Electric Dipole Moments: Theory

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Theoretical Nuclear, Particle, Astrophysics & Cosmology

http://www.physics.wisc.edu/groups/particle-theory/

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Goals

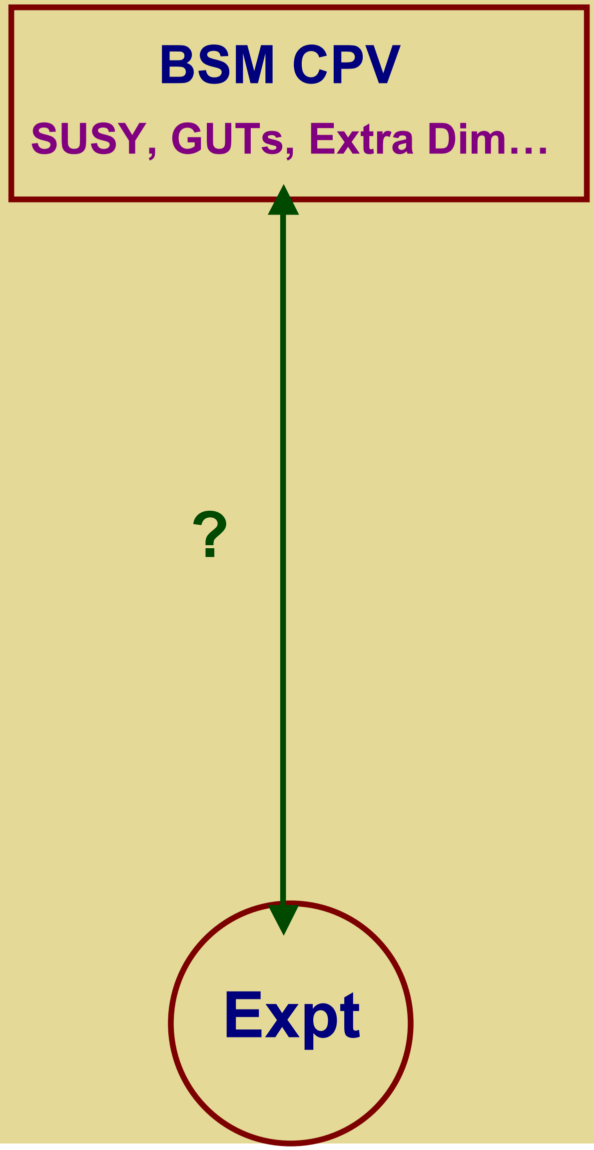
- *Provide the framework for interpreting EDM measurements*
- *Introduce terminology*
- *Discuss illustrative phenomenology & cosmological implications*

Outline

1. EDM Interpretation: Multiple Scales
2. Effective Operators: Classification
3. Origin of Wilson Coefficients: Examples
4. Low Scale Observables
5. Running & Matching
6. Implications & Open Problems

- J. Engel, U. van Kolck, MRM 1303.2371
- T. Chupp, MRM in progress

EDM Interpretation & Multiple Scales



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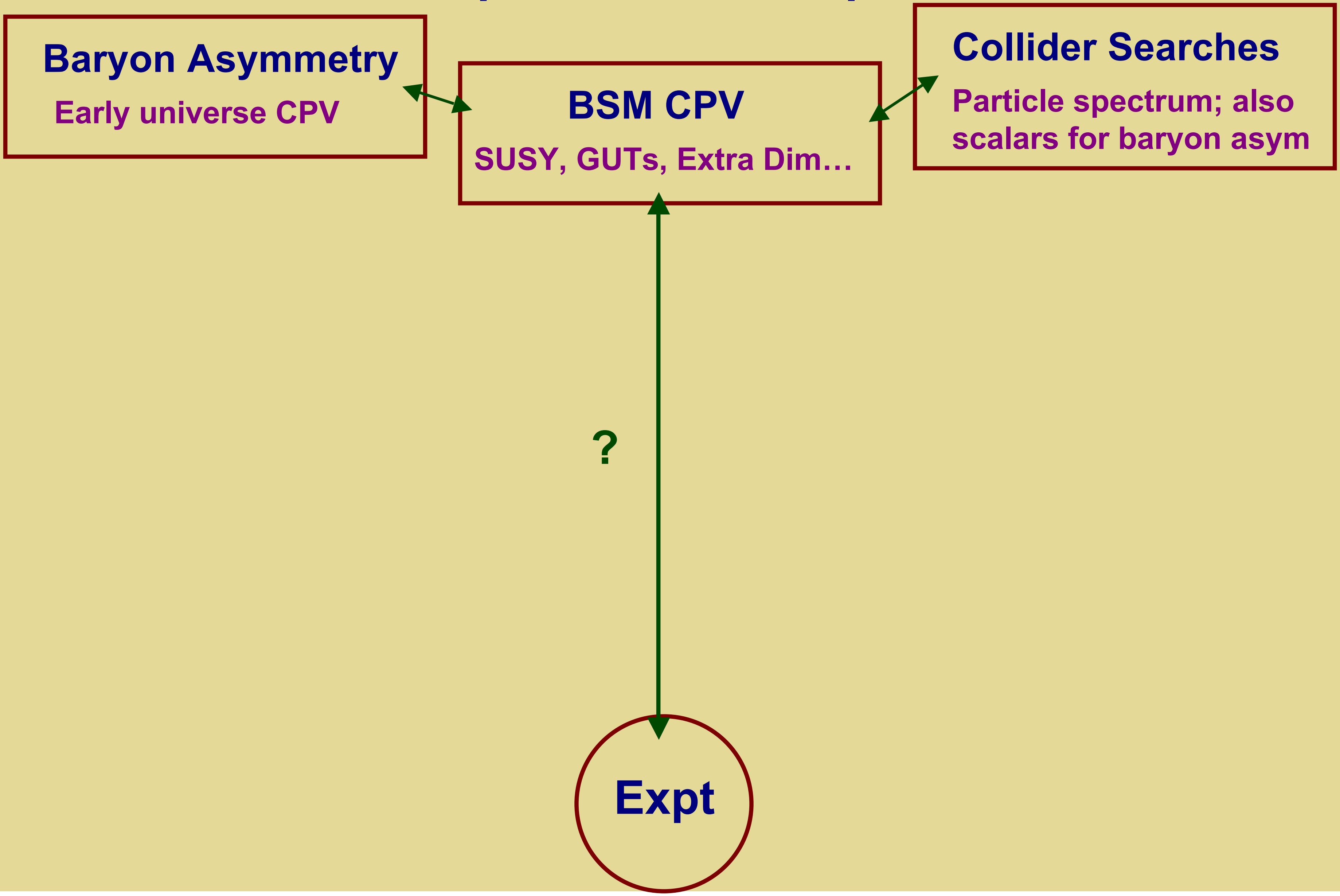
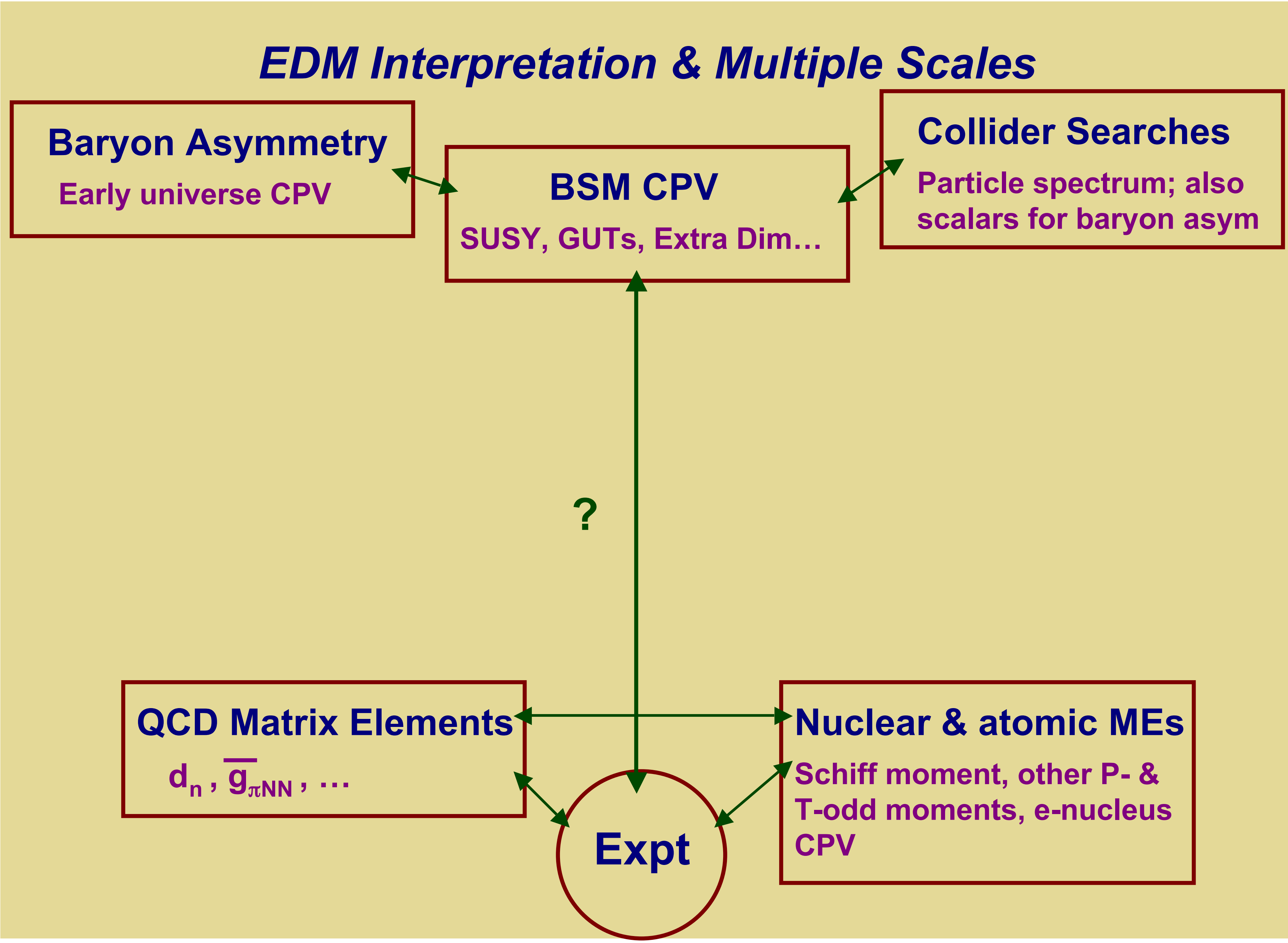
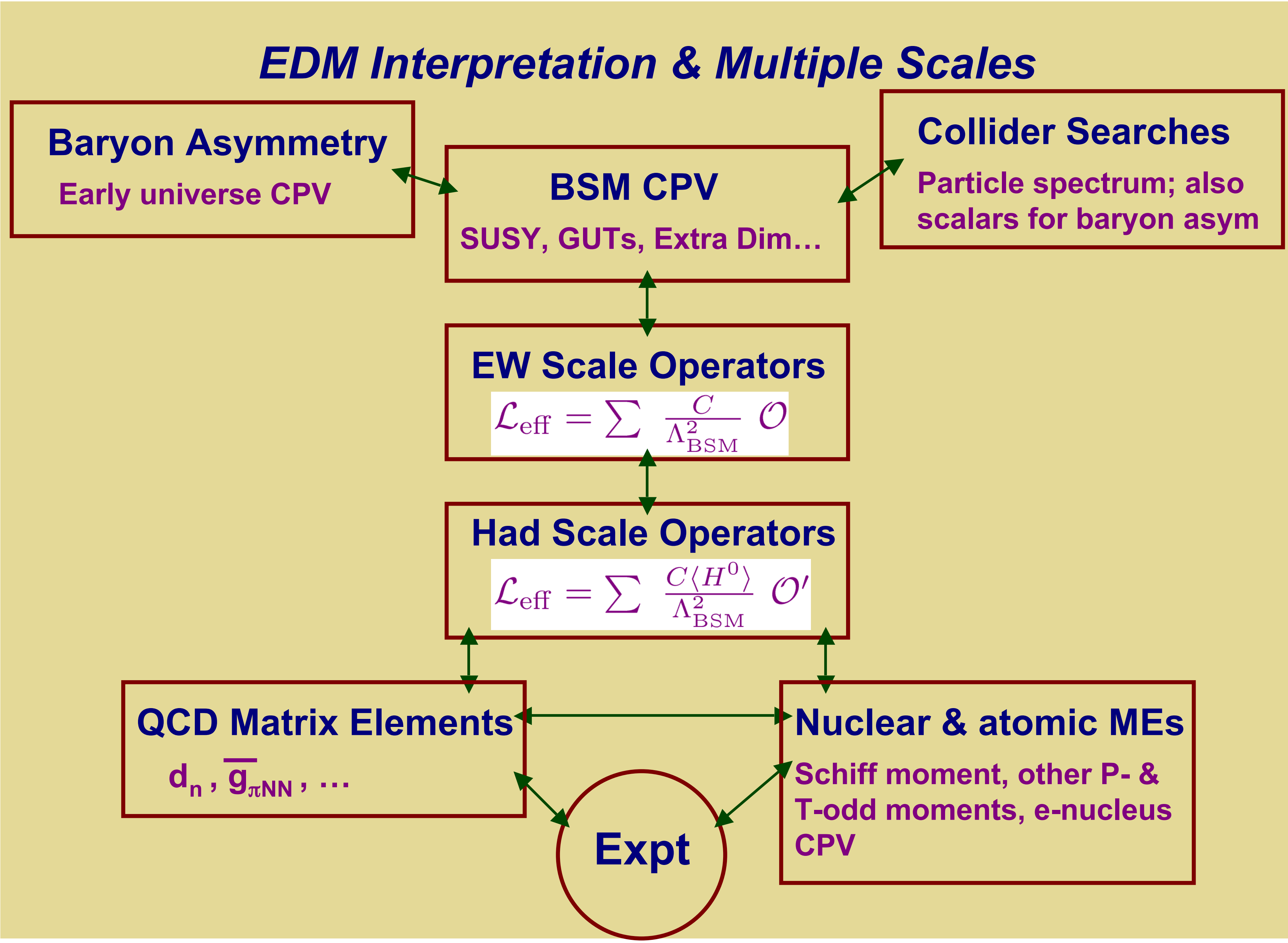



EDM Interpretation & Multiple Scales
Baryon Asymmetry
Early universe CPV
BSM CPV
SUSY, GUTs, Extra Dim…
Collider Searches
Particle spectrum; also scalars for baryon asym
?
QCD Matrix Elements
d_n, $\bar{g}_{\pi NN}$, …
Nuclear & atomic MEs
Schiff moment, other P- & T-odd moments, e-nucleus CPV
Expt

Effective Operators

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

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


EDM Interpretation & Multiple Scales
Baryon Asymmetry
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Particle spectrum; also scalars for baryon asym
EW Scale Operators
$\mathcal{L}_{\rm eff} = \sum \frac{C}{\Lambda^2_{\rm BSM}} \mathcal{O}$
Had Scale Operators
$\mathcal{L}_{\rm eff} = \sum \frac{C\langle H^0 \rangle}{\Lambda^2_{\rm BSM}} \mathcal{O}'$
QCD Matrix Elements
d_n, $\bar{g}_{\pi NN}$, …
Nuclear & atomic MEs
Schiff moment, other P- & T-odd moments, e-nucleus CPV
Expt

Dimension Six Operators

- *What are they ?*
- *Where do they come from ?*
- *How do they appear in hadronic, nuclear, and atomic systems ?*
- *How well can we match them onto physics of many-body and non-perturbative systems ?*
- *What are present & prospective experimental constraints ?*

Dimension Six Operators: I

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Operator Classification

Pure Gauge		Gauge-Higgs		Gauge-Higgs-Fermion	
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{uG}	$(\bar{Q}\sigma^{\mu\nu}T^A u)\widetilde{\varphi}\,G_{\mu\nu}^A$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{dG}	$(\bar{Q}\sigma^{\mu\nu}T^A d)\varphi\,G_{\mu\nu}^A$
		$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{fW}	$(\bar{F}\sigma^{\mu\nu}f)\tau^I\Phi\,W_{\mu\nu}^I$
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Weinberg 3 gluon

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$$\varphi^{+}\varphi \to v^{2}$$

θ-term renormalization

Operator Classification

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Quark chromo-EDM

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Fermion EDM

Operator Classification

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{L}^j e)(\bar{d} Q^j)$
$Q_{quqd}^{(1)}$	$(\bar{Q}^j u)\epsilon_{jk}(\bar{Q}^k d)$
$Q_{quqd}^{(8)}$	$(\bar{Q}^j T^A u)\epsilon_{jk}(\bar{Q}^k T^A d)$
$Q_{lequ}^{(1)}$	$(\bar{L}^j e)\epsilon_{jk}(\bar{Q}^k u)$
$Q_{lequ}^{(3)}$	$(\bar{L}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{Q}^k \sigma^{\mu\nu} u)$

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Semileptonic: atomic & molecular EDMs

Operator Classification

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Nonleptonic: hadronic EDMs & Schiff moment

Operator Classification

$$Q_{\varphi ud} = i\tilde{\varphi}^\dagger D_\mu \varphi \bar{u}_R \gamma^\mu d_R$$

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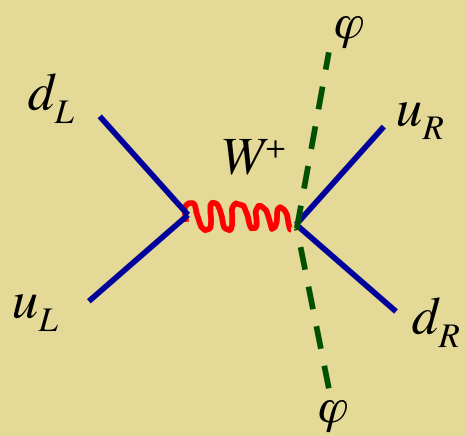

$\varphi \to v$

$$\mathcal{L}^{\text{eff}}_{\text{LR, CPV}} = -i\frac{\text{Im}\, C_{\varphi ud}}{\Lambda^2}\left[\bar{d}_L\gamma^\mu u_L\, \bar{u}_R\gamma_\mu d_R - \bar{u}_L\gamma^\mu d_L\, \bar{d}_R\gamma_\mu u_R\right]$$

Nonleptonic: hadronic EDMs & Schiff moment

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 →

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

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)

Dimension Six Operators: II

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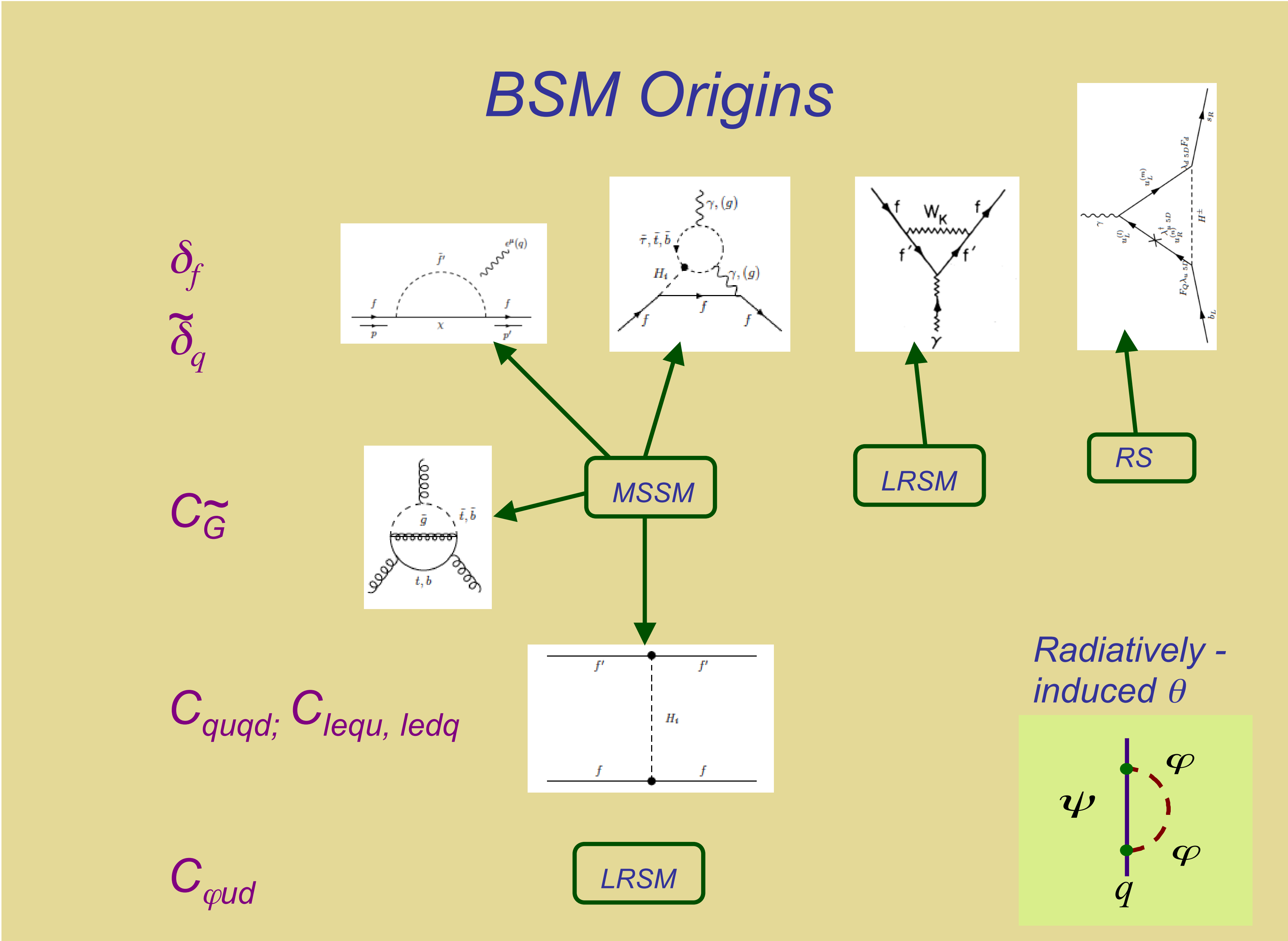
BSM Origins

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
δ_f
$\tilde{\delta}_q$
$C_{\tilde{G}}$
C_{quqd}; $C_{lequ,\ ledq}$
$C_{\varphi ud}$
MSSM
LRSM
RS
LRSM
Radiatively - induced θ
ψ
φ
φ
q
W_K
f
f
f′
f′
γ
H_t
$\tilde{g}$
t, b
$\tilde{t}, \tilde{b}$
χ
$\tilde{f}'$
$\gamma, (g)$
$H^{\pm}$

Dimension Six Operators: III

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Low Scale Observables

$$\mathcal{L}_{N\pi}^{\mathrm{PVTV}} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right)S_\mu N\, v_\nu F^{\mu\nu}$$

$$+\,\bar{N}\left[\bar{g}_\pi^{(0)}\boldsymbol{\tau}\cdot\boldsymbol{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}\left(3\tau_3\pi^0 - \boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]N$$

$$+\bar{C}_1\bar{N}N\,\partial_\mu\left(\bar{N}S^\mu N\right) + \bar{C}_2\bar{N}\boldsymbol{\tau}N\cdot\partial_\mu\left(\bar{N}S^\mu\boldsymbol{\tau}N\right) + \cdots$$

Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

Low Scale Observables

$$\mathcal{L}_{N\pi}^{\mathrm{PVTV}} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S_\mu N\, v_\nu F^{\mu\nu}$$
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Nucleon EDMs

Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

Low Scale Observables

$$\mathcal{L}_{N\pi}^{\text{PVTV}} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S_\mu N\, v_\nu F^{\mu\nu}$$

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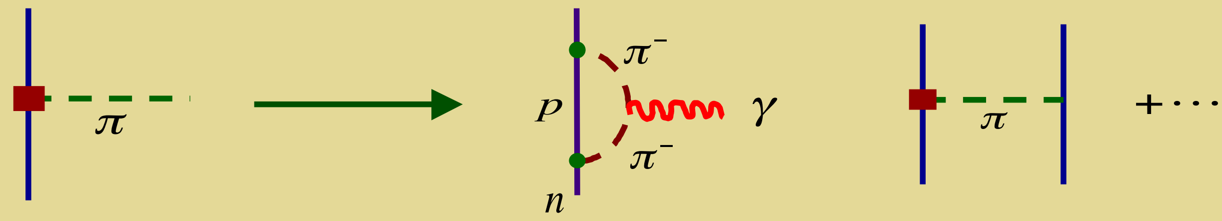
I = 0, 1, 2

PVTV πN interaction



Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

Low Scale Observables

$$\mathcal{L}_{N\pi}^{\mathrm{PVTV}} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S_\mu N\, v_\nu F^{\mu\nu}$$
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$$+ \bar{C}_1 \bar{N}N\, \partial_\mu\left(\bar{N}S^\mu N\right) + \bar{C}_2 \bar{N}\boldsymbol{\tau}N\cdot\partial_\mu\left(\bar{N}S^\mu\boldsymbol{\tau}N\right) + \cdots$$

PVTV 4N interaction

Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

Low Scale Observables

Nuclear Moments

	$P\ T$	$\not{P}\ T$	$P\ \not{T}$	$\not{P}\ \not{T}$
C_J	E	✖	✖	O
T^M_J	O	✖	✖	E
T^E_J	✖	O	E	✖

Low Scale Observables

Nuclear Moments

	$P\,T$	$\not{P}\,T$	$P\,\not{T}$	$\not{P}\,\not{T}$	
C_J	E	✖	✖	O	*EDM, Schiff…*
$T^M{}_J$	O	✖	✖	E	*MQM….*
$T^E{}_J$	✖	O	E	✖	

Low Scale Observables

Nuclear Moments

	$P\ T$	$\not{P}\ T$	$P\ \not{T}$	$\not{P}\ \not{T}$	
C_J	E	✖	✖	O	*EDM, Schiff…*
T^M_J	O	✖	✖	E	*MQM….*
T^E_J	✖	O	E	✖	*Anapole…*

Low Scale Observables

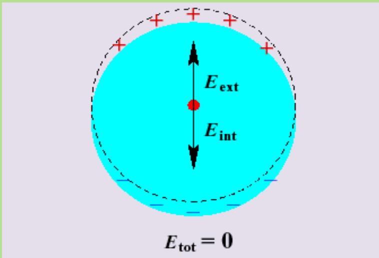
Nuclear Moments

	$P\,T$	$\not{P}\,T$	$P\,\not{T}$	$\not{P}\,\not{T}$	
C_J	E	✖	✖	O	*EDM, Schiff…*
$T^M{}_J$	O	✖	✖	E	*MQM….*
$T^E{}_J$	✖	O	E	✖	*Anapole…*

Nuclear Enhancements

Nuclear Schiff Moment

Schiff Screening



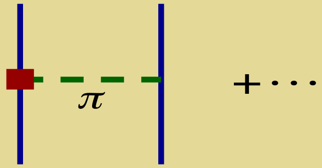
Atomic effect from nuclear finite size: Schiff moment

Nuclear Schiff Moment

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

Nuclear EDM: Screened in atoms

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



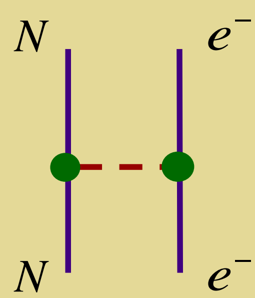
EDMs of diamagnetic atoms (^{199}Hg)

Semileptonic CPV

$$\mathcal{L}_{eN}^{\mathrm{eff}} = \frac{G_F}{\sqrt{2}}\Big\{\bar{e}i\gamma_5 e\ \bar{N}\left[C_S^{(0)} + C_S^{(1)}\tau_3\right] N$$

$$+ 8\bar{e}\sigma_{\mu\nu}e\ v^\nu \bar{N}\left[C_T^{(0)} + C_T^{(1)}\tau_3\right] S^\mu N\Big\} + \cdots$$

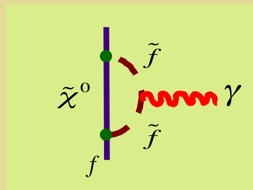
EDMs of atoms & molecules (Tl, YbF…)



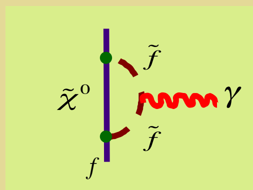
EDMs: Complementary Searches

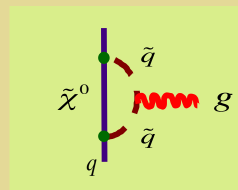
Improvements of 10^2 to 10^3

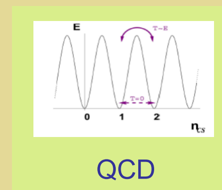
Electron



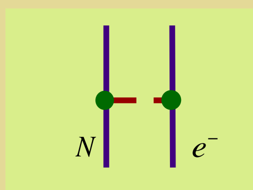
Neutron

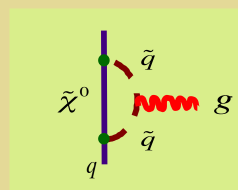


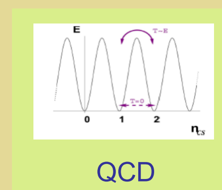




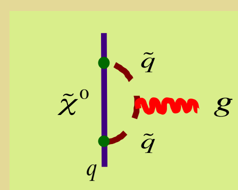
Neutral Atoms

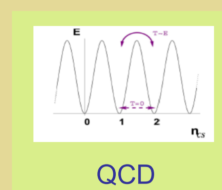






Deuteron





Dimension Six Operators: IV

- *What are they ?*
- *Where do they come from ?*
- *How do they appear in hadronic, nuclear, and atomic systems ?*
- *How well can we match them onto physics of many-body and non-perturbative systems ?* *Not this talk*
- *What are present & prospective experimental constraints ?*

Dimension Six Operators: V

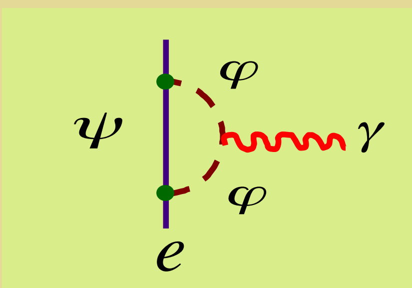
- What are they ?
- Where do they come from ?
- How do they appear in hadronic, nuclear, and atomic systems ?
- How well can we match them onto physics of many-body and non-perturbative systems ?
- What are present & prospective experimental constraints ?

Generic Implications

In units of e cm, selected EDM limits are:

Particle	EDM limit	System	SM Prediction	New Physics
e	10.5×10^{-28}	YbF	10^{-38}	10^{-27}
μ	1.1×10^{-19}	rest frame $\vec{E}$	10^{-35}	10^{-22}
τ	3.1×10^{-16}	$e^+e^- \to \tau^+\tau^-\gamma$	10^{-34}	10^{-20}
p	6.5×10^{-23}	TlF molecule	10^{-31}	10^{-26}
n	2.9×10^{-26}	UCN	10^{-31}	10^{-26}
^{199}Hg	3.1×10^{-29}	atom cell	10^{-33}	10^{-28}

Mass Scale & ϕ_{CP} Sensitivity



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

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

Analysis Strategies

- *Work within a given BSM scenario: constraints on ϕ_{CPV} , M,…*
- *Model-independent analysis: constraints on Wilson coefficients*

MSSM Global Analysis

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

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

MSSM Global Analysis

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

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

$\phi_j = arg\ (\mu M_j b^*)$

$\phi_A = arg\ (A_f M_j)$

Li, Profumo, R-M '10

- *Dominant operators: EDM, CEDM*
- *No theory error (QCD SR)*
- *Includes full 2-loop (Li, Profumo, R-M)*

MSSM Global Analysis

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

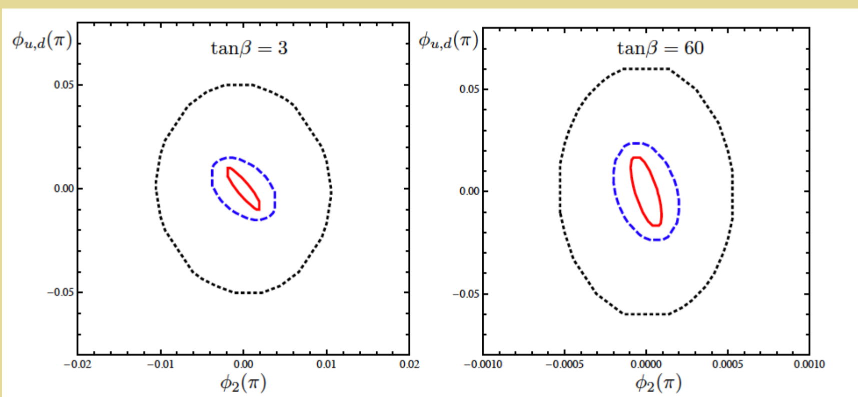
$$\begin{aligned}\mathcal{L}_{\rm soft} \;=\; & -\frac{1}{2}\left(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}\right) + c.c. \\ & -\left(\tilde{\bar{u}}\,\mathbf{a_u}\tilde{Q}H_u - \tilde{\bar{d}}\,\mathbf{a_d}\tilde{Q}H_d - \tilde{\bar{e}}\,\mathbf{a_e}\tilde{L}H_d\right)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

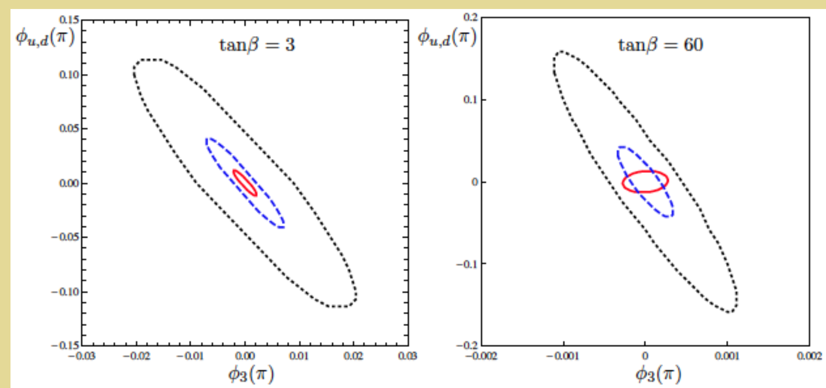
$\phi_j = arg\,(\mu M_j b^*)$

$\phi_A = arg\,(A_f M_j)$

Correlated Constraints

Li, Profumo, R-M '10





Present

Present: [199]Hg impact

MSSM Global Analysis

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

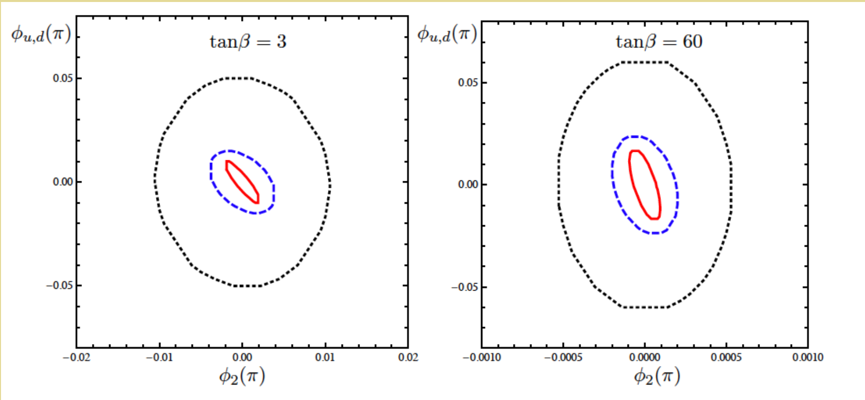
$$\begin{aligned}\mathcal{L}_{\rm soft} \;=\; & -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \\ & -(\tilde{\bar{u}}\mathbf{a_u}\tilde{Q}H_u - \tilde{\bar{d}}\mathbf{a_d}\tilde{Q}H_d - \tilde{\bar{e}}\mathbf{a_e}\tilde{L}H_d) + c.c. \\ & -\tilde{Q}^\dagger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

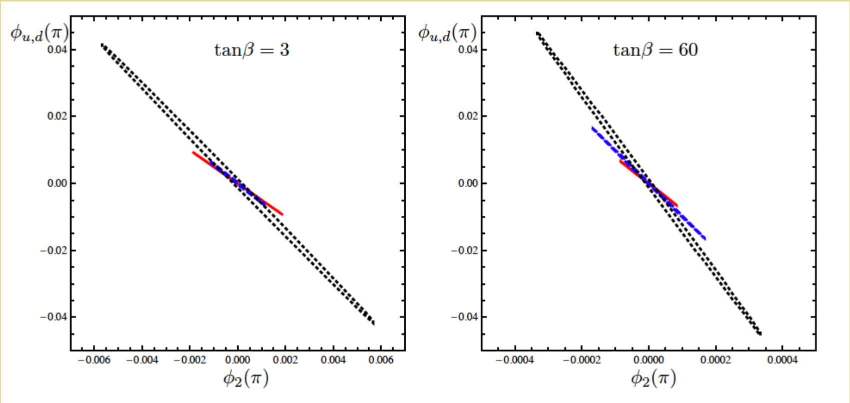
$\phi_j = arg\ (\mu M_j b^*)$

$\phi_A = arg\ (A_f M_j)$

Correlated Constraints

Li, Profumo, R-M '10

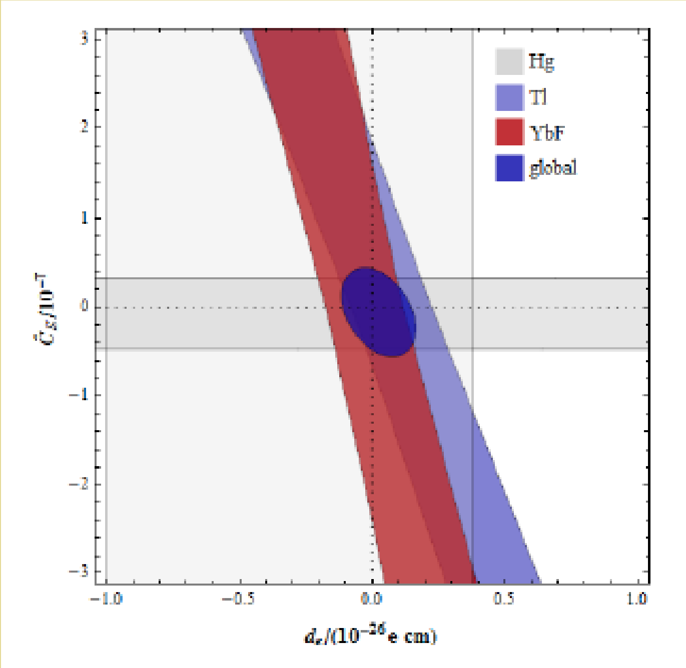




Present

Future d_n : 100 x present sensitivity

AMO Global Analysis

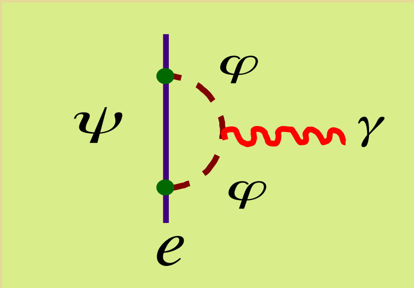


Jung '13

$$\frac{k_S^{(0)}}{e\zeta_A^e} \approx -37$$

- Dominant operators: e EDM, $C_S^{(0)} \sim \mathrm{Im}\, C_{eq}^{(-)}$
- Includes ^{199}Hg w/ $C_S^{(0)}$ no Schiff moment !
- Tl & YbF only: $|d_e| < 0.89 \times 10^{-26}$ e cm

EDM Probes: EWB Implications



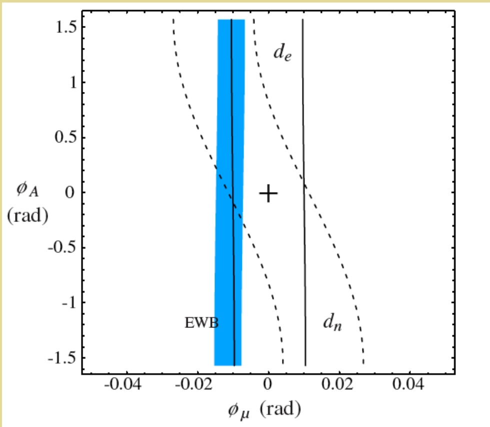
$sin\phi_{CP}$ ~ 1 $\rightarrow$ M > 5000 GeV

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

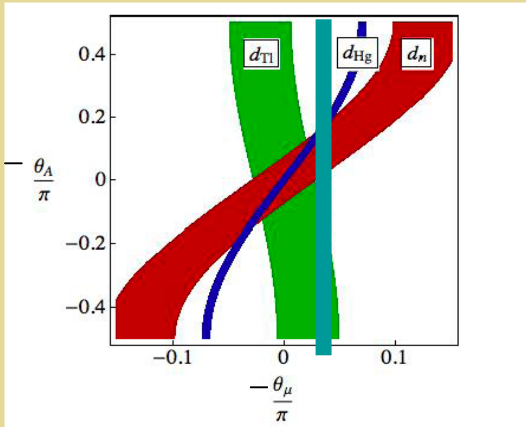
Universal gaugino phases

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

$Arg(\mu M_j b^*)$



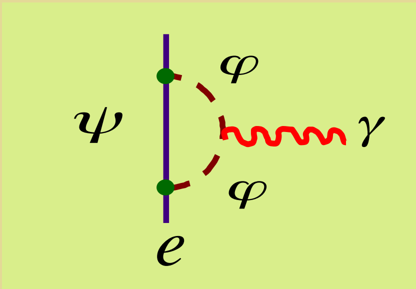
Cirigliano, R-M, Tulin, Lee '06



Ritz CIPANP 09 +

Cirigliano, R-M, Tulin, Lee '06

EDM Probes: EWB Implications



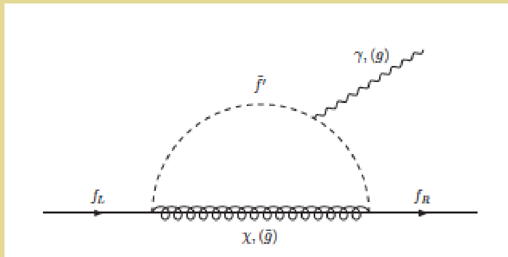
$\sin\phi_{CP} \sim 1 \;\longrightarrow\; M > 5000$ GeV

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

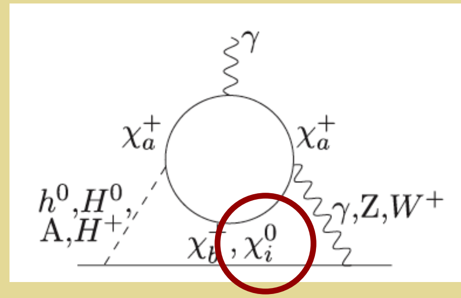
Viable EWB & CPV:

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

EDM Probes: EWB Implications

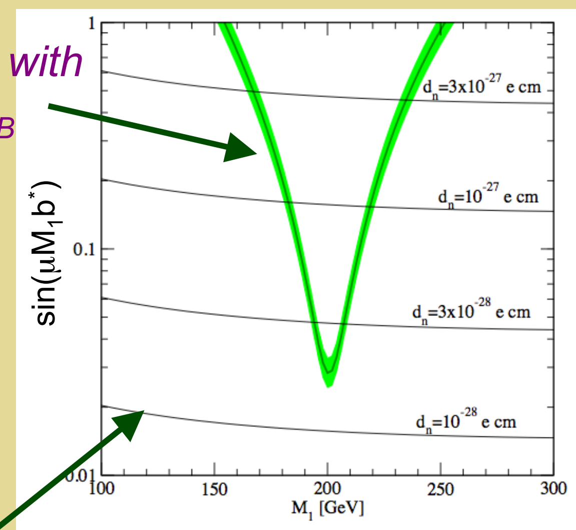


Heavy sfermions: LHC consistent & suppress 1-loop EDMs



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

Compatible with observed Y_B



Next generation d_n

Li, Profumo, RM

Viable EWB & CPV:

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

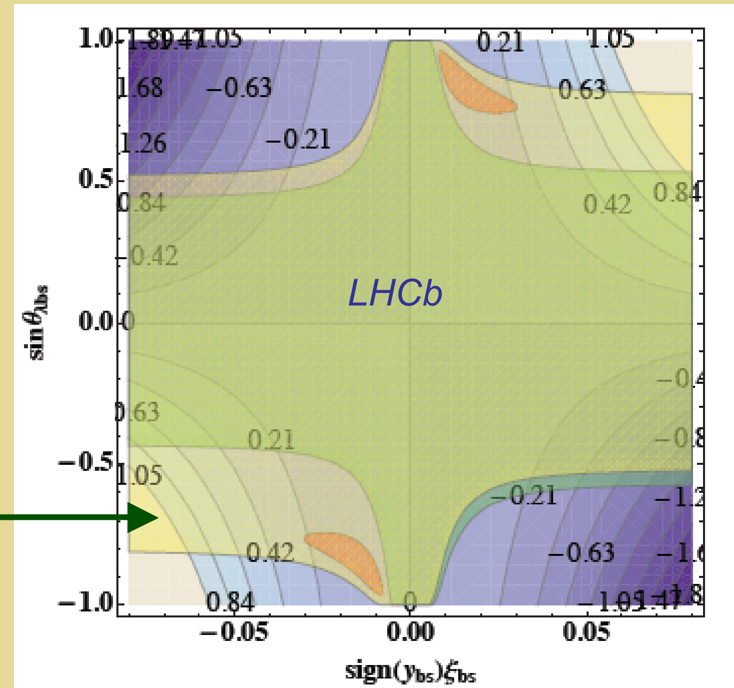
Flavored CPV & EWB

CPV & 2HDM

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

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

constant n_B / s



Viable EWB & CPV:

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

Open Problems

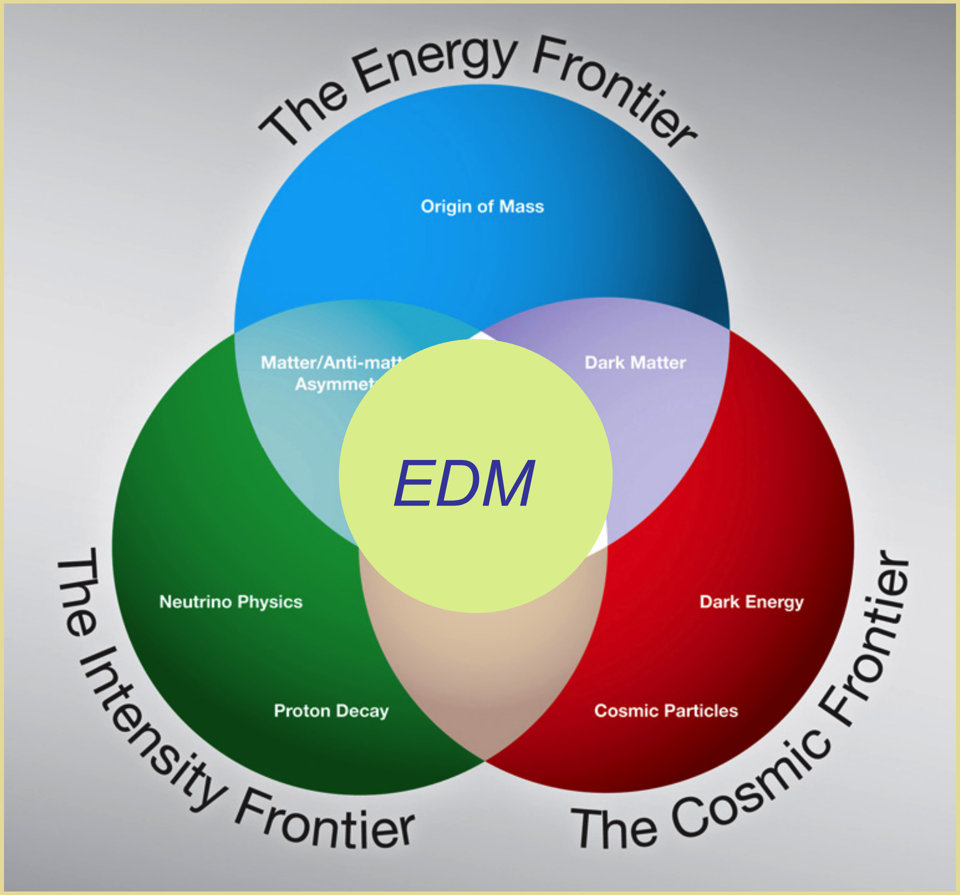
- *How many complementary EDM searches needed*
- *What is robust theory error at hadronic, nuclear, and AMO levels ?*

Hadronic Matrix Elements

Param	Coeff	Best value[a]	Range	Coeff	Best value[b,c]	Range[b,c]
$\bar{\theta}$	α_n	0.002	(0.0005–0.004)	$\lambda_{(0)}$	0.02	(0.005–0.04)
	α_p	0.002	(0.0005–0.004)	$\lambda_{(1)}$	2×10^{-4}	$(0.5 - 4) \times 10^{-4}$
Im C_{qG}	β_n^{uG}	4×10^{-4}	$(1 - 10) \times 10^{-4}$	$\gamma_{(0)}^{+G}$	−0.01	(−0.03)–0.03
	β_n^{dG}	8×10^{-4}	$(2 - 18) \times 10^{-4}$	$\gamma_{(1)}^{-G}$	−0.02	(−0.07)–(−0.01)
$\tilde{d}_q$	$e\tilde{\rho}_n^u$	−0.35	−(0.09 − 0.9)	$\tilde{\omega}_{(0)}$	8.8	(−25)–25
	$e\tilde{\rho}_n^d$	−0.7	−(0.2 − 1.8)	$\tilde{\omega}_{(1)}$	17.7	9–62
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2 - 20) \times 10^{-9}$	$\tilde{\eta}_{(0)}$	-2×10^{-7}	$(-6 - 6) \times 10^{-7}$
	$e\tilde{\zeta}_n^d$	16.3×10^{-9}	$(4 - 40) \times 10^{-9}$	$\tilde{\eta}_{(1)}$	-4×10^{-7}	$-(2 - 14) \times 10^{-7}$
Im $C_{q\gamma}$	$\beta_n^{u\gamma}$	0.4×10^{-3}	$(0.2 - 0.6) \times 10^{-3}$	$\gamma_{(0)}^{+\gamma}$	–	–
	$\beta_n^{d\gamma}$	-1.6×10^{-3}	$-(0.8 - 2.4) \times 10^{-3}$	$\gamma_{(1)}^{-\gamma}$	–	–
d_q	ρ_n^u	−0.35	(−0.17)–0.52	$\omega_{(0)}$	–	–
	ρ_n^d	1.4	0.7–2.1	$\omega_{(1)}$	–	–
δ_q	ζ_n^u	8.2×10^{-9}	$(4 - 12) \times 10^{-9}$	$\eta_{(0)}$	–	–
	ζ_n^d	-33×10^{-9}	$-(16 - 50) \times 10^{-9}$	$\eta_{(1)}$	–	–
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2 - 40) \times 10^{-7}$	$\gamma_{(i)}^{\tilde{G}}$	2×10^{-6}	$(1 - 10) \times 10^{-6}$
Im $C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1 - 10) \times 10^{-8}$	$\gamma_{(1)}^{\varphi ud}$	1×10^{-6}	$(5 - 150) \times 10^{-7}$
Im $C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10 - 80) \times 10^{-7}$	$\gamma_{(i)}^{quqd}$	2×10^{-6}	$(1 - 10) \times 10^{-6}$
Im $C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11–14.5			
Im $C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6–1.2			

J. Engel, U. van Kolck, MRM 1303.2371

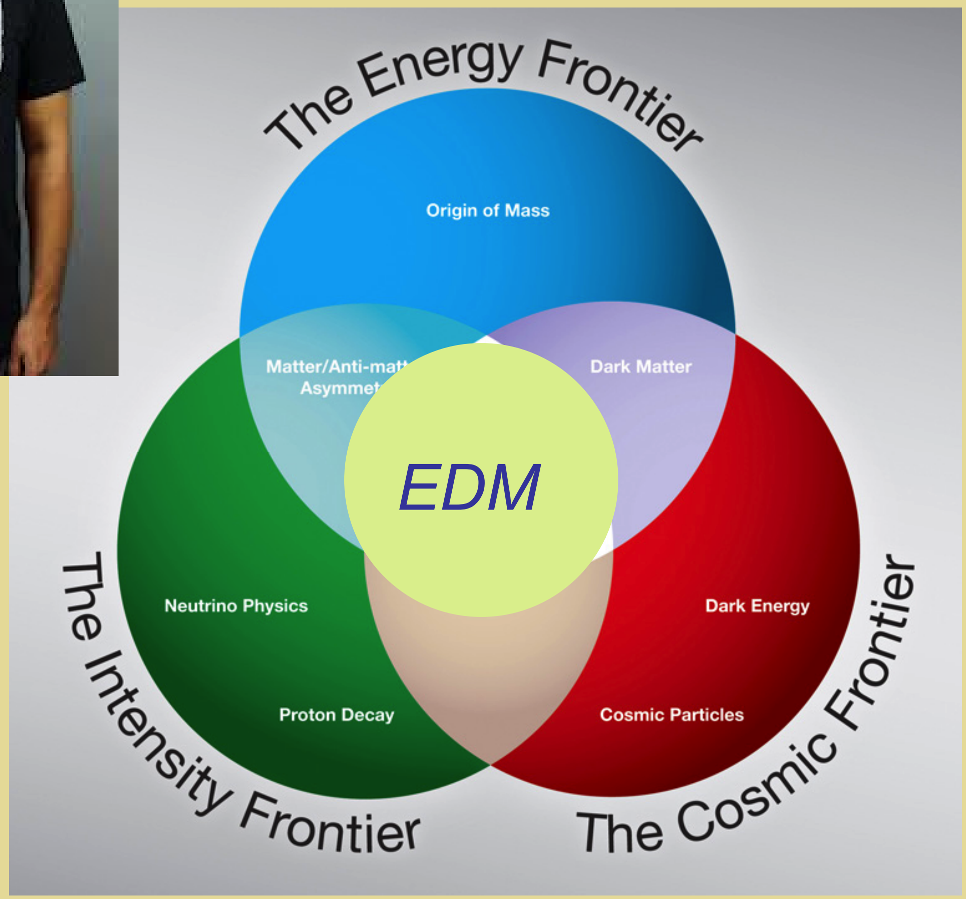
Summary



The Energy Frontier
Origin of Mass
Dark Matter
EDM
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier


POSTER
CHILD

Summary


The Energy Frontier
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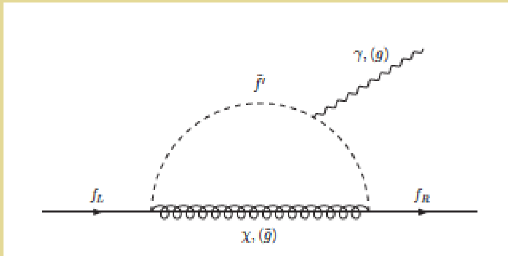
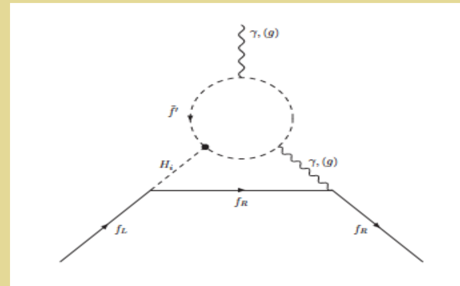
Back Up Slides

EDM Probes: EWB Implications



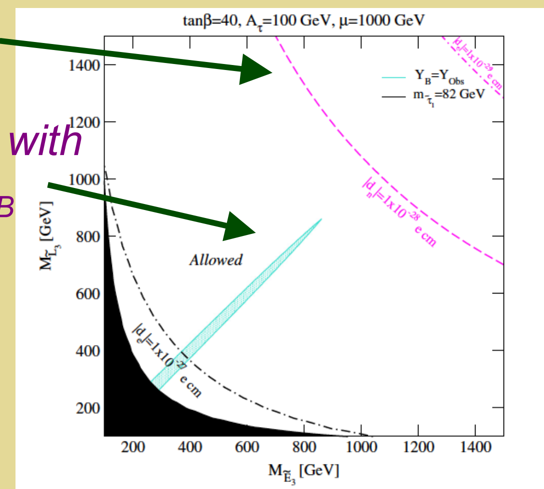
Light staus: LHC consistent & suppress 1-loop EDMs



No CEDM (^{199}Hg): EWB-viable but $m_H \rightarrow$ New scalars for EWPT

Next gen d_n

Compatible with observed Y_B



Viable EWB & CPV:

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

Kozaczuk, Wainwright, Profumo, RM

Wilson Coefficients: EDM & CEDM

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

→

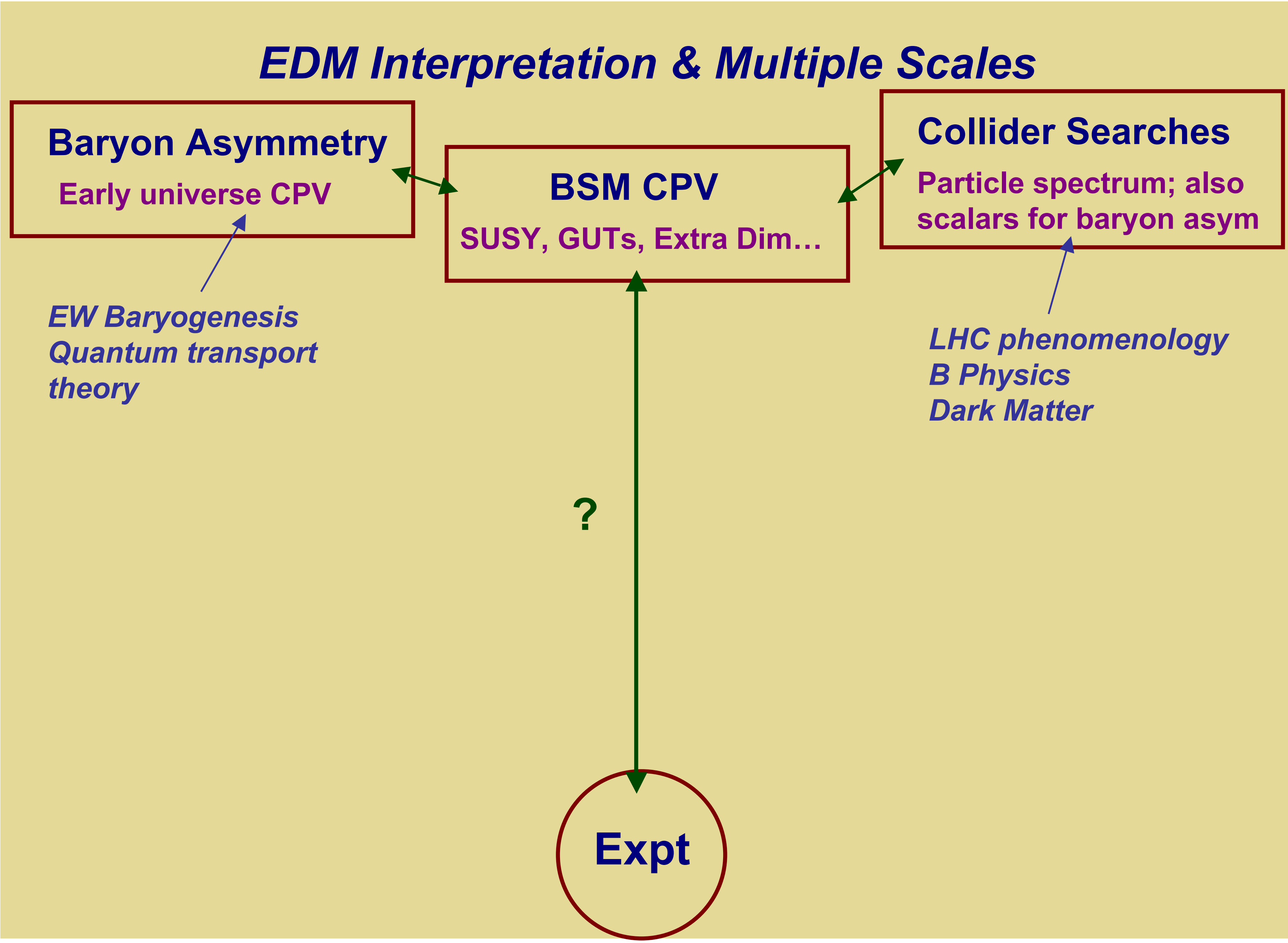
$$\mathcal{L}^{\rm CEDM} = -i \sum_q \frac{g_3 \tilde{d}_q}{2}\, \bar{q}\sigma^{\mu\nu}T^A\gamma_5 q\; G^A_{\mu\nu}$$
$$\mathcal{L}^{\rm EDM} = -i \sum_f \frac{d_f}{2} \bar{f}\sigma^{\mu\nu}\gamma_5 f\;\, F_{\mu\nu}$$

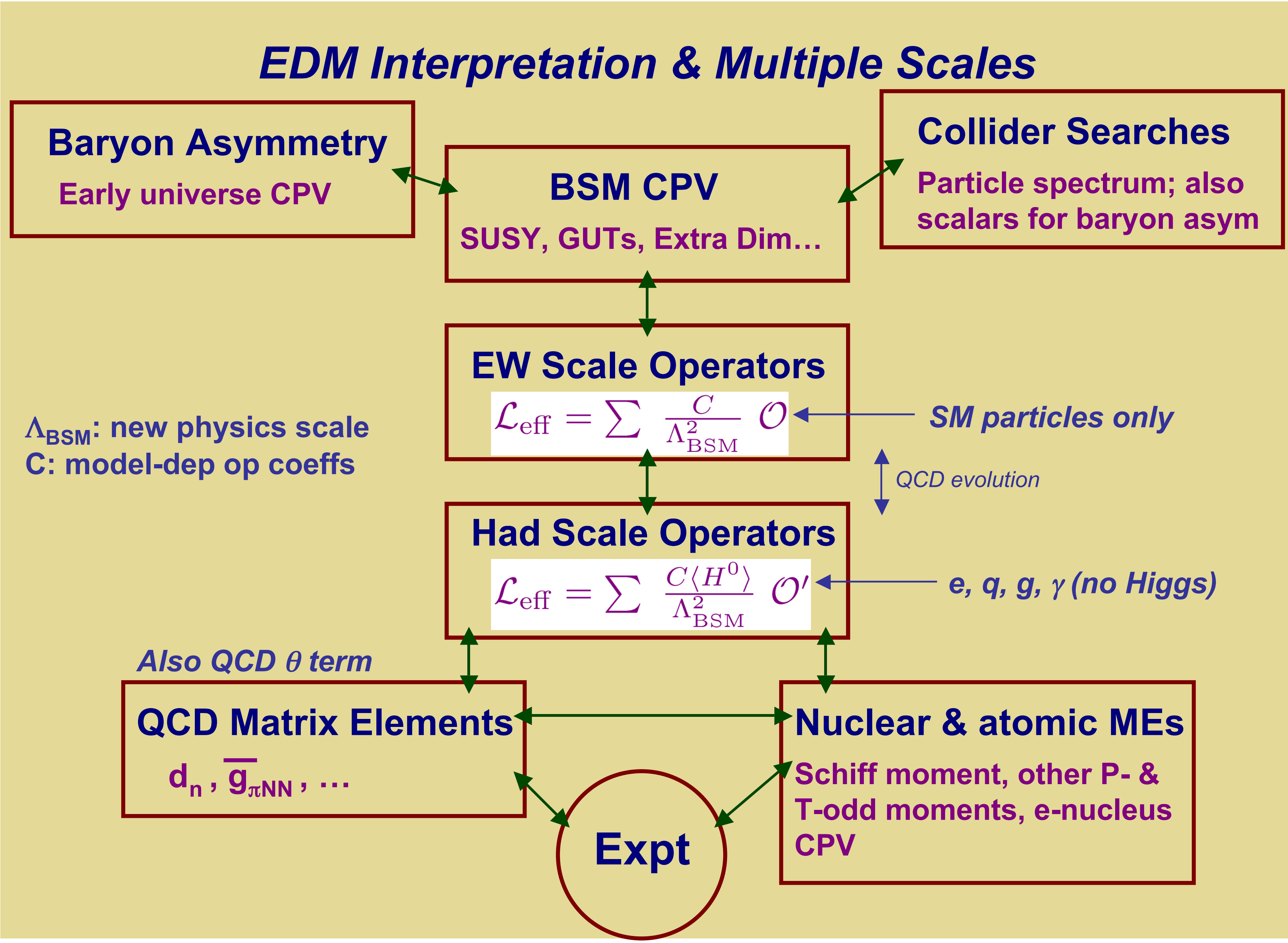
$$\alpha^{(6)}_{fV_k} \equiv g_k C_{fV_k}$$

→

$$\tilde{d}_q \;=\; -\frac{\sqrt{2}}{v}\left(\frac{v}{\Lambda}\right)^2 \;{\rm Im}\; C_{qG}\;,$$
$$d_f \;=\; -\frac{\sqrt{2}e}{v}\;\left(\frac{v}{\Lambda}\right)^2\; {\rm Im}\; C_{f\gamma}$$

$${\rm Im}\; C_{f\gamma} \equiv {\rm Im}\; C_{fB} + 2I_3^f\; {\rm Im}\; C_{fW}$$


EDM Interpretation & Multiple Scales
Baryon Asymmetry
Early universe CPV
BSM CPV
SUSY, GUTs, Extra Dim…
Collider Searches
Particle spectrum; also
scalars for baryon asym
EW Baryogenesis
Quantum transport
theory
LHC phenomenology
B Physics
Dark Matter
?
Expt


EDM Interpretation & Multiple Scales
Baryon Asymmetry
Early universe CPV
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SUSY, GUTs, Extra Dim…
Collider Searches
Particle spectrum; also scalars for baryon asym
EW Scale Operators
$\mathcal{L}_{\rm eff} = \sum \frac{C}{\Lambda_{\rm BSM}^2} \mathcal{O}$
SM particles only
$\Lambda_{\rm BSM}$: new physics scale
C: model-dep op coeffs
QCD evolution
Had Scale Operators
$\mathcal{L}_{\rm eff} = \sum \frac{C\langle H^0 \rangle}{\Lambda_{\rm BSM}^2} \mathcal{O}'$
e, q, g, γ (no Higgs)
Also QCD θ term
QCD Matrix Elements
d_n , $\bar{g}_{\pi NN}$, …
Nuclear & atomic MEs
Schiff moment, other P- & T-odd moments, e-nucleus CPV
Expt

Operator Classification

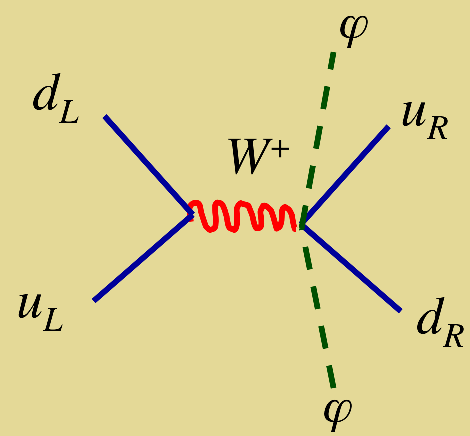
$$\mathcal{L}^{\mathrm{eq}}_{\mathrm{CPV}} = i\frac{\mathrm{Im}C_{\ell edq}}{2\Lambda^2}\left[\bar{e}\gamma_5 e\ \bar{d}d - \bar{e}e\ \bar{d}\gamma_5 d\right] - i\frac{\mathrm{Im}C^{(1)}_{\ell equ}}{2\Lambda^2}\left[\bar{e}\gamma_5 e\ \bar{u}u + \bar{e}e\ \bar{u}\gamma_5 u\right] - \frac{\mathrm{Im}C^{(3)}_{\ell equ}}{2\Lambda^2}\ \epsilon_{\mu\nu\alpha\beta}\ \bar{e}\sigma^{\mu\nu}e\ \bar{u}\sigma^{\alpha\beta}u$$

$$\mathcal{L}^{\mathrm{qq}}_{\mathrm{CPV}} = i\frac{g_3^2\,\mathrm{Im}C^{(1)}_{qugd}}{2\Lambda^2}\left[\bar{u}\gamma_5 u\ \bar{d}d + \bar{u}u\ \bar{d}\gamma_5 d - \bar{d}\gamma_5 u\ \bar{u}d - \bar{d}u\ \bar{u}\gamma_5 d\right] + i\frac{g_3^2\,\mathrm{Im}C^{(8)}_{qugd}}{2\Lambda^2}\left[\bar{u}\gamma_5 T^A u\ \bar{d}T^A d + \bar{u}T^A u\ \bar{d}\gamma_5 T^A d - \bar{d}\gamma_5 T^A u\ \bar{u}T^A d - \bar{d}T^A u\ \bar{u}\gamma_5 T^A d\right]$$

Nonleptonic: hadronic
EDMs & Schiff moment

Operator Classification

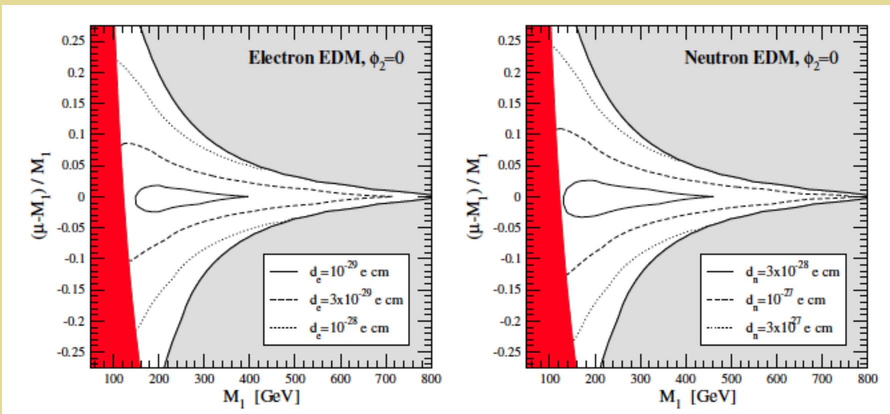
$$Q_{\varphi ud} = i\tilde{\varphi}^\dagger D_\mu \varphi \bar{u}_R \gamma^\mu d_R$$



Baryogenesis Implications

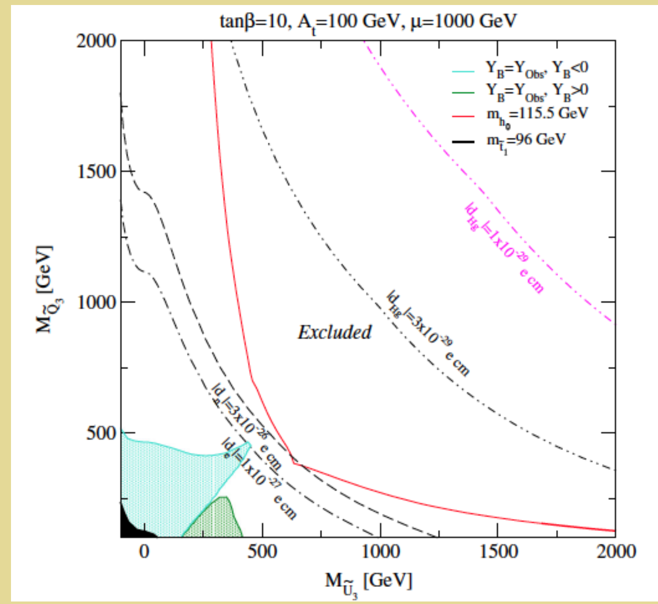
MSSM: ϕ_1 only

Gaugino sources



Cirigliano, Li, Profumo, R-M '10

Sfermion (stop) sources



Kocaczuk, Wainwright, Profumo, R-M '12

Effective Operators & θ_{ind}

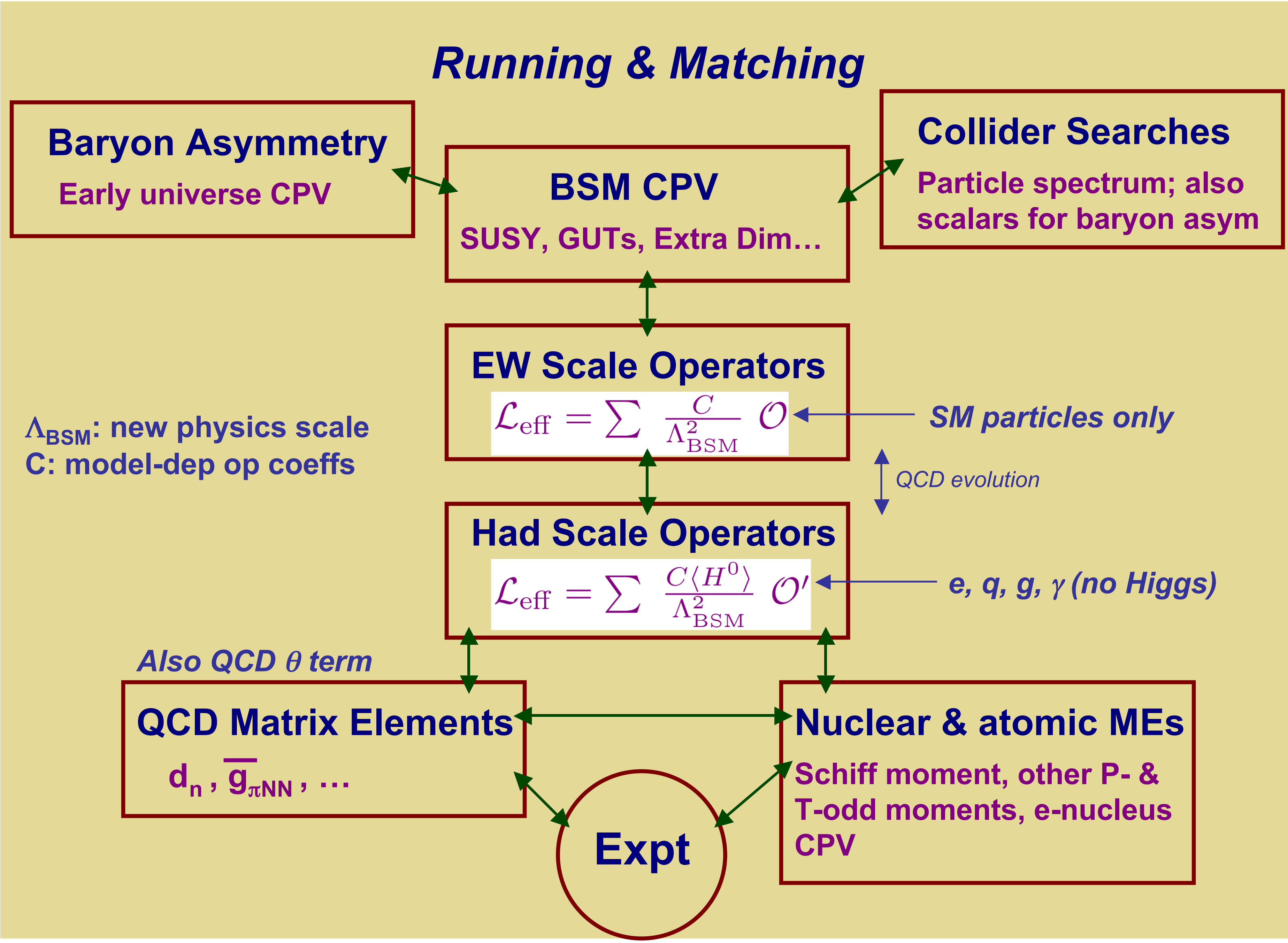
$$\mathcal{L}_{\rm axion} = \frac{1}{2}\partial^\mu a \partial_\mu a - V(a) - \frac{a(x)}{f_a}\,\frac{g_3^2\bar{\theta}}{16\pi^2}\,{\rm Tr}\left(G^{\mu\nu}\tilde{G}_{\mu\nu}\right)$$

$$V(a) = \chi(0)_{\mathcal{O}_{\rm CPV}}\left(\bar{\theta} - \frac{a}{f_a}\right) + \frac{1}{2}\chi(0)\left(\bar{\theta} + \frac{a}{f_a}\right)^2 + \cdots\ ,$$

$$\chi(0)_{\mathcal{O}_{\rm CPV}} = -i\lim_{k\to 0}\int d^4x\, e^{ix\cdot k}\,\langle 0|\, T\{G\tilde{G}(x), \mathcal{O}_{\rm CPV}(0)\}\,|0\rangle$$

12 total + $\overline{\theta}$

$\bar{\theta} \to \theta_{ind} \propto \tilde{\delta}_q$, C, …


Running & Matching
Baryon Asymmetry
Early universe CPV
BSM CPV
SUSY, GUTs, Extra Dim…
Collider Searches
Particle spectrum; also scalars for baryon asym
EW Scale Operators
$\mathcal{L}_{\text{eff}} = \sum \frac{C}{\Lambda_{\text{BSM}}^2} \mathcal{O}$
SM particles only
Λ_{BSM}: new physics scale
C: model-dep op coeffs
QCD evolution
Had Scale Operators
$\mathcal{L}_{\text{eff}} = \sum \frac{C\langle H^0\rangle}{\Lambda_{\text{BSM}}^2} \mathcal{O}'$
e, q, g, γ (no Higgs)
Also QCD θ term
QCD Matrix Elements
d_n , $\bar{g}_{\pi NN}$, …
Nuclear & atomic MEs
Schiff moment, other P- & T-odd moments, e-nucleus CPV
Expt

Running & Matching

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

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

Running & Matching *Hadronic*

$$d_N = \alpha_N \, \bar\theta + \left(\frac{v}{\Lambda}\right)^2 \sum_k \beta_N^{(k)} \, (\mathrm{Im}\, C_k)$$

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

$$\left(\frac{v}{\Lambda}\right)^2 \left[\beta_N^{qG} \, (\mathrm{Im}\, C_{qG}) + \beta_N^{q\gamma} \, (\mathrm{Im}\, C_{q\gamma})\right] = e\, \tilde\rho_N^q \, \tilde d_q + \rho_N^q \, d_q = \left(\frac{v}{\Lambda}\right)^2 \left[e\, \tilde\zeta_N^q \, \tilde\delta_q + e\, \zeta_N^q \, \delta_q\right]$$

$$\left(\frac{v}{\Lambda}\right)^2 \left[\gamma_{(i)}^{qG} \, (\mathrm{Im}\, C_{qG}) + \gamma_{(i)}^{q\gamma} \, (\mathrm{Im}\, C_{q\gamma})\right] = \tilde\omega_{(i)}^q \, \tilde d_q + \omega_{(i)}^q \, d_q = \left(\frac{v}{\Lambda}\right)^2 \left[\tilde\eta_{(i)}^q \, \tilde\delta_q + \eta_{(i)}^q \, \delta_q\right]$$

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

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

Running & Matching

Atomic & Molecular

$$
\begin{aligned}
d_A \;=\; & \rho_A^e\, d_e + \sum_{N=p,n} \rho_Z^N\, d_N + \kappa_S\, S \\
+ & \left(\frac{v}{\Lambda}\right)^2 \Bigg\{ \left[k_S^{(0)} g_S^{(0)} + k_P^{(1)} g_P^{(1)}\right]\ \mathrm{Im} C_{eq}^{(-)} \\
+ & \left[k_S^{(1)} g_S^{(1)} + k_P^{(0)} g_P^{(0)}\right]\ \mathrm{Im} C_{eq}^{(+)} \\
+ & \left[k_T^{(0)} g_T^{(0)} + k_T^{(1)} g_T^{(1)}\right]\ \mathrm{Im} C_{\ell equ}^{(3)} \Bigg\}
\end{aligned}
$$

$$
\rho_A^e\, d_e = e\, \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e
$$

$$
C_{eq}^{(\pm)} = C_{\ell edq} \pm C_{\ell equ}^{(1)}
$$

Running & Matching

Atomic & Molecular

$$d_A = \rho_A^e \, d_e + \sum_{N=p,n} \rho_Z^N \boxed{d_N} + \kappa_S \boxed{S}$$
$$+ \left(\frac{v}{\Lambda}\right)^2 \Big\{ \left[k_S^{(0)} g_S^{(0)} + k_P^{(1)} g_P^{(1)}\right] \; \mathrm{Im} C_{eq}^{(-)}$$
$$+ \left[k_S^{(1)} g_S^{(1)} + k_P^{(0)} g_P^{(0)}\right] \; \mathrm{Im} C_{eq}^{(+)}$$
$$+ \left[k_T^{(0)} g_T^{(0)} + k_T^{(1)} g_T^{(1)}\right] \; \mathrm{Im} C_{\ell equ}^{(3)} \Big\}$$

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

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

$$\rho_A^e \, d_e = e \, \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e$$

$$C_{eq}^{(\pm)} = C_{\ell edq} \pm C_{\ell equ}^{(1)}$$

Running & Matching

Atomic & Molecular

$$d_A = \rho_A^e\, d_e + \sum_{N=p,n} \rho_Z^N \boxed{d_N} + \kappa_S \boxed{S}$$
$$+ \left(\frac{v}{\Lambda}\right)^2 \Big\{ \left[k_S^{(0)} \boxed{g_S^{(0)}} + k_P^{(1)} \boxed{g_P^{(1)}}\right] \; \mathrm{Im} C_{eq}^{(-)}$$
$$+ \left[k_S^{(1)} \boxed{g_S^{(1)}} + k_P^{(0)} \boxed{g_P^{(0)}}\right] \; \mathrm{Im} C_{eq}^{(+)}$$
$$+ \left[k_T^{(0)} \boxed{g_T^{(0)}} + k_T^{(1)} \boxed{g_T^{(1)}}\right] \; \mathrm{Im} C_{\ell equ}^{(3)} \Big\}$$

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

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

Hadronic coefficients, including form factors g_Γ

$$\rho_A^e\, d_e = e\, \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e$$

$$C_{eq}^{(\pm)} = C_{\ell edq} \pm C_{\ell equ}^{(1)}$$

Running & Matching

Atomic & Molecular

$$d_A = \rho_A^e d_e + \sum_{N=p,n} \rho_Z^N d_N + \kappa_S S$$
$$+ \left(\frac{v}{\Lambda}\right)^2 \left\{ \left[k_S^{(0)} g_S^{(0)} + k_P^{(1)} g_P^{(1)}\right] \mathrm{Im} C_{eq}^{(-)} \right.$$
$$+ \left[k_S^{(1)} g_S^{(1)} + k_P^{(0)} g_P^{(0)}\right] \mathrm{Im} C_{eq}^{(+)}$$
$$\left. + \left[k_T^{(0)} g_T^{(0)} + k_T^{(1)} g_T^{(1)}\right] \mathrm{Im} C_{\ell equ}^{(3)} \right\}$$

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

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

Atomic / molecular coefficients

$$\rho_A^e\, d_e = e\, \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e$$

$$C_{eq}^{(\pm)} = C_{\ell edq} \pm C_{\ell equ}^{(1)}$$

Running & Matching

Atomic & Molecular

$$d_A = \rho_A^e d_e + \sum_{N=p,n} \rho_Z^N d_N + \kappa_S S$$
$$+ \left(\frac{v}{\Lambda}\right)^2 \Big\{ \left[k_S^{(0)} g_S^{(0)} + k_P^{(1)} g_P^{(1)} \right] \mathrm{Im} C_{eq}^{(-)}$$
$$+ \left[k_S^{(1)} g_S^{(1)} + k_P^{(0)} g_P^{(0)} \right] \mathrm{Im} C_{eq}^{(+)}$$
$$+ \left[k_T^{(0)} g_T^{(0)} + k_T^{(1)} g_T^{(1)} \right] \mathrm{Im} C_{\ell equ}^{(3)} \Big\}$$

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

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

Atomic / molecular coefficients

Paramag*: δ_e, Im $C_{eq}^{(-)}$ (k_s^0)

Diamag**: S, Im $C_{lequ}^{(3)}$ (k_T)

$$\rho_A^e\, d_e = e\, \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e$$

$$C_{eq}^{(\pm)} = C_{\ell edq} \pm C_{\ell equ}^{(1)}$$

* Tl, Cs, YbF…

** Hg, Ra, Rn…

Hadronic Matching: χ Sym

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

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

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

Matching: χ Sym & Other Methods

CPV Parameter	Coefficient	Method	Value	Remarks
$\bar{\theta}$	α_n	ChPT	$\sim 0.002\ e$ fm	
$\bar{\theta}$	α_n	Lattice QCD[30]	-0.040(28) e-fm	$m_\pi = 0.53$ GeV
$\bar{\theta}$	α_p	Lattice QCD[30]	0.072(49) e-fm	$m_\pi = 0.53$ GeV
$\bar{\theta}$	α_n	Lattice QCD[31]	-0.049(5) e-fm	$m_\pi \approx 0.61$ GeV
$\bar{\theta}$	α_p	Lattice QCD[31]	0.080(10) e-fm	$m_\pi \approx 0.61$ GeV
$\bar{\theta}$	α_n	QCD Sum Rules[6]	(0.0025 ± 0.0013) e-fm	λ from QCD SR
$\bar{\theta}$	α_n	QCD Sum Rules[35]	$(0.0004^{+0.0003}_{-0.0002})$ e-fm	λ from lattice
$\bar{\theta}$	$\lambda_{(0)}$	ChPT	$\sim m_\pi^2/\Lambda_\chi F_\pi$	See Eq. (3.62)
			-0.05	See Eq. (3.60)
$\bar{\theta}$	$\lambda_{(1)}$	ChPT	$\sim m_\pi^4/\Lambda_\chi^3 F_\pi$	See Eq. (3.63)

θ term

Matching: χ Sym & Other Methods

CPV Parameter	Coefficient	Method	Value	Remarks
$\tilde{d}_q$	$\tilde{\rho}_N$	ChPT	~ -0.7	
$\tilde{d}_q$	$\tilde{\rho}_N^u$	QCD SR[6]	0.55 ± 2.8	PQ assumed
$\tilde{d}_q$	$\tilde{\rho}_N^d$	QCD SR[6]	1.1 ± 0.55	PQ assumed
$\tilde{d}_u$	$\tilde{\rho}_N$	QM/NDA	~ -0.09	includes K_{qG}
$\tilde{d}_d$	$\tilde{\rho}_N$	QM/NDA	~ 0.36	includes K_{qG}
$\tilde{\delta}_q$	$e\tilde{\zeta}_N$	ChPT	$\sim 5 \times 10^{-8}\ e$ fm	
$\tilde{\delta}_u$	$e\tilde{\zeta}_N^u$	QCD SR[6]	$-(0.9 \pm 0.5) \times 10^{-8}\ e$ fm	PQ assumed
$\tilde{\delta}_d$	$e\tilde{\zeta}_N^d$	QCD SR[6]	$(-3.6 \pm 1.8) \times 10^{-8}\ e$ fm	PQ assumed
$\tilde{\delta}_u$	$e\tilde{\zeta}_N^u$	QM/NDA	$\sim 0.15 \times 10^{-8}\ e$ fm	includes K_{qG}
$\tilde{\delta}_d$	$e\tilde{\zeta}_N^d$	QM/NDA	$\sim -1.2 \times 10^{-8}\ e$ fm	includes K_{qG}

CEDM

AMO Global Analysis

Atomic & Molecular

$$d_A = \rho_A^e d_e + \sum_{N=p,n} \rho_Z^N d_N + \kappa_S S + \left(\frac{v}{\Lambda}\right)^2 \left\{ \left[k_S^{(0)} g_S^{(0)} + k_P^{(1)} g_P^{(1)}\right] \mathrm{Im}C_{eq}^{(-)} + \left[k_S^{(1)} g_S^{(1)} + k_P^{(0)} g_P^{(0)}\right] \mathrm{Im}C_{eq}^{(+)} + \left[k_T^{(0)} g_T^{(0)} + k_T^{(1)} g_T^{(1)}\right] \mathrm{Im}C_{\ell equ}^{(3)} \right\}$$

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

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

Atomic / molecular coefficients

Paramag: δ_e, Im $C_{eq}^{(-)}$ (k_s^0)*

*Diamag**: S, Im $C_{lequ}^{(3)}$ (k_T)*

$$\rho_A^e\, d_e = e\, \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e$$

$$C_{eq}^{(\pm)} = C_{\ell edq} \pm C_{\ell equ}^{(1)}$$

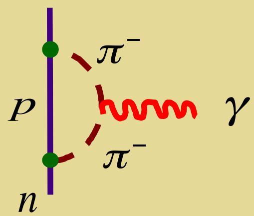
** Tl, Cs, YbF…*

*** Hg, Ra, Rn…*

Global Analysis: Hadronic

$$\mathcal{L}_{N\pi}^{\rm PVTV} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S_\mu N\, v_\nu F^{\mu\nu}$$

$$+ \bar{N}\left[\bar{g}_\pi^{(0)}\boldsymbol{\tau}\cdot\boldsymbol{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}\left(3\tau_3\pi^0 - \boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]N$$



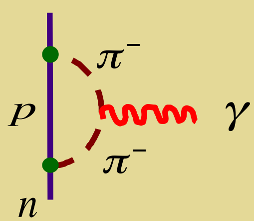
$$d_0 = \bar{d}_0 - \frac{eg_A}{16\pi F_\pi}\left\{\bar{g}_\pi^{(0)}\left[\frac{3m_\pi}{m_N} - \frac{4(\Delta m_N)_q}{m_\pi}\right] + \bar{g}_\pi^{(1)}\frac{m_\pi}{m_N}\right\}$$

$$d_1 = \bar{d}_1(\mu) + \delta\bar{d}_1(\mu) - \frac{eg_A}{(2\pi)^2 F_\pi}\left\{\bar{g}_\pi^{(0)}\left[\ln\frac{m_N^2}{m_\pi^2} + \frac{5\pi m_\pi}{4m_N} - \frac{\Delta m_\pi^2}{m_\pi^2}\right] - \bar{g}_\pi^{(1)}\frac{\pi m_\pi}{4m_N}\right\}$$

Global Analysis: Hadronic

$$\mathcal{L}_{N\pi}^{\mathrm{PVTV}} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S_\mu N \, v_\nu F^{\mu\nu}$$

$$+ \bar{N}\left[\bar{g}_\pi^{(0)}\boldsymbol{\tau}\cdot\boldsymbol{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}\left(3\tau_3\pi^0 - \boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]N$$



$$d_0 = \bar{d}_0 - \frac{e g_A}{16\pi F_\pi}\left\{\bar{g}_\pi^{(0)}\left[\frac{3m_\pi}{m_N} - \frac{4(\Delta m_N)_q}{m_\pi}\right] + \bar{g}_\pi^{(1)}\frac{m_\pi}{m_N}\right\}$$

$$d_1 = \bar{d}_1(\mu) + \delta\bar{d}_1(\mu) - \frac{e g_A}{(2\pi)^2 F_\pi}\left\{\bar{g}_\pi^{(0)}\left[\ln\frac{m_N^2}{m_\pi^2} + \frac{5\pi m_\pi}{4m_N} - \frac{\Delta m_\pi^2}{m_\pi^2}\right] - \bar{g}_\pi^{(1)}\frac{\pi m_\pi}{4m_N}\right\}$$

δ_q, $\tilde{\delta}_q$, θ,… $\tilde{\delta}_q$, θ,… $C_{\varphi ud}$, $\tilde{\delta}_q$, …

Need multiple hadronic systems to disentangle

EDMs: SM & BSM CPV?

In units of e cm, selected EDM limits are:

Particle	EDM limit	System	SM Prediction	New Physics
e	10.5×10^{-28}	YbF	10^{-38}	10^{-27}
μ	1.1×10^{-19}	rest frame $\vec{E}$	10^{-35}	10^{-22}
τ	3.1×10^{-16}	$e^+e^- \to \tau^+\tau^-\gamma$	10^{-34}	10^{-20}
p	6.5×10^{-23}	TlF molecule	10^{-31}	10^{-26}
n	2.9×10^{-26}	UCN	10^{-31}	10^{-26}
^{199}Hg	3.1×10^{-29}	atom cell	10^{-33}	10^{-28}

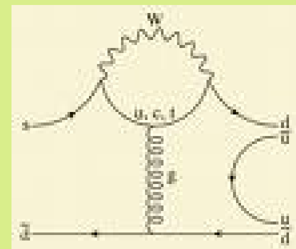
A non-exhaustive list:

Leptonic EDMs		Hadronic EDMs	
System	Group	System	Group
Cs (trapped)	Penn St.	n (UCN)	SNS
Cs (trapped)	Texas	n (UCN)	ILL
Cs (fountain)	LBNL	n (UCN)	PSI
YbF (beam)	Imperial	n (UCN)	Munich
PbO (cell)	Yale	^{199}Hg (cell)	Seattle
HBr^+ (trapped)	JILA	^{129}Xe (liquid)	Princeton
PbF (trapped)	Oklahoma	^{225}Ra (trapped)	Argonne
GdIG (solid)	Amherst	^{213,225}Ra (trapped)	KVI
GGG (solid)	Yale/Indiana	^{223}Rn (trapped)	TRIUMF
muon (ring)	J-PARC	deuteron (ring)	BNL?

EDMs: Standard Model CKM

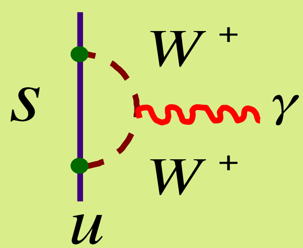
In units of *e* cm, selected EDM limits are:

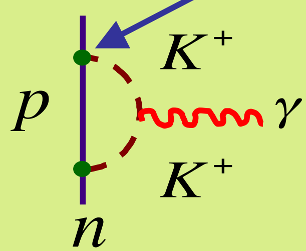
Particle	EDM limit	System	SM Prediction
e	10.5×10^{-28}	YbF	10^{-38}
μ	1.1×10^{-19}	rest frame $\vec{E}$	10^{-35}
τ	3.1×10^{-16}	$e^+e^- \to \tau^+\tau^-\gamma$	10^{-34}
p	6.5×10^{-23}	TlF molecule	10^{-31}
n	2.9×10^{-26}	UCN	10^{-31}
^{199}Hg	3.1×10^{-29}	atom cell	10^{-33}

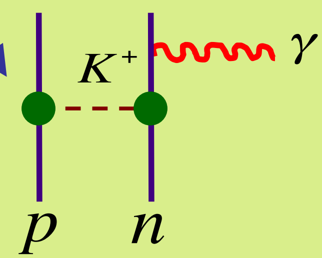


Penguin: ΔS = 1

CKM CPV







- *1 loop vanishes (~ V_{us} V_{us}^*)*
- *2 loop shown to vanish explicitly*

- *Khriplovich et al; McKellar…*

- *Donoghue, Holstein, RM; Khriplovich et al*

EDMs: Standard Model θ-term

In units of e cm, selected EDM limits are:

Particle	EDM limit	System	SM Prediction
e	10.5×10^{-28}	YbF	10^{-38}
μ	1.1×10^{-19}	rest frame $\vec{E}$	10^{-35}
τ	3.1×10^{-16}	$e^+e^- \to \tau^+\tau^-\gamma$	10^{-34}
p	6.5×10^{-23}	TlF molecule	10^{-31}
n	2.9×10^{-26}	UCN	10^{-31}
^{199}Hg	3.1×10^{-29}	atom cell	10^{-33}

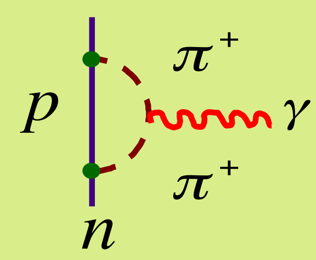
d_n & d_A (^{199}Hg):

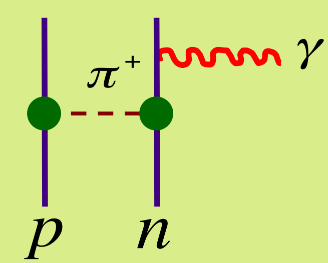
$$\bar{\theta} < 10^{-10}$$

Peccei -Quinn Sym?

$\mathcal{L}^{\theta}_{QCD}$

$$\frac{\alpha_s \bar{\theta}}{4\pi} \mathrm{Tr}\, \tilde{G}_{\mu\nu} G^{\mu\nu}$$





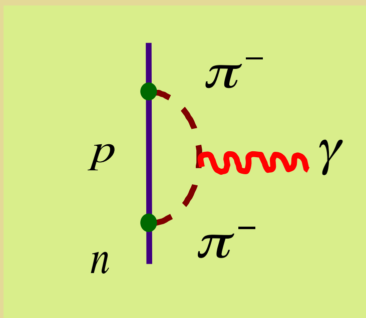
- *vanishes for any m_q=0*
- *"bar" : absorb quark field redefinition*

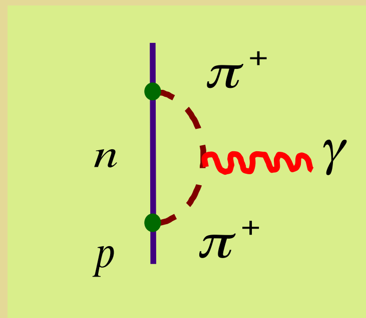
- *Crewther et al; van Kolck et al ; Herczeg*

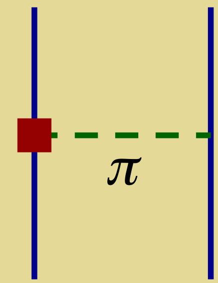
- *Haxton & Henley; Engel;*

EDMs & Isospin Filter: n, p, A

Chiral limit:







$+\cdots$

Nucleons

Schiff Moments

$$d_n - d_p \sim \bar{g}_0 \qquad d_n + d_p \sim \bar{g}_1$$

$$d_N^{I=1} \simeq 0.87(d_u - d_d) + 0.27e(d_u^c - d_d^c)$$

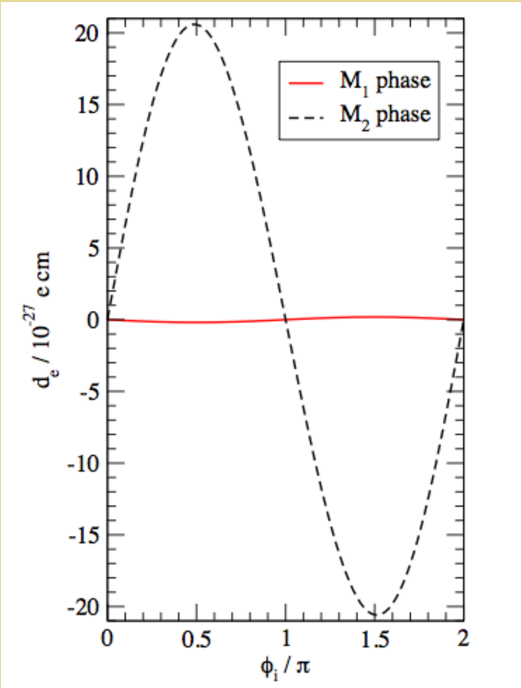
$$d_N^{I=0} \simeq 0.5(d_u + d_d) + 0.83e(d_u^c + d_d^c)$$

Schiff Moment in ^{199}Hg

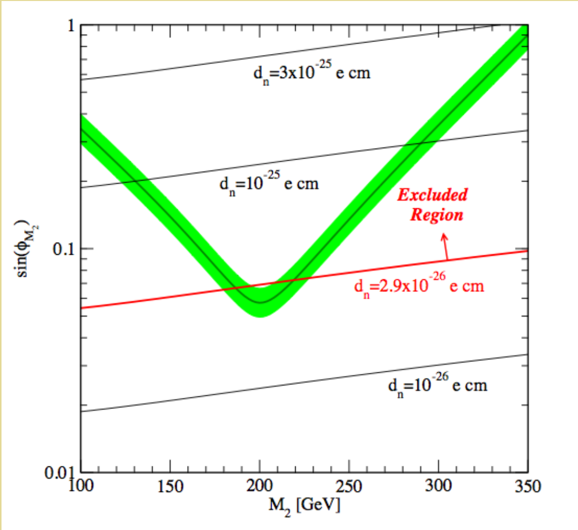
$$S_{^{199}\mathrm{Hg}}^{\mathrm{ave}} = 0.007\, g\bar{g}_0 + 0.071\, g\bar{g}_1 + 0.018\, g\bar{g}_2\ [e\,\mathrm{fm}^3]$$

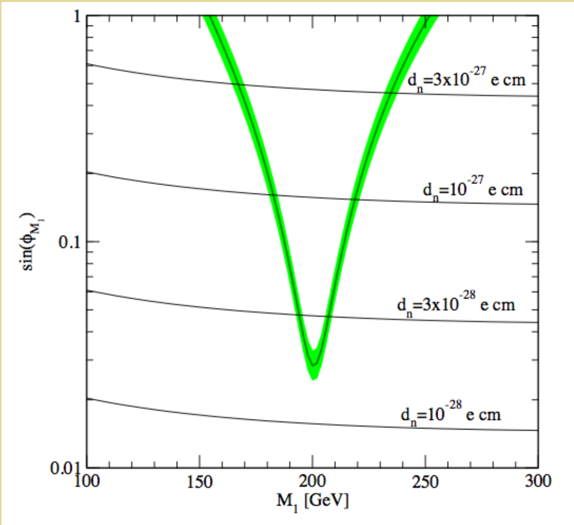
EDMs & EWB: 2 Loop Regime

Arg($\mu M_1 b^*$) ≠ Arg($\mu M_2 b^*$)



Weak dependence of d_e, d_n on Arg($\mu M_1 b^*$)





Li, Profumo, R-M: PLB 673:95 (2009)

Res χ^+ EWB not compatible with d_n

Res & non-res χ^0 EWB compatible with future d_n, light m_A, & moderate tanβ