Recent results using lattice QCD simulations

Constantia Alexandrou
University of Cyprus and The Cyprus Institute

XLV International Symposium on Multiparticle Dynamics
Wildbad Kreuth, Germany

Outline

1. **Introduction**
   - Computer and algorithmic developments
   - Hadron spectrum
   - Hyperons and Charmed baryons
2. **Hadron structure**
   - Nucleon scalar, axial and tensor charges
   - Hyperon axial charges
   - Generalized Parton Distributions
     - Momentum fraction of the pion
     - Nucleon GPDs
3. **Nuclear Physics**
4. **Finite temperature and density, g_μ-2, B-physics, resonances, rare decays, TMDs, $\cdots$ (not covered)**
5. **Conclusions**

Quantum ChromoDynamics (QCD)

QCD-Gauge theory of the strong interaction
Lagrangian: formulated in terms of quarks and gluons

$$\mathcal{L}_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \sum_{f=u,d,s,c,b,t} \bar{\psi}_f \left(i\gamma^\mu D_\mu - m_f \right) \psi_f$$

$$D_\mu = \partial_\mu - ig\frac{\lambda^a}{2} A^a_\mu$$

Harald Fritzsch

Murray Gell-Mann

Heinrich Leutwyler

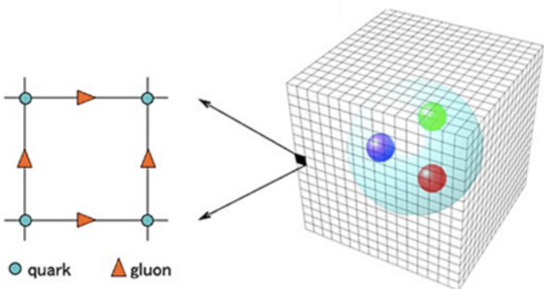
This "simple" Lagrangian produces the amazingly rich structure of strongly interacting matter in the universe.

Numerical simulation of QCD provides essential input for a wide class of complex strong interaction phenomena
→ In this talk: Mostly results on nucleon structure.

Introduction of QCD on the lattice

QCD Lagrangian: formulated in terms of quarks and gluons

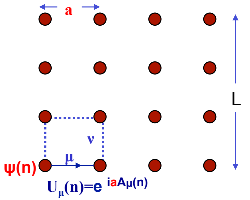
$$\mathcal{L}_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \sum_{f=u,d,s,c,b,t} \bar{\psi}_f \left[i\gamma^\mu \left(\partial_\mu - igA_\mu \right) - m_f \right] \psi_f$$



- Gauge invariant discretization of QCD on a space-time lattice
- Finite lattice spacing a provides an ultraviolet cutoff at π/a
- Lattice provides a non-perturbative regularization
  $\rightarrow$ "lattice regularization" well suited for an asymptotically free theory like QCD
- Theory described by a discrete action S: $S = S_G + S_F$ where $S_F = \sum_x \bar{\psi}(x) D \psi(x)$
  $\longrightarrow$ fermions can be integrated out of the path integral to yield $\det(D[U])$

Introduction of QCD on the lattice

Lattice QCD Lagrangian: formulated in terms of quarks and gluons



- For numerical evaluation:
  - Finite box $L^3 \times T$
  - Fermion degrees of freedom integrated out
  - Rotate into imaginary time - most drastic operation
- Path integral over gauge fields:

  Partition function: $Z = \int \mathcal{D}U_\mu(x) \prod_f det(D_f[U])\, e^{-S_G[U]}$ with $f = u, d, s, c$.
  - Monte Carlo simulation to produce a representative ensemble of $\{U_\mu(x)\}$ using the largest supercomputers
  - Computation of observables: $\langle \mathcal{O} \rangle = \sum_{\{U_\mu\}} O(D_f^{-1}, U_\mu)$ need inverse of Dirac matrix, typically of $10^8 \times 10^8$ dimensions

8.0 Pflop/s (10^{15} flop/s), biggest in Europe

Fermion actions

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

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

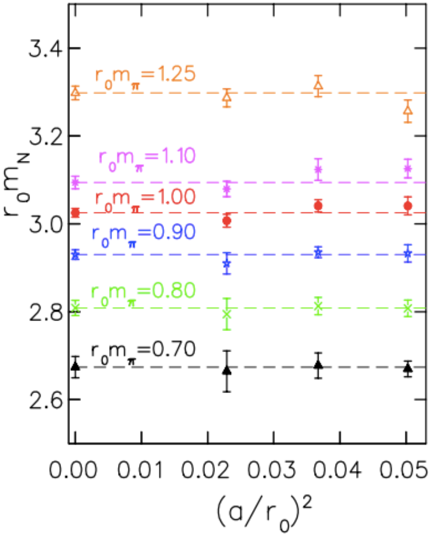
Action	Advantages	Disadvantages
Clover improved Wilson	computationally fast	breaks chiral symmetry needs operator improvement
Twisted mass (TM)	computationally fast automatic improvement	breaks chiral symmetry violation of isospin
Staggered	computational fast	four doublers (fourth root issue) complicated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

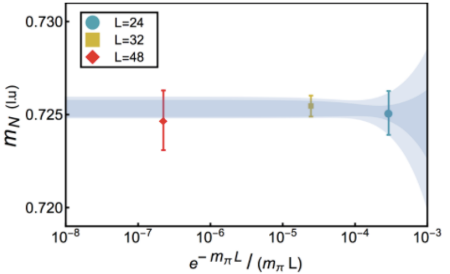
Several collaborations:

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

Systematic uncertainties

- Finite lattice spacing a - take the continuum limit $a \to 0$
- Finite volume L - take infinite volume limit $L \to \infty$



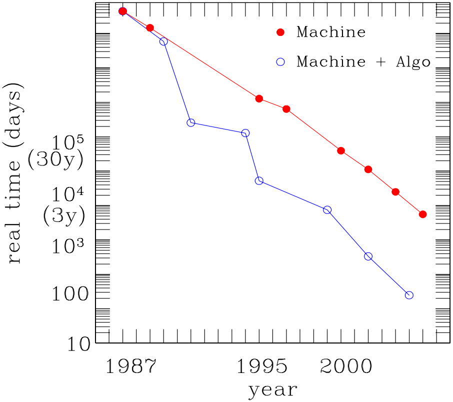


Volume dependence of nucleon mass for $m_\pi \sim 450$ MeV, $N_f = 2+1$ Clover and $a \sim 0.12$ fm, K. Orginos *et al.* (NPLQCD), arXiv:1508.07583

C.A. *et al.* (ETMC), arXiv:0710.1173

Computer and algorithmic development

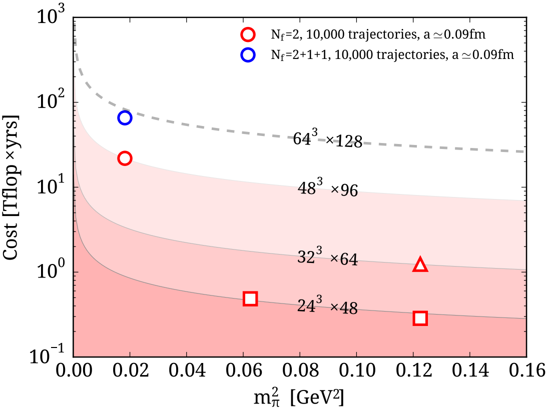
Algorithm development has been decisive



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

ETMC simulations with physical quark masses

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



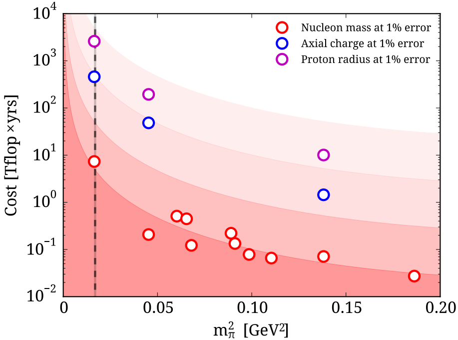
Simulation cost: $C_{\rm sim} \propto \left(\frac{300\rm MeV}{m_\pi}\right)^{c_m} \left(\frac{L}{3\rm fm}\right)^{c_L} \left(\frac{0.1\rm fm}{a}\right)^{c_a}$

We find $c_L \sim 4.5$ and $c_m \sim 2$ for a fixed lattice spacing.

A. Abdel-Rehim *et al.* (ETMC), arXiv:1507.05068

Observables at physical quark mass

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

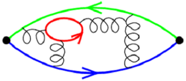


Inversion cost (for a lattice of $64^3 x128$)
Methods to reduce further the statistical error are being developed

Hadron mass

First goal: reproduce the low-lying masses

- Use Euclidean correlation functions:

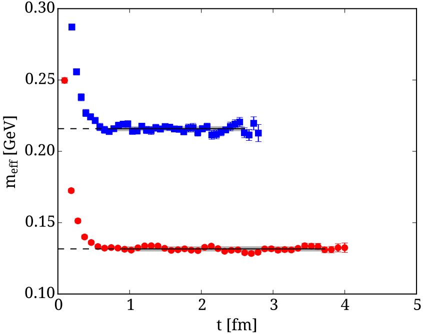


$$G(\vec{q}, t_s) = \sum_{\vec{x}_s} e^{-i\vec{x}_s\cdot\vec{q}} \langle J(\vec{x}_s, t_s) J^\dagger(0)\rangle$$

$$= \sum_{n=0,\cdots,\infty} A_n e^{-E_n(\vec{q})t_s} \stackrel{t_s\to\infty}{\longrightarrow} A_0 e^{-E_0(\vec{q})t_s}$$

Interpolating field with the quantum numbers of π^+: $J(x) = \bar{d}(x)\gamma_5 u(x)$

- Large Euclidean time evolution gives ground state for given quantum numbers $\Longrightarrow$ enables determination of low-lying hadron properties
- $aE_{\rm eff}(\vec{q}, t_s) = \ln\left[G(\vec{q}, t_s)/G(\vec{q}, t_s + a)\right]$
  $= aE_0(\vec{q}) + \text{excited}\rangle\text{states}$
  $\to aE_0(\vec{q}) \stackrel{\vec{q}=0}{\to} am$



$N_f = 2 + 1 + 1$ TM fermions at $m_\pi = 210$ MeV
$N_f = 2$ TM plus clover fermions at physical pion mass

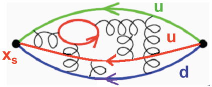
Hadron mass

First goal: reproduce the low-lying masses

- Use Euclidean correlation functions:

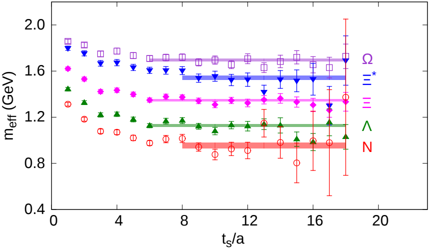
$$G(\vec{q}, t_s) = \sum_{\vec{x}_s} e^{-i\vec{x}_s\cdot\vec{q}} \langle J(\vec{x}_s, t_s) J^\dagger(0)\rangle$$

$$= \sum_{n=0,\cdots,\infty} A_n e^{-E_n(\vec{q})t_s} \xrightarrow{t_s\to\infty} A_0 e^{-E_0(\vec{q})t_s}$$



Interpolating field with the quantum numbers of p: $J(x) = \epsilon^{abc}\left(u^{a\top}(x) C\gamma_5 d^b(x)\right) u^c(x)$

- Large Euclidean time evolution gives ground state for given quantum numbers $\Longrightarrow$ enables determination of low-lying hadron properties
- $aE_{\rm eff}(\vec{q}, t_s) = \ln\left[G(\vec{q}, t_s)/G(\vec{q}, t_s + a)\right]$
  $= aE_0(\vec{q}) + \text{excited}\rangle\text{states}$
  $\to aE_0(\vec{q}) \stackrel{\vec{q}=0}{\to} am$



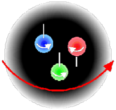
$N_f = 2$ TM plus clover fermions at physical pion mass

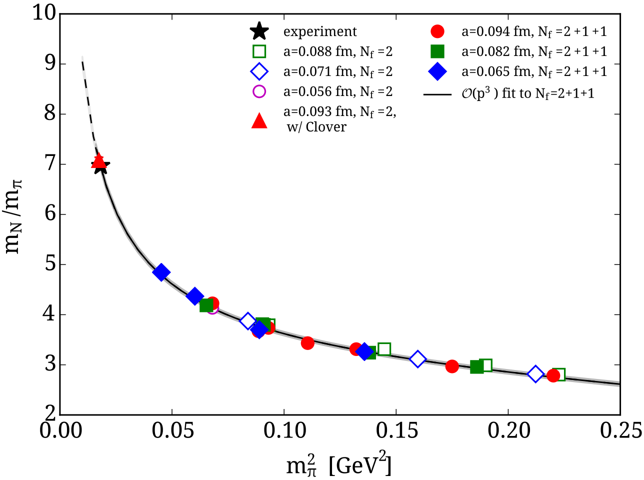
Noise to signal increases with t_s:$\sim e^{(m_h - \frac{3}{2}m_\pi)t_s}$

Simulations with physical quark masses

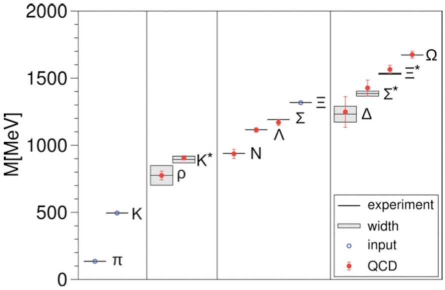
A number of collaborations are producing simulations with physical values of the quark mass

European Twisted Mass Collaboration (ETMC): The nucleon, A. Abdel-Rehim *et al.* (ETMC) arXiv:1507.04936





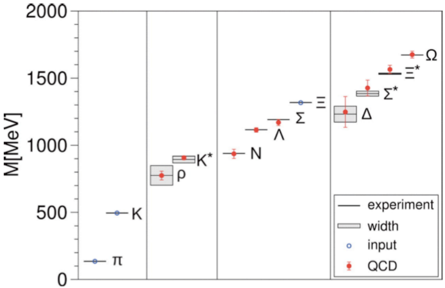
Hadron spectrum



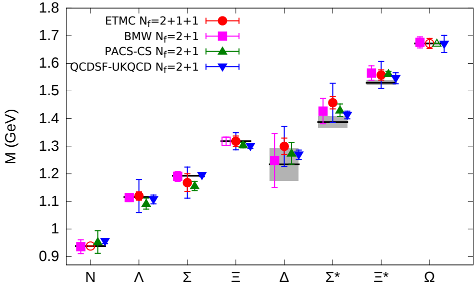
$N_f = 2 + 1$ Clover, BMW, Science 322 (2008)

Milestone calculation for lattice QCD $\rightarrow$ agreement with experiment is a success for QCD & LQCD

Hadron spectrum



$N_f = 2 + 1$ Clover, BMW, Science 322 (2008)

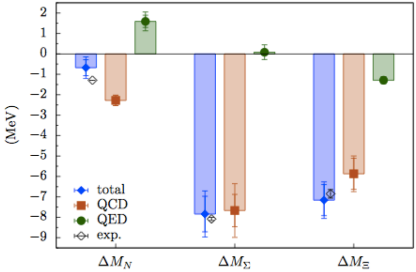


Several collaborations producing the hadron spectrum

Milestone calculation for lattice QCD $\rightarrow$ agreement with experiment is a success for QCD & LQCD

Isospin and electromagnetic mass splitting

RBC and BMW collaborations: Treat isospin and electromagnetic effects to LO

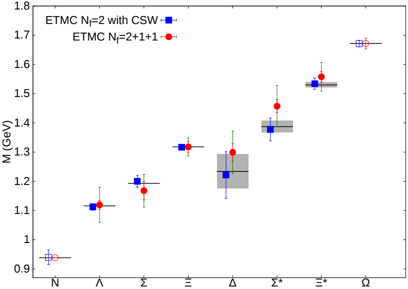


Baryon spectrum with mass splitting from BMW

- Nucleon mass: isospin and electromagnetic effects with opposite signs
- Physical splitting reproduced

Hyperons and Charmed baryons

- Spectrum using $N_f = 2 + 1 + 1$ for a range of pion masses from about 450 MeV to 210 MeV, 3 lattice spacings and different volumes
- Spectrum using an $N_f = 2$ ensemble with physical pion mass

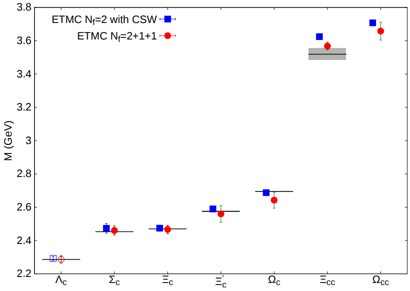


- Continuum extrapolation using three lattice spacings, $a = 0.094$ fm, 0.082 fm and 0.065 fm
- Volume dependence - no observable effects within our statistics
- Chiral extrapolation - biggest systematic error
- Strange quark mass fixed using the Ω^- mass (open symbols)
- The lattice spacing was fixed using the nucleon mass (open symbols)

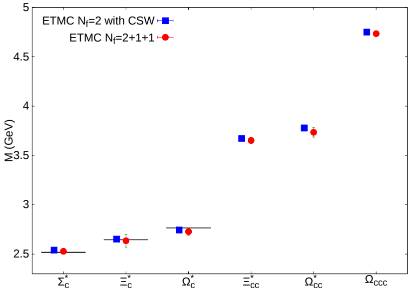
C. Alexandrou, V. Drach, K. Jansen, C. Kallidonis, G. Koutsou, Phys.Rev. D90 (2014) 7, 074501; C. Alexandrou *et al.* (ETMC) to appear

Hyperons and Charmed baryons

- Spectrum using $N_f = 2 + 1 + 1$ for a range of pion masses from about 450 MeV to 210 MeV, 3 lattice spacings and different volumes
- Spectrum using an $N_f = 2$ ensemble with physical pion mass



Spin-1/2 charmed baryons



Spin-3/2 charmed baryons

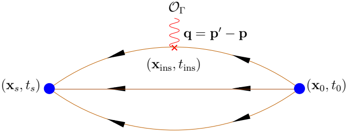
• The charm quark mass was fixed using the Λ_c mass (open symbols)

C. Alexandrou, V. Drach, K. Jansen, C. Kallidonis, G. Koutsou, Phys.Rev. D90 (2014) 7, 074501; C. Alexandrou *et al.* (ETMC) to appear

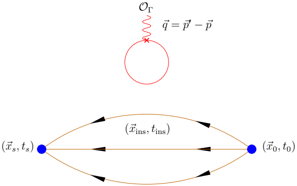
Hadron structure

Evaluation of matrix elements

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



connected contribution



disconnected contribution

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

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

- $\mathcal{M}$ 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

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: $\mathcal{O}^a_S = \bar{\psi}(x)\frac{\tau^a}{2}\psi(x)$

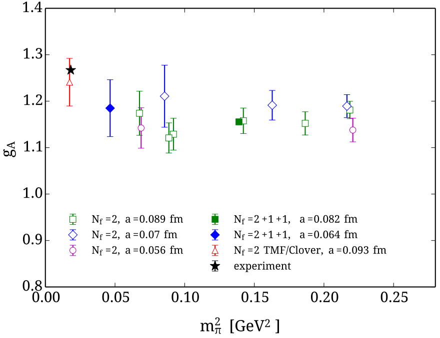
$\Longrightarrow \langle N(\vec{p}')\mathcal{O}_\Gamma N(\vec{p})\rangle|_{q^2=0}$ yields $g_s,\ g_A,\ g_T$

Nucleon charges: Axial-vector charge g_A

The good news:

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

Isovector



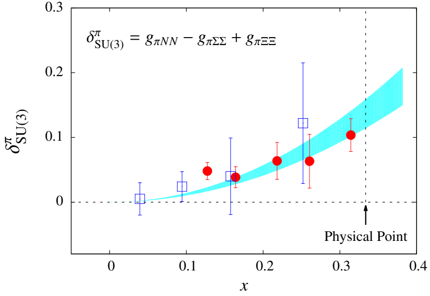
A. Abdel-Rehim *et al.* (ETMC) arXiv:1507.04936

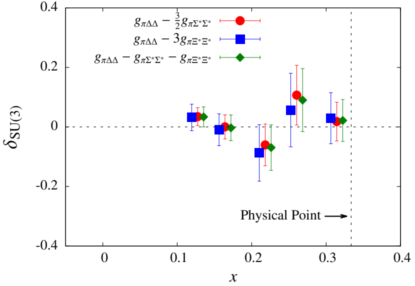
- g_A at the physical point using $\sim$ 1500 measurements indicates agreement with the physical value $\rightarrow$ important to reduce error
- many results from other collaborations, e.g.
  - $N_f = 2+1$ Clover, J. R. Green *et al.*, arXiv:1209.1687
  - $N_f = 2$ Clover, R.Hosley *et al.*, arXiv:1302.2233
  - $N_f = 2$ 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

Hyperon axial charges

- Hyperon axial charges: $g_{\Lambda\Sigma} \sim 0.60$, $g_{\Sigma\Sigma}$, $g_{\Xi\Xi}$ not known experimentally
- Calculation equivalent to g_A of the nucleon:$\langle h|\bar{\psi}\gamma_\mu\gamma_5\psi|h\rangle|_{q^2=0}$ - Efficient to calculate with fixed current method
- $SU(3)$ breaking can be checked systematically

Preliminary





Also results from H.- W. Lin and K. Orginos, PRD 79, (2009)

Probe deviation:

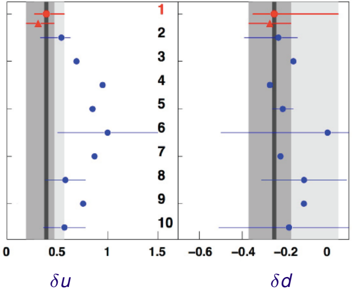
- Octet: $\delta_{SU(3)} = g_A^N - g_A^\Sigma + g_A^\Xi$ versus $x = (m_K^2 - m_\pi^2)/4\pi^2 f_\pi^2$
- Decuplet: Three relations one can check

Nucleon charges: g_s, g_T

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

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

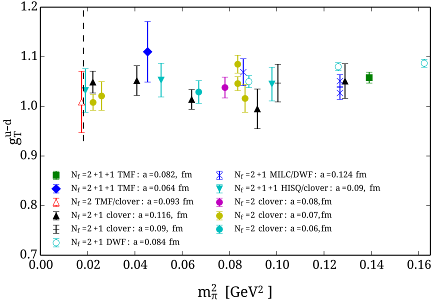
Planned experiment at JLab, SIDIS on ^{3}He/Proton at 11 GeV:

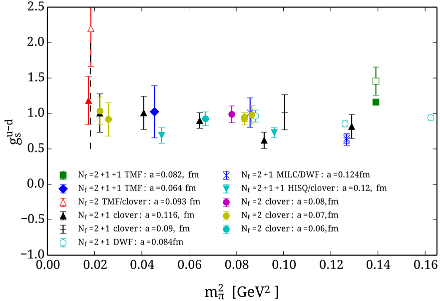


Experimental values: $\delta u = 0.39^{+0.18}_{-0.12}$ and $\delta d = -0.25^{+0.3}_{-0.1}$

Nucleon charges: g_S, g_T

Isovector



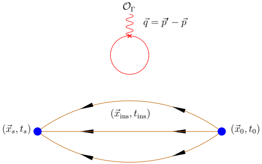


- Experimental value of $g_T \sim 0.54^{+0.30}_{-0.13}$ from global analysis of HERMES, COMPASS and Belle e^+e^- data, M. Anselmino *et al.* (2013).
  New analysis of COMPASS and Belle data :$g_T^{u-d} = 0.81(44)$, M. R. A. Courtoy, A. Bacchettad, M. Guagnellia, arXiv: 1503.03495
- For g_s increasing the sink-source time separation to ~ 1.5 fm is crucial

Disconnected quark loop contributions

Notoriously difficult

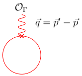
- $L(x_{\rm ins}) = Tr\,[\Gamma G(x_{\rm ins}; x_{\rm ins})]\rangle \rightarrow$ need quark propagators from all $\vec{x}_{\rm ins}$ or L^3 more expensive as compared to the calculation of hadron masses
- Large gauge noise $\rightarrow$ large statistics



- 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) $\rightarrow$ need to develop special multi-GPU codes

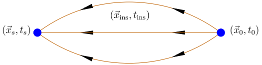
C. A., M. Constantinou, S. Dinter, V. Drach, K. Hadjiyiannakou, K. Jansen, G. Koutsou, A. Strelchenko, A. Vaquero arXiv:1211.0126
C.A., K. Hadjiyiannakou, G. Koutsou, A. O'Cais, A. Strelchenko, arXiv:1108.2473

Disconnected quark loop contributions



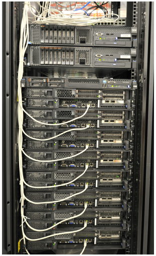
Notoriously difficult

- $L(x_{\rm ins}) = Tr\,[\Gamma G(x_{\rm ins}; x_{\rm ins})]\rangle \rightarrow$ 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 $\rightarrow$ 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) $\rightarrow$ need to develop special multi-GPU codes

A Fermi card



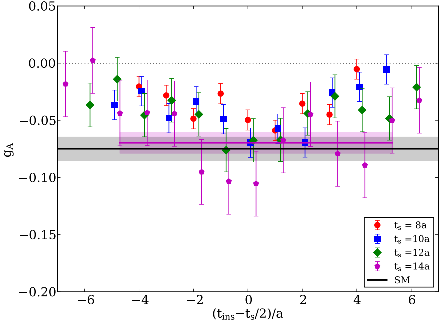
Cluster of 8 nodes of Fermi GPUs at the Cyprus Institute

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

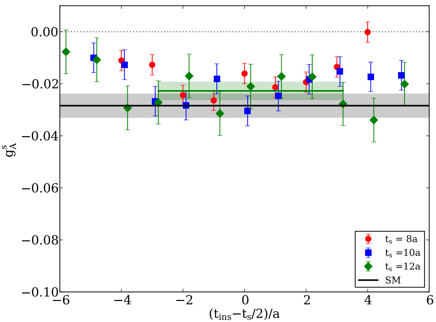
C.A., K. Hadjiyiannakou, G. Koutsou, A. O'Cais, A. Strelchenko, arXiv:1108.2473

Nucleon axial and tensor charges)

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



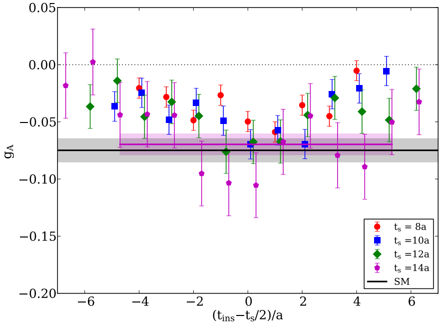
Disconnected isoscalar, agrees with Bali *et al.* (QCDSF), Phys.Rev.Lett. 108 (2012) 222001

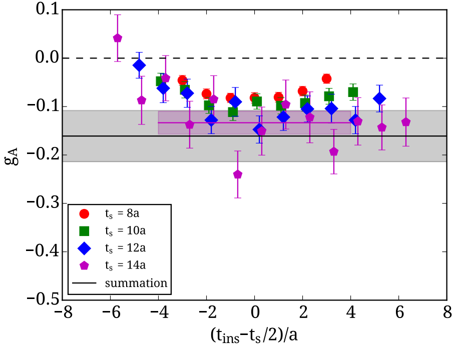


Strange quark loop

Nucleon axial and tensor charges)

- $N_f = 2 + 1 + 1$ twisted mass, $a = 0.082$ fm, $m_\pi = 373$ MeV
- $N_f = 2$ twisted mass plus clover, $a = 0.093$ fm, $m_\pi = 133$ MeV





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

- $\sim$ 150 000 statistics using GPUs
- Small contamination from excited states
- Compute perturbatively the difference between isovector and isoscalar renormalization constants at two-loop, H. Panagopoulos *et al.*

Parton Distribution Functions

Generalized Parton Distributions

Factorization leads to matrix elements of local operators:

- vector operator

$$\mathcal{O}_{V^a}^{\mu_1\cdots\mu_n} = \bar{\psi}(x)\gamma^{\{\mu_1} i \overleftrightarrow{D}^{\mu_2} \dots i \overleftrightarrow{D}^{\mu_n\}} \frac{\tau^a}{2}\psi(x)$$

- axial-vector operator

$$\mathcal{O}_{A^a}^{\mu_1\cdots\mu_n} = \bar{\psi}(x)\gamma^{\{\mu_1} i \overleftrightarrow{D}^{\mu_2} \dots i \overleftrightarrow{D}^{\mu_n\}} \gamma_5 \frac{\tau^a}{2}\psi(x)$$

- tensor operator

$$\mathcal{O}_{T^a}^{\mu_1\cdots\mu_n} = \bar{\psi}(x)\sigma^{\{\mu_1,\mu_2} i \overleftrightarrow{D}^{\mu_3} \dots i \overleftrightarrow{D}^{\mu_n\}} \frac{\tau^a}{2}\psi(x)$$

Special cases:

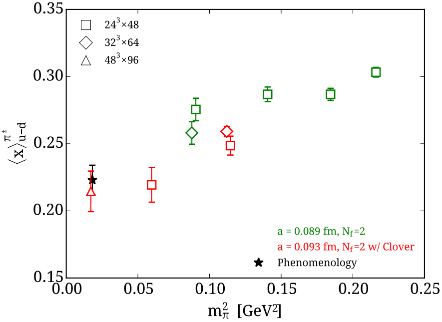
- no-derivative $\rightarrow$ nucleon form factors
- For $Q^2 = 0 \rightarrow$ parton distribution functions
  one-derivative $\rightarrow$ first moments e.g. average momentum fraction $\langle x \rangle$
  Generalized form factor decomposition:

$$\langle N(p',s')|\mathcal{O}_{V3}^{\mu\nu}|N(p,s)\rangle = \bar{u}_N(p',s')\left[A_{20}(q^2)\gamma^{\{\mu}P^{\nu\}} + B_{20}(q^2)\frac{i\sigma^{\{\mu\alpha}q_\alpha P^{\nu\}}}{2m} + C_{20}(q^2)\frac{q^{\{\mu}q^{\nu\}}}{m}\right]\frac{1}{2}u_N(p,s)$$

Nucleon spin $J^q = \frac{1}{2}\left[A_{20}(0) + B_{20}(0)\right]$ and $\langle x \rangle_q = A_{20}(0)$

Momentum fraction for the pion

What is the distribution of the pion momentum among the quarks in the pion?
$\langle x \rangle$ obtained in the $\overline{MS}$ scheme at $\mu = 2$ GeV.

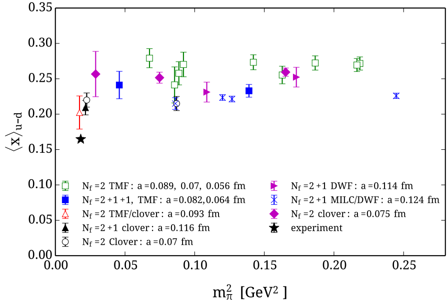


- Agreement between the clover-improved and non-clover improved ensembles, A. Abdel-Rehim *et al.* 1507.05068
- No volume effects observed within our statistical errors
- $\langle x \rangle_{u-d}$ agrees with the phenomenological value extracted from a next-to-leading order analysis from Fermilab E-615 pionic Drell-Yan data, K. Wijesooriya, P. Reimer, and R. Holt, Phys.Rev. C72, 065203 (2005), nucl-ex/0509012

Momentum fraction and the nucleon spin

What is the distribution of the nucleon momentum among the nucleon constituents?

$\langle x \rangle$ obtained in the $\overline{MS}$ scheme at $\mu = 2$ GeV.



Near the physical point we show results from:

- $N_f = 2$ twisted mass plus clover-impoved from ETMC fermions, A. Abdel-Rehim *et al.* 1507.05068
- $N_f = 2 + 1$ clover fermions with 2-HEX smearing from LHPC, J. Green *et al.*, 1209.1687
- $N_f = 2$ clover fermions, G. Bali *et al.*, 1408.6850
- $N_f = 2$ clover fermions from QCDSF/UKQCD, D. Pleiter *et al.*, 1101.2326

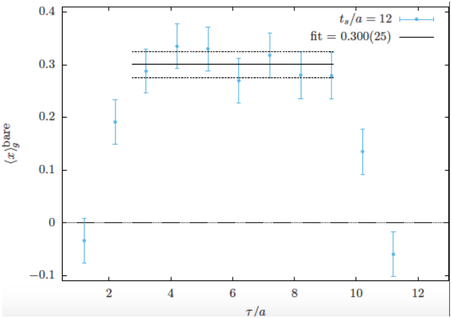
- $\langle x \rangle_{u-d}$ approach physical value for bigger source-sink separations $\rightarrow$ need an equivalent high statistics study
- Can provide a prediction for $\langle x \rangle_{\delta u - \delta d}$

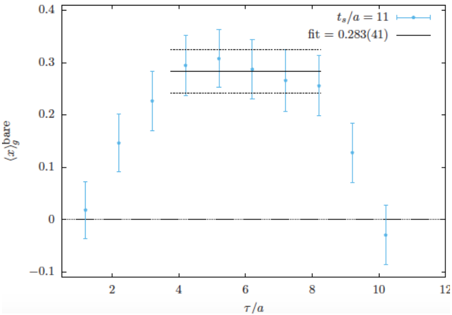
Experimental value:

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

Nucleon gluon moment

- $N_f = 2+1+1$ twisted mass, a = 0.082 fm, m_π = 373 MeV, $\sim$ 34,470 statistics
- $N_f = 2$ twisted mass plus clover, $a = 0.093$ fm, $m_\pi = 132$ MeV, $\sim$155,800 statistics



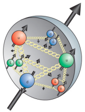


- Matrix element of the gluon operator $O_{\mu\nu} = -\mathrm{Tr}[G_{\mu\rho} G_{\nu\rho}]$
- We consider $\langle N | O_{44} - \frac{1}{3} O_{jj} | N \rangle$ at zero momentum, which yields directly $\langle x \rangle_g$
- HYP-smearing to reduce noise
- Perturbative renormalization
- Preliminary value: $\langle x \rangle_g = 0.282(39)$ for the physical ensemble in $\overline{\mathrm{MS}}$ at $\mu = 2$ GeV

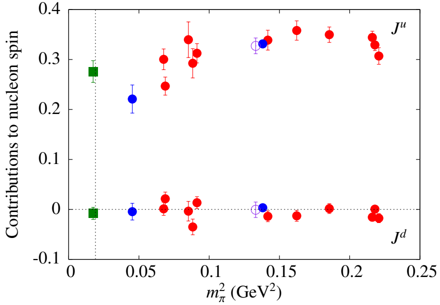
Where is the nucleon spin?

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

$J^q = A_{20}^q(0) + B_{20}^q(0)$ and $\Delta\Sigma^q = g_A^q$



Disconnected contribution using $\mathcal{O}(150,000)$ statistics for $m_\pi = 373$ MeV and for $m_\pi = 133$ MeV

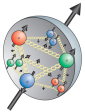


$\Longrightarrow$ Total spin for u-quarks $J^u \stackrel{\sim}{<} 0.25$ and for d-quark $J^d \sim 0$

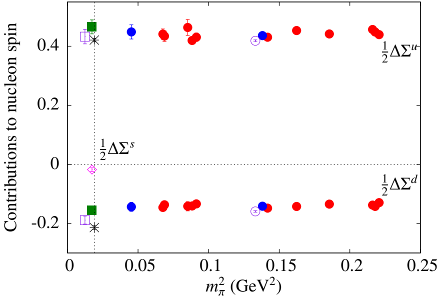
Where is the nucleon spin?

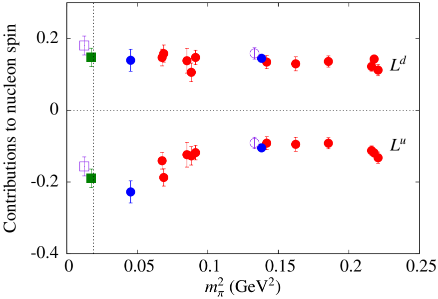
Spin sum: $\frac{1}{2} = \sum_q \underbrace{\left(\frac{1}{2}\Delta\Sigma^q + L^q\right)}_{J^q} + J^G$

$J^q = A_{20}^q(0) + B_{20}^q(0)$ and $\Delta\Sigma^q = g_A^q$



Disconnected contribution using $\mathcal{O}(150,000)$ statistics for $m_\pi = 373$ MeV and for $m_\pi = 133$ MeV





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

Direct evaluation of parton distribution functions - an exploratory study

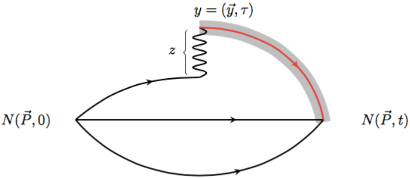
$$\tilde{a}_n(x, \Lambda, P_3) = \int_{-\infty}^{+\infty} dx\, x^{n-1}\, \tilde{q}(x, \Lambda, P_3)\rangle,$$

$$\tilde{q}(x, \Lambda, P_3) = \int_{-\infty}^{+\infty} \frac{dz}{4\pi} e^{-izxP_3} \underbrace{\langle P|\bar{\psi}(z,0)\rangle\gamma_3\, W(z)\psi(0,0)|P\rangle}_{h(P_3,z)}$$

is the quasi-distribution defined by X. Ji Phys.Rev.Lett. 110 (2013) 262002, arXiv:1305.1539

$h(P_3, z)$ can be computed in lattice QCD

- We use our test ensemble with $m_\pi = 373$ MeV
- Perform HYP-smearing on the gauge links
- Use the stochastic all-to-all propagator in the three-point function
- Extract quasi-distribution for $\frac{2\pi}{L}$, $\frac{4\pi}{L}$, $\frac{6\pi}{L}$



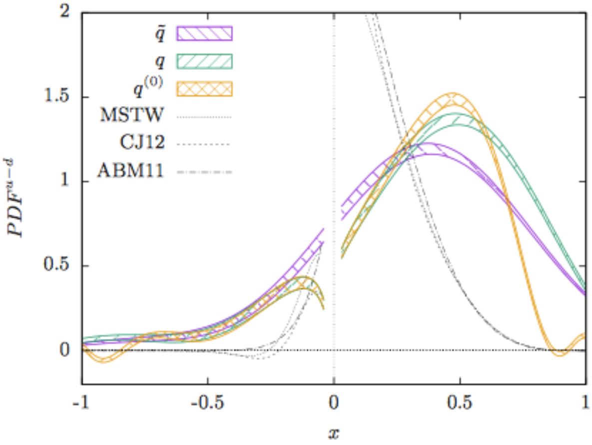
Comments

Our starting point is

$$q(x,\mu) = \tilde{q}(x,\Lambda,P_3) - \frac{\alpha_s}{2\pi}\tilde{q}(x,\Lambda,P_3)\delta Z_F^{(1)}\left(\frac{\mu}{P_3},\frac{\Lambda}{P_3}\right) - \frac{\alpha_s}{2\pi}\int_{-1}^{1}\frac{dy}{y}Z^{(1)}\left(\frac{x}{y},\frac{\mu}{P_3},\frac{\Lambda}{P_3}\right)\tilde{q}(y,\Lambda,P_3) + \mathcal{O}(\alpha_s^2)$$

- The calculation of the leading UV divergences in $\tilde{q}$ in PT are done keeping P_3 fixed while taking $\Lambda \to \infty$ (in contrast to first taking $P_3 \to \infty$ for the renormalization of q)
- We still do not have a renormalization procedure
  $\to$ identify the UV regulator as μ for q and as Λ for the case of the quasi-distribution.
- The dependence on the UV regulator Λ will be translated, in the end, into a renormalization scale μ after proper renormalization
- Single pole terms cancel when combining the vertex and wave function corrections, and double poles are reduced to a single pole that are taken care via the principal value prescription
- A divergent term remains in $\delta Z^{(1)}$ that depends on the cut-off x_c

Preliminary results

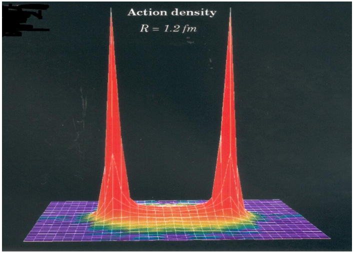


Results for 5-HYP steps, $P_3 = 4\pi/L$

Renormalization still has to be done to remove the cut-off x_c and the remaining divergent term $\sim \ln(x_c^2 - 1)$

Ab Initio Nuclear Physics?

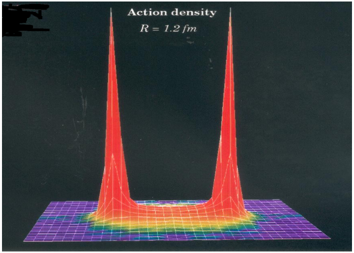
From the $q\bar{q}$ potential to the determination of nuclear forces



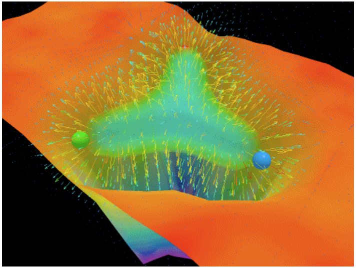
K. Schilling, G. Bali and C. Schlichter, 1995

Ab Initio Nuclear Physics?

From the $q\bar{q}$ potential to the determination of nuclear forces



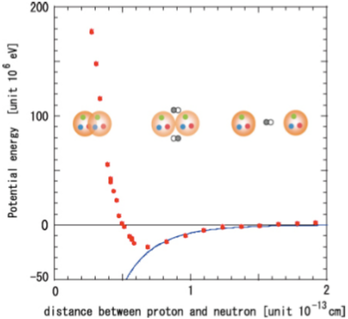
K. Schilling, G. Bali and C. Schlichter, 1995

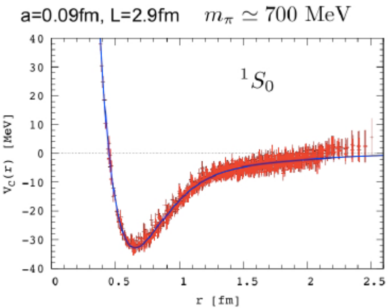


A.I. Signal, F.R.P. Bissey and D. Leinweber, arXiv:0806.0644

Ab Initio Nuclear Physics?

From the $q\bar{q}$ potential to the determination of nuclear forces





Two approaches:

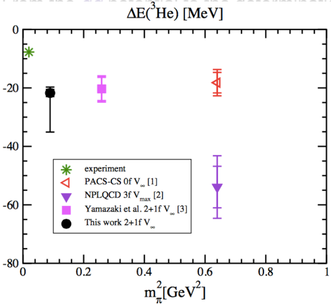
- Determine N-N energy as a function of $L \rightarrow$ extract phase shift - NPQCD
- Detemine BS wave function $\langle 0|N(\vec{r})N(\vec{0})|NN\rangle$ and exract asymptotically the phase shift - HALQCD

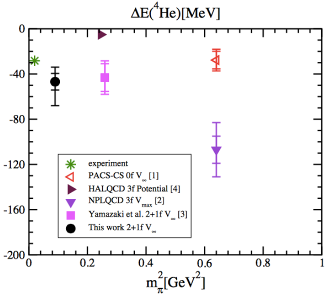
$\rightarrow$ study nuclear physics, neutron stars, ...

Only at the begining...

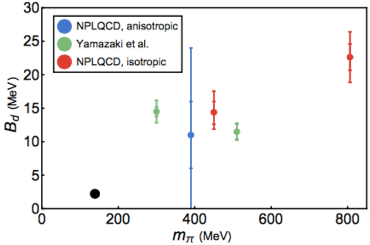
Ab Initio **Nuclear Physics?**

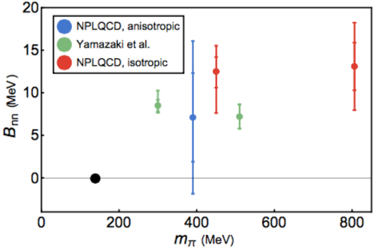
From the $q\bar{q}$ potential to the determination of nuclear for





T.Yamazaki, K. Ishikawa, Y. Kuramashi, A. Ukawa, 1502.04182





Deuteron and nn ($^1S_0$ channel) binding energy, K. Orginos *et al.* 1508.07583

Only at the begining...

Conclusions

Future Perspectives

- Confirm g_A, $\langle x \rangle_{u-d}$, etc, at the physical point using $N_f = 2$ and $N_f = 2+1+1$
- Provide predictions for g_s, g_T, tensor moment, sigma-terms, etc.
- Compute hadron GPDs using new techniques
- Provide input on the proton radius using position methods
- Develop methods for resonances
- *Ab initio* Nuclear Physics
- . . .

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

Conference on *Electromagnetic Interactions with Nucleons and Nuclei*, 1-7 Nov. 2015

ORGANISERS

Conference:
Constantia Alexandrou (Chair)
Richard G. Milner (Vice-Chair)

Workshops:
Zein-Eddine Meziani (Chair)
Marc Vanderhaeghen (Co-chair)

Pre-conference:
Or Hen and Charlotte Van Hulse

IMPORTANT DEADLINE

15TH SEP 2015

- Registration
- Abstract submission

CONTACT DETAILS

Academic Matters
Prof. Constantia Alexandrou
alexand@ucy.ac.cy
+357 22892829

Organisational Matters
Easy Conferences
info@easyconferences.org
+357 22591900

Organised by:

University of Cyprus

Sponsored by:

EPS · HIM Helmholtz-Institut Mainz · Jefferson Lab · TEMPLE UNIVERSITY · MIT Massachusetts Institute of Technology · SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

EINN2015

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.

INTERNATIONAL ADVISORY COMMITTEE

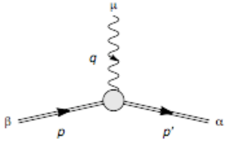
- Mauro Anselmino (University of Torino, Italy)
- Sinya Aoki (University of Kyoto, Japan)
- Reinhard Beck (University of Bonn, Germany)
- Andrea Bressan (CERN, Switzerland)
- Annalisa D'Angelo (University of Rome-II, Italy)
- Achim Denig (University of Mainz, Germany)
- Rolf Ent (JLab, USA)
- Hideto Enyo (Riken, Japan)
- Haiyan Gao (Duke, USA)
- Michel Garcon (Saclay, France)
- Paola Gianotti (Frascati, Italy)
- Michel Guidal (Orsay, France)
- Barry Holstein (University of Massachusetts, USA)
- Karl Jansen (DESY, NIC, Germany)
- Xiangdong Ji (University of Maryland, USA)
- Max Klein (DESY, Germany)
- Karlheinz Langanke (GSI, Germany)
- Gerhard Mallot (CERN, Switzerland)
- William Marciano (BNL, USA)
- Robert McKeown (JLab, USA)
- Piet Mulders (VU University, The Netherlands)
- Costas Papanicolas (The Cyprus Institute, Cyprus)
- Bernard Pire (Ecole Polytechnique, France)
- Xiaoyan Shen (IHEP, China)
- Toshimi Suda (Tohoku University, Japan)
- Marc Vanderhaeghen (Mainz University, Germany)

Join us!
Paphos, Cyprus

Backup slides

Electromagnetic form factors

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

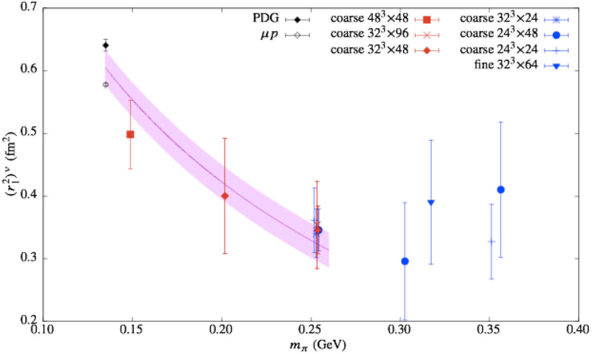


- Proton radius extracted from muonic hydrogen is 7.7 σ different from the one extracted from electron scattering, R. Pohl *et al.*, Nature 466 (2010) 213
- Muonic measurement is ten times more accurate

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

Isovector charge radius $r_{E,\text{iso}}$

Consider isovector rms charge radius of the nucleon:

$$r^2_{E,\text{iso}} = -6 \frac{d}{dQ^2} G_E(Q^2)\Big|_{Q^2=0} \; .$$

- Start from most simple relation for $G_E(Q^2)$:

$$\Pi_0\left(\vec{q}, \Gamma_0\right) = -\sqrt{\frac{E_N + m_N}{2E_N}} G_E\left(Q^2\right) \; .$$

Position methods

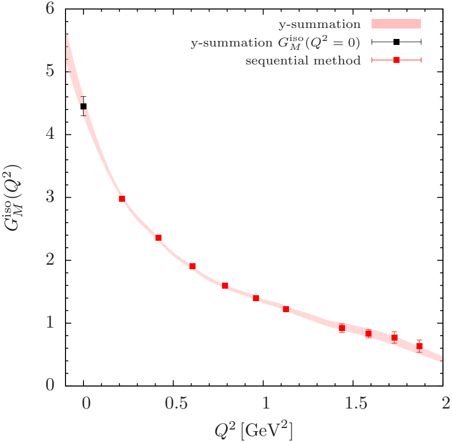
- Avoid model dependence-fits
- Application to Sachs form factors $\rightarrow$ nucleon isovector magnetic moment $G_M^{\rm iso}(0)$
- Isovector rms charge radius of the nucleon
- Neutron electric dipole moment

As a first step we calculated $G_M(0)$ (equivalently $F_2(0)$) at $m_\pi = 373$ MeV.

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

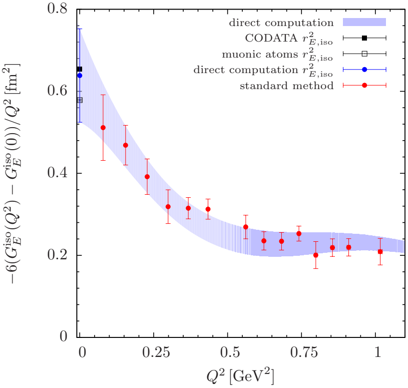
Magnetic moment $G_M^{\rm iso}(0)$

- In principle, values at larger Q^2 have very little influence
- Value for $G_M^{\rm iso} = 4.45(15)_{\rm stat}$ larger than result from dipole fit $3.99(9)_{\rm stat}$
- Closer to exp. value (4.71)



$G_M^{\rm iso}(0)$ from $\mathcal{O}(4700)$ gauge confs of B55; $t_s/a = 14$

Results for $r_E^{\rm iso}$



- We use an ETMC $48^3 \times 96$, $N_f = 2$ ensemble with **physical pion mass**
- Data shown in plot are for $O(1400)$ confs
- $t_s/a = 14$ **compatible with experiment!**
- Unfortunately errors are still not small enough to distinguish the two experimental values