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Recent results for the proton spin decomposition from lattice QCD.

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Outline.

- Introduction
- Spin puzzle & Ji's sum rule
- Form factors from Lattice QCD
- Quark form factors
- Gluon form factors
- Conclusion & Outlook

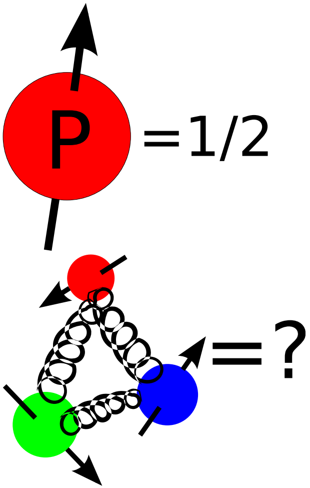
Introduction.

- crucial question: where does the proton spin come from?

→ more precise: how do quarks and gluons compose the proton spin?

- world-wide effort to measure relevant spin structure constants
- phenomenological fit to DIS data
- results depend on the fitting scheme and selected data
- gluon spin contribution can only be extracted with very poor precision

→ it would be useful to have an additional non-perturbative ab initio prediction for the spin decomposition



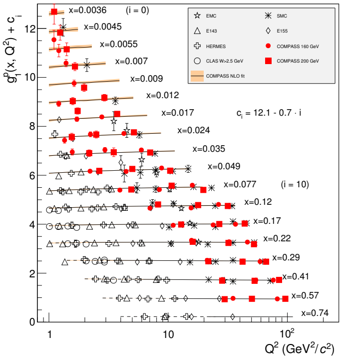
Quark helicity and spin puzzle.

- spin dependend DIS are/were measured in several facilities including CERN, SLAC, DESY and JLab
- global results for g_1^p can be used to extract the quark helicity

→ $0.26 < \Delta\Sigma < 0.36$

- the quark spin contribution to the total proton spin is $\frac{1}{2}\Delta\Sigma$
- very small contribution compared e.g. to the momentum contribution $< x >_q \approx 0.6$

→ spin puzzle



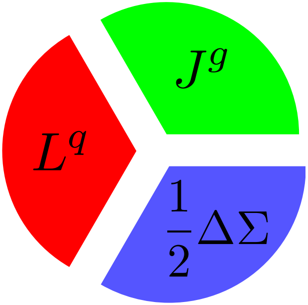
The COMPASS Collaboration, arXiv:1503.08935

Spin puzzle and Ji's sum rule.

- in order to understand the spin puzzle we must know its pieces
- one possibility of decomposition: Ji's sum rule (Ji, 1996)
- $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$
- the quark total angular momentum is composed from the quark spin and the orbital angular momentum

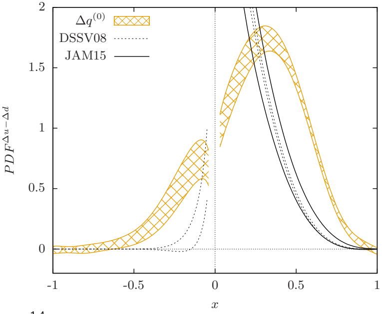
→ $J_q = \frac{1}{2}\Delta\Sigma + L_q$

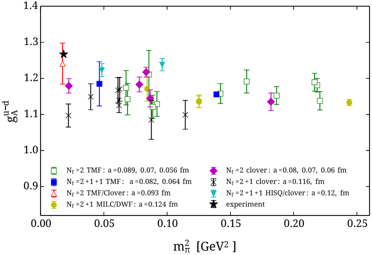
- furthermore the total angular momenta J_q and J_g can be written as a sum of certain form factors → later



Connection to lattice QCD.

- we saw: spin structure of the proton is closely related to certain proton form factors
- suitable ab-initio approach is lattice QCD
- either direct computation of helicity distribution (talk by Fernanda Steffens) $\rightarrow$ very recent approach, still exploring
- more common: compute the proton form factors from matrix elements of local operators
- e.g. $\langle P|\overline{q}\gamma^{\mu}\gamma^{5}q|P\rangle = \overline{U}(P)G_A^q(0)U(P)$

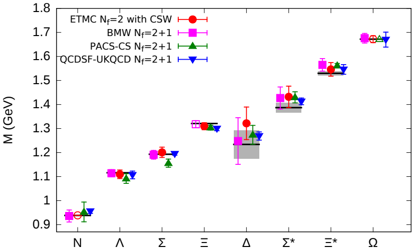




ETMC, arXiv:1507.04936

Modern lattice QCD simulations.

- modern Hybrid-Monte-Carlo algorithms use the lattice QCD action to generate ensembles of gauge configurations on which the expectation value of local operators can be computed
- lattices with a size larger than $48^3 \times 96$
- physical values of the quark / pion masses
- dynamical light, strange and charm quarks
- successful example: baryon spectrum



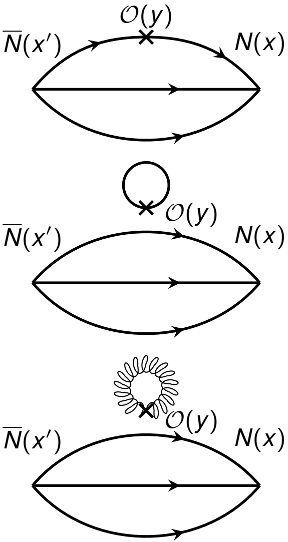
ETMC, arXiv:1411.3494

Form factors from the lattice

- we can extract form factors from matrix elements of local operators $\langle P|\mathcal{O}|P\rangle$

$\rightarrow$ on the lattice these can be related to the expectation values of three-point functions $\langle \bar{N}(x')\mathcal{O}(y)N(x)\rangle$

- expectation value of quark fields cannot directly be computed $\rightarrow$ they must be written in terms of quark propagators $\bar{u}(x')u(x) \rightarrow Q^{-1(u)}(x', x)$ (inverse Dirac operator)
- thus different types of contractions, since quark fields must be connected in all possible ways
- connected and disconnected diagrams



Relevant form factors.

We are interested in the following form factors:

- $\Delta\Sigma = g_A^{(0)} = g_{A,(u+d)}^{\text{conn}} + g_{A,(u+d)}^{\text{disc}} + g_{A,(s)}^{\text{disc}} + \ldots$
- the total angular momentum can be expressed by a sum of generalized form factors which are moments of GPDs
- $J^q = \frac{1}{2}(A_{20}^q(0) + B_{20}^q(0))$ (Ji, 1996)
  - $A_{20}^q = \int_{-1}^{1} dx\, x\, H^q(x,0,0) = \langle x \rangle_q$
  - $B_{20}^q = \int_{-1}^{1} dx\, x\, E^q(x,0,0)$
- $A_{20}^q = A_{20}^{(u+d),\text{conn}} + A_{20}^{(u+d),\text{disc}} + A_{20}^{(s),\text{disc}} + \ldots$
- equivalent for B_{20}^q
- first approaches to compute J^g

Lattice setup.

- results from a recent lattice gauge ensembles generated by the European Twisted Mass Collaboration (ETMC)
- $N_f = 2$ maximally twisted mass fermions $\rightarrow$ ensures an improved continuum limit for all here considered observables
- physical value of the pion mass: $m_\pi \approx 133\,\mathrm{MeV}$
- lattice spacing: 0.093 fm
- lattice extension: $48^3 \times 96 \Rightarrow L \approx 4.5 fm$ (larger in progress)
- statistics for connected contractions: $\sim$ 4800 measurements (16 $\times$ 425 gauge configurations)
- disconnected contractions: $\sim$ 200000 measurements (100 $\times$ 1996 gauge configurations) + improved algorithms

Summary of quark spin form factors.

$\Delta\Sigma$	up	down	strange	combined
connected	0.897(23)	-0.314(12)	-	0.583(24)
disconnected	-0.060(10)	-0.060(10)	-0.045(10)	-0.165(17)
combined	0.837(25)	-0.374(16)	-0.045(10)	0.418(29)

A_{20}	up	down	strange	combined
connected	0.389(15)	0.157(8)	-	0.545(19)
disconnected	0.018(7)	0.018(7)	0.014(4)	0.049(16)
combined	0.407(17)	0.175(11)	0.014(4)	0.594(25)

B_{20}	up	down	strange	combined
connected	0.133(40)	-0.149(40)	-	-0.016(56)

Quark spin contribution.

- quark spin $\frac{1}{2}\Delta\Sigma = 0.209(15)$
- $\frac{1}{2}\Delta u = 0.419(13), \frac{1}{2}\Delta d = -0.187(8), \frac{1}{2}\Delta s = -0.023(5)$

$\frac{1}{2}\Delta\Sigma$ slightly above the experiments: $0.13 < \frac{1}{2}\Delta\Sigma < 0.18$

- total angular momentum $J^q = \frac{1}{2}(A_{20}^q(0) + B_{20}^q(0))$

$\rightarrow$ $J^u = 0.270(22)$, $J^d = 0.013(21)$, $J^s = 0.007(2)$

$\rightarrow$ $\sum_q J^q = 0.289(31)$

J^q is dominated by the up quarks

- orbital angular momentum $L_q = J^q - \frac{1}{2}\Delta q$

$\rightarrow$ $L_u = -0.149(26)$ $L_d = 0.200(22)$ $L_s = 0.030(5)$

$\rightarrow$ $\sum_q L_q = 0.080(34)$

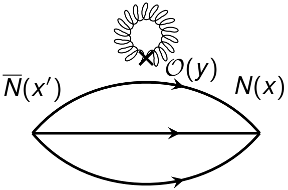
L_q is small, but not negligible

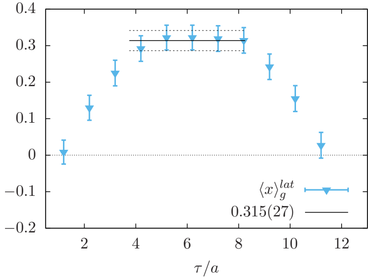
Gluon spin contribution.

- expectation:
  $J^g = \frac{1}{2} - \sum_q J^q \Rightarrow J^g = 0.213(32)$
- alternative: extract A_{20}^g and B_{20}^g from matrix elements of gluon operator
  e.g. $\langle P | T_g^{\{\mu\nu\}} | P \rangle = 2A_{20}^g(0) P^{\{\mu} P^{\nu\}}$
- current status: we computed $A_{20}^g = \langle x \rangle_g$

$\rightarrow$ very first lattice calculation with dynamical sea quarks

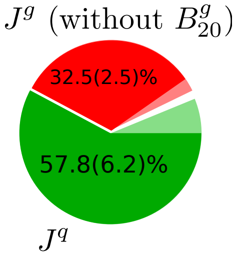
- disconnected: correlation of nucleon two-point functions with Wilson plaquettes with large statistics
- complicated perturbative lattice renormalization applied
- result from combined fit: $A_{20}^g = 0.325(25)$

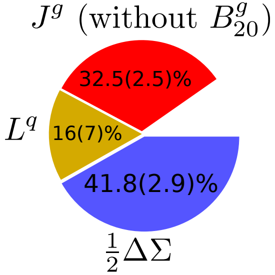




Spin sum rule conclusion.

- neglecting B_{20}^g we get the following composition of the proton spin
  - $\rightarrow$ 10 percent missing
    - caused by B_{20}^g or B_{20}^q disconnected?
    - statistical effect?
- keep in mind : no final results, merely a first look at the spin composition from a physical point ensemble





Summary & Outlook.

Achievements

- we successfully showed that it is possible to compute (almost) all necessary form factors for the proton spin decompostion on the lattice

→ B_{20}^{g} and disconnected B_{20}^{q} have yet to be tackled

- we found promising results that are able to make quantitative prediction for the proton spin decomposition from first principles

Challenges

- continuum limit has to be studied
  - smaller lattice spacings require larger lattices
- study further systematic effects: e.g. excited states, finite volume
- decrease the statistical error
  - explore new algorithms, usage of GPUs
- include dynamical strange and charm quarks

Thanks.

Thank you for your attention and future discussions.