

# SM AND BSM TIME-REVERSAL VIOLATION IN LIGHT NUCLEI

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with

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# Outline

- Time-Reversal Violation: SM and BSM
- Nucleon Electric Dipole Form Factor
- Light-Nuclear T-Violating Form Factors
- Outlook & Conclusion

For a review,

J. Engel, M.J. Ramsey-Musolf, U. van Kolck, Prog. Part. Nucl. Phys. 71 (2013) 21

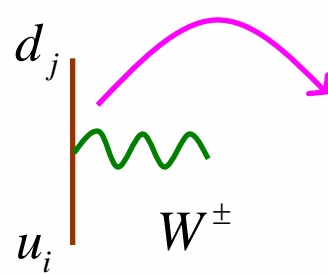
# Time Reversal (T)

$$\begin{cases} t \rightarrow -t \\ \vec{r} \rightarrow \vec{r} \end{cases}$$

$$i \rightarrow -i$$

$\mathcal{T}$  : little in weak interactions

Wolfenstein '83

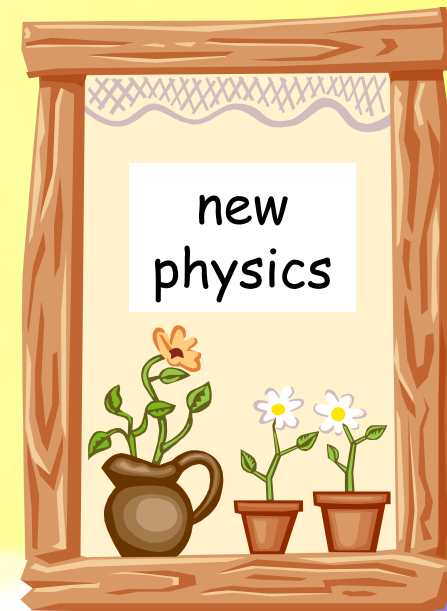
■   $U_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & \lambda^3 A (\rho - i\eta (1 - \lambda^2/2)) \\ -\lambda & 1 - \lambda^2/2 - i\eta A^2 \lambda^4 & \lambda^2 A (1 + i\eta \lambda^2) \\ \lambda^3 A (1 - \rho - i\eta) & -\lambda^2 A & 1 \end{pmatrix} + \dots$

$$\lambda \cong 0.22 \quad A, \rho, \eta = \mathcal{O}(1)$$

$$J_{CP} = A^2 \lambda^6 \eta + \mathcal{O}(\lambda^8) \simeq 3 \cdot 10^{-5}$$

Jarlskog '85

- insufficient for electroweak baryogenesis !?



# Electric Dipole Moment (EDM)

$$H_{edm} = -\underbrace{d}_{\vec{d}} \cdot \vec{S} \cdot \vec{E} \quad \begin{cases} \xrightarrow{T} -d(-\vec{S}) \cdot \vec{E} = -H_{edm} \\ \xrightarrow{P} -d\vec{S} \cdot (-\vec{E}) = -H_{edm} \end{cases}$$

Radius of corresponding FF: Schiff moment (SM)  $S'$

Weak interactions:  $d_n \sim e \frac{G_F^2}{(4\pi)^4} \left( \frac{m_t}{M_W} \right)^2 J_{CP} (4\pi f_\pi)^3 \approx 10^{-19} e \text{ fm}$

*e.g. Donoghue, Golowich + Holstein '92*

Experiment:

$$d_n = (0.2 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})) \cdot 10^{-13} e \text{ fm}$$

$$\sim \triangleright 10^{-15} e \text{ fm (UCN, proposed)}$$

*Baker et al '06 (ILL)*

*Bodek et al (PSI)*  
*Budker et al (SNS)*

...

$$|d_{Hg}| < 3.1 \cdot 10^{-16} e \text{ fm (95% c.l.)}$$

*Griffith et al '09 (UW)*

Nuclear Schiff moment from RPA, ...

*Dmitriev + Sen'kov '03*

$$|d_p| < 7.9 \cdot 10^{-12} e \text{ fm}$$

# The new kid on the block: charged particle in storage ring

$$\frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega}$$

charge

anomalous MDM

$$\vec{\Omega} = \frac{q}{m} \left[ a\vec{B} + \left( \frac{1}{v^2} - a \right) \vec{v} \times \vec{E} \right] + 2d \left( \vec{E} + \vec{v} \times \vec{B} \right)$$

Bargmann, Michel  
+ Telegdi '59

$$(\vec{v} \cdot \vec{B} = 0 = \vec{v} \cdot \vec{E})$$

precession sensitive to EDM

*e.g.*  $d_{\mu} \lesssim 10^{-6} e \text{ fm}$       Bennett *et al* (BNL g-2) '09

Orlov *et al* (Fermilab? COSY?)

choose radius and combination of E&M fields:

$|d_d| \sim 10^{-16} e \text{ fm}$  (storage ring, proposed)

*e.g.*  $R \sim 10 \text{ m}$

$B \sim 0.5 \text{ T}$

Proton and helion as well? How about triton?

$E \sim 17 \text{ MV/m}$

Magnetic quadrupole moment (MQM)  $\mathcal{M}_d$ ?

Fact:

T violated in SM by a dim-4 operator,  
so it should be violated also by other operators

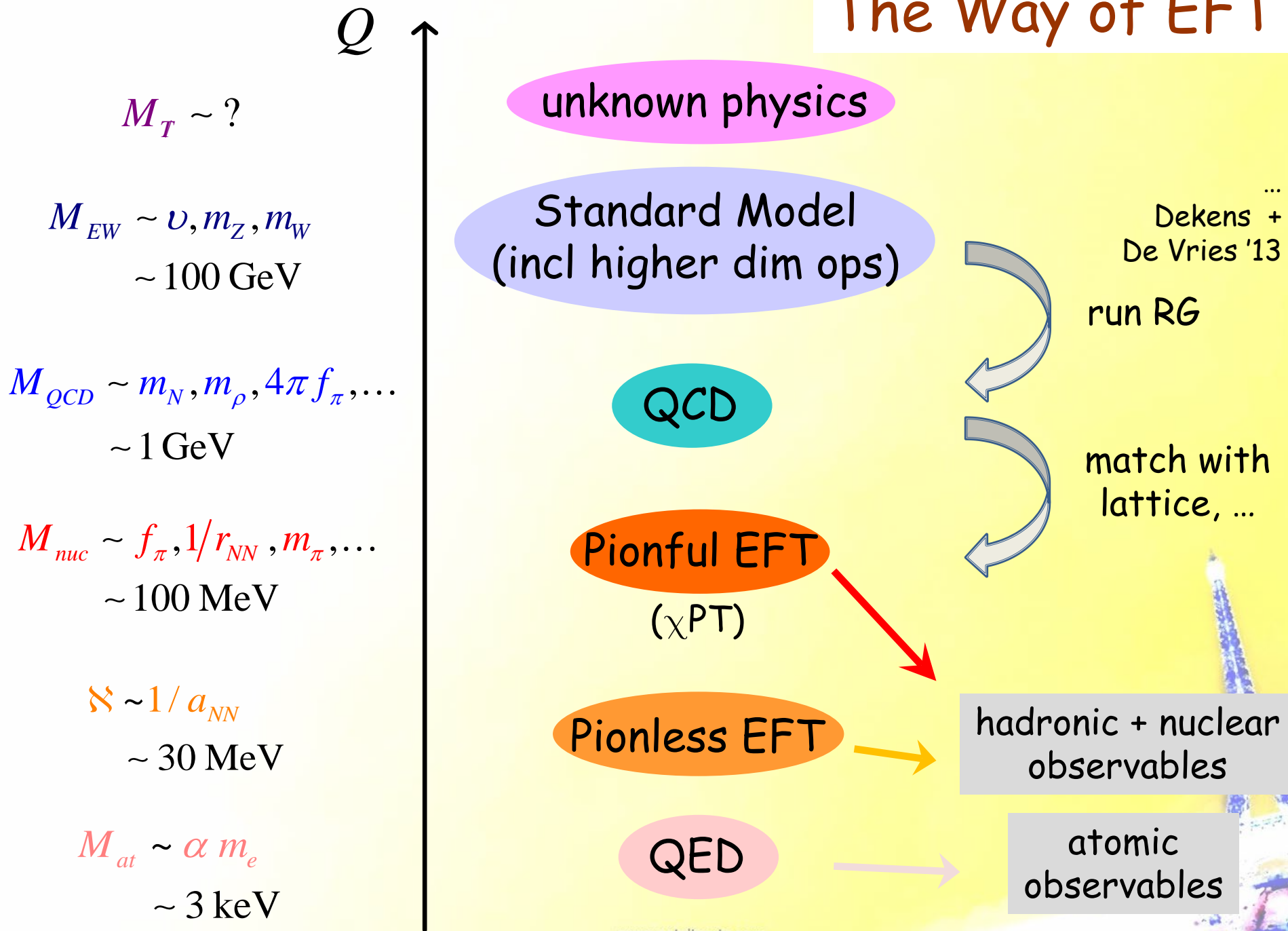
Issue:

once a hadronic/nuclear EDM is observed,  
how many/which observables do we need to  
identify the source(s) of T violation?

Strategy:

use Effective Field Theory  
to study various hadronic T-violating effects

# The Way of EFT



# TV Sources

Jarlskog '85

CKM matrix (dim=4)

$$J_{CP} \approx 3 \cdot 10^{-5}$$

small... 't Hooft '76

$\theta$  term (dim=4)

$$\bar{\theta} \lesssim 10^{-10}$$

$$\mathcal{L}_{SM} = \bar{q}_L \gamma^\mu \left[ \dots - g_2 \tau_\pm W_{\pm\mu} U_q \right] q_L$$

$$+ \bar{q}_L \left[ f_u \varphi_u u_R + f_d \varphi_d d_R \right] + \text{H.c.} + \frac{g_s^2 \bar{\theta}}{16\pi^2} \text{Tr} G^{\mu\nu} \tilde{G}_{\mu\nu} + \dots$$

e.g. single Higgs  $\varphi_u^i = \varepsilon^{ij} \varphi_{dj}^*$

$$\tilde{G}_{\mu\nu} \equiv \varepsilon_{\mu\nu\rho\sigma} G^{\rho\sigma}$$

$$- \frac{1}{M_{\mathcal{F}}^2} \bar{q}_L \sigma^{\mu\nu} \left[ \tilde{G}_{\mu\nu} (\hat{g}_u \varphi_u u_R + \hat{g}_d \varphi_d d_R) \right] + \text{H.c.}$$

→ quark color-EDM (eff dim=6)

$$+ \left( \tilde{g}_{Bu} \tilde{B}_{\mu\nu} + \tilde{g}_{Wu} \tilde{W}_{\mu\nu} \tau_3 \right) \varphi_u u_R + \left( \tilde{g}_{Bd} \tilde{B}_{\mu\nu} + \tilde{g}_{Wd} \tilde{W}_{\mu\nu} \tau_3 \right) \varphi_d d_R \Big] + \text{H.c.}$$

$$+ \frac{w}{M_{\mathcal{F}}^2} f^{abc} G_{\mu\nu}^a \tilde{G}^{b\nu\rho} G_{\rho}^{c\mu}$$

→ quark EDM (eff dim=6)

→ gluon color-EDM (dim=6)

$$+ \frac{(4\pi)^2}{M_{\mathcal{F}}^2} i \varepsilon_{ij} \left( \sigma_1 \bar{q}_L^i u_R \bar{q}_L^j d_R + \sigma_8 \bar{q}_L^i \lambda^a u_R \bar{q}_L^j \lambda^a d_R \right) + \text{H.c.}$$

→ four-quark contact (dim=6)

$$+ \frac{(4\pi)^2 \xi}{M_{\mathcal{F}}^2} \bar{u}_R \gamma^\mu d_R \varphi_u^\dagger i D_\mu \varphi_d + \text{H.c.}$$

→ LR four-quark contact (dim=6)

Buchmüller + Wyler '86

Weinberg '89

de Rujula *et al.* '91

Ng + Tulin '11

dimension ↓



$$\mathcal{L}_{QCD} = \bar{q} (i\partial + g_s \mathbf{G}) q - \frac{1}{2} \text{Tr} G^{\mu\nu} G_{\mu\nu}$$

$$- \bar{m} \bar{q} q + \varepsilon \bar{m} \bar{q} \tau_3 q + \frac{\bar{m}}{2} (1 - \varepsilon^2) \bar{\theta} \bar{q} i \gamma_5 q$$

$\theta$

$$- \frac{1}{2} \bar{q} (c_q^{(0)} + c_q^{(1)} \tau_3) \sigma_{\mu\nu} \tilde{G}^{\mu\nu} q$$

qCEDM

$$- \frac{1}{2} \bar{q} (d_q^{(0)} + d_q^{(1)} \tau_3) \sigma_{\mu\nu} q \tilde{F}^{\mu\nu}$$

qEDM

$$+ \frac{c_G}{6} f^{abc} G_{\mu\nu}^a \tilde{G}^{b\nu\rho} G_{\rho}^{c\mu}$$

gCEDM

$$+ \frac{C_1}{4} (\bar{q} q \bar{q} i \gamma_5 q - \bar{q} \boldsymbol{\tau} q \cdot \bar{q} i \gamma_5 \boldsymbol{\tau} q)$$

4QC

$$+ \frac{C_8}{4} (\bar{q} \lambda^a q \bar{q} i \gamma_5 \lambda^a q - \bar{q} \boldsymbol{\tau} \lambda^a q \cdot \bar{q} i \gamma_5 \boldsymbol{\tau} \lambda^a q)$$

$$+ \frac{D_1}{4} \varepsilon_{3ij} \bar{q} \tau_i \gamma^\mu q \bar{q} \tau_j \gamma_\mu \gamma_5 q$$

LRC

$$+ \frac{D_8}{4} \varepsilon_{3ij} \bar{q} \tau_i \gamma^\mu \lambda^a q \bar{q} \tau_j \gamma_\mu \gamma_5 \lambda^a q$$

+ ...

N.B. To this order,  $\mathcal{Y} \rightarrow \mathcal{P}$

two flavors  $q = \begin{pmatrix} u \\ d \end{pmatrix}$

$SU_L(2) \times SU_R(2) \sim SO(4)$

chiral symmetry

$$c_q^{(i)} = \mathcal{O} \left( \frac{\tilde{g}}{f} \frac{\bar{m}}{M_{\mathcal{Y}}^2} \right)$$

$$d_q^{(i)} = \mathcal{O} \left( \frac{e \tilde{g}}{f} \frac{\bar{m}}{M_{\mathcal{Y}}^2} \right)$$

$$c_G = \mathcal{O} \left( \frac{w}{M_{\mathcal{Y}}^2} \right)$$

$$C_i = \mathcal{O} \left( \frac{(4\pi)^2 \sigma_i}{M_{\mathcal{Y}}^2} \right)$$

$$D_i = \mathcal{O} \left( \frac{(4\pi)^2 \xi}{M_{\mathcal{Y}}^2} \right)$$

# Each breaks chiral symmetry in a particular way, and produces different hadronic interactions.

Mereghetti,  
Hockings + v.K.  
'10  
De Vries *et al*,  
'13

chiral invariants (CI): cannot be separated at low energies,  $\{w, \sigma_1, \sigma_8\} \rightarrow w$

$$\begin{aligned} \mathcal{L}_{\chi PT} = & -\frac{m_\pi^2 \bar{g}_0}{2f_\pi (m_n - m_p)_{qm}} \boldsymbol{\pi}^2 \pi_3 \\ & - 2\bar{N} (\bar{d}_0 + \bar{d}_1 \tau_3) S_\mu N v_\nu F^{\mu\nu} \\ & - \frac{1}{2f_\pi} \bar{N} (\bar{g}_0 \boldsymbol{\tau} \cdot \boldsymbol{\pi} + \bar{g}_1 \pi_3) N \\ & + \bar{C}_1 \bar{N} N \partial_\mu (\bar{N} S^\mu N) + \bar{C}_2 \bar{N} \boldsymbol{\tau} N \cdot \partial_\mu (\bar{N} S^\mu \boldsymbol{\tau} N) \\ & + \dots \end{aligned}$$

terms related by  
chiral symmetry  
+ higher orders

six LO couplings  
for EDMs

Where are the differences?

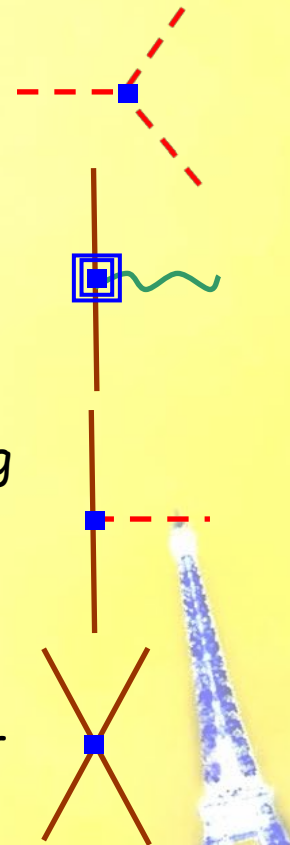
three-pion  
coupling

short-range EDM  
contribution

PV, TV  
pion-nucleon coupling

PV, TV  
two-nucleon contact

cf. Barton '61  
and nuclear followers



There are differences! For example,

$$\mathcal{L}_{\mathcal{Y}, \pi N} = -\frac{1}{2f_\pi D} \bar{N} [\bar{g}_0 \boldsymbol{\tau} \cdot \boldsymbol{\pi} + \bar{g}_1 \pi_3] N + \dots$$

$$\bar{g}_0 = \mathcal{O} \left( \bar{\theta} \frac{m_\pi^2}{M_{QCD}}, \frac{\hat{g}}{f} \frac{m_\pi^2 M_{QCD}}{M_{\mathcal{Y}}^2}, \frac{\check{g}}{f} \frac{\alpha m_\pi^2 M_{QCD}}{\pi M_{\mathcal{Y}}^2}, w \frac{m_\pi^2 M_{QCD}}{M_{\mathcal{Y}}^2}, \varepsilon \xi \frac{M_{QCD}^3}{M_{\mathcal{Y}}^2} \right)$$

$$\bar{g}_1 = \mathcal{O} \left( \bar{\theta} \frac{m_\pi^4}{M_{QCD}^3}, \frac{\hat{g}}{f} \frac{m_\pi^2 M_{QCD}}{M_{\mathcal{Y}}^2}, \frac{\check{g}}{f} \frac{\alpha m_\pi^2 M_{QCD}}{\pi M_{\mathcal{Y}}^2}, \varepsilon w \frac{m_\pi^2 M_{QCD}}{M_{\mathcal{Y}}^2}, \xi \frac{M_{QCD}^3}{M_{\mathcal{Y}}^2} \right)$$

different orders;  
two-derivative interactions  
important at higher order

pion physics  
suppressed

comparable to  
two-derivative  
interactions

- N.B.
- 1)  $\bar{g}_2 \bar{N} \pi_3 \tau_3 N$  at higher orders for *all* sources up to dim 6
  - 2) for  $\theta$ , link to CSB, e.g.

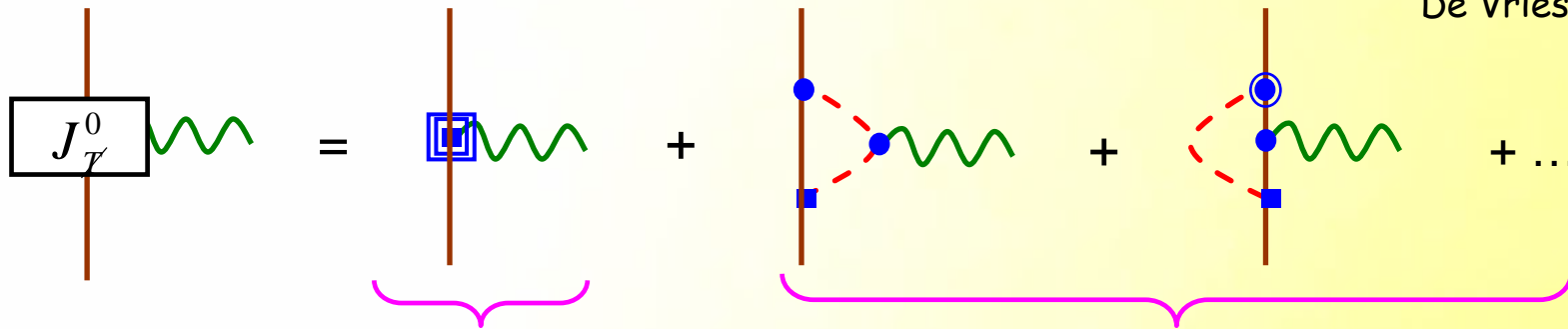
$$\bar{g}_0 \approx \frac{\bar{\theta}}{2\varepsilon} (m_n - m_p)_{qm}$$

$$\approx 3 \bar{\theta} \text{ MeV}$$

Mereghetti,  
Hockings + v.K. '10

using lattice QCD  
(Beane et al '06)

# Nucleon EDFF (to NLO)



LO for all sources

- ensures RG invariance
- brings in two parameters

order depends on source

- can provide estimates using reasonable renormalization scale

cf. lattice simulations, only for  $\theta$  term and situation unclear:

quenched,  $\frac{m_\pi}{m_\rho} = 0.63$ : signal 10x larger than NDA! Shintani *et al* (CP-PACS) '05

full,  $\frac{m_u, m_d}{m_s} \approx 1$ : no signal at same level

Berruto *et al* (RBC) '05

...

# A few details

$$\langle p', s' | J_N^\mu | p, s \rangle = \bar{u}_{s'}(p') \left[ \gamma^\mu F_1(-q^2) - i\sigma^{\mu\nu} q_\nu F_2(-q^2) \right.$$

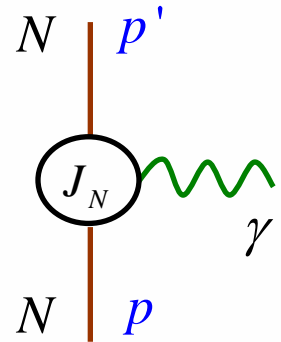
Bernard *et al*'92 '98

$$+ \left( \gamma^\mu \gamma_5 q^2 + 2m_N \gamma_5 q^\mu \right) F_{T1}(-q^2)$$

Maekawa + v.K. '00  
Maekawa, Veiga + v.K. '00

$$\left. + \frac{i}{2} \varepsilon^{\mu\nu\rho\sigma} \sigma_{\rho\sigma} q_\nu F_{E1}(-q^2) \right] u_s(p)$$

Hockings + v.K. '05  
De Vries *et al*'10 '12



$$q = p - p'$$

$$k = \frac{1}{2}(p + p') - m_N v$$

$$v^\mu = (1, \vec{0}) \quad \text{velocity}$$

$$S^\mu = (0, \frac{\vec{\sigma}}{2}) \quad \text{spin}$$

rest frame

$$\xrightarrow{|\vec{p}|, |\vec{p}'| \ll m_N} \chi_{s'}^\dagger(k - q/2) J_{E1}^\mu(q, k) \chi_s(k + q/2)$$

$$J_{E1}^\mu(q, k) = -2 \left( \eta^{\mu\rho} q^\sigma - \eta^{\mu\sigma} q^\rho \right) S^\nu$$

$$\times \left[ \left( v_\rho + \frac{k_\rho}{m_N} \right) \eta_{\nu\sigma} + v_\rho \frac{k_\nu k_\sigma}{2m_N^2} + \dots \right]$$

EDFF

$$\times \left( F_{E1}^{(0)}(-q^2) + F_{E1}^{(1)}(-q^2) \tau_3 \right)$$

(similar for  
3He and 3H)

$$F_{E1}^{(i)}(-q^2) = d^{(i)} + S^{(i)} q^2 + H^{(i)}(-q^2)$$

## Example: qCEDM

$$d^{(1)} = \bar{d}^{(1)} + \frac{eg_A \bar{g}_0}{(4\pi f_\pi)^2} \left[ \left( \bar{\Delta} + 2 \ln \frac{\mu}{m_\pi} \right) + \frac{5\pi}{4} \frac{m_\pi}{m_N} \left( 1 + \frac{\bar{g}_1}{5\bar{g}_0} \right) - \frac{\check{\delta} m_\pi^2}{m_\pi^2} + \mathcal{O} \left( \frac{m_\pi^2}{M_{QCD}^2} \right) \right]$$

$$\bar{\Delta} \equiv \frac{2}{4-d} - \gamma_E + \ln 4\pi$$

renormalization

$$\theta \quad |d_n| \gtrsim \frac{2eg_A \delta m_N}{(4\pi f_\pi)^2} \frac{1-\varepsilon^2}{2\varepsilon} \bar{\theta} \ln \frac{m_N}{m_\pi}$$

$$\approx 2.0 \cdot 10^{-3} \bar{\theta} \text{ e fm}$$

cf. Crewther et al '79

$$d^{(0)} = \bar{d}^{(0)} + \frac{eg_A \bar{g}_0}{(4\pi f_\pi)^2} \left[ 0 + \frac{3\pi}{4} \frac{m_\pi}{m_N} \left( 1 + \frac{\bar{g}_1}{3\bar{g}_0} \right) - \frac{\delta m_N}{m_\pi} + \mathcal{O} \left( \frac{m_\pi^2}{M_{QCD}^2} \right) \right]$$

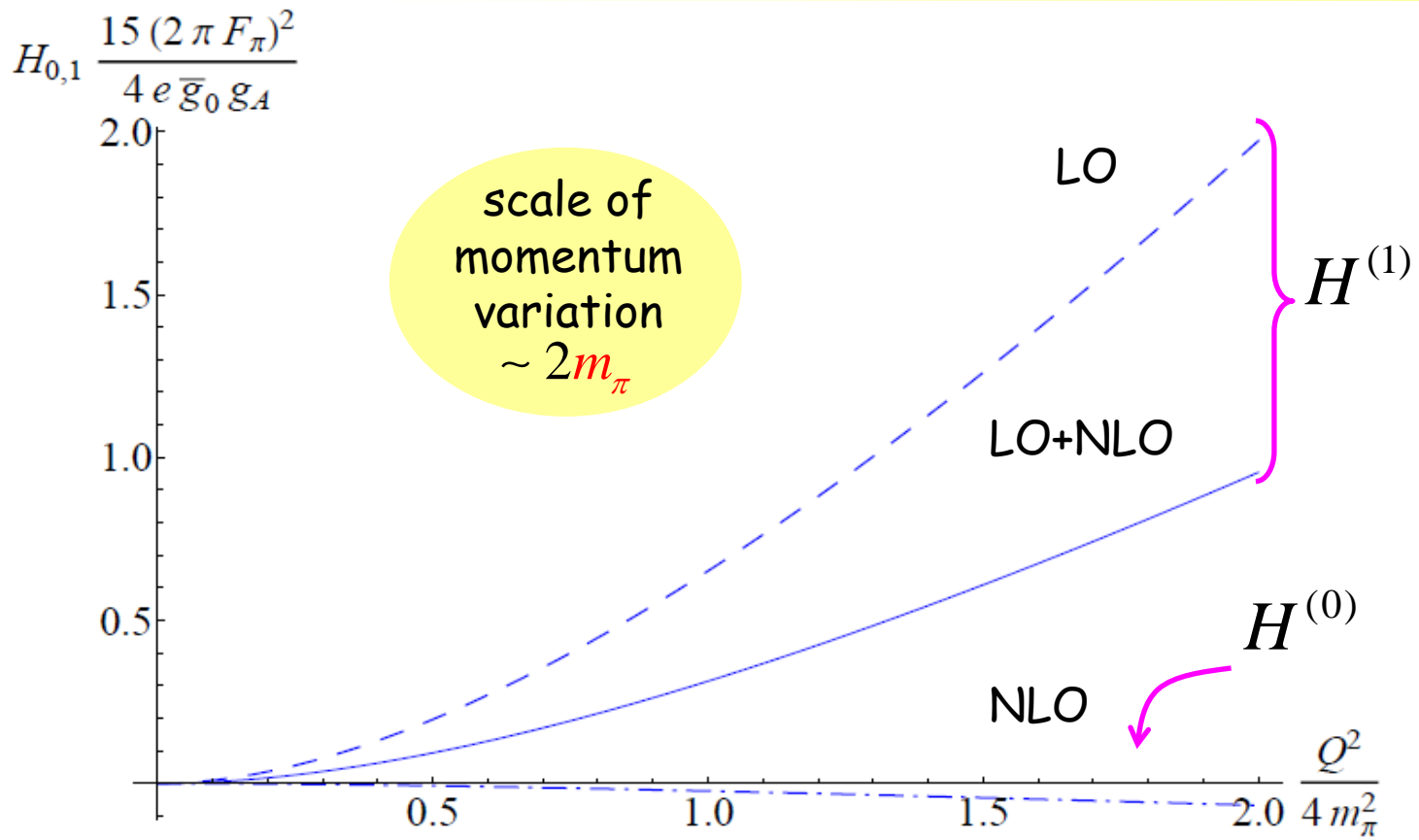
$$\theta \quad |d^{(0)}| \gtrsim \frac{eg_A \delta m_N}{(4\pi f_\pi)^2} \frac{1-\varepsilon^2}{2\varepsilon} \bar{\theta} \left[ \frac{3\pi}{4} \frac{m_\pi}{m_N} - \frac{\delta m_N}{m_\pi} \right]$$

$$\approx 1.4 \cdot 10^{-4} \bar{\theta} \text{ e fm}$$

Thomas '95

$$\begin{cases}
 S^{(1)} = \frac{e g_A \bar{g}_0}{6(4\pi f_\pi)^2 m_\pi^2} \left[ 1 - \frac{5\pi}{4} \frac{m_\pi}{m_N} - \frac{\tilde{\delta} m_\pi^2}{m_\pi^2} + \mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right) \right] \\
 S^{(0)} = -\frac{e g_A \bar{g}_0}{6(4\pi f_\pi)^2 m_\pi^2} \left[ 0 + \frac{\pi}{2} \frac{\delta m_N}{m_\pi} + \mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right) \right]
 \end{cases}$$

$$\begin{cases}
 \theta \approx 6.8 \cdot 10^{-5} \bar{\theta} \text{ e fm}^3 \\
 \theta \approx -5.0 \cdot 10^{-6} \bar{\theta} \text{ e fm}^3
 \end{cases}$$



# Nucleon EDM (to NLO)

	$\theta$ term	qCEDM	LRC	qEDM	CI
$m_n \frac{d_n}{e}$	$\mathcal{O}\left(\bar{\theta} \frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{\hat{g}}{f} \frac{m_\pi^2}{M_Y^2}\right)$	$\mathcal{O}\left(\xi \frac{M_{QCD}^2}{M_Y^2}\right)$	$\mathcal{O}\left(\frac{\check{g}}{f} \frac{m_\pi^2}{M_Y^2}\right)$	$\mathcal{O}\left(w \frac{M_{QCD}^2}{M_Y^2}\right)$
$\frac{d_p}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

➤  $|d_N| \gtrsim 2 \cdot 10^{-3} \bar{\theta} e \text{ fm}$  from long-range contributions

➤  $d_n = (0.2 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})) \cdot 10^{-13} e \text{ fm}$   $\Rightarrow$   $\left\{ \begin{array}{l} \bar{\theta} \lesssim 10^{-10} \\ \frac{\hat{g}}{f} M_Y^{-2}, \frac{\check{g}}{f} M_Y^{-2} \lesssim (10^5 \text{ GeV})^{-2} \\ w M_Y^{-2}, \xi M_Y^{-2} \lesssim (10^6 \text{ GeV})^{-2} \end{array} \right.$

Baker *et al* '06 (ILL)

➤  $d_n(\text{CKM}) \sim \frac{e}{M_{QCD}} (G_F f_\pi^2)^2 J_{CP} \approx 10^{-19} e \text{ fm}$   $\Rightarrow$  measurement much above this means new source

➤ n and p EDMs can be fitted with any one source

LHC-type scales!

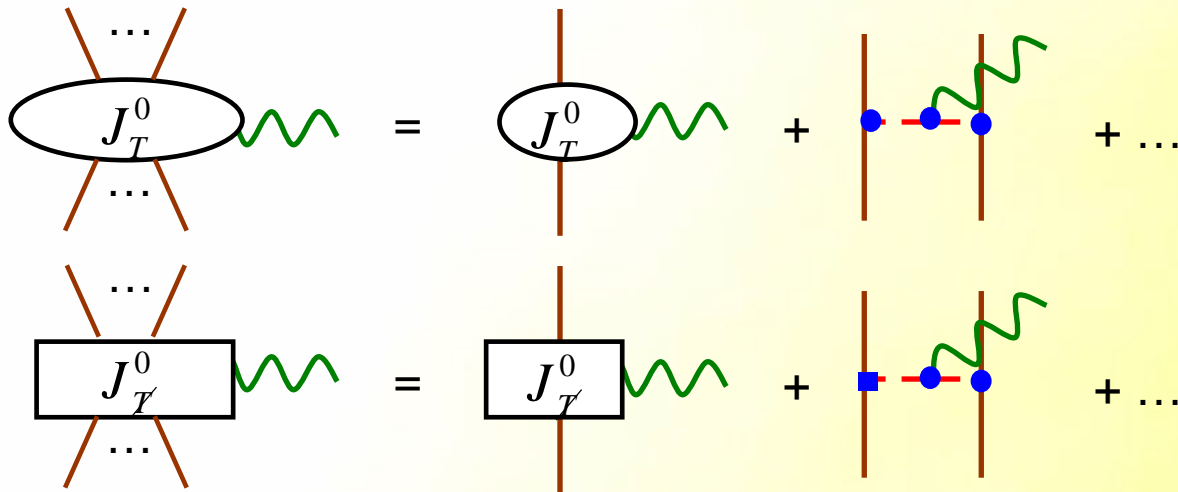
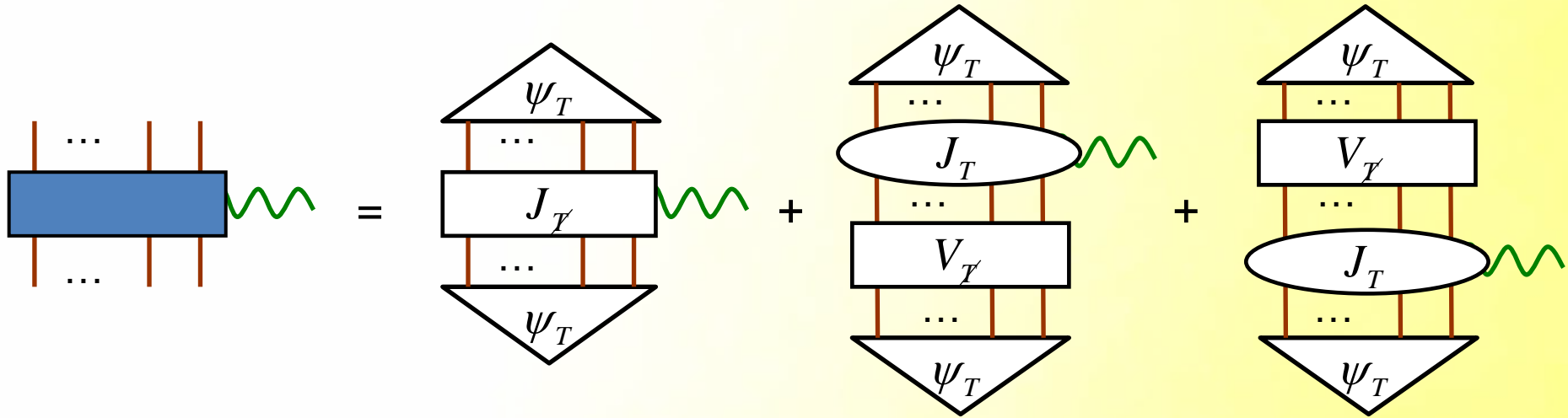


# Nucleon EDM (to NLO)

	$\theta$ term	qCEDM	LRC	qEDM	CI
$m_n \frac{d_n}{e}$	$\mathcal{O}\left(\bar{\theta} \frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{\hat{g}}{f} \frac{m_\pi^2}{M_Y^2}\right)$	$\mathcal{O}\left(\xi \frac{M_{QCD}^2}{M_Y^2}\right)$	$\mathcal{O}\left(\frac{\check{g}}{f} \frac{m_\pi^2}{M_Y^2}\right)$	$\mathcal{O}\left(w \frac{M_{QCD}^2}{M_Y^2}\right)$
$\frac{d_p}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$(2m_\pi)^2 \frac{S'_p}{d_p}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$
$(2m_\pi)^2 \frac{S_N^{(0)}}{d_n}$	$\mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$

SM partially sensitive  
to sources

# Nuclear EDFs & MQFFs

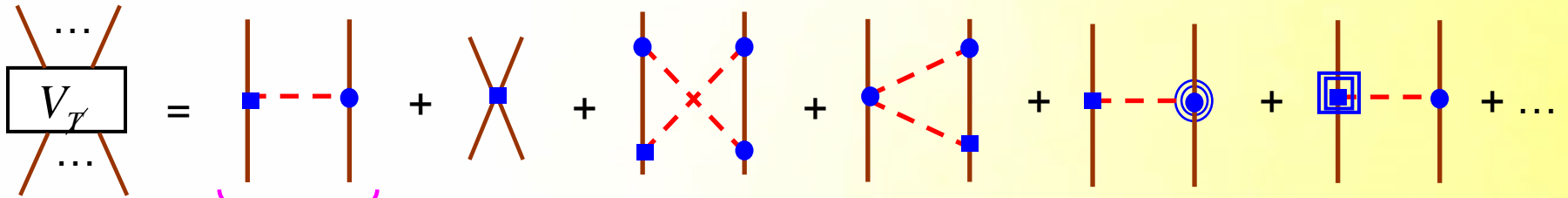


Park, Min + Rho '95  
...

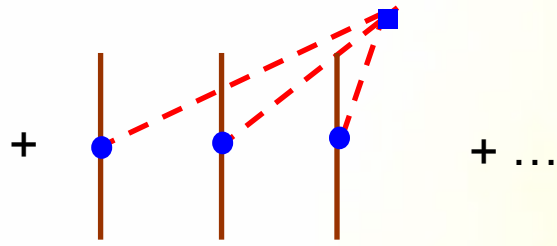
De Vries, Mereghetti,  
Higa, Liu, Stetcu,  
Timmermans + v.K. '11

Analogous for  $\vec{J}_T, \vec{J}_T$

De Vries, Mereghetti, Liu,  
Timmermans + v.K. '12



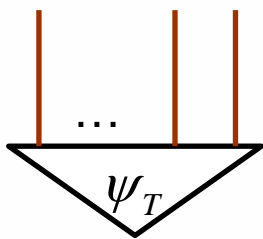
generic LO,  
but effect vanishes for  $\theta$  when  $N=Z$



LO for LRC only

Maekawa, Mereghetti, De Vries + v.K. '11  
De Vries, Mereghetti, Timmermans + v.K. '13

Weinberg '90, '91  
Ordóñez + v.K. '92



from solution of the Schrödinger equation

for now, phenom pots (AV18, Reid93, Idaho: agree +/- 10%)  
eventually, consistent EFT approach

introduces dependence on binding energy  $B_A$

# A few details

(perturbative pions)

$$\langle p', j | J_d^\mu | p, i \rangle = e \delta_{ij} \left[ v^\mu + \frac{k^\mu}{m_d} + \dots \right] F_{E0}(-q^2)$$

$$+ ie S_{\sigma ij} \left[ \varepsilon^{\mu\sigma\nu\rho} q_\nu v_\rho + \dots \right] F_{M1}(-q^2)$$

$$+ e \left( q_i q_i - \frac{q^2}{3} \delta_{ij} \right) \left[ v^\mu + \dots \right] F_{E2}(-q^2)$$

$$+ S_{\sigma ij} \left[ \eta^{\mu\sigma} q^2 - q^\mu q^\sigma + \dots \right] F_{T1}(-q^2)$$

$$- 2i S_{\sigma ij} \left[ v^\mu q^\sigma - \eta^{\mu\sigma} v \cdot q + \dots \right] F_{E1}(-q^2)$$

$$+ \frac{1}{4} \varepsilon^{\mu\nu\lambda\rho} \left( q_i \delta_{\lambda j} + q_j \delta_{\lambda i} \right) q_\nu \left[ v_\rho + \dots \right] F_{M2}(-q^2)$$

$$+ i \left[ q_i q_j q^\mu + \frac{q^2}{2} \left( \eta_i^\mu q_j + \eta_j^\mu q_i \right) + \dots \right] F_{T2}(-q^2)$$

$$F_{M2}(-q^2) = \mathcal{M} \left[ 1 + K(-q^2) \right]$$

Kaplan,  
Savage +  
Wise '98

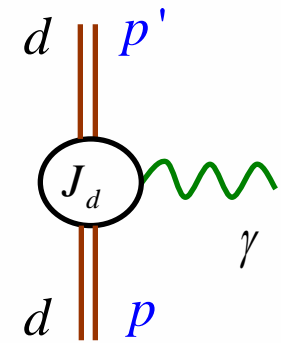
Savage +  
Springer '01

De Vries,  
Mereghetti,  
Timmermans  
+ v.K. '11

MQFF

Mereghetti,  
De Vries,  
Timmermans  
+ v.K. '13

EDFF



$$q = p - p'$$

$$k = \frac{1}{2} [p + p' - m_d v]$$

$$v^\mu = (1, \vec{0}) \text{ velocity}$$

$$S_{ij}^\mu = (0, i\varepsilon_{ijk}) \text{ spin}$$

rest frame

# Example: qCEDM

deuteron EDFF; pert pions

De Vries *et al* '10  
cf. Khriplovich + Korkin '00

$$F_{E1,d}(-q^2) = -\frac{eg_A\bar{g}_1}{6m_\pi} \frac{m_N}{4\pi f_\pi^2} \frac{1 + \gamma/m_\pi}{(1 + 2\gamma/m_\pi)^2} F_2\left(-q^2/(4\gamma)^2\right) \left[1 + \mathcal{O}\left(\frac{m_\pi}{M_{NN}}\right)\right]$$

$\frac{m_N}{4\pi f_\pi^2} \equiv 1/M_{NN}$        $(1 + 2\gamma/m_\pi)^2 \equiv \sqrt{m_N B_d}$

$F_2(x) = 1 + \mathcal{O}(x)$

scale of momentum variation  
 $\sim 4\gamma$

$\Rightarrow d_d \simeq -0.12 \frac{\bar{g}_1}{f_\pi} e \text{ fm}$

deuteron, helion, triton EDMs; non-pert pions

De Vries *et al* '11  
cf. Liu + Timmermans '04  
Gudkov, Lazauskas + Song '12

$$\left\{ \begin{aligned} d_d &\simeq -0.10 \frac{\bar{g}_1}{f_\pi} e \text{ fm} \\ d_h &\simeq 0.83 \bar{d}_0 - 0.93 \bar{d}_1 - \left( 0.08 \frac{\bar{g}_0}{f_\pi} + 0.14 \frac{\bar{g}_1}{f_\pi} \right) e \text{ fm} \\ d_t &\simeq 0.85 \bar{d}_0 - 0.95 \bar{d}_1 + \left( 0.08 \frac{\bar{g}_0}{f_\pi} - 0.14 \frac{\bar{g}_1}{f_\pi} \right) e \text{ fm} \end{aligned} \right.$$

De Vries *et al* '10  
cf. Khriplovich + Korkin '00

deuteron MQFF; pert pions

$$F_{M2,d}(-q^2) = \left[ 1 + \kappa_1 + 3(1 + \kappa_0) \frac{\bar{g}_0}{\bar{g}_1} \right] \frac{F_{E1,d}(-q^2)}{m_N} \left[ 1 + \mathcal{O}\left(\frac{m_\pi}{M_{NN}}\right) \right]$$

$$\Rightarrow \frac{m_d \mathcal{M}_d}{d_d} \simeq 2 \left[ 1 + \kappa_1 + 3(1 + \kappa_0) \frac{\bar{g}_0}{\bar{g}_1} \right]$$

De Vries *et al* '12  
cf. Liu + Timmermans '04

deuteron MQM; non-pert pions

$$\frac{m_d \mathcal{M}_d}{d_d} \simeq 1.6 \left[ 1 + \kappa_1 + 1.4(1 + \kappa_0) \frac{\bar{g}_0}{\bar{g}_1} + 0.4 \right]$$

# Deuteron EDM (LO)

$$m_d \frac{d_d}{e} \quad \theta \text{ term} \quad \text{qCEDM} \quad \text{LRC} \quad \text{qEDM} \quad \text{CI}$$

$$\mathcal{O}\left(\bar{\theta} \frac{m_\pi^2}{M_{QCD}^2}\right) \quad \mathcal{O}\left(\frac{\hat{g}}{f} \frac{M_{QCD}^2}{M_Y^2}\right) \quad \mathcal{O}\left(\xi \frac{M_{QCD}^2}{M_Y^2}\right) \quad \mathcal{O}\left(\frac{\check{g}}{f} \frac{m_\pi^2}{M_Y^2}\right) \quad \mathcal{O}\left(w \frac{M_{QCD}^2}{M_Y^2}\right)$$

➤  $|d_d| \gtrsim 3 \cdot 10^{-4} \bar{\theta} e \text{ fm}$  from long-range contributions to  $d_N^{(0)}$

➤  $|d_d| < 10^{-16} e \text{ fm}$   $\Rightarrow$   $\left\{ \begin{array}{l} \bar{\theta} \lesssim 3 \cdot 10^{-13} \\ \frac{\check{g}}{f} M_Y^{-2} \lesssim (5 \cdot 10^6 \text{ GeV})^{-2} \\ \frac{\hat{g}}{f} M_Y^{-2}, w M_Y^{-2}, \xi M_Y^{-2} \lesssim (3 \cdot 10^7 \text{ GeV})^{-2} \end{array} \right.$

Fermilab? COSY?

Improved reach for BSM physics!

➤ d EDM can be fitted with any one source

# Deuteron EDM (LO)

	$\theta$ term	qCEDM	LRC	qEDM	CI
$m_d \frac{d_d}{e}$	$\mathcal{O}\left(\bar{\theta} \frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{\hat{g}}{f} \frac{M_{QCD}^2}{M_Y^2}\right)$	$\mathcal{O}\left(\xi \frac{M_{QCD}^2}{M_Y^2}\right)$	$\mathcal{O}\left(\frac{\check{g}}{f} \frac{m_\pi^2}{M_Y^2}\right)$	$\mathcal{O}\left(w \frac{M_{QCD}^2}{M_Y^2}\right)$
$\frac{d_d}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

- $d_d \simeq d_n + d_p$  for  $\theta$  term, qEDM, and CI
- n and d EDMs could isolate qCEDM and LRC



# Deuteron EDM (LO)

	$\theta$ term	qCEDM	LRC	qEDM	CI
$m_d \frac{d_d}{e}$	$\mathcal{O}\left(\bar{\theta} \frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{\hat{g}}{f} \frac{M_{QCD}^2}{M_Y^2}\right)$	$\mathcal{O}\left(\xi \frac{M_{QCD}^2}{M_Y^2}\right)$	$\mathcal{O}\left(\frac{\check{g}}{f} \frac{m_\pi^2}{M_Y^2}\right)$	$\mathcal{O}\left(w \frac{M_{QCD}^2}{M_Y^2}\right)$
$\frac{d_d}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$16m_N B_d \frac{S'_d}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$m_d \frac{\mathcal{M}_d}{d_d}$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{\sqrt{m_N B_d}}{m_\pi}\right)$	$\mathcal{O}(1)$

$\mathcal{M}_d \cong 2 \cdot 10^{-3} \bar{\theta} e \text{ fm}^2$   
 (no short-range assumptions)

can be isolated

could be isolated if MQM measured

# Triton and Helion EDMs (LO)

	$\theta$ term	qCEDM	LRC	qEDM	CI
$m_h \frac{d_h}{e}$	$\mathcal{O}(\bar{\theta})$	$\mathcal{O}\left(\frac{\hat{g}}{f} \frac{M_{QCD}^2}{M_{\mathcal{Y}}^2}\right)$	$\mathcal{O}\left(\xi \frac{M_{QCD}^2}{M_{\mathcal{Y}}^2}\right)$	$\mathcal{O}\left(\frac{\check{g}}{f} \frac{m_\pi^2}{M_{\mathcal{Y}}^2}\right)$	$\mathcal{O}\left(w \frac{M_{QCD}^2}{M_{\mathcal{Y}}^2}\right)$
$\frac{d_t}{d_h}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

- t and h EDMs can be fitted with any one source

# Triton and Helion EDMs (LO)

	$\theta$ term	qCEDM	LRC	qEDM	CI
$m_h \frac{d_h}{e}$	$\mathcal{O}(\bar{\theta})$	$\mathcal{O}\left(\frac{\hat{g}}{f} \frac{M_{QCD}^2}{M_Y^2}\right)$	$\mathcal{O}\left(\xi \frac{M_{QCD}^2}{M_Y^2}\right)$	$\mathcal{O}\left(\frac{\check{g}}{f} \frac{m_\pi^2}{M_Y^2}\right)$	$\mathcal{O}\left(w \frac{M_{QCD}^2}{M_Y^2}\right)$
$\frac{d_t}{d_h}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\frac{d_h}{d_n}$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

$\left\{ \begin{array}{l} d_h + d_t \simeq 0.84(d_n + d_p) \\ d_h - d_t \simeq 0.94(d_n - d_p) \\ d_h + d_t \simeq 3d_d \\ \alpha_1 d_h + \alpha_2 d_t \simeq \beta_1 d_n + \beta_2 d_p + d_d \end{array} \right.$

for qEDM and  $\theta$  term  
 for qEDM  
 for qCEDM  
 for LRC

- n, p, d and h EDMs could isolate  $\theta$  term, qCEDM and LRC, and adding t EDM might isolate qEDM and LRC

# What's needed?

- Triton and helion for LRC ( $\alpha_{1,2}, \beta_{1,2} = ?$ )
- Deuteron, triton and helion at NLO to test convergence
- EDMs of larger nuclei in terms of same six LECs?  
cf. Haxton + Henley '83
- Calculation of LECs for each source in lattice QCD
- Generalization to SU(3)
- Measurements...

# Conclusion

- ◆ QCD-based framework exists for calculation of nuclear T-violating observables
- ◆ Chiral symmetry properties determine form of effective T-violating interactions.
- ◆ Pattern of nucleon, deuteron, helion and triton T-violating FFs partially reflects T-violating source