Quark scalar, axial and tensor charges in the Schwinger-Dyson formalism

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Quark scalar charge

$$\langle N|\bar{q}q|N\rangle = \langle N|q^\dagger \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} q|N\rangle$$ **(Dirac representation)**

Scalar charge probes the relativistic effect of the quark in nucleon

c.f. : vector charge = quark number

$$\langle N|\bar{q}\gamma_0 q|N\rangle = \langle N|q^\dagger \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} q|N\rangle$$

Relativistic component with different sign

Same Nonrelativistic limit

Why interesting?

- Quark mass contribution to the nucleon mass
- Interaction with the dark matter

Known data:

- Pion-nucleon sigma term : $\sigma_{\pi N} = m_q \langle N|\bar{q}q|N\rangle \sim 40$ MeV
- Strange content : $\sigma_s = m_s \langle N|\bar{s}s|N\rangle \sim 10$ MeV

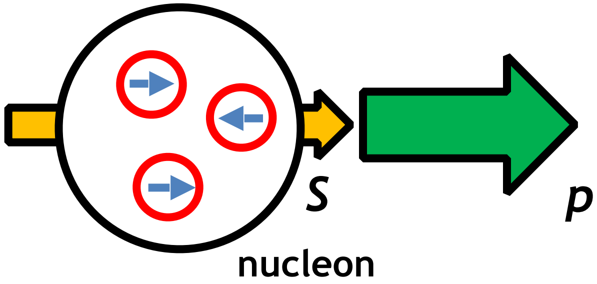
Quark axial and tensor charges

Probe the spin structure of nucleon, non/relativistic polarized component

Axial charge:

Nucleon axial charge probes the quark longitudinal polarization (helicity)

$$\langle N(p,S)|\bar{q}\gamma^\mu\gamma_5 q|N(p,S)\rangle = S^\mu \Delta q$$



Important problem:

Proton spin crisis

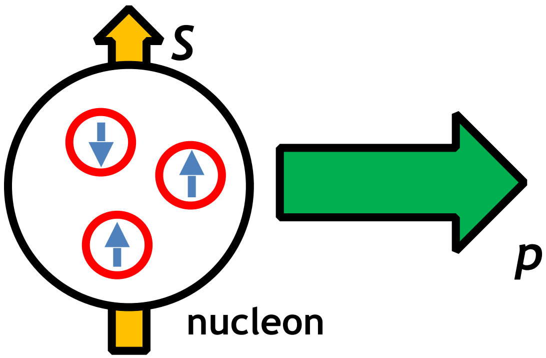
⇒ Why quark spin fraction so small ?

$$\left(\sum_q \Delta q \sim 0.3 \neq 1\right)$$

Tensor charge:

Nucleon tensor charge probes the quark transverse polarization (transversity)

$$\langle N(p,S)|\bar{q}i\sigma^{\mu\nu}\gamma_5 q|N(p,S)\rangle = 2(S^\mu p^\nu - S^\nu p^\mu)\delta q$$



Why important:

Related to the quark EDM contribution to the nucleon EDM

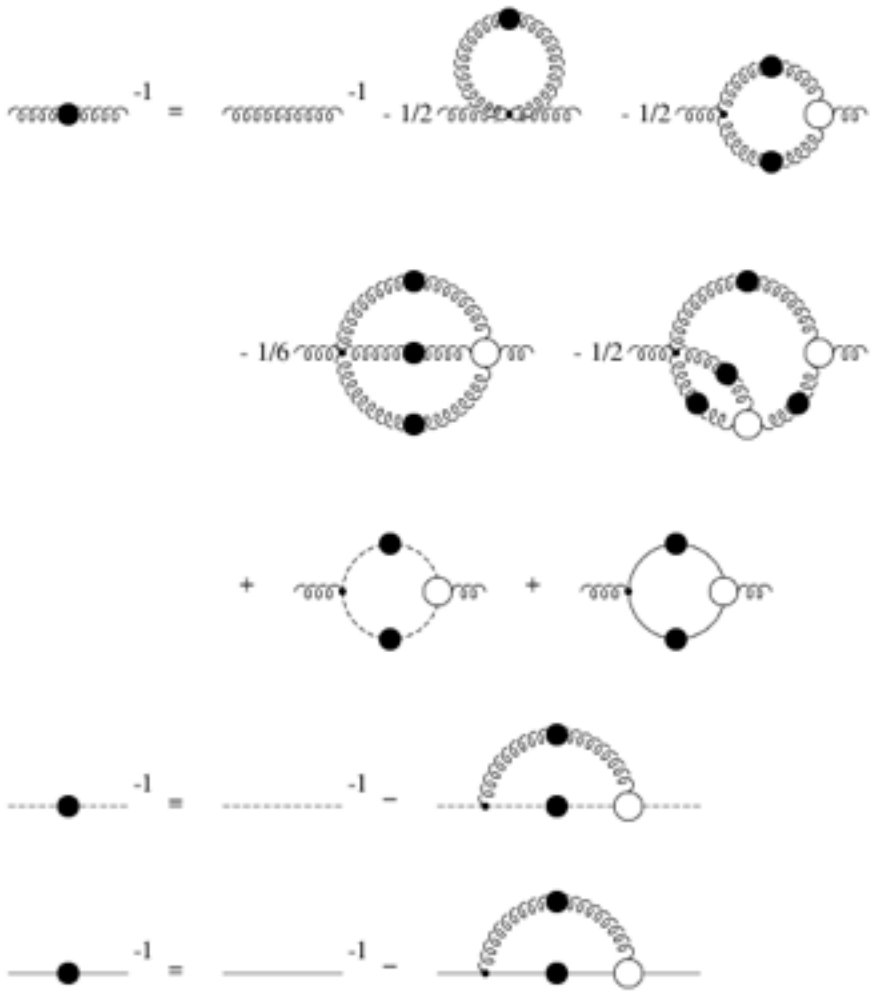
(EDM is a powerful probe of new physics beyond standard model)

Object of study

Object of study:

Evaluate the nonperturbative effect to the nucleon scalar, axial and tensor charges in the SD formalism for IR cut and singular quark-gluon vertex.

Full Schwinger-Dyson equation



Black blobs : full propagator
White blobs : full 1PI vertex

If the 1PI vertices are full, then exact solution of QCD (gluon, ghost, quark propagators)

To obtain the full solution, we need to solve a tower of infinite set of self-consistent equations (n-point vertices)

⇒ Need to truncate the SDE

⇒ Ansatze and approximations for vertices and dressing functions

R. Alkofer and L. von Smekal, Phys. Rep. **353**, 281 (2001).

How to extract the physics of quark charges of nucleon

The experimental data of nucleon charges are well known.
Lattice QCD data are also consistent.

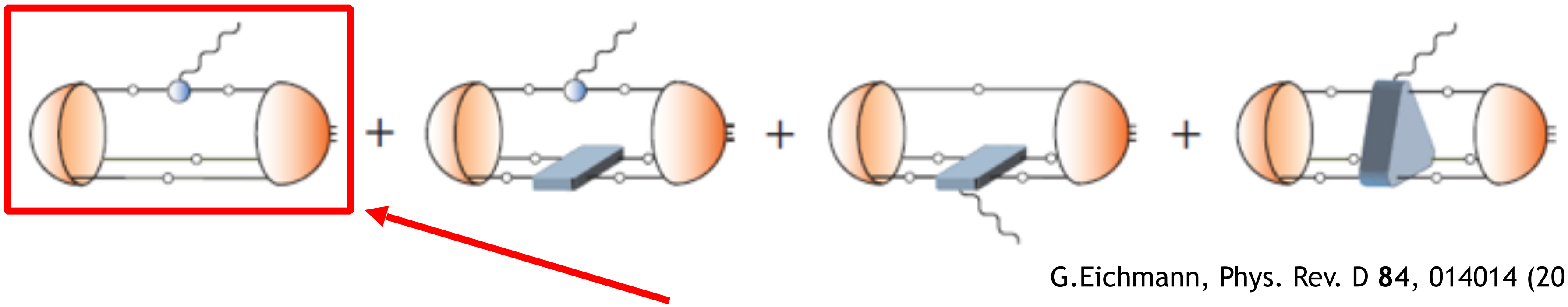
… But we do not have the physical explanation of them.

To explain the physics of nucleon structure, we need an analytical approach.

⇒ Schwinger-Dyson (SD) formalism !

General strategy to calculate the nucleon charges:

⇒ We must solve the relativistic Faddeev equation



G.Eichmann, Phys. Rev. D **84**, 014014 (2011).

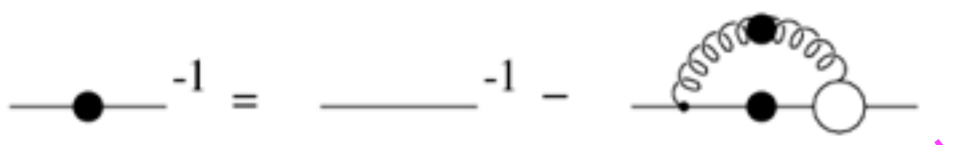
As a first study, we consider the single quark effect (gluon dressing effect), and the many body effect is considered through the NR quark model (we do not calculate Faddeev equation)

The gluon dressing effect can be evaluated with the SD formalism

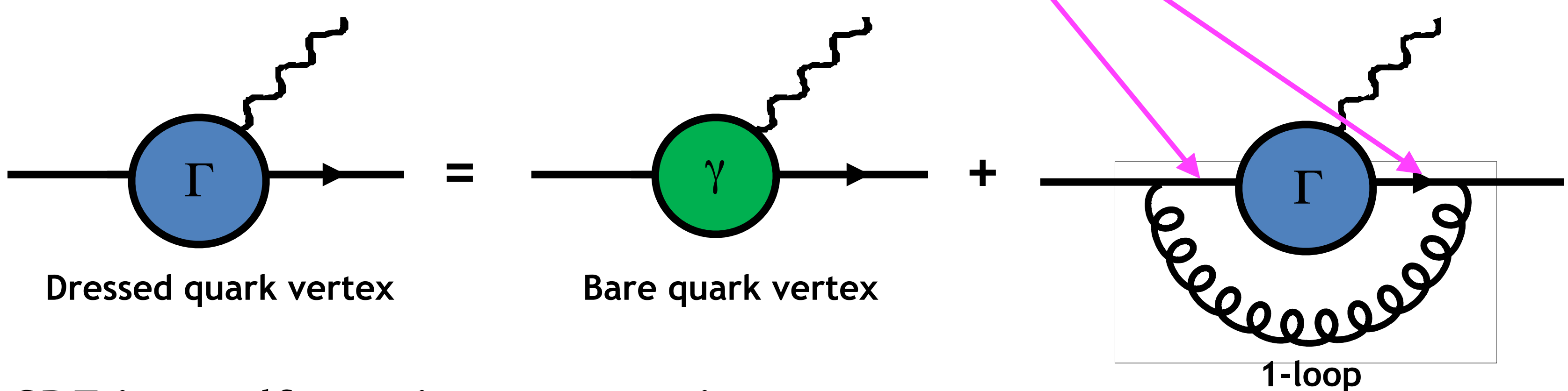
Gluon and quark-gluon vertex dressings:

⇒ Will be seen later for 2 cases

Quark propagator SDE:



Quark charge SDE: rainbow-ladder



SDE is a self-consistent equation :

⇒ Can consider the infinite sum of a class of diagrams

⇒ Evaluate non-perturbative effect of quark charges

IR cut analysis

NY, T. M. Doi, S. Imai, H. Suganuma, Phys. Rev. D **88**, 074036 (2013).

NY, S. Imai, T. M. Doi, H. Suganuma, Phys. Rev. D **89**, 074017 (2014).

Setup of the SD formalism

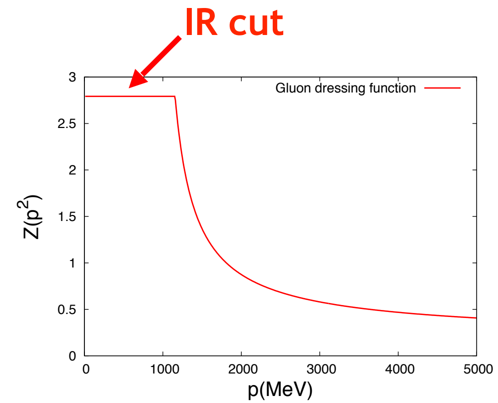
- **Landau gauge**
- **Gluon dressing function:**

  Approximate with RG improved strong coupling with IR cut

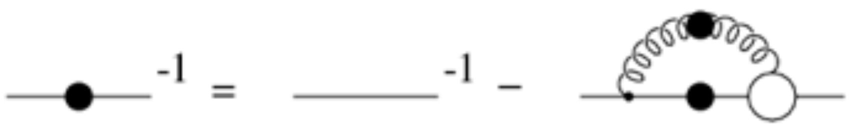
  ⇒ UV contribution is correctly included.

  ⇒ IR contribution is cut.

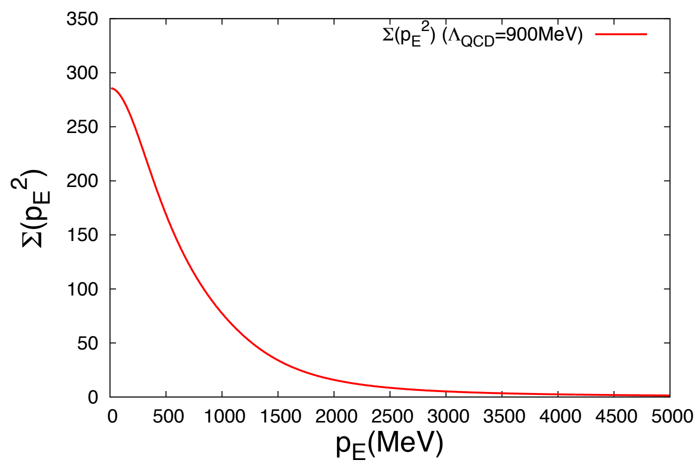
  K. Higashijima, Phys. Rev. D **29**, 1228 (1984).



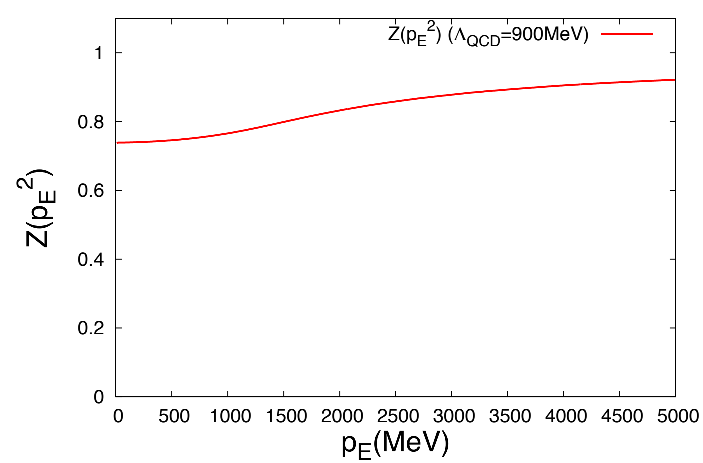
- **Quark propagator Schwinger-Dyson equation**



→ Rainbow-ladder approximation with constant vertex dressing



Dynamical mass



Wave function renormalization

Result

Isoscalar proton charges:

	Exp. data	Lattice	Our result
Scalar	10	10 ～ 15	24
Axial	0.32	0.6	0.85
Tensor	0.7	0.6	0.6

Reasonable agreement

Isovector proton charges:

	Exp. data	Lattice	Our result
Scalar	～ 1 (baryon mass)	1	8
Axial	1.27	～ 1.2	1.4
Tensor	1.0	～ 1	1.0

Renormalization scale : 2 GeV

NY, T. M. Doi, S. Imai, H. Suganuma, Phys. Rev. D **88**, 074036 (2013).
NY, S. Imai, T. M. Doi, H. Suganuma, Phys. Rev. D **89**, 074017 (2014).

IR singular quark-gluon vertex: failure

Setup of the SD formalism

We introduce singular quark-gluon vertex

Singular quark-gluon vertex can explain linear potential, η’ mass.

R. Alkofer, C. S. Fischer, R. Williams, Eur. Phys. J. A **38**, 53 (2008).

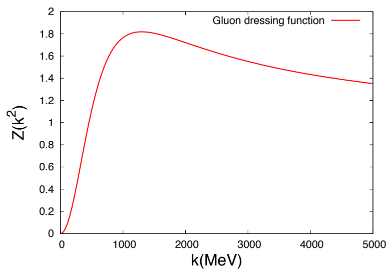
Almost same parameter set as R. Alkofer et al., but with

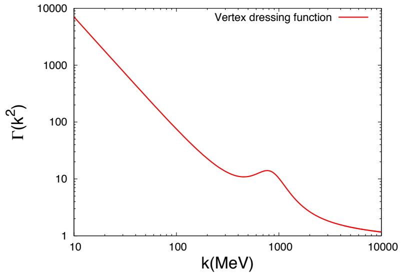
Vertex dressing: $\Gamma(k^2) \propto \dfrac{1}{k^2}$

Gluon dressing: $Z(k^2) \propto k^2$

(in IR region)

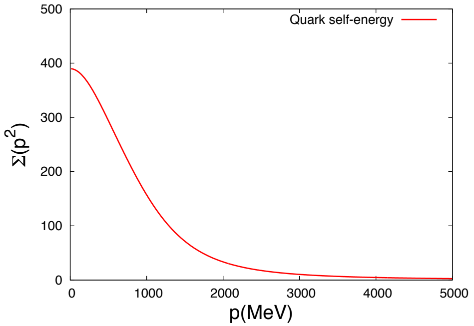
(refers to κ = 0.5)

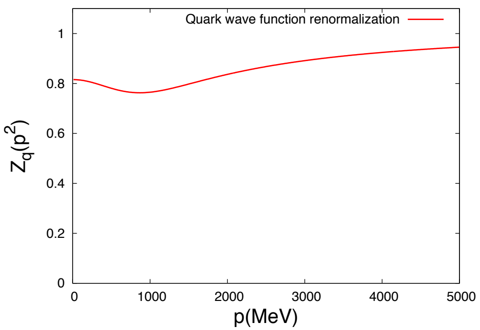




IR finiteness of gluon propagator in Landau gauge is suggested by many recent works

Solve quark propagator SDE:





⇒ Pion decay constant: 92 MeV

Result

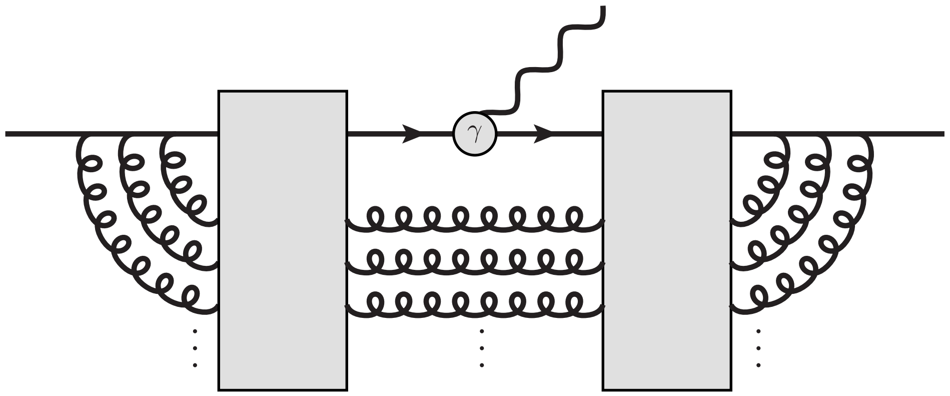
No results:

The SDE does not converge!!

… But there is a physical explanation

Why failed?

Gluons are correlated during vertex dressing



⇒ Rainbow-ladder approximation does not work

Due to the interaction among gluons and quark,
we expect a strong damping of process with spread multi-gluon in the IR

⇒ UV-gluon contribution is dominant!

Summary and future prospects

Summary:

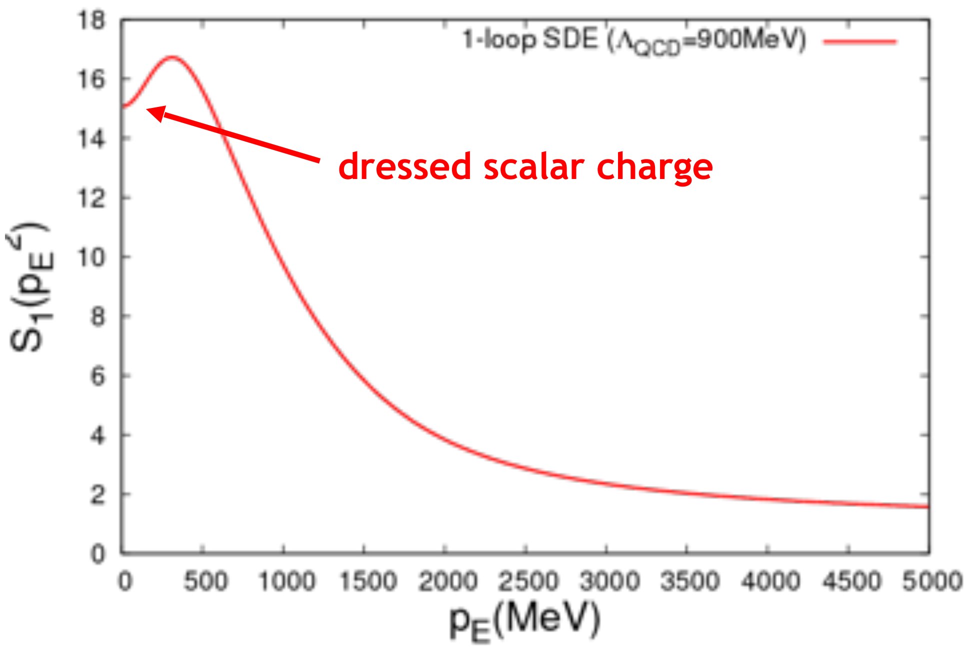
- We have calculated the quark scalar, axial and tensor charges in the Schwinger-Dyson formalism with a simple setup.
- Quark scalar charge is enhanced, axial and tensor charges are suppressed due to gluon dressing : reasonable agreement.
- Inclusion of IR singular quark-gluon vertex fails in rainbow-ladder approx.: gluons and quark are correlated in the IR. ⇒ Strong IR damping expected.

Future subjects:

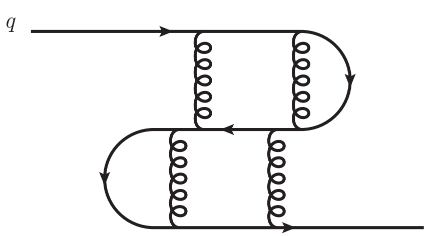
- Study of the unquenching effect.
- To work the many-body effect in the nucleon, we need to solve relativistic Faddeev equation.

Backup slide

Quark scalar charge : result



Bare scalar charge : 1
Dressed scalar charge ~ 9
(renormalized)



Relativistic effect : Z graph

⇒ Quark scalar charge is enhanced from the bare charge

⇒ Agreement with exp. data of sigma term

⇒ Relativistic effect is important for single quark

Meaning of scalar charge: how much and wide can we find quark?

NY, S. Imai, T. M. Doi, H. Suganuma, Phys. Rev. D **89**, 074017 (2014).

Experimental data

Quark axial charge:

- **Isovector axial coupling:**

  g_A = 1.27 (exp) g_A ~ 1.2 (lattice QCD) g_A = 1.67 (NR quark model)

  UCNA Coll., PRC **87**, 032501 (2013) T. Bhattacharya *et al.*, arXiv:1306.5435

- **Isoscalar axial coupling:**

  $\Delta\Sigma$ = 0.32±0.04 (exp) $\Delta\Sigma$ ~ 0.6 (lattice QCD) $\Delta\Sigma$ = 1 (NR quark model)

  COMPASS, PLB **693**, 227 2010 T. Bhattacharya *et al.*, arXiv:1306.5435

  ⇒ Proton spin crisis

Quark tensor charge:

- **Extraction from experiment:**

$$\begin{cases} \delta u &= 0.860 \pm 0.248 \\ \delta d &= -0.119 \pm 0.060 \end{cases}$$

(renormalized at μ = 4 GeV)

⇒ Extracted from exp data of deeply virtual π^0 photoproduction

I. Bedlinskiy et al. (JLAB), Phys. Rev. Lett. **109**, 112001 (2012).
G. R. Goldstein, J. O. Gopnzalez Hernandez, S. Liuti, arXiv:1401.0438.

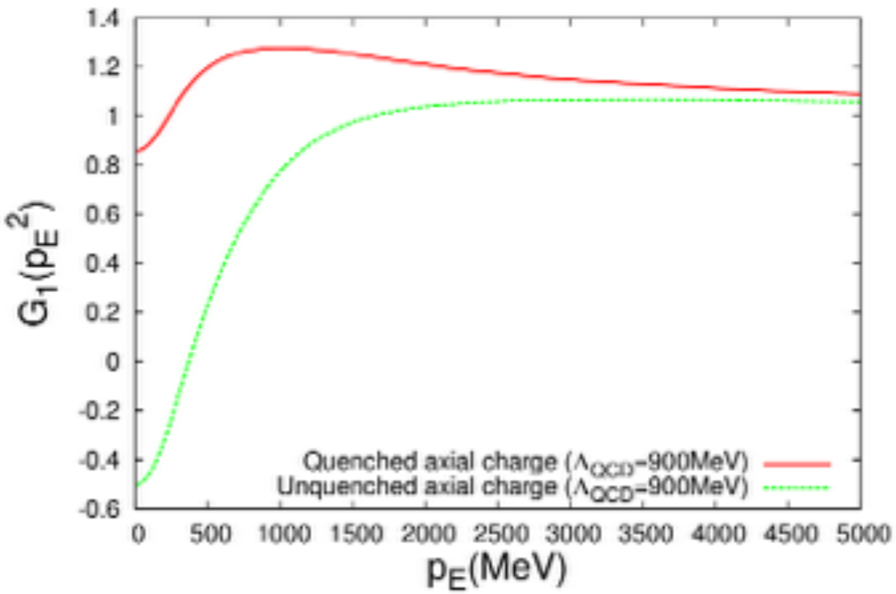
- **Lattice QCD result:**

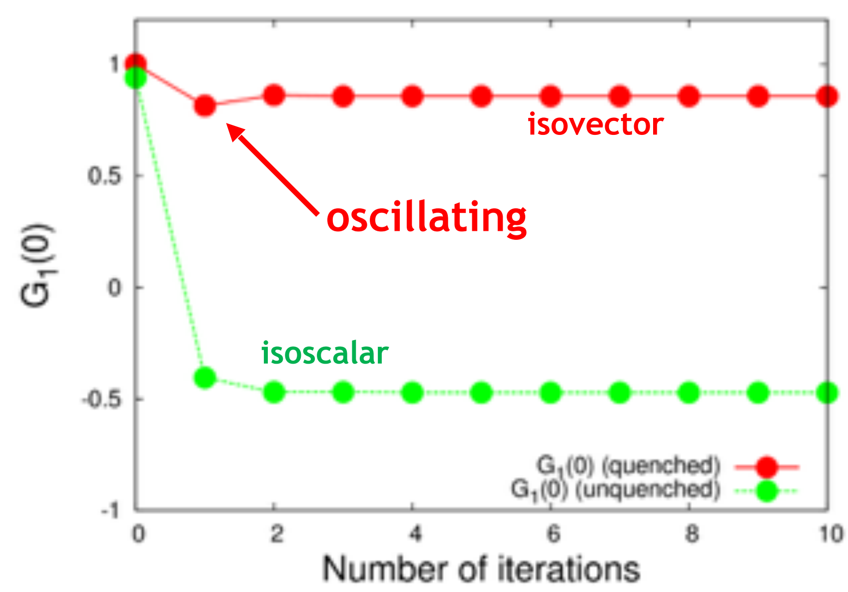
$$\begin{cases} \delta u &= 0.839 \pm 0.060 \\ \delta d &= -0.231 \pm 0.055 \end{cases}$$

(renormalized at μ = 2 GeV)

S. Aoki, M. Doui, T. Hatsuda and Y. Kuramashi, Phys. Rev. D **56**, 433 (1997);
T. Bhattacharya et al., arXiv:1306.5435.

Axial charge: result





- **Isovector axial vector coupling:**

  $g_A \sim 1.4$

  → **Suppression (c.f. NRQM) due to gluon emission/absorption**

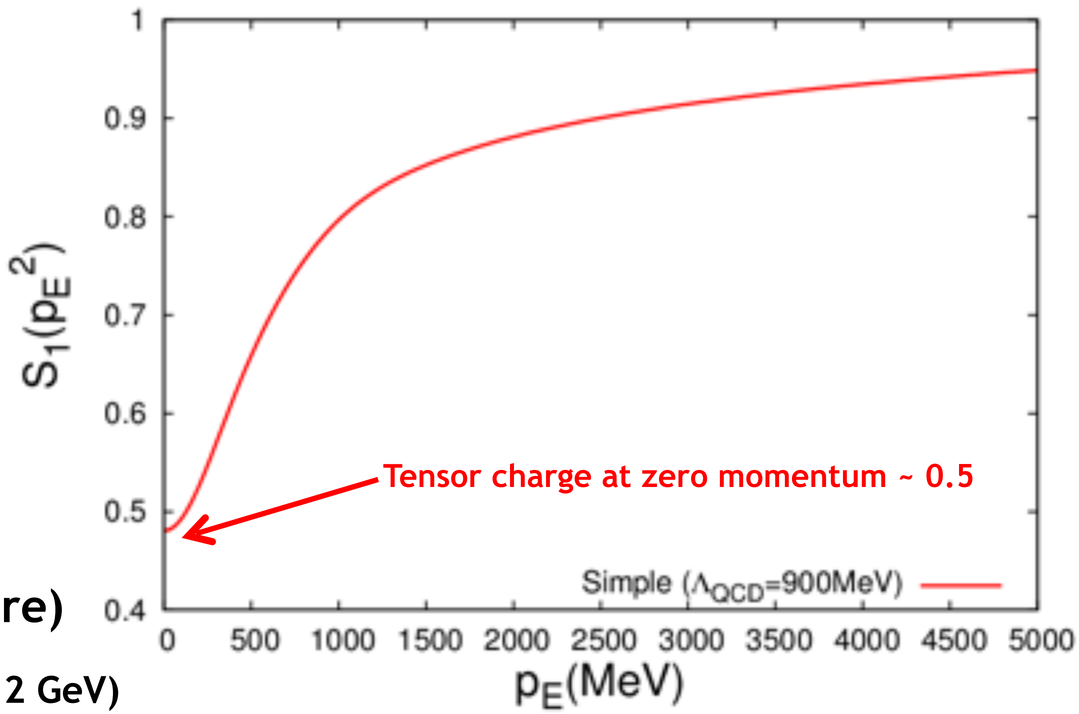
  → **Similar mechanism as the tensor charge**

NY, S. Imai, T. M. Doi, H. Suganuma, Phys. Rev. D **89**, 074017 (2014).

Tensor charge: result

tensor charge at zero momentum:

~ 0.5 (not renormalized)



$\delta q^{(dressed)} \sim 0.6\ \delta q^{(bare)}$

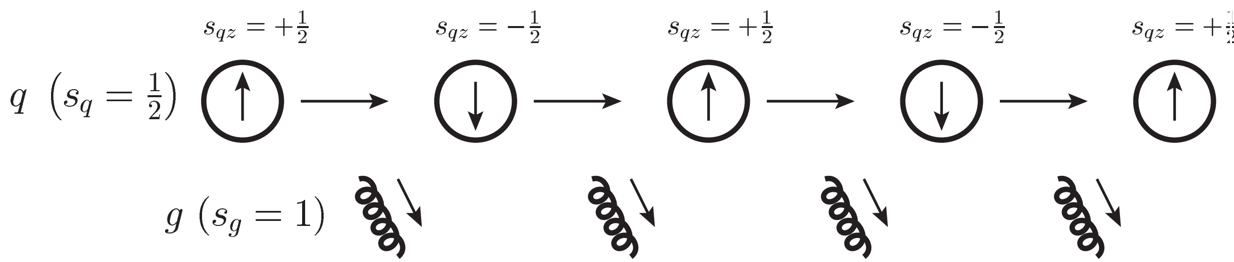
(Renormalization scale μ = 2 GeV)

⇒ The bare quark tensor charge is significantly suppressed by the gluon dressing

NY, T. M. Doi, S. Imai, H. Suganuma, Phys. Rev. D**88**, 074036 (2013).

Interpretation: superposition of quark spin flip

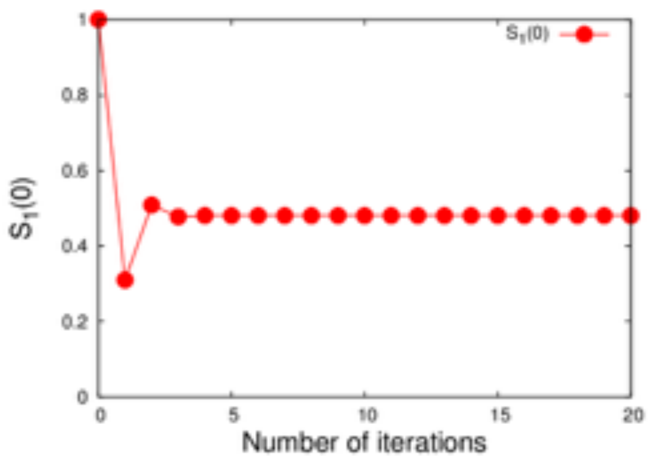
Quark spin (1/2) flips after each gluon emission/absorption (spin 1)



⇒ Sum (infinite) of contribution is always smaller than the bare one

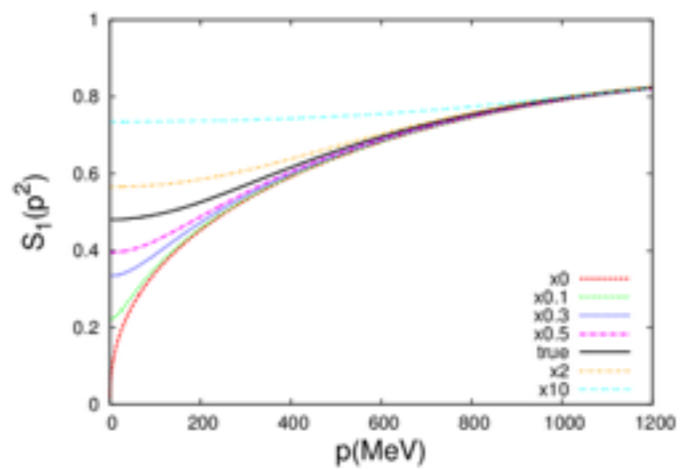
⇨ $\delta q^{(\text{dressed})} < \delta q^{(\text{bare})}$

Iteration ≈ ladder expansion



⇒ oscillation = sum of spin flip

Resizing dynamical quark mass



⇒ light = easy to flip