EDMs at Dimension Six

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NPAC

Theoretical Nuclear, Particle, Astrophysics & Cosmology

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

EDMs 13, FNAL, February 2013

Goals

- *Set framework for interpreting EDM searches in terms of BSM CPV*
- *Delineate physics at multiple scales that enters the EDM search interpretation*
- *Identify open problems*
- *Provide a few examples*
- *Set stage for rest of workshop*

Key Themes

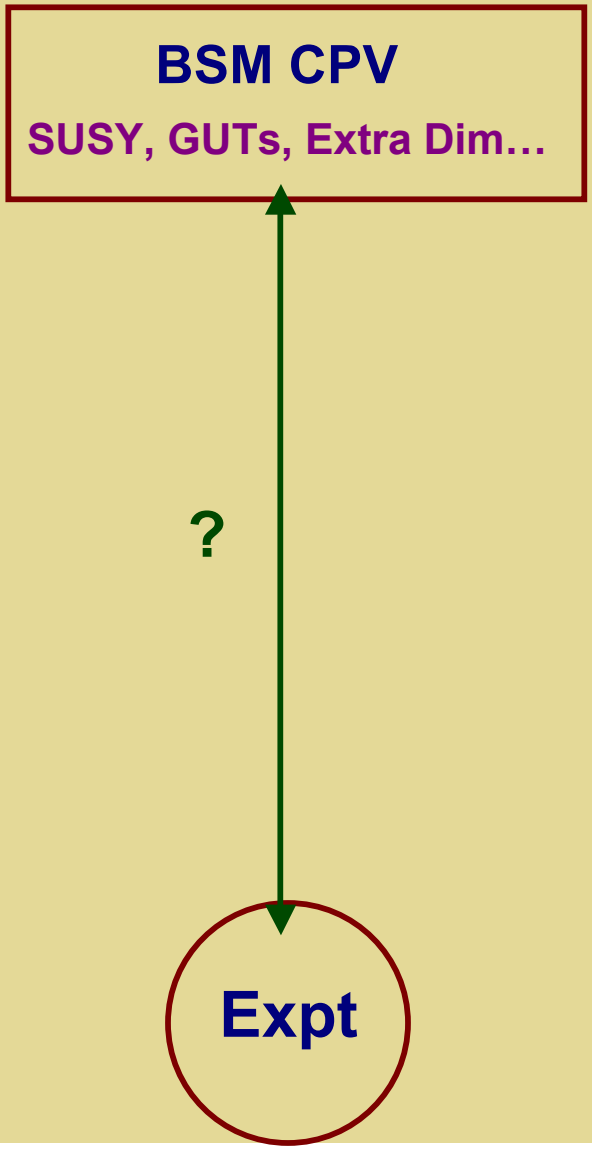
- *BSM CPV at d=6 provides a bridge between low-scale EDM physics (atomic, nuclear, hadronic) and high scale BSM physics and cosmology*
- *Challenging interpretation problem requiring refinements of non-perturbative and many-body computations*
- *Additional, complementary EDM searches needed to provide comprehensive probe of possible flavor diagonal CPV that may be living at the multi-TeV scale*

Outline

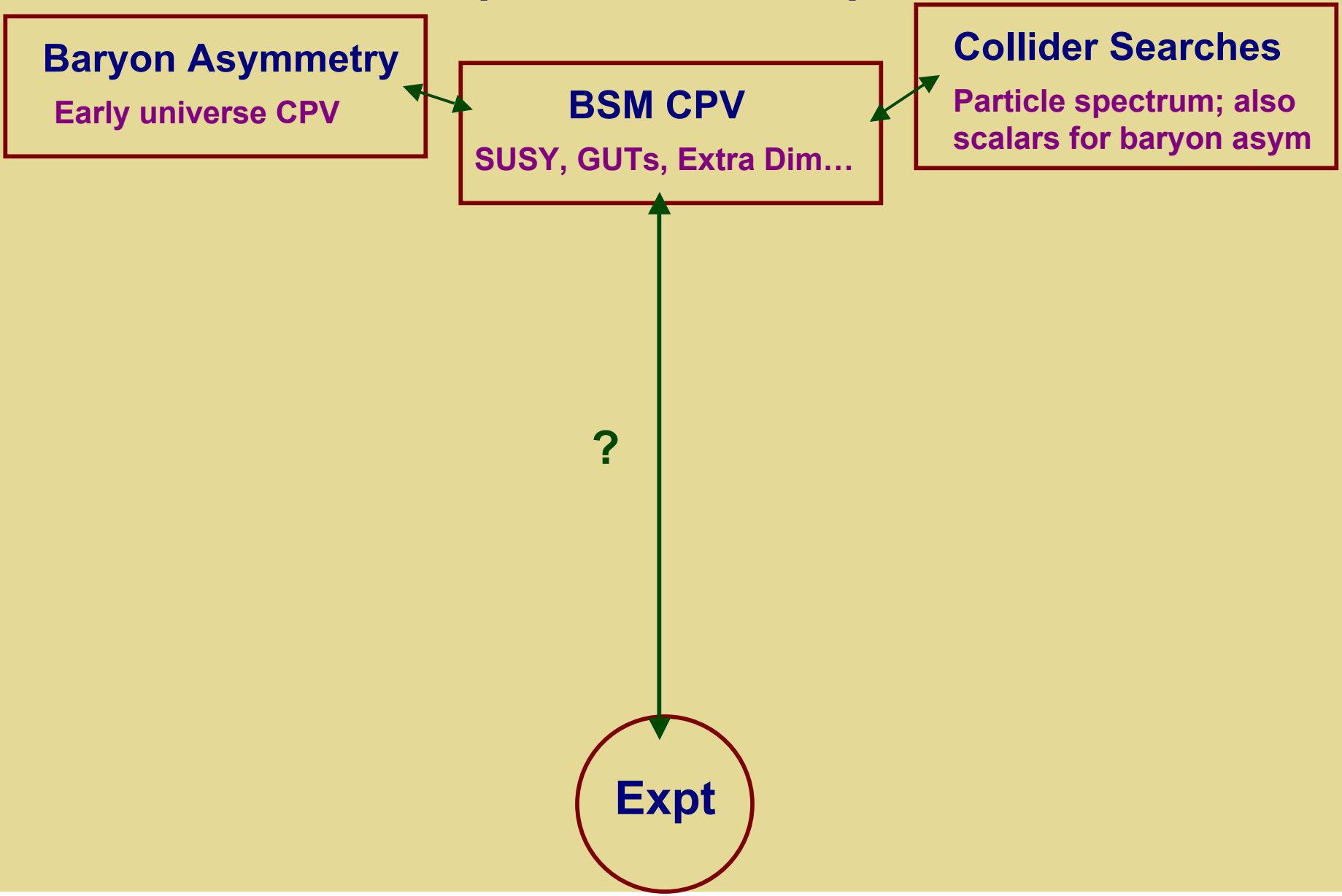
1. *EDM Interpretation: Multiple Scales*
2. *Effective Operators: Classification*
3. *Origin of Wilson Coefficients: Examples*
4. *Low Scale Observables*
5. *Running & Matching*
6. *Implications & Open Problems*

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

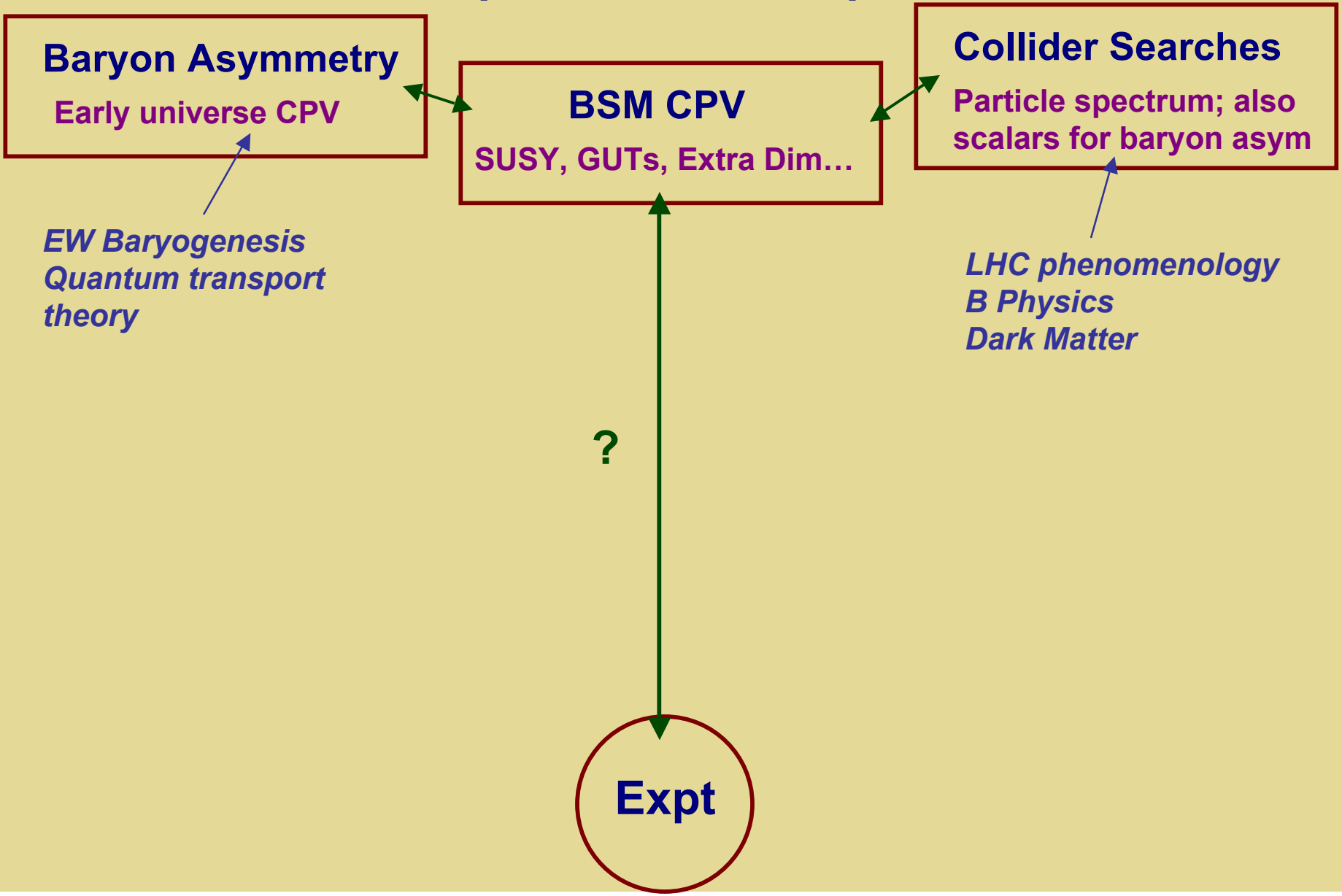
EDM Interpretation & Multiple Scales



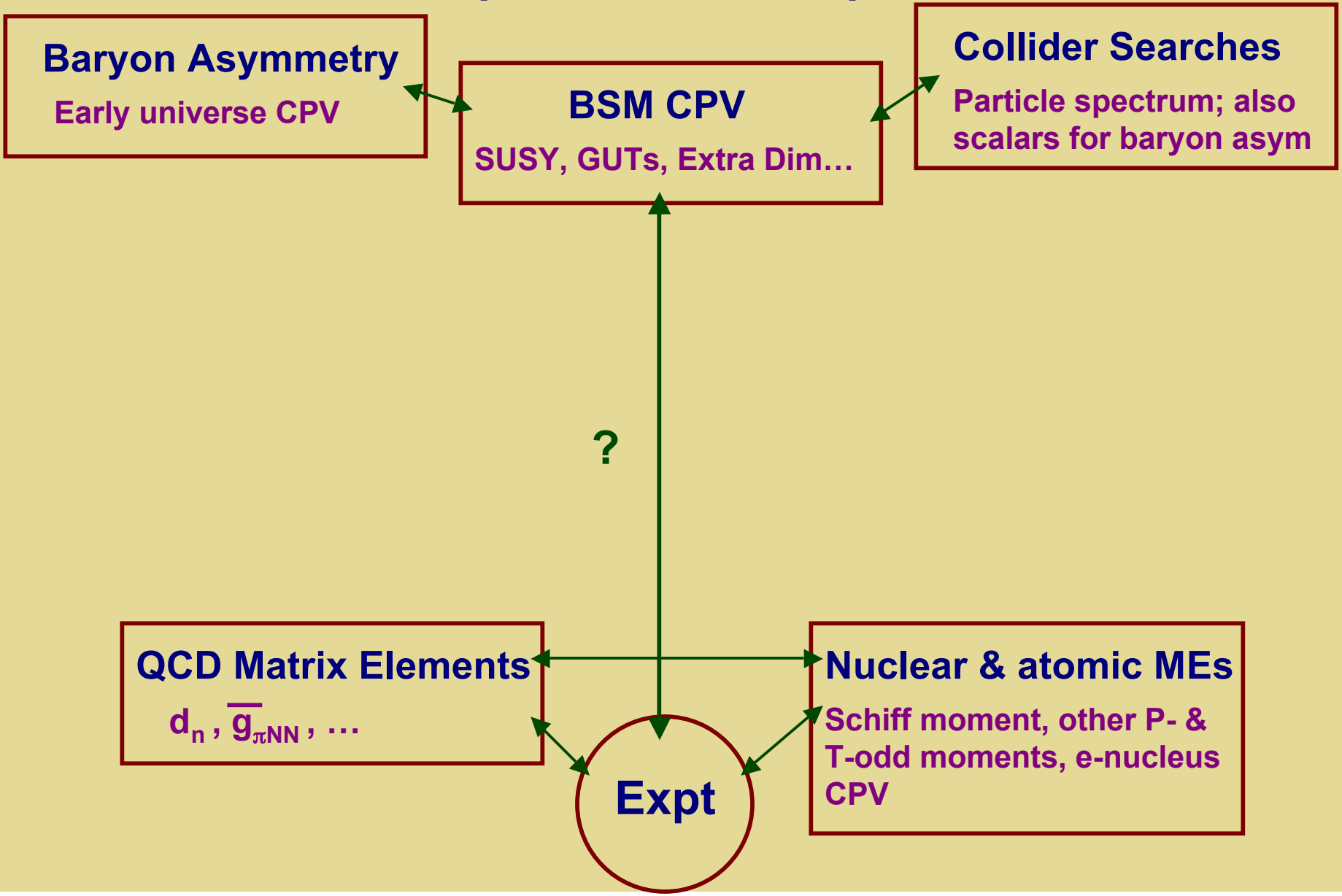
EDM Interpretation & Multiple Scales



EDM Interpretation & Multiple Scales



EDM Interpretation & Multiple Scales



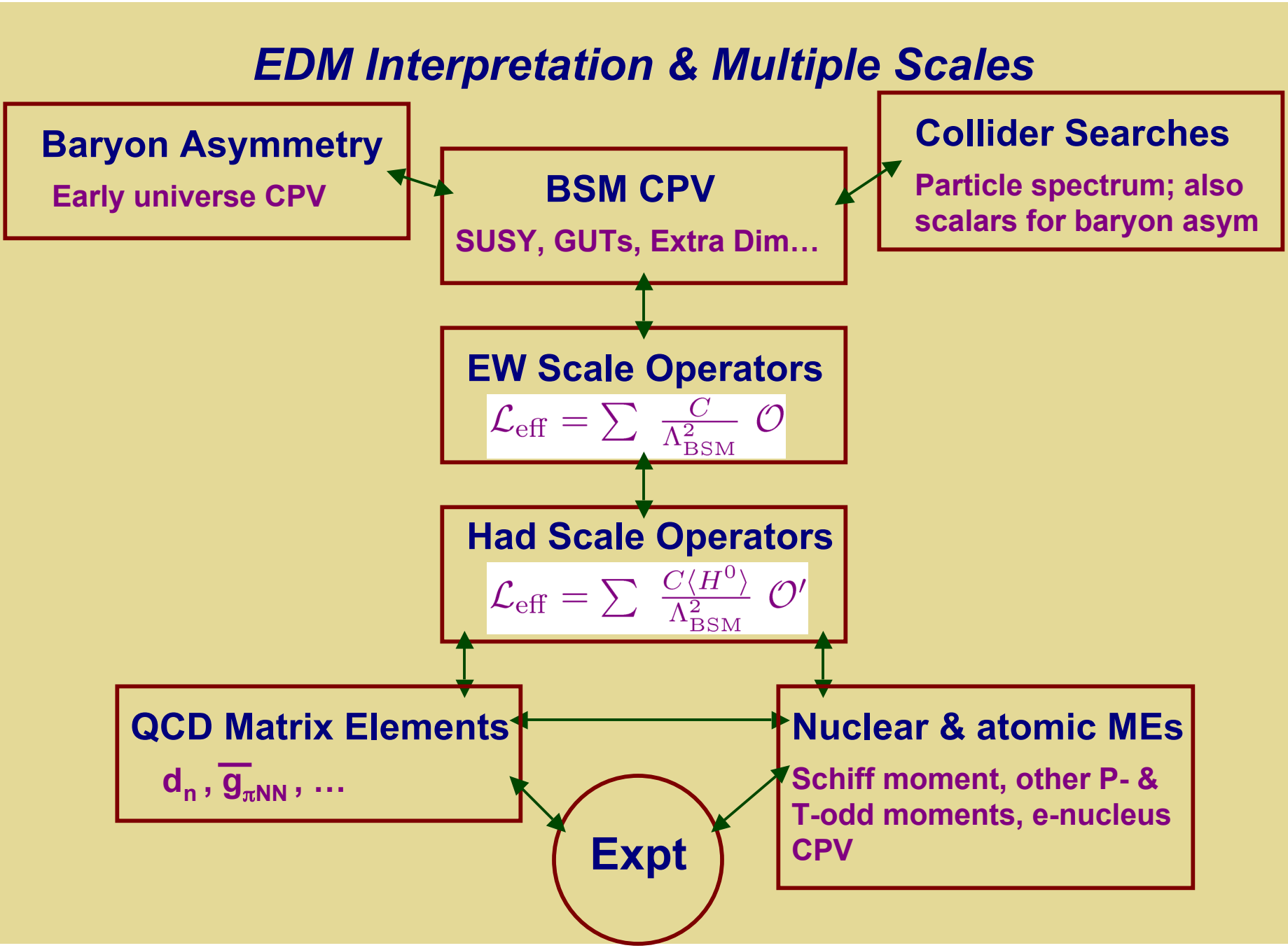
Effective Operators

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

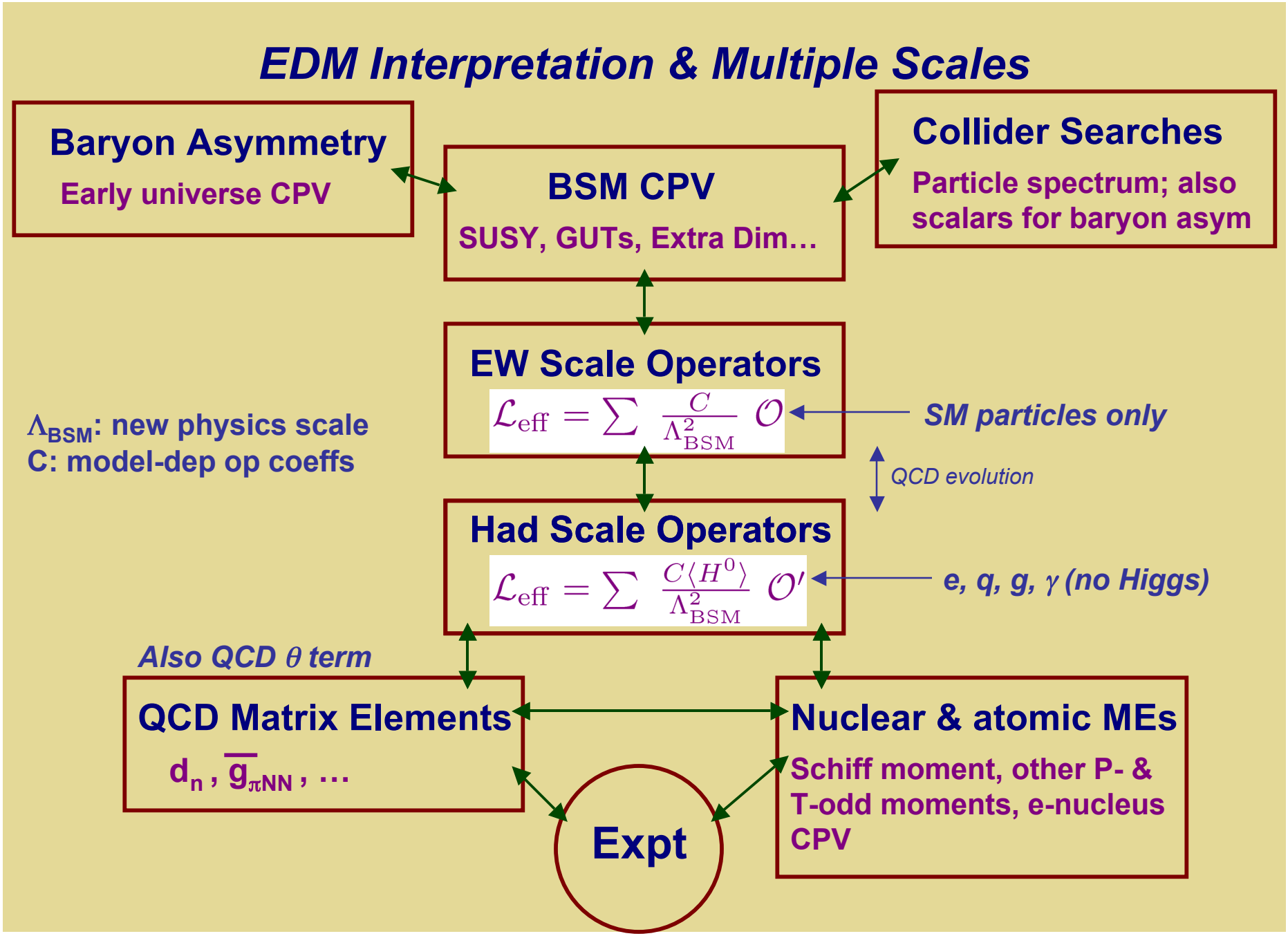
$$\mathcal{L}^{\rm eff}_{\rm BSM} = \frac{1}{\Lambda^2} \sum_i \alpha_i^{(n)} O_i^{(6)}$$

+…

EDM Interpretation & Multiple Scales



EDM Interpretation & Multiple Scales



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

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

θ-term renormalization

Operator Classification

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Quark chromo-EDM

Operator Classification

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Fermion EDM

Operator Classification

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

Operator Classification

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Semileptonic: atomic & molecular EDMs

Operator Classification

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{L}^j e)(\bar{d}Q^j)$
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Nonleptonic: hadronic
EDMs & Schiff moment

Operator Classification

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

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

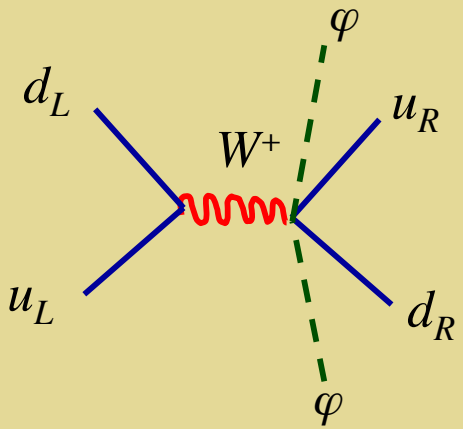
Nonleptonic: hadronic
EDMs & Schiff moment

Operator Classification

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

Operator Classification

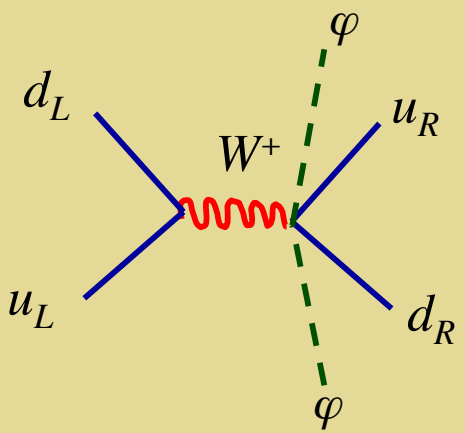
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Operator Classification

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

$\varphi \to v$



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

Nonleptonic: hadronic EDMs & Schiff moment

Wilson Coefficients: EDM & CEDM

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

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

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

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

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

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

Wilson Coefficients: EDM & CEDM

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

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

Chirality flipping

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

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 + $\overline{\theta}$

light flavors only (e,u,d)

Dimension Six Operators: II

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- *Where do they come from ?*
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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})

11 total + $\overline{\theta}$

light flavors only (u,d)

BSM Origins

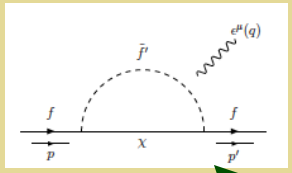
δ_f

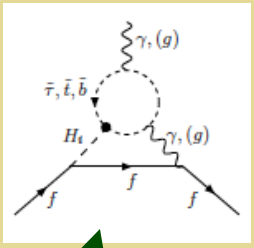
$\tilde{\delta}_q$

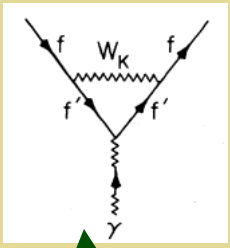
$C_{\tilde{G}}$

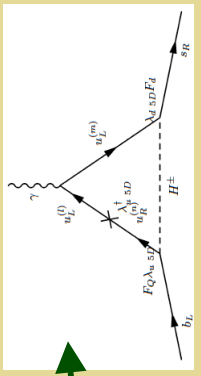
C_{quqd}; $C_{lequ,\ ledq}$

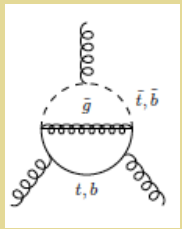
$C_{\varphi ud}$







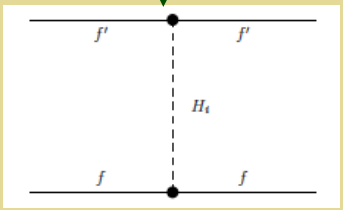




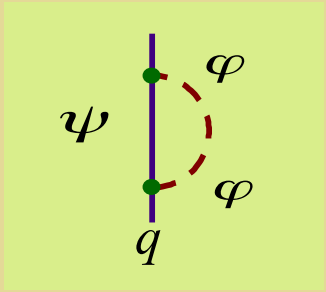
MSSM

LRSM

RS



Radiatively - induced θ



Effective Operators & θ_{ind}

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

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

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

11 total + $\overline{\theta}$

$\bar{\theta} \rightarrow \theta_{ind} \propto \tilde{\delta_q}$, *C*, *…*

Dimension Six Operators: III

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Low Scale Observables

$$
\begin{aligned}
\mathcal{L}_{N\pi}^{\mathrm{PVTV}} \;=\; & -2\bar{N}\left(\bar{d}_0+\bar{d}_1\tau_3\right) S_\mu N\, v_\nu F^{\mu\nu} \\
& + \bar{N}\left[\bar{g}_\pi^{(0)}\boldsymbol{\tau}\cdot\boldsymbol{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}\left(3\tau_3\pi^0 - \boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right] N \\
& + \bar{C}_1\bar{N}N\,\partial_\mu\left(\bar{N}S^\mu N\right) + \bar{C}_2\bar{N}\boldsymbol{\tau}N\cdot\partial_\mu\left(\bar{N}S^\mu\boldsymbol{\tau}N\right) + \cdots
\end{aligned}
$$

Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

Low Scale Observables

$$\mathcal{L}_{N\pi}^{\mathrm{PVTV}} = -2\bar{N}\left(\bar{d}_0+\bar{d}_1\tau_3\right)S_\mu N\, v_\nu F^{\mu\nu}$$
$$+\bar{N}\left[\bar{g}_\pi^{(0)}\boldsymbol{\tau}\cdot\boldsymbol{\pi}+\bar{g}_\pi^{(1)}\pi^0+\bar{g}_\pi^{(2)}\left(3\tau_3\pi^0-\boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]N$$
$$+\bar{C}_1\bar{N}N\,\partial_\mu\left(\bar{N}S^\mu N\right)+\bar{C}_2\bar{N}\boldsymbol{\tau}N\cdot\partial_\mu\left(\bar{N}S^\mu\boldsymbol{\tau}N\right)+\cdots$$

Nucleon EDMs

Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

Low Scale Observables

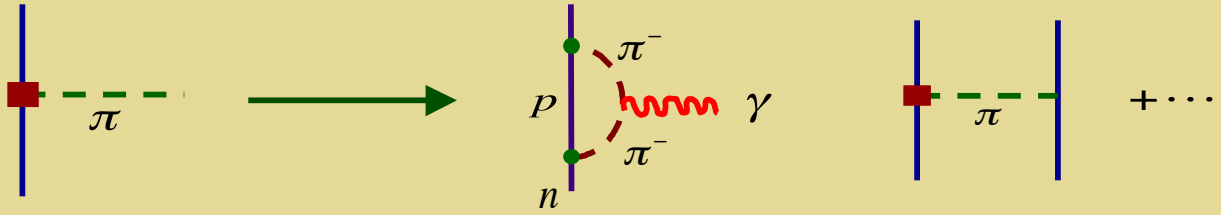
$$\mathcal{L}_{N\pi}^{\mathrm{PVTV}} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S_\mu N\, v_\nu F^{\mu\nu}$$

I = 0, 1, 2

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

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

PVTV πN interaction



Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

Low Scale Observables

$$\begin{aligned}\mathcal{L}_{N\pi}^{\mathrm{PVTV}} &= -2\bar{N}\left(\bar{d}_0+\bar{d}_1\tau_3\right)S_\mu N\, v_\nu F^{\mu\nu} \\ &\quad + \bar{N}\left[\bar{g}_\pi^{(0)}\boldsymbol{\tau}\cdot\boldsymbol{\pi}+\bar{g}_\pi^{(1)}\pi^0+\bar{g}_\pi^{(2)}\left(3\tau_3\pi^0-\boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]N \\ &\quad + \bar{C}_1\bar{N}N\,\partial_\mu\left(\bar{N}S^\mu N\right)+\bar{C}_2\bar{N}\boldsymbol{\tau}N\cdot\partial_\mu\left(\bar{N}S^\mu\boldsymbol{\tau}N\right)+\cdots\end{aligned}$$

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

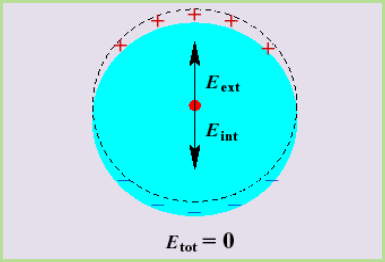
Nuclear Moments

	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



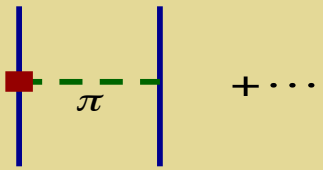
Atomic effect from nuclear finite size: Schiff moment

Nuclear Schiff Moment

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

Nuclear EDM: Screened in atoms

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

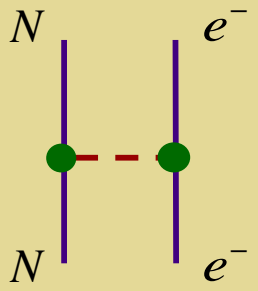


EDMs of diamagnetic atoms (^{199}Hg)

Semileptonic CPV

$$\mathcal{L}_{eN}^{\text{eff}} = \frac{G_F}{\sqrt{2}}\left\{\bar{e}i\gamma_5 e\ \bar{N}\left[C_S^{(0)} + C_S^{(1)}\tau_3\right]N + 8\bar{e}\sigma_{\mu\nu}e\ v^\nu \bar{N}\left[C_T^{(0)} + C_T^{(1)}\tau_3\right]S^\mu N\right\} + \cdots$$

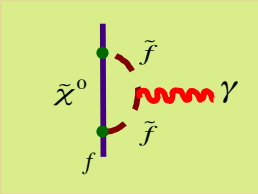
EDMs of atoms & molecules (Tl, YbF…)



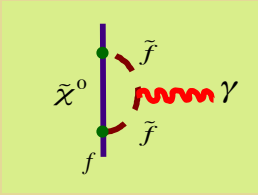
EDMs: Complementary Searches

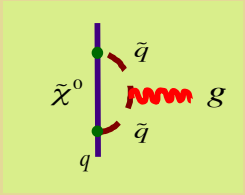
Improvements of 10^2 to 10^3

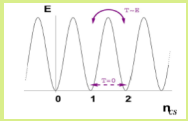
Electron



Neutron

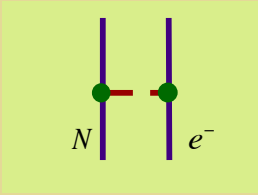


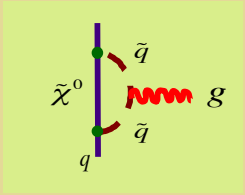


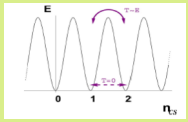


QCD

Neutral Atoms

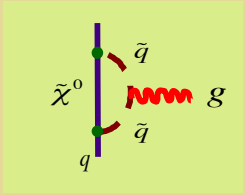


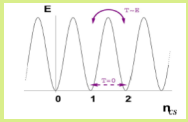




QCD

Deuteron

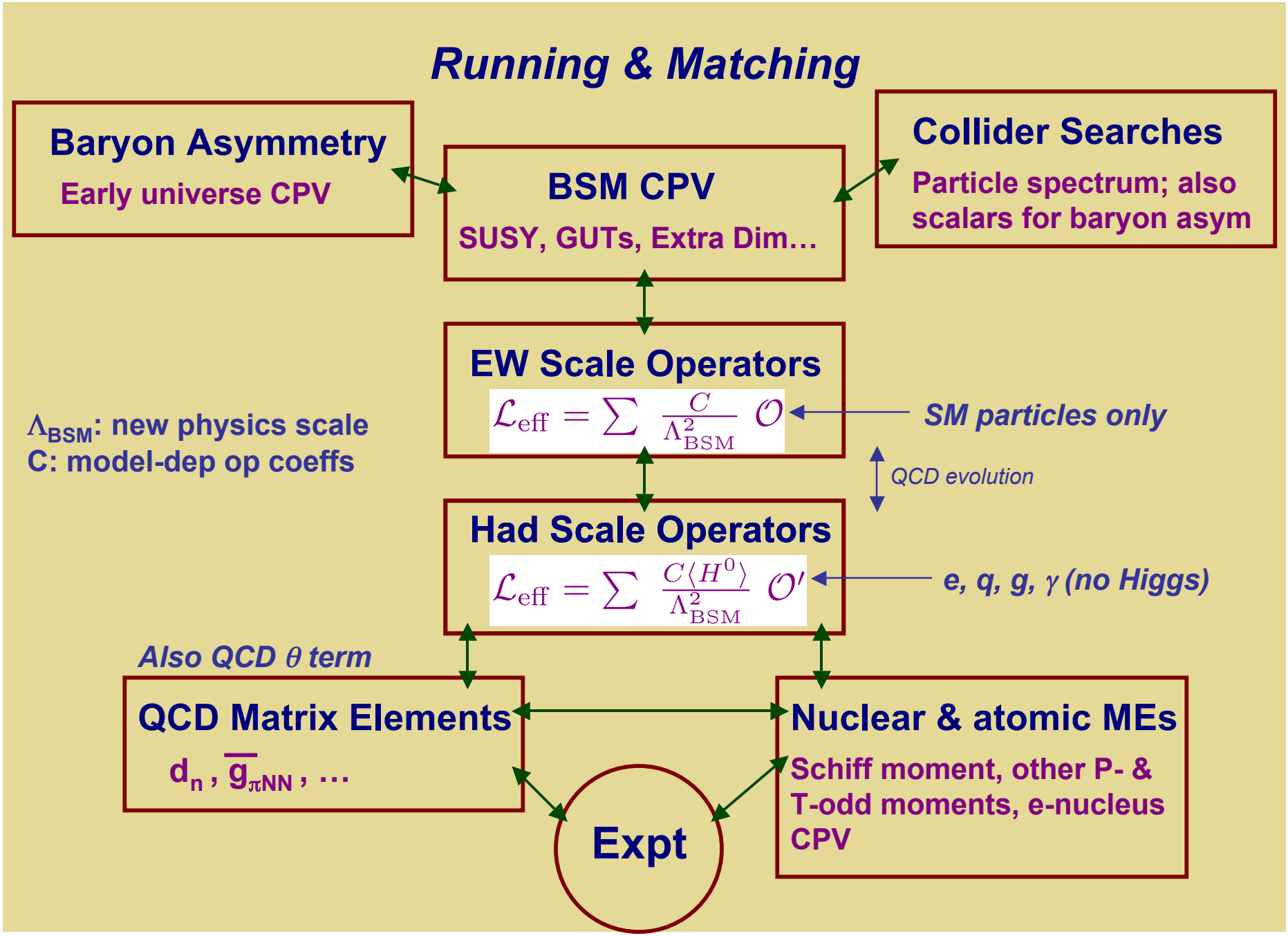




QCD

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 ?*
- *What are present & prospective experimental constraints ?*


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
$\mathcal{L}_{\rm eff} = \sum \frac{C}{\Lambda^2_{\rm BSM}} \mathcal{O}$
SM particles only
QCD evolution
$\Lambda_{\rm BSM}$: new physics scale
C: model-dep op coeffs
Had Scale Operators
$\mathcal{L}_{\rm eff} = \sum \frac{C\langle H^0\rangle}{\Lambda^2_{\rm BSM}} \mathcal{O}'$
e, q, g, γ (no Higgs)
Also QCD θ term
QCD Matrix Elements
d_n , $\overline{g}_{\pi NN}$, …
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]
$Q^{(1,8)}_{quqd}$		

Running & Matching *Hadronic*

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

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

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

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

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

Non-perturbative hadronic computations

Running & Matching

Atomic & Molecular

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

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

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

Running & Matching

Atomic & Molecular

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

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

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

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

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

Running & Matching

Atomic & Molecular

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

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

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

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

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

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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

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

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

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

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, ... ?

Hadronic Matching: χ Sym

$$Q \to \exp\left[i\boldsymbol{\tau}\cdot(\boldsymbol{\theta}_R P_R + \boldsymbol{\theta}_L P_L)\right]\ Q$$

$$Q \to \exp\left[i\boldsymbol{\tau}\cdot(\boldsymbol{\theta}_V P + \boldsymbol{\theta}_A \gamma_5)\right]\ Q$$

$$V = \begin{pmatrix} \boldsymbol{V} \\ V_4 \end{pmatrix}$$

$$\delta V = \begin{pmatrix} \boldsymbol{V}\times\boldsymbol{\theta}_V + V_4\,\boldsymbol{\theta}_A \\ -\boldsymbol{\theta}_A\cdot\boldsymbol{V} \end{pmatrix}$$

$$S = \begin{pmatrix} -i\bar{q}\boldsymbol{\tau}\gamma_5 q \\ \bar{q}q \end{pmatrix} \quad \text{and} \quad P = \begin{pmatrix} \bar{q}\boldsymbol{\tau}q \\ i\bar{q}\gamma_5 q \end{pmatrix}$$

Hadronic Matching: χ Sym

$$\begin{aligned} \boldsymbol{V}[\boldsymbol{\pi}, N] &= \boldsymbol{V}[0, N] + \frac{2}{D}\boldsymbol{\xi}\left(V_4[0, N] - \boldsymbol{\xi}\cdot\boldsymbol{V}[0, N]\right) \ , \\ V_4[\boldsymbol{\pi}, N] &= \frac{1}{D}\left(1 - \boldsymbol{\xi}^2\right) V_4[0, N] - \frac{2}{D}\boldsymbol{\xi}\cdot\boldsymbol{V}[0, N] \ , \end{aligned}$$

$$D = 1 + \boldsymbol{\pi}^2/F_\pi^2 \text{ and } \boldsymbol{\xi} = \boldsymbol{\pi}/F_\pi$$

$$S[0, N] = \begin{pmatrix} \mathbf{0} \\ \bar{N}N \end{pmatrix} \qquad \text{and} \qquad P[0, N] = \begin{pmatrix} \bar{N}\boldsymbol{\tau}N \\ 0 \end{pmatrix}$$

Hadronic Matching: χ Sym

$$\mathcal{L}_{\bar{\theta}} \leftrightarrow \mathcal{L}^{\rm QCD}_{\rm CPV} = -\frac{\bar{m}}{2}\left(1-\epsilon^2\right)\bar{\theta}\;\bar{q}i\gamma_5 q$$

$$-\mathcal{L}^{\rm quark}_{\rm mass} = \bar{m}\bar{q}q - \epsilon\bar{m}\bar{q}\tau_3 q$$

$$S = \begin{pmatrix} -i\bar{q}\boldsymbol{\tau}\gamma_5 q \\ \bar{q}q \end{pmatrix} \qquad \text{and} \qquad P = \begin{pmatrix} \bar{q}\boldsymbol{\tau}q \\ i\bar{q}\gamma_5 q \end{pmatrix}$$

Hadronic matrix elements of quark mass splitting and θ-term operators related by χ sym

Hadronic Matching: χ Sym

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Hadronic matrix elements of quark mass splitting and θ-term operators related by χ sym

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$$-\mathcal{L}^{N}_{\rm mass} = \left(\bar{m}_N\right)_q \bar{N}N - \left(\Delta m_N\right)_q \bar{N}\frac{\tau_3}{2}N$$

$$\mathcal{L}^{\rm PVTV}_{N\pi} = \bar{N}\left[\bar{g}^{(0)}_{\pi}\boldsymbol{\tau}\cdot\boldsymbol{\pi}\right]N$$

Hadronic Matching: χ Sym

$$\mathcal{L}_{\bar{\theta}} \leftrightarrow \mathcal{L}^{\rm QCD}_{\rm CPV} = -\frac{\bar{m}}{2}\left(1-\epsilon^2\right)\bar{\theta}\,\bar{q}i\gamma_5 q$$

$$-\mathcal{L}^{\rm quark}_{\rm mass} = \bar{m}\bar{q}q - \epsilon\bar{m}\bar{q}\tau_3 q$$

$$S = \begin{pmatrix} -i\bar{q}\boldsymbol{\tau}\gamma_5 q \\ \bar{q}q \end{pmatrix} \quad \text{and} \quad P = \begin{pmatrix} \bar{q}\boldsymbol{\tau}q \\ i\bar{q}\gamma_5 q \end{pmatrix}$$

$$-\mathcal{L}^{N}_{\rm mass} = \left(\bar{m}_N\right)_q \bar{N}N - \left(\Delta m_N\right)_q \bar{N}\frac{\tau_3}{2}N$$

$$\mathcal{L}^{\rm PVTV}_{N\pi} = \bar{N}\left[\bar{g}^{(0)}_{\pi}\boldsymbol{\tau}\cdot\boldsymbol{\pi}\right]N$$

Quark & hadron P_3

Quark & hadron P_4

Hadronic Matching: χ Sym

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

$$\lambda_{(0)} = -\frac{1-\epsilon^2}{2\epsilon}\,\frac{(\Delta m_N)_q}{F_\pi}$$

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

Dimension Six Operators: V

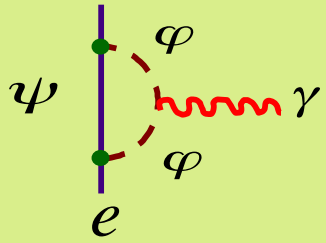
- *What are they ?*
- *Where do they come from ?*
- *How do they appear in hadronic, nuclear, and atomic systems ?*
- *How well can we match them onto physics of many-body and non-perturbative systems ?*
- *What are present & prospective experimental constraints ?*

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



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

$M < 500$ 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

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

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

MSSM Global Analysis

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

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

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

$\phi_A = \arg(A_f M_j)$

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

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

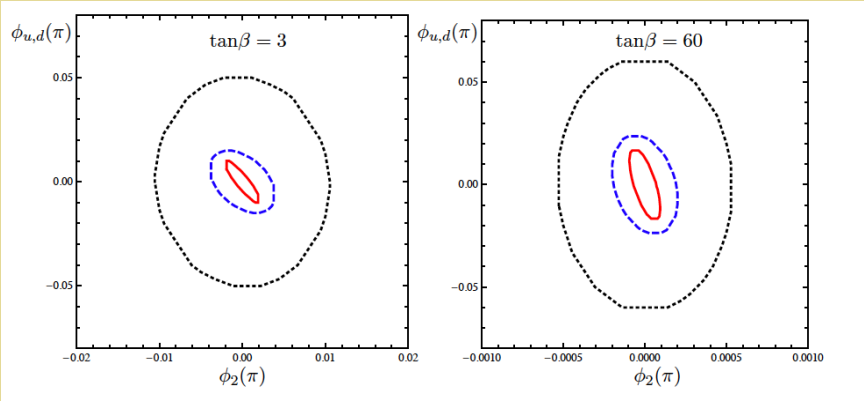
$$\begin{aligned}\mathcal{L}_{\rm soft} \;=\; & -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \\ & -(\tilde{u}\mathbf{a_u}\tilde{Q}H_u - \tilde{d}\mathbf{a_d}\tilde{Q}H_d - \tilde{e}\mathbf{a_e}\tilde{L}H_d) + c.c. \\ & -\tilde{Q}^\dagger \mathbf{m_Q^2}\tilde{Q}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

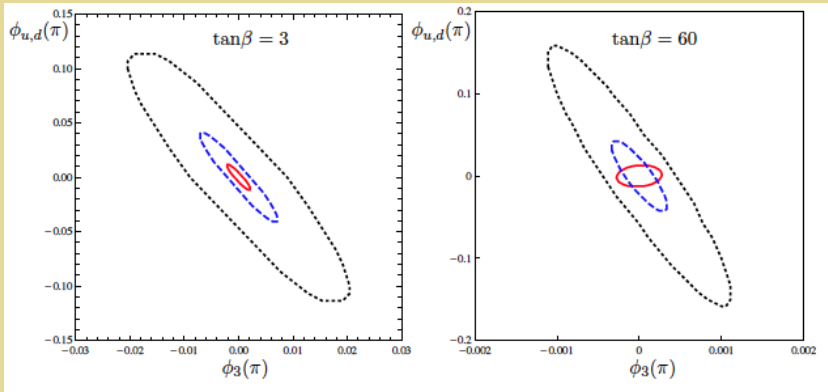
$\phi_j = \arg(\mu M_j b^*)$

$\phi_A = \arg(A_f M_j)$

Correlated Constraints

Li, Profumo, R-M '10





Present

Present: ^{199}Hg impact

MSSM Global Analysis

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

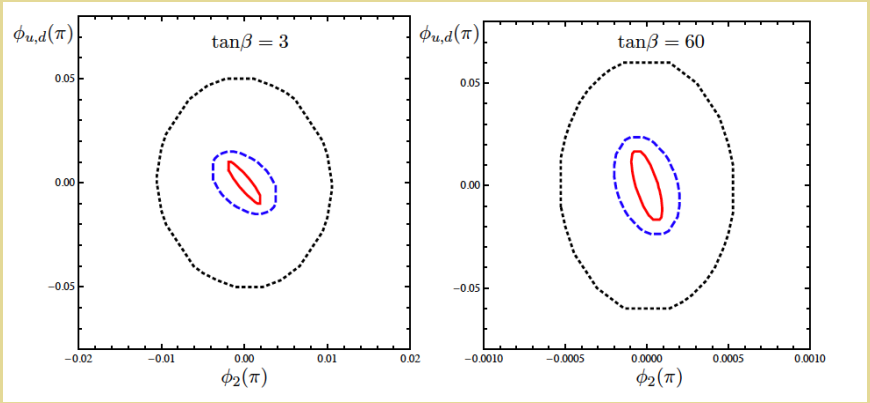
$$\begin{aligned}\mathcal{L}_{\rm soft} \;=\; & -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \\ & -(\tilde{u}\mathbf{a_u}\tilde{Q}H_u - \tilde{d}\mathbf{a_d}\tilde{Q}H_d - \tilde{e}\mathbf{a_e}\tilde{L}H_d) + c.c. \\ & -\tilde{Q}^\dagger \mathbf{m_Q^2}\tilde{Q}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

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

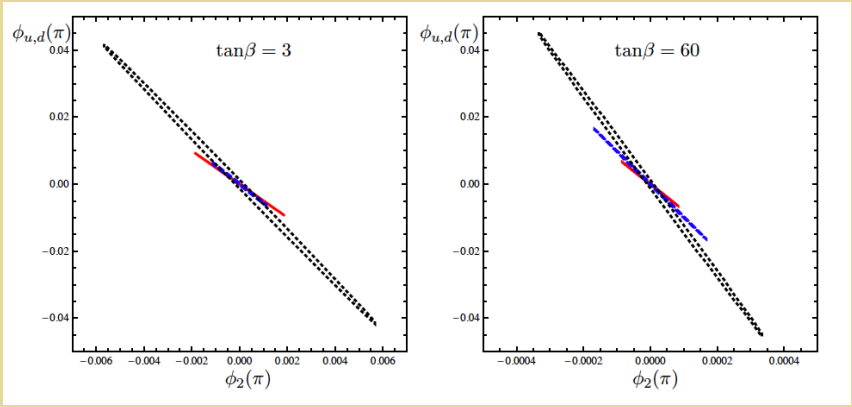
$\phi_A = \arg(A_f M_j)$

Correlated Constraints

Li, Profumo, R-M '10



Present

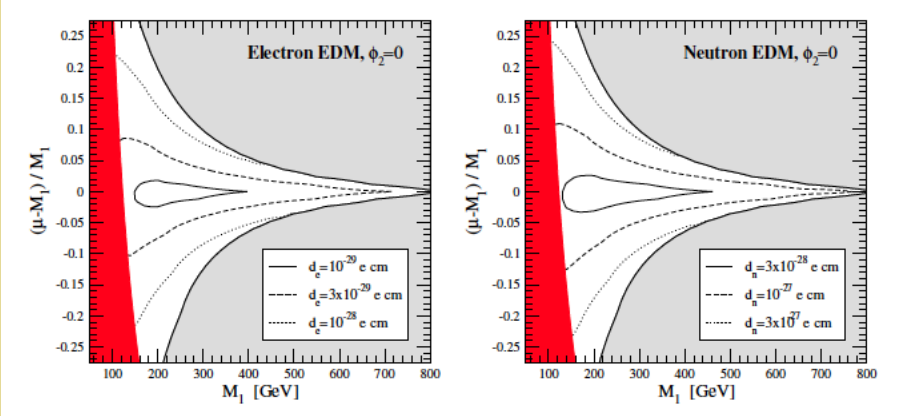


Future d_n: 100 x present sensitivity

Baryogenesis Implications

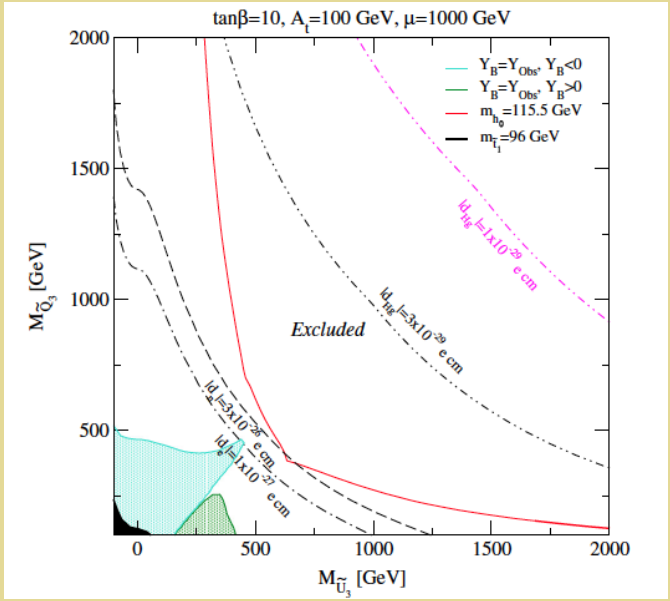
MSSM: ϕ_1 only

Gaugino sources



Cirigliano, Li, Profumo, R-M '10

Sfermon (stop) sources



Kocaczuk, Wainwright, Profumo, R-M '12

AMO Global Analysis

Atomic & Molecular

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

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

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

Atomic / molecular coefficients

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

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

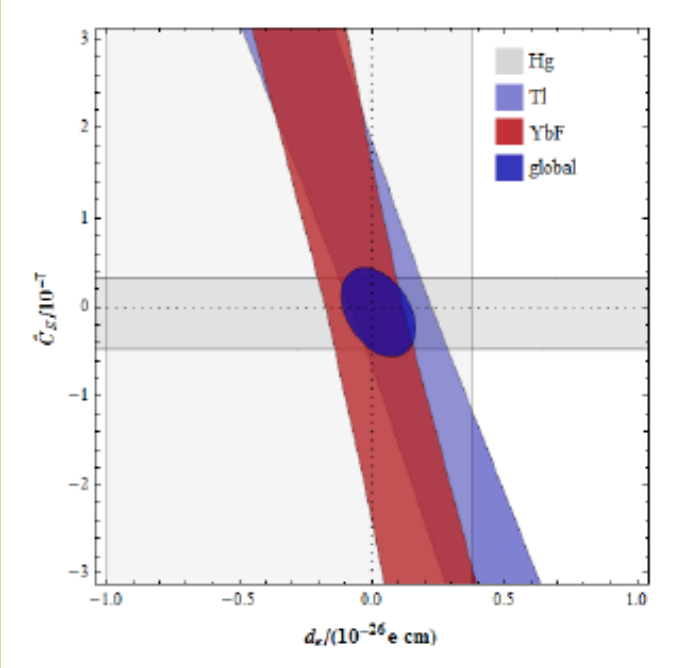
$$\rho_A^e d_e = e\, \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e$$

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

* Tl, Cs, YbF…

** Hg, Ra, Rn…

AMO Global Analysis



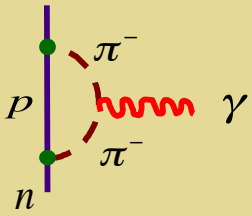
Jung '13

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

- *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*

Global Analysis: Hadronic

$$\mathcal{L}_{N\pi}^{\rm PVTV} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S_\mu N\, v_\nu F^{\mu\nu}$$
$$+ \bar{N}\left[\bar{g}_\pi^{(0)}\boldsymbol{\tau}\cdot\boldsymbol{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}\left(3\tau_3\pi^0 - \boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]N$$

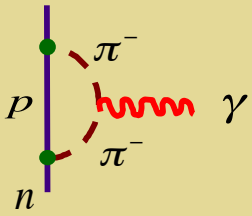


$$d_0 = \bar{d}_0 - \frac{eg_A}{16\pi F_\pi}\left\{\bar{g}_\pi^{(0)}\left[\frac{3m_\pi}{m_N} - \frac{4(\Delta m_N)_q}{m_\pi}\right] + \bar{g}_\pi^{(1)}\frac{m_\pi}{m_N}\right\}$$

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

Global Analysis: Hadronic

$$\mathcal{L}_{N\pi}^{\rm PVTV} = -2\bar{N}\left(\bar{d}_0+\bar{d}_1\tau_3\right)S_\mu N\, v_\nu F^{\mu\nu}$$
$$+\bar{N}\left[\bar{g}_\pi^{(0)}\boldsymbol{\tau}\cdot\boldsymbol{\pi}+\bar{g}_\pi^{(1)}\pi^0+\bar{g}_\pi^{(2)}\left(3\tau_3\pi^0-\boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]N$$



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

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

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

Need multiple hadronic systems to disentangle

Open Problems

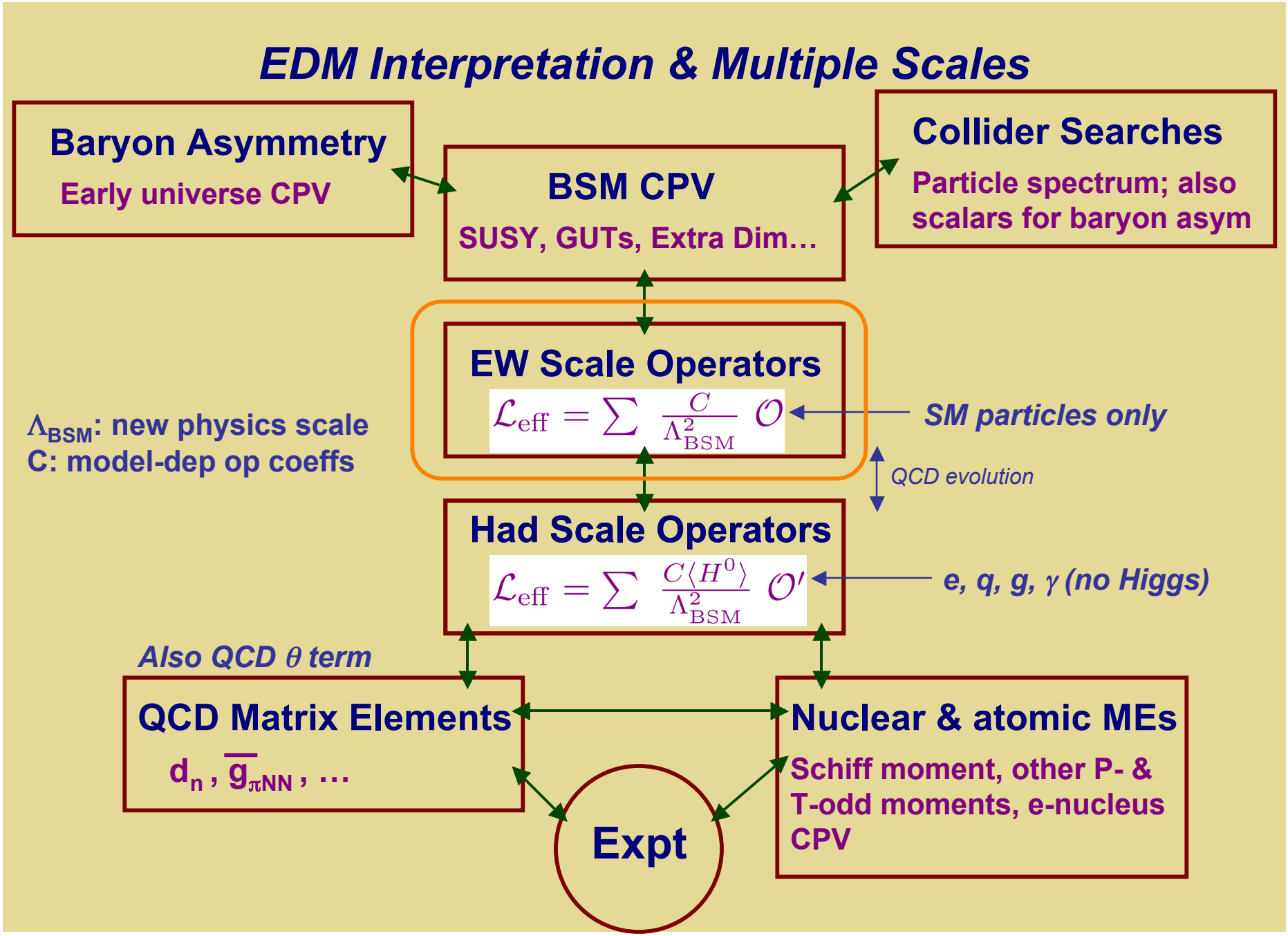
- *How many complementary EDM searches needed*
- *What is robust theory error at hadronic, nuclear, and AMO levels ?*

Summary

- *BSM CPV at d=6 provides a bridge between low-scale EDM physics (atomic, nuclear, hadronic) and high scale BSM physics and cosmology*
- *Challenging interpretation problem requiring refinements of non-perturbative and many-body computations*
- *Additional, complementary EDM searches needed to provide comprehensive probe of possible flavor diagonal CPV that may be living at the multi-TeV scale*

Back Matter

EDM Interpretation & Multiple Scales



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}

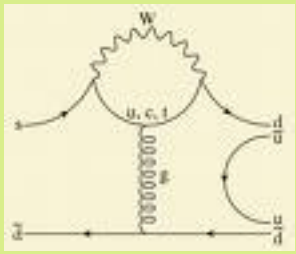
A non-exhaustive list:

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

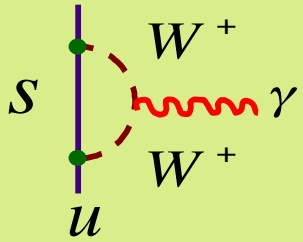
In units of e cm, selected EDM limits are:

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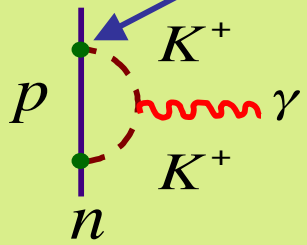


Penguin: $\Delta S = 1$

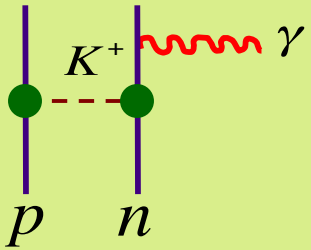
CKM CPV



- *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):

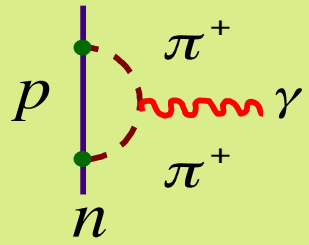
$$\bar{\theta} < 10^{-10}$$

Peccei -Quinn Sym?

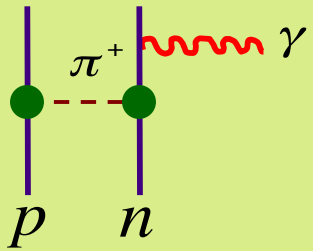
$\mathcal{L}^{\theta}_{QCD}$

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

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



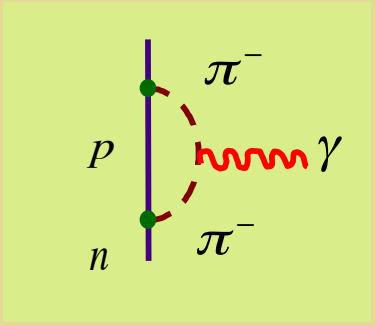
- *Crewther et al; van Kolck et al ; Herczeg*

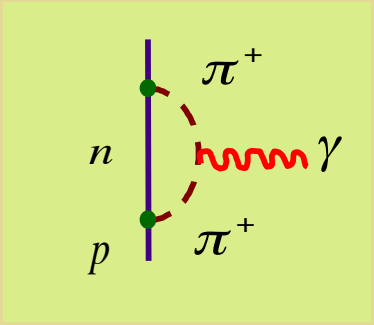


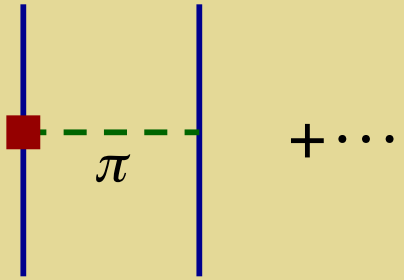
- *Haxton & Henley; Engel;*

EDMs & Isospin Filter: n, p, A

Chiral limit:







Nucleons

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

Schiff Moments

$$d_N^{I=1} \simeq 0.87\left(d_u - d_d\right) + 0.27e\left(d_u^c - d_d^c\right)$$
$$d_N^{I=0} \simeq 0.5\left(d_u + d_d\right) + 0.83e\left(d_u^c + d_d^c\right)$$

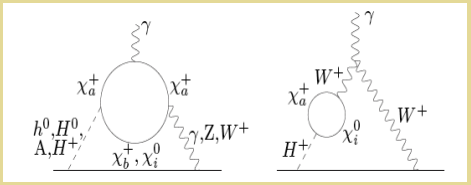
Schiff Moment in ^{199}Hg

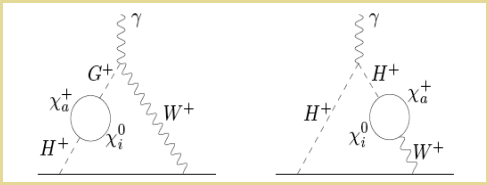
$$S_{^{199}\mathrm{Hg}}^{\mathrm{ave}} = 0.007 g \bar{g}_0 + 0.071 g \bar{g}_1 + 0.018 g \bar{g}_2 \; [e\,\mathrm{fm}^3]$$

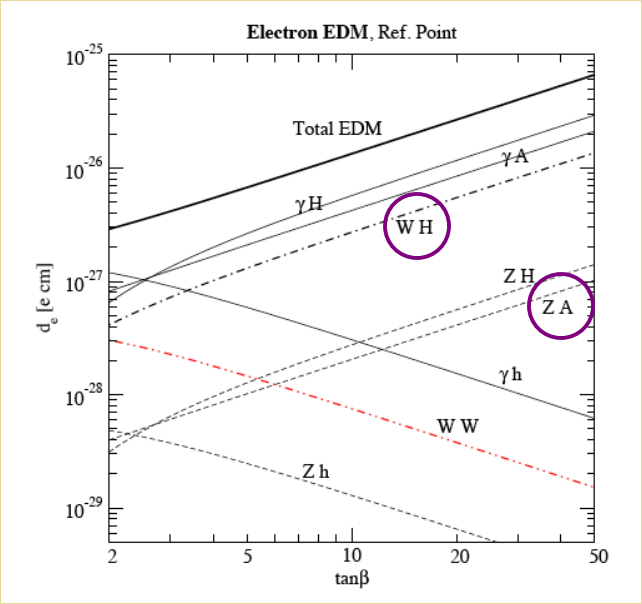
Heavy Sfermions: Two-loop EDMs

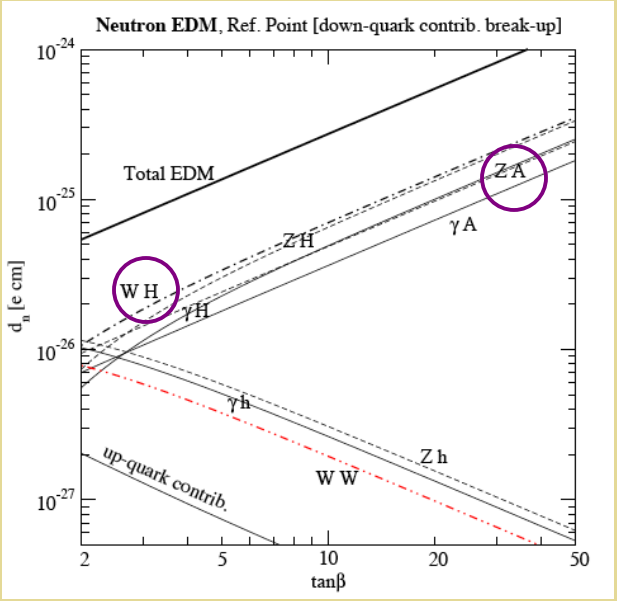
One loop EDMs suppressed in heavy sfermion regime

Li, Profumo, R-M: PRD 78:075009 (2008)









m_A=300 GeV, μ=300 GeV, M_2=2M_1=290 GeV

$$d_n = \sum_K H_k(g_i, M_i) \sin\phi_k$$



WH Loops dominate for neutron & comparable to γH, γA for electron

EDM Interpretation: MSSM

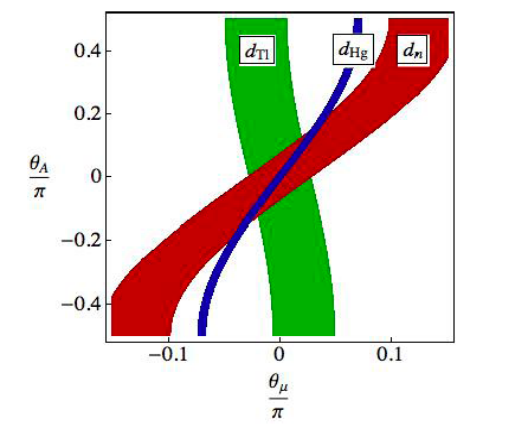
$$W_{\rm MSSM} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\rm yukawa}$$

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

Universality Assumption

$\phi_1 = \phi_2 = \phi_3$

Common ϕ_A



1-loop: Universal Phases

Ritz CIPANP 09

EDM Interpretation: MSSM

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

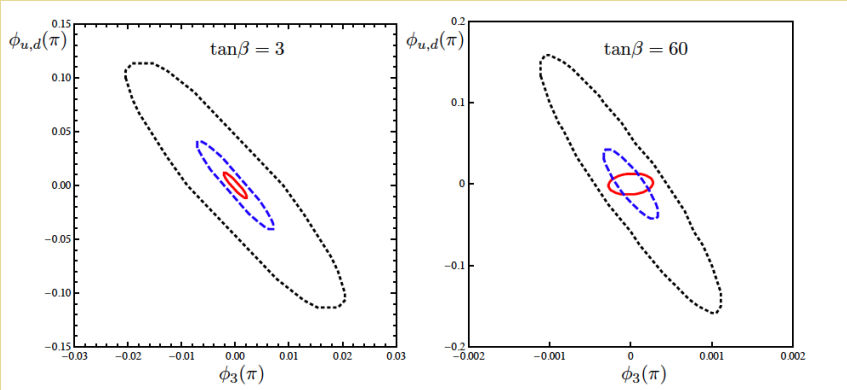
$$\begin{aligned}
\mathcal{L}_{\rm soft} \;=\; & -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \\
& -(\tilde{u}\mathbf{a_u}\tilde{Q}H_u - \tilde{d}\mathbf{a_d}\tilde{Q}H_d - \tilde{e}\mathbf{a_e}\tilde{L}H_d) + c.c. \\
& -\tilde{Q}^\dagger \mathbf{m_Q^2}\tilde{Q}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

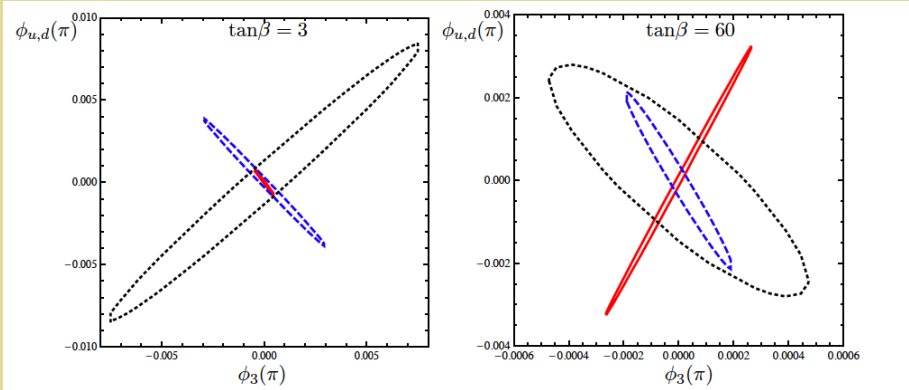
$\phi_j = \arg(\mu M_j b^*)$

$\phi_A = \arg(A_f M_j)$

Correlated Constraints

Li, Profumo, R-M '10





Present

Future d_n: 100 x present sensitivity

EDM Interpretation: MSSM at 2 Loop

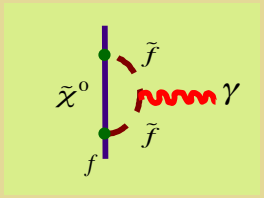
$$W_{\rm MSSM} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\rm yukawa}$$

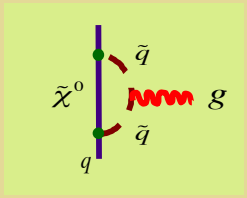
$$\begin{aligned}\mathcal{L}_{\rm soft} \;=\; & -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \\ & -(\tilde{u}\mathbf{a_u}\tilde{Q}H_u - \tilde{d}\mathbf{a_d}\tilde{Q}H_d - \tilde{e}\mathbf{a_e}\tilde{L}H_d) + c.c. \\ & -\tilde{Q}^\dagger \mathbf{m_Q^2}\tilde{Q}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

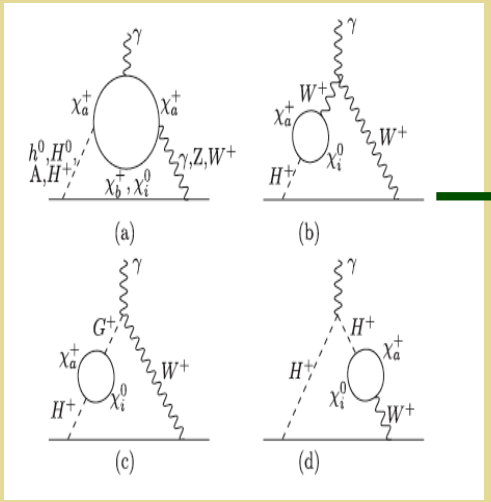
$\phi_j = \arg(\mu M_j b^*)$

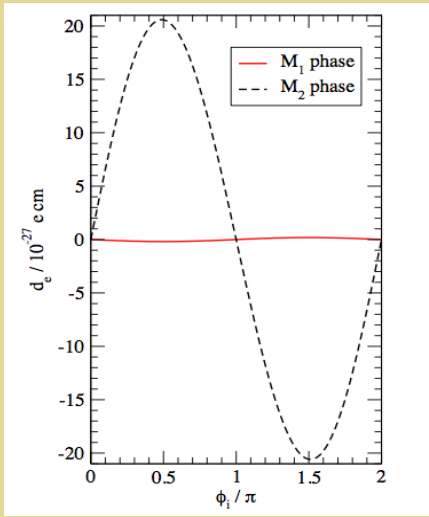
$\phi_A = \arg(A_f M_j)$

Decouple in heavy sfermion regime





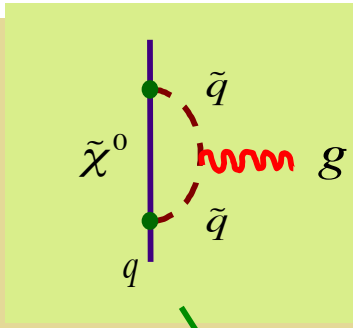


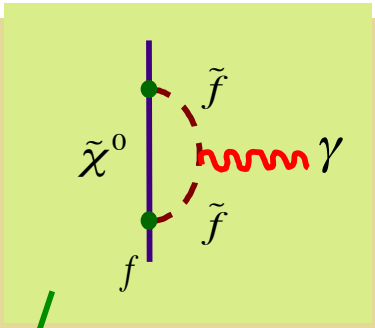


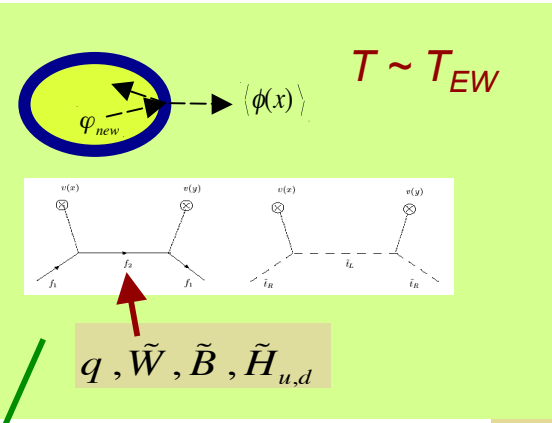
2-loop: Non-universal Phases

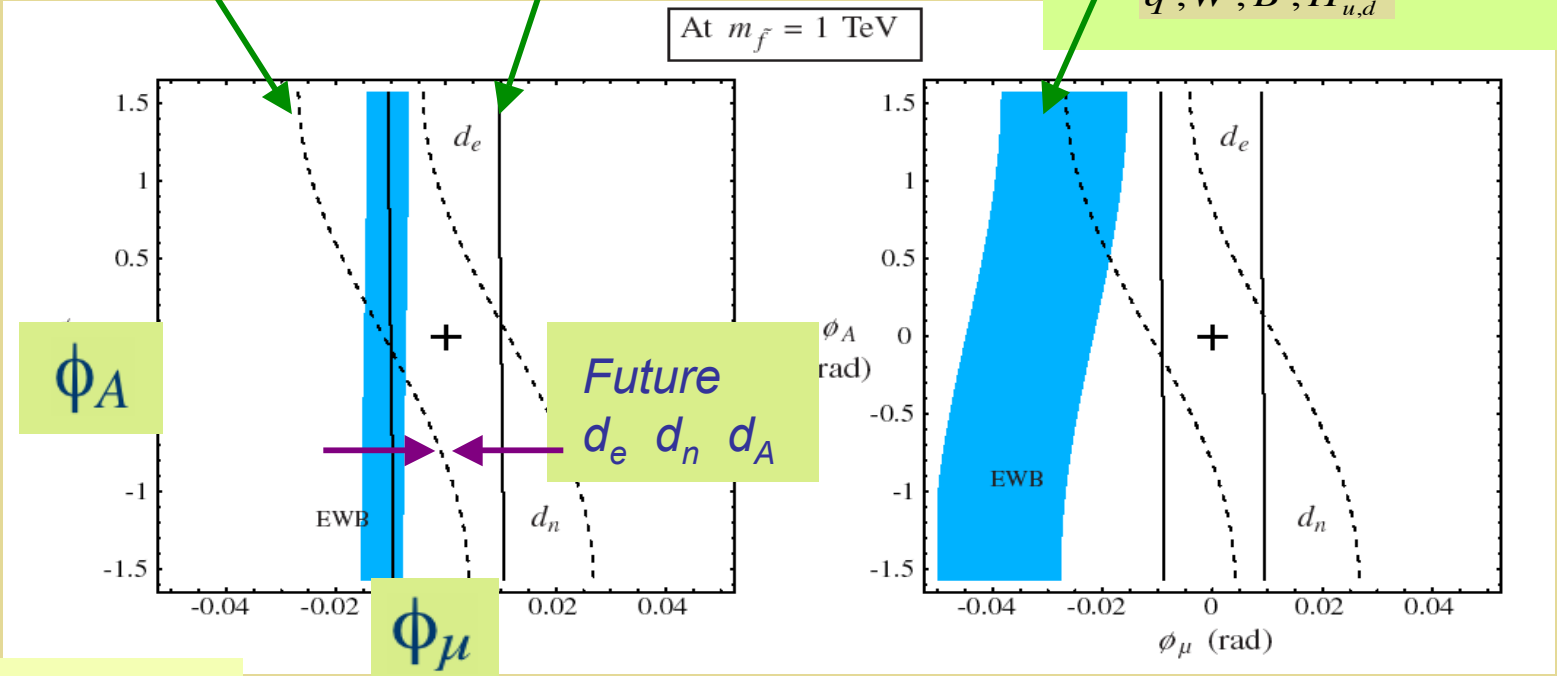
Li, Profumo, R-M 09

One Loop EDMs & Baryogenesis









ϕ_A

ϕ_μ

Future
d_e d_n d_A

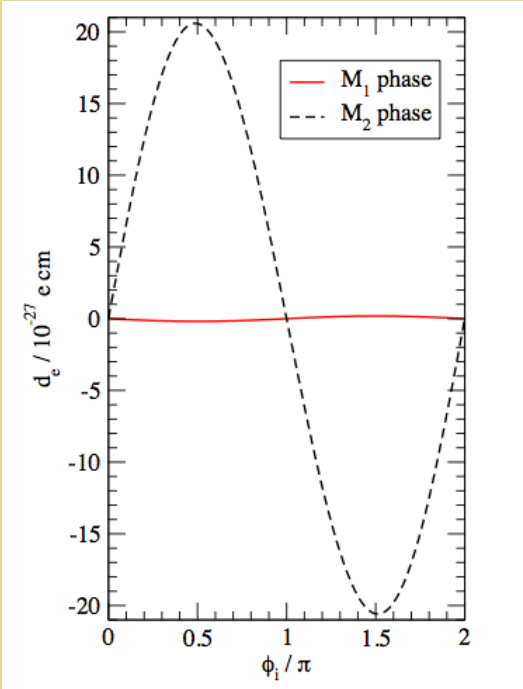
Cirigliano, Lee, Tulin, R-M

Resonant

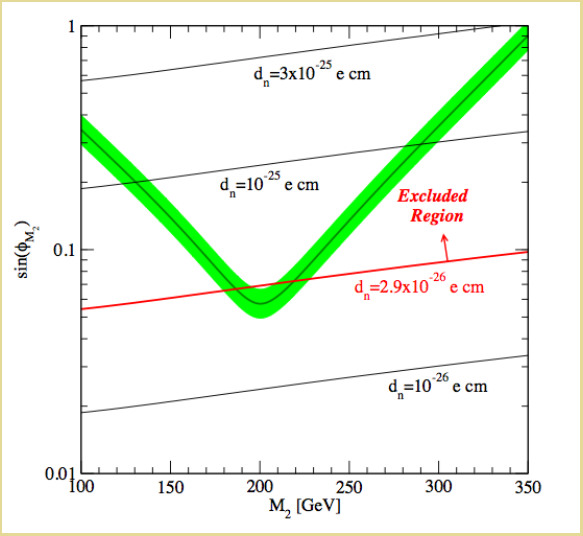
Non-resonant

EDMs & EWB: 2 Loop Regime

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

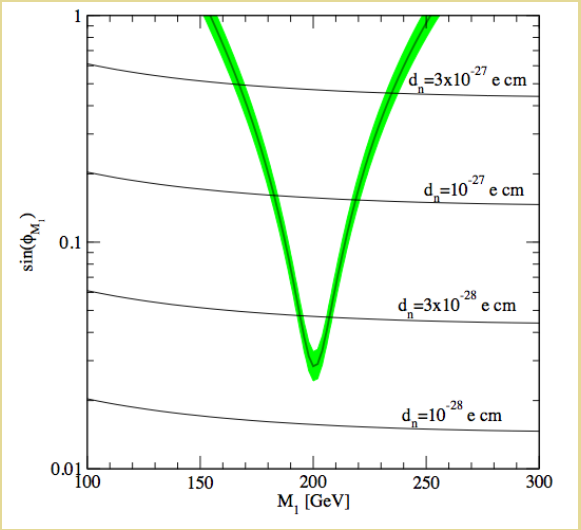


Weak dependence of d_e , d_n on $Arg(\mu M_1 b^*)$



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