Computing the visible universe via large-scale simulations of QCD

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The Cyprus Institute

Supermassive Computations in Theoretical Physics
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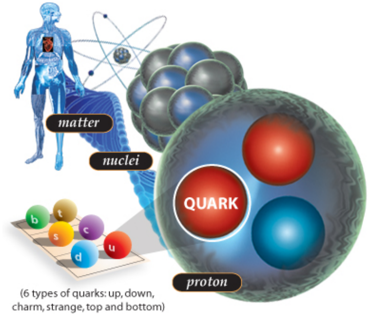
Outline

1. **Motivation**
2. **Introduction to Lattice QCD**
3. **Recent achievements**
   - Simulations with physical values of the quark masses
   - Masses of Hyperons and Charmed baryons
   - Isospin effects
4. **Challenges and future perspectives**
   - Nucleon Structure
     - Electromagnetic form factors
     - Axial, scalar and tensor charges
     - Proton spin puzzle
   - Nuclear Physics
   - QCD phase diagram
5. **Conclusions**

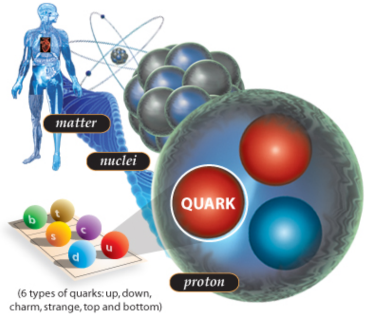
Strong Interactions

The quarks and the gluons are the elementary particles of the strong interactions

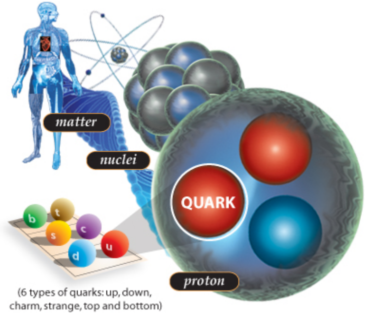


Strong Interactions

The quarks and the gluons are the elementary particles of the strong interactions revealed in scattering experiments at accelerator facilities.

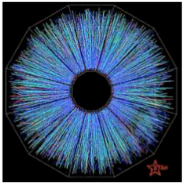


Strong Interactions

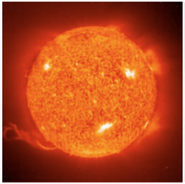


- Quark-Gluon plasma existed at $t \sim 10^{-32}$s and $T \sim 10^{27}$, studied in heavy ion collisions at RHIC and LHC
- Hadrons formed at $t \sim 10^{-6}$ s, and studied in many experimental facilities word-wide e.g. at CERN, JLab, Mainz.
- Matter-antimatter asymmetry: $t \sim 10^{-6}$s

The Strong Interactions describe the evolution from the big-bag to the present universe and beyond.



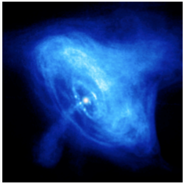
Birth



Fusion

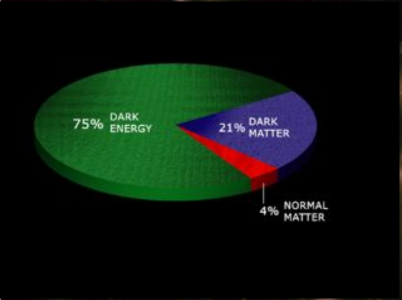
Metals

Supernova

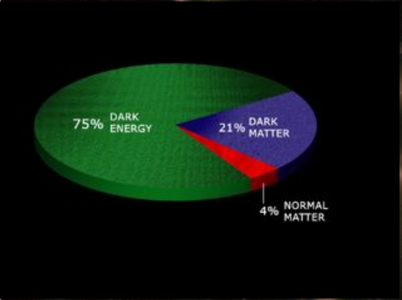


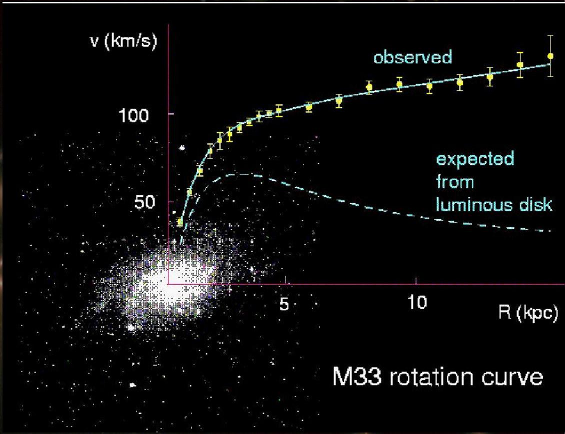
Collapse

Physics beyond the standard model



Physics beyond the standard model





The galaxy rotation problem is the discrepancy between observed galaxy rotation curves and the theoretical prediction based on luminous material → Dark matter

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

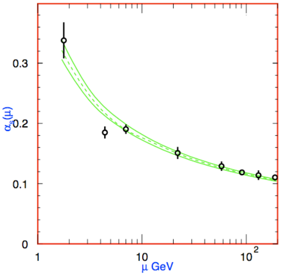
Heinrich Leutwyler

Phys.Lett. B47 (1973) 365

This “simple” Lagrangian produces the amazingly rich structure of strongly interacting matter in the universe.
Very elegant but **very difficult to solve**
$\Longrightarrow$ use large-scale numerical simulation

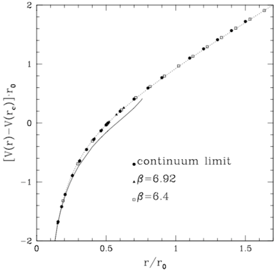
Properties of QCD

Asymptotic freedom: $g(\mu)$

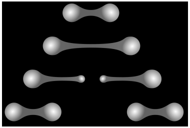


[Yao et al., PDG 2006]

Confinement



[Necco & Sommer, Nucl Phys B622 (2002) 328]

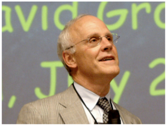


proton (artist's impression)

Protons make up to 99.9% of the visible matter in our universe

Nobel Prize in Physics 2004

"...for the discovery of asymptotic freedom in the theory of the strong interaction"



David Gross

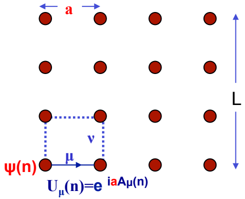
Frank Wilczek

David Politzer

QCD is a unique theory:

- Confinement - quarks can never be free! Unlike any physical system we knew up to now.
- Almost all mass is generated by interactions
- But at high energy QCD behaves like a free theory $\rightarrow$ asymptotic freedom

QCD on the lattice

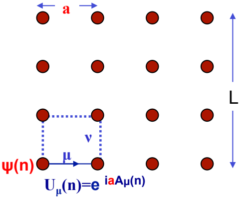


Lattice QCD: K. Wilson, 1974 provided the formulation; M. Creutz, 1980 performed the first numerical simulation

Discretization of space-time with lattice spacing a ensuring gauge invariance

- Define quark fields $\psi(x)$ and $\bar{\psi}(x)$ on lattice sites
- Introduce parallel transporter connecting point x and $x + a\hat{\mu}$:
  $U_\mu(x) = e^{iaA_\mu(x)}$ i.e. gauge field $U_\mu(x)$ is defined on links
  - Finite a provides an ultraviolet cutoff at $\pi/a \rightarrow$ non-perturbative regularization
  - Finite $L \rightarrow$ discrete momenta in units of $2\pi/L$ if periodic b.c.
- Construct an appropriate action S: $S = S_G + S_F$ where
  $S_F = a^4 \sum_x \bar{\psi}(x) D \psi(x)$ i.e. quadratic in the fermions
  $\longrightarrow$ can be integrated out leaving a path integral over gauge fields

QCD on the lattice



Lattice QCD: K. Wilson, 1974 provided the formulation; M. Creutz, 1980 performed the first numerical simulation

Discretization of space-time with lattice spacing *a* ensuring gauge invariance

- Go to imaginary time: $\langle \mathcal{O} \rangle = \frac{1}{Z} \int_U \mathcal{O}(D^{-1}, U)\, det(D[U])^{n_f}\, e^{-S_G[U]}$
  $\rightarrow$ Monte Carlo simulation to produce a representative ensemble of $\{U_\mu(x)\}$ using the largest supercomputers
  $\rightarrow$ Observables: $\langle \mathcal{O} \rangle = \frac{1}{Z} \sum_{\{U_\mu\}} O(D^{-1}, U_\mu)$

COURTESY: FORSCHUNGSZENTRUM JÜLICH

5.0 Pflop/s, second biggest in Europe, 8th in the world - TOP 500 Nov. 2014

Fermion action

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
Overlap	JLQCD

Systematic uncertainties

- Finite lattice spacing a - take the continuum limit $a \to 0$
- Finite volume L - take infinite volume limit $L \to \infty$
- Identification of hadron state of interest

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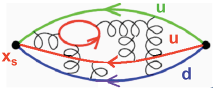
Creation operator for zero momentum: $J_p^\dagger(t_s) = \sum_{\vec{x}_s} J_p^\dagger(\vec{x}_s, t_s)$
Proton propagator:



$$\begin{aligned}\langle J_p(t_s) J_p^\dagger(0)\rangle &= \sum_n \langle 0| J_p\, e^{-H_{QCD} t_s} |n><n| J_p^\dagger |0\rangle \\ &= \sum_n |\langle 0|J_p|n\rangle|^2 e^{-E_n t_s} \xrightarrow{t_s \to \infty} |\langle 0|J_p|p\rangle|^2\, e^{-m_p t_s}\end{aligned}$$

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

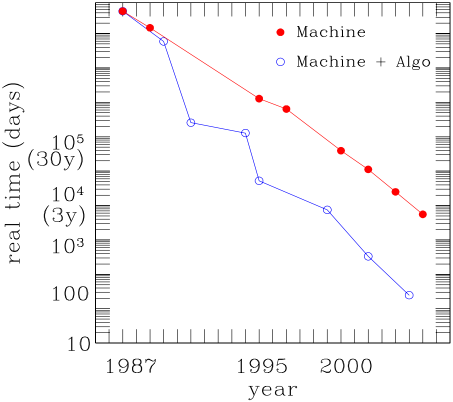
Systematic uncertainties

- Finite lattice spacing a - take the continuum limit $a \to 0$
- Finite volume L - take infinite volume limit $L \to \infty$
- Identification of hadron state of interest
- Simulation at physical quark masses - now feasible
- Computation of valence quark loops - now feasible

Recent achievements

Computer and algorithmic development

Algorithm development has been decisive

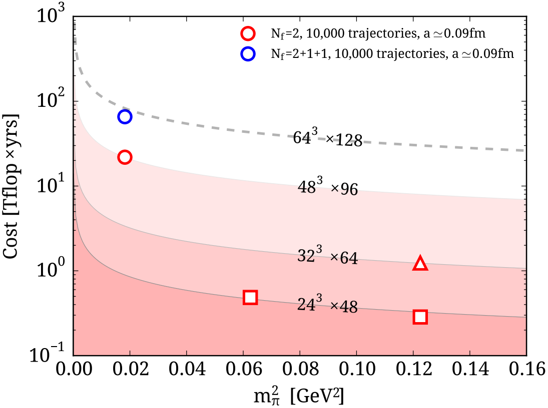


Simulation on a $32^3 \times 64$ lattice, 5000 configurations

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

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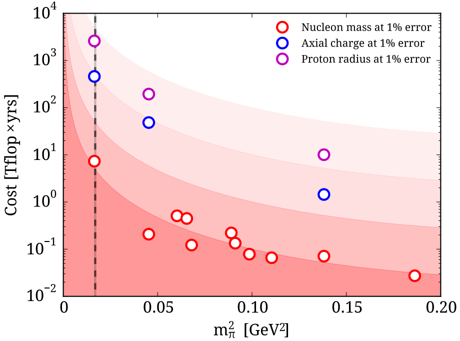

Inversion cost (for a lattice of 64^3x128):$\sim e^{(m_p - \frac{3}{2}m_\pi)t_s}$

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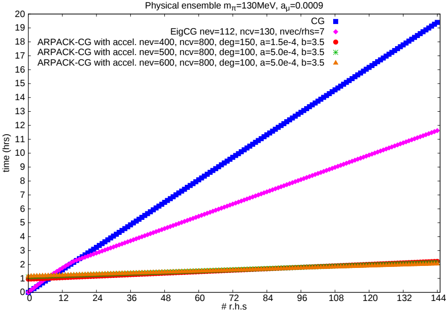
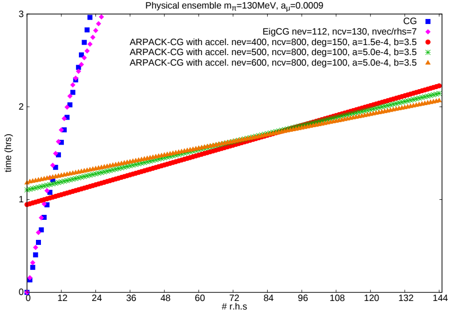
Deflation of lower eigenvalues essential for computations at the physical point → reduction of cost by ~ 20 times.





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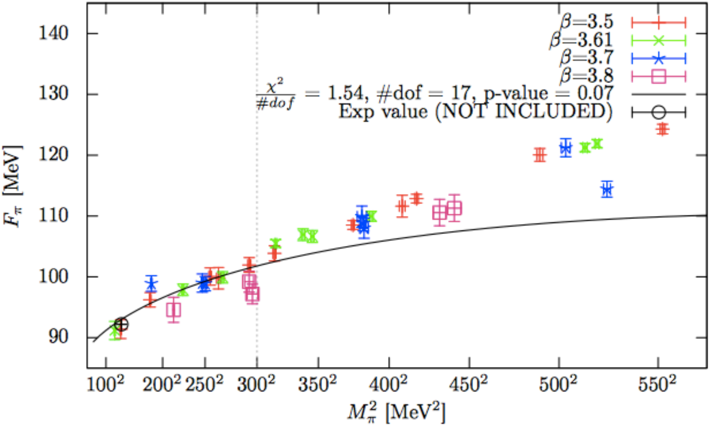
Budapest-Marseille-Wuppertal (BMW) Collaboration: $N_f = 2 + 1$ Clover improved Wilson fermions with HEX smearing



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

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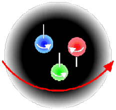
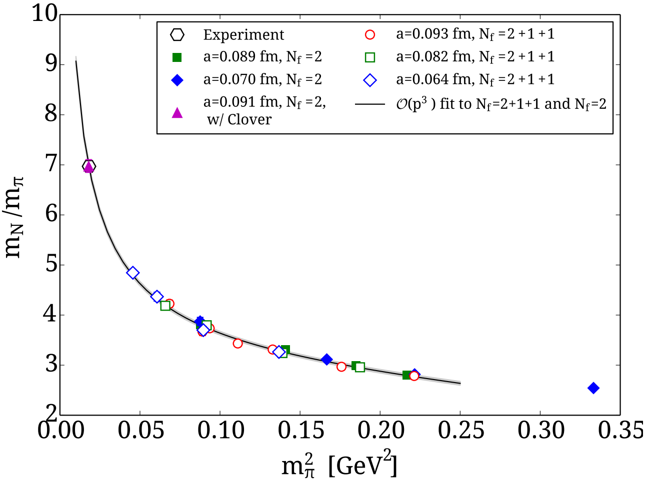
The proton:



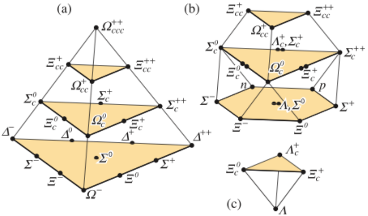


$L \sim 3$ fm and $a \sim 0.1$ fm; Lowest order heavy baryon chiral perturbation theory with experimental value excluded

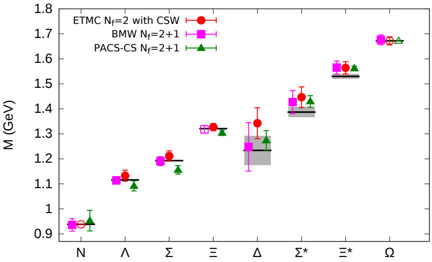
Hyperons and Charmed baryons

SU(4) representations:

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



First goal: reproduce the low-lying masses



Results by ETM Collaboration using $N_f = 2$ simulations with physical pion mass for one lattice volume and lattice spacing $a = 0.091$ fm

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

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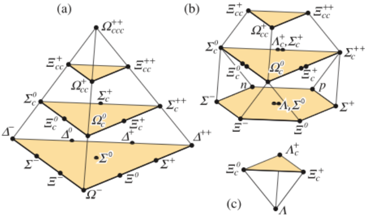
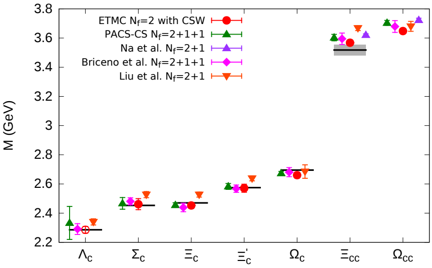
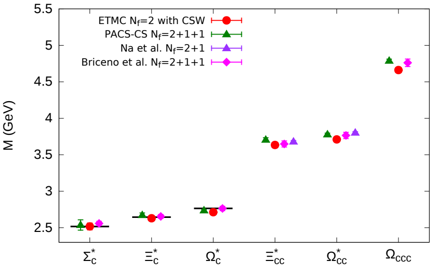


First goal: reproduce the low-lying masses and make predictions





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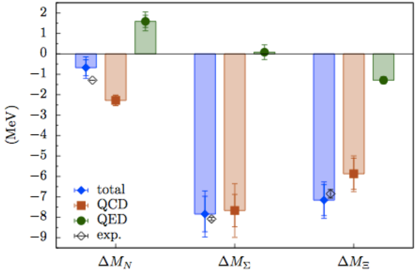
Isospin and electromagnetic mass splitting

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



Baryon spectrum with mass splitting from BMW, Sz. Borsanyi *et al.*, Phys. Rev. Lett. 111 (2013) 252001

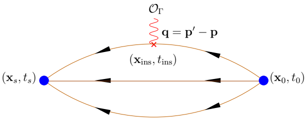
- Nucleon mass: isospin and electromagnetic effects with opposite signs
- Physical splitting reproduced

Challenges and future perspectives

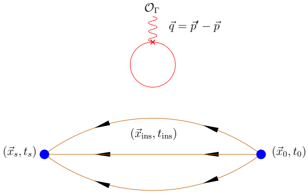
Challenges: I. Nucleon structure

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

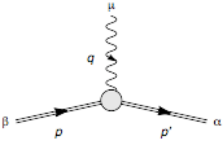


disconnected contribution

- $\mathcal{M}$ 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

Electromagnetic form factors

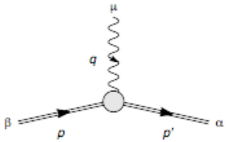
$$\langle N(p',s')|j^\mu(0)|N(p,s)\rangle = \bar{u}_N(p',s')\left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2)\right]u_N(p,s)$$



- 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

Electromagnetic form factors

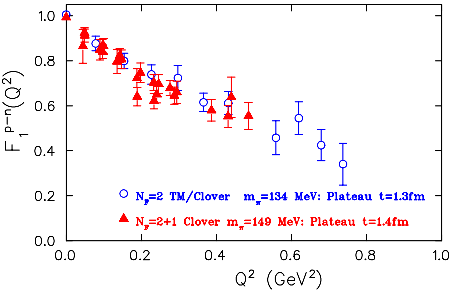
$$\langle N(p', s')|j^\mu(0)|N(p, s)\rangle = \bar{u}_N(p', s')\left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2)\right]u_N(p, s)$$

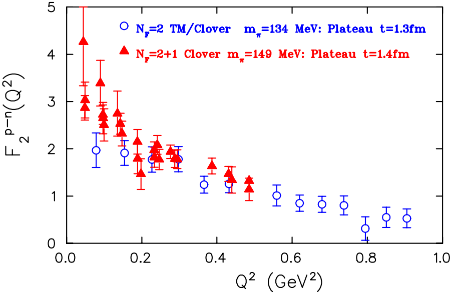


The good news

Two studies at near physical pion mass:

- ETMC: $N_f = 2$ twisted mass with clover, a = 0.091 fm, m_π = 134 MeV, 1020 statistics
- MIT: $N_f = 2 + 1$ clover produced by the BMW collaboration, $a = 0.116$ MeV, $m_\pi = 149$ MeV, $\sim$7750 statistics, J.M. Green *et al.* 1404.4029



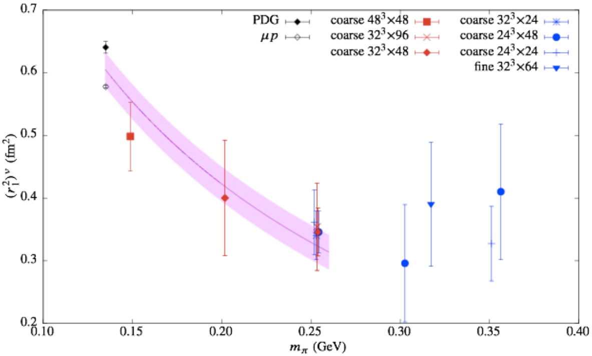


Agreement even before taking the continuum limit

Dirac and Pauli radii

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

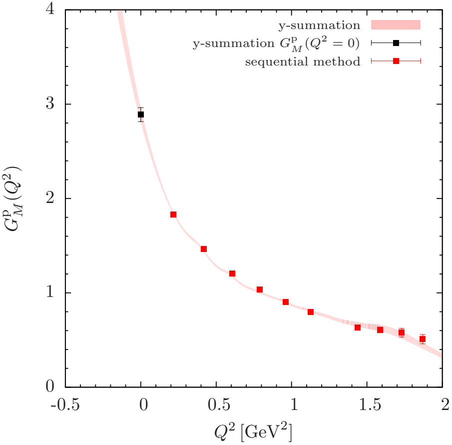
Need better accuracy at the physical point

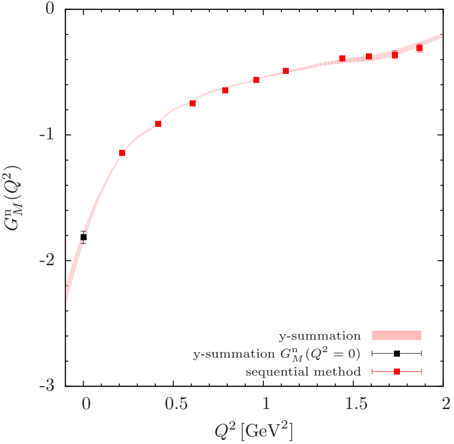


Using results from summation method, J. M. Green *et al.*, 1404.4029

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
Disconnected contributions small





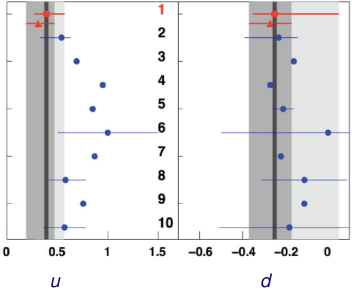
C.A., G. Koutsou, K. Ottnad, M. Petschlies, PoS(Lattice2014), 144

Nucleon charges: g_A, 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: $\mathcal{O}_T^a = \bar{\psi}(x)\sigma^{\mu\nu}\frac{\tau^a}{2}\psi(x)$

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

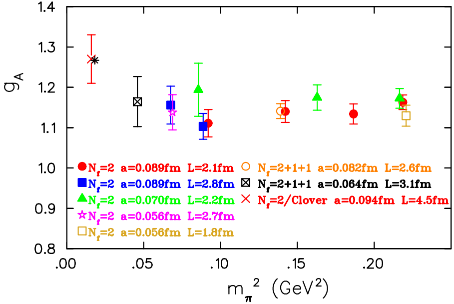
Planned experiment at JLab, SIDIS on ^{3}He/Proton at 11 GeV:

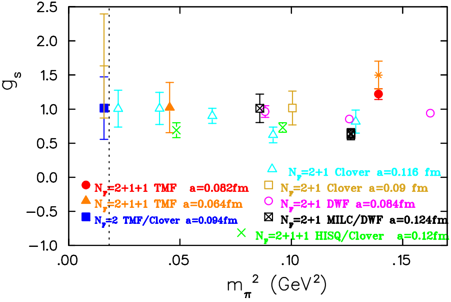


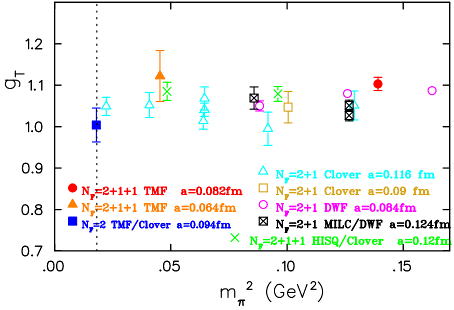
Experimental values: $g_T^u = 0.39^{+0.18}_{-0.12}$ and $g_T^d = -0.25^{+0.3}_{-0.1}$

Nucleon charges: g_A, g_S, g_T

Isovector



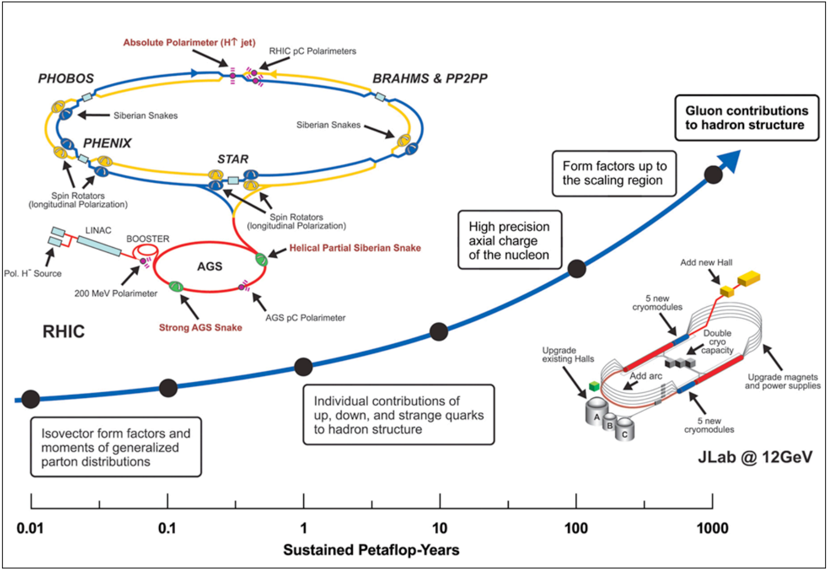




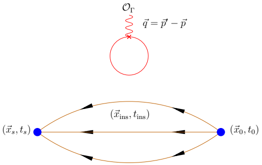
- g_A at the physical point mass indicates agreement with the physical value $\rightarrow$ important to reduce error - many results from other collaborations
- Experimental value of $g_T \sim 0.54^{+0.30}_{-0.13}$ from global analysis of HERMES, COMPASS and Belle e^+e^- data, M. Anselmino *et al.* (2013)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

Computational resources

Report on Nuclear Physics, Extreme Computing, Washington D.C., USA, Jan. 26-28, 2009.



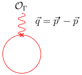
Disconnected quark loop contributions



Notoriously difficult

- $L(x_{ins}) = Tr\,[\Gamma G(x_{ins}; x_{ins})]$ $\rightarrow$ need quark propagators from all $\vec{x}_{ins}$ 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, (see talk by Mario Schröck on Modern hardware for lattice QCD)

Disconnected quark loop contributions



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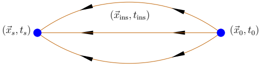

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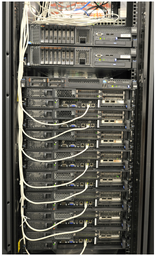
A Fermi card

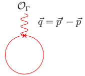


Cluster of 8 nodes of Fermi GPUs

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



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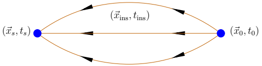

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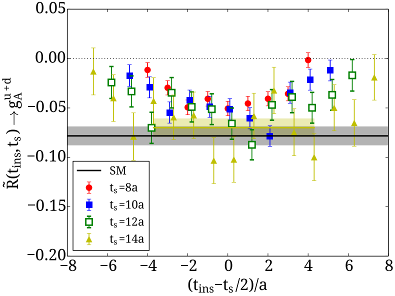
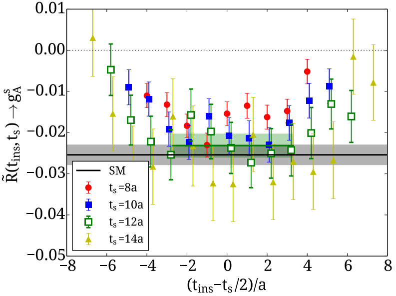
$N_f = 2+1+1$ twisted mass, a = 0.082 fm, m_π = 373 MeV, $\sim$ **150, 000** statistics (on 4700 confs)



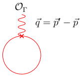
Disconnected isoscalar, agrees with Bali *et al.* (QCDSF) Phys.Rev.Lett. 108 (2012) 222001



Strange quark loop

Disconnected quark loop contributions

Notoriously difficult



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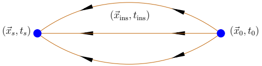

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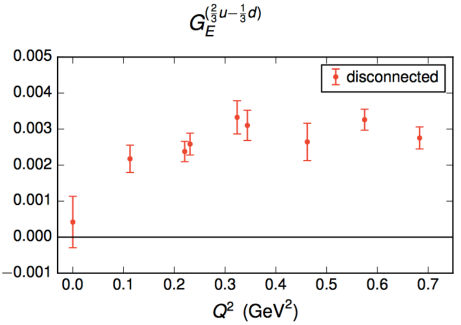
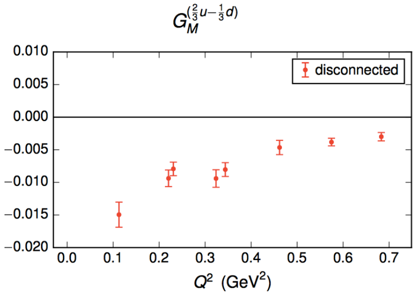




100,000 Statistics using hierarchical probing, $N_f = 2+1$ clover (one level of stout smearing), $V = 32^3 \times 96$, $a \sim 0.114$ fm, $m_\pi \sim 320$ MeV, St. Meinel *et al.*, Lattice 2014, N. York, June, 2014

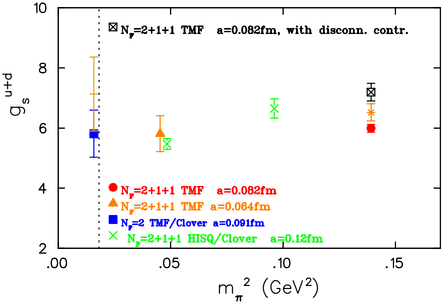
Isoscalar nucleon charges: g_A, g_s, g_T

- 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: $\mathcal{O}_T^a = \bar{\psi}(x)\sigma^{\mu\nu}\frac{\tau^a}{2}\psi(x)$

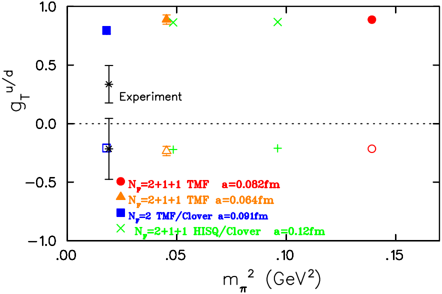
- $N_f = 2+1+1$ twisted mass, a = 0.082 fm, m_π = 373 MeV
- Disconnected part, $\sim$ 150 000 statistics using GPUs

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

Analysis at the physical point still preliminary



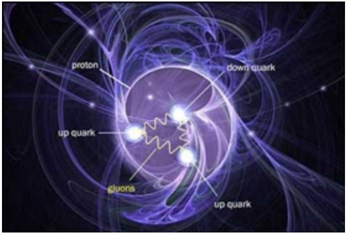
Large source-sink separation and inclusion of disconnected is required



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

Nucleon spin puzzle

Since 1987 we know that quarks can account for only a small portion of a proton spin
Who carries the rest?
$\rightarrow$ needs knowledge of the parton distribution functions (PDFs) measured 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: $\langle x^n \rangle_{\delta q} = \int_0^1 dx x^n \left[\delta q(x) - (-1)^n \delta\bar{q}(x)\right]$, $\delta q(x) = q(x)_\perp + q(x)_\top$

Nucleon spin puzzle

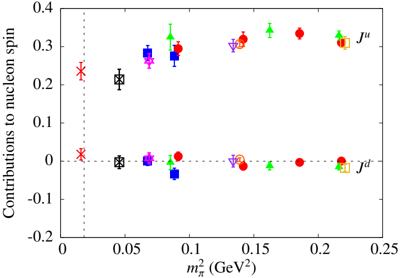
Who carries the rest?

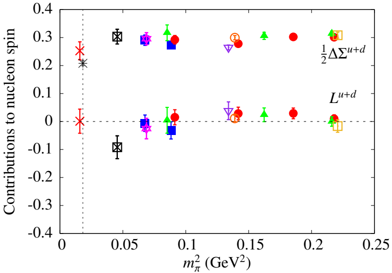
→ needs knowledge of the parton distribution functions (PDFs) measured in DIS

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

$J^q = \frac{1}{2}\left(A_{20}^q(0) + B_{20}^q(0)\right)$ and $\Delta\Sigma^q = g_A^q$

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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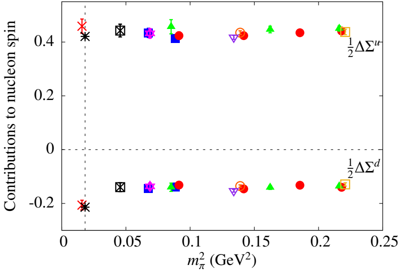

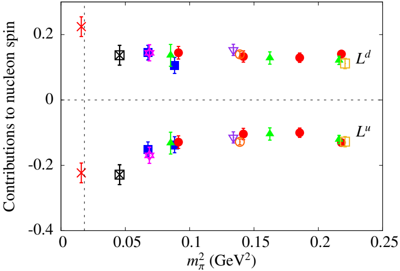

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The quark content of the nucleon

- $\sigma_l \equiv m_l \langle N|\bar{u}u + \bar{d}d|N\rangle$: 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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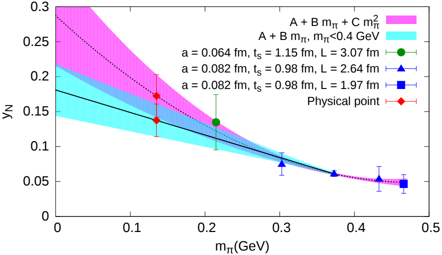
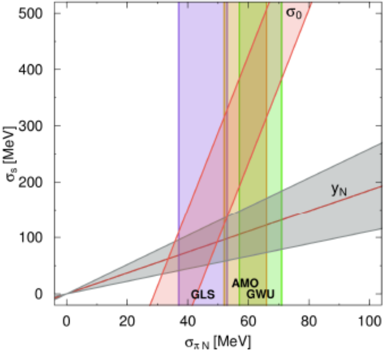


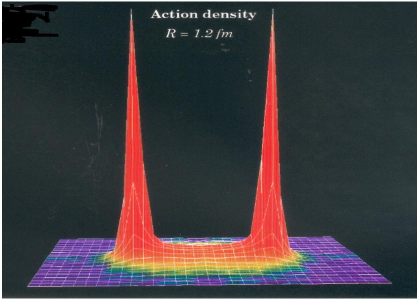
We find $y_N = 0.135\underbrace{(22)}_{\text{stat.}}\underbrace{(33)}_{\text{ch.extr.}}\underbrace{(22)}_{\text{exc.stat.}}\underbrace{(9)}_{\text{fin.a}}$



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

Challenges: II. Nuclear forces

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



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

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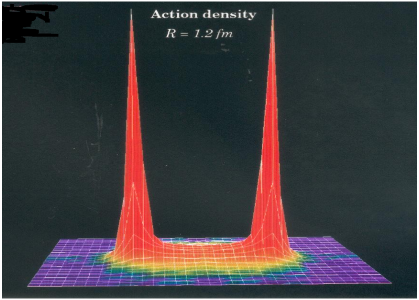

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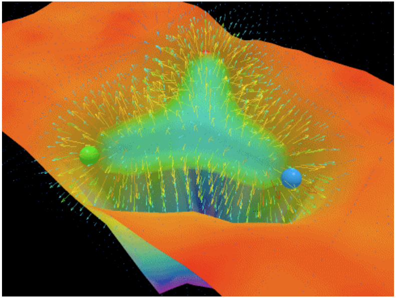


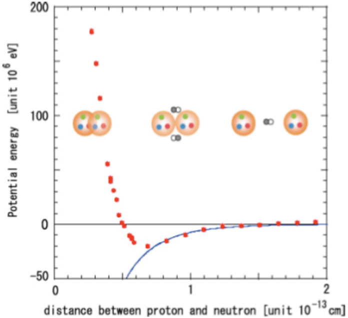
A.I. Signal, F.R.P. Bissey and D. Leinweber, arXiv:0806.0644

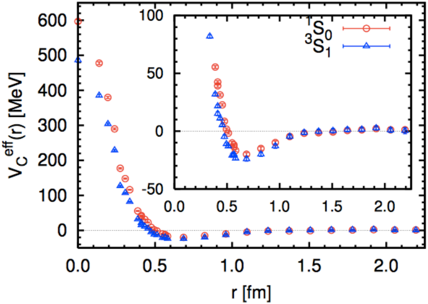
Challenges: II. Nuclear forces

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

Determination of the nuclear force is essential for understanding the binding and stability of atomic nuclei, the structure of neutron stars and supernova explosions
Two approaches:

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

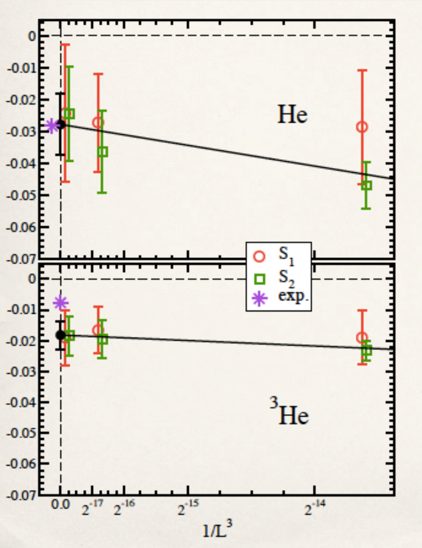


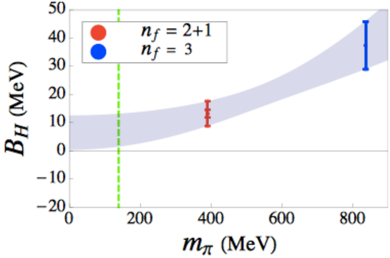


HAL QCD: Compute the Bethe-Salpeter amplitude and extract the NN (effective) central potential for the spin-singlet and spin-triplet channel, $m_\pi = 529$ MeV, S. Aoki, T. Hatsuda and N. Ishii, Prog.Theor.Phys.123 (2010) 89

Challenges: III. Nuclear Physics

Going beyond single hadrons
First attempts by HAL QCD and NPLQCD → study nuclear physics, neutron stars, ...





H-dibaryon: a bound system with the quantum numbers of $\Lambda\Lambda$, R. L. Jaffe, Phys. Rev. Lett. 38, 195 (1977)
Still inconclusive:

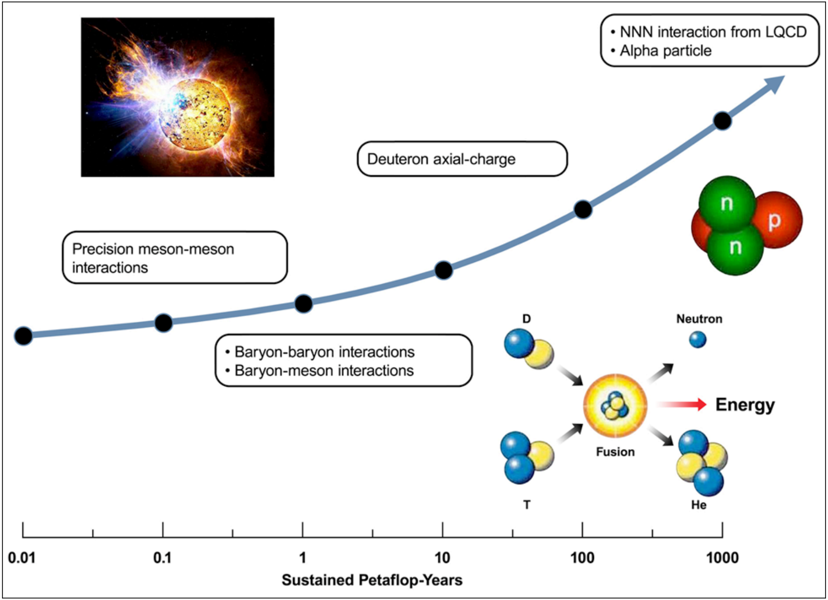
- NPLQCD $N_f = 2+1$: Not bound, S.R. Beane *et al.*, Phys.Rev. D85 (2012) 054511.
- HAL QCD $N_f = 3$: Bound H-dibaryon with the binding energy of 30-40 MeV for $m_\pi \sim 673 - 1015$ MeV, T. Inoue *et al.*, Phys. Rev. Lett. 106 (2011) 162002.

Need a $\Lambda\Lambda - N\Xi - \Sigma\Sigma$ coupled channel analysis

Only at the beginning...

Computational resources

Report on Nuclear Physics, Extreme Computing, Washington D.C., USA, Jan. 26-28, 2009.



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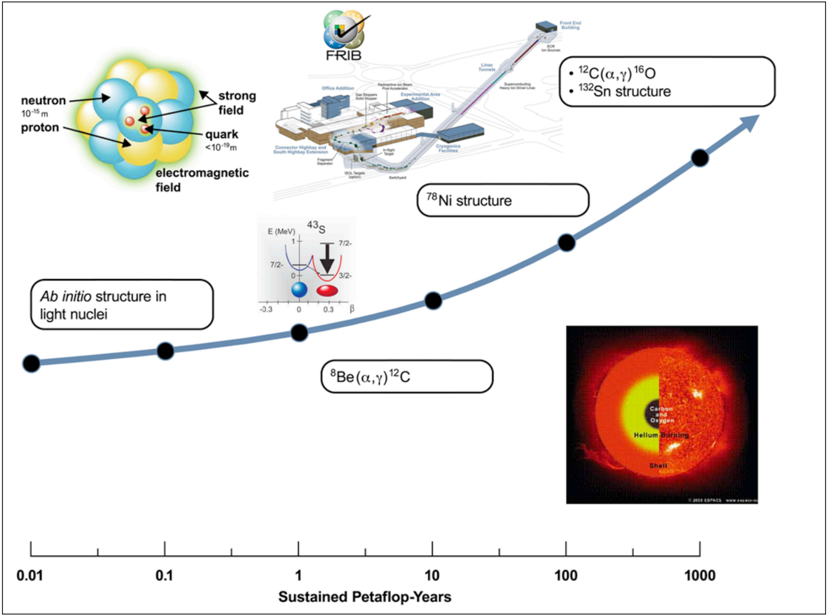
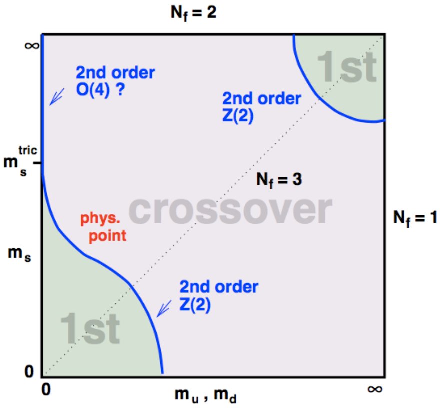


Challenges IV. QCD phase diagram

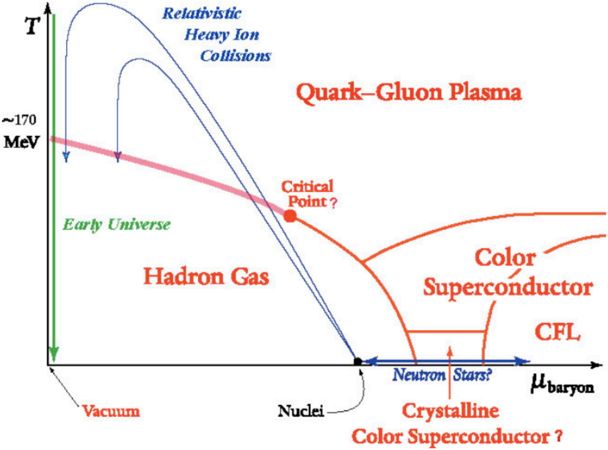
Zero baryon density, phase transition extensively studied



- 1[st] order transition for large quark masses
- 1[st] order transition for small quark masses
- No transition for physical u-, d- and s- quarks

Challenges IV. QCD phase diagram

Non-zero density action becomes complex $\rightarrow$ need new techniques



see talks by Francesco Negro and Leonardo Cosmai

Computational resources

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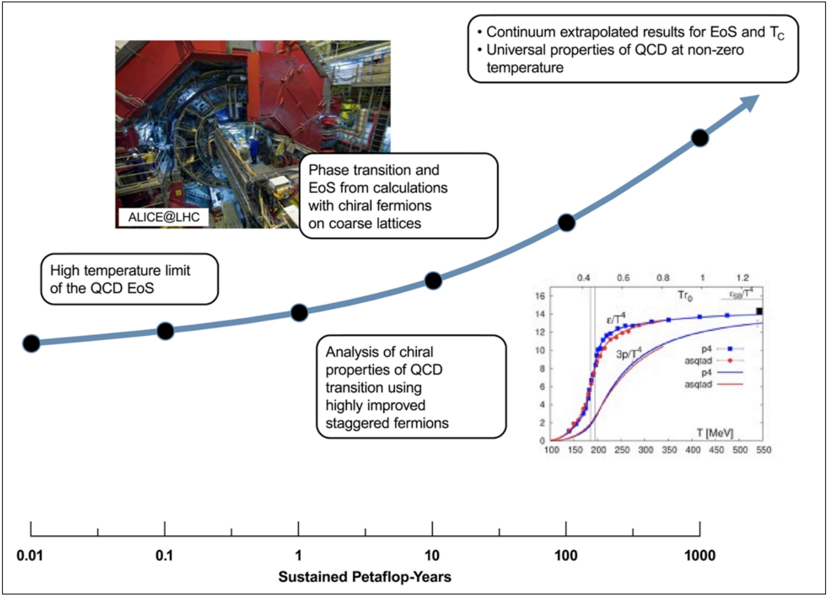

Conclusions

Simulations at the physical point $\rightarrow$ that's where we always wanted to be!

- Results on g_A, $\langle x \rangle_{u-d}$ etc at the physical point 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 - need to make our methods work at the physical point
- 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
- The study of excited states and resonances is under way $\rightarrow$ provide insight into the structure of hadrons and input that is crucial for new physics
- New methods for finite density simulations, *ab Initio* Nuclear Physics
- Many challenges ahead ...

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- Evaluation of quark loop diagrams has become feasible - need to make our methods work at the physical point
- 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 → 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
- The study of excited states and resonances is under way → provide insight into the structure of hadrons and input that is crucial for new physics
- New methods for finite density simulations, *ab Initio* Nuclear Physics
- Many challenges ahead ...

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

Acknowledgments

European Twisted Mass Collaboration (ETMC)

European Twisted Mass Collaboration

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)

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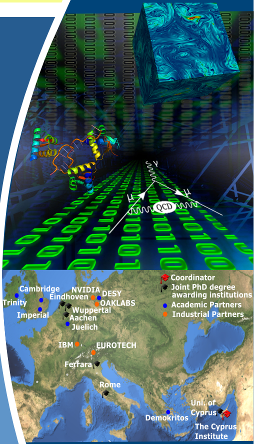

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