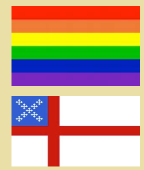
Hadronic Tests of CP & T

M.J. Ramsey-Musolf

U Mass Amherst



AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

ACFI Workshop, Amherst
November 2014

Goals for this talk

- *Set the context: T- and C-violation in EFT framework*
- *Review the present & prospective EDM results & implications*
- *Review the theoretical treatment of P-conserving T- and C-violation*
- *Pose questions for discussion*

Key Questions for Workshop: A Personal View

- *Are nuclear and hadronic probes of P-conserving T- or C-violation relevant in view of present & prospective EDM results ?*
- *If so, under what scenarios ?*
- *Is there any relevant window for non-EDM probes of P- and T-violation ?*
- *Are there new opportunities for nuclear and hadronic probes of ultra-light weakly coupled bosons ?*

Key Questions for Workshop: A Personal View

This talk

- *Are nuclear and hadronic probes of P-conserving T- or C-violation relevant in view of present & prospective EDM results ?*
- *If so, under what scenarios ?*
- *Is there any relevant window for non-EDM probes of P- and T-violation ?*
- *Are there new opportunities for nuclear and hadronic probes of ultra-light weakly coupled bosons ?*

Outline

I. Electric Dipole Moments

II. P-conserving C- or T-violation

III. Summary and questions

III. Electric Dipole Moments

- *Discovery potential & interpretation: need for searches in multiple systems*
- *Benchmark sensitivities: three examples*
- *Challenges & new theoretical developments*

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	3.1×10^{-29}	10^{-33}	10^{-29}
ThO	8.7×10^{-29} **	10^{-38}	10^{-28}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** e^- equivalent

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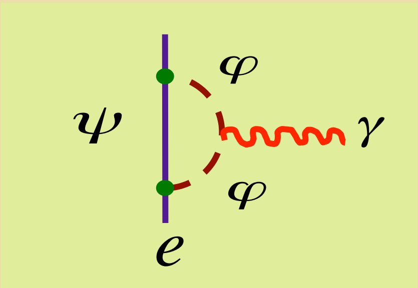
Mass Scale Sensitivity



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

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

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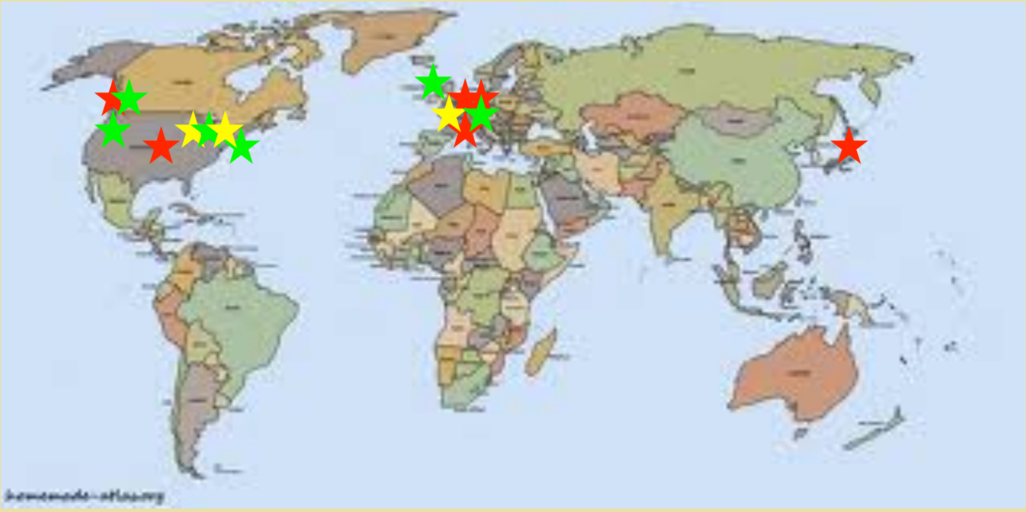


★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

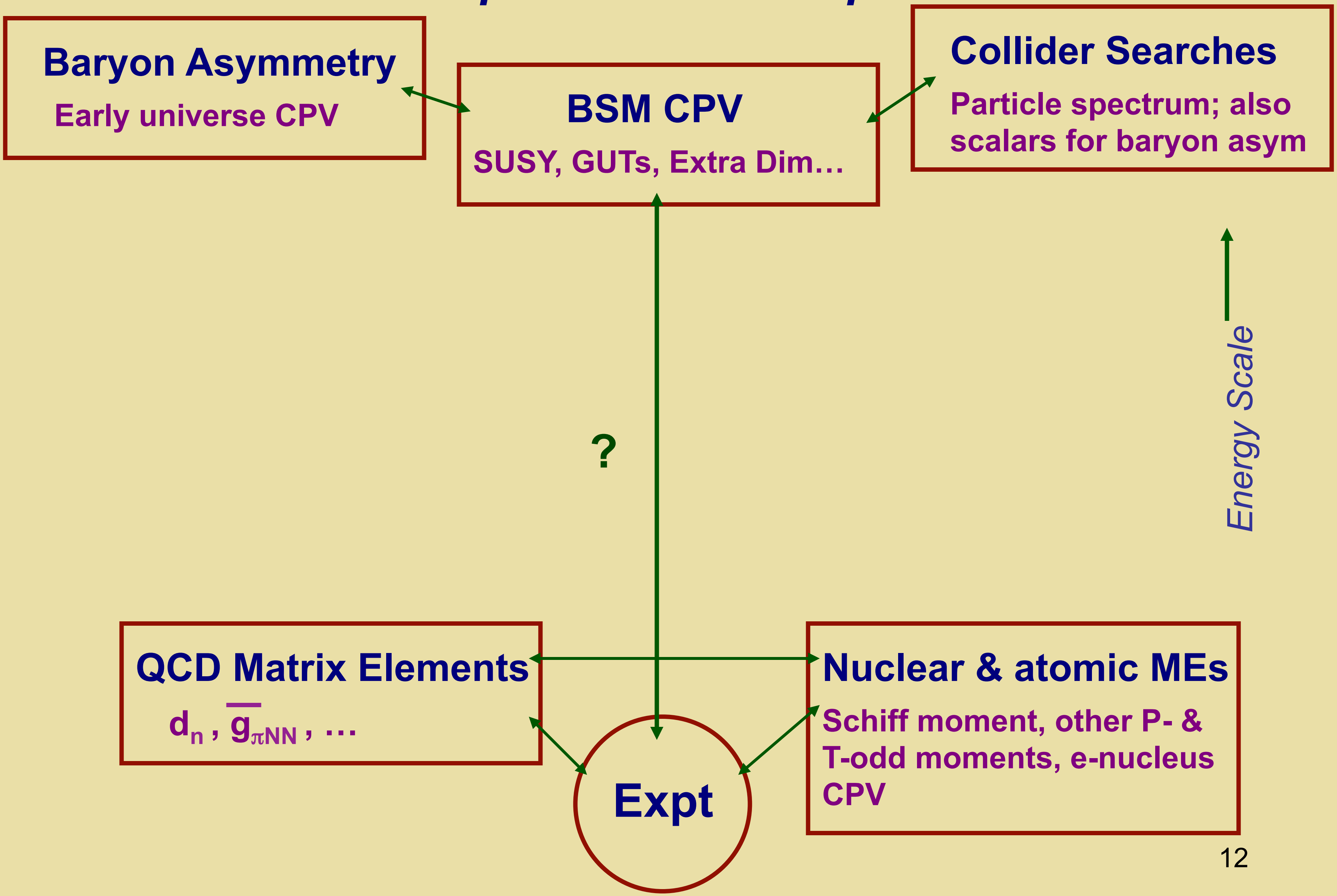
Not shown: muon

Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

EDM Interpretation & Multiple Scales

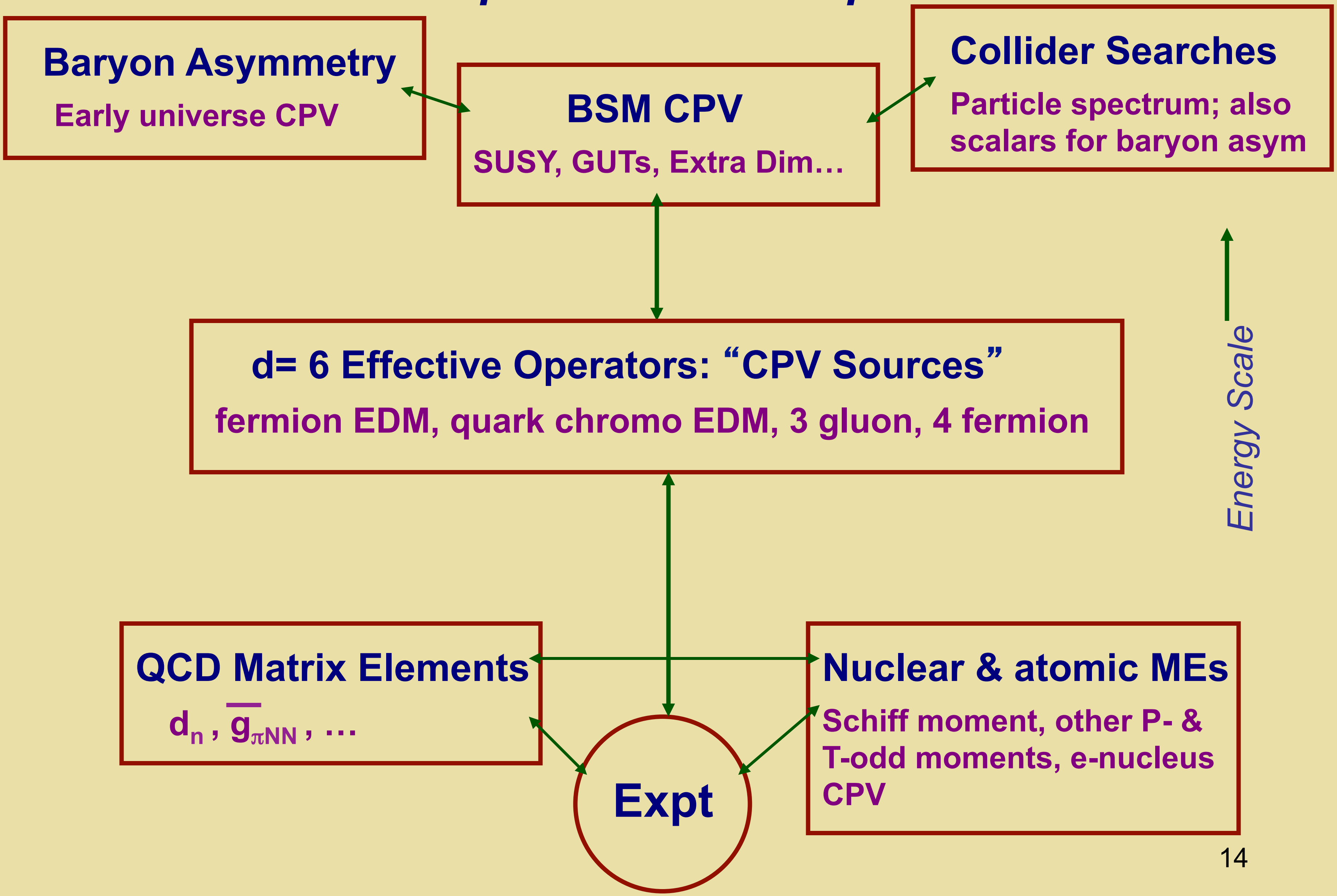


Effective Operators: The Bridge

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

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

EDM Interpretation & Multiple Scales



Wilson Coefficients: 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)

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δ_f	*fermion EDM*	*(3)*
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12 total + $\bar{\theta}$

light flavors only (e,u,d)

Complementary searches needed

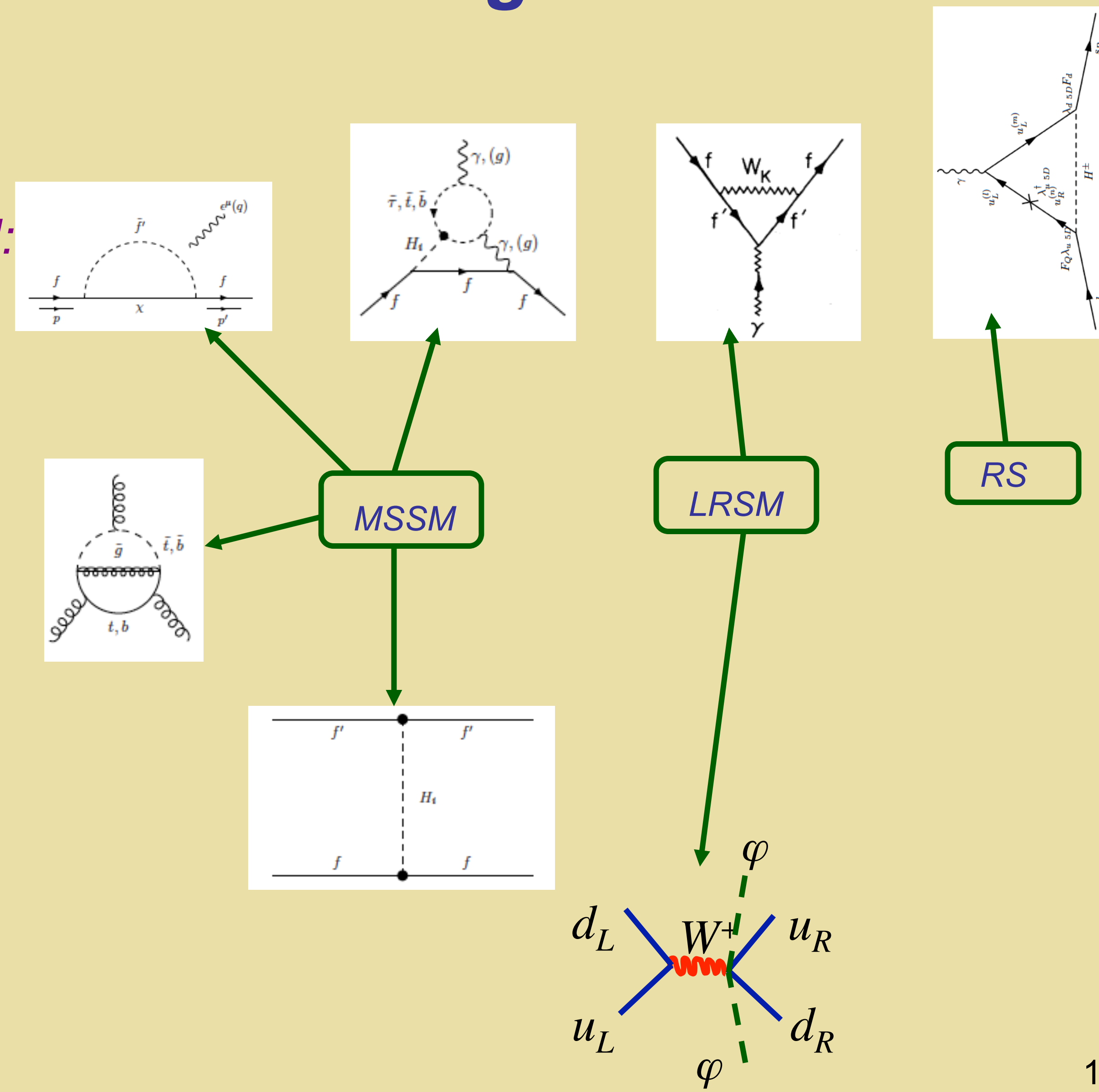
BSM Origins

EDM: γff CEDM: gff

Weinberg ggg:

Four fermion

udHH



Complementarity: Three Illustrations

- *CPV in an extended scalar sector (2HDM): "Higgs portal CPV"*
- *Weak scale baryogenesis (MSSM)*
- *Model-independent*

Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

$\lambda_{6,7}$ = 0 for simplicity

$$V = \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right]$$
$$-\frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}.$$

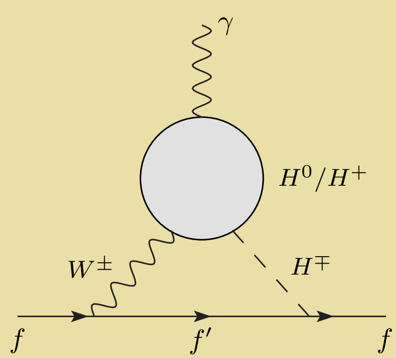
$$\begin{aligned}\delta_1 &= \text{Arg}\left[\lambda_5^*(m_{12}^2)^2\right] \ , \\ \delta_2 &= \text{Arg}\left[\lambda_5^*(m_{12}^2)v_1 v_2^*\right]\end{aligned}$$

$\xrightarrow{\text{EWSB}}$

$$\delta_2 \approx \frac{1 - \left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}{1 - 2\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}\delta_1$$

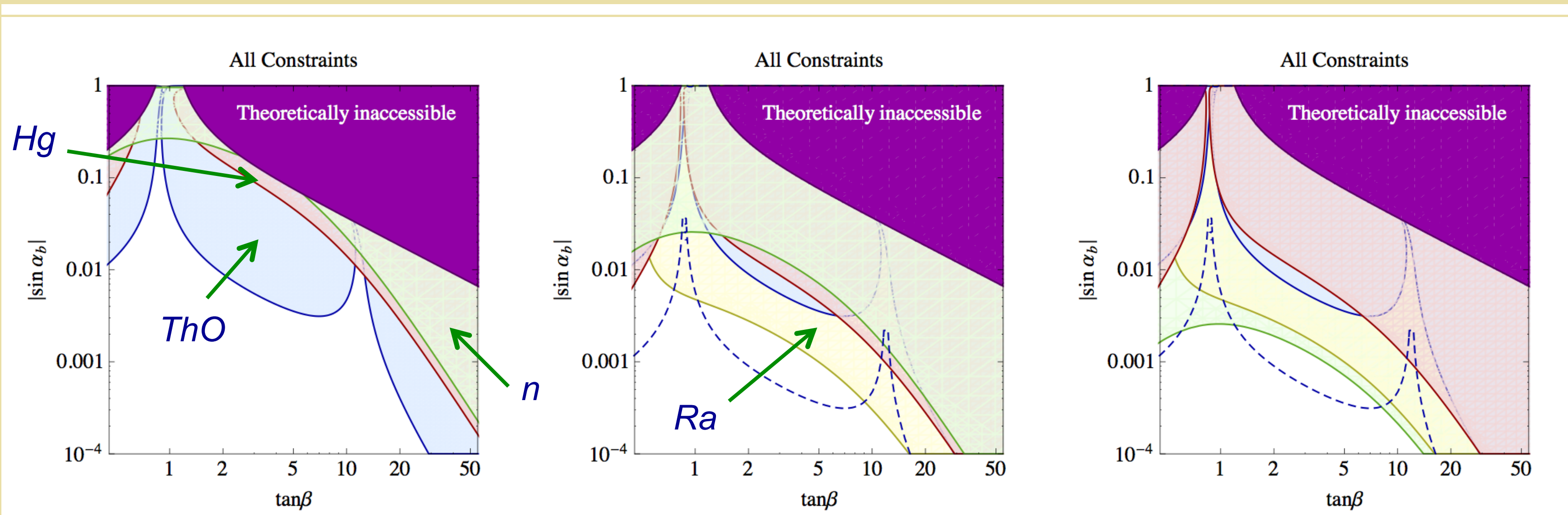
Viable EWB & CPV:

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



Future Reach: Higgs Portal CPV

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*



Present

Future:

d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

Future:

d_n x 0.01

d_A(Hg) x 0.1

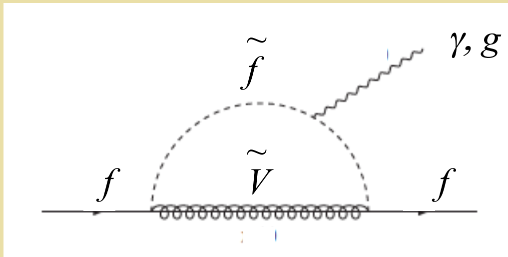
d_{ThO} x 0.1

d_A(Ra)

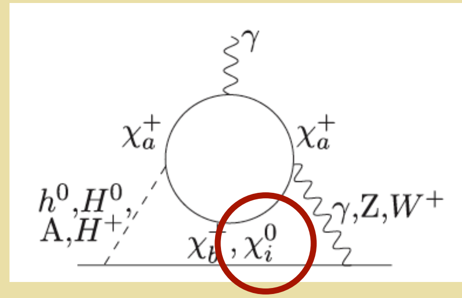
sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

EDMs & EW Baryogenesis: MSSM

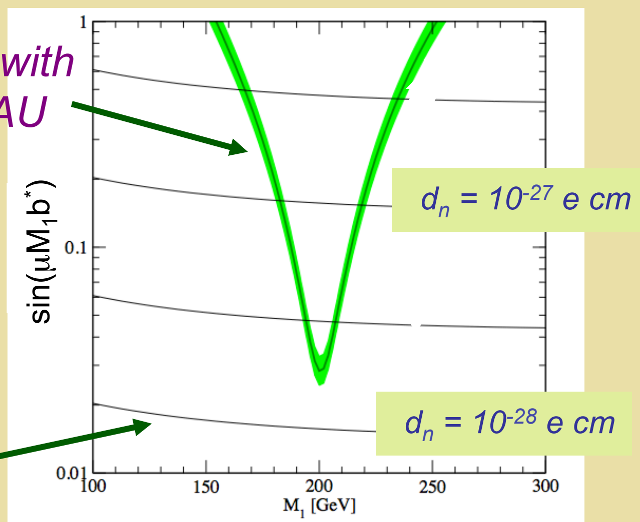


Heavy sfermions: LHC consistent & suppress 1-loop EDMs

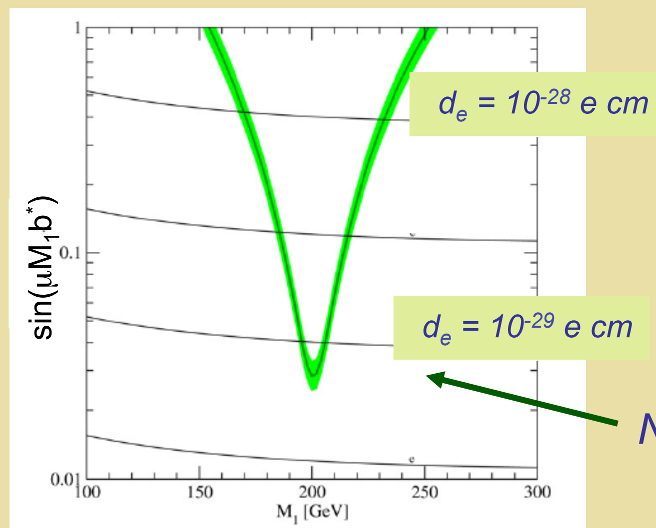


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU



Next gen d_n

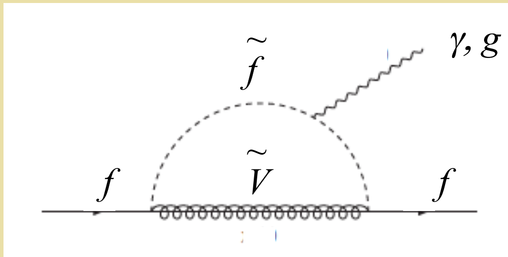


ACME: ThO

Next gen d_e

Li, Profumo, RM '09-'10

EDMs & EW Baryogenesis: MSSM



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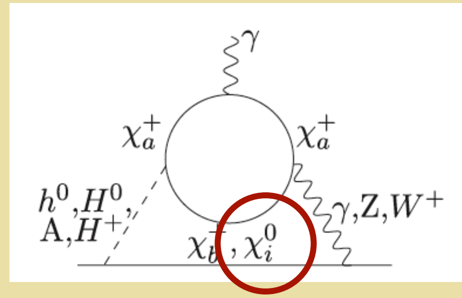

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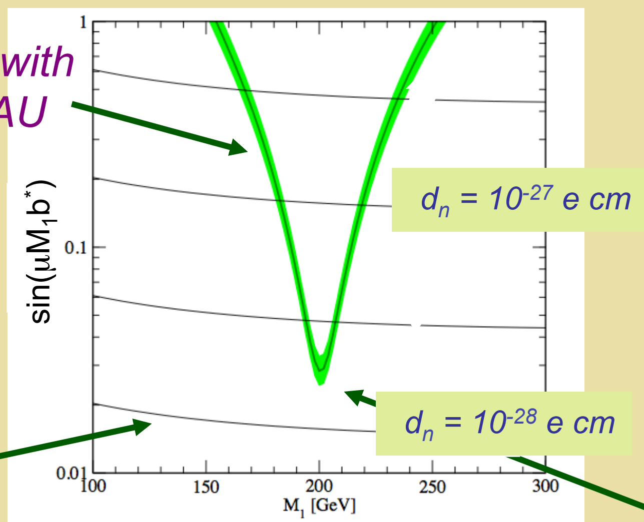
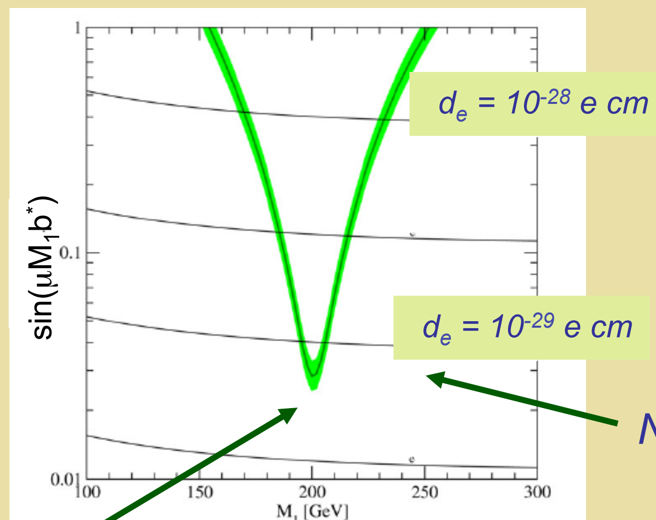


Next gen d_n



ACME: ThO

Next gen d_e

Li, Profumo, RM '09-'10

Compressed spectrum (stealthy SUSY)

Wilson Coefficients: Model Independent

δ_f	fermion EDM	(3)
$\tilde{\delta}_q$	quark CEDM	(2)
$C_{\tilde{G}}$	3 gluon	(1)
C_{quqd}	non-leptonic	(2)
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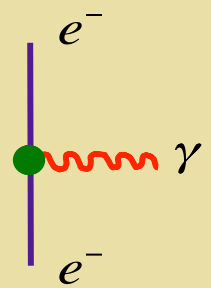
12 total + $\overline{\theta}$

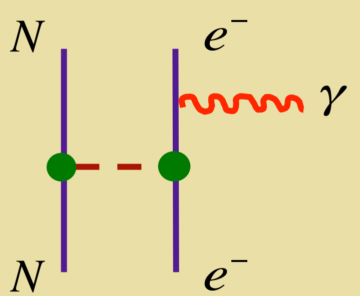
light flavors only (e,u,d)

Paramagnetic Systems: Two Sources

Electron EDM



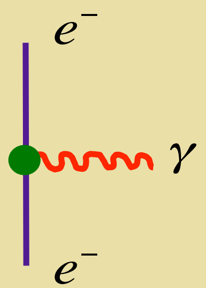
(Scalar q) x (PS e^-)



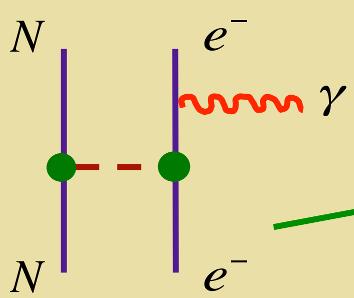
Tl, YbF, ThO…

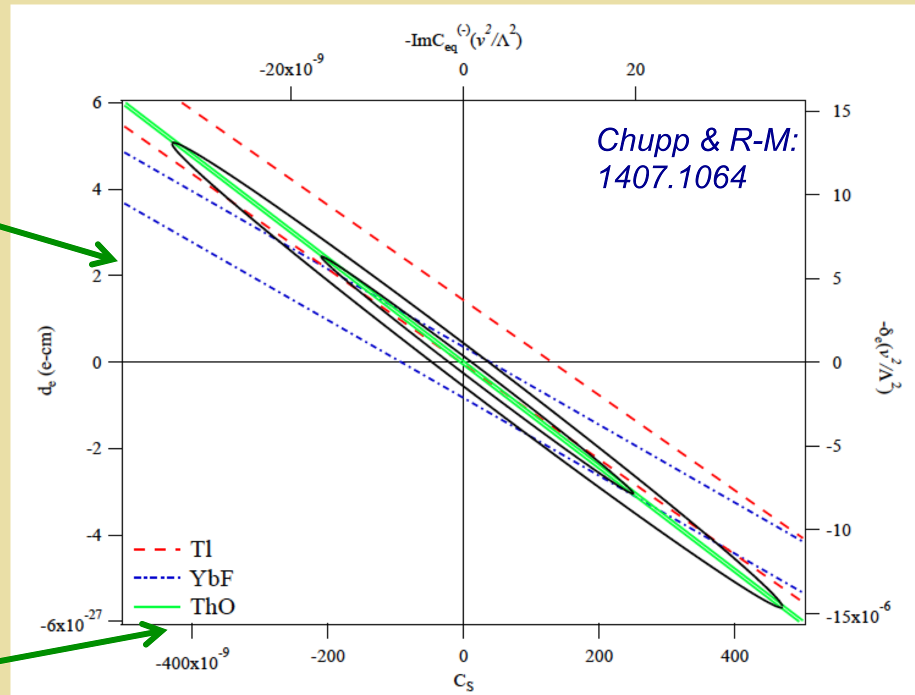
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e⁻)





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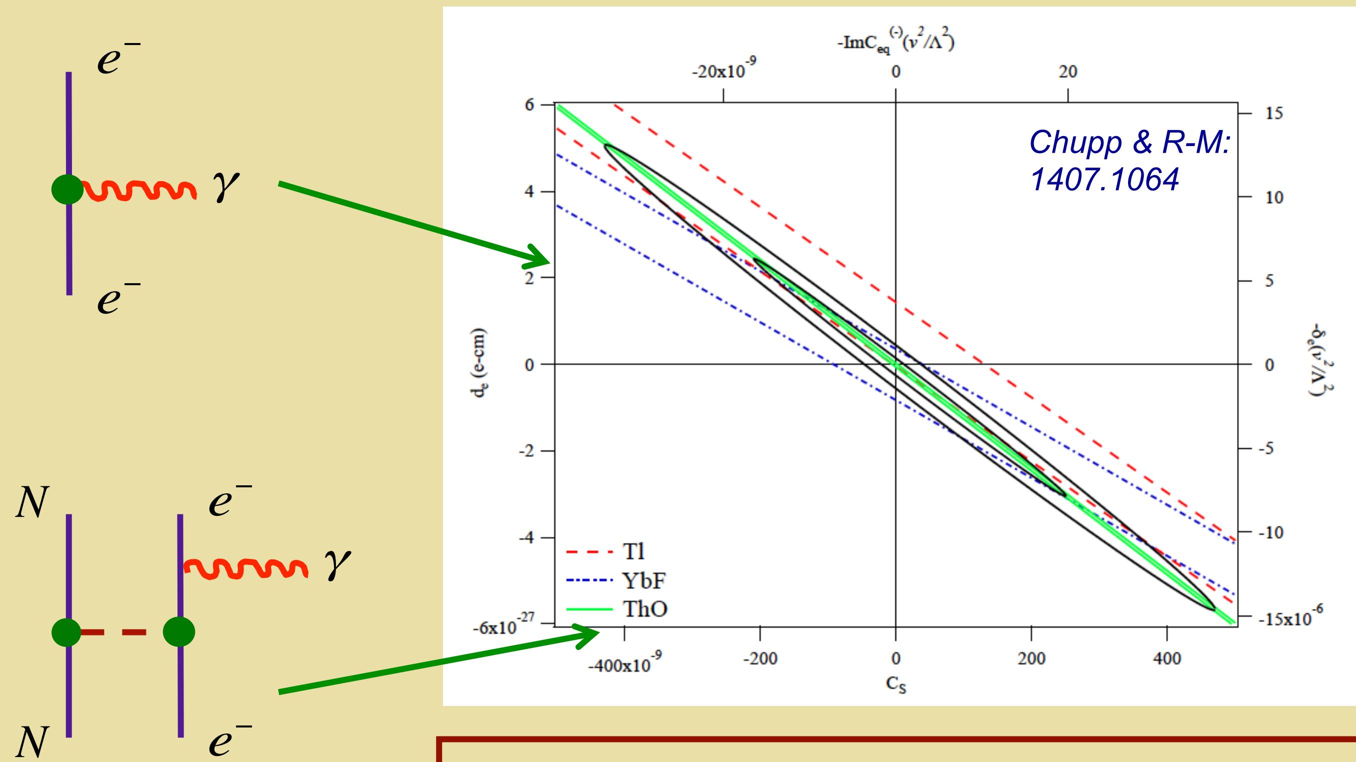
Paramagnetic Systems: Two Sources

Electron EDM

(Scalar q) x (PS e⁻)



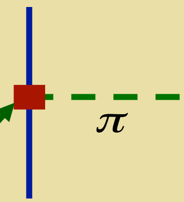
$$\Lambda \gtrsim (1.5\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}} \qquad \text{Electron EDM (global)}$$

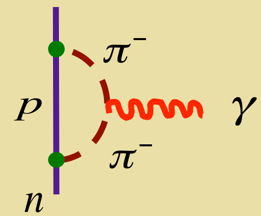
$$\Lambda \gtrsim (1300\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}} \qquad C_S\ \text{(global)}$$

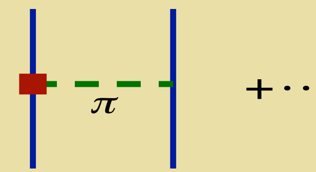
Tl, YbF, ThO…

Hadronic CPV: Nucleons, Nuclei, Atoms

PVTV πN interaction







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

Nucleon EDM

+ quark EDM

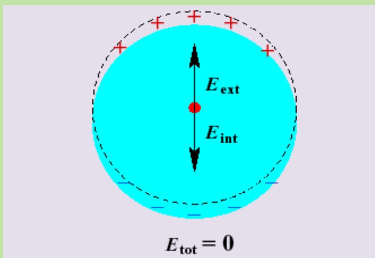
Nuclear EDM & Schiff moment

+ ~~quark EDM~~

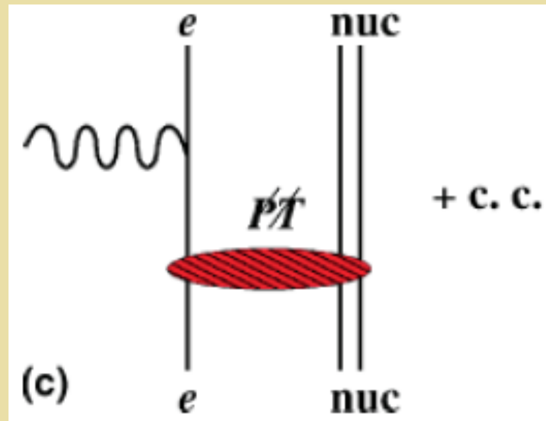
Neutron, proton & light nuclei (future), diamagnetic atoms

Diamagnetic Systems: P- & T-Odd Moments

Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Schiff moment, MQM,…

EDMs of diamagnetic atoms (^{199}Hg)

Diamagnetic Systems

Nuclear Moments

	PT	$\cancel{P}T$	$P\cancel{T}$	$\cancel{P}\cancel{T}$
C_J	E	✖	✖	O
$T^M{}_J$	O	✖	✖	E
$T^E{}_J$	✖	O	E	✖

Diamagnetic Systems

Nuclear Moments

	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….*
$T^E{}_J$	✖	$\boxed{\text{O}}$	E	✖	*Anapole…*

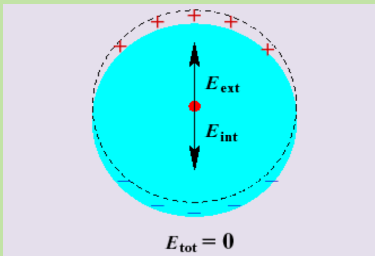
Diamagnetic Systems

Nuclear Moments

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

Diamagnetic Systems: Schiff Moments

Schiff Screening



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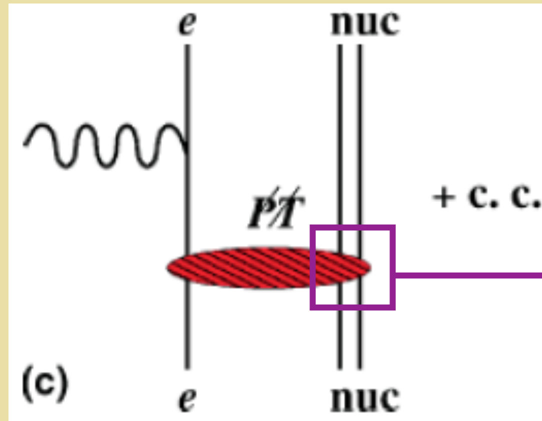


Schiff moment, MQM,…

Nuclear Schiff Moment

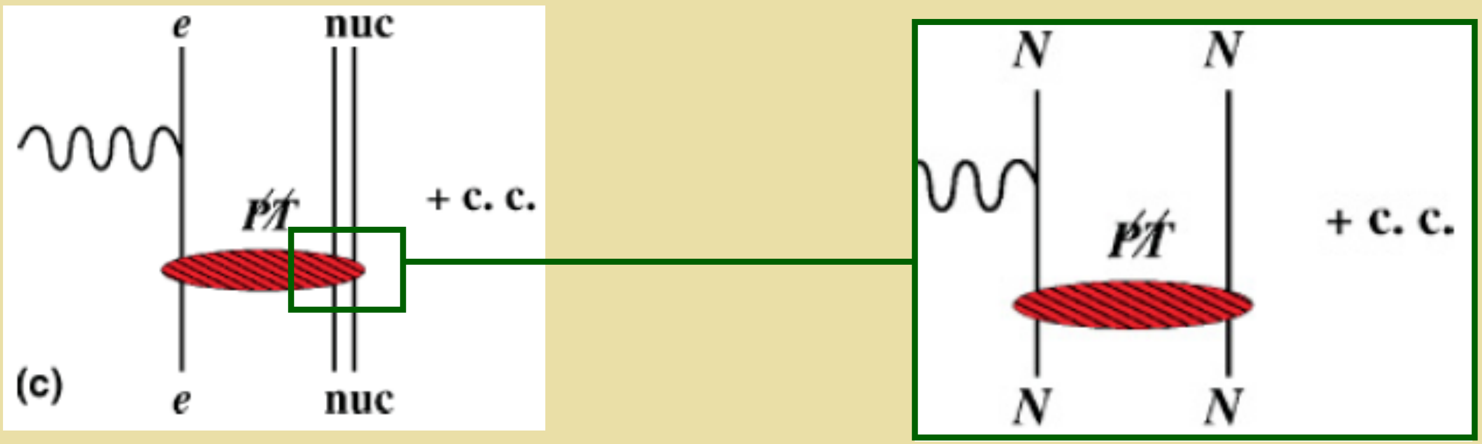
$$S \sim \int d^3x\, x^2\, \vec{x}\, \rho(\vec{x})^{\mathrm{CPV}}$$

$(R_N / R_A)^2$ suppression

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

Nuclear Enhancements



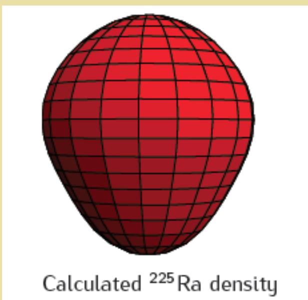
Schiff moment, MQM,…

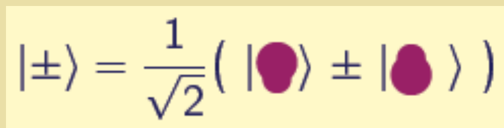
Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

EDMs of diamagnetic atoms (^{199}Hg)

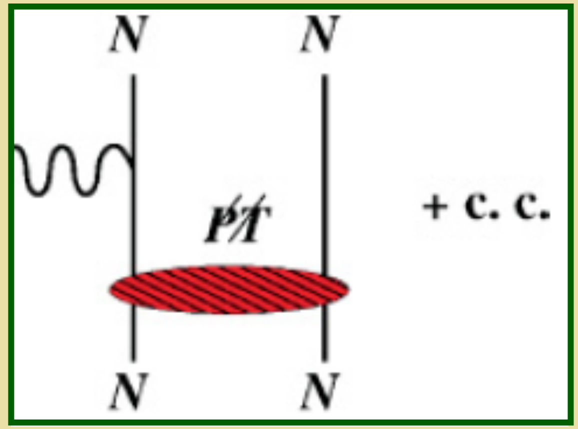
Nuclear Schiff Moment

Nuclear Enhancements:
Octupole Deformation


Calculated ^{225}Ra density



Opposite parity states mixed by H^{TVPV}



"Nuclear amplifier"

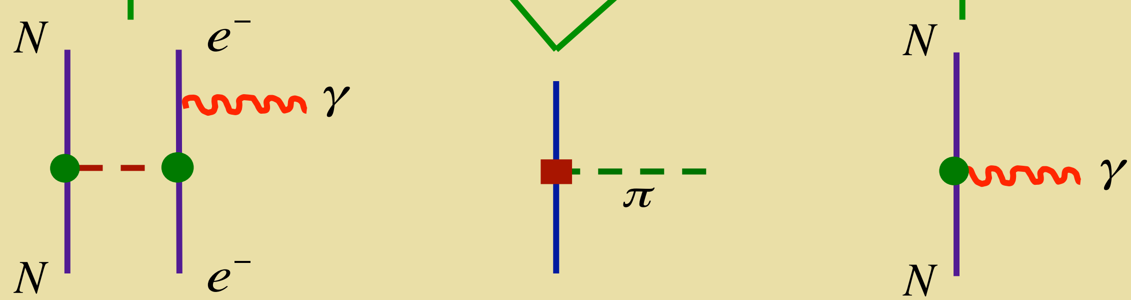
Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

EDMs of diamagnetic atoms (^{225}Ra)

Thanks: J. Engel

Diamagnetic Global Fit

	$C_T \times 10^7$	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$\bar{d}_n$ (e-cm)
Exact solution	1.265	-6.687×10^{-10}	1.4308×10^{-10}	9.878×10^{-24}
Range from best values of α_{ij}	$(-7.6 - 9.5)$	$(-5.0 - 4.0) \times 10^{-9}$	$(-0.2 - 0.4) \times 10^{-9}$	$(-5.9 - 7.4) \times 10^{-23}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = -4.9 \times 10^{-17}$	$(-7.6 - 8.4)$	$(-7.0 - 4.0) \times 10^{-9}$	$(0 - 0.2) \times 10^{-9}$	$(5.9 - 10.4) \times 10^{-23}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = +1.6 \times 10^{-17}$	$(-9.2 - 12.4)$	$(-4.0 - 4.0) \times 10^{-9}$	$(-0.4 - 0.8) \times 10^{-9}$	$(-5.9 - 5.9) \times 10^{-23}$
Range from full variation of α_{ij}	$(-10.8 - 15.6)$	$(-10.0 - 8.1) \times 10^{-9}$	$(-0.6 - 1.2) \times 10^{-9}$	$(-12.0 - 14.8) \times 10^{-23}$



Tensor eq　　*TVPV πNN*　　*Short distance d_n*

Diamagnetic Global Fit

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Isoscalar CEDM

$$\boxed{\tilde{\delta}_q^{(+)} \left(\frac{v}{\Lambda}\right)^2 \lesssim 0.01 \qquad \Lambda \gtrsim (2\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}}$$

Caveat: Large hadronic uncertainty

Chupp & R-M: 1407.1064

Nuclear Matrix Elements

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

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

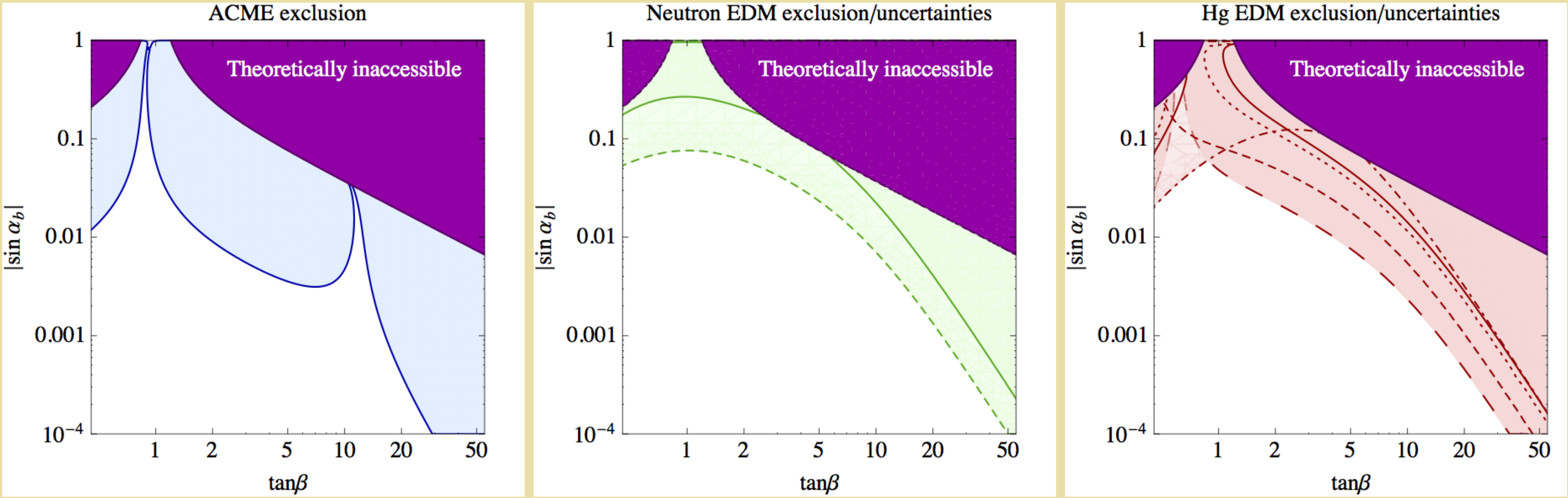
Range		
a_0	a_1	a_2
0.005–0.05	−0.03–(+0.09)	0.01–0.06
−0.005–(−0.05)	−0.003–(−0.05)	−0.005–(−0.1)
−1–(−6)	4–24	−3–(−15)

Engel, R-M, van Kolck '13

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

$\lambda_{6,7}$ = 0 for simplicity



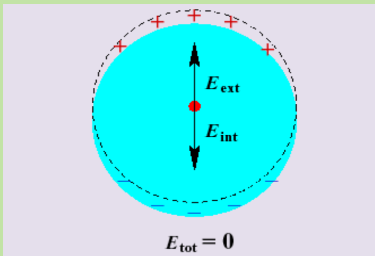
Present

$\sin \alpha_b$: CPV scalar mixing

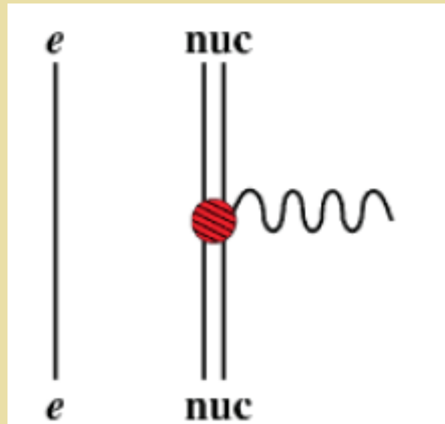
Inoue, R-M, Zhang: 1403.4257

Schiff Screening & Corrections

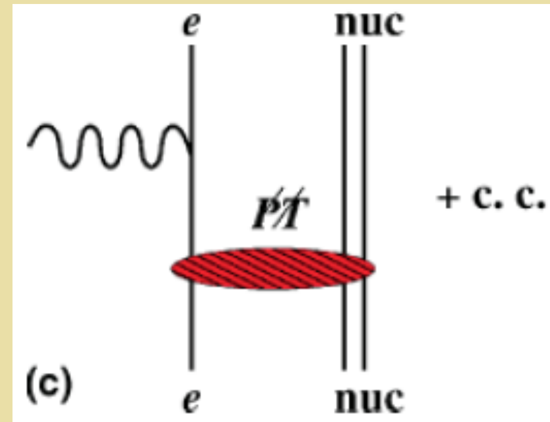
Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Screened EDM



Schiff moment, MQM,…

	PT	$\not{P}T$	$P\not{T}$	$\not{P}\not{T}$	
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

Electric Dipole Moments

- *Present EDM reach ranges from few to ~ 1000 TeV*
- *Next generation experiments will increase mass reach by an order of magnitude; sensitivity scales as* $(\upsilon / \Lambda)^2$
- *BSM scenarios & matter-antimatter asymmetry strongly motivate effort required to achieve next generation sensitivity*
- *Diamagnetic atom sensitivity may be even stronger due to previously neglected* $T^E_{J=1} \otimes T^E_{J=2}$ *contribution*

II. P-Conserving T- and C-Violation

- *Motivation & theoretical background*
- *Relating TVPC and CVPC interactions and EDMs in the EFT framework*
- *Open questions*

C and P Symmetries (assuming CPT)

D. Mack, MENU

C	**C, P, CP** Strong, EM Big SM "background" in any search for new forces	**C, ~~P~~, ~~CP~~** Weak (loop-level) Small SM "background". New sources of ~~P~~, ~~CP~~ constrained by EDM searches
~~C~~	**~~C~~, P, ~~CP~~** Weak (loop-level) Small SM "background". New sources of P, ~~CP~~ less constrained by EDM searches	**~~C~~, ~~P~~, CP** Weak Big SM "background" in any search for new forces New sources of PV also constrained by amplitude-sensitive PV asymmetry measurements

C Violation Basics

D. Mack, MENU

The charge conjugation operator C reverses all generalized charges, effectively replacing a particle by its anti-particle.

C violation is known only in

1. Weak interactions at tree level which violate P (hence conserving CP)
2. Weak interactions at loop level which violate CP

Both C- and CP-violation are among the Sakharov criteria for baryogensis.

Everybody knows strong and EM forces conserve C …. but direct bounds on C violation in these amplitudes are only ~0.5%. How to improve this?

It is surprisingly hard:

i. Only a few neutral particles are states of good C and thus suitable for tests (γ, π^0, η, J/ψ, or a self-conjugate system like e^+e^-).

ii. Most of the particles of good C appropriate for initial states aren't easy to make in large quantities (and with sufficiently low backgrounds).

D. Mack, MENU

η Decays Testing C Violation

Why η's?

- The η full width is only 1.3 keV . It cannot decay by the isospin conserving strong interaction. This means that achievable BR's of 10^{-6} to 10^{-7} probe the weak scale.
- η decays are flavor-conserving, a sector less thoroughly studied than $\Delta S = 1$, etc.
- Theory calculations predict large mass enhancements, hence relatively crude η decay BR upper limits place tighter constraints than more precise π^0 decay BR upper limits.
- The η has a significant s-sbar content, unlike the π^0 or nucleon.

3γ	$< 1.6 \cdot 10^{-5}$	3
"$\pi^0\gamma$"	$< 9 \cdot 10^{-5}$	
$2\pi^0\gamma$	$< 5 \cdot 10^{-4}$	5
$3\gamma\pi^0$	Nothing published	
$3\pi^0\gamma$	$< 6 \cdot 10^{-5}$	7
$3\gamma 2\pi^0$	Nothing published	

PDG 2012

Considerations of acceptance and phase space have focused us on $\eta \rightarrow 3\gamma$ and $\eta \rightarrow 2\pi^0\gamma$.

Most C test channels are <u>all-neutral</u> except for $\eta \rightarrow \pi^0\gamma^* \rightarrow \pi^0 l^+ l^-$.

D. Mack, MENU

Theory Issues for C Violation

Placing the tightest *__direct__* *limits on C violation sounds interesting to experimentalists, but what about theorists?*

- *Little literature on C violation with P conservation.*

  (appropriate models for this would be non-renormalizable - Herczeg)

- *Some literature on T violation with P conservation*

  (under CPT, equivalent to C violation with P conservation).

- *By contrast, tremendous literature on CP violation and EDM's.*

- *C violation without P violation is apparently not on the radar of those working with SUSY, leptoquarks.*

- *C violation does arise in discussions of violation of Lorentz invariance, but the predicted C violating η decay BR's are effectively zero for any experiment, ever.*

We'd like theorists studying T violation with P conservation to know that η decays can place tight limits in an isospin-violating sector.

TVPC Interactions: Background

TVPC Interactions

- *Herczeg: No renormalizable TVPC boson-exchange interactions involving only SM fields [Hyperfine Int, **75** (1992) 127]*

- *Low-energy ($k << \Lambda_{EW}$) four fermion flavor conserving interactions first arise at d=7 :*

$$\boxed{\mathcal{O}_7^{ff'} = C_7^{ff'}\, \bar{\psi}_f \overleftrightarrow{D}_\mu \gamma_5 \psi_f \bar{\psi}_{f'} \gamma^\mu \gamma_5 \psi_{f'}}$$

Khriplovich '91
Conti & Khriplovich '92
Engel, Frampton, Springer '96

TVPC Interactions, cont'd

- *Additional low-energy (k << Λ_{EW}) d=7 interactions:*

$$\mathcal{O}_7^{\gamma g} = C_7^{\gamma g}\,\bar{\psi}\sigma_{\mu\nu}\lambda^a\psi F^{\mu\lambda}G^{a\nu}_{\lambda}$$

$$\mathcal{O}_7^{\gamma Z} = C_7^{\gamma Z}\,\bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\lambda}Z^{\nu}_{\lambda}$$

+ …

MR-M '99
Kurylov, McLaughlin, MR-M '01

TPVC Observables

- "D Coefficient" in β-decay:

$$\boxed{\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi \left\{ 1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \frac{\vec{J}}{J} \rangle \cdot \left[A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + D\,\frac{\vec{p}_e \times \vec{p}_\nu}{E_e\, E_\nu} \right] + \ldots \right\}}$$

- Correlations in $\vec{n}$+A scattering:

$$\boxed{\vec{\sigma}_n \cdot \vec{k}_n \times \vec{J} \, \left(\vec{k}_n \cdot \vec{J} \right)}$$

- $\eta \to 3\,\gamma\,,\ \eta \to 2\pi^0\,\gamma\,, \ldots$:

TPVC Observables

- *"D Coefficient" in β-decay:*

C. Seng talk

$$\boxed{\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi \left\{ 1 + b\frac{m_e}{E_e} + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle\frac{\vec{J}}{J}\rangle \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] + \ldots \right\}}$$

- *Correlations in $\vec{n}$+A scattering:*

$$\boxed{\vec{\sigma}_n \cdot \vec{k}_n \times \vec{J} \left(\vec{k}_n \cdot \vec{J} \right)}$$

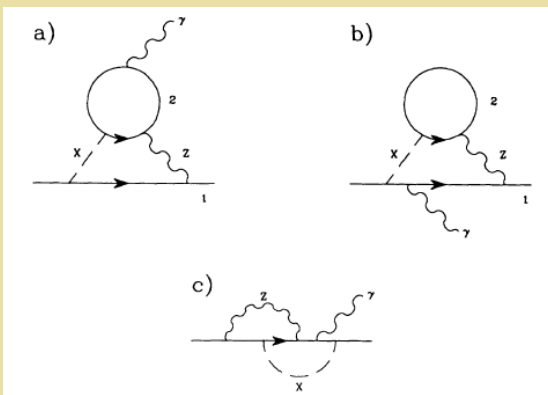
V. Gudkov, D. Bowman,…talks

- $\eta \to 3\gamma$, $\eta \to 2\pi^0\gamma$,… :

C. Seng, S. Gardner talks

TPVC Interactions & EDMs

- *Conti & Khriplovich: TVPC interactions + SM radiative corrections (PV) induce non-vanishing EDMs*



$$\mathcal{O}_5 = -\frac{i}{2} C_5^f \bar{\psi} \sigma_{\mu\nu} \gamma_5 \psi F^{\mu\nu}$$

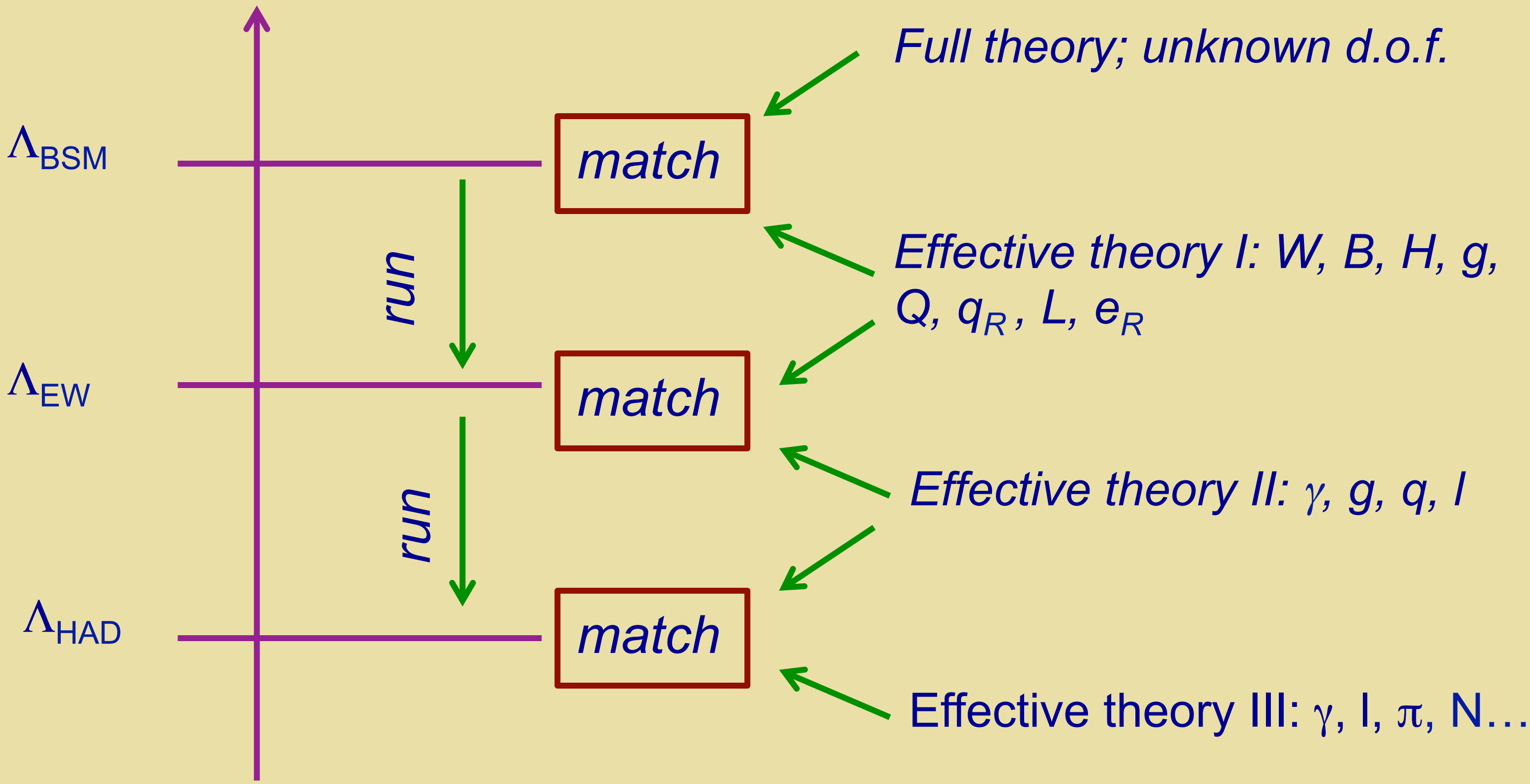
- *EDM limits imply vanishingly small effects from TVPC interactions*

$$C_7^{ff'} \lesssim \left(\frac{\Lambda_{TVPC}}{1\ \mathrm{TeV}} \right) \times 10^{-3}$$

How Robust Is Bound?

- *Non-renormalizable interactions: EFT, running, matching & “naturalness”*
- *Illustration with neutrino magnetic moments*
- *Application to TVPC interactions*

Non-Renormalizable Interactions & EFT



Effective Theory I

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

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

Effective theory I: W, B, H, g,
Q, q_R, L, e_R

Effective Theory II

$$\mathcal{L}_{\text{new}} = \mathcal{L}_4 + \frac{1}{\Lambda_{\text{TVPC}}}\mathcal{L}_5 + \frac{1}{\Lambda_{\text{TVPC}}^2}\mathcal{L}_6 + \frac{1}{\Lambda_{\text{TVPC}}^3}\mathcal{L}_7 + \ldots,$$

+…

Effective theory II: γ, g, q, l

Effective Theory II

$$\mathcal{L}_{\text{new}} = \mathcal{L}_4 + \frac{1}{\Lambda_{\text{TVPC}}}\mathcal{L}_5 + \frac{1}{\Lambda_{\text{TVPC}}^2}\mathcal{L}_6 + \frac{1}{\Lambda_{\text{TVPC}}^3}\mathcal{L}_7 + \dots,$$

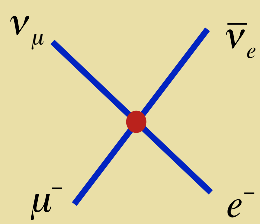
+…

Effective theory II: γ, g, q, l

Matching I & II: compute in II with massive W,Z

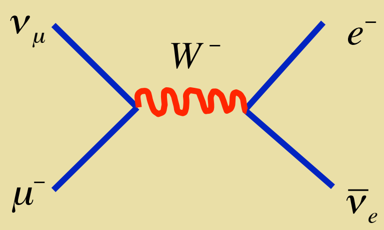
Matching

Fermi Effective Theory



$\sim O(\mathrm{G_F})$

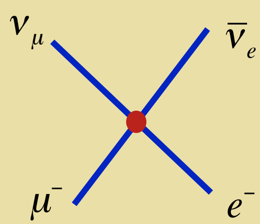
Standard Model



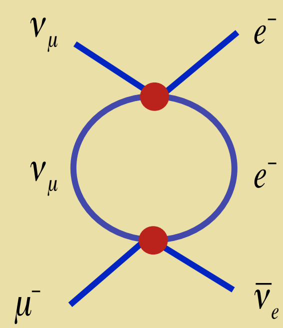
$\sim O(\mathrm{G_F})$

Matching

Fermi Effective Theory



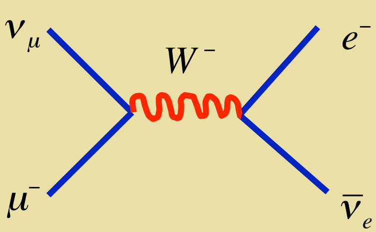
$\sim \mathcal{O}(\mathrm{G_F})$



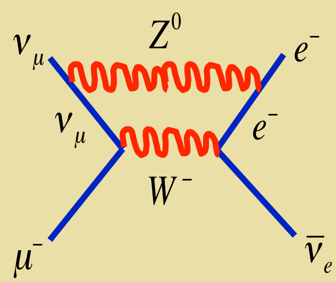
$\sim \mathcal{O}(\mathrm{G_F}^2\ \mathrm{m_e}^2)$

Loop momenta
$\mathrm{p} << \mathrm{M_W}^2$

Standard Model



$\sim \mathcal{O}(\mathrm{G_F})$

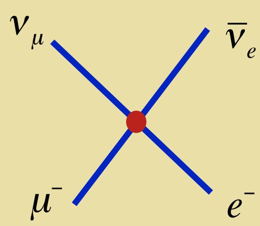


$\sim \mathcal{O}(\mathrm{G_F}\ \alpha / \pi)$

Loop momenta
$\mathrm{p} \sim \mathrm{M_W}^2$

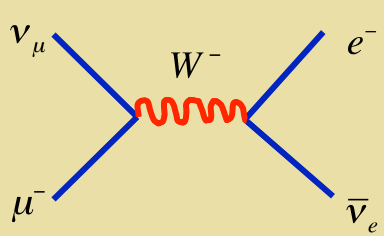
Matching

Fermi Effective Theory



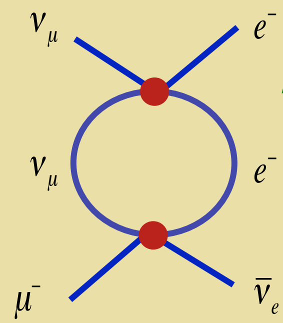
$\sim \mathcal{O}(G_F)$

Standard Model



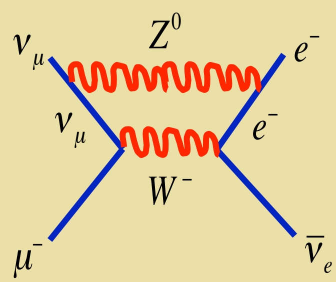
$\sim \mathcal{O}(G_F)$

Match EFT onto full theory
by considering $p \sim \Lambda$ (NDA)



$\sim \mathcal{O}(G_F^2\ m_e^2)$

Loop momenta
$p \ll M_W^2$



$\sim \mathcal{O}(G_F\ \alpha\ /\ \pi)$

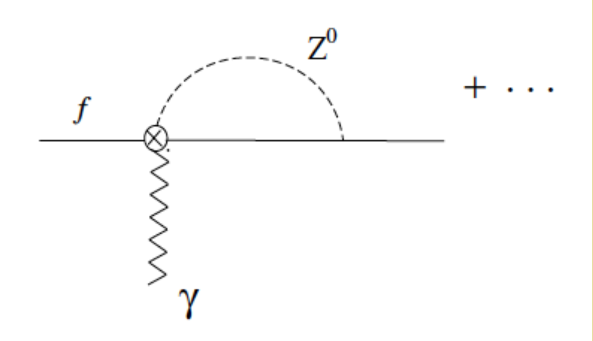
Loop momenta
$p \sim M_W^2$

Applying to TVPC Interactions & EDMs

- Khripolovich approach: compute in EFT II w/ cut-off regulator
- Khriplovich approach a la MR-M: compute in EFT II w/ dim reg
- Recast in EFT I framework

Applying to TVPC Interactions & EDMs

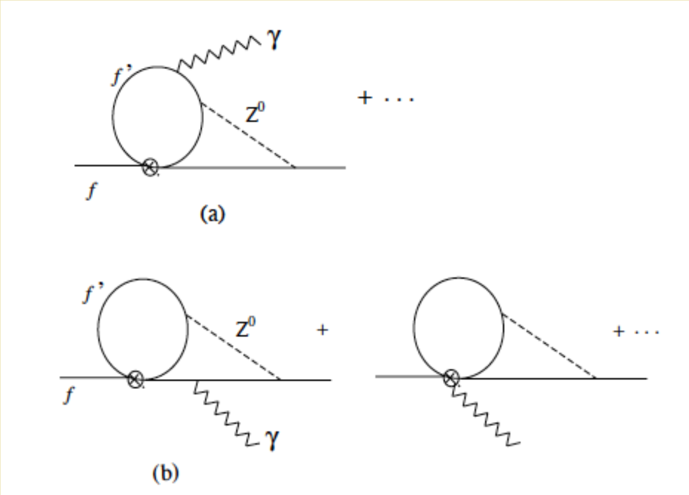
$$\boxed{\begin{aligned} \mathcal{O}_7^{\gamma g} &= C_7^{\gamma g}\bar{\psi}\sigma_{\mu\nu}\lambda^a\psi F^{\mu\lambda}G_\lambda^{a\nu} \\ \mathcal{O}_7^{\gamma Z} &= C_7^{\gamma Z}\bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\lambda}Z_\lambda^{\nu} \end{aligned}}$$



$$C_5^f \sim eC_7^{\gamma Z}\left(\frac{M_Z}{\Lambda_{\mathrm{TVPC}}}\right)^2\left(\frac{1}{s_W c_W}\right)g_A^f\left(\frac{1}{96\pi^2}\right)\ln\frac{M_Z^2}{\mu^2}$$

Applying to TVPC Interactions & EDMs

$$\mathcal{O}_7^{ff'} = C_7^{ff'} \bar{\psi}_f \overleftrightarrow{D}_\mu \gamma_5 \psi_f \bar{\psi}_{f'} \gamma^\mu \gamma_5 \psi_{f'}$$



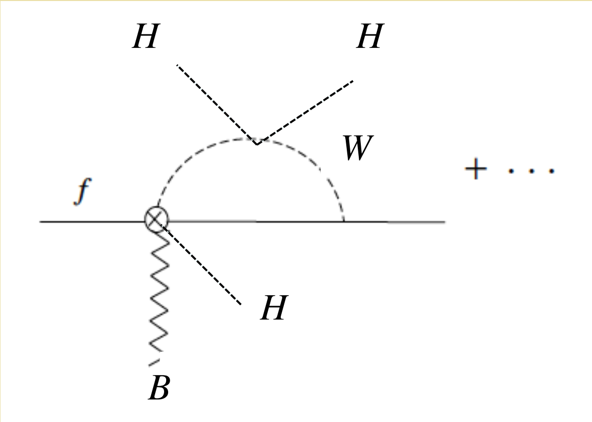
$$C_5^f \sim -eC_7^{ff'}\left(\frac{5}{12}\right)\left(\frac{M_Z}{\Lambda_{\rm TVPC}}\right)^2 Q_f g_V^f g_A^{f'}\left(\frac{G_F M_Z^2}{\sqrt{2}}\right) \times \left(\frac{1}{8\pi^2}\right)^2\left(\ln\frac{M_Z^2}{\mu^2}\right)^2,$$

The EFT I Computation

$$\mathcal{O}^{(8)}_{\rm fWB} = \bar{F}\sigma^{\mu\nu}\frac{\tau^a}{2}H\, f_R\, \widetilde{W}^a_{\mu\alpha}B^\alpha_\nu$$

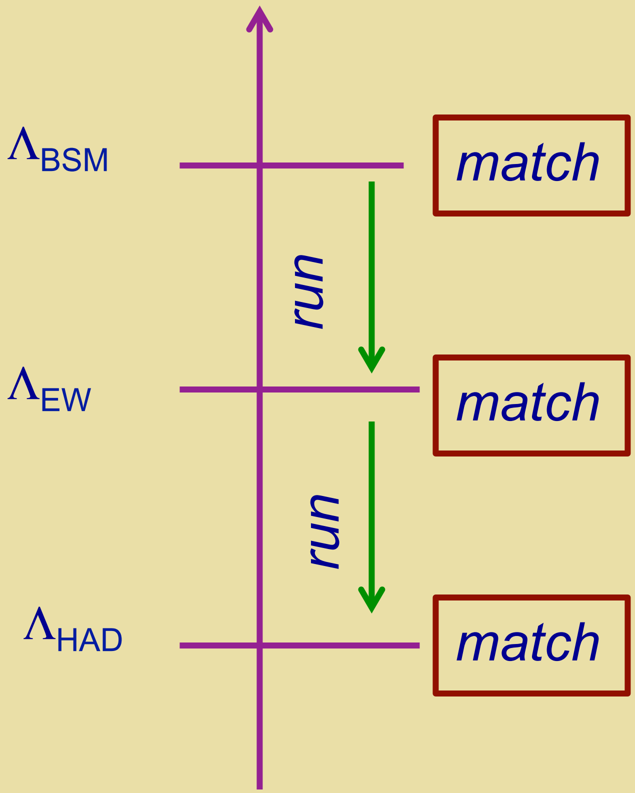
$$\mathcal{O}^{(8)}_{\rm fW} = \bar{F}\sigma^{\mu\nu}\frac{\tau^a}{2}H\, f_R\, \widetilde{W}^a_{\mu\alpha}\, H^\dagger H$$

$$\mathcal{O}^{(8)}_{\rm fB} = \bar{F}\sigma^{\mu\nu}H\, f_R\, \widetilde{B}^a_{\mu\alpha}\, H^\dagger H$$



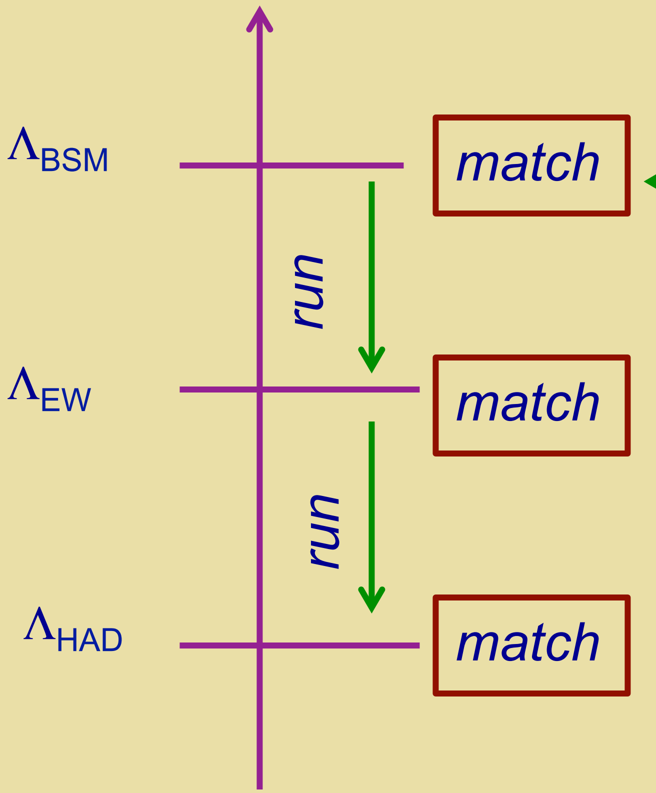
$$C^{(8)}_{\rm fV} \sim \left(\frac{\alpha}{4\pi}\right) C^{(8)}_{\rm TVPC}$$

Interpretation



$$d_f \sim \frac{1}{v}\left[C_{\mathrm{fV}}^{(6)}\left(\frac{v}{\Lambda}\right)^2 + C_{\mathrm{fV}}^{(8)}\left(\frac{v}{\Lambda}\right)^8 + \cdots\right]$$

Interpretation

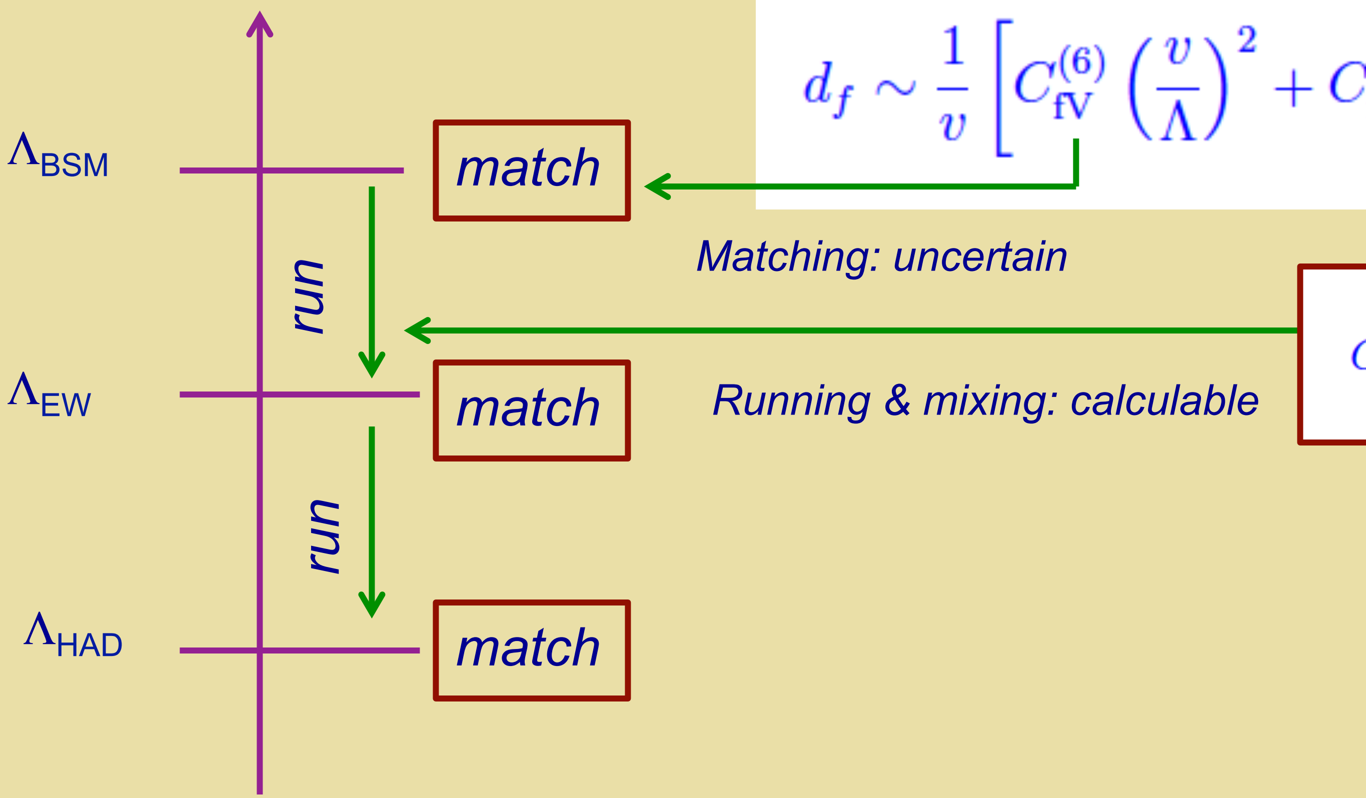


$$d_f \sim \frac{1}{v}\left[C_{\mathrm{fV}}^{(6)}\left(\frac{v}{\Lambda}\right)^2 + C_{\mathrm{fV}}^{(8)}\left(\frac{v}{\Lambda}\right)^8 + \cdots\right]$$

Matching: uncertain

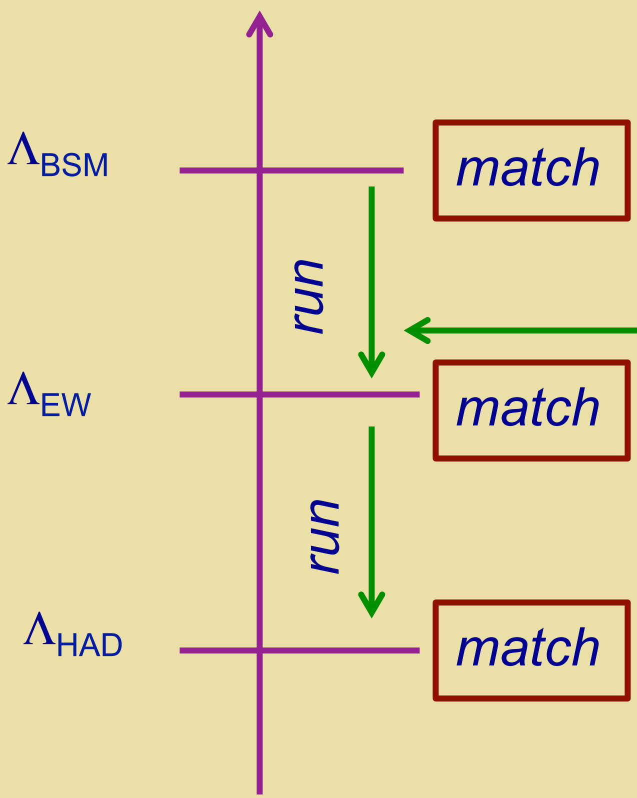
Interpretation

$$d_f \sim \frac{1}{v}\left[C_{\mathrm{fV}}^{(6)}\left(\frac{v}{\Lambda}\right)^2 + C_{\mathrm{fV}}^{(8)}\left(\frac{v}{\Lambda}\right)^8 + \cdots\right]$$



$$C_{\mathrm{fV}}^{(8)} \sim \left(\frac{\alpha}{4\pi}\right) C_{\mathrm{TVPC}}^{(8)}$$

Limits: Short Distance Parity Cons



$$d_f \sim \frac{1}{v}\left[C_{\mathrm{fV}}^{(6)}\left(\frac{v}{\Lambda}\right)^2 + C_{\mathrm{fV}}^{(8)}\left(\frac{v}{\Lambda}\right)^8 + \cdots\right]$$

Matching: uncertain

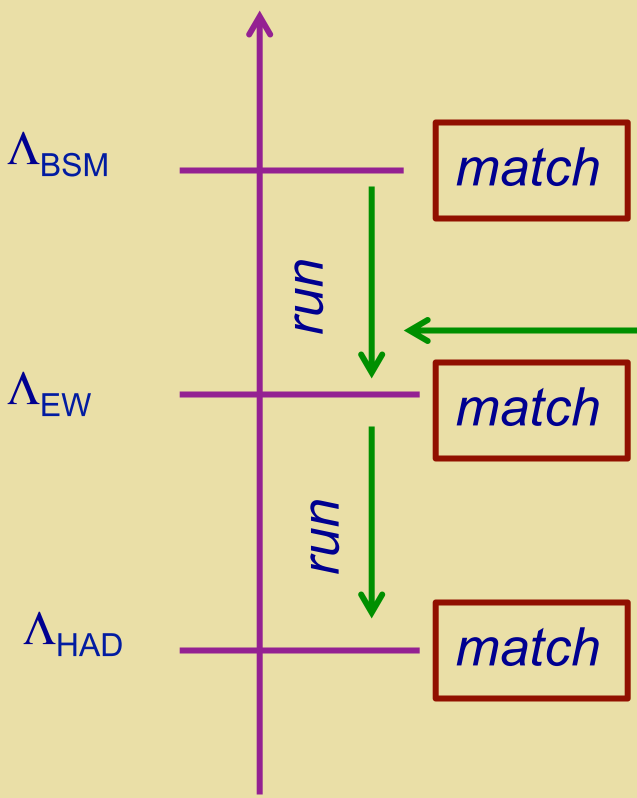
$$C_{\mathrm{fV}}^{(8)} \sim \left(\frac{\alpha}{4\pi}\right) C_{\mathrm{TVPC}}^{(8)}$$

Running & mixing: calculable

A. $\Lambda_{PV} < \Lambda_{TVPC}$: $C_{fV}^{(6)} = 0$

$$C_{\mathrm{TVPC}}^{(8)}\left(\frac{v}{\Lambda_{TVPC}}\right)^4 \lesssim 10^{-7}$$

Limits: Naturaleness



$$d_f \sim \frac{1}{v}\left[C_{\text{fV}}^{(6)}\left(\frac{v}{\Lambda}\right)^2 + C_{\text{fV}}^{(8)}\left(\frac{v}{\Lambda}\right)^8 + \cdots\right]$$

Matching: uncertain

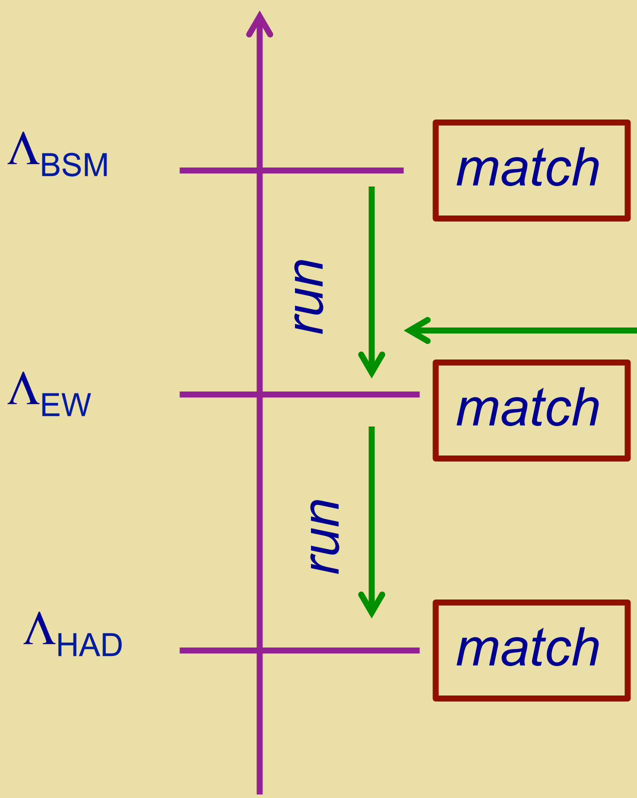
$$C_{\text{fV}}^{(8)} \sim \left(\frac{\alpha}{4\pi}\right) C_{\text{TVPC}}^{(8)}$$

Running & mixing: calculable

B. “Naturalness”:

$$\boxed{C_{\text{TVPC}}^{(8)}\left(\frac{v}{\Lambda_{TVPC}}\right)^4 \lesssim 10^{-7}}$$

Limits: Symmetry or Conspiracy



$$d_f \sim \frac{1}{v}\left[C_{\mathrm{fV}}^{(6)}\left(\frac{v}{\Lambda}\right)^2 + C_{\mathrm{fV}}^{(8)}\left(\frac{v}{\Lambda}\right)^8 + \cdots\right]$$

Matching: uncertain

Running & mixing: calculable

$$C_{\mathrm{fV}}^{(8)} \sim \left(\frac{\alpha}{4\pi}\right) C_{\mathrm{TVPC}}^{(8)}$$

C. Symmetry or conspiracy:

d_f suppressed $\rightarrow$ C_{TVPC} unconstrained

Implications

A. $\Lambda_{PV} < \Lambda_{TVPC}$: $C_{fV}^{(6)} = 0$

B. "Naturalness"

$$\boxed{\alpha_T = \frac{\langle f|\, \mathcal{O}^{(8)}_{TVPC}\, |i\rangle}{\langle f|\, \mathcal{O}_{QCD}\, |i\rangle} \sim C^{(8)}_{\mathrm{TVPC}} \left(\frac{v}{\Lambda_{TVPC}}\right) \left(\frac{p}{\Lambda_{TVPC}}\right)^3 \lesssim 10^{-15}}$$

for $\Lambda_{TVPC} \sim v$, $p \sim 1$ GeV

C. Symmetry or conspiracy

$$\boxed{\alpha_T = \frac{\langle f|\, \mathcal{O}^{(8)}_{TVPC}\, |i\rangle}{\langle f|\, \mathcal{O}_{QCD}\, |i\rangle} \sim C^{(8)}_{\mathrm{TVPC}} \left(\frac{v}{\Lambda_{TVPC}}\right) \left(\frac{p}{\Lambda_{TVPC}}\right)^3 \lesssim 10^{-7}}$$

for $\Lambda_{TVPC} \sim v$, $p \sim 1$ GeV , and $C_{TVPC} \sim 1$

II. P-Conserving T- and C-Violation

- *Does the conspiracy scenario survive one-loop RGE ?*
- *If so, does it survive at higher order ?*
- *Are there well-motivated BSM scenarios that generate non-vanishing C_{TVPC} ?*
- *What is the corresponding situation for other TVPC observables (D coeff) ?*
- *What are implications for P-conserving C-violation ?*
- *Can there be ultralight mediators of P-conserving T-violation/C-violation that evade these arguments ?*

Implications: Further Thoughts

C. Symmetry or conspiracy

$$\mathcal{O}^{(8)}_{\rm fWB} = \bar{F}\sigma^{\mu\nu}\frac{\tau^a}{2}H f_R \widetilde{W}^a_{\mu\alpha}B^\alpha_\nu$$

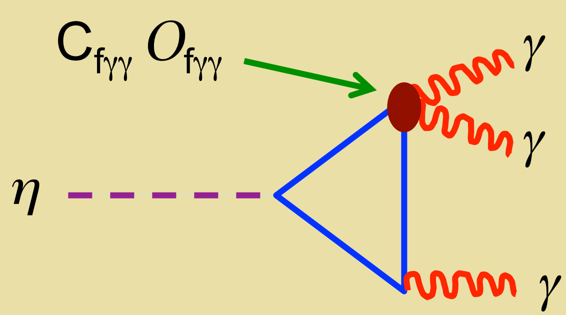
$$\mathcal{O}^{(8)}_{\rm fWW} = \bar{F}\sigma^{\mu\nu}H f_R \widetilde{W}^a_{\mu\alpha}W^{a\,\alpha}_\mu$$

$$\mathcal{O}^{(8)}_{\rm fBB} = \bar{F}\sigma^{\mu\nu}\ H f_R \widetilde{B}_{\mu\alpha}B^\alpha_\nu$$

$$\mathcal{O}^{(8)}_{\rm f\gamma\gamma} = \bar{F}\sigma^{\mu\nu}f_R \widetilde{F}_{\mu\alpha}F^\alpha_\nu \qquad \eta \to 3\,\gamma$$

$$\mathcal{O}^{(8)}_{\rm f\gamma Z} = \bar{F}\sigma^{\mu\nu}f_R \widetilde{F}_{\mu\alpha}Z^\alpha_\nu \qquad \text{EDM}$$

$$C_{fWB}\,,\ C_{fWW}\,,\ C_{fBB} \xrightarrow{?} C_{f\gamma Z} = 0\,,\ C_{f\gamma\gamma} \neq 0$$



$\longrightarrow$?

Summary & Outlook

- *C-Violating $\leftrightarrow$ TVPC interactions are a largely unexplored direction for fundamental symmetry tests*

- *Analyzing their effects for light quark systems requires an EFT approach, as the do not arise at tree-level via renormalizable gauge interactions*

- *In general, EDMs place stringent constraints on such interactions via EW radiative corrections from the standpoint of short distance parity restoration and/or naturalness*

- *Exceptions may exist in the presence of a conspiracy or new symmetry at the TVPC matching scale*

- *Magnitude of low-energy amplitude ~ $(p/\Lambda)^3 < 10^{-7}$ for $\Lambda > v$*

- *C-Violating $\leftrightarrow$ TVPC interactions are an interesting direction worthy of further exploration*

II. P-Conserving T- and C-Violation

- *Does the conspiracy scenario survive one-loop RGE ?*
- *If so, does it survive at higher order ?*
- *Are there well-motivated BSM scenarios that generate non-vanishing C_{TVPC} ?*
- *What is the corresponding situation for other TVPC observables (D coeff) ?*
- *What are implications for P-conserving C-violation ?*
- *Can there be ultralight mediators of P-conserving T-violation/C-violation that evade these arguments ?*

Back Up Slides

EFT Ilustration: m_ν & μ_ν

Bell, Cirigliano, R-M, Vogel, Wise '05
Also
Bell, Gorchtein, R-M, Vogel, Wang '06
Erwin, Kile, R-M, Wang '07
Kile, R-M '07

Neutrino Magnetic Moments

Can neutrinos have magnetic moments?

Dirac neutrinos

$$\nu_L \longrightarrow e^{i\alpha_L}\,\nu_L \quad \nu_R \longrightarrow e^{i\alpha_R}\,\nu_R$$

$$m_\nu\,\bar{\nu}\nu = m_\nu\{\bar{\nu}_L\nu_R + \bar{\nu}_R\nu_L\}$$

$\mathcal{L}$ not invariant if $m_\nu \neq 0$ and $\alpha_L \neq \alpha_R$

Magnetic moment operator forbidden

$$\mu_\nu\,\bar{\nu}\sigma_{\alpha\beta}\nu\,F^{\alpha\beta} = \mu_\nu\{\bar{\nu}_L\sigma_{\alpha\beta}\nu_R + \bar{\nu}_R\sigma_{\alpha\beta}\nu_L\}F^{\alpha\beta}$$

The Scale of m_ν and μ_ν

Minimal extension of the Standard Model with ν_R and non-vanishing m_ν gives

$$\mu_\nu \approx 3 \times 10^{-19} \mu_B \, [m_\nu / 1\,\mathrm{eV}]$$

Too small to be observed

What about new physics at scale $\Lambda > \upsilon$? NDA

$$\mu_\nu \sim eG/\Lambda \quad , \quad m_\nu \sim G\Lambda$$

$$m_\nu \sim \frac{\Lambda^2}{2m_e} \frac{\mu_\nu}{\mu_B} \sim \frac{\mu_\nu}{10^{-18}\mu_B} \left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^2 \mathrm{eV}$$

Evading the NDA Estimates

NDA

$$m_\nu \sim \frac{\Lambda^2}{2m_e} \frac{\mu_\nu}{\mu_B} \sim \frac{\mu_\nu}{10^{-18}\mu_B} \left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^2 \mathrm{eV}$$

The "Voloshin" mechanism : a loophole

$SU(2)_\nu$ symmetry:

(ν, ν^c) transf as doublet

m_ν term transforms as triplet — forbidden

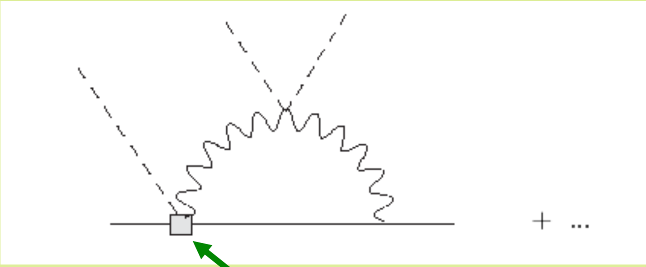
μ_ν transforms as singlet — allowed

Evading the NDA Estimates

NDA

$$m_\nu \sim \frac{\Lambda^2}{2m_e} \frac{\mu_\nu}{\mu_B} \sim \frac{\mu_\nu}{10^{-18}\mu_B} \left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^2 \mathrm{eV}$$

The "Voloshin" mechanism: a loophole



electroweak μ_ν operators

Radiatively-induced neutrino mass

Voloshin sym & generalizations broken by SM gauge & Yukawa interactions: m_ν bounds on μ_ν

Dirac Neutrinos

$$\delta m_\nu = -C_3^6(v)\frac{v^3}{2\sqrt{2}\Lambda^2} \qquad \frac{\mu_\nu}{\mu_B} = -4\sqrt{2}\left(\frac{m_e v}{\Lambda^2}\right) C_+(v) \qquad C_+ = C_1^6 + C_2^6$$

Operator Basis:

$$O_M^{(4)} = \bar{L}\tilde{\phi}\nu_R \qquad \tilde{\phi} = i\tau_2\phi^*$$

$$O_1^{(6)} = g_1(\bar{L}\sigma^{\mu\nu}\tilde{\phi})\ell_R B_{\mu\nu}$$

$$O_2^{(6)} = g_2(\bar{L}\sigma^{\mu\nu}\tau^a\tilde{\phi})\nu_R W_{\mu\nu}^a$$

$$O_3^{(6)} = (\bar{L}\tilde{\phi}\nu_R)\ (\phi^+\phi)$$

Dirac Neutrinos

$$\delta m_\nu = -C_3^6(v)\frac{v^3}{2\sqrt{2}\Lambda^2} \qquad \frac{\mu_\nu}{\mu_B} = -4\sqrt{2}\left(\frac{m_e v}{\Lambda^2}\right)C_+(v) \qquad C_+ = C_1^6 + C_2^6$$

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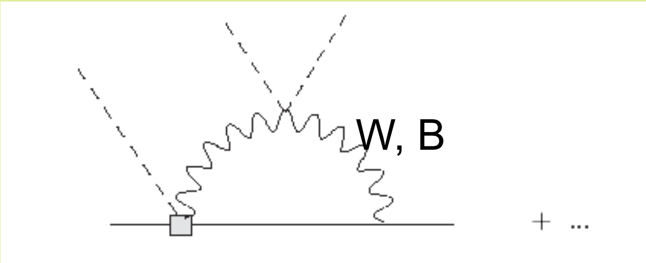
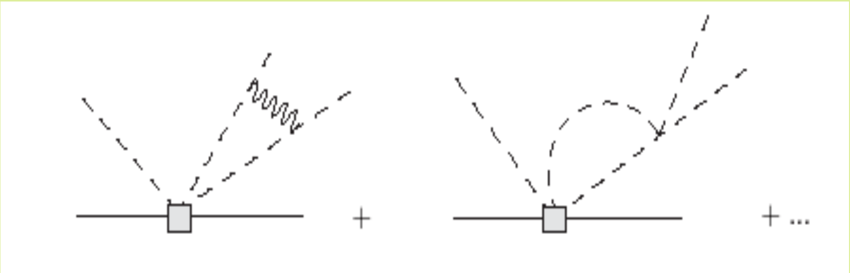
Close under renormalization

Dirac Neutrinos: Mixing

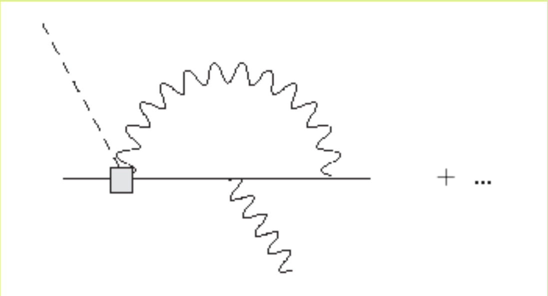




Operator Basis:

$$O_M^{(4)} = \bar{L}\tilde{\phi}\nu_R \qquad \tilde{\phi} = i\tau_2\phi^*$$

$$\boxed{\begin{aligned} O_1^{(6)} &= g_1(\bar{L}\sigma^{\mu\nu}\tilde{\phi})\ell_R B_{\mu\nu} \\ O_2^{(6)} &= g_2(\bar{L}\sigma^{\mu\nu}\tau^a\widetilde{\phi})\nu_R W^a_{\mu\nu} \\ O_3^{(6)} &= (\bar{L}\widetilde{\phi}\nu_R)\ (\phi^+\phi) \end{aligned}}$$



Close under
renormalization

Dirac Neutrinos: Mixing & "Naturalness"

Renormalization Group: Leading Log

Solution with $C_3^{\,6}(\Lambda) = 0$: δm_ν generated entirely from radiative corrections

$$\frac{|\mu_\nu|}{\mu_B} = \frac{G_F m_e}{\sqrt{2}\pi\alpha}\left[\frac{\delta m_\nu}{\alpha \ln(\Lambda/v)}\right]\frac{32\pi \sin^4\theta_W}{9|f|}$$

$$f = (1-r) - \frac{2}{3} r \tan^2\theta_W - \frac{1}{3}(1+r)\tan^4\theta_W \qquad r = C_-/C_+$$

$$\frac{|\mu_\nu|}{\mu_B} \lesssim 8\times 10^{-15} \times \left(\frac{\delta m_\nu}{1\,\mathrm{eV}}\right)\frac{1}{|f|}$$

Dirac Neutrinos

$$\delta m_\nu = -C_3^6(v)\frac{v^3}{2\sqrt{2}\Lambda^2} \qquad \frac{\mu_\nu}{\mu_B} = -4\sqrt{2}\left(\frac{m_e v}{\Lambda^2}\right) C_+(v) \qquad C_+ = C_1^6 + C_2^6$$

Operator Basis:

$$\boxed{O_M^{(4)} = \bar{L}\tilde{\phi}\nu_R} \qquad \tilde{\phi} = i\tau_2\phi^*$$

Matching at scale Λ

$$O_1^{(6)} = g_1(\bar{L}\sigma^{\mu\nu}\tilde{\phi})\ell_R B_{\mu\nu}$$

$$O_2^{(6)} = g_2(\bar{L}\sigma^{\mu\nu}\tau^a\tilde{\phi})\nu_R W_{\mu\nu}^a$$

$$O_3^{(6)} = (\bar{L}\tilde{\phi}\nu_R)\ (\phi^+\phi)$$

Close under renormalization

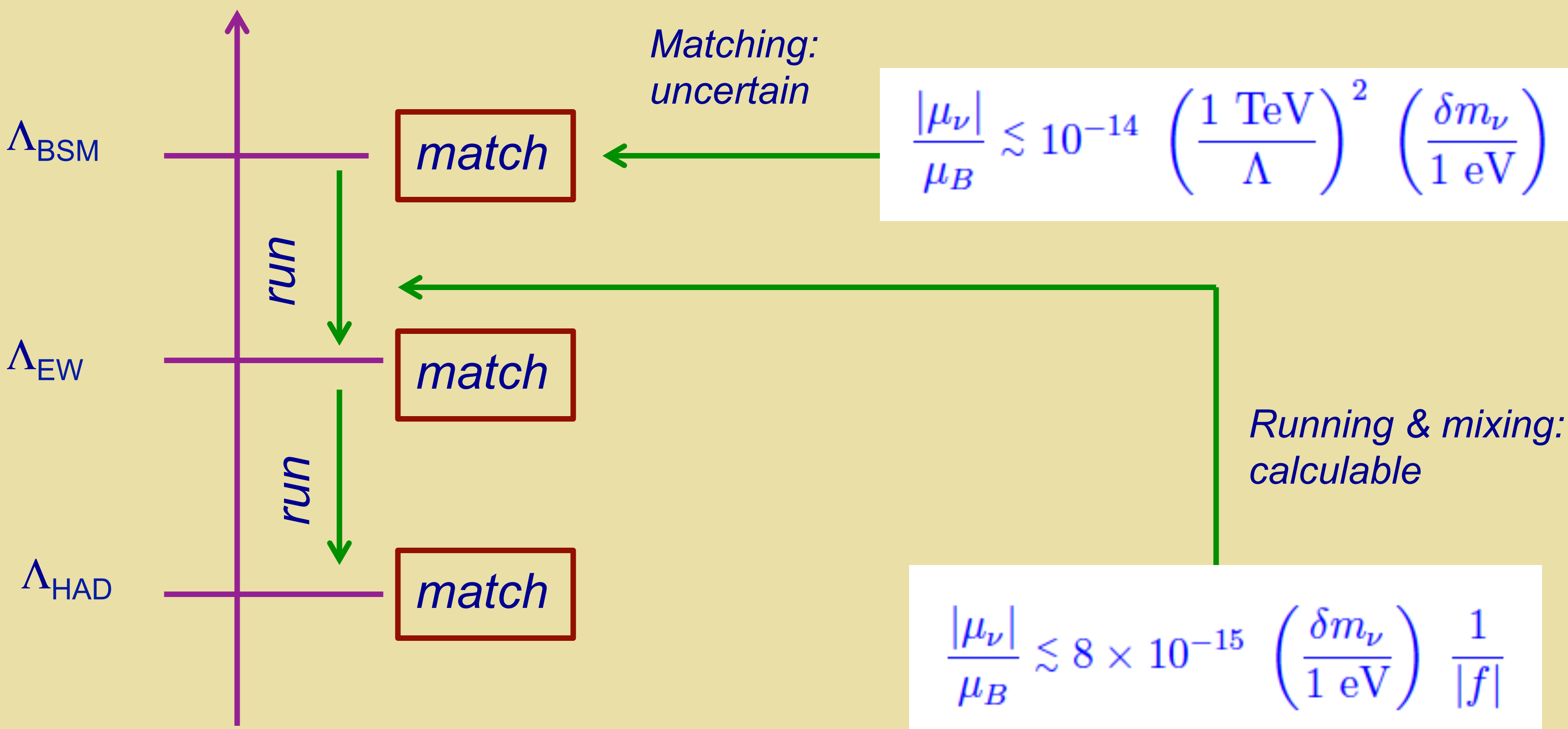
Dirac Neutrinos: Matching & "Naturalness"

Solution with $C_3^6(\Lambda) = 0$: δm_ν generated entirely from radiative corrections via $k_{loop} \sim \Lambda$, thereby inducing nonzero $C_M^4(\Lambda)$

$$\delta m_\nu \sim \frac{\alpha}{32\pi} \frac{\Lambda^2}{m_e} \frac{\mu_\nu}{\mu_B},$$

$$\frac{\mu_\nu}{\mu_B} \lesssim 10^{-14} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 \left(\frac{\delta m_\nu}{1\ \mathrm{eV}}\right)$$

Interpretation



$$\frac{|\mu_\nu|}{\mu_B} \lesssim 10^{-14} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 \left(\frac{\delta m_\nu}{1\ \mathrm{eV}}\right)$$

$$\frac{|\mu_\nu|}{\mu_B} \lesssim 8 \times 10^{-15} \left(\frac{\delta m_\nu}{1\ \mathrm{eV}}\right) \frac{1}{|f|}$$