Hadronic EDMs from Dyson-Schwinger
ρ-Meson & Nucleon

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Introduction

- Introduction
- Part A: *The Theoretical Framework*
- Part B: *The ρ-Meson*
- Part C: *The Nucleon*

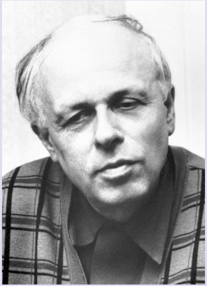
Introduction: Electric Dipole Moments

EDM signals P & T violation & (if CPT holds)
CP violation

"Sakharov" conditions (1967)

for observed anti-/matter asymmetry in universe

1. Baryon number violation
2. C & CP violation
3. Interactions out of thermal equilibrium



SM - CP violation **"too small"** for observed asymmetry

Introduction: The Energy Scale

BSM CPV   *(SUSY, GUTs, extra Dim. . .)*

$\Updownarrow$

EW Scale Operators $\mathcal{L}_{\text{eff}} = \sum \frac{C}{\Lambda^2_{BSM}} \mathcal{O}$

$\Updownarrow$

Had Scale Operators $\mathcal{L}_{\text{eff}} = \sum \frac{C \langle H^0 \rangle}{\Lambda^2_{BSM}} \mathcal{O}'$

$\Updownarrow$

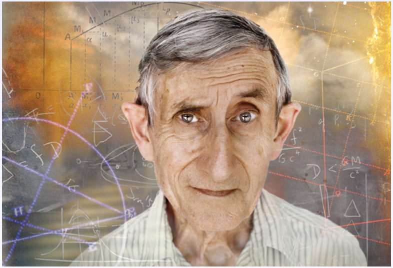
QCD **Matrix Elements** $d_n, \bar{g}_{\pi NN}, \ldots$

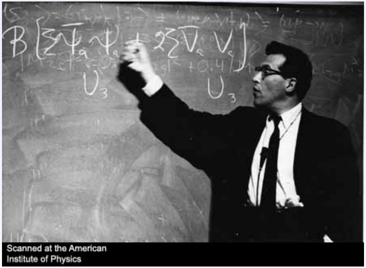
$\Updownarrow$

Experiment

Part A:
The Theoretical Framework

1. Dyson-Schwinger Equations





Dyson-Schwinger Equation

- *Non-perturbative continuum* approach to any QFT
- A shift in the integration variable ($\varphi(x) \to \varphi(x) + \lambda(x)$), does not change the path integral for suitable b.c., i.e.

$$\int D[\varphi]\, \frac{\delta}{\delta\varphi} f[\varphi] = 0$$

- Application to the *generating functional* $Z[J]$ yields

$$\int D[\varphi] \left[-\frac{\delta S}{\delta\varphi} + J \right] e^{-S + \int d^4x\, J\varphi} = 0$$

with the action $S = \int d^4x\, \mathcal{L}$. This can be rewritten as

$$\left[-\frac{\delta S}{\delta\varphi}\left(\frac{\delta}{\delta J}\right) + J \right] Z[J] = 0$$

Dyson-Schwinger Equation

In *QCD* the *fermion propagator* is obtained by derivation of

$$\left[-\frac{\delta S}{\delta\bar{\psi}(x)}\left(\frac{\delta}{\delta\bar{\eta}},-\frac{\delta}{\delta\eta},\frac{\delta}{\delta J_\mu}\right)+\eta(x)\right]Z[\eta,\bar{\eta},J]=0$$

with respect to η leading after several formal manipulations to the

Gap Equation for quark propagator

$$\begin{aligned}S_F(p)^{-1} = & \, i\not{p}\, Z_2 + m_q(\mu)\, Z_4 \\ & + Z_1 \int \frac{d^4q}{(2\pi)^4}\, g^2 D_{\mu\nu}(k-p)\gamma_\mu \frac{\lambda^i}{2} S_F(k)\Gamma_\nu(k,p)\end{aligned}$$

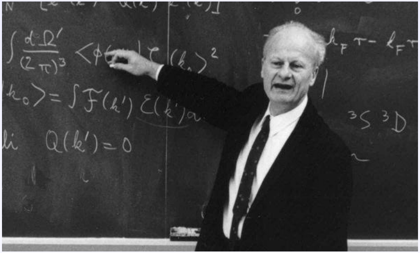
Dyson-Schwinger Equation

1. *Gap equation* contains the *full vertex* Γ_μ and *full gluon propagator* $D_{\mu\nu}(k-p)$, each satisfies it's own DSE
2. DSE for the *full vertex* Γ_μ contains the *four-point vertex*, which has it's own $DSE\ldots$

$\Longrightarrow$ DSE is an *infinite tower of equations relating all correlation functions*

- DSE are **exact relations** and are the *quantum Euler-Lagrange equations* for *any* QFT
- *Perturbative Expansion* yields *standard perturbative* QFT

2. Bethe-Salpeter Equations



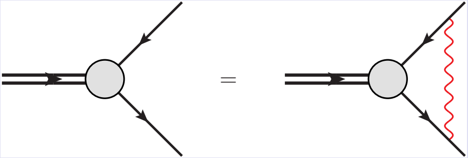
Bethe-Salpeter Equations

Bethe-Salpeter equation is the *DSE* describing a *bound 2 body system*

Obtained by *four derivatives of the generating functional* and *several formal manipulations*

$$\Gamma(k;P) = \int \frac{d^4q}{(2\pi)^4} K(q,k;P) S_F\left(q+\frac{P}{2}\right)\Gamma(q;P)S_F\left(q-\frac{P}{2}\right)$$

Solutions for discrete set P^2 yield *mass spectra*



Rainbow-Ladder Truncation

A *symmetry-preserving truncation* of the *infinite set of DSEs* which respects *relevant (global) symmetries of QCD* is the

rainbow-ladder truncation in combination with the *impulse approximation*

1. In *BSE kernel*

$$K(p,p';k,k') \to -\mathcal{G}\ell(q^2) D^{\text{free}}_{\mu\nu}(q) \frac{\lambda^a}{2}\gamma_\mu \otimes \frac{\lambda^a}{2}\gamma_\nu$$

2. In *gap equation*

$$Z_1 g^2 D_{\mu\nu}(q) \Gamma^a_\nu(k,p) \to \mathcal{G}\ell(q^2) D^{\text{free}}_{\mu\nu}(q) \frac{\lambda^a}{2}\gamma_\nu$$

R-LT is *first term* in *systematic expansion of $q\bar{q}$ scattering kernel $K(p,p';k,k')$*

Gluon Propagator

- *DSE* and *unquenched QCD lattice* studies show that the

Full gluon propagator

$$D^{ab}_{\mu\nu}(p) = \delta^{ab}\,\frac{\mathcal{G}\ell(p^2)}{p^2}\left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right)$$

is *IR finite*, i.e.

$$\lim_{p^2\to 0} D^{ab}_{\mu\nu}(p) = \textit{finite}$$

- the *gluon* has *dynamically generated mass* in the *IR*

- *EM Observables* in the static limit ($q_\mu \to 0$) probe *gluon propagator* for *small transversed momenta* $\Longrightarrow$

Point-like vector $\otimes$ vector contact interaction

$$g^2 D^{ab}_{\mu\nu}(p) = \delta^{ab}\delta_{\mu\nu}\frac{4\pi\alpha_{\mathrm{IR}}}{m_G^2}$$

Contact Interaction Model

This implies

- Non-renormalizable theory
- Introduce *proper-time regularization*

1. $\Lambda_{uv} = 1/\tau_{uv}$ *cannot be removed* but plays a dynamical role and sets the scale of all dimensioned quantities
2. $\Lambda_{ir} = 1/\tau_{ir}$ implements *confinement* by ensuring the *absence of quark production tresholds*

- Scale m_G, is set in agreement with *observables*
- In the *static limit* $q^2 \to 0$ results *"indistinguishable"* from any other *however sophisticated* *DSE* approach
- For $q^2 \gtrsim M^2_{\text{dressed}}$ *deviations* are expected from other experimental values

Part B:

[1]The ρ Meson

[1] M. P., C. Y. Seng, M. J. Ramsey-Musolf, C. D. Roberts, S. M. Schmidt and D. J. Wilson, Phys. Rev. C **87** (2013) 015205.

The ρ Meson

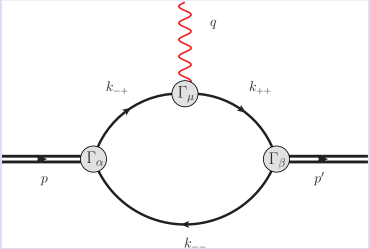
- *"Per se"* from an experimental point of view *uninteresting*
- *Short lifetime* ($\sim 10^{-24}\ s$) makes EDM measurements *hard (or rather impossible)*
- *Simplest system* possibly providing EDM and hence *perfect prototype particle*
- Results available in QCD *sum rules* and *other techniques*

Profile

1. $I^G(J^{PC}) = 1^+(1^{--})$
2. $m = 775.49 \pm 0.34$ MeV,
   $\Gamma = 149.1 \pm 0.8$ MeV
3. Primary decay mode ($\sim 100\%$): $\rho \to \pi\pi$

The ρ-Meson in Impulse Approximation

Impulse Approximation



$$\Gamma^{(u)}_{\alpha\mu\beta} \propto \int \frac{d^4k}{(2\pi)^4} \mathrm{Tr}_{CD}\left\{\Gamma^{\rho(u)}_{\beta} S(k_{++}) \Gamma^{(u)}_{\mu} S(k_{-+}) \Gamma^{\rho(u)}_{\alpha} S(k_{--})\right\}$$

EDM sources induce *CP* violating corrections to the

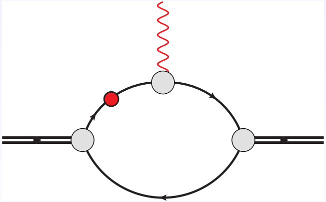
1. *$q\gamma q$ vertex*
2. *Bethe-Salpeter amplitude*
3. *Propagator*

The Θ-Term

- *Only* CP violating dimension 4 operator

$$\mathcal{L}_{\text{eff}} = -i\bar{\Theta}\frac{g_s^2}{32\pi^2}\, G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}$$

- *No suppression by heavy scale* (strong CP problem)
- $U(1)_A$ anomaly allows to rotate it into complex mass for evaluation *(effective propagator correction)*



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QCD sum rules	$4.4 \times 10^{-3}\, e\,\bar{\Theta}/1$ GeV

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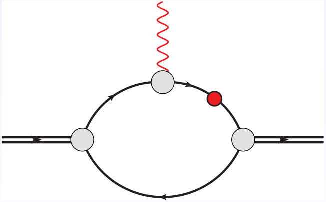

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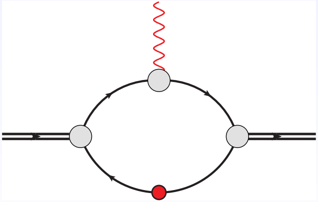

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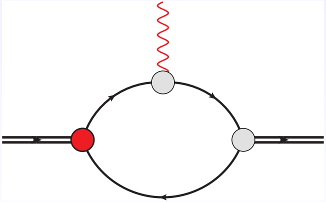

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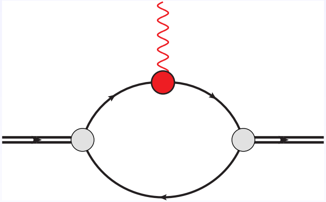

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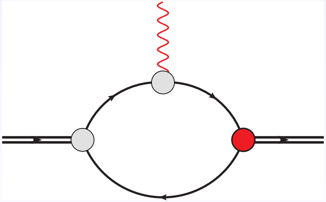

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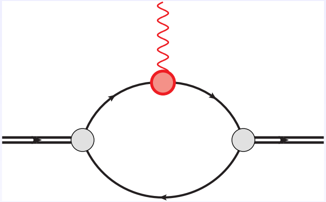
The Quark-EDM

- The *intrinsic EDM* of a *quark* itself

$$\mathcal{L}_{\text{eff}} = -\frac{i}{2} \sum_{q=u,d} d_q \, \bar{q} \sigma_{\mu\nu} \gamma_5 q \, F_{\mu\nu}$$

- *Effective $q\gamma q$ vertex correction*



DSE - *CIM*	$0.79\,(d_u - d_d)$
DSE	$0.72\,(d_u - d_d)$
Bag Model	$0.83\,(d_u - d_d)$
QCD sum rules	$0.51\,(d_u - d_d)$
Non-relativistic quark model	$1.00\,(d_u - d_d)$

The Chromo-EDM

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$$\mathcal{L}_{\text{eff}} = -\frac{i}{2} g_s \sum_{q=u,d} \tilde{d}_q \, \bar{q} \, \frac{1}{2} \lambda^a \sigma_{\mu\nu} \gamma_5 q \, G^a_{\mu\nu}$$

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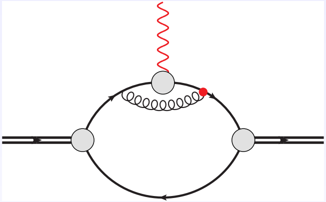

DSE - $q\gamma q$	$-0.07\, e\tilde{d}_- - 0.20\, e\tilde{d}_+$
DSE - BSA	$-0.12\, e\tilde{d}_- + 0.11\, e\tilde{d}_+$
DSE - Propagator	$1.35\, e\tilde{d}_- - 0.60\, e\tilde{d}_+$
DSE	$1.16\, e\tilde{d}_- - 0.69\, e\tilde{d}_+$
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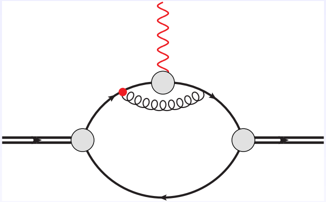

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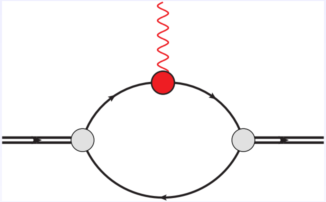

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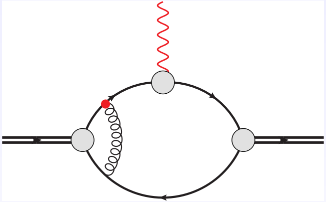

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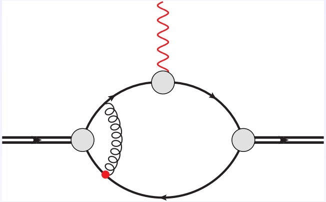

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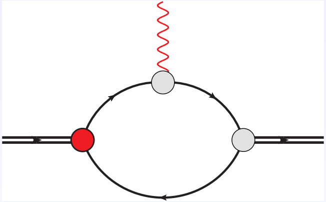

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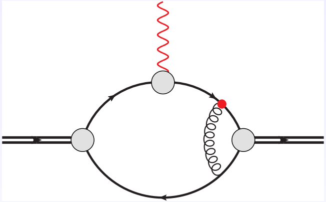

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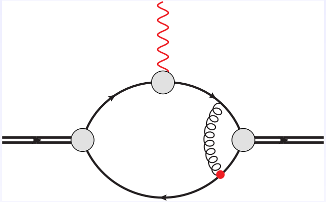

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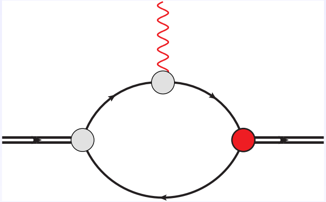

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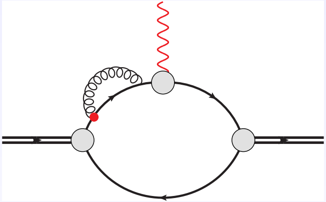
- *Effective propagator correction*



DSE - $q\gamma q$	$-0.07\, e\tilde{d}_- - 0.20\, e\tilde{d}_+$
DSE - BSA	$-0.12\, e\tilde{d}_- + 0.11\, e\tilde{d}_+$
DSE - *Propagator*	$1.35\, e\tilde{d}_- - 0.60\, e\tilde{d}_+$
DSE	$1.16\, e\tilde{d}_- - 0.69\, e\tilde{d}_+$
QCD sum rules	$-0.13\, e\tilde{d}_-$

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- The *Intrinsic Chromo-EDM* of a *quark* itself

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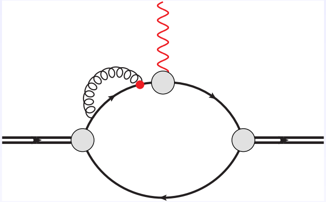

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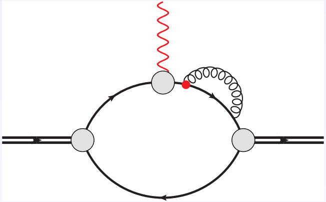

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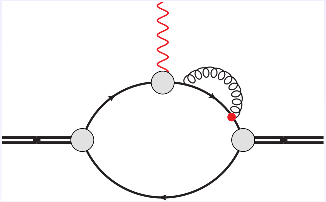

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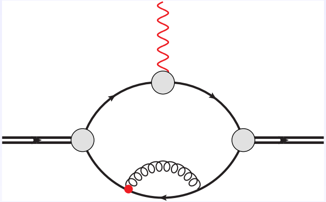

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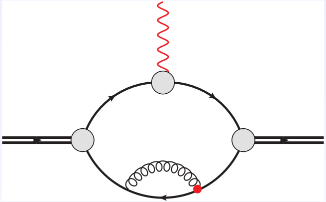

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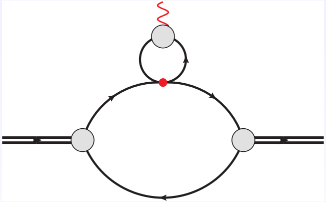
The Effective 4-Quark Operator

- The *effective 4-quark operator*

$$\mathcal{L} = i\frac{\mathcal{K}}{\Lambda^2}\,\varepsilon_{ij}\,(\bar{Q}_i d)(\bar{Q}_j\gamma_5 u) \quad \text{with} \quad \bar{Q}_i = \begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix}$$

- No results obtained in other methods yet
- *Effective $q\gamma q$ vertex correction*



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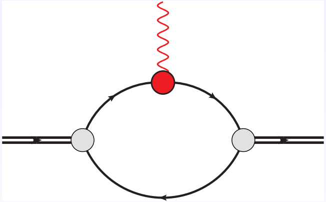

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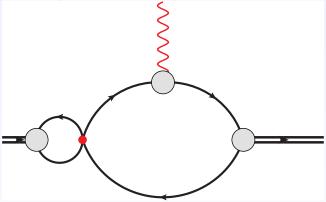

DSE - $q\gamma q$	$-1.00 \times 10^{-5}\,\mathcal{K} e \nu_H/\Lambda^2$
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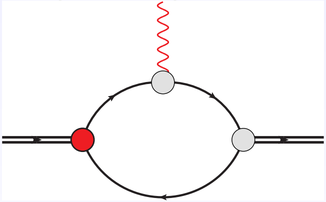

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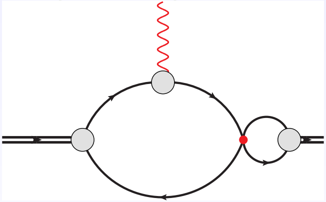

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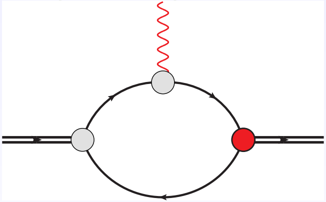

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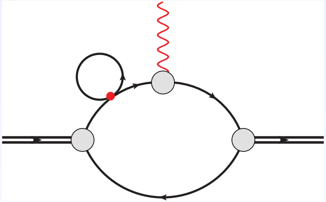

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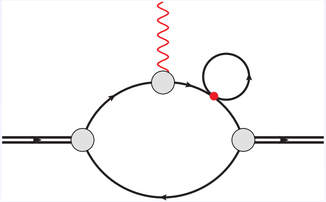

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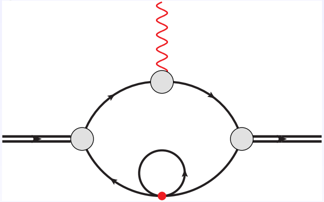

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Part C:

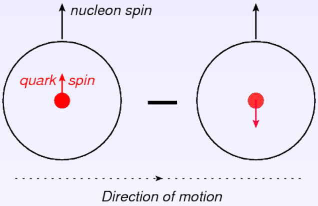
[2]The Nucleon

[2] M. P., C. Y. Seng, C. D. Roberts and S. M. Schmidt, Phys. Rev. D **91** (2015) 074004.;
S.-S. Xu, C. Chen, I. C. Cloet, C. D. Roberts, J. Segovia and H.-S. Zong, Phys. Rev. D **92** (2015) 114034.

Introduction

Nucleon's tensor charge

$$\langle P(p,\sigma)|\bar{q}\sigma_{\mu\nu}q|P(p,\sigma)\rangle = \delta_T q\, \bar{\mathrm{u}}(p,\sigma)\sigma_{\mu\nu}\mathrm{u}(p,\sigma) \qquad (q = u, d, \ldots)$$



$$\delta_T q = \int_{-1}^{1} dx\, h_{1T}^{q}(x) = \int_{0}^{1} dx\, [h_{1T}^{q}(x) - h_{1T}^{\bar{q}}(x)]$$

h_{1T} ... *transversity distribution*

measures the *light-front number-density* of quarks with transverse polarisation *parallel* to that of the proton minus that of quarks with *antiparallel polarisation*

Introduction

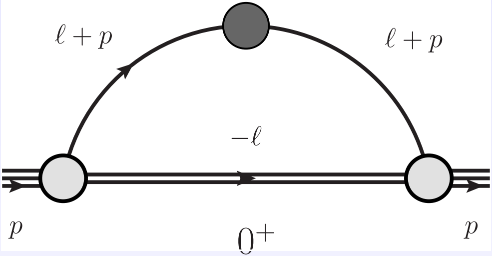
Relation tensor charge to qEDM

$$
\begin{aligned}
d_p\, \bar{\mathrm{u}}(p,\sigma)\sigma_{\mu\nu}\gamma_5 \mathrm{u}(p,\sigma) &= \sum_{q=u,d} d_q \, \langle P(p,\sigma)|\bar{q}\sigma_{\mu\nu}\gamma_5 q|P(p,\sigma)\rangle \\
&= \frac{1}{2}\,\varepsilon_{\mu\nu\alpha\beta} \sum_{q=u,d} d_q \, \langle P(p,\sigma)|\bar{q}\sigma_{\alpha\beta} q|P(p,\sigma)\rangle \\
&= \frac{1}{2}\,\varepsilon_{\mu\nu\alpha\beta}\, \bar{\mathrm{u}}(p,\sigma)\sigma_{\alpha\beta}\mathrm{u}(p,\sigma) \sum_{q=u,d} d_q\, \delta_T q \\
&= \bar{\mathrm{u}}(p,\sigma)\sigma_{\mu\nu}\gamma_5 \mathrm{u}(p,\sigma) \sum_{q=u,d} d_q\, \delta_T q
\end{aligned}
$$

Proton *EDM*: $d_p = d_u\, \delta_T u + d_d\, \delta_T d$

Neutron *EDM*: $d_n = d_u\, \delta_T d + d_d\, \delta_T u$

Nucleon Tensor Charge



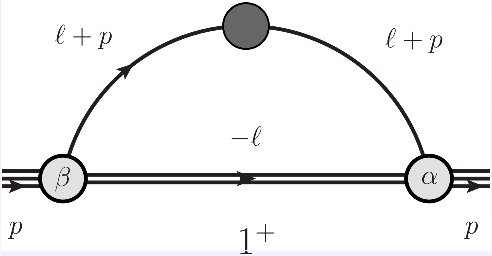
$$\Lambda^+(p)\mathcal{S}(-p)\int \frac{d^4\ell}{(2\pi)^4}\, S^{(u)}(\ell+p)\sigma_{\mu\nu}S^{(u)}(\ell+p)\Delta^{0^+}(-\ell)\mathcal{S}(p)\Lambda^+(p)$$

$$= \mathcal{N}\,\delta_T d\,\Lambda^+(p)\sigma_{\mu\nu}\Lambda^+(p)$$

$$\mathcal{S}(p) = s(p)\,\mathbf{1}_D \qquad \big(s(p) = 0.8810\big)$$

$$\Lambda^+(p) = \frac{1}{2m_N}\,(-i\gamma\cdot p + m_N)$$

Nucleon Tensor Charge



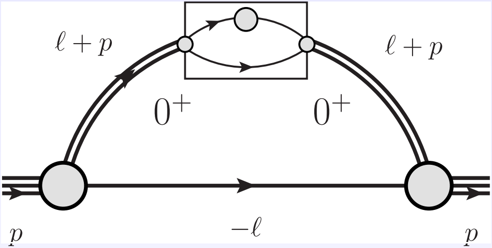
$$\Lambda^+(p)\mathcal{A}^i_\alpha(-p)\int \frac{d^4\ell}{(2\pi)^4} S^{(q)}(\ell+p)\sigma_{\mu\nu}S^{(q)}(\ell+p)\Delta^{1^+}_{\alpha\beta}(-\ell)\mathcal{A}^i_\beta(p)\Lambda^+(p)$$

$$= \mathcal{N}\,\delta_T q\,\Lambda^+(p)\sigma_{\mu\nu}\Lambda^+(p)$$

$$\mathcal{A}^i_\mu(p) = a^i_1(p)\,\gamma_5\gamma_\mu + a^i_2(p)\,\gamma_5\,\hat{p}_\mu \qquad (\hat{p}^2 = -1, i = +, 0)$$

$$a^+_1 = -0.380,\ a^+_2 = -0.065,\ a^0_1 = 0.270,\ a^0_2 = 0.046$$

Nucleon Tensor Charge

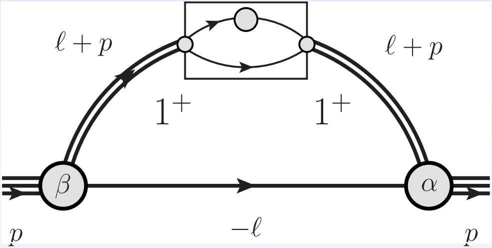


$$\Lambda^+(p)\mathcal{S}(-p)\int\frac{d^4\ell}{(2\pi)^4}\,\Delta^{0^+}_{\alpha\alpha'}(\ell+p)\Lambda_{\mu\nu}\Delta^{0^+}_{\beta'\beta}(\ell+p)S^{(q)}(-\ell)\mathcal{S}(p)\Lambda^+(p)$$

$$= 0$$

"A *spinless particle* cannot have a *vectorial/tensorial structure* of any kind!"

Nucleon Tensor Charge



$$\Lambda^+ \mathcal{A}^i_\alpha(-p) \int \frac{d^4\ell}{(2\pi)^4} \Delta^{1^+}_{\alpha\alpha'}(\ell + p) \Lambda_{\alpha'\mu\nu\beta'} \Delta^{1^+}_{\beta'\beta}(\ell + p) S^{(q)}(-\ell) \mathcal{A}^i_\beta(p) \Lambda^+$$

$$= \mathcal{N}\, \delta_T q\, \Lambda^+(p) \sigma_{\mu\nu} \Lambda^+(p)$$

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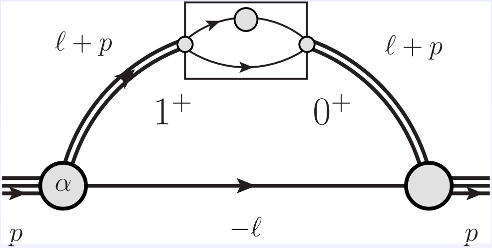

$$\Lambda^+(p)\mathcal{S}(-p)\int\frac{d^4\ell}{(2\pi)^4}\,\Delta^{0^+}(\ell+p)\Lambda_{\mu\nu\alpha}\Delta^{1^+}_{\alpha\beta}(\ell+p)S^{(u)}(-\ell)\mathcal{A}^0_\beta(p)\Lambda^+(p)$$

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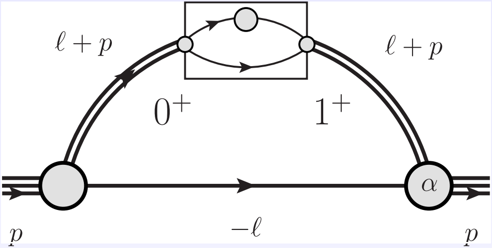

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Nucleon Tensor Charge

"*Static Approximation*"

$\zeta_H = 2$ GeV	$\delta_T u$	$\delta_T d$	$g_T^{(0)}$	$g_T^{(1)}$
Diagrams 1 + 2	0.44	−0.03	0.42	0.47
Diagrams 3 + 4	0.23	0.05	0.28	0.18
Diagrams 5 + 6	−0.20	−0.20	−0.40	0
Total Result	0.48	−0.18	0.30	0.67

"*Dynamical Dressed Quark Exchange*"

$\zeta_H = 2$ GeV	$\delta_T u$	$\delta_T d$	$g_T^{(0)}$	$g_T^{(1)}$
Diagrams 1 + 2	0.57	−0.03	0.54	0.60
Diagrams 3 + 4	0.11	0.02	0.13	0.09
Diagrams 5 + 6	−0.15	−0.15	−0.30	0
DDQE	0.10	−0.04	0.06	0.13
Total Result	0.63(9)	−0.20(3)	0.43(6)	0.83(12)

Nucleon Tensor Charge

Significance of $\delta_T u$

α_{IR} *reduced* by 20% leads to $\delta_T u$ *reduced* by 20% with $\delta_T d$ practically *unchanged*

$\Longrightarrow$ $\delta_T u$ is a direct probe of *DCSB*

Significance of $\delta_T d$

$\delta_T d$ is non-zero only due to *Axial-vector correlations*

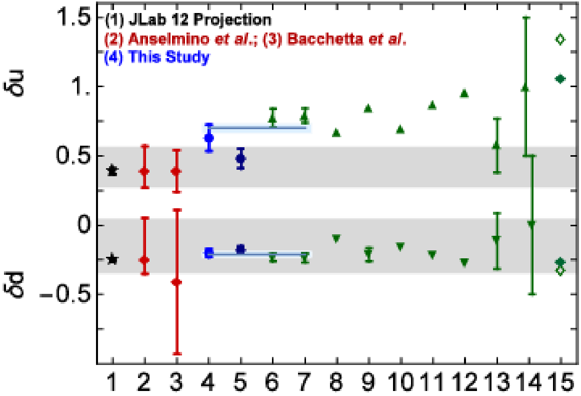
$\Longrightarrow$ $\delta_T d$ is a probe of *Axial-vector correlations*

$\delta_T u$ is increased by 11% in the absence of *Axial-vector correlations*

$\Longrightarrow$ $\delta_T u$ is suppressed by *Axial-vector correlations*

The Quark-EDM

Flavour separation of the proton's tensor charge



$$d_p|_{\zeta_H=2\text{ GeV}} = \quad 0.63(9)\, d_u - 0.20(3)\, d_d$$

$$d_n|_{\zeta_H=2\text{ GeV}} = -0.20(3)\, d_u + 0.63(9)\, d_d$$

Conclusion

- *Continuum approach* to any QFT
- Originates at the *QCD current quark/gluon level*, i.e. all operators are "implemented" at that level
- "Rigid structure" – few model parameters
- Has been shown to work well in the *CP conserving sector*

Collaboration

The results, expounded in this talk, were obtained in Collaboration with

- Craig D. Roberts – ANL
- Michael J. Ramsey-Musolf – UMass Amherst
- Chien-Yeah Seng – UMass Amherst

Thank You For Your Attention!