Hadronic EDMs & Form Factors from Dyson-Schwinger Equations

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Introduction

- Introduction
- Part A: *DSE Contact Interaction Model*
- Part B: *The ρ Meson*
- Part C: *The Nucleon*
- Conclusion & Outlook

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

Introduction: The Energy Scale & Effective EDM Operators for dim ≥ 4 at scale ~ 1 GeV

Calculation of hadronic EDMs naturally splits into 2 parts

1. Calculation of Wilson coefficients
   by integrating out short distances
2. Switching from perturbative quark-gluon description to non-perturbative treatment
   – *(much harder and larger uncertainties)*

Effective EDM Operators for dim ≥ 4 at scale ~ 1 GeV

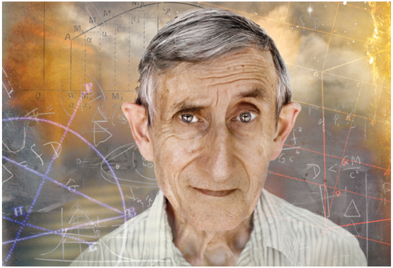
$$\mathcal{L}_M^{1GeV} = \frac{g_s^2}{32\pi^2} \Theta \, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

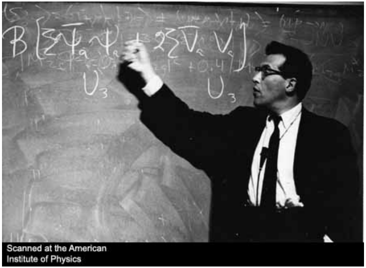
$$- \frac{i}{2} \sum_{i=e,u,d,s} d_i \, \bar{\psi}_i \, (F \cdot \sigma) \, \gamma^5 \psi_i - \frac{i}{2} \, g_s \sum_{i=u,d,s} \tilde{d}_i \, \bar{\psi}_i \, (G \cdot \sigma) \, \gamma^5 \psi_i$$

$$+ \sum_{i,j=e,u,d,s} C_{ij} (\bar{\psi}_i \psi_i)(\bar{\psi}_j i \gamma^5 \psi_j) + \cdots$$

Part A:
DSE Contact Interaction Model

1. Dyson-Schwinger Equations





- *Non-perturbative continuum* approach to any QFT
  $\Longrightarrow$ 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*
- DSE provides *Dynamical Chiral Symmetry Breaking*, i.e *dynamically induced mass* even in the *chiral limit* *("mass from nothing")*

Gluon Propagator

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

full gluon propagator

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

is *IR finite*, i.e.

$$\lim_{p^2 \to 0} D_{\mu\nu}^{ab}(p) = \mathit{finite}$$

- 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 $\times$ vector contact interaction

$$g^2 D_{\mu\nu}^{ab}(p) = \delta^{ab} \delta_{\mu\nu} \frac{1}{m_G^2}$$

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 C:
The ρ Meson

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*

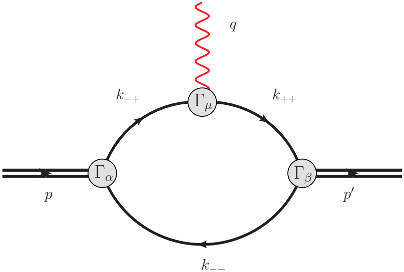
Profile

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 $\rho\gamma\rho$ vertex

$$
\begin{aligned}
&d_{\alpha\nu}(p)\Gamma_{\nu\mu\sigma}d_{\sigma\beta}(p') = \\
&\quad d_{\alpha\nu}(p)\Big\{(p+p')_\mu[-\delta_{\nu\sigma}\,\mathcal{E}(q^2) + q_\nu q_\sigma\,\mathcal{Q}(q^2)] \\
&\qquad + (\delta_{\mu\nu}q_\sigma - \delta_{\mu\sigma}q_\nu)\,\mathcal{M}(q^2) - i\varepsilon_{\nu\sigma\mu\rho}q_\rho\,\mathcal{D}(q^2)\Big\}d_{\sigma\beta}(p')
\end{aligned}
$$

with CP conserving form factors

- for *charge* $\mathcal{E}(0) = 1$
- *magnetic dipole moment* $\mathcal{M}(0)$ in units $e/(2m_\rho)$
- *quadrupole moment* $Q(0)$ with form factor $\mathcal{Q}(0) = (2/m^2)(Q + \mu - 1)$

and CP violating term

- *electric dipole moment* $\mathcal{D}(0)$ in units $e/(2m_\rho)$

Form factors will be *projected out* by appropriate *projection operators*

The Magnetic Moment

Results for $\mathcal{M}(0)$ in units $e/(2m_\rho)$

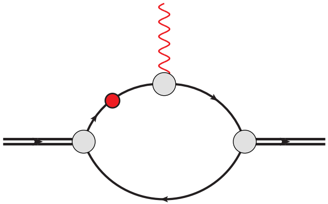
DSE - *CIM*	2.11
DSE - *RL RGI-improved*	2.01
DSE - *EF parametrisation*	2.69
LF - *CQM*	2.14
LF - *CQM*	1.92
QCD sum rules	1.8 ± 0.3
point particle	2

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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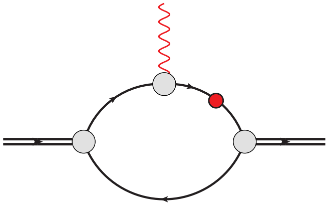

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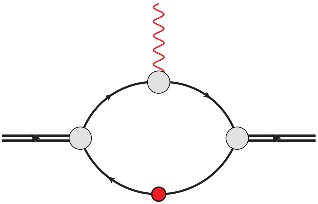

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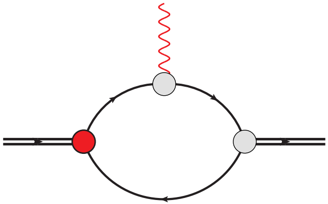

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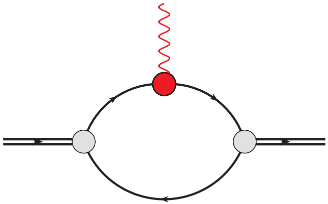

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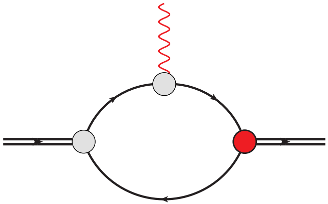

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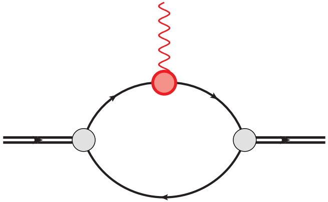
The Quark-EDM

- 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

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

$$\mathcal{L}_{\text{eff}} = -\frac{i}{2} g_s \sum_{q=u,d} \tilde{d}_q \, \bar{q} \, \frac{1}{2} \lambda^a \sigma_{\mu\nu} \gamma^5 q \, G^a_{\mu\nu}$$

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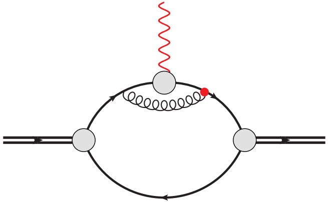

DSE - $q\gamma q$	$-0.07\, e\tilde{d}_- - 0.20\, e\tilde{d}_+$
DSE - *BSA*	$-0.12\, e\tilde{d}_- + 0.11\, e\tilde{d}_+$
DSE - *Propagator*	$1.35\, e\tilde{d}_- - 0.60\, e\tilde{d}_+$
DSE	$1.16\, e\tilde{d}_- - 0.69\, e\tilde{d}_+$
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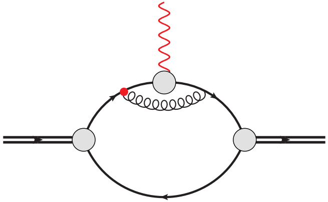

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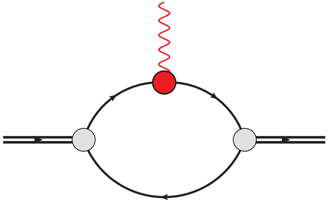

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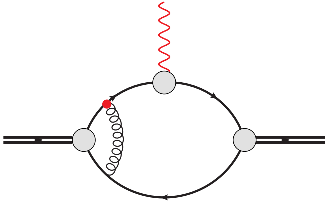
- *Effective Bethe-Salpeter amplitude correction*



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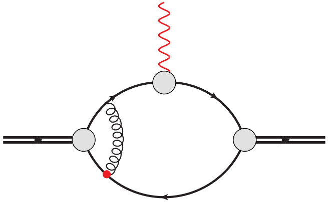

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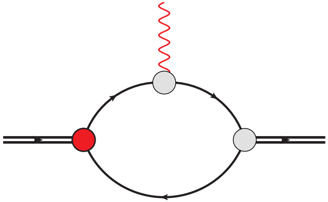

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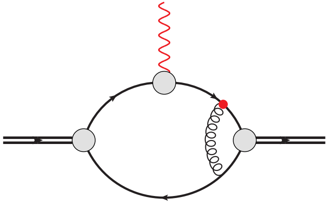

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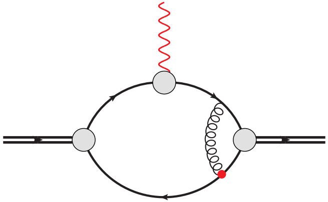

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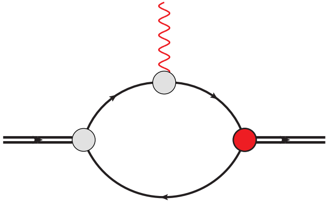

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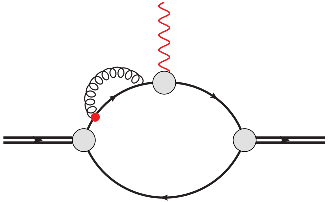

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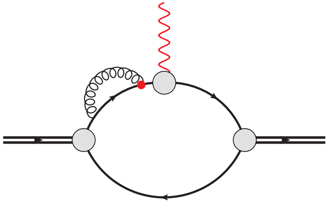

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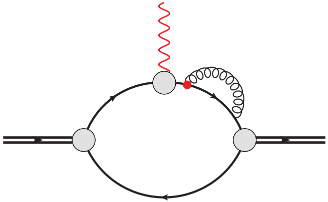
The Chromo-EDM

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

$$\mathcal{L}_{\text{eff}} = -\frac{i}{2}\, g_s \sum_{q=u,d} \tilde{d}_q\, \bar{q}\, \frac{1}{2}\lambda^a \sigma_{\mu\nu}\gamma^5 q\, G^a_{\mu\nu}$$

- *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*	$1.35\, e\tilde{d}_- - 0.60\, e\tilde{d}_+$
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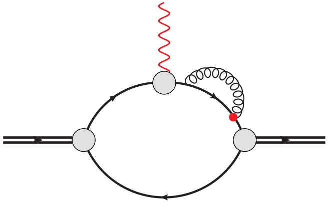

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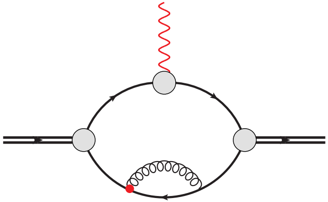

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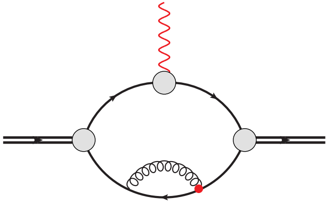

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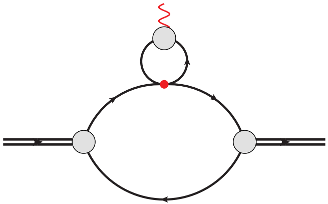
The Effective 4-Quark Operator

- 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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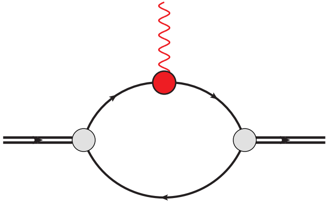

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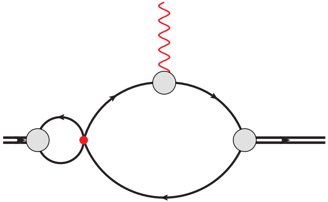

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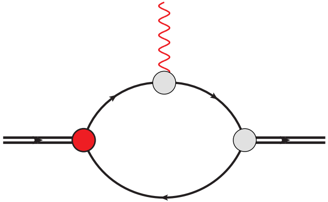

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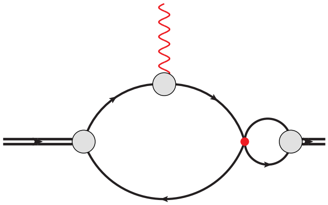

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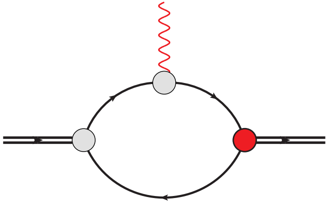

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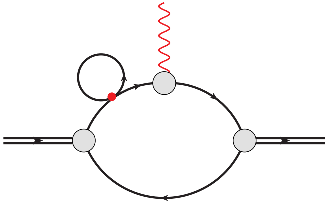

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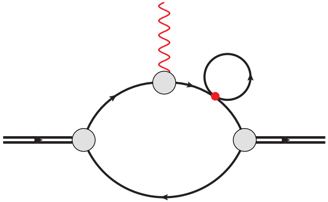

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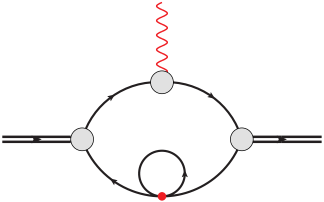

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Conclusion I

- *Chromo-EDM* contribution (despite loop suppression) is of *comparable size* with *quark-EDM* contribution *(corroborates QCD SR result by Ritz & Pospelov)*
- Some models suggest $d_f = D_q \frac{e\,\nu_H}{\Lambda^2} \sim \frac{m_f}{\nu_H}\frac{e\,\nu_H}{\Lambda^2} \sim 10^{-5}\frac{e\,\nu_H}{\Lambda^2}$ in which case EDM sources considered here (except θ) give *comparable contributions*
- *DSE - CIM* yields reliable results for a whole class of observables in the static limit, which makes it important for *EDM calculations*

Part D:
The Nucleon

Introduction

Nucleon's *tensor charge*

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

Isoscalar tensor current:

$$(\delta u + \delta d)\,\bar{u}(p)\sigma_{\mu\nu}u(p) = g_T^{(0)}\,\bar{u}(p)\sigma_{\mu\nu}u(p)$$

Isovector tensor current:

$$\langle p|\bar{u}\sigma_{\mu\nu}u - \bar{d}\sigma_{\mu\nu}d|p\rangle = \langle p|\bar{u}\sigma_{\mu\nu}d|n\rangle$$

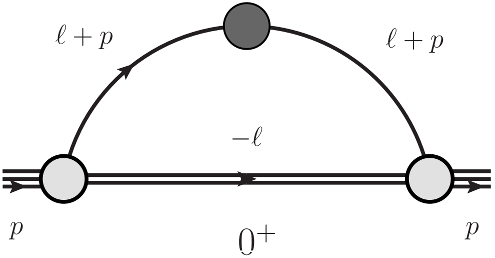
$$\Updownarrow \qquad\qquad\qquad \Updownarrow$$

$$(\delta u - \delta d)\,\bar{u}(p)\sigma_{\mu\nu}u(p) = g_T^{(1)}\,\bar{u}(p)\sigma_{\mu\nu}u(p)$$

hence $\delta u - \delta d$ is experimentally accessible via neutron β–decay

Relation to EDM via $\sigma_{\alpha\beta}\gamma^5 = \frac{1}{2}\varepsilon_{\alpha\beta\mu\nu}\sigma_{\mu\nu}$

$$\langle P(p,\sigma)|\bar{q}\sigma_{\alpha\beta}\gamma^5 q|P(p,\sigma)\rangle = \delta q\,\bar{u}(p,\sigma)\sigma_{\alpha\beta}\gamma^5 u(p,\sigma) \quad (q=u,d,\ldots)$$

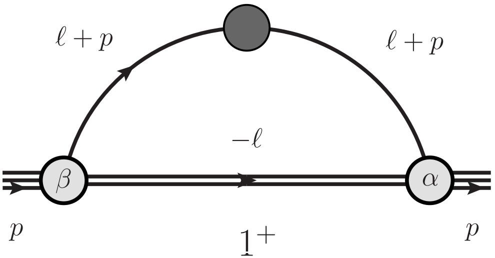


$$\Lambda^+(p)\mathcal{S}\int \frac{d^4\ell}{(2\pi)^4}\, S^{(u)}(\ell+p)\sigma_{\mu\nu}S^{(u)}(\ell+p)\Delta^{0^+}(-\ell)\mathcal{S}\Lambda^+(p)$$

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

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

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

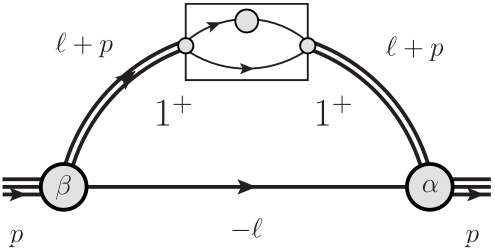


$$\Lambda^+(p)\mathcal{A}^j_\alpha(-p)\int\frac{d^4\ell}{(2\pi)^4}\,S^{(q)}(\ell+p)\sigma_{\mu\nu}S^{(q)}(\ell+p)\Delta^{1^+}_{\alpha\beta}(-\ell)\mathcal{A}^j_\beta(p)\Lambda^+(p)$$

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

$$\mathcal{A}^j_\mu(p)=a^j_1(p)\,i\gamma_5\gamma_\mu+a^j_2(p)\,\gamma_5\hat{p}_\mu \qquad (\hat{p}^2=-1, j=+,0)$$

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

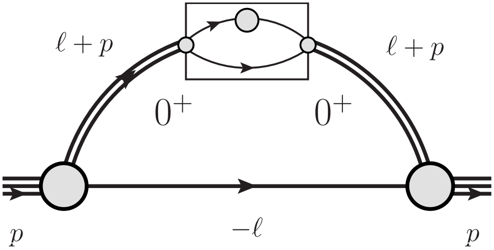


$$\Lambda^+ \mathcal{A}^j_\alpha(-p) \int \frac{d^4\ell}{(2\pi)^4} \Delta^{1^+}_{\alpha\alpha'}(\ell+p) \Lambda_{\alpha'\mu\nu\beta'} \Delta^{1^+}_{\beta'\beta}(\ell+p) S^{(q)}(-\ell) \mathcal{A}^j_\beta(p) \Lambda^+$$

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

$$\mathcal{A}^j_\mu(p) = a^j_1(p)\, \gamma_5\gamma_\mu + a^j_2(p)\, \gamma_5 \hat{p}_\mu \qquad (\hat{p}^2 = -1, j = +, 0)$$

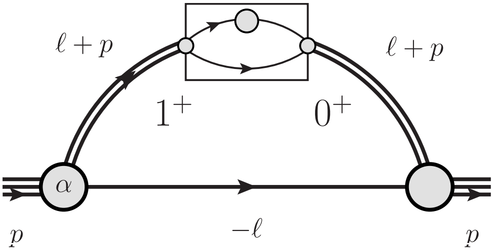
$$a^+_1 = -0.380,\ a^+_2 = -0.065,\ a^0_1 = 0.270,\ a^0_2 = 0.046$$



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

$$= \; 0$$

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



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

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

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

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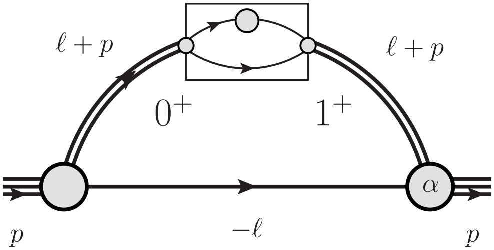

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1 - JLab 12
2 - Anselmino et al., Nucl.Phys.Proc.Suppl. (2009)
3 - Cloet, Bentz and Thomas, Phys.Lett.B (2008)
4 - Wakamatsu, Phys.Lett.B (2007)
5 - Gockeler et al., Phys.Lett.B (2005)
6 - He and Ji, Phys. Rev. D (1995)
7 - Pasquini et al, Phys. Rev. D (2007)
8 - Gamberg and Goldstein, Phys. Rev. Lett. (2001)
9 - Hecht, Roberts and Schmidt Phys. Rev. C (2001)

$\delta q = \int dx \, (h_1^q(x) - h_1^{\bar{q}}(x))$

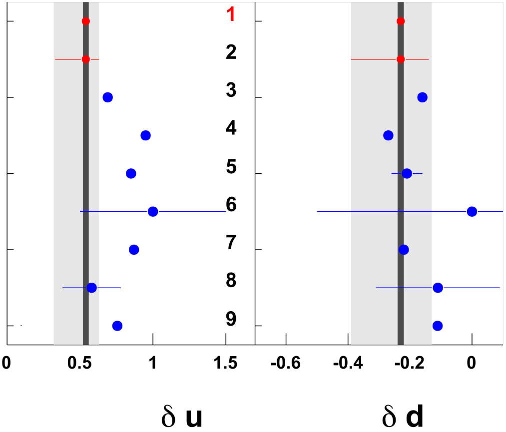
This work (preliminary): δu = 0.44, δd = -0.20

$\delta u = 0.54^{+0.09}_{-0.22}, \ \delta d = -0.23^{+0.09}_{-0.16}$

JLab 12 Proton and He^3 targets

$\delta u = 0.54^{+0.02}_{-0.02}, \ \delta d = -0.23^{+0.01}_{-0.01}$

Statistical errors only



Conclusion II

- Originates at the *QCD current quark/gluon level*,
  i.e. all operators are "implemented" at that level
  (compared to NDA, χPT)
- "Rigid structure" – few model parameters
- has shown to work well in the *CP conserving sector*
- Still a lot to do: *other effective operators, PQ, error bars, ...*

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!