Electric Dipole Moments: A Theory Overview

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Workshop on Low-Energy Precision Physics, MITP Mainz October 2013

Questions for Week Three

I. *What are the most significant implications of present & prospective EDM searches ?*

II. *What are the primary theoretical challenges & strategies for addressing them ?*

III. *What do we learn from existing and planned experiments and what are the most compelling new directions ?*

Outline

I. *Introduction & general considerations*

II. *Connecting with the LHC, Flavor, & Cosmology*

III. *Theoretical challenges*

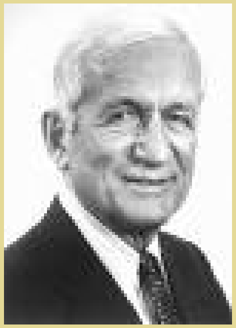
IV. *Theory-Experiment interface*

V. *Outlook*

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

I. Introduction

EDM Experiments



PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

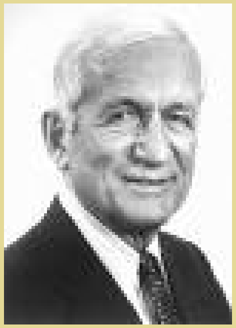
Experimental Limit to the Electric Dipole Moment of the Neutron

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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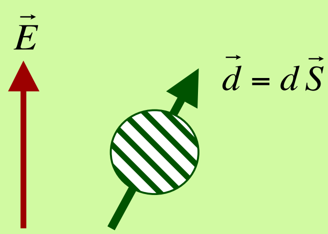
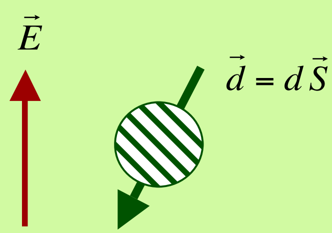
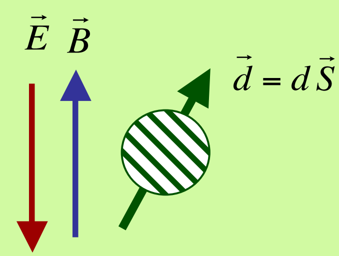


$$\nu_{EDM} = -\frac{d\vec{S}\cdot\vec{E}}{h}$$



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

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}
YbF	1.8×10^{-21} **	10^{-32}	10^{-22}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** e^- equivalent: 10.5×10^{-28} (thanks: T. Chupp)

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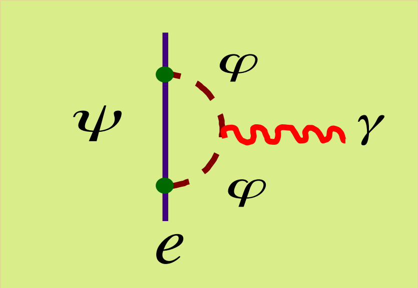
Mass Scale Sensitivity



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

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

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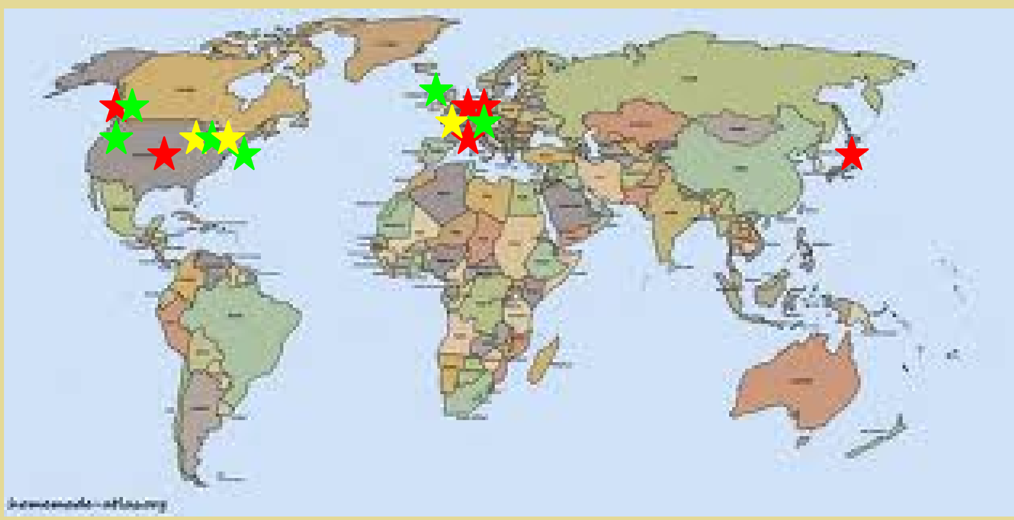


★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

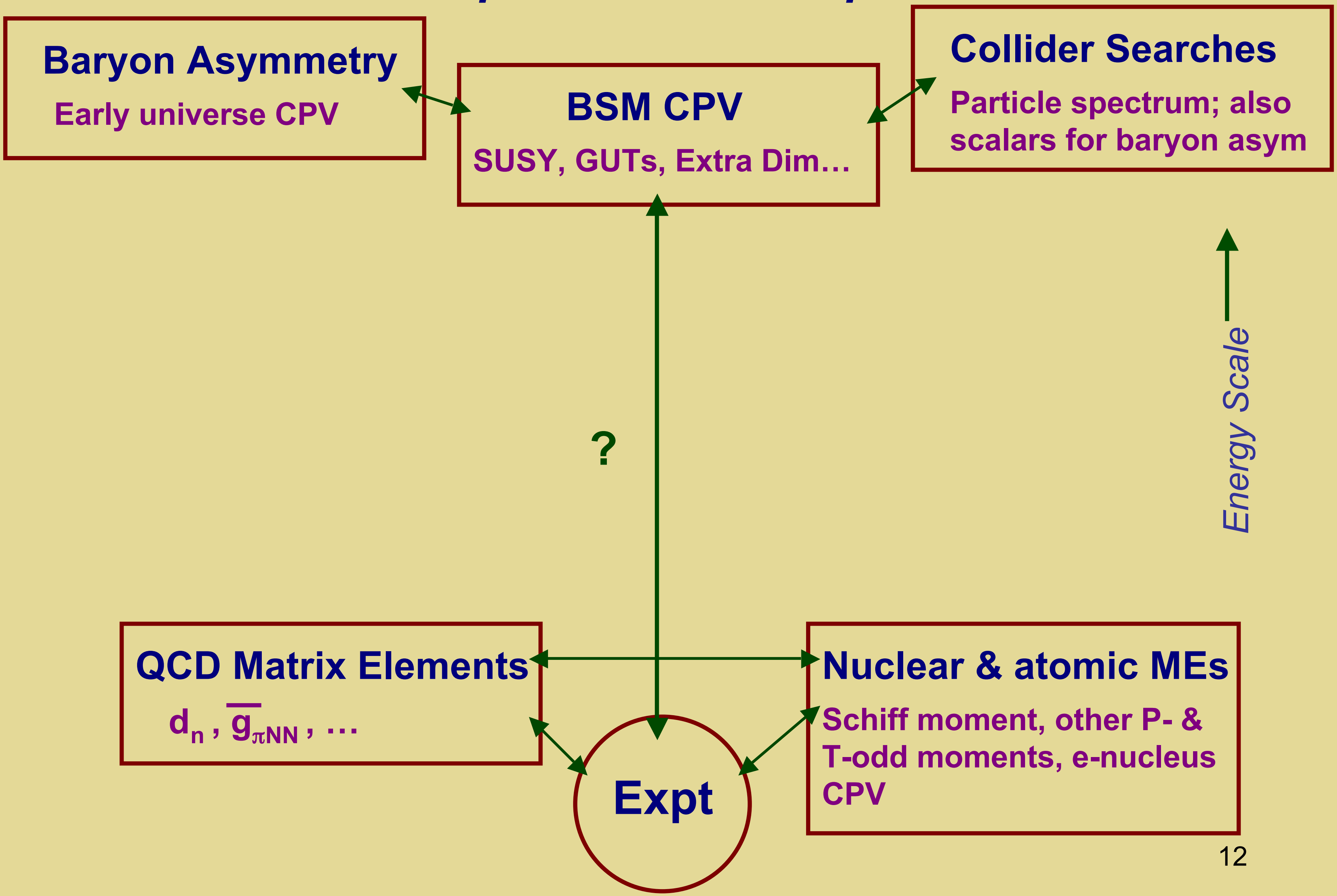
Not shown: muon

Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

EDM Interpretation & Multiple Scales



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

Baryon Asymmetry

Early universe CPV

BSM CPV

SUSY, GUTs, Extra Dim…

Collider Searches

Particle spectrum; also scalars for baryon asym

d= 6 Effective Operators: "CPV Sources"

fermion EDM, quark chromo EDM, 3 gluon, 4 fermion

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

Wilson Coefficients: EDM & CEDM

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

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

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

Chirality flipping

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

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)

Issues for Theory

A. Connecting w/ LHC, flavor physics, & cosmology

B. Matching onto physics at lower scales

- *QCD running (recent work)*
- *Hadronic matrix elements (large uncertainties)*
- *Nuclear matrix elements (large uncertainties)*
- *Atomic calculations*

Issues at Theory - Exp Interface

A. What can existing measurements teach us about Wilson coefficients and/or underlying high scale parameters ?

B. Are there new experiments that could provide complementary information ?

II. Connecting w/ High Scale Interactions & Cosmology

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

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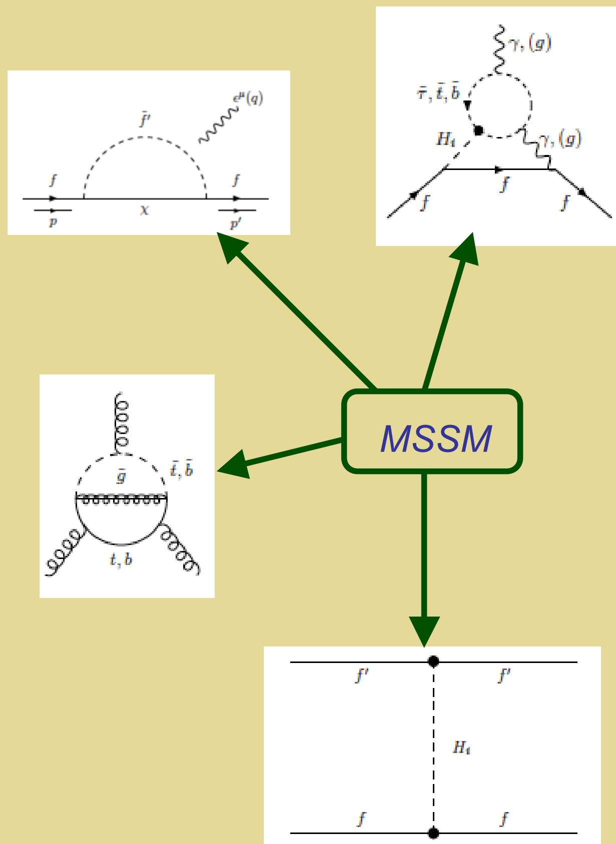

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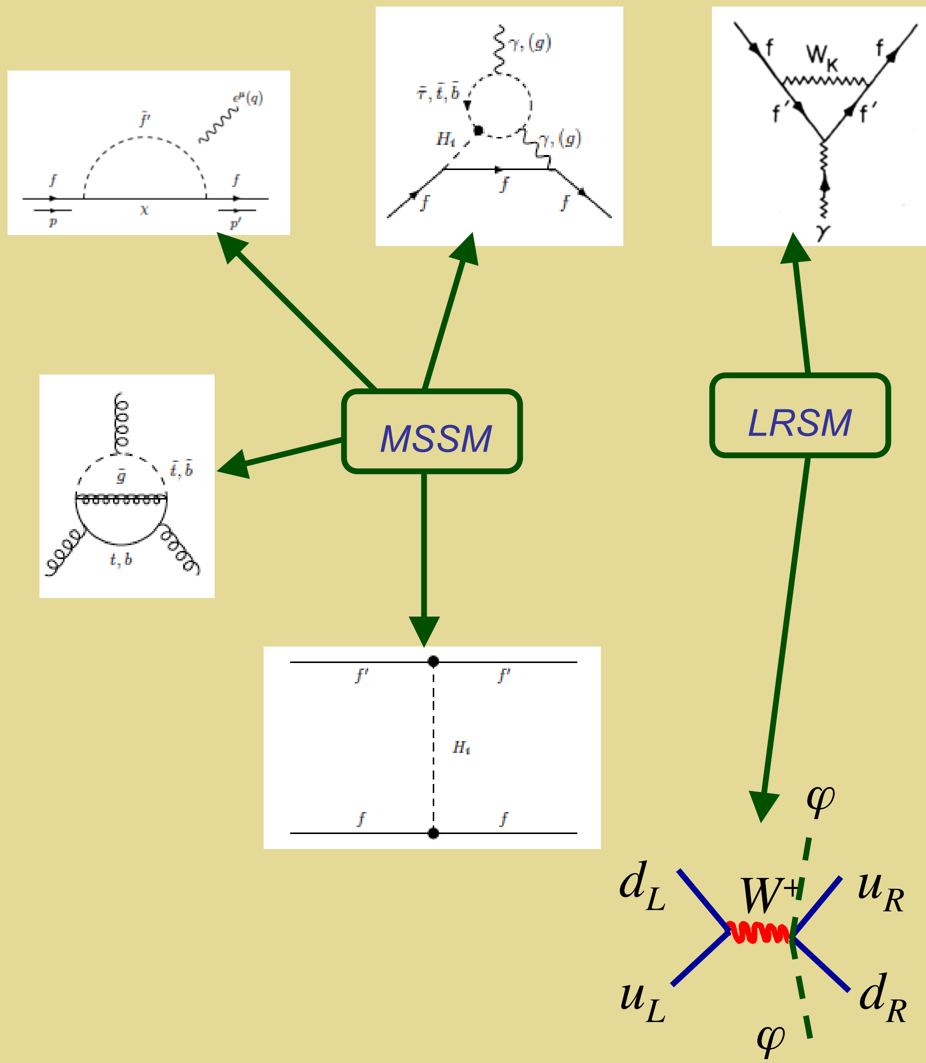

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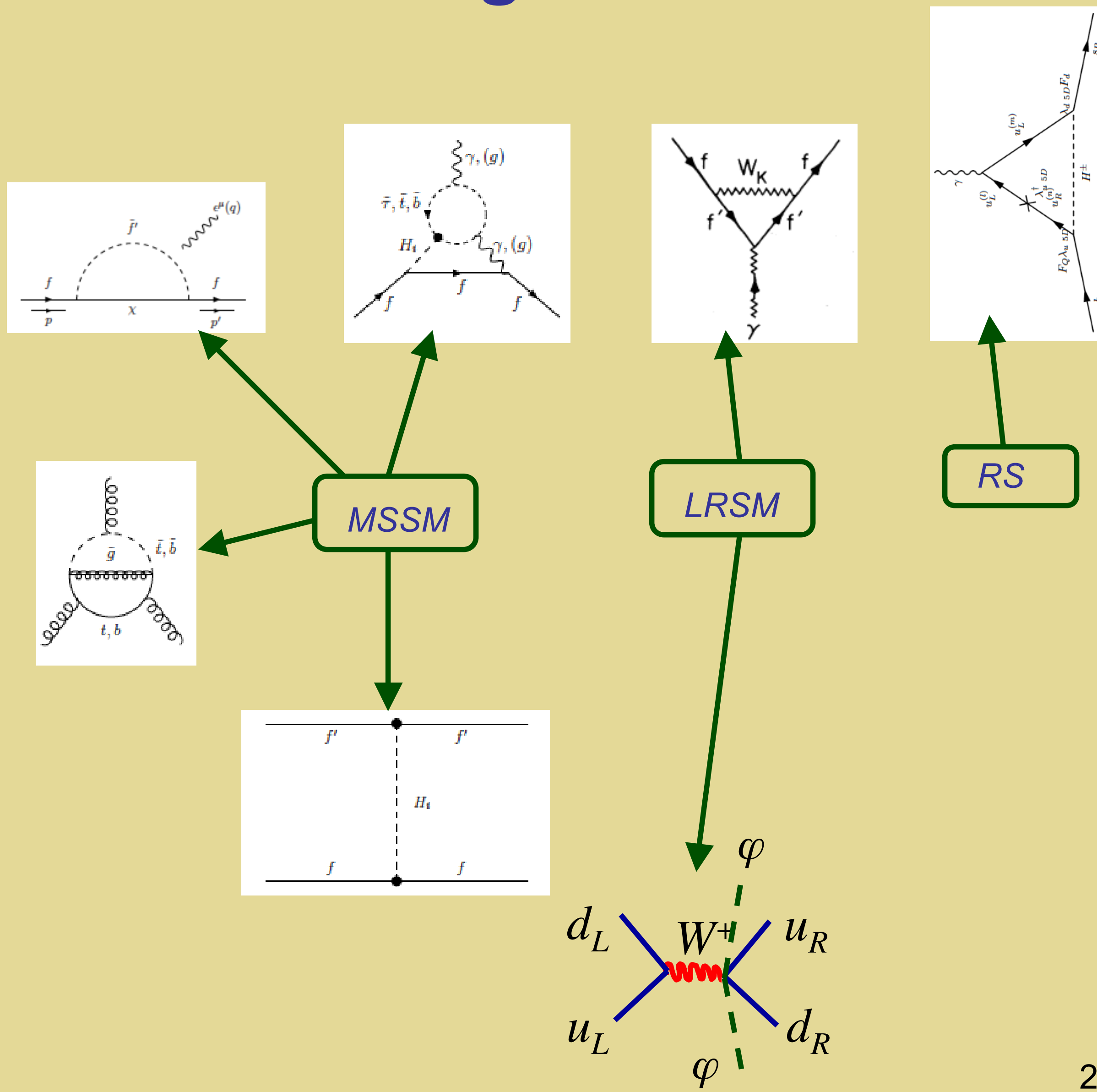


Illustrative Results

MSSM Global Analysis

$$W_{\rm MSSM} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\rm yukawa}$$

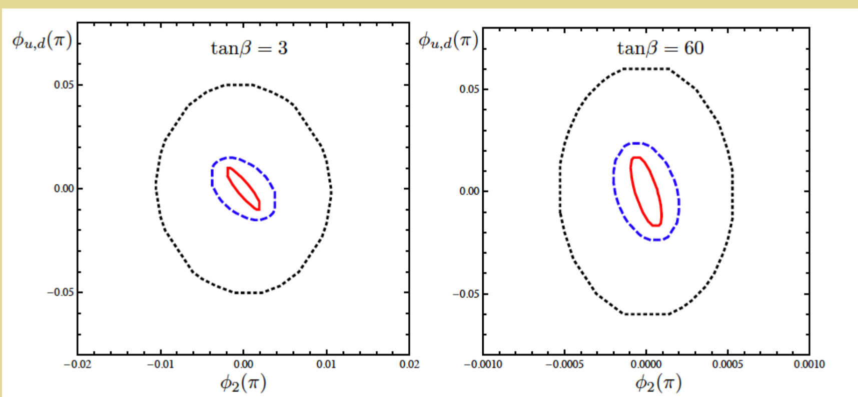
$$\begin{aligned}\mathcal{L}_{\rm soft} \quad = \quad & -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \\ & -(\tilde{\bar{u}}\mathbf{a_u}\tilde{Q}H_u - \tilde{\bar{d}}\mathbf{a_d}\tilde{Q}H_d - \tilde{\bar{e}}\mathbf{a_e}\tilde{L}H_d) + c.c. \\ & -\tilde{Q}^\dagger \mathbf{m^2_Q}\tilde{Q} - \tilde{L}^\dagger \mathbf{m^2_L}\tilde{L} - \tilde{\bar{u}}\mathbf{\bar{m}^2_{\bar{u}}}\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\mathbf{m^2_{\bar{d}}}\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\mathbf{m^2_{\bar{e}}}\tilde{\bar{e}}^\dagger - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d \\ & -(bH_uH_d + c.c.)\end{aligned}$$

ϕ_j = arg ($\mu M_j b^*$)

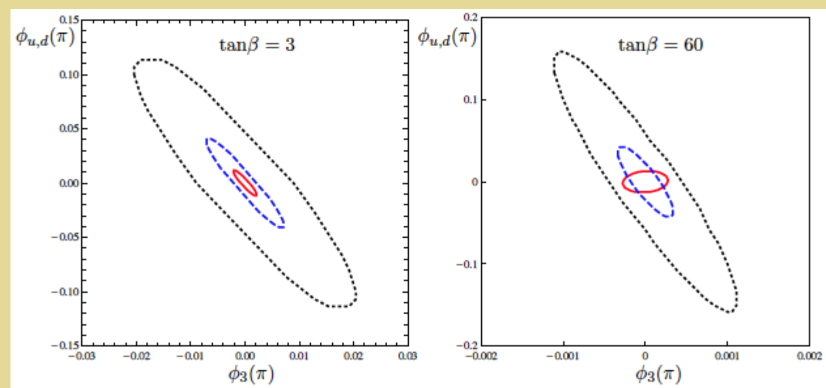
ϕ_A = arg ($A_f M_j$)

Correlated Constraints

Li, Profumo, R-M '10



Present



Present: ^{199}Hg impact

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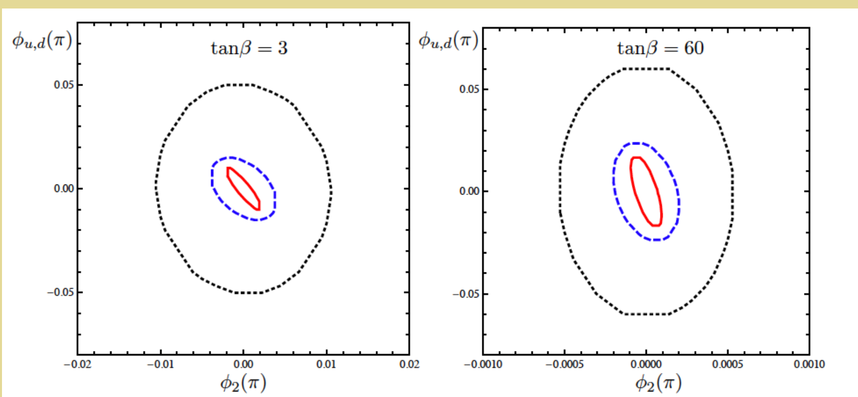
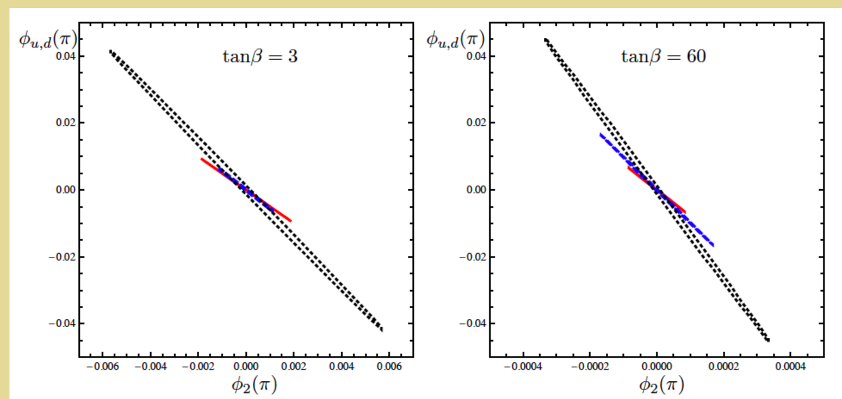
Li, Profumo, R-M '10



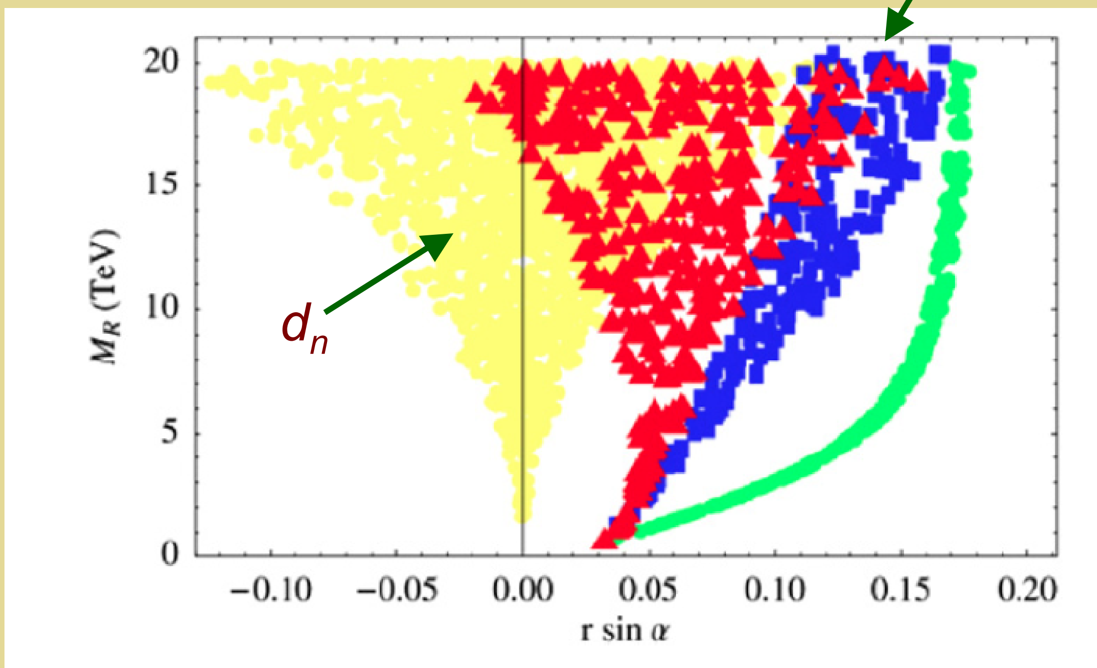


Present

Future d_n : 100 x present sensitivity

LRSM

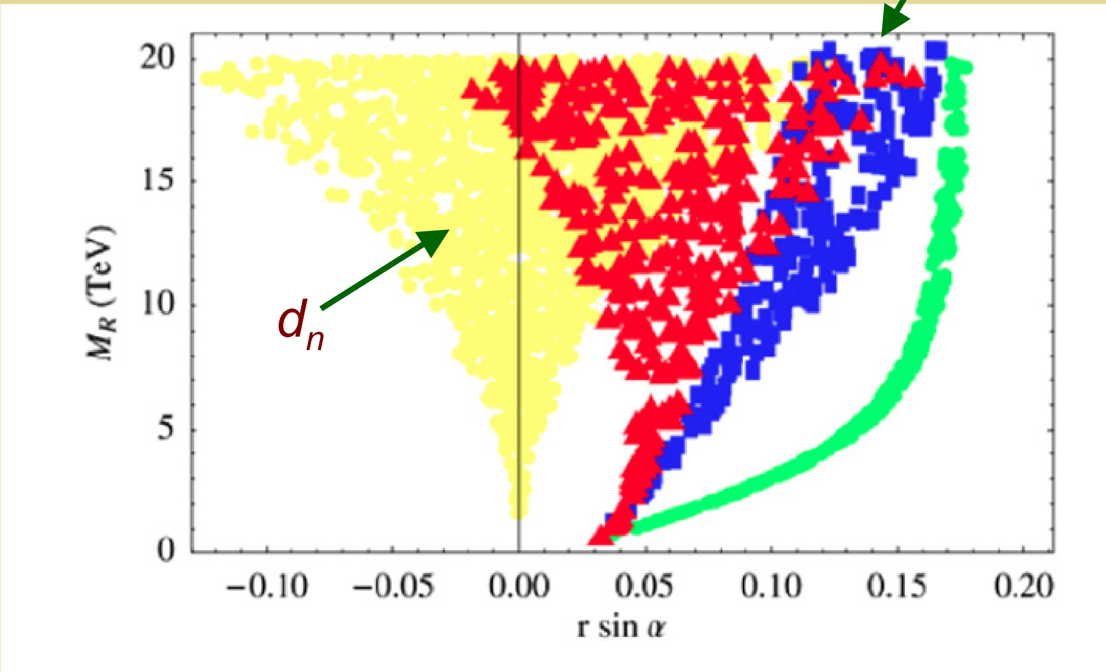
ε for different m_H



Zhang, An, Ji, Mohapatra ‘08

LRSM

ε for different m_H



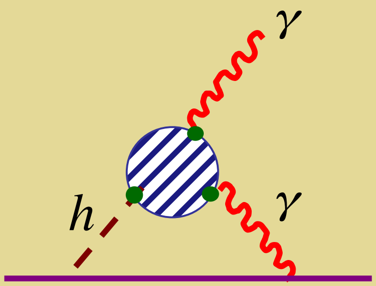
d_n

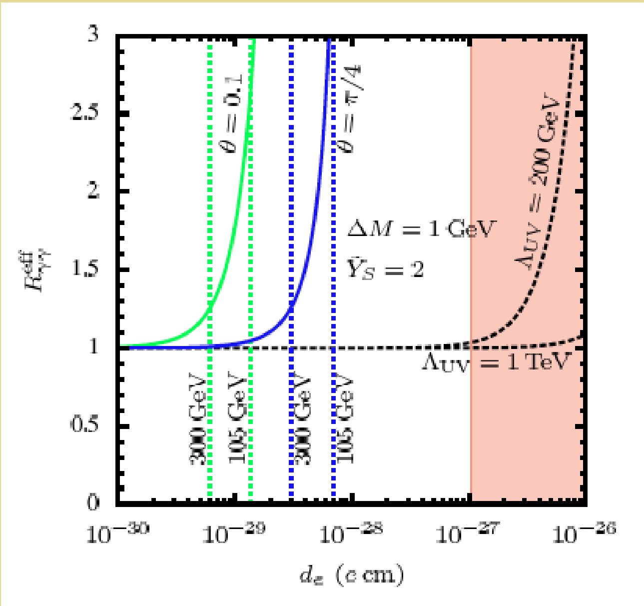
Caveat: χPT calc of d_n

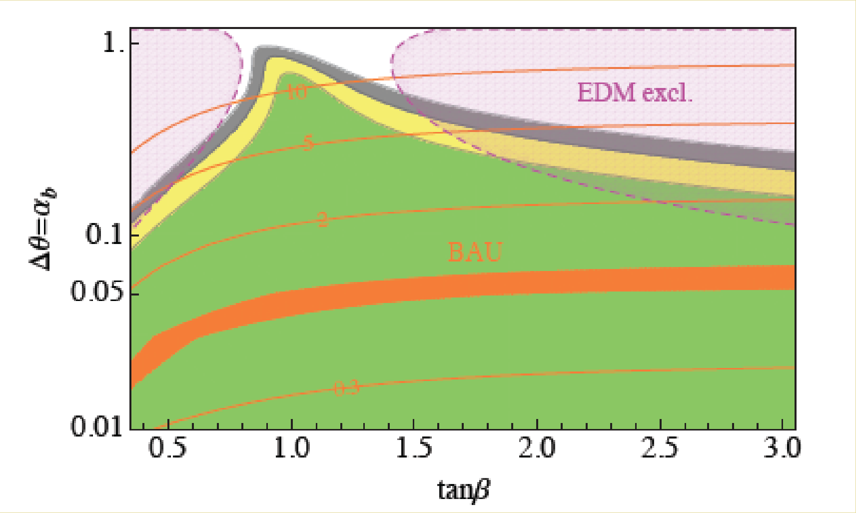
Zhang, An, Ji, Mohapatra '08

Recent Interest: EDMs & H→γγ

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







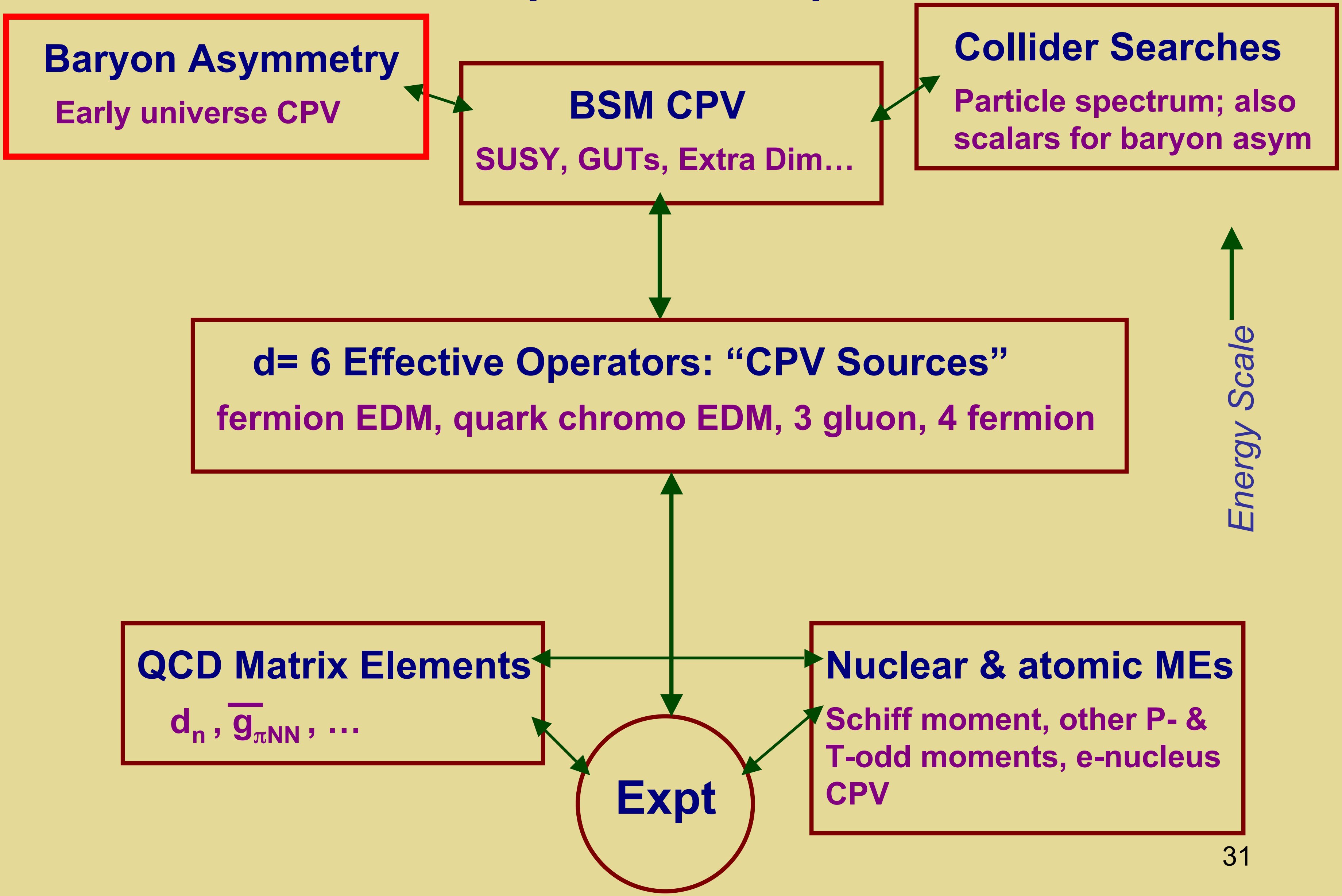
McKeen, Pospelov, Ritz '12

SM + singlet & vector-like leptons

Shu, Zhang '13

2HDM & connection with BAU

EDM Interpretation: Implications



EDMs & Baryogenesis

	Standard Model	BSM
• B violation (sphalerons)	✔	✔
• C & CP violation (BSM)	✖	✔
• Out-of-equilibrium or CPT violation (BSM)	✖	✔

EDMs & Baryogenesis

Electroweak baryogenesis

- *Testable*
- *Was BAU produced ~ 10ps after Big Bang or earlier ?*

	Standard Model	BSM
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EDMs & Baryogenesis

Electroweak baryogenesis

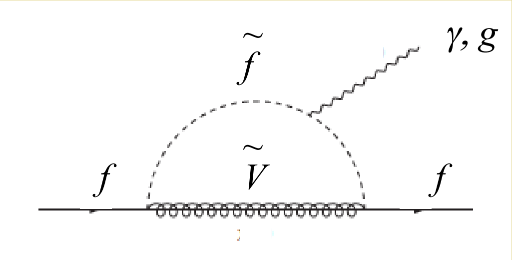
- *Testable*
- *Was BAU produced ~ 10ps after Big Bang or earlier ?*

Illustrative case: MSSM

	Standard Model	*BSM*
• *B violation (sphalerons)*	✔	✔
• *C & CP violation (BSM)*	✖	✔
• *Out-of-equilibrium or CPT violation (BSM)*	✖	✔

EDMs & EW Baryogenesis: MSSM

One-loop EDMs preclude MSSM baryogenesis



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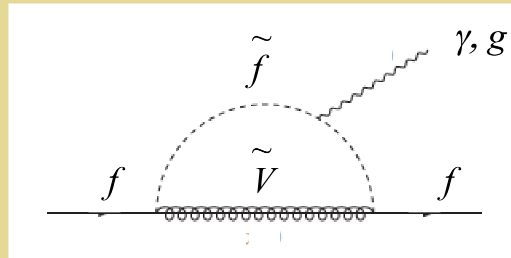
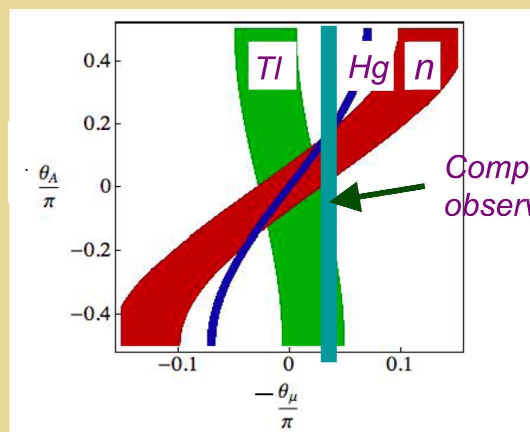


Universal gaugino phases

$Arg(\mu M_i b^*) =$

$Arg(\mu M_j b^*)$

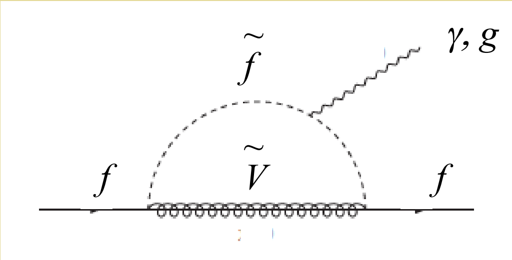


Compatible with observed BAU

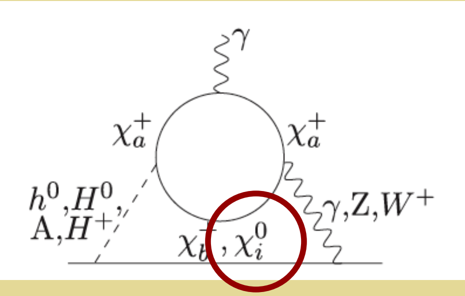
Ritz CIPANP 09 +

Cirigliano, R-M, Tulin, Lee ‘06

EDMs & EW Baryogenesis: MSSM

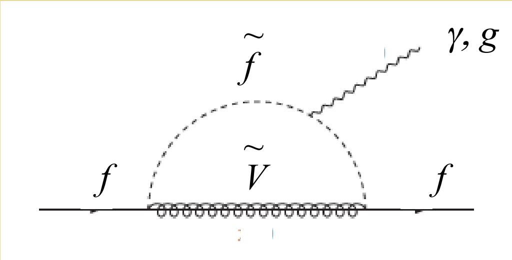


Heavy sfermions: LHC consistent & suppress 1-loop EDMs



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

EDMs & EW Baryogenesis: MSSM



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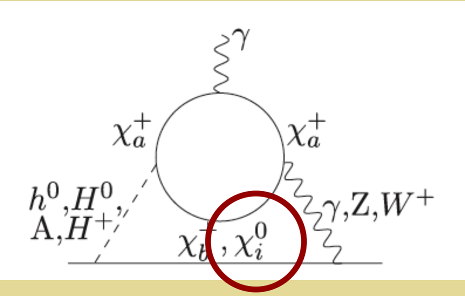
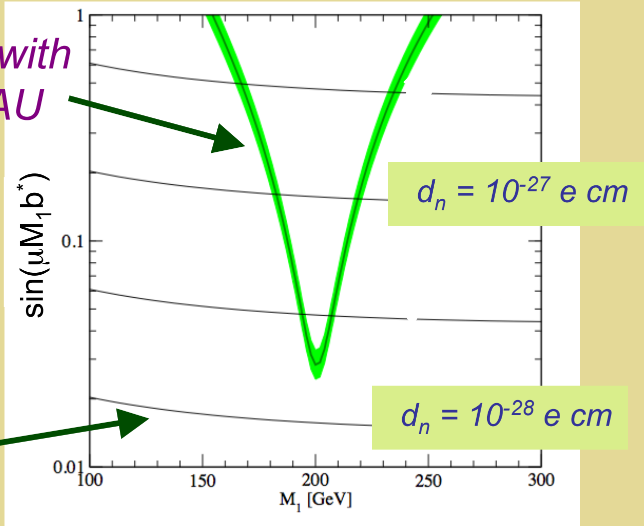


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

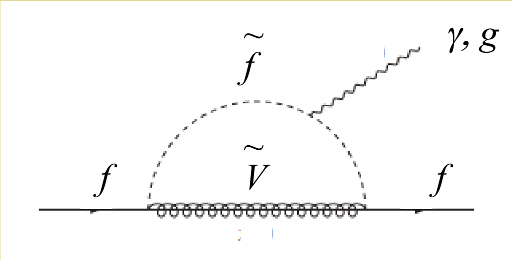
Compatible with observed BAU



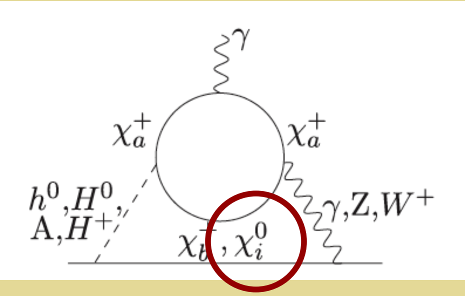
Next generation d_n

Li, Profumo, RM '09-'10

EDMs & EW Baryogenesis: MSSM



Heavy sfermions: LHC consistent & suppress 1-loop EDMs



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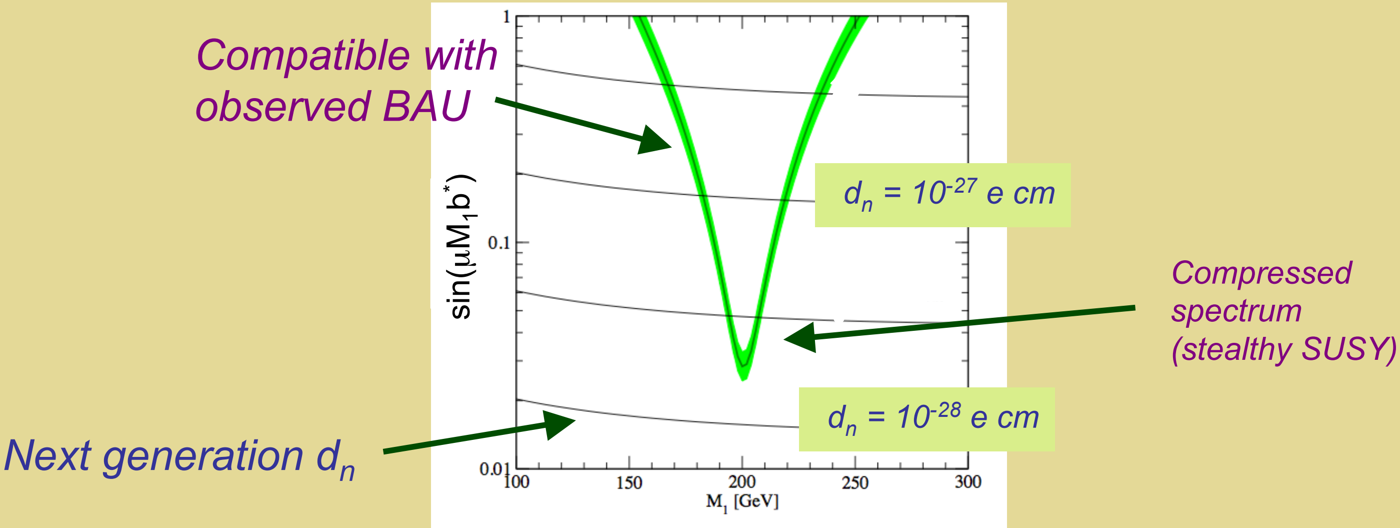


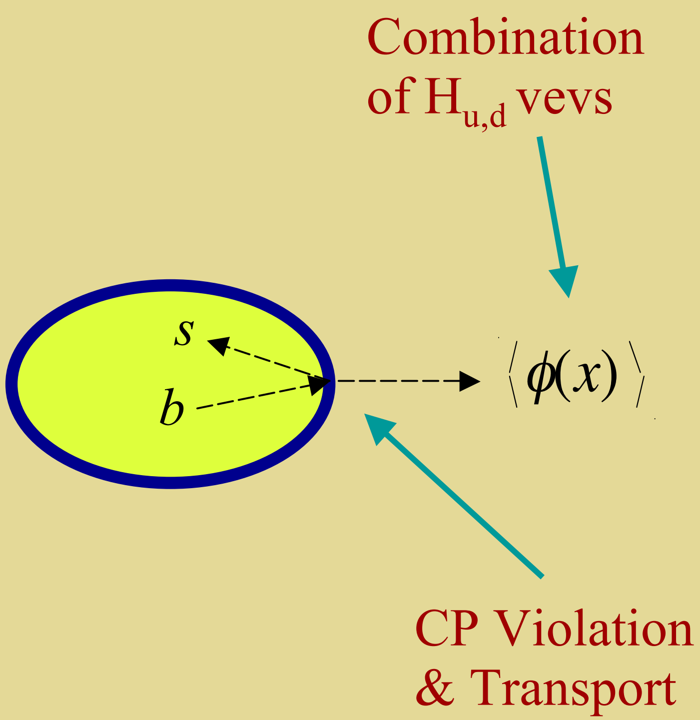
Li, Profumo, RM '09-'10

Flavored CPV & EWB

CPV & 2HDM

$$\mathcal{L} = -y_{ij}^u \bar{Q}^i (\epsilon H_u^\dagger) u_R^j - y_{ij}^d \bar{Q}^i H_u d_R^j$$
$$-\lambda_{ij}^u \bar{Q}^i H_d u_R^j - \lambda_{ij}^d \bar{Q}^i (\epsilon H_d^\dagger) d_R^j + h.c..$$

Liu, R-M, Shu '11; see also Tulin & Winslow '11; Cline et al '11



Viable EWB & CPV:

- *EDMs are 2-loop*
- *CPV is flavor non-diag*

Flavored CPV & EWB

CPV & 2HDM

$$\mathcal{L} = -y^u_{ij}\bar{Q}^i(\epsilon H_u^\dagger)u^j_R - y^d_{ij}\bar{Q}^i H_u d^j_R$$
$$-\lambda^u_{ij}\bar{Q}^i H_d u^j_R - \lambda^d_{ij}\bar{Q}^i(\epsilon H_d^\dagger)d^j_R + h.c..$$

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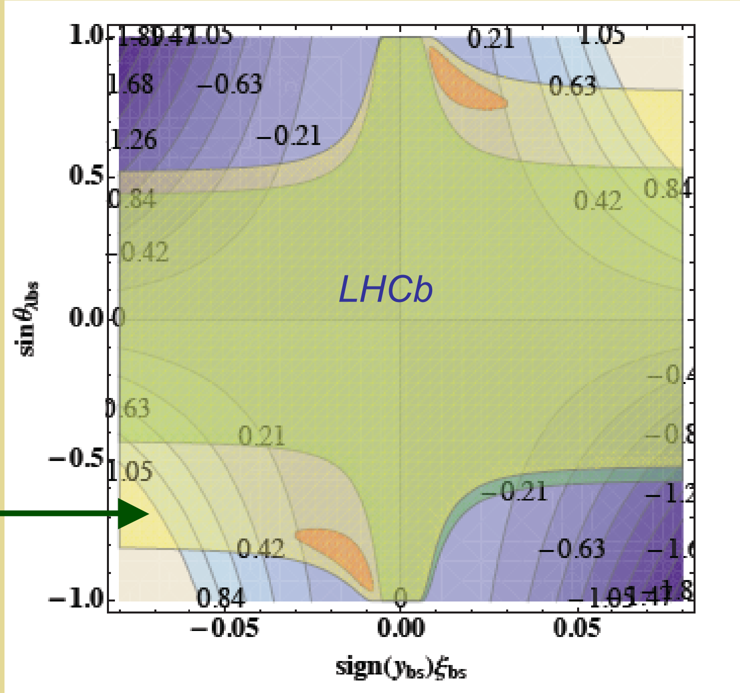
constant n_B / s



Viable EWB & CPV:

- *EDMs are 2-loop*
- *CPV is flavor non-diag*

Largely unexplored: flavored EWB

III. Theoretical Interpreration: Challenges

Matching at Hadronic Scale

Running & Matching

$$\mathrm{Im}\, C_j(\Lambda_\chi) = K_{jk}\, \mathrm{Im}\, C_k(\Lambda)$$

Operator	K_Q	Reference
Q_{qG}	3.30	[35]
$Q_{qV},\ V = B, W$	1.53	[35]
$Q_{\tilde{G}}$	3.30	[35, 36]
$Q_{quqd}^{(1,8)}$		

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

Running & Matching

$$Im\ C_j(\Lambda_\chi) = K_{jk}\, Im\ C_k(\Lambda)$$

Operator	K_Q	Reference
$\boxed{Q_{qG}}$	$\boxed{3.30}$	$\boxed{[35]}$
$Q_{qV},\ V = B, W$	1.53	[35]
$Q_{\tilde{G}}$	3.30	[35, 36]
$Q^{(1,8)}_{quqd}$		

Correct ?

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

Running & Matching *Hadronic*

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

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

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

Hadronic Matrix Elements

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
$\mathrm{Im}\, C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6–1.2

Engel, R-M, van Kolck:

Hadronic Matrix Elements

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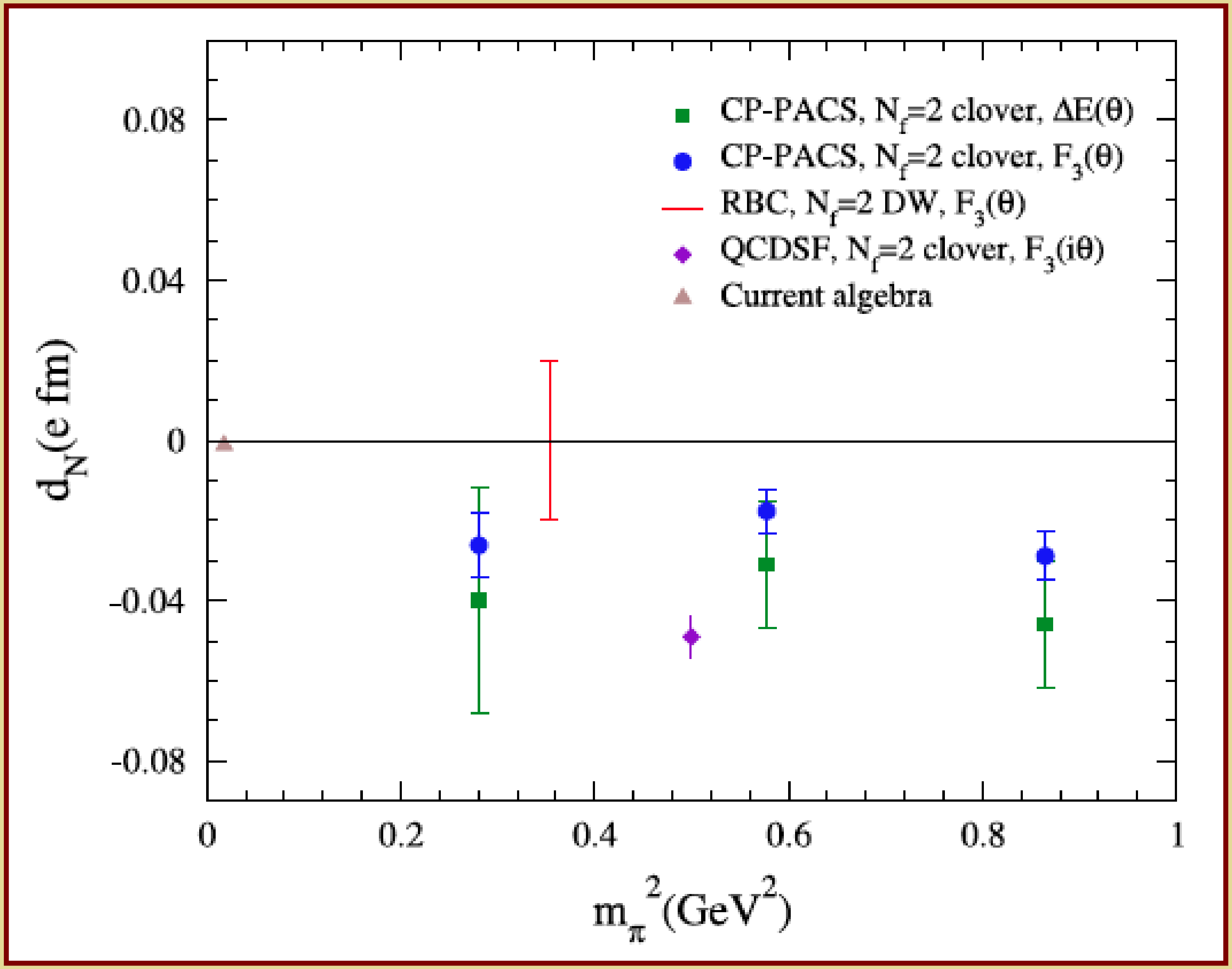
Engel, R-M, van Kolck:

Hadronic Matrix Elements



Shintani et al

Hadronic Matrix Elements

$q\gamma q$	$-0.066\,\tilde{d}^e_- - 0.199\,\tilde{d}^e_+$
BSA	$-0.120\,\tilde{d}^e_- + 0.108\,\tilde{d}^e_+$
$S(k)$	$1.538\,\tilde{d}^e_-$
acm $(\times\mu^{\text{acm}})$	$0.775\,\tilde{d}^e_- + 2.396\,\tilde{d}^e_+$
our CEDM	$(1.35 + 0.78\,\mu^{\text{acm}})\,\tilde{d}^e_- - (0.09 - 2.40\,\mu^{\text{acm}})\,\tilde{d}^e_+$
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

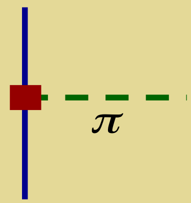
Why Multiple Systems ?

Multiple sources & multiple scales

Exploit complementary sensitivity to search for & identify CPV

Hadronic CPV: Nucleons, Nuclei, Atoms

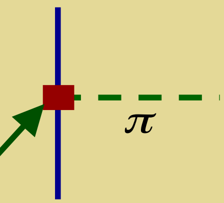
PVTV πN interaction



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

Hadronic CPV: Nucleons, Nuclei, Atoms

PVTV πN interaction

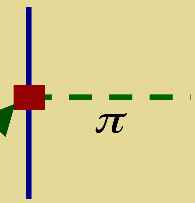


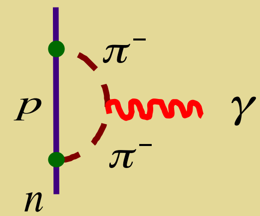
- *chromo EDM*
- *3 gluon*
- *4 quark*
- θ_{QCD}

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

Hadronic CPV: Nucleons, Nuclei, Atoms

PVTV πN interaction





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

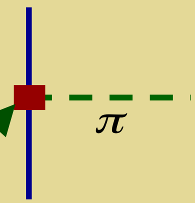
Nucleon EDM

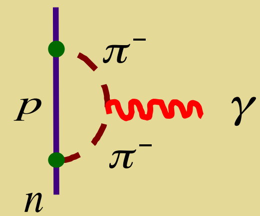
+ *quark EDM*

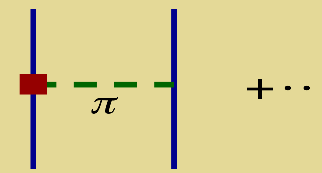
Neutron, proton & light nuclei (future), diamagnetic atoms

Hadronic CPV: Nucleons, Nuclei, Atoms

PVTV πN interaction







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

Nucleon EDM

+ quark EDM

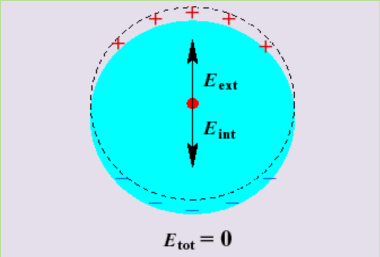
Nuclear EDM & Schiff moment

+ ~~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

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

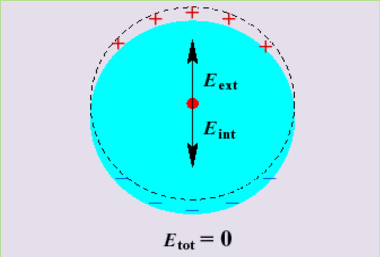
Nuclear Moments

	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…*

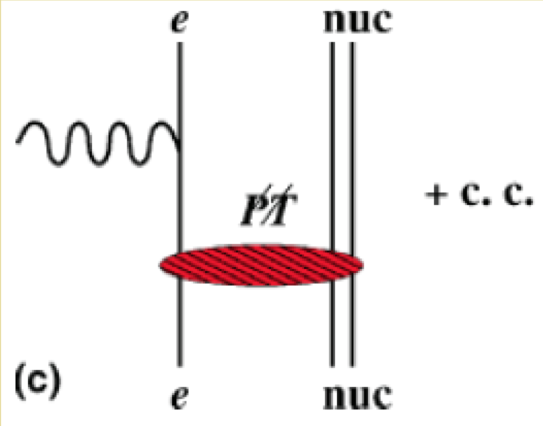
Nuclear Enhancements

Diamagnetic Systems: Schiff Moments

Schiff Screening



Atomic effect from nuclear finite size: Schiff moment

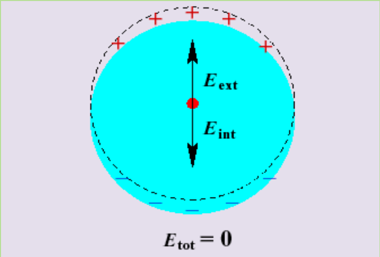


Schiff moment, MQM,…

EDMs of diamagnetic atoms (^{199}Hg)

Diamagnetic Systems: Schiff Moments

Schiff Screening



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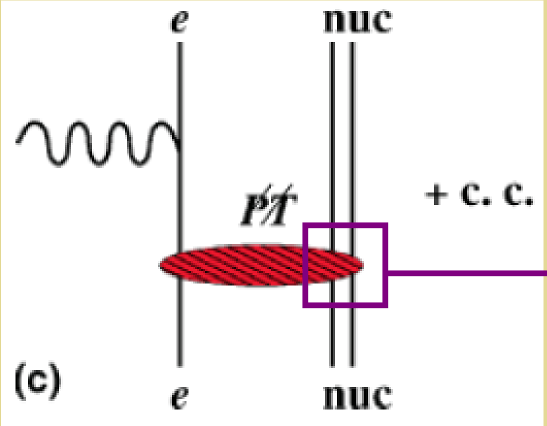


Schiff moment, MQM,…

Nuclear Schiff Moment

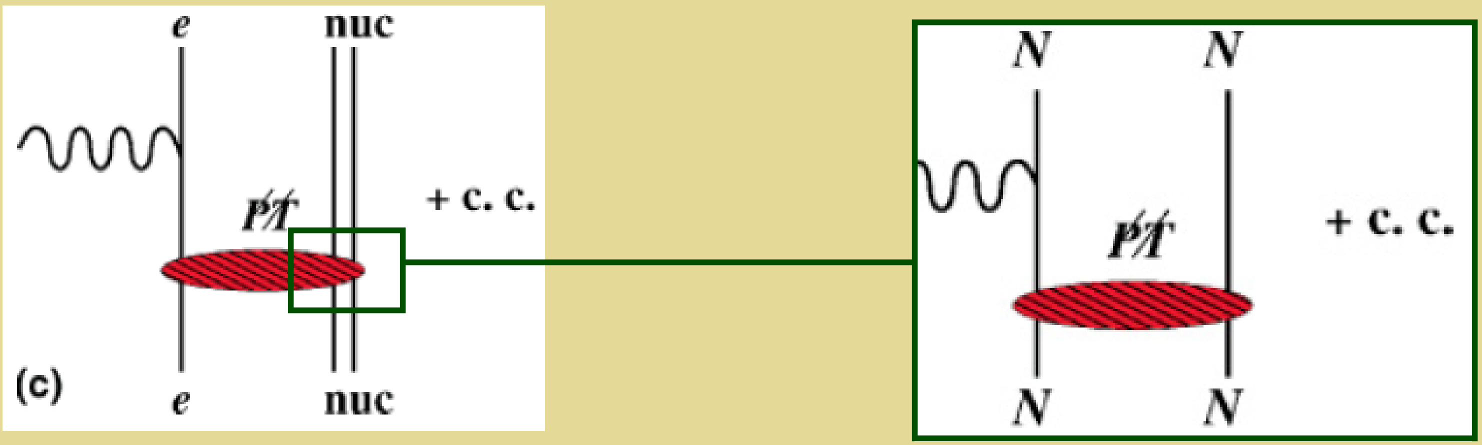
$$S \sim \int d^3x\, x^2\, \vec{x}\, \rho(\vec{x})^{\mathrm{CPV}}$$

$(R_N / R_A)^2$ suppression

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

Nuclear Enhancements



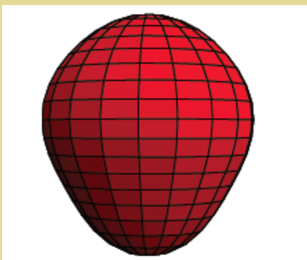
Schiff moment, MQM,…

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

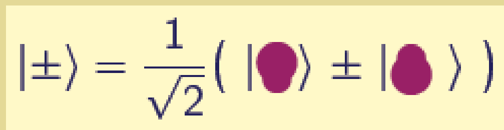
EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

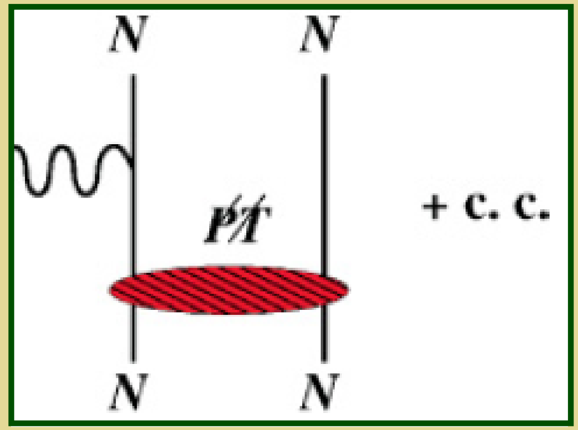
Nuclear Enhancements:
Octupole Deformation



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

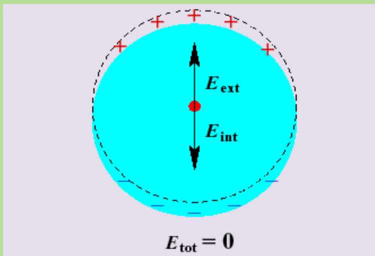
Nucl.	Best value		
	a_0	a_1	a_2
^{199}Hg	0.01	$\pm$ 0.02	0.02
^{129}Xe	−0.008	−0.006	−0.009
^{225}Ra	−1.5	6.0	−4.0

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)

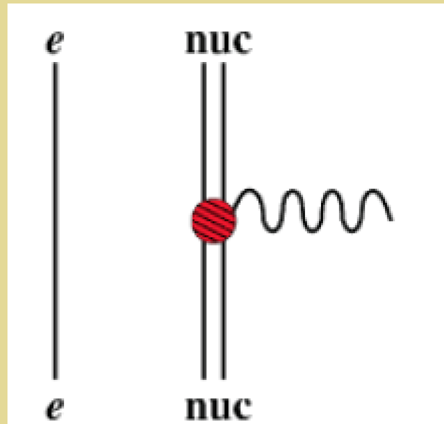
Engel, R-M, van Kolck:

Schiff Screening & Corrections

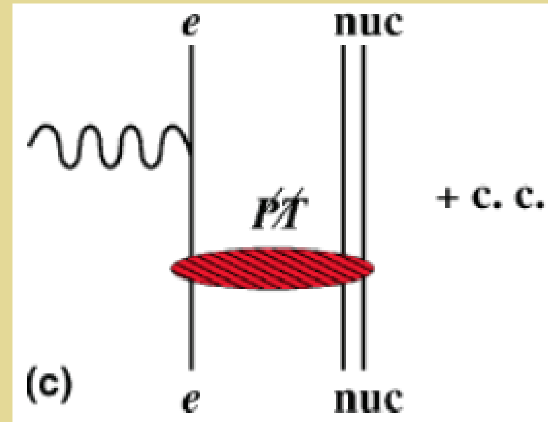
Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Screened EDM



Schiff moment, MQM,…

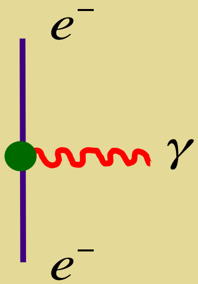
	PT	$\cancel{P}T$	$P\cancel{T}$	$\cancel{P}\cancel{T}$	
C_J	E	✖	✖	$\boxed{\text{O}}$	*EDM, Schiff…*
$T^M{}_J$	O	✖	✖	$\boxed{\text{E}}$	*MQM….*
$T^E{}_J$	✖	$\boxed{\text{O}}$	$\boxed{\text{E}}$	✖	$T^E{}_{J=1} \otimes T^E{}_{J=2}$?

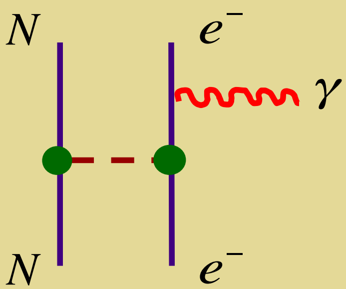
EDMs of diamagnetic atoms (^{199}Hg)

Inoue

IV. Theory-Experiment Interface

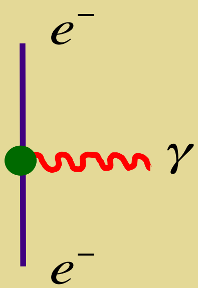
Paramagnetic Systems: Two Sources



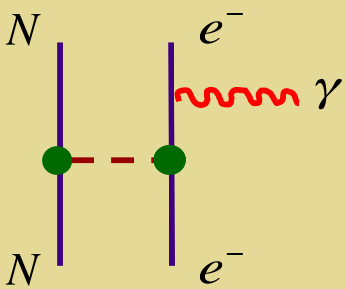


Tl, YbF, ThO…

Paramagnetic Systems: Two Sources



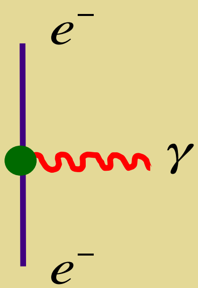
$$d_f = -(1.13 \times 10^{-3}\, e\,\mathrm{fm}) \left(\frac{v}{\Lambda}\right)^2 Y_f\, \delta_f$$



$$C_S^{(0)} = -g_S^{(0)} \left(\frac{v}{\Lambda}\right)^2 \mathrm{Im}\, C_{eq}^{(-)}$$

Tl, YbF, ThO…

Paramagnetic Systems: Two Sources



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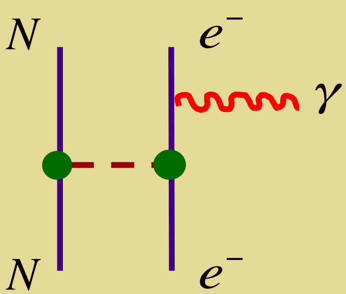

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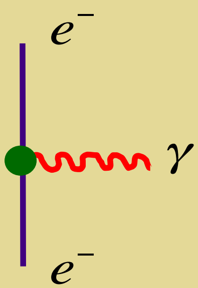

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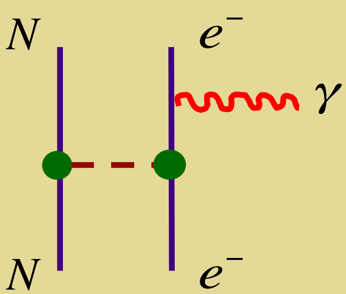
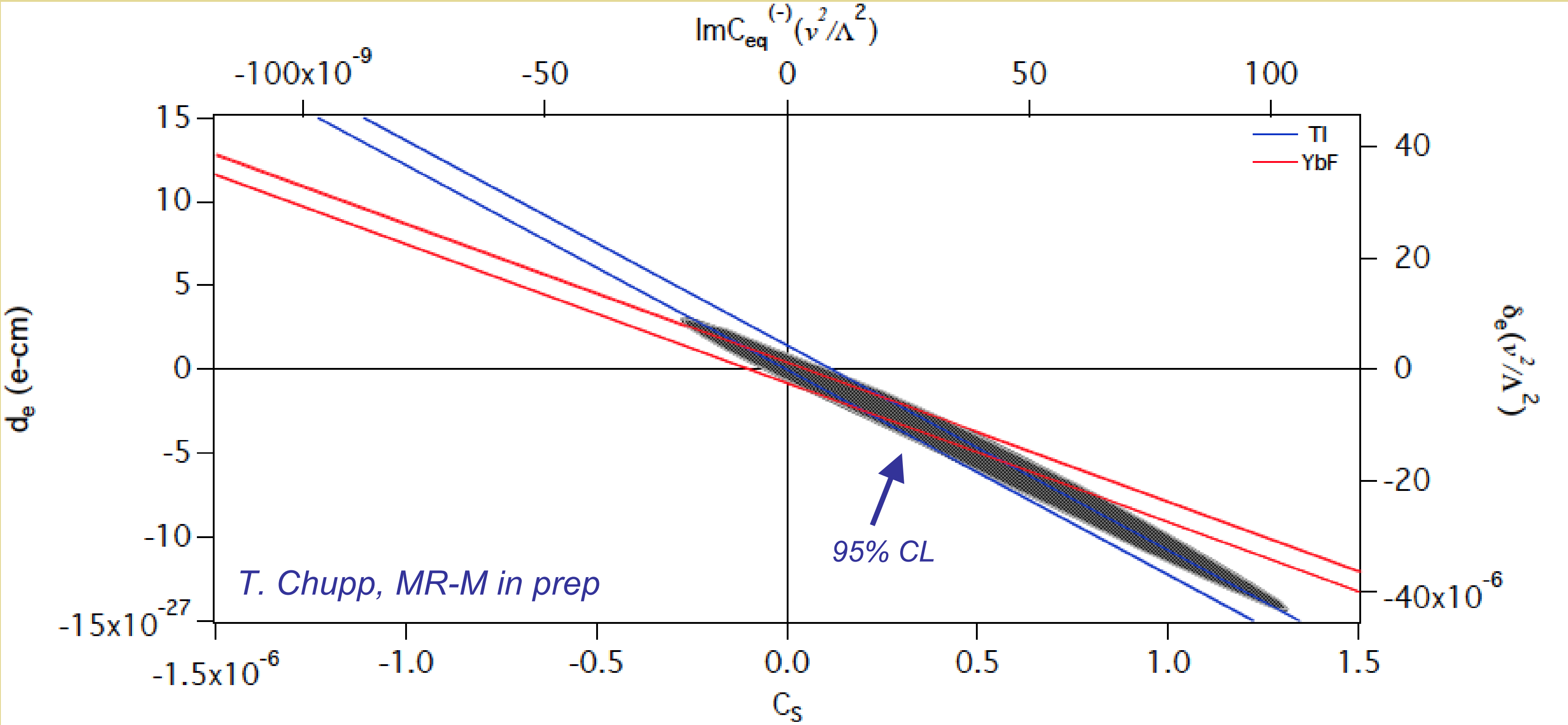


$$C_S^{(0)} = -g_S^{(0)} \left(\frac{v}{\Lambda}\right)^2 \mathrm{Im}\, C_{eq}^{(-)}$$

~ 100 x greater sensitivity to C_{eq} than to δ_e

Tl, YbF, ThO…

Paramagnetic Global Fit



- *Im C_{eq} $(v/\Lambda)^2 < 5.6 \times 10^{-8}$*
- *δ_e $(v/\Lambda)^2 < 2.2 \times 10^{-5} \leftrightarrow d_e < 7.3 \times 10^{-27}$ e cm*

See also Jung '13

Diagmagetic atoms and nucleons

T.C. & M. Ramsey-Musolf – in preparation

	θ_{QCD}	$d_n^{\ 0}$	$d_n^{\ 1}$	C_T	$g_\pi^{\ 0}$	$g_\pi^{\ 1}$
neutron	x	1	-1			
Xe, Hg, TlF	x			x	x	x
Ra, Rn	x			x	x	x
proton	x	1	+1			
d, ^{3}H, ^{3}He	x				x	x

Schiff Moment

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

$$d_n \approx \bar{d}_n + (1.44 \times 10^{-14} g_\pi^{(0)} - 8.3 \times 10^{-16} g_\pi^{(1)})\ \mathrm{e-cm}$$

$$\bar{g}^0_{CP} \approx 0.027\ \theta_{QCD}$$

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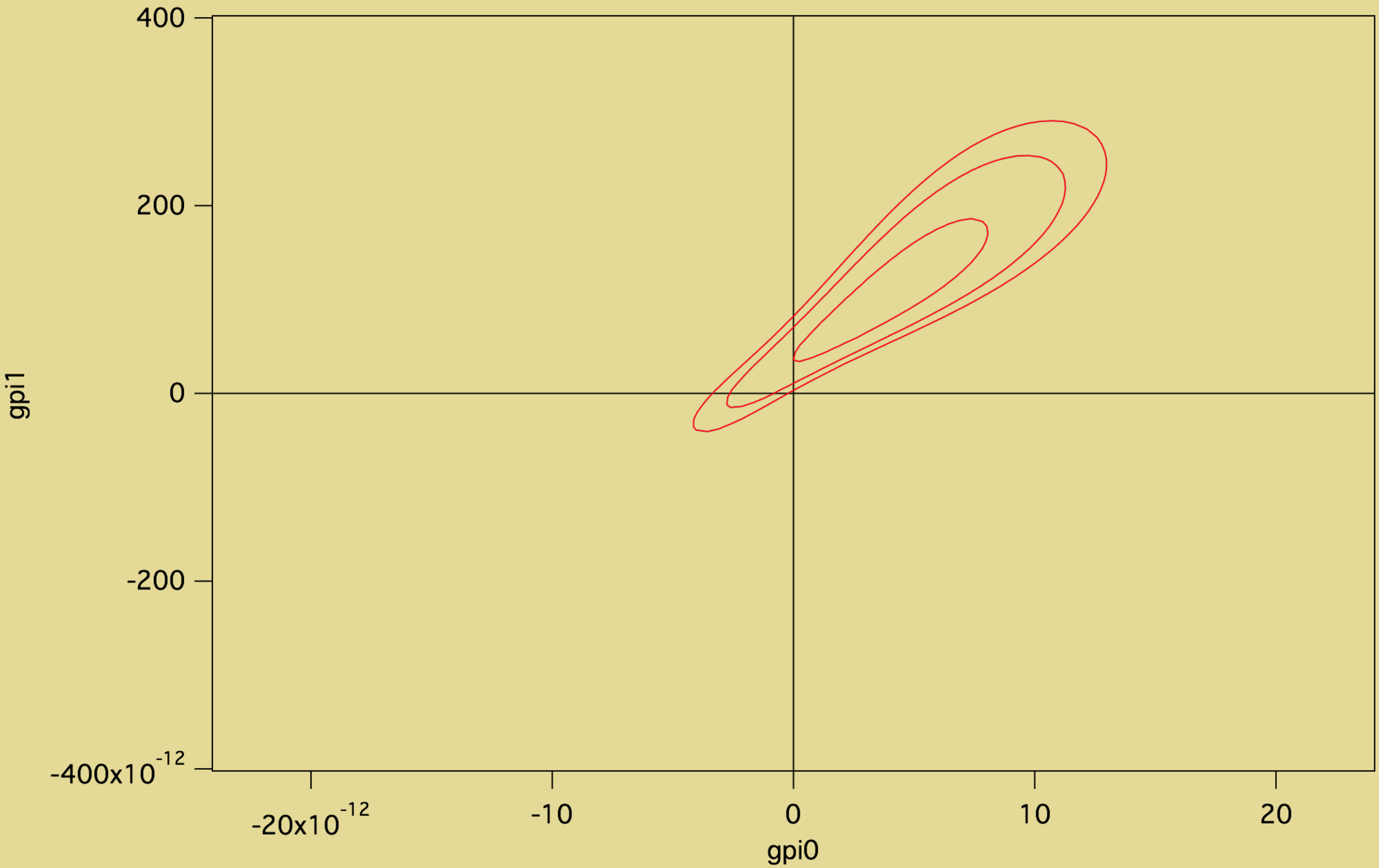

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Questions for Week Three

I. *What are the most significant implications of present & prospective EDM searches ?*

II. *What are the primary theoretical challenges & strategies for addressing them ?*

III. *What do we learn from existing and planned experiments and what are the most compelling new directions ?*

Thanks !

- *MITP Faculty & Staff*
- *T. Chupp*

Further reading:

- *EDM: 1303.2371, hep-ph/0504231*
- *Project X: 1306.5009*