Hadronic Matrix Elements & EDMs

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Lattice Meets Experiment Workshop
BNL, December 2013

Outline

1. *Introduction: Motivation & Experimental Situation*
2. *Interpreting EDMs*
3. *EDMs in Strongly Interacting Systems*
4. *Hadronic Matrix Elements: The Challenge*
5. *Implications & Outlook*

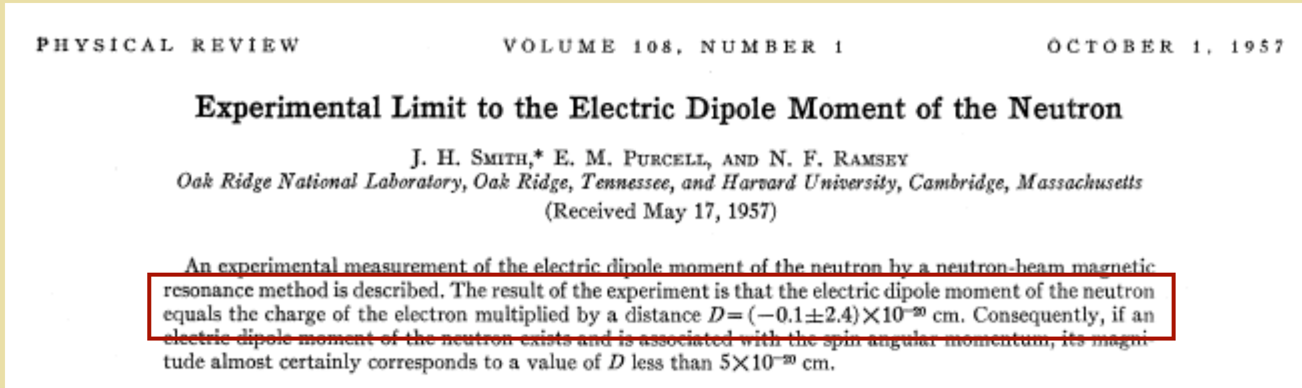
Engel, R-M, van Kolck: 1303.2371, PPNP 71 (2013) 21

I. Introduction

Why are EDMs Interesting ?

- *Does QCD violate CP ?*
- *What is the BSM CPV needed for baryogenesis?*
- *What is the BSM mass scale ?*

EDM Experiments



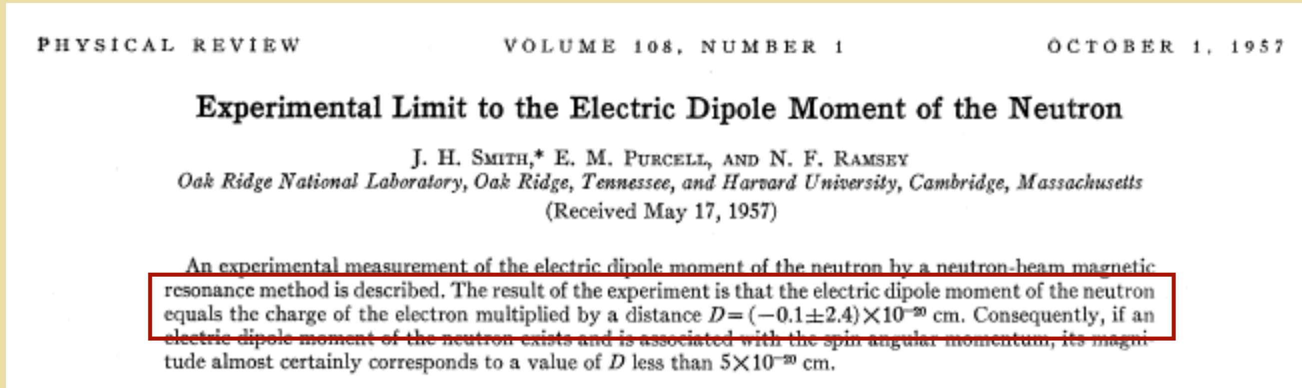
PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

Experimental Limit to the Electric Dipole Moment of the Neutron

J. H. Smith,* E. M. Purcell, and N. F. Ramsey
Oak Ridge National Laboratory, Oak Ridge, Tennessee, and Harvard University, Cambridge, Massachusetts
(Received May 17, 1957)

An experimental measurement of the electric dipole moment of the neutron by a neutron-beam magnetic resonance method is described. The result of the experiment is that the electric dipole moment of the neutron equals the charge of the electron multiplied by a distance $D=(-0.1\pm2.4)\times10^{-20}$ cm. Consequently, if an electric dipole moment of the neutron exists and is associated with the spin angular momentum, its magnitude almost certainly corresponds to a value of D less than 5×10^{-20} cm.

EDM Experiments



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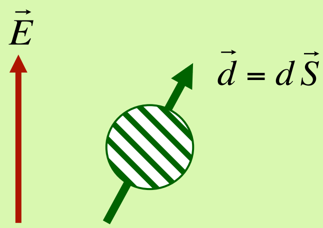
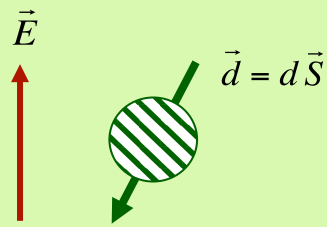
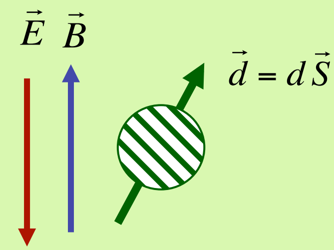


$$\nu_{EDM} = -\frac{d\vec{S}\cdot\vec{E}}{h}$$



$$\nu_{EDM} = -\frac{d(-\vec{S})\cdot\vec{E}}{h}$$

T-odd $\rightarrow$ CP-odd by CPT theorem



$$\nu_{EDM} = -\frac{d\vec{S}\cdot(-\vec{E})}{h}$$

P-odd: used to find signal

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	3.1×10^{-29}	10^{-33}	10^{-29}
d_e (ThO)	8.7×10^{-29} **	10^{-38}	10^{-29}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** 90% CL, no eq CPV (thanks: T. Chupp)

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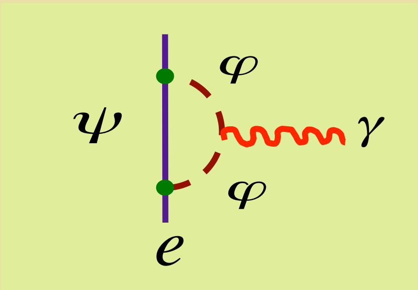
Mass Scale Sensitivity



$\sin\phi_{CP} \sim 1 \rightarrow \; M > 5000$ GeV

$M < 500$ GeV $\rightarrow \sin\phi_{CP} < 10^{-2}$

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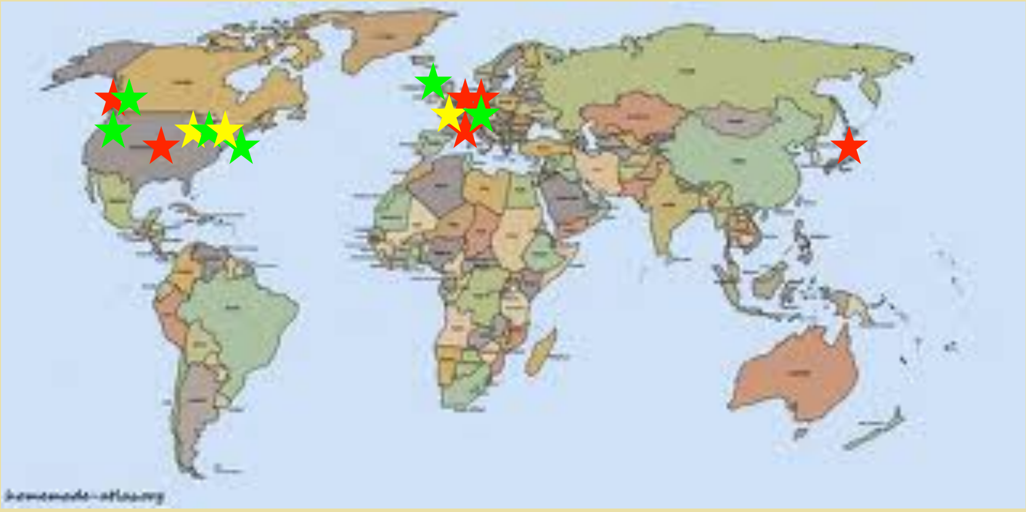


★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

II. Interpreting EDMs

Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

EDM Interpretation & Multiple Scales

Baryon Asymmetry

Early universe CPV

BSM CPV

SUSY, GUTs, Extra Dim…

Collider Searches

Particle spectrum; also scalars for baryon asym

?

Energy Scale

QCD Matrix Elements

d_n , $\bar{g}_{\pi NN}$, …

Nuclear & atomic MEs

Schiff moment, other P- & T-odd moments, e-nucleus CPV

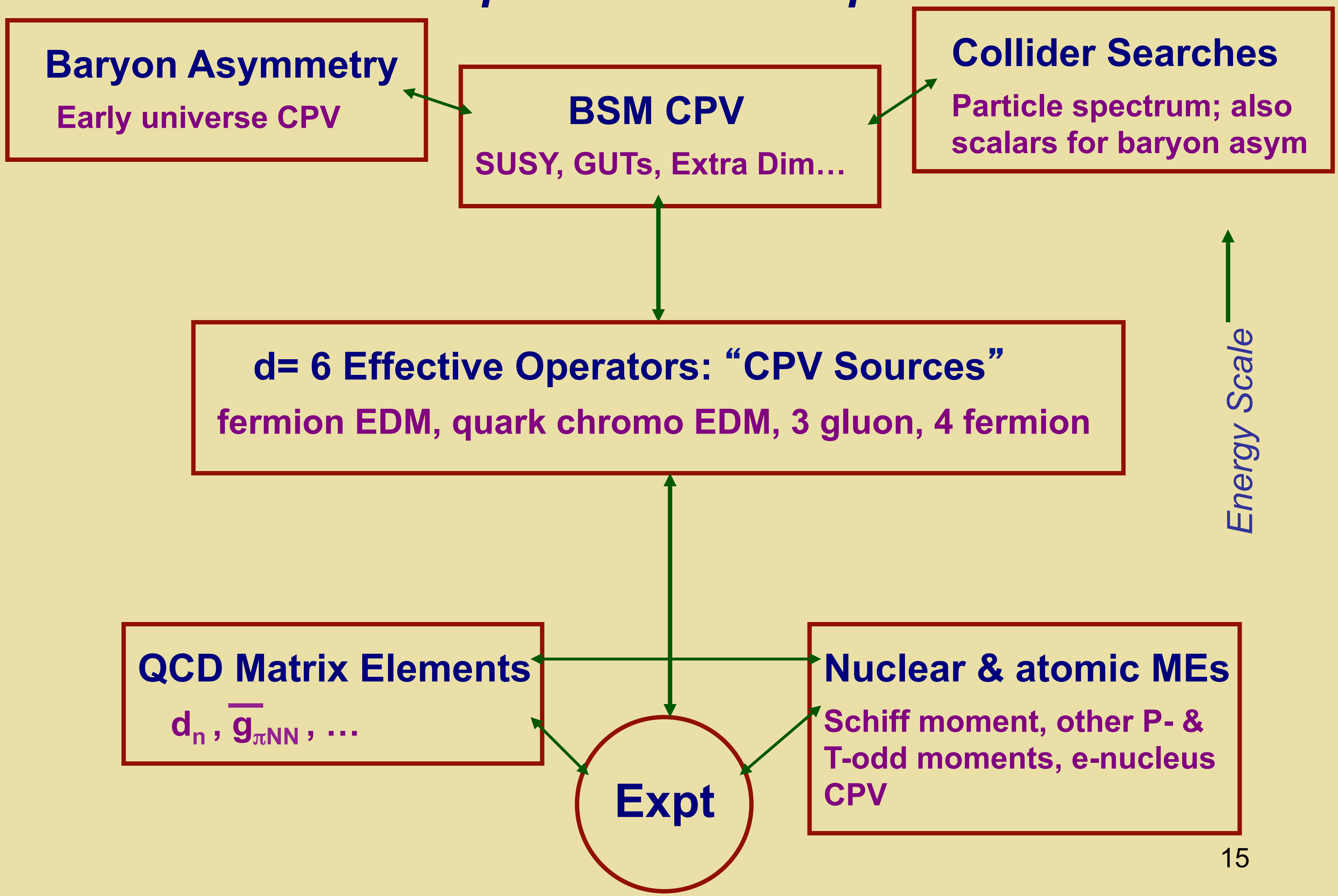
Expt

Effective Operators

$$\boxed{\mathcal{L}_{\mathrm{CPV}} = \mathcal{L}_{\mathrm{CKM}} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\mathrm{BSM}}^{\mathrm{eff}}}$$

$$\boxed{\mathcal{L}_{\mathrm{BSM}}^{\mathrm{eff}} = \frac{1}{\Lambda^2} \sum_i \alpha_i^{(n)} O_i^{(6)}} \quad + \ldots$$

EDM Interpretation & Multiple Scales



Wilson Coefficients: EDM & CEDM

$$(\bar{Q}\sigma^{\mu\nu}T^A u)\widetilde{\varphi}\, G^A_{\mu\nu}$$
$$(\bar{Q}\sigma^{\mu\nu}T^A d)\varphi\, G^A_{\mu\nu}$$
$$(\bar{F}\sigma^{\mu\nu} f)\tau^I \Phi\, W^I_{\mu\nu}$$
$$(\bar{F}\sigma^{\mu\nu} f)\Phi\, B_{\mu\nu}$$

$$\mathcal{L}^{\rm CEDM} = -i \sum_q \frac{g_3 \tilde{d}_q}{2}\, \bar{q}\sigma^{\mu\nu}T^A\gamma_5 q\; G^A_{\mu\nu}$$

$$\mathcal{L}^{\rm EDM} = -i \sum_f \frac{d_f}{2} \bar{f}\sigma^{\mu\nu}\gamma_5 f\; F_{\mu\nu}$$

Chirality flipping

$$\begin{aligned} {\rm Im}\, C_{qG} &\equiv Y_q\, \tilde{\delta}_q \to \tilde{d}_q = -\frac{2m_q}{v^2}\left(\frac{v}{\Lambda}\right)^2 \tilde{\delta}_q, \\ {\rm Im}\, C_{f\gamma} &\equiv Y_f\, \delta_f \to d_f = -e\frac{2m_f}{v^2}\left(\frac{v}{\Lambda}\right)^2 \delta_f \end{aligned}$$

δ_f , $\tilde{\delta}_q$ appropriate for comparison with other d=6 Wilson coefficients

Wilson Coefficients: Summary

δ_f	fermion EDM	(3)
$\tilde{\delta}_q$	quark CEDM	(2)
$C_{\tilde{G}}$	3 gluon	(1)
C_{quqd}	non-leptonic	(2)
$C_{lequ,\ ledq}$	semi-leptonic	(3)
$C_{\varphi ud}$	induced 4f	(1)

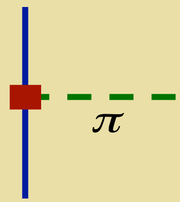
12 total + $\bar{\theta}$

light flavors only (e,u,d)

III. EDMs of Strongly Interacting Systems

Hadronic CPV: Nucleons, Nuclei, Atoms

PVTV πN interaction



Neutron, proton & light nuclei (future), diamagnetic atoms

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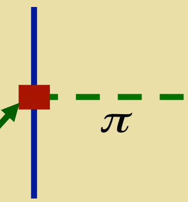

- *chromo EDM*
- *3 gluon*
- *4 quark*
- θ_{QCD}

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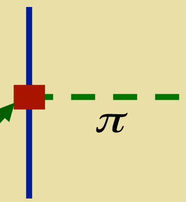

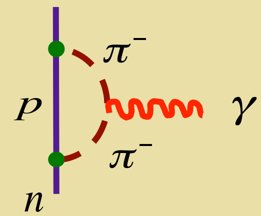

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Nucleon EDM

+ quark EDM

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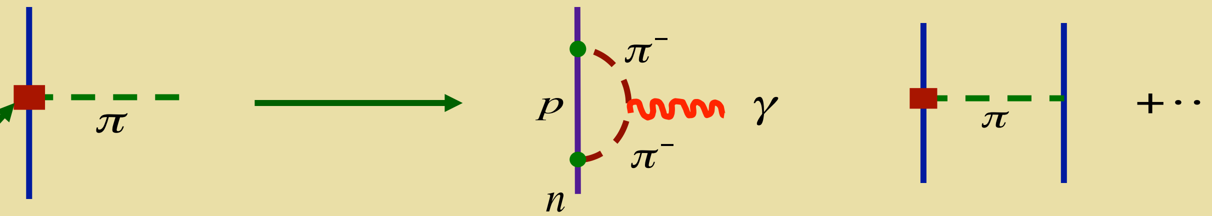

- *chromo EDM*
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- θ_{QCD}

Nucleon EDM

+ quark EDM

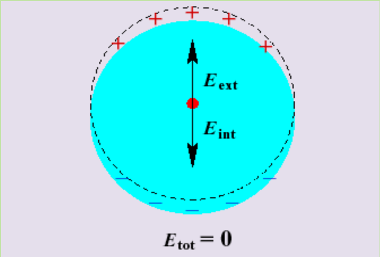
Nuclear EDM & Schiff moment

+ ~~quark EDM~~

Neutron, proton & light nuclei (future), diamagnetic atoms

Diamagnetic Systems: Schiff Moments

Schiff Screening



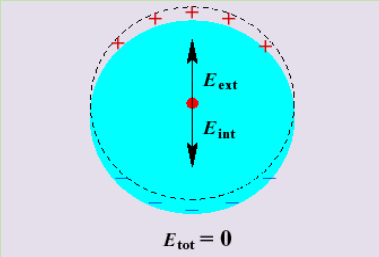
Atomic effect from nuclear finite size: Schiff moment

Neutral atoms: nuclear EDM invisible to external probe

EDMs of diamagnetic atoms (^{199}Hg)

Diamagnetic Systems: Schiff Moments

Schiff Screening



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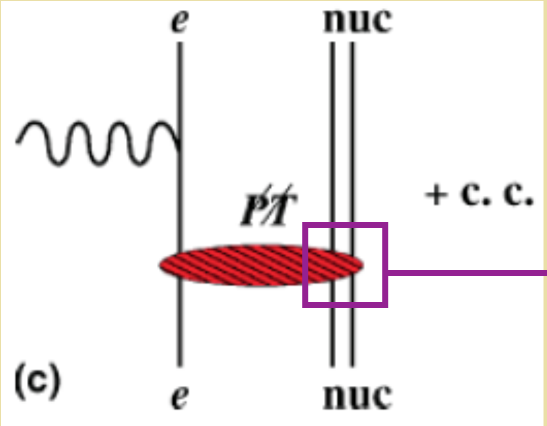


Schiff moment, MQM,…

Nuclear Schiff Moment

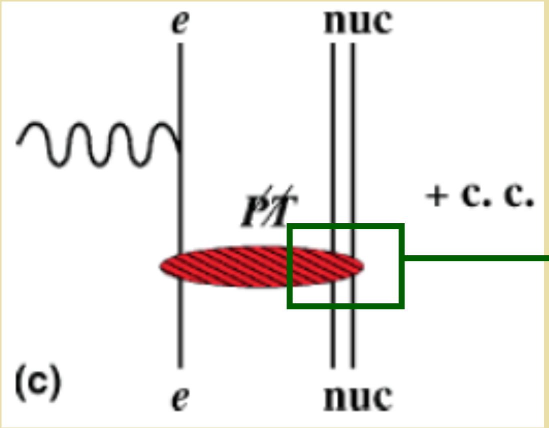
$$S \sim \int d^3x \, x^2 \, \vec{x} \, \rho(\vec{x})^{\mathrm{CPV}}$$

$(R_N / R_A)^2$ suppression

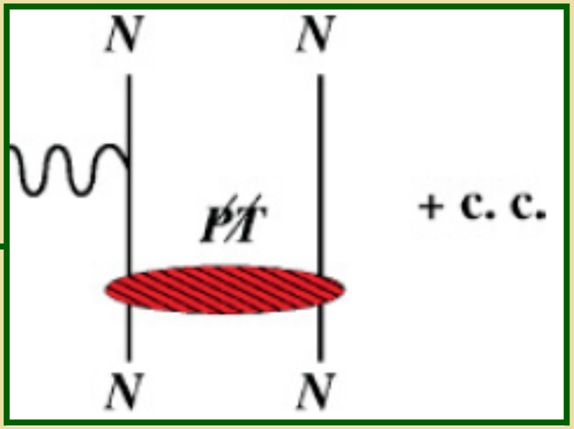
EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

Nuclear Enhancements



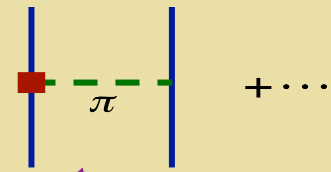
Schiff moment, MQM,…



Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment



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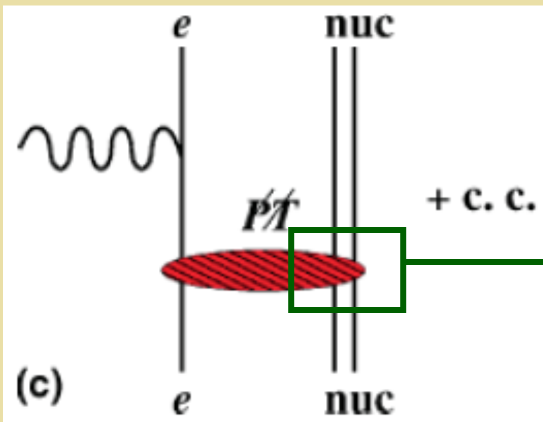

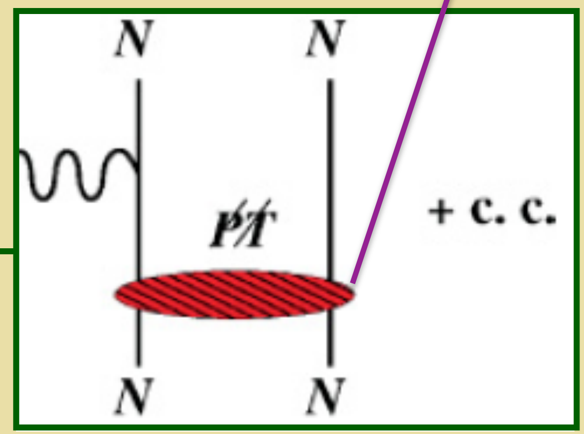

Schiff moment, MQM,…

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EDMs of diamagnetic atoms (^{199}Hg)

IV. Hadronic Matrix Elements: Challenges

Hadronic Matrix Elements

$\overline{d}_N$ "Short distance" nucleon EDM

$\overline{g}_\pi^{(i)}$ TVPV πNN couplings: i=0,1,2

$$\boxed{d_n = \bar{d}_n - \frac{e g_A}{4\pi^2 F_\pi}\left\{\bar{g}_\pi^{(0)}\left(\ln\frac{m_\pi^2}{m_N^2} - \frac{\pi m_\pi}{2m_N}\right) + \frac{\bar{g}_\pi^{(1)}}{4}(\kappa_1 - \kappa_0)\frac{m_\pi^2}{m_N^2}\ln\frac{m_\pi^2}{m_N^2}\right\}}$$

de Vries, Mereghetti, Patel, R-M, Seng '13

Running & Matching *Hadronic*

$$
\begin{aligned}
d_N &= \alpha_N\,\bar\theta + \left(\frac{v}{\Lambda}\right)^2 \sum_k \beta_N^{(k)}\,(\mathrm{Im}\,C_k) \\
\bar g_\pi^{(i)} &= \lambda_{(i)}\,\bar\theta + \left(\frac{v}{\Lambda}\right)^2 \sum_k \gamma_{(i)}^{(k)}\,(\mathrm{Im}\,C_k)
\end{aligned}
$$

$$
\begin{aligned}
\left(\frac{v}{\Lambda}\right)^2 \left[\beta_N^{qG}\,(\mathrm{Im}\,C_{qG}) + \beta_N^{q\gamma}\,(\mathrm{Im}\,C_{q\gamma})\right] &= e\,\tilde\rho_N^q\,\tilde d_q + \rho_N^q\,d_q = \left(\frac{v}{\Lambda}\right)^2 \left[e\,\tilde\zeta_N^q\,\tilde\delta_q + e\,\zeta_N^q\,\delta_q\right] \\
\left(\frac{v}{\Lambda}\right)^2 \left[\gamma_{(i)}^{qG}\,(\mathrm{Im}\,C_{qG}) + \gamma_{(i)}^{q\gamma}\,(\mathrm{Im}\,C_{q\gamma})\right] &= \tilde\omega_{(i)}^q\,\tilde d_q + \omega_{(i)}^q\,d_q = \left(\frac{v}{\Lambda}\right)^2 \left[\tilde\eta_{(i)}^q\,\tilde\delta_q + \eta_{(i)}^q\,\delta_q\right]
\end{aligned}
$$

How well can we compute the β, ρ, ζ, ... ?

Hadronic Matrix Elements: Approaches

- *Chiral symmetry & NDA*
- *Lattice*
- *QCD Sum Rules*
- *Dyson Schwinger Equations*
- *Quark Models*
- *…*

Hadronic Matrix Elements

Param	Coeff	Best value[a]	Range
$\bar{\theta}$	α_n	0.002	(0.0005–0.004)
	α_p	0.002	(0.0005–0.004)
$\mathrm{Im}\, C_{qG}$	β_n^{uG}	4×10^{-4}	$(1 - 10) \times 10^{-4}$
	β_n^{dG}	8×10^{-4}	$(2 - 18) \times 10^{-4}$
$\tilde{d}_q$	$e\tilde{\rho}_n^u$	-0.35	$-(0.09 - 0.9)$
	$e\tilde{\rho}_n^d$	-0.7	$-(0.2 - 1.8)$
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2 - 20) \times 10^{-9}$
	$e\tilde{\zeta}_n^d$	16.3×10^{-9}	$(4 - 40) \times 10^{-9}$
$\mathrm{Im}\, C_{q\gamma}$	$\beta_n^{u\gamma}$	0.4×10^{-3}	$(0.2 - 0.6) \times 10^{-3}$
	$\beta_n^{d\gamma}$	-1.6×10^{-3}	$-(0.8 - 2.4) \times 10^{-3}$
d_q	ρ_n^u	-0.35	(-0.17)–0.52
	ρ_n^d	1.4	0.7–2.1
δ_q	ζ_n^u	8.2×10^{-9}	$(4 - 12) \times 10^{-9}$
	ζ_n^d	-33×10^{-9}	$-(16 - 50) \times 10^{-9}$
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2 - 40) \times 10^{-7}$
$\mathrm{Im}\, C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1 - 10) \times 10^{-8}$
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10 - 80) \times 10^{-7}$
$\mathrm{Im}\, C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11–14.5
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Engel, R-M, van Kolck:

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Engel, R-M, van Kolck:

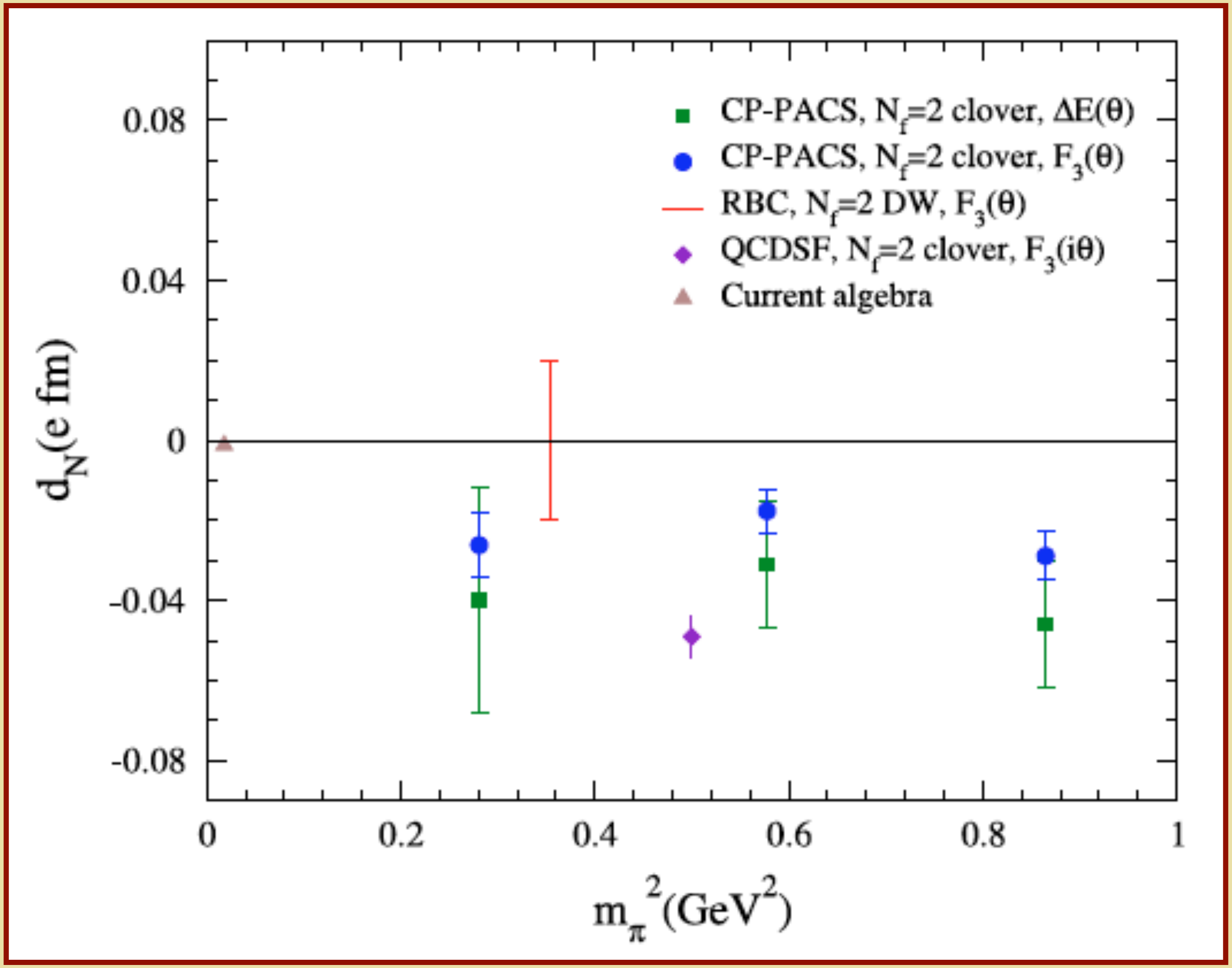
Hadronic Matrix Elements: θ_{QCD}

- *Chiral symmetry & NDA*

$$\bar{g}_\pi^{(0)} = \frac{1-\epsilon^2}{2\epsilon}\,\frac{(\Delta m_N)_q}{F_\pi}\,\bar{\theta} \quad \longrightarrow \quad \lambda_{(0)} = \frac{1-\epsilon^2}{2\epsilon}\,\frac{(\Delta m_N)_q}{F_\pi}$$

$$\bar{d}_{0,1} \sim e\bar{\theta}\,\frac{m_\pi^2}{\Lambda_\chi^3} \quad \longrightarrow \quad \alpha_N \sim e\,\frac{m_\pi^2}{\Lambda_\chi^3} \sim 0.2\,\frac{m_\pi^2}{\Lambda_\chi^2}\,e\,\mathrm{fm}$$

Hadronic Matrix Elements



Shintani et al

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Engel, R-M, van Kolck:

Hadronic Matrix Elements

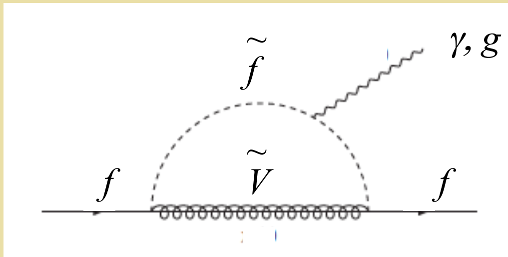
ρ EDM

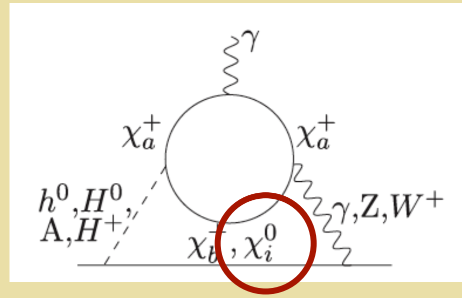
$q\gamma q$	$-0.066\,\tilde{d}^e_- - 0.199\,\tilde{d}^e_+$
BSA	$-0.120\,\tilde{d}^e_- + 0.108\,\tilde{d}^e_+$
$S(k)$	$1.538\,\tilde{d}^e_-$
acm $(\times\mu^{\mathrm{acm}})$	$0.775\,\tilde{d}^e_- + 2.396\,\tilde{d}^e_+$
our CEDM	$(1.35 + 0.78\,\mu^{\mathrm{acm}})\,\tilde{d}^e_- - (0.09 - 2.40\,\mu^{\mathrm{acm}})\,\tilde{d}^e_+$
total	$1.16\,\tilde{d}^e_- - 0.69\,\tilde{d}^e_+$
sum rules [15]	$-0.13\,\tilde{d}^e_-$

DSE: Pitschmann et al, 1209.4352,
PRC 87 (2013) 015205

V. Implications & Outlook

EDMs & EW Baryogenesis: MSSM

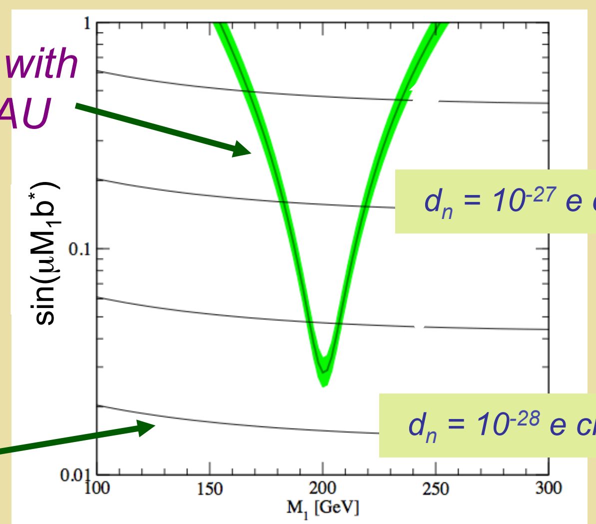




Heavy sfermions: LHC consistent & suppress 1-loop EDMs

Sub-TeV EW-inos: LHC & EWB -viable but non-universal phases

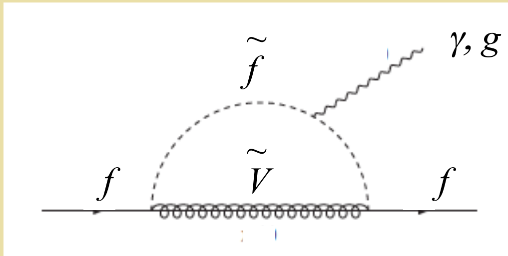
Compatible with observed BAU



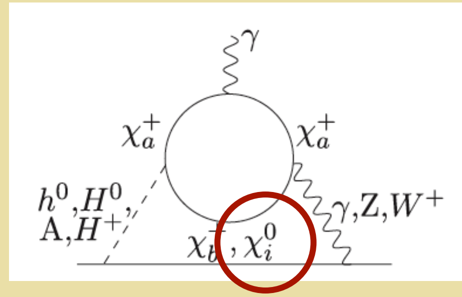
Next generation d_n

Li, Profumo, RM '09-'10

EDMs & EW Baryogenesis: MSSM



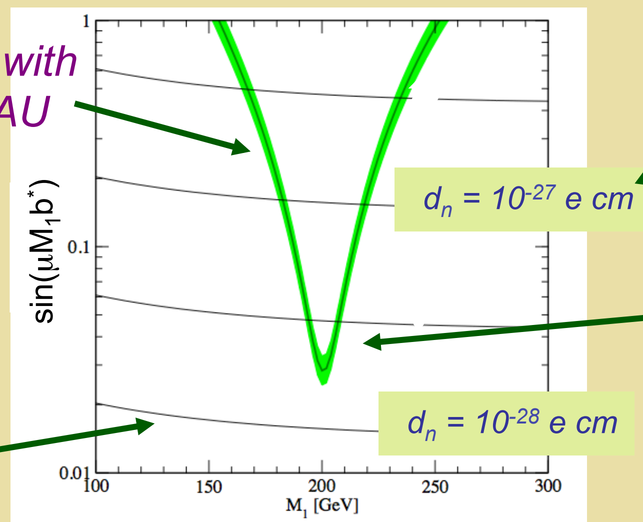
Heavy sfermions: LHC consistent & suppress 1-loop EDMs



Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU

How reliably can we locate these lines?



Compressed spectrum (stealthy SUSY)

Next generation d_n

Li, Profumo, RM '09-'10

V. Implications & Outlook

- *EDMs provide a powerful probe of CPV physics at the multi-TeV scale*
- *Searches in a variety of systems needed to uncover and disentangle effects associated with different “sources” (eg, d=6 operators)*
- *Obtaining reliable non-perturbative computations remains a key open challenge, with implications for interpretation of EDMs in terms of BSM physics & cosmology*

Back Up Slides

BSM Origins

δ_f	MSSM, RS, LRSM	1 & 2 loop
$\tilde{\delta}_q$	MSSM, RS, LRSM	1 & 2 loop
$C_{\tilde{G}}$	MSSM	2 loop
C_{quqd}	(MSSM d=8)	
$C_{lequ,\ ledq}$	(MSSM d=8)	
$C_{\varphi ud}$	LRSM	tree (θ_{LR})

12 total + $\bar{\theta}$

light flavors only (e,u,d)

BSM Origins

EDM: γff

CEDM: gff

Weinberg ggg:

Four fermion

udHH

BSM Origins

EDM: γff

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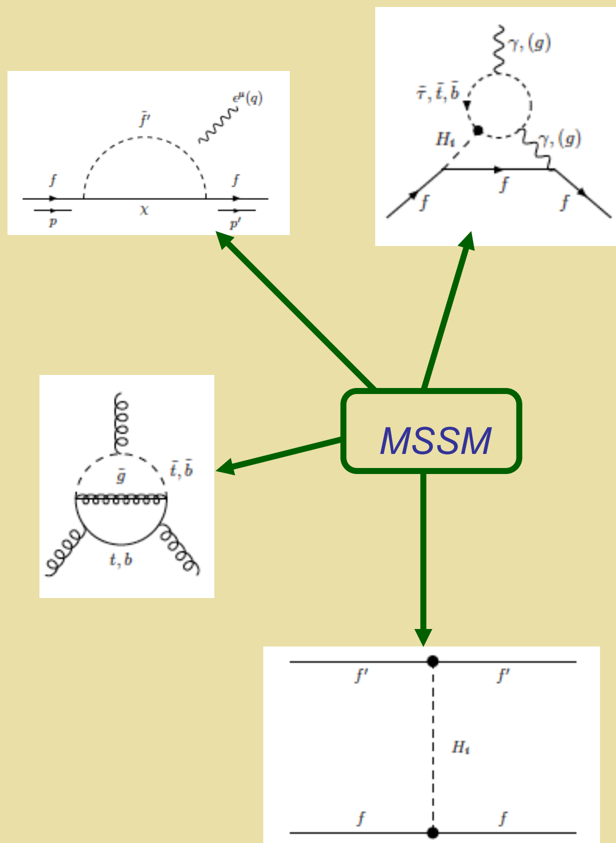
udHH



BSM Origins

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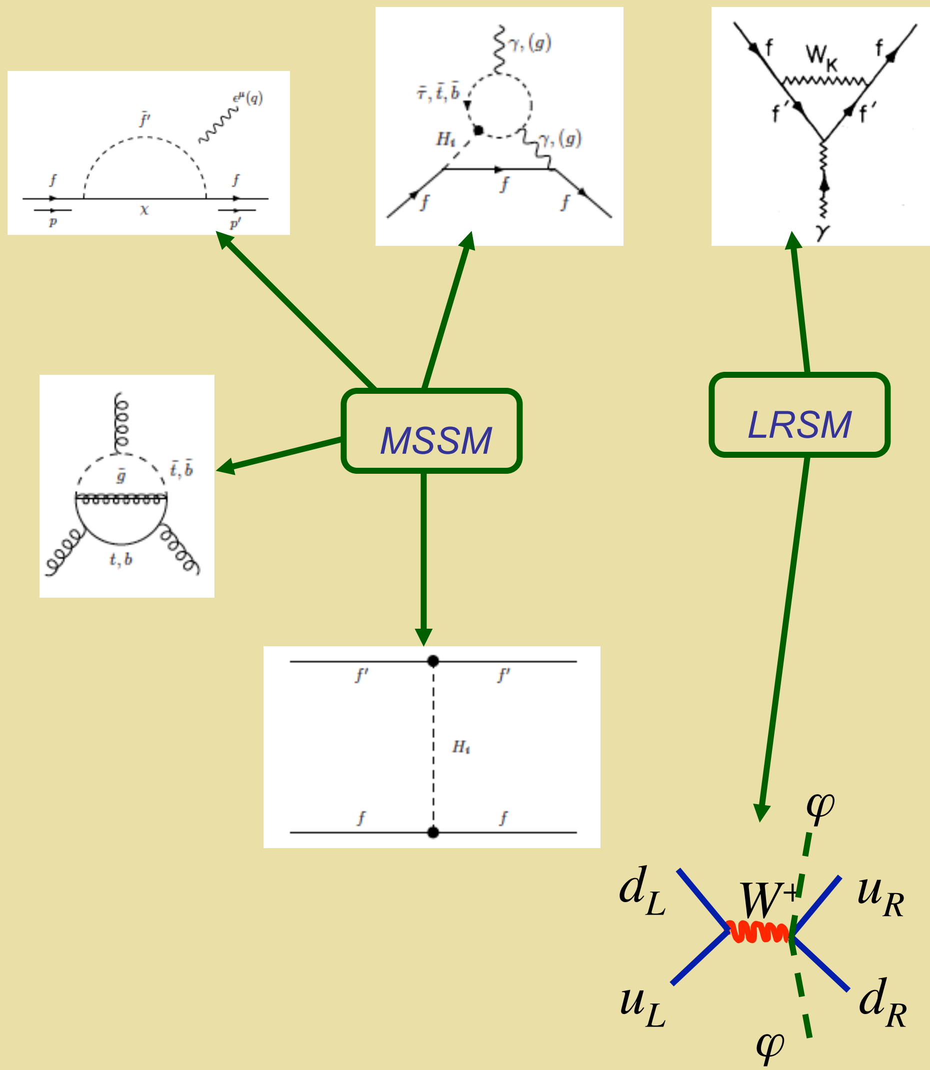

BSM Origins

EDM: γff

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Four fermion

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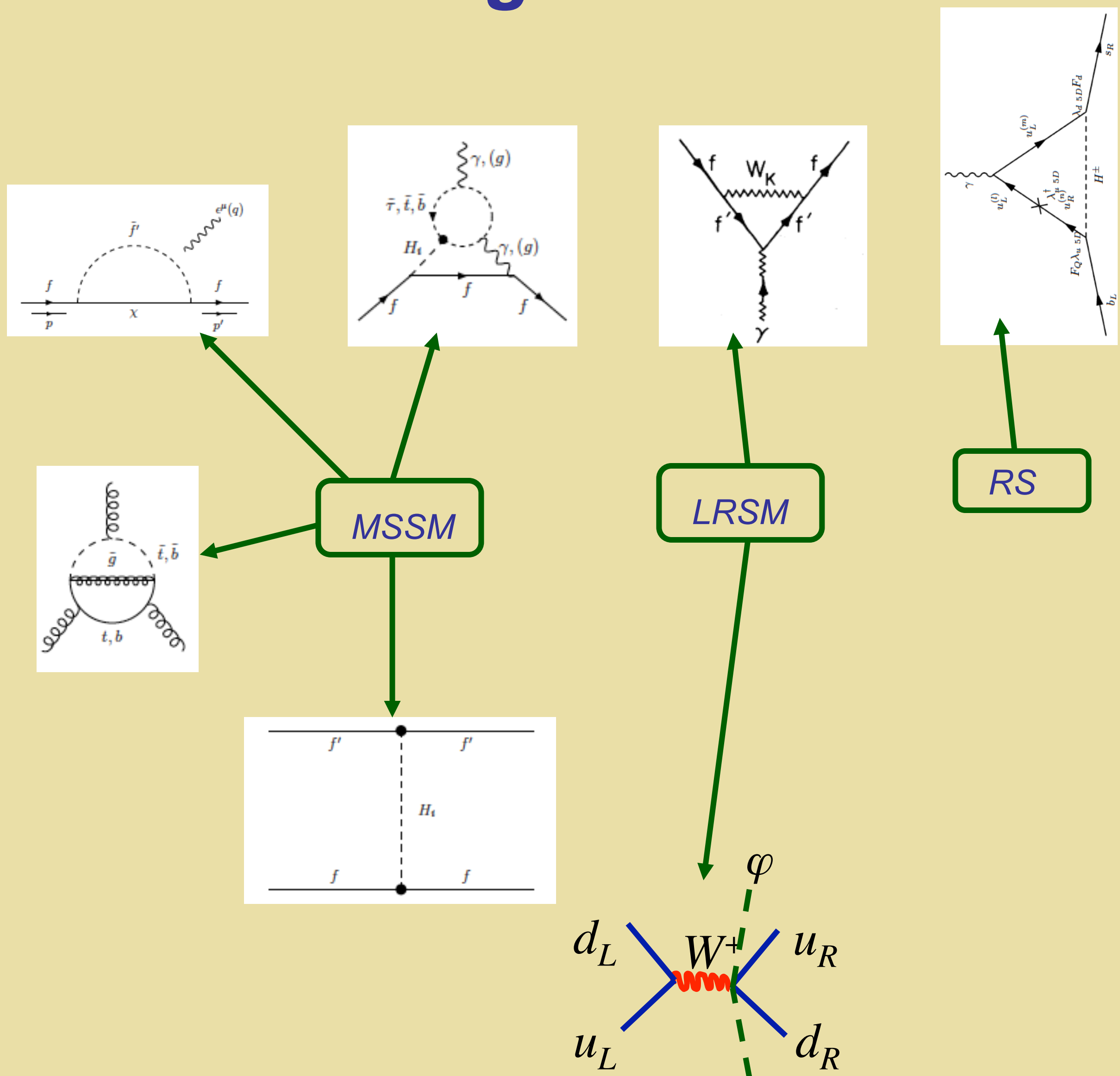
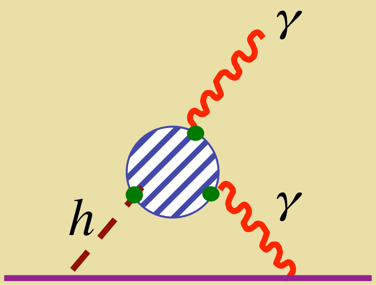
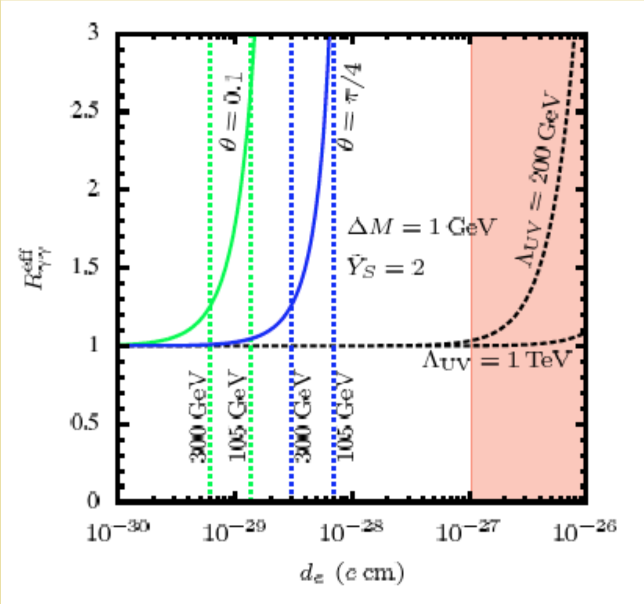
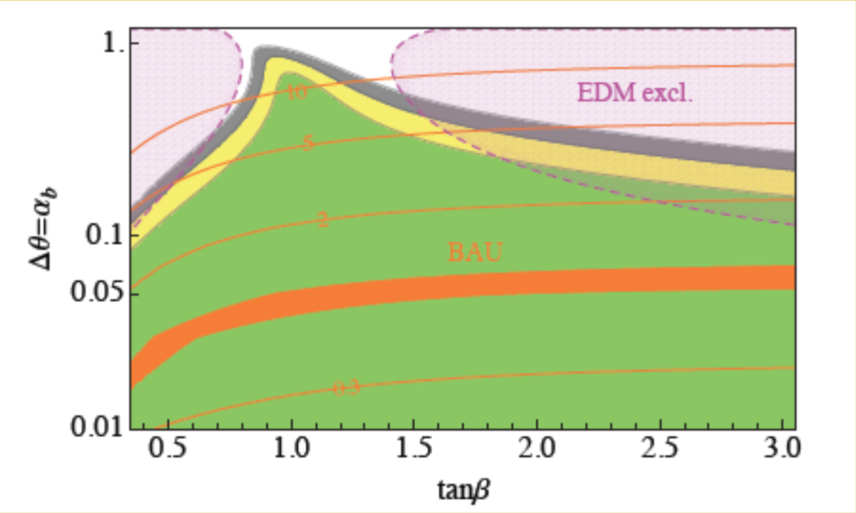


Recent Interest: EDMs & H→γγ

$$\boxed{\frac{c_h v}{\Lambda^2} h F_{\mu\nu} F^{\mu\nu} + \frac{\tilde{c}_h v}{\tilde{\Lambda}^2} h F_{\mu\nu} \tilde{F}^{\mu\nu}}$$







McKeen, Pospelov, Ritz ‘12

SM + singlet & vector-like leptons

Shu, Zhang ‘13

2HDM & connection with BAU

Diamagnetic Systems

Nuclear Moments

	$P\ T$	$\cancel{P}\ T$	$P\ \cancel{T}$	$\cancel{P}\ \cancel{T}$	
C_J	E	✖	✖	$\boxed{\text{O}}$	*EDM, Schiff…*
$T^M{}_J$	O	✖	✖	$\boxed{\text{E}}$	*MQM….*
$T^E{}_J$	✖	$\boxed{\text{O}}$	E	✖	*Anapole…*

Diamagnetic Systems

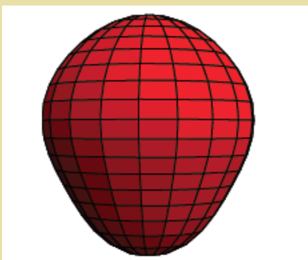
Nuclear Moments

	PT	$\cancel{P}T$	$P\cancel{T}$	$\cancel{P}\cancel{T}$	
C_J	E	✖	✖	$\boxed{\text{O}}$	$\boxed{\textit{EDM, Schiff…}}$
$T^M{}_J$	O	✖	✖	$\boxed{\text{E}}$	*MQM….*
$T^E{}_J$	✖	$\boxed{\text{O}}$	E	✖	*Anapole…*

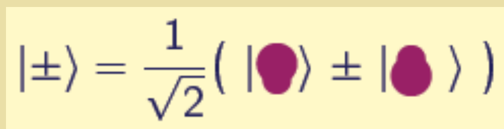
Nuclear Enhancements

Nuclear Schiff Moment

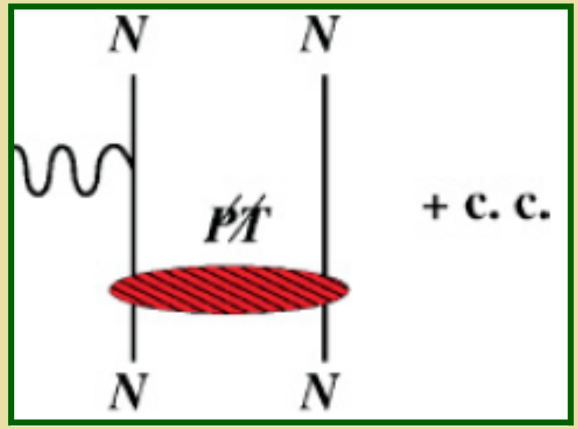
Nuclear Enhancements:
Octupole Deformation



Calculated ^{225}Ra density



Opposite parity states mixed by H^{TVPV}



Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

"Nuclear amplifier"

EDMs of diamagnetic atoms (^{225}Ra)

Thanks: J. Engel

Running & Matching *Nuclear*

$$S = a_0\, g\, \bar{g}_\pi^{(0)} + a_1\, g\, \bar{g}_\pi^{(1)} + a_2\, g\, \bar{g}_\pi^{(2)}$$

Nuclear many-body computations

$$\bar{g}_\pi^{(i)} \;=\; \lambda_{(i)}\, \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \gamma_{(i)}^{(k)}\, (\mathrm{Im}\, C_k)$$

Non-perturbative hadronic computations

Nuclear Matrix Elements

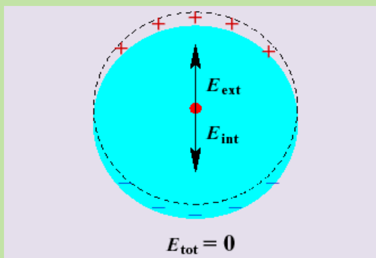
Nucl.	Best value		
	a_0	a_1	a_2
^{199}Hg	0.01	$\pm$ 0.02	0.02
^{129}Xe	−0.008	−0.006	−0.009
^{225}Ra	−1.5	6.0	−4.0

Range		
a_0	a_1	a_2
0.005–0.05	−0.03–(+0.09)	0.01–0.06
−0.005–(−0.05)	−0.003–(−0.05)	−0.005–(−0.1)
−1–(−6)	4–24	−3–(−15)

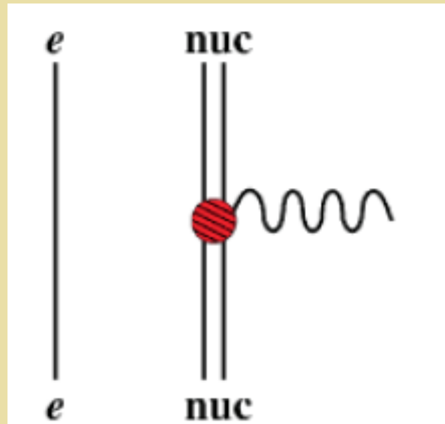
Engel, R-M,
van Kolck:

Schiff Screening & Corrections

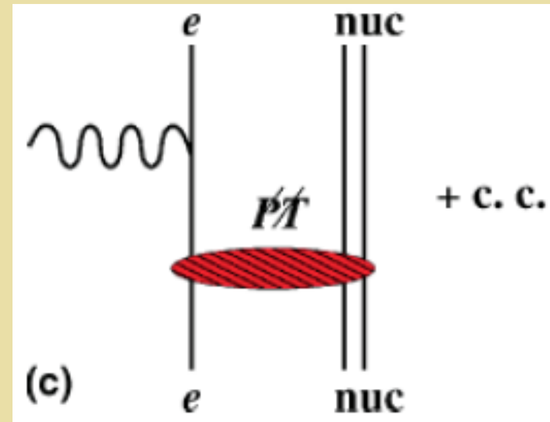
Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Screened EDM



Schiff moment, MQM,…

	PT	$\cancel{P}T$	$P\cancel{T}$	$\cancel{P}\cancel{T}$	
C_J	E	✖	✖	$\boxed{\text{O}}$	*EDM, Schiff…*
$T^M{}_J$	O	✖	✖	$\boxed{\text{E}}$	*MQM….*
$T^E{}_J$	✖	$\boxed{\text{O}}$	$\boxed{\text{E}}$	✖	$T^E{}_{J=1} \otimes T^E{}_{J=2}$?

EDMs of diamagnetic atoms (^{199}Hg)