, S. Capitani *et al.* arXiv:1205.0180
  - $N_f = 2 + 1$ Clover, CSSM, B. J. Owen *et al.*, arXiv:1212.4668
  - $N_f = 2 + 1 + 1$ Mixed action (HISQ/Clover), PNDME, T. Bhattacharya *et al.*, arXiv:1306.5435
  - $N_f = 2$ Clover G. Bali *et al.*, arXiv:1412.7336

Nucleon isovector charges: g_A, g_s, g_T

Isovector

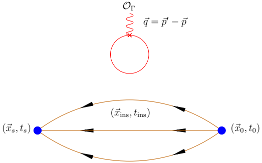






- g_A at the physical point mass indicates agreement with the physical value $\rightarrow$ important to reduce error - many results from other collaborations
- Experimental value of $g_T \sim 0.54^{+0.30}_{-0.13}$ from global analysis of HERMES, COMPASS and Belle e^+e^- data, M. Anselmino *et al.* (2013)
- Large excited state contributions to g_s: increasing the sink-source time separation to $\sim$ 1.5 fm is crucial

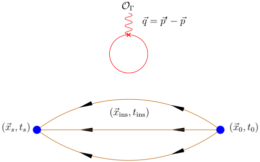
Disconnected quark loop contributions



Notoriously difficult

- $L(x_{\rm ins}) = Tr\,[\Gamma G(x_{\rm ins}; x_{\rm ins})]$ $\rightarrow$ need quark propagators from all $\vec{x}_{\rm ins}$ or L^3 more expensive as compared to the calculation of hadron masses
- Large gauge noise → large statistics
- Use special techniques that utilize stochastic noise on all spatial lattice sites $\rightarrow$ N_r more expensive that hadron masses with $N_r \ll L^3$
- Reduce noise by increasing statistics
  $\Longrightarrow$ take advantage of graphics cards (GPUs) → need to develop special multi-GPU codes

Disconnected quark loop contributions



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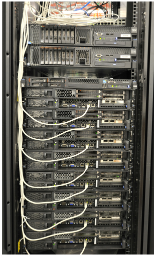
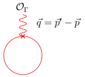
A Fermi card



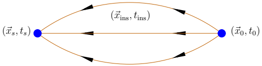
Cluster of 8 nodes of Fermi GPUs

Quark loop contributions



Notoriously difficult

- $L(x) = Tr\,[\Gamma G(x;x)]$ → need all-to-all propagator
- Large gauge noise → large statistics



- Use stochastic noise η → solve $Dv_r = \eta_r$, $r = 1, \ldots, N_r$ → $D^{-1} = \lim_{N_r \to \infty} \frac{1}{N_r} \sum_{j=1}^{N_r} |s_j\rangle\langle\eta_j|$
- Reduce noise by increasing statistics
  $\Longrightarrow$ Take advantage of graphics cards (GPUs) → Develop fast contraction multi-GPU codes in QUDA package
- 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 → Reduce noise by increasing statistics at low cost → 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

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

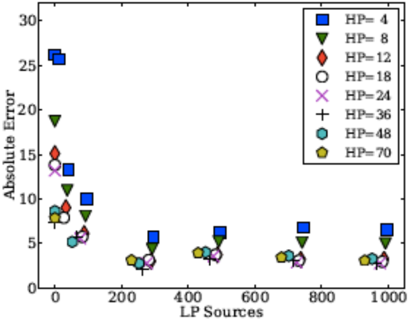
with $D|s_j >= |\eta_j >$

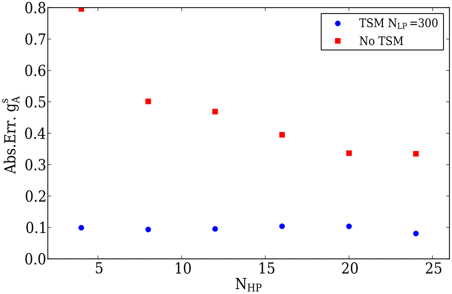
- Need to tune in addition to the high precision noise vectors $N_{\rm HP}$ and number of low precision vectors $N_{\rm LP}$
- Since the LP sources don't require an accurate inversion, we can take advantage of the half precision algorithms for GPUs - use the QUDA library
- To compute the isoscalar disconnected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

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

Tunning of Truncated solver parameters

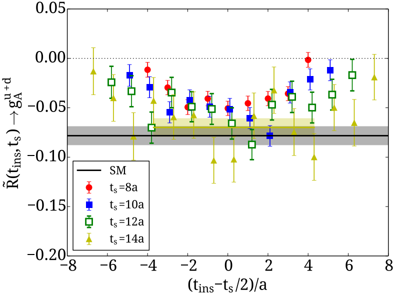
$N_f = 2 + 1 + 1$ twisted mass, a = 0.082 fm, m_π = 373 MeV



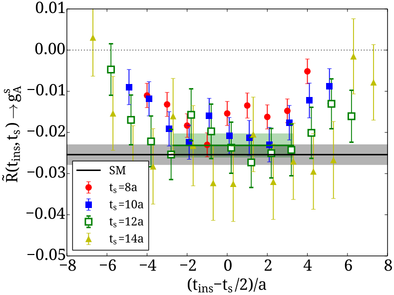


Quark loop contributions

$N_f = 2 + 1 + 1$ twisted mass, a = 0.082 fm, m_π = 373 MeV, $\sim$ **150, 000** statistics (on 4700 confs)



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



Strange quark loop

Singlet renormalization deviates from non-singlet starting at $\mathcal{O}(a^2)$ in perturbation theory, found to be small, A. Skouroupathis and H. Panagopoulos, Phys. Rev. D 79, 094508 (2009)
We neglected this difference as well as the mixing for now

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

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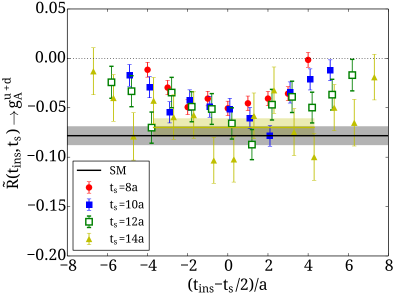

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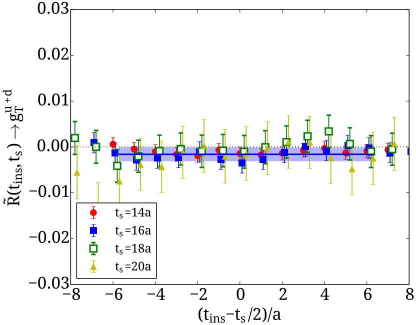

Consistent with zero

Singlet renormalization deviates from non-singlet starting at $\mathcal{O}(a^2)$ in perturbation theory, found to be small, A. Skouroupathis and H. Panagopoulos, Phys. Rev. D 79, 094508 (2009)

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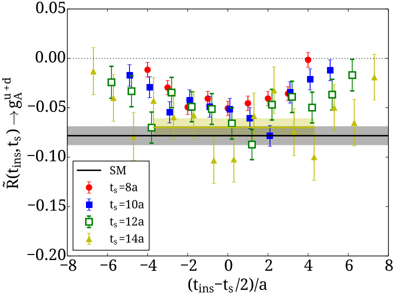

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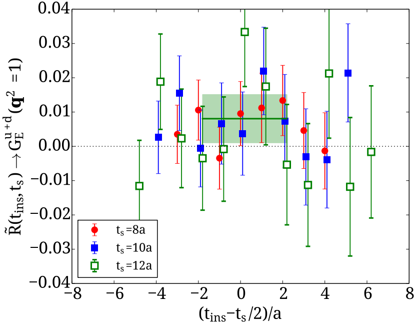

In agreement with St. Meinel *et al.*, Lattice 2014

Singlet renormalization deviates from non-singlet starting at $\mathcal{O}(a^2)$ in perturbation theory, found to be small, A. Skouroupathis and H. Panagopoulos, Phys. Rev. D 79, 094508 (2009)

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Nucleon scalar charge g_s^{u+d}

- $N_f = 2+1+1$ twisted mass, a = 0.082 fm, m_π = 373 MeV
- Disconnected part, $\sim$ 150 000 statistics using GPUs

Use property of TFM: $D_u - D_d = 2i\mu a\gamma_5 \rightarrow D_u^{-1} - D_d^{-1} = -2i\mu a D_d^{-1}\gamma_5 D_u^{-1}$
$\Longrightarrow$ Fluctuations are reduced by the μ factor and product brings a sum over V terms leading to improved signal-to-noise

Nucleon scalar charge g_s^{u+d}

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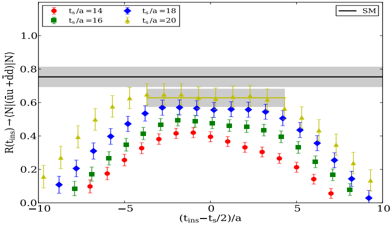
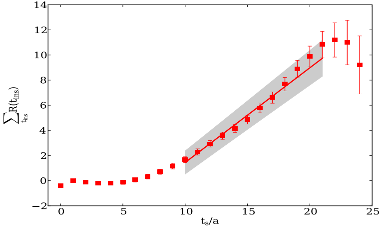
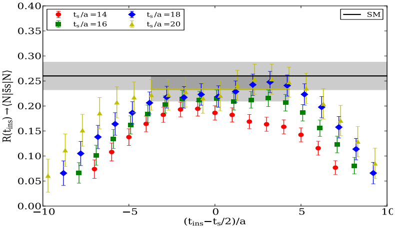
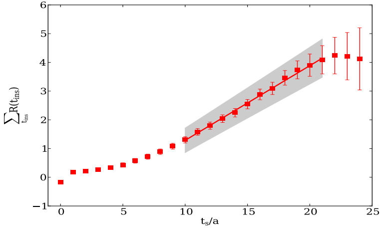








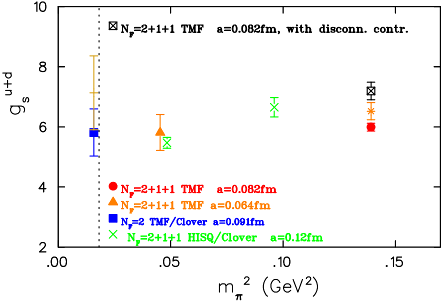
- Large contamination from excited states

Nucleon charges: g_s^{u+d}, g_T^q

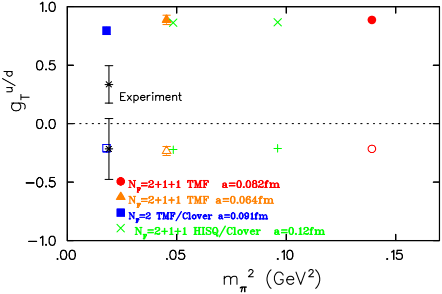
- $N_f = 2+1+1$ twisted mass, a = 0.082 fm, m_π = 373 MeV
- Disconnected part, $\sim$ 150 000 statistics using GPUs

Results shown in $\overline{MS}$ at 4 GeV^2

Analysis at the physical point still preliminary



Large source-sink separation and inclusion of disconnected is required



Experimental values from global analysis of HERMES, COMPASS and Belle e^+e^- data, M. Anselmino *et al.* (2013)

Nucleon moments of parton distribution

What is the distribution of the nucleon momentum among the nucleon constituents?
→ needs knowledge of the parton distribution functions (PDFs)
One measures moments of parton distributions,in DIS:

- Unpolarized moments: $\langle x^n\rangle_q = \int_0^1 dx x^n \left[q(x) - (-1)^n \bar{q}(x)\right]$, $q(x) = q(x)_\downarrow + q(x)_\uparrow$
- Helicity moments: $\langle x^n\rangle_{\Delta q} = \int_0^1 dx x^n \left[\Delta q(x) + (-1)^n \Delta\bar{q}(x)\right]$, $\Delta q(x) = q(x)_\downarrow - q(x)_\uparrow$
- Transversity moments: $\langle x^n\rangle_{\delta q} = \int_0^1 dx x^n \left[\delta q(x) - (-1)^n \delta\bar{q}(x)\right]$, $\delta q(x) = q(x)_\perp + q(x)_\top$

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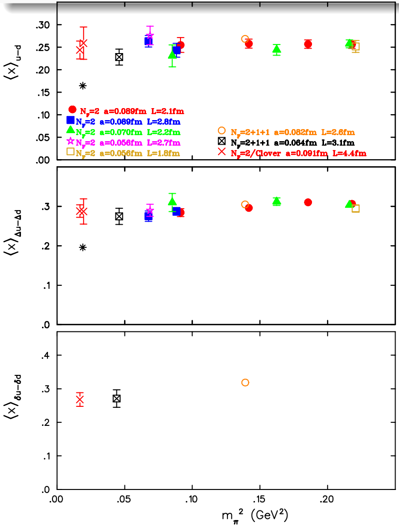


Consider $n = 1$; results obtained in the $\overline{MS}$ scheme at $\mu = 2$ GeV.

- $\langle x \rangle_{u-d}$ and $\langle x \rangle_{\Delta u - \Delta d}$ approach physical value for bigger source-sink separations → need an equivalent high statistics study as at $m_\pi = 373$ MeV
- Can provide a prediction for $\langle x \rangle_{\delta u - \delta d}$

Experimental values:

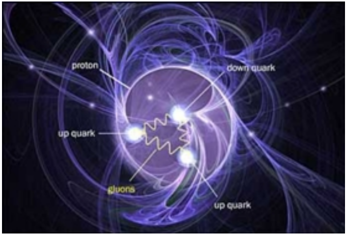
- $\langle x \rangle_{u-d}$ from S. Alekhin *et al.* arXiv:1202.2281
- $\langle x \rangle_{\Delta u - \Delta d}$ from Blumlein *et al.* arXiv:1005.3113

Nucleon spin puzzle

Since 1987 we know that quarks can account for only a small portion of a proton spin

Who carries the rest?

→ needs knowledge of the parton distribution functions (PDFs) measured in DIS



Nucleon spin puzzle

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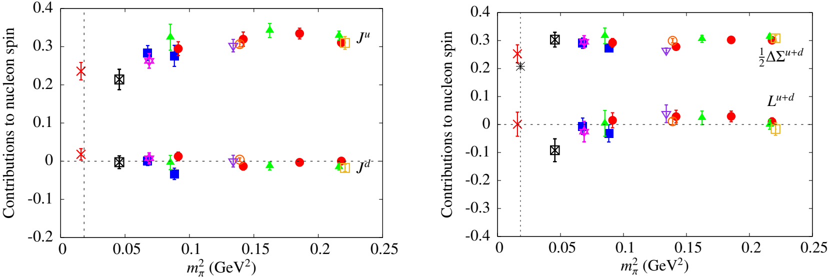
Spin sum: $\frac{1}{2} = \sum_q \underbrace{\left(\frac{1}{2}\Delta\Sigma^q + L^q\right)}_{J^q} + J^G$

$J^q = \frac{1}{2}\left(A^q_{20}(0) + B^q_{20}(0)\right)$ and $\Delta\Sigma^q = g^q_A$

Connected only, except for one ensemble at $m_\pi = 373$ MeV where we have the disconnected contribution → we can check the effect on the observables, $\mathcal{O}(150,000)$ statistics



- Disconnected quark loop contributions non-zero for $\Delta\Sigma^{u,d,s}$
- $L^d \sim -L^u$
- The total spin $J^{u+d} \sim 0.25 \implies$ Where is the other half?
- Contributions from J^G?
  → on-going efforts to measure J_G at RHIC using polarized protons, E. R.Nocera *et al.* (NNPDF Collaboration), arXiv:1406.5539
  → first efforts to compute J_G in lattice QCD e.g. K.-F. Liu (χQCD), arXiv:1203.6388; C.A. *et al.*, arXiv:1311.3174

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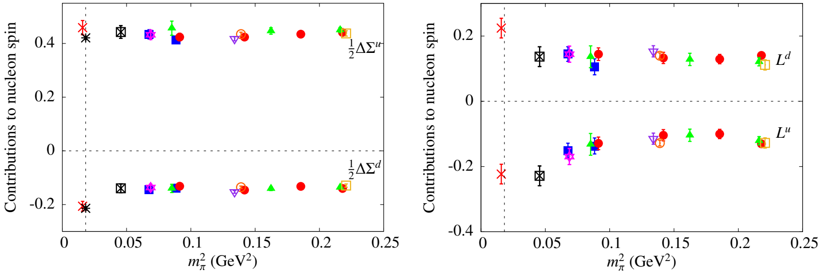

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The quark content of the nucleon

- $\sigma_l \equiv m_l \langle N|\bar{u}u + \bar{d}d|N\rangle$: measures the explicit breaking of chiral symmetry
  Extracted from analysis of low-energy pion-proton scattering data
  Largest uncertainty in interpreting experiments for dark matter searches - Higgs-nucleon coupling depends on σ_l, J. Ellis, K. Olive, C. Savage, arXiv:0801.3656
- In lattice QCD it can be obtained via the Feynman-Hellman theorem: $\sigma_l = m_l \frac{\partial m_N}{\partial m_l}$
- Similarly $\sigma_s \equiv m_s \langle N|\bar{s}s|N\rangle >= m_s \frac{\partial m_N}{\partial m_s}$
- The strange quark content of the nucleon: $y_N = \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u+\bar{d}d|N\rangle} = 1 - \frac{\sigma_0}{\sigma_l}$, where σ_0 is the flavor non-singlet
- A number of groups have used the spectral method to extract the σ-terms, R. Young, Lattice 2012
  But they can be also calculated directly

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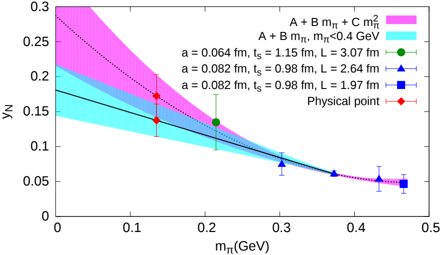
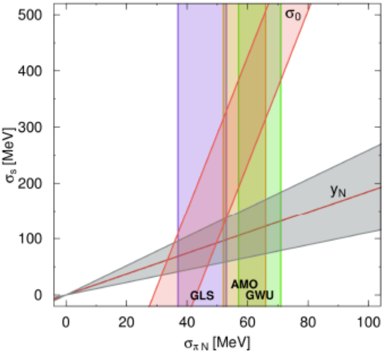


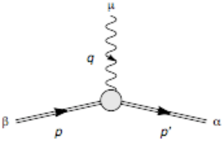


We find $y_N = 0.135\,\underbrace{(22)}_{\text{stat.}}\,\underbrace{(33)}_{\text{ch.extr.}}\,\underbrace{(22)}_{\text{exc.stat.}}\,\underbrace{(9)}_{\text{fin.a}}$

Using $\sigma_s = \frac{1}{2}\frac{m_s}{m_l}y_N\sigma_l$ we find σ_s to be less $\sim$ 150 MeV

Electromagnetic form factors

$$\langle N(p',s')|j^\mu(0)|N(p,s)\rangle = \bar{u}_N(p',s')\left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2)\right]u_N(p,s)$$

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PLAGIARISM
It's worse than you think

CHIMPANZEES
The battle for survival

SHRINKING THE PROTON
New value from exotic atom trims radius by four per cent

NATUREJOBS
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- Proton radius extracted from muonic hydrogen is 7.7 σ different from the one extracted from electron scattering, R. Pohl *et al.*, Nature 466 (2010) 213
- Muonic measurement is ten times more accurate

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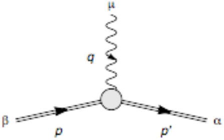
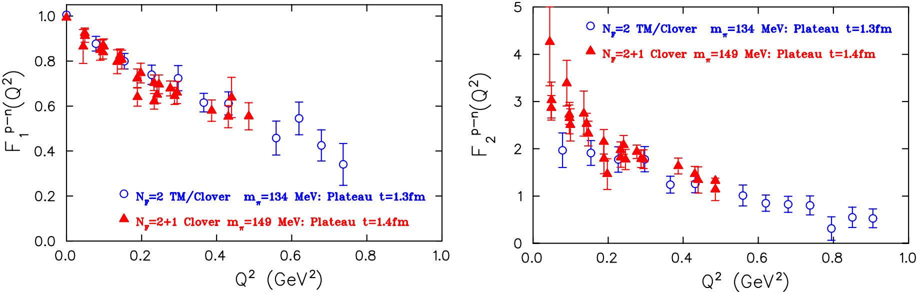


The good news

Two studies at near physical pion mass:

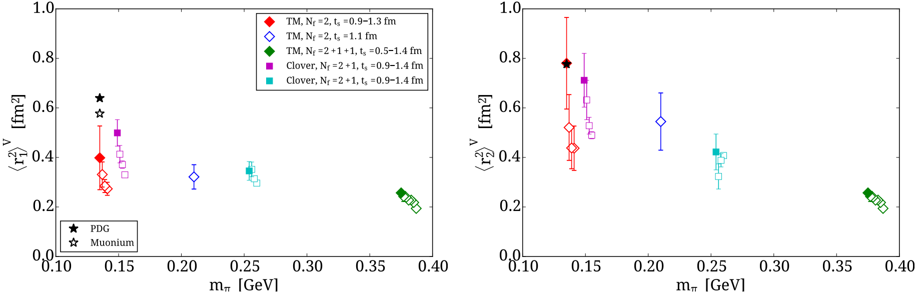
- ETMC: $N_f = 2$ twisted mass with clover, a = 0.094 fm, m_π = 130 MeV, 1020 statistics
- MIT: $N_f = 2 + 1$ clover produced by the BMW collaboration, $a = 0.116$ MeV, $m_\pi = 149$ MeV, ∼7750 statistics, J.M. Green *et al.* 1404.4029



Agreement even before taking the continuum limit

Dirac and Pauli radii

Dipole fits: $\frac{G_0}{(1+Q^2/M^2)^2} \Rightarrow \langle r_i^2 \rangle = -\frac{6}{F_i}\frac{dF_i}{dQ^2}|_{Q^2=0} = \frac{12}{M_i^2}$

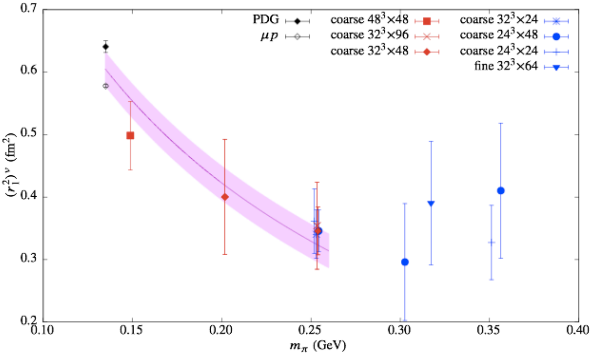


Varying t_s and using summation method increases the radius

Dirac and Pauli radii

Dipole fits: $\frac{G_0}{(1+Q^2/M^2)^2} \Rightarrow \langle r_i^2 \rangle = -\frac{6}{F_i}\frac{dF_i}{dQ^2}\Big|_{Q^2=0} = \frac{12}{M_i^2}$

Need better accuracy at the physical point



Using results from summation method, J. M. Green *et al.*, 1404.4029

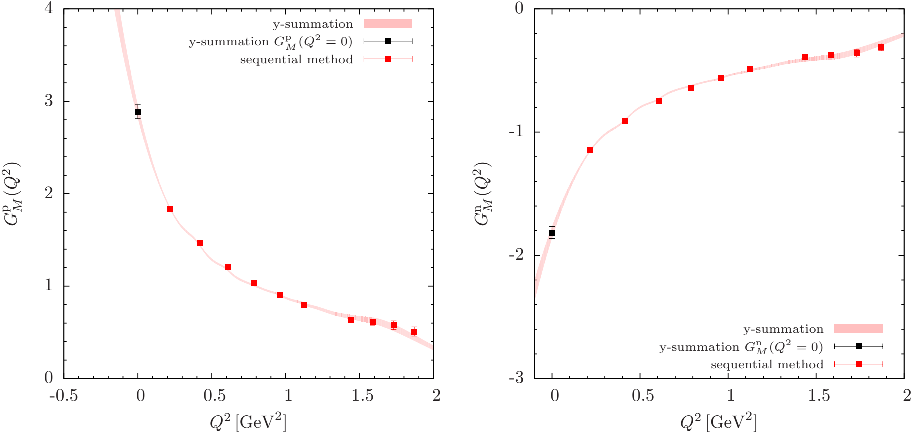
Momentum dependence of form factors

Avoid model dependence-fits: As a first step we calculated $G_M(0)$ (equivalently $F_2(0)$) at $m_\pi = 373$ MeV.

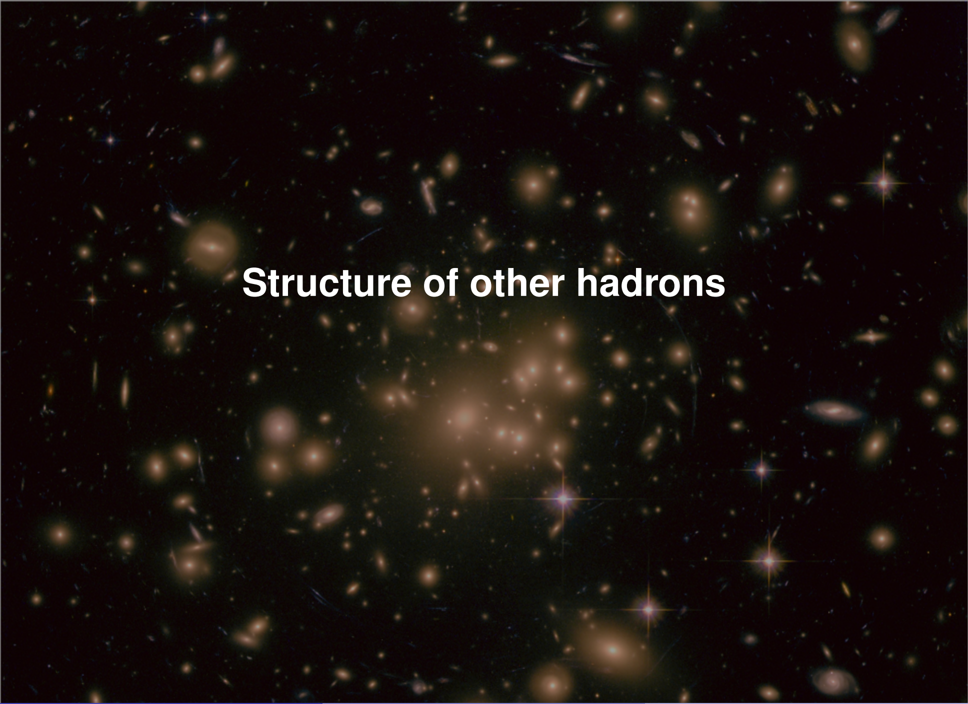
Use position space methods: Apply derivative to ratio

$$\lim_{Q^2\to 0} \frac{\partial}{\partial q_j} R(t_s, t_{\rm ins}, t_0) = \lim_{Q^2\to 0} \frac{\langle \frac{\partial}{\partial q_j} C^{3pt}(t_s, t_{\rm ins}, \vec{q})\rangle}{\langle C^{2pt}(t_s, \vec{0})\rangle}$$

Disconnected contributions small



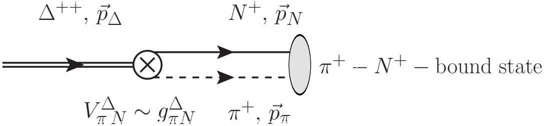
C.A., G. Koutsou, K. Ottnad, M. Petschlies, PoS(Lattice2014), 144



Structure of other hadrons

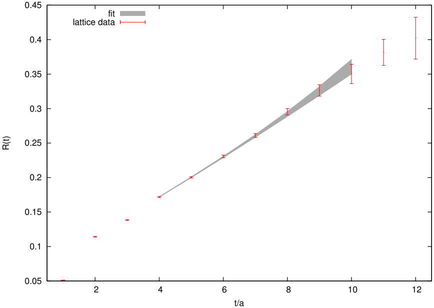
Decay width of baryons

Use the transition amplitude method, C. McNeile, C. Michael, P. Pennanen, PRD 65 094505 (2002)
Test the method for the Δ



- Restrict to the Δ and πN states $\rightarrow$ transfer matrix $T = \mathrm{e}^{-a\bar{E}} \begin{pmatrix} \mathrm{e}^{-a\delta/2} & ax \\ ax & \mathrm{e}^{+a\delta/2} \end{pmatrix}$
- Need $E_\Delta \sim E_\pi + E_N$

$\Longrightarrow$ compute transition amplitude $x = \langle \Delta | N\pi \rangle$ from the correlator $G^{\Delta \rightarrow N\pi}$
Hybrid calculation at $m_\pi \sim 360$ MeV with $L = 3.6$ fm



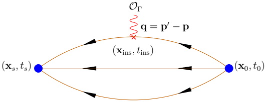
$$R(t) = \frac{G^{\Delta \rightarrow \pi N}(t, \vec{Q}, \vec{q})}{\sqrt{G^{\Delta}(t, \vec{q})\, G^{N\pi}(t, \vec{Q}, \vec{q})}} \sim A + B\frac{sinh(\Delta t/2)}{sinh(a\Delta/2)}$$

$$\sim A + Bt$$

To leading order we connect using effective field theory to the coupling constant $g_{\Delta\pi N} = 27.0(0.6)(1.5) \rightarrow \Gamma_\Delta = 99(12)$ MeV

C. A., J. W. Negele, M. Petschlies, A. Tsapalis, PRD 88 031501 (2013)

Axial charges of hyperons

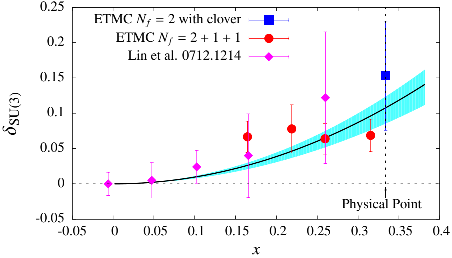


- Hyperon axial charges: $g_{\Lambda\Sigma}\sim 0.60$, $g_{\Sigma\Sigma}$, $g_{\Xi\Xi}$ not known experimentally
- Calculation equivalent to g_A:$\langle h|\bar\psi\gamma_\mu\gamma_5\psi|h\rangle|_{q^2=0}$ - Efficient to calculate with fixed current method

If exact SU(3) flavor symmetry:

- $g_A^N=F+D$, $g_A^\Sigma=2F$, $g_A^\Xi=-D+F\Longrightarrow g_A^N-g_A^\Sigma+g_A^\Xi=0$

Probe deviation: $\delta_{\rm SU(3)}=g_A^N-g_A^\Sigma+g_A^\Xi$ versus $x=(m_K^2-m_\pi^2)/4\pi^2f_\pi^2$, H.- W. Lin and K. Orginos, PRD 79, 034507 (2009)



Breaking $\sim x^2$ leads to about 15% at the physical point
$x_{\rm phy}=0.33$

Axial charges of hyperons

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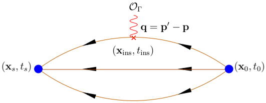

If exact SU(3) flavor symmetry:

- $g_A^N = F + D$, $g_A^\Sigma = 2F$, $g_A^\Xi = -D + F \Longrightarrow g_A^N - g_A^\Sigma + g_A^\Xi = 0$

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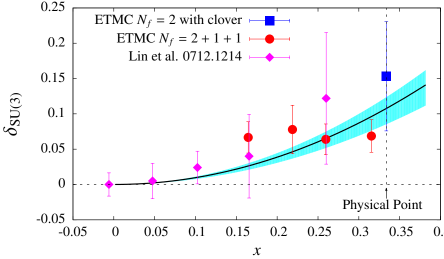

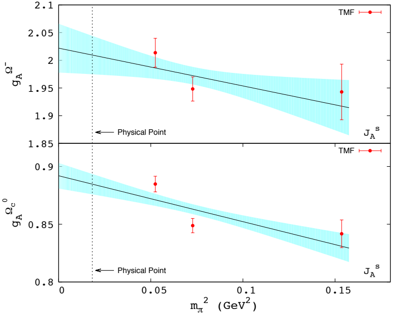

Breaking $\sim x^2$ leads to about 15% at the physical point
$x_{\rm phy} = 0.33$

Conclusions

Simulations at the physical point → that's where we always wanted to be!

Future Perspectives

- Confirm g_A, $\langle x \rangle_{u-d}$, etc, at the physical point
- Provide predictions for g_s, g_T, tensor moment, sigma-terms, etc.
- Provide accurate results on proton radius
- Develop methods for resonances
- Develop methods for calculating the neutron electic dipole moment and other challenging obsrervables

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Many challenges ahead ...
But as simulations at the physical pion mass and more computer resources are becoming available we expect many physical results on key hadron observables that will impact both experiments and phenomenology

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Pre-conference:
Or Hen and Charlotte Van Hulse

IMPORTANT DEADLINE

15TH SEP 2015

- Registration
- Abstract submission

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11th European Research Conference on
"Electromagnetic Interactions with Nucleons and Nuclei"
1-7 November 2015
Annabelle Hotel, Paphos, Cyprus

OVERVIEW

Pre-conference: 1-2 November 2015

- Frontiers and Careers in Photonuclear Physics - skill development and talks for students
- Introductory talks

Main conference: 3-7 November 2015

Conference Topics

- Nucleon form factors and low-energy hadron structure
- Partonic structure of nucleons and nuclei
- Precision electroweak physics and new physics searches
- Meson structure
- Baryon and light-meson spectroscopy
- Nuclear effects and few-body physics

Parallel Workshops

I. Spin structure of nucleons and nuclei from low to large energy scales
II. Spectroscopy – status and future prospects

Poster Session

We invite you to submit abstracts for talks at the workshops and for the poster session. Contributions not selected for talks will be given the option of a poster presentation.

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Acknowledgments

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STRUCTURAL FUNDS
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our ideas, actions for development

ITN STRONGnet

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