Hadronic EDMs from Dyson Schwinger

Mario Pitschmann

Institute of Atomic and Subatomic Physics,
Vienna University of Technology

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Introduction

- Introduction
- Part A: *Overview of Techniques*
- Part B: *The Theoretical Framework*
- Part C: *The ρ Meson*
- Part D: *The Nucleon*

Introduction: The Energy Scale

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

$\Updownarrow$

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

$\Updownarrow$

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

$\Updownarrow$

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:
Overview of Techniques

Hadronic Matrix Elements

Non-perturbative techniques:

- Lattice
- QCD sum rules
- Wave functions (including light-cone input)
- $1/N_c$ approximation
- Relativistic Quark-Parton Model
- Chiral Quark Model
- χPT
- DSE

Hadronic Matrix Elements

Non-relativistic $SU(6)$ Quark Model

- *most widely used* for quark EDMs to nEDM
- **disadvantage:** cannot be used for a wider class of CP-odd sources relevant for d_n and $\bar{g}_{\pi NN}$
- **result:** $d_n(d_q) = \frac{1}{3}(4d_d - d_u)$

Naive dimensional analysis

- *conceptually simplest* approach/ QCD power counting
- **disadvantage:** does not allow in general to combine different contributions
- **results:** $d_n(d_q, \mu) \sim d_q(\mu)$

$$d_n(\Theta_q, \mu) \sim e\,\Theta_q(\mu)\frac{m_q(\mu)}{\Lambda_{had}^2}$$

$$d_n(\tilde{d}_q, \mu) \sim \frac{e}{4\pi}\tilde{d}_q(\mu)$$

Hadronic Matrix Elements

Chiral techniques

- CP odd $\bar{g}_{\pi NN}$ contributes to nEDM via π^- loop
- **disadvantage:** *limited applicability*, chiral enhancement is no numerical enhancement in the physical regime ($m_\pi \neq 0$)
- **result:** $d_n^{\chi\,\log} = \frac{e}{4\pi^2 M_n}\, g_{\pi NN}\, \bar{g}_{\pi NN}^{(0)} \ln \frac{\Lambda}{m_\pi}$

QCD sum-rules techniques

- start at high energies, use operator product expansion, construct QCD sum rules
- **disadvantage:** dependence on partly know spectral function
- **results:** $d_n^{est} = \frac{4}{3} d_d - \frac{1}{3} d_u - \frac{2 m_\pi^2 e}{m_n (m_u + m_d)} \left(\frac{2}{3} \tilde{d}_d + \frac{1}{3} \tilde{d}_u \right)$ (PQ)

Hadronic Matrix Elements

Lattice

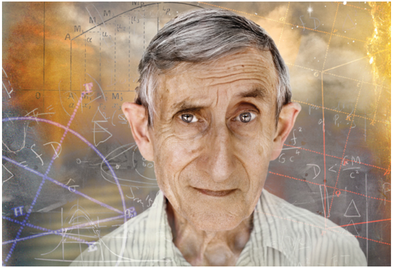
- assumedly ultimate choice for calculating hadronic matrix elements but *difficult*
- **disadvantage:** modest finite volume, quark masses higher than real physical values $\Longrightarrow$ *extrapolation* to real physical conditions by other techniques *(e.g. chiral techniques)*

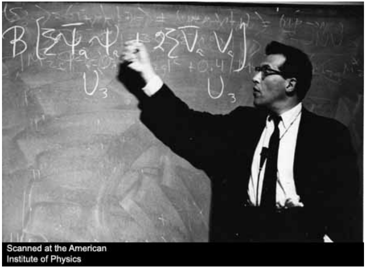
Conclusion

- Many different techniques available
- Each with varying advantages and disadvantages
- Have been used complimentary
- MUCH room for improvement

Part B:
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

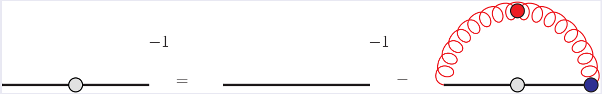
In QCD the *fermion propagator* is obtained by derivation of

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

with respect to η leading after several formal manipulations to the

Gap Equation for the *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...

$\Longrightarrow$ 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*

Dyson-Schwinger Equation

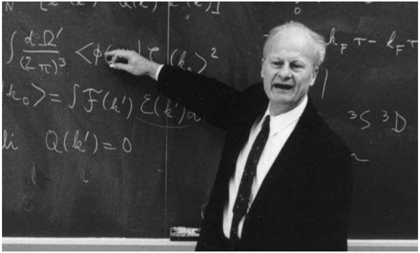
DSE provides *Dynamical Chiral Symmetry Breaking*, i.e *dynamically induced mass* even in the *chiral limit* *("mass from nothing")*

"Dressed" mass in *Weak coupling expansion*

$$M(p^2) \simeq m \left(1 - \frac{3\alpha_s}{4\pi} \ln[p^2/m^2] + \ldots \right)$$

$\Longrightarrow$ *chiral limit* ($m \to 0$) yields *vanishing mass correction* (i.e. $m_N, \ldots \to 0$)

One has to apply *non-perturbative* methods, i.e. one has to sum an *infinite number of diagrams* for *DCSB*


Q(k′) = 0
³S ³D

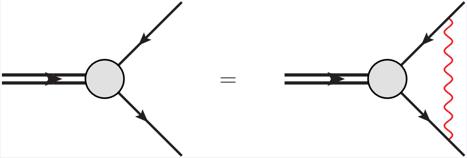
Bethe-Salpeter Equations

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*



3. Ward-Takahashi Identities & Approximations

Ward-Takahashi Identities & Truncation

Observing that *"a gauge transformation does not change the path integral"* $\Longrightarrow$

1. Vector WTI - ensures *EM current conservation*
2. Axial-vector WTI - gives large mass splittings between chiral partners & ensures *massless ground state PS mesons* in *chiral limit* despite *strong enhancement of quark mass function in the IR*

Calculations in *non-perturbative regime* demand a *symmetry-preserving truncation* of the *infinite set of DSEs* which has to respect *relevant (global) symmetries of QCD* such as

- Chiral symmetry
- Lorentz invariance and
- Renormalisation group invariance
- EM current conservation

Rainbow-Ladder Truncation

A viable truncation 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 $K(p,p';k,k')$*
- Reduces to *leading-order perturbation theory asymptotically*

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.

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

- 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 × vector contact interaction

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

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

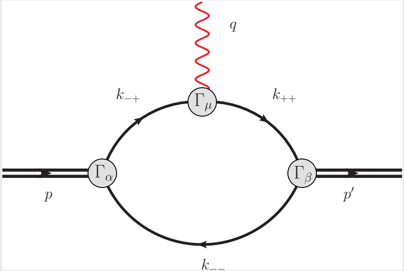
- *"Per se"* from an experimental point of view *uninteresting*
- *Short lifetime* ($\sim 10^{-24}\,s$) makes EDM measurements *hard (or rather impossible)*
- *Simplest system* possibly providing EDM and hence *perfect prototype particle*
- Results available in *QCD sum rules* and *other techniques*

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

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

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 $e/(2m_\rho)$

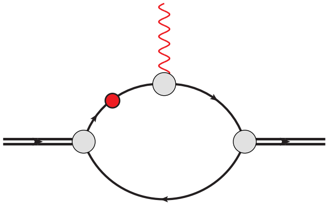
DSE - *CIM*	2.11
DSE - *RL RGI-improved*	2.01
DSE - *EF parametrisation*	2.69
LF - *CQM*	2.14
LF - *CQM*	1.92
QCD sum rules	1.8 ± 0.3
point particle	2

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)*



DSE	$0.7 \times 10^{-3}\, e\,\bar{\Theta}/1$ GeV
QCD sum rules	$4.4 \times 10^{-3}\, e\,\bar{\Theta}/1$ GeV

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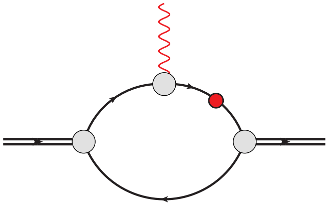

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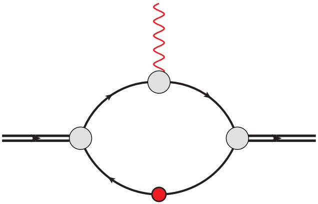

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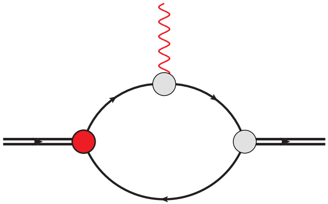

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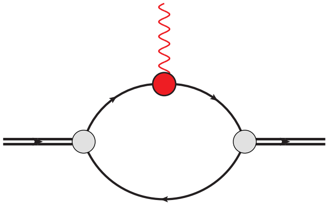

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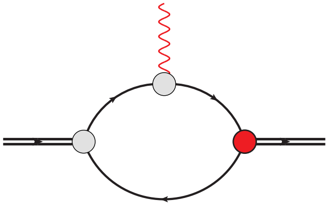

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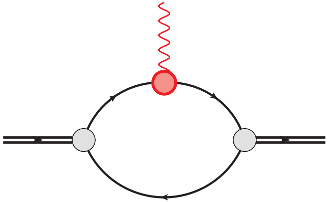
The Quark-EDM

- 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*



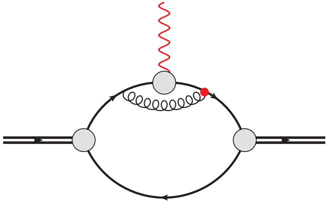
DSE - *CIM*	$0.79\,(d_u - d_d)$
DSE	$0.72\,(d_u - d_d)$
Bag Model	$0.83\,(d_u - d_d)$
QCD sum rules	$0.51\,(d_u - d_d)$
Non-relativistic quark model	$1.00\,(d_u - d_d)$

The Chromo-EDM

- 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 $q\gamma q$ vertex 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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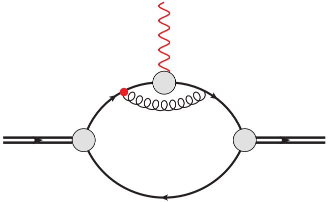

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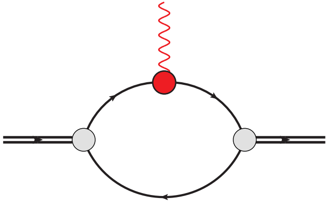

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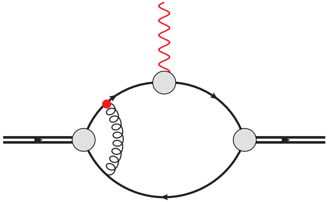
- *Effective Bethe-Salpeter amplitude correction*



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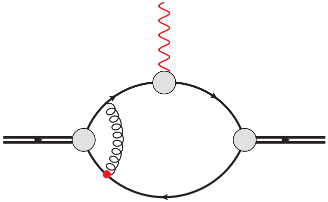

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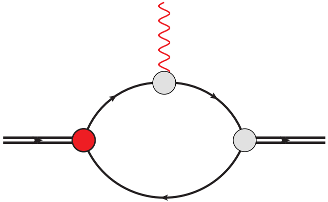

DSE - $q\gamma q$	$-0.07\, e\tilde{d}_- - 0.20\, e\tilde{d}_+$
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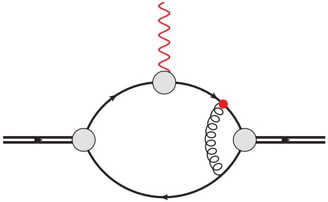

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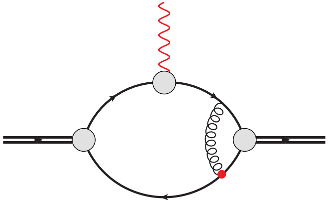

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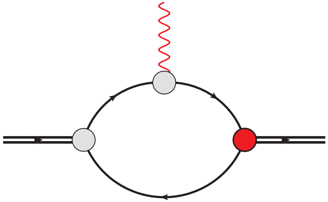

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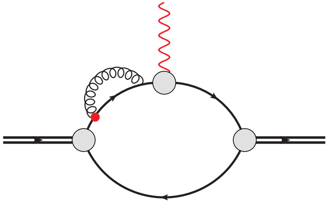

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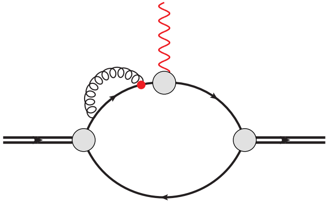

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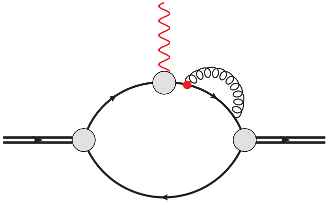

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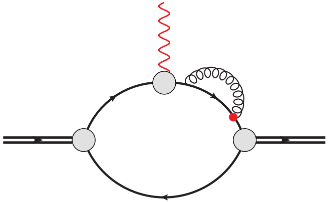

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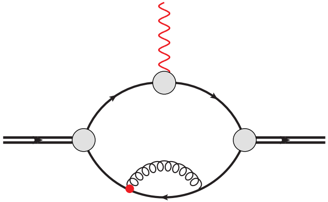

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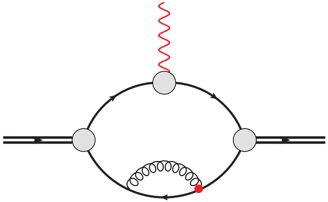

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- No results obtained in other methods yet
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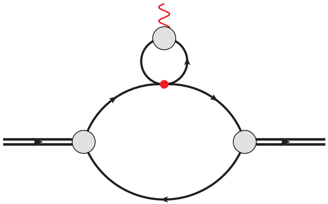

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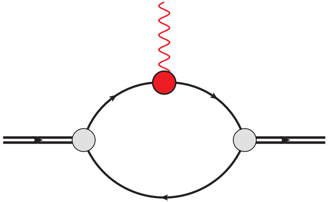

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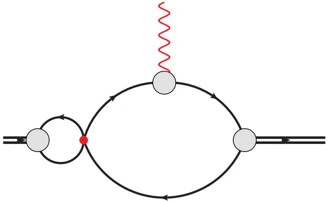

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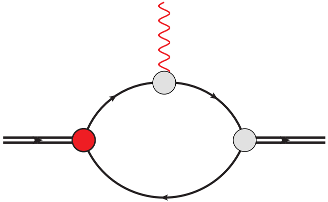

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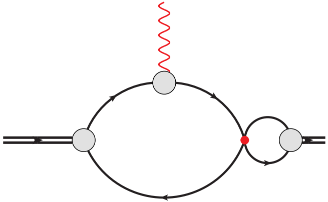

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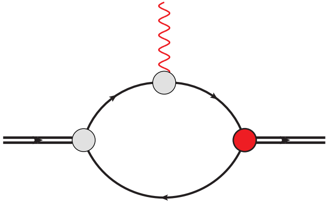

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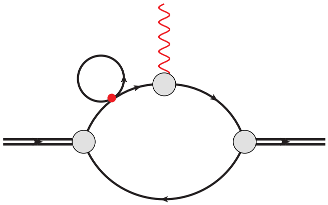

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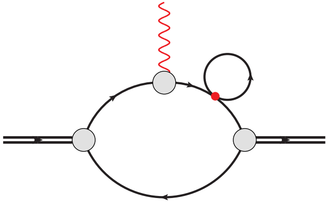

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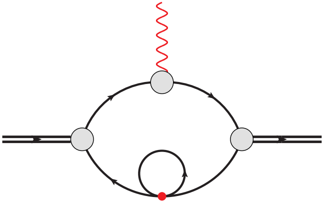

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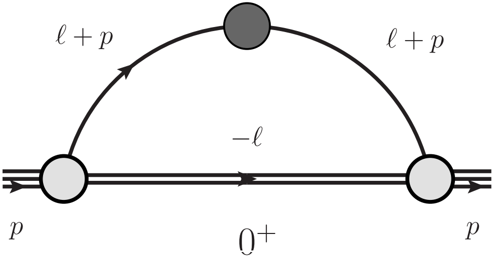
Conclusion I

- *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

- DSE neutron calculation *not yet available*
- Nucleon *scalar and tensor form factor* calculations are currently done
- *Tensor form factor* of the neutron $\sim$ qEDM

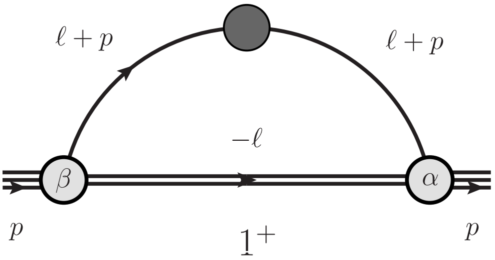


$$\Lambda^+(p)\mathcal{S}(-p)\int \frac{d^4\ell}{(2\pi)^4}\, S^{(u)}(\ell+p)\sigma_{\mu\nu}S^{(u)}(\ell+p)\Delta^{0^+}(-\ell)\mathcal{S}(p)\Lambda^+(p)$$

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

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

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

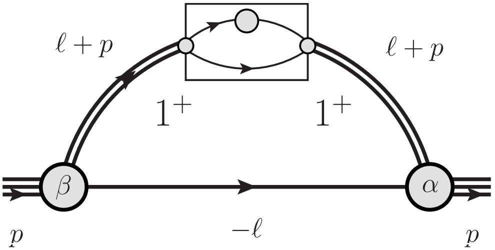


$$\Lambda^+(p)\mathcal{A}^i_\alpha(-p)\int\frac{d^4\ell}{(2\pi)^4}\,S^{(q)}(\ell+p)\sigma_{\mu\nu}S^{(q)}(\ell+p)\Delta^{1^+}_{\alpha\beta}(-\ell)\mathcal{A}^i_\beta(p)\Lambda^+(p)$$

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

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

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

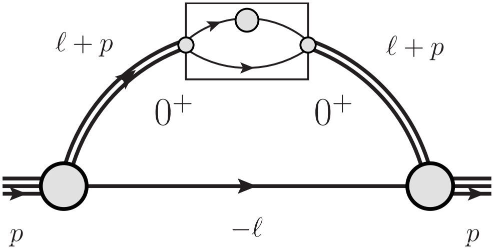


$$\Lambda^+ \mathcal{A}^i_\alpha(-p) \int \frac{d^4\ell}{(2\pi)^4}\, \Delta^{1^+}_{\alpha\alpha'}(\ell+p)\Lambda_{\alpha'\mu\nu\beta'}\Delta^{1^+}_{\beta'\beta}(\ell+p)S^{(q)}(-\ell)\mathcal{A}^i_\beta(p)\Lambda^+$$

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

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

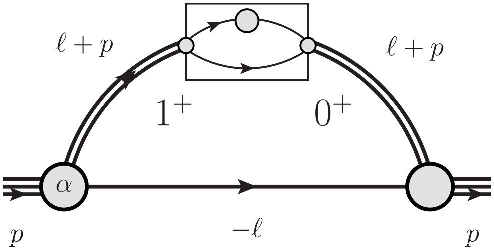
$$a^+_1 = -0.380,\; a^+_2 = -0.065,\; a^0_1 = 0.270,\; a^0_2 = 0.046$$



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

$$= 0$$

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

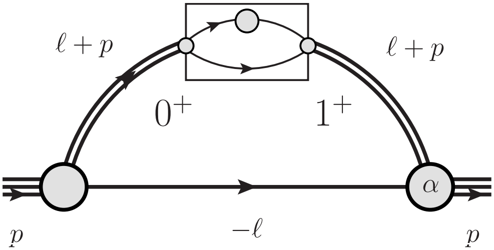


$$\Lambda^+(p)\mathcal{S}(-p)\int \frac{d^4\ell}{(2\pi)^4}\,\Delta^{0^+}(\ell+p)\Lambda_{\mu\nu\alpha}\Delta^{1^+}_{\alpha\beta}(\ell+p)S^{(u)}(-\ell)\mathcal{A}^0_\beta(p)\Lambda^+(p)$$

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

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

$$\mathcal{A}^0_\mu(p) = a^0_1(p)\,\gamma_5\gamma_\mu + a^0_2(p)\,\gamma_5\hat{p}_\mu \qquad \big(a^0_1 = 0.270,\ a^0_2 = 0.046\big)$$



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

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

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

$$\mathcal{A}^0_\mu(p)=a^0_1(p)\,\gamma_5\gamma_\mu+a^0_2(p)\,\gamma_5\hat{p}_\mu \qquad \big(a^0_1=0.270,\ a^0_2=0.046\big)$$

Conclusion II

- *Continuum approach* to any QFT
- Originates at the *QCD current quark/gluon level*, i.e. all operators are "implemented" at that level
- *Truncations* have to be performed (RL: dressed quark-gluon vertex, dressed gluon propagator)
- *Works good* for 3 external particles *(PS mesons, vector particles, N, Δ)* but *bad* for ≥ 4 e.p. *($\pi\pi$ scattering. . .)*
- "rigid structure" – few model parameters
- has shown to work well in the CP conserving sector
- still a lot to do: *error bars, PQ, ...*

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!