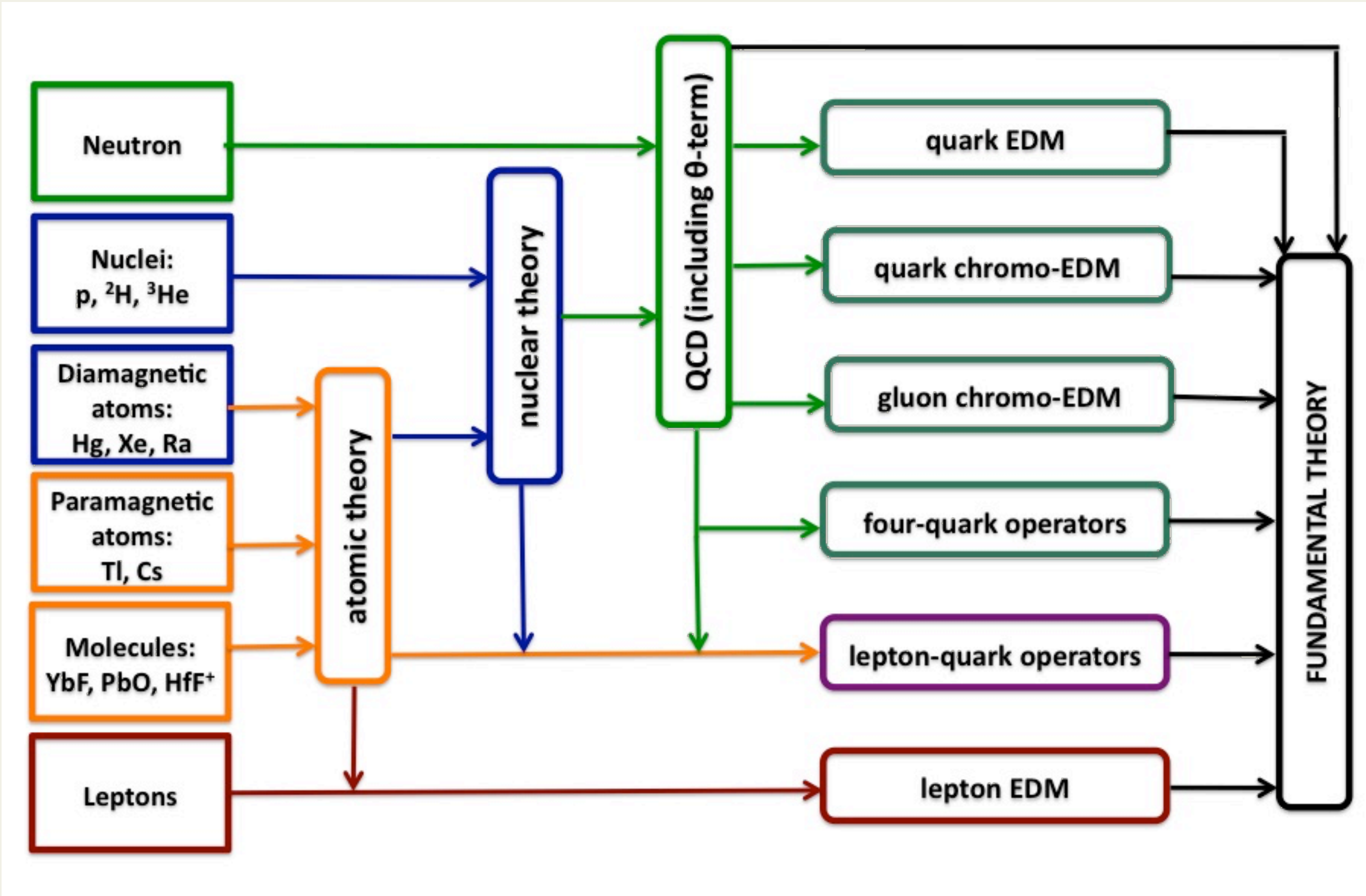
EDMs in the era of the LHC

Jordy de Vries, Nikhef, Amsterdam

Topical Lectures on electric dipole moments, Dec. 14-16

The EDM metromap



EDMs and new CP violation

- **Aim: connect low-energy EDM experiments to high-energy physics**

1. We do not know if and what BSM physics exists. **How do we start?**

2. How to go from a scale ~ TeV to ~ eV experiments ?

3. EDM experiments involve complex things (nuclei, atoms, molecules)
   - How do we interpret the experimental constraints ?

4. Say we can do all this: how do we compare **EDMs** to other experiments like **LHCb** or **ATLAS/CMS** ?

Describing the unknown

Beyond-the-Standard Model (BSM) physics

Basically two methods of describing unknown high-energy physics

Models

(SUSY, multi-higgs, Kaluza-Klein, Left-Right, ….)

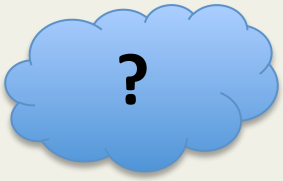
- Often well motivated (solution of physical problems, e.g. hierarchy problem)
- Relations between observables

- Often many parameters
- Partially based on 'theoretical bias' (simplicity)
- 'epi-cycles'

Effective Field Theory

Describing the unknown

Beyond-the-Standard Model (BSM) physics



Basically two methods of describing unknown high-energy physics

Models

(SUSY, multi-higgs, Kaluza-Klein, Left-Right, ….)

- Often well motivated (solution of physical problems, e.g. hierarchy problem)
- Relations between observables

- Often many parameters
- Partially based on 'theoretical bias' (simplicity)
- 'epi-cycles'

Effective Field Theory

- General: only minimal assumptions on BSM physics
- Simple to use
- Exhaustive (barring higher-dimensional operators…)

- No relation between low-energy constants and thus different observables
- Often many low-energy constants

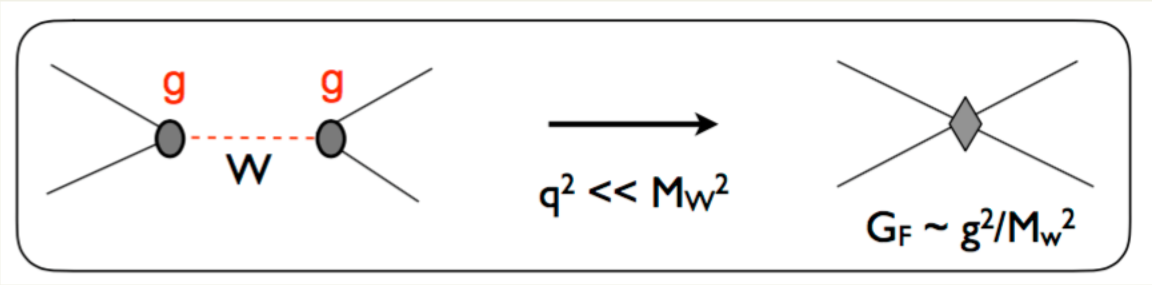
Footprints of high-energy physics

- In chemistry we do not care about nuclear structure
- And for nuclear structure we ignore quarks/gluons
- **Concept of effective field theory**
- At a certain energy scale, we can ‘integrate out’ fields associated with higher energies (smaller distances)

Footprints of high-energy physics

- In chemistry we do not care about nuclear structure
- And for nuclear structure we ignore quarks/gluons
- **Concept of effective field theory**
- At a certain energy scale, we can 'integrate out' fields associated with higher energies (smaller distances)

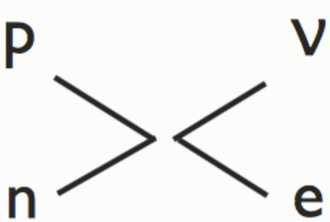
- Very well-known example: Fermi-theory of beta decay



- We don't need 'high-energy details', i.e. the W boson, at low energies !

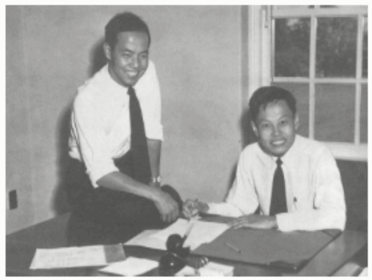
**EFT for β-decays and the making of the SM

Fermi, 1934



Current-current, parity conserving

Lee and Yang, 1956



Parity conserving: VV, AA, SS, TT ...

Parity violating: VA, SP, ...

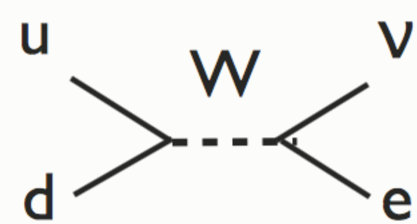
Feynman & Gell-Mann, 1958

Marshak & Sudarshan

It's (V-A)*(V-A) !!

"V-A was the key"
S. Weinberg

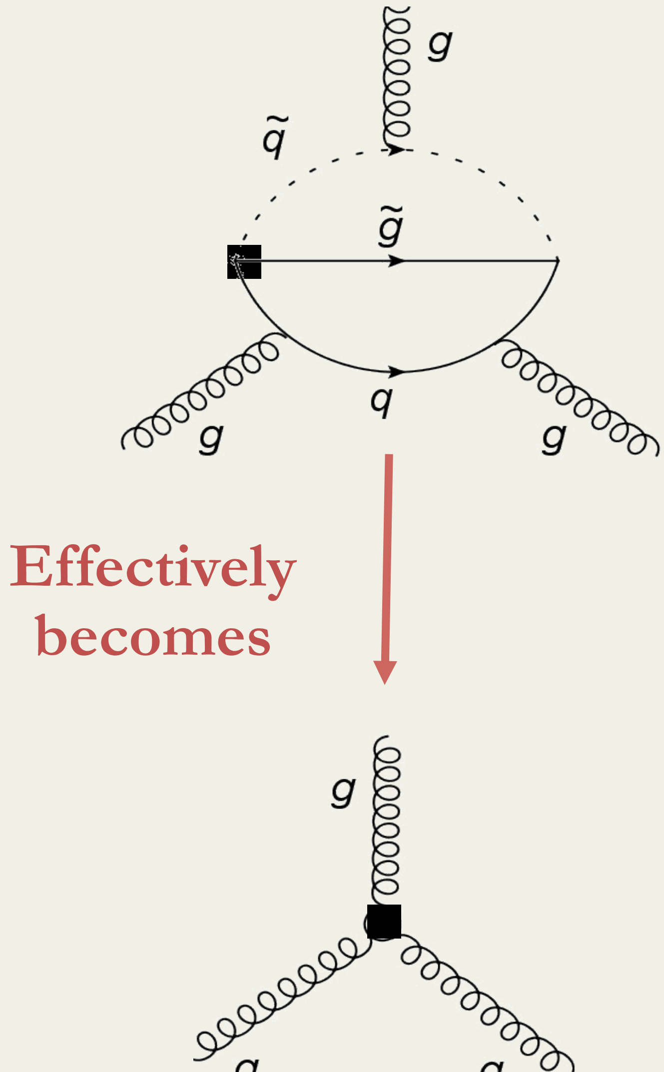
Glashow, Salam, Weinberg



Embed in non-abelian chiral gauge theory, predict neutral currents

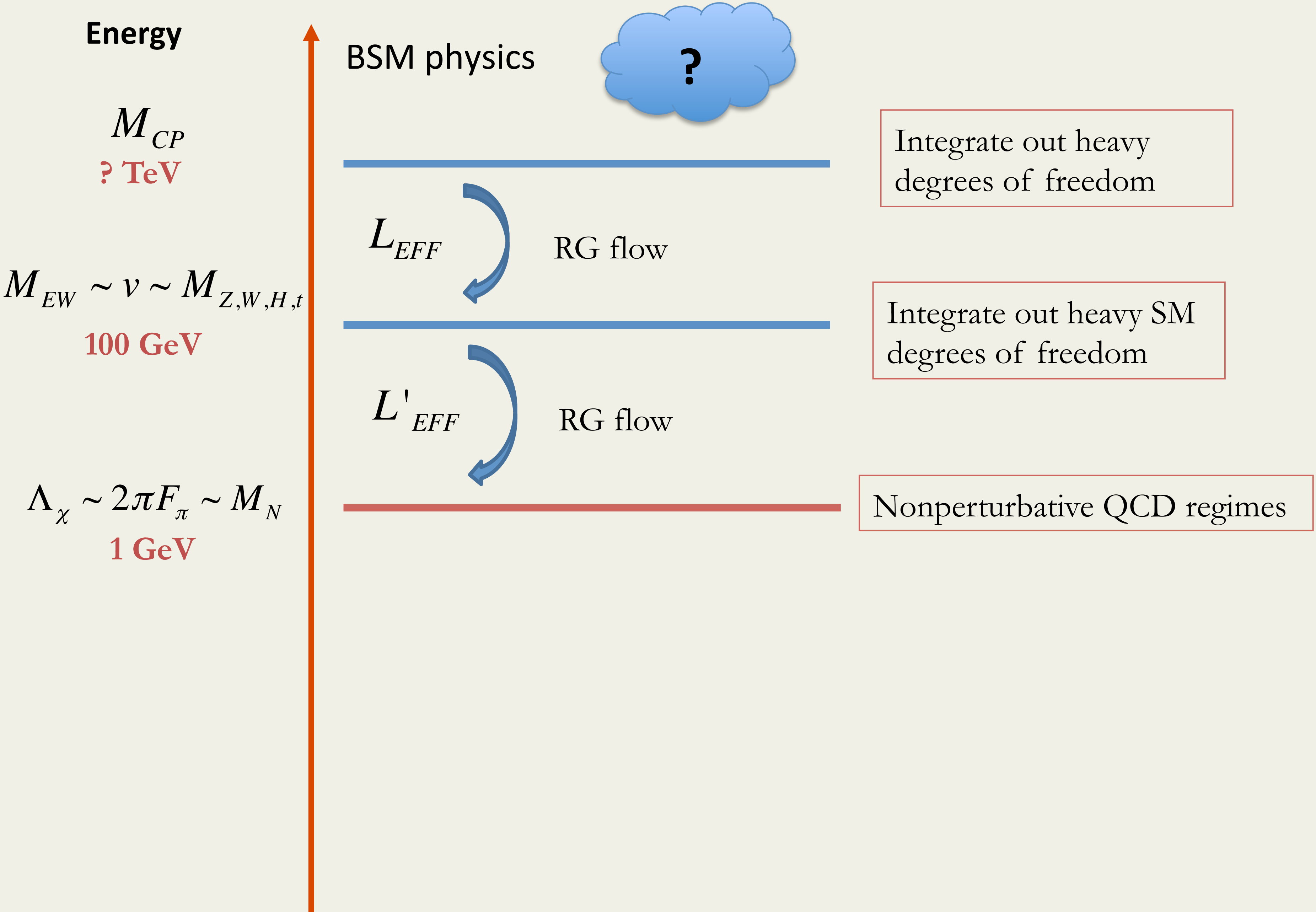
Slide stolen from
V. Cirigliano, INT '15

EFT for new physics

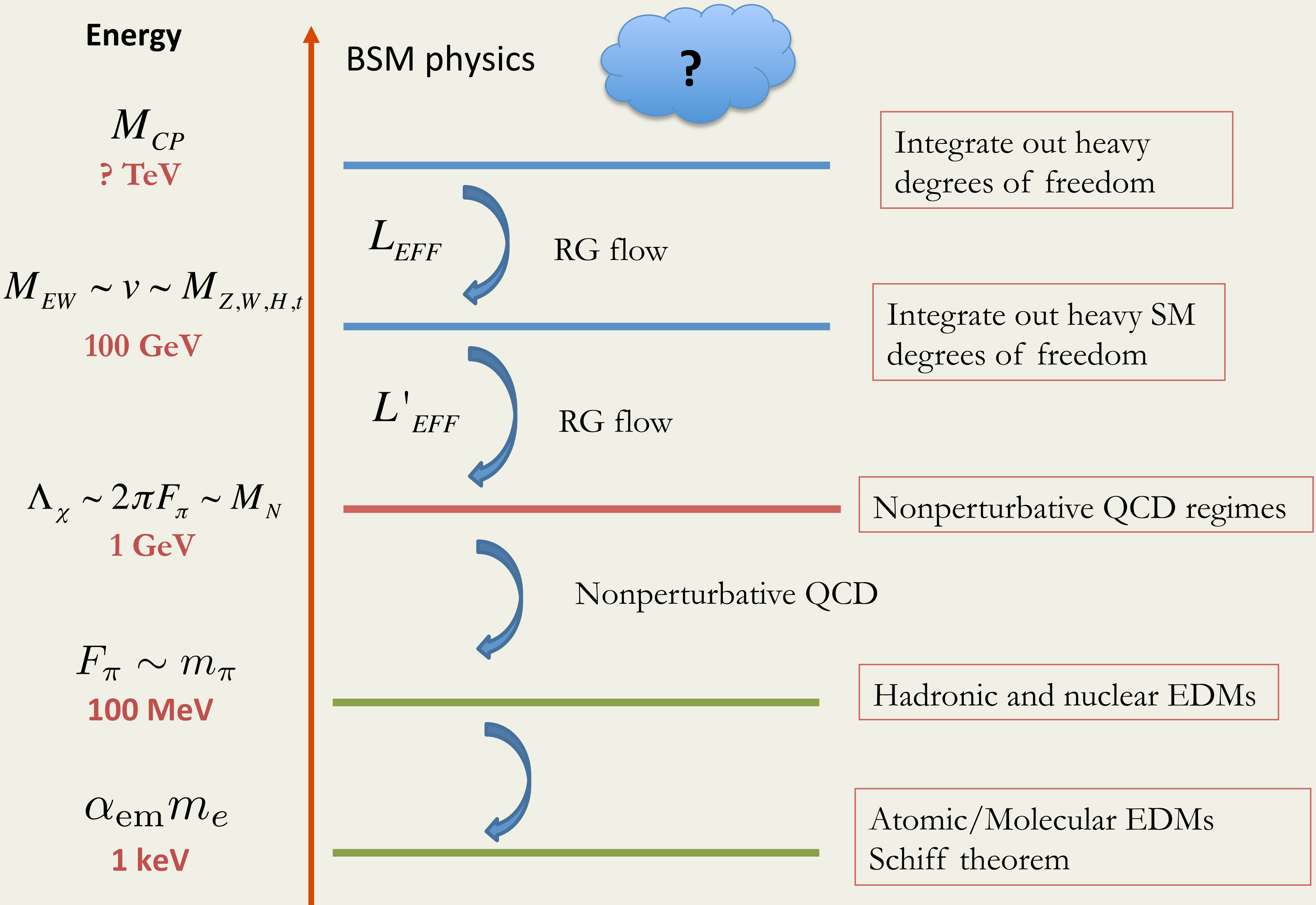


$$\propto \frac{1}{\Lambda^2}$$

Separation of scales



Separation of scales



Standard model as an EFT

- Assume any BSM physics lives at scales $\Lambda >> M_{EW} \sim 100$ GeV
- Match to set of **effective** operators (model independent)

1) Degrees of freedom: Only Standard Model fields ! !

2) Symmetries: Lorentz, **SU(3)xSU(2)xU(1), nothing else**

Standard model as an EFT

- Assume any BSM physics lives at scales $\Lambda >> M_{EW} \sim 100$ GeV
- Match to set of **effective** operators (model independent)

1) Degrees of freedom: Only Standard Model fields ! !

2) Symmetries: Lorentz, **SU(3)xSU(2)xU(1), nothing else**

$$L_{new} = \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots$$

- **At energy E, operators of dimension (4+n) contribute as**

$$\left(\frac{E}{\Lambda}\right)^n$$

so at low energy: lowest-dim operators are relevant !

Operator dimension clear ?

Example of higher-dim operator

$$L_{new} = \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots$$

- Gauge symmetry is restrictive! Only **one** gauge-invariant dim-5 operator

$$\ell = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \boxed{\hat{O}_{\text{dim}=5} = \ell^T C \epsilon \varphi \; \varphi^T \epsilon \ell} \qquad \begin{array}{c} C = i\gamma_2\gamma_0 \\ \epsilon = i\sigma_2 \end{array}$$

- Violates lepton number ! Who cares, SM has it but it is **accidental**

Example of higher-dim operator

$$L_{new} = \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots$$

- Gauge symmetry is restrictive! Only **one** gauge-invariant dim-5 operator

$$\ell = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \hat{O}_{\mathrm{dim}=5} = \ell^T C \epsilon \varphi \, \varphi^T \epsilon \ell \qquad \begin{array}{c} C = i\gamma_2\gamma_0 \\ \epsilon = i\sigma_2 \end{array}$$

- Violates lepton number ! Who cares, SM has it but it is **accidental**
- Once Higgs gets vacuum expectation value → Majorana neutrino mass

$$\frac{1}{\Lambda}\hat{O}_{\mathrm{dim}=5} \xrightarrow{\langle\varphi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}} \frac{v^2}{\Lambda} \nu_L^T C \nu_L$$

- If neutrino mass ~ 1 eV, then $\Lambda \sim 10^{13}$ GeV
- If this is the only new physics, then it will be hard to probe

Higher-dimensional CPV operators

- To get CPV we need to go to **dimension six !**
- Already explains a bit the suppression of new physics (2 powers)

- There are **59** 'structures' at dimension six, but most we can ignore
- **Here I just give a few examples**

$$L_{new} = \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots$$

Dipole operators

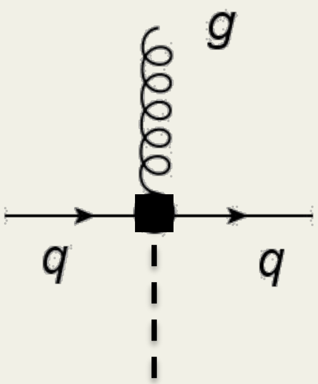
X=W, B, G

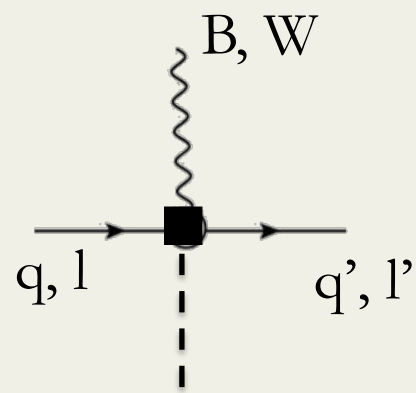
Requires Higgs: $\Gamma_X \bar{\Psi}_L \sigma^{\mu\nu} \Psi_R X_{\mu\nu} \varphi + h.c.$

In most models: $\Gamma_X \propto \dfrac{m_\Psi}{v\, M_{CP}^2}$ **dipoles scale with mass !**

M_{CP}

? TeV

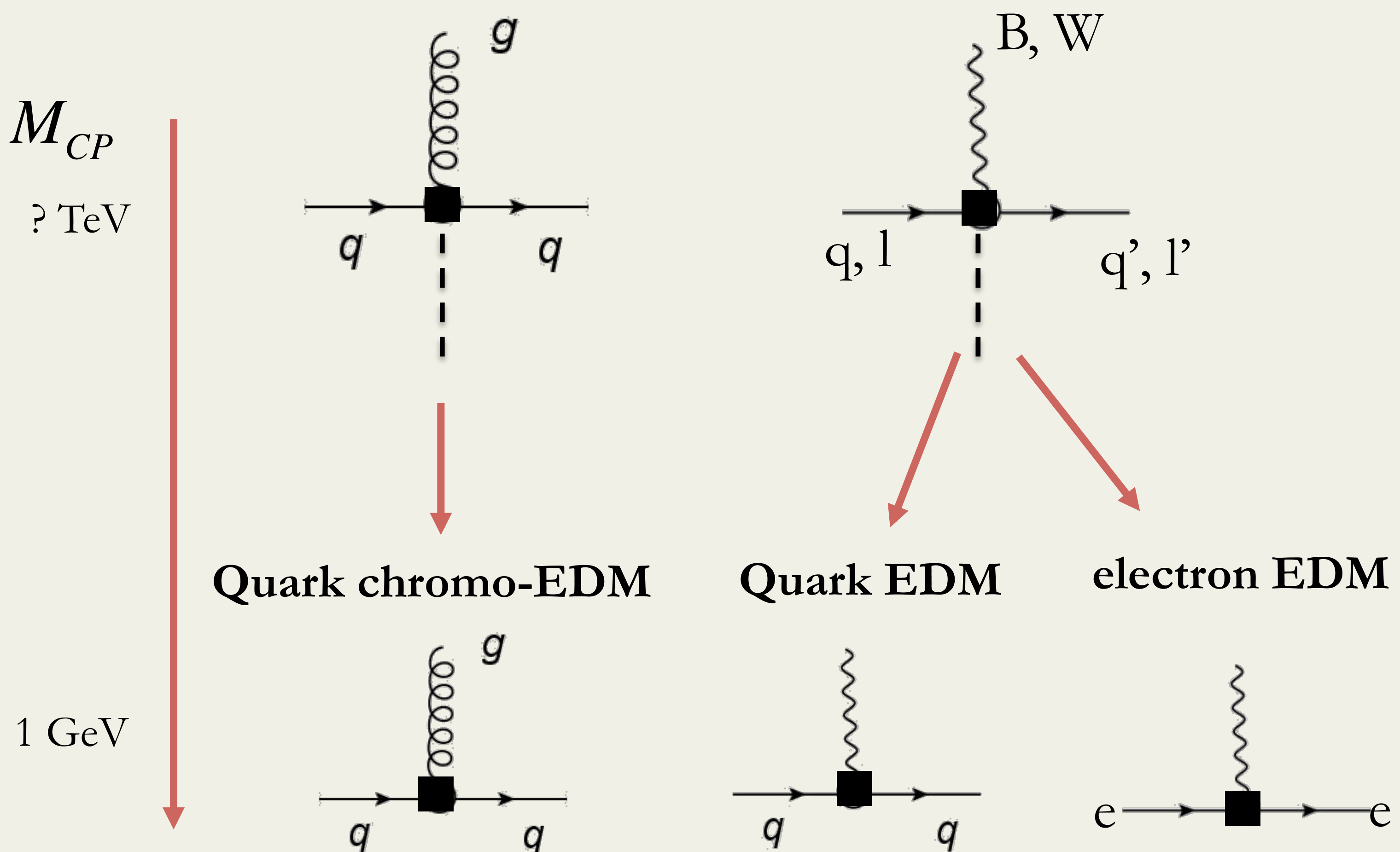




Dipole operators

Requires Higgs: $\Gamma_X \bar{\Psi}_L \sigma^{\mu\nu} \Psi_R X_{\mu\nu} \varphi + h.c.$ X=W, B, G

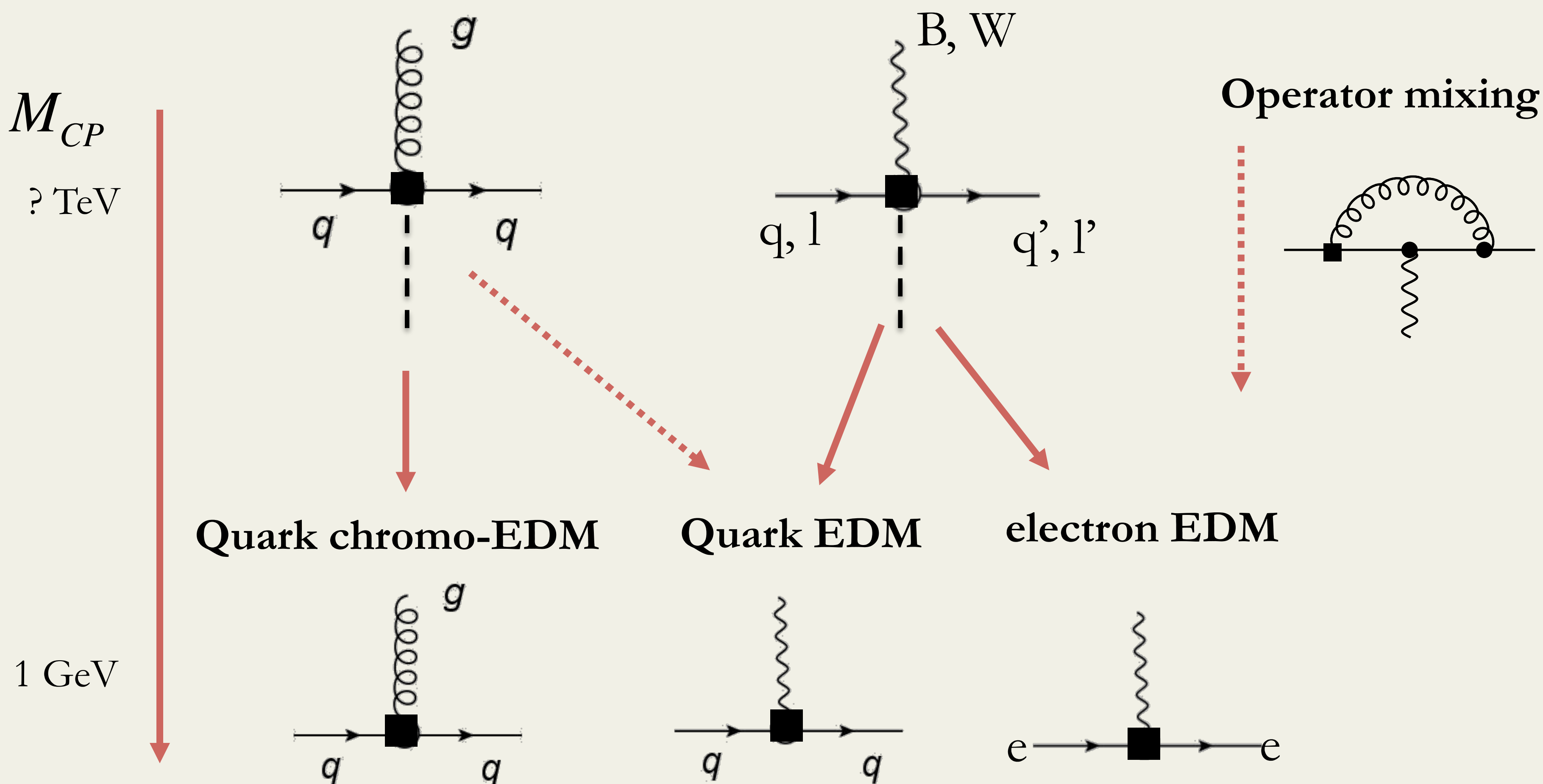
In most models: $\Gamma_X \propto \frac{m_\Psi}{v\, M_{CP}^2}$ **dipoles scale with mass !**



Dipole operators

Requires Higgs: $\Gamma_X \bar{\Psi}_L \sigma^{\mu\nu} \Psi_R X_{\mu\nu} \varphi + h.c.$ X=W, B, G

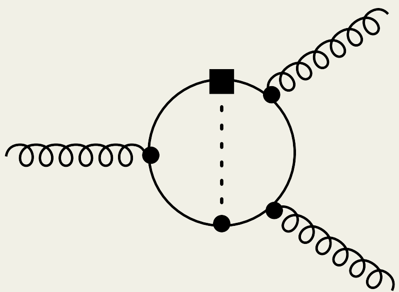
In most models: $\Gamma_X \propto \dfrac{m_\Psi}{v\, M_{CP}^2}$ **dipoles scale with mass !**



Gluon chromo-EDM

Weinberg PRL '89
Braaten et al PRL '90

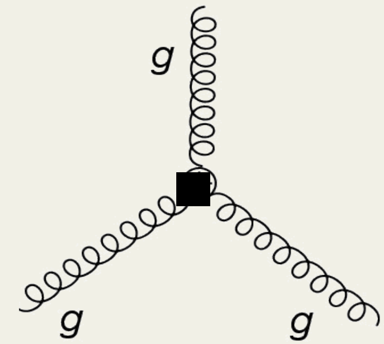
M_{CP}
? TeV



SUSY:
gluino-squark loop

2HDM:
heavy scalar exchange

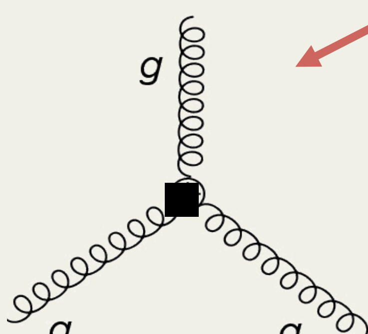
Weinberg operator

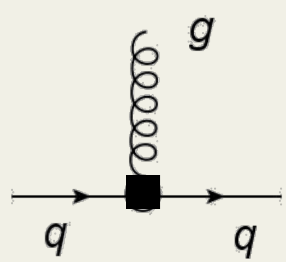


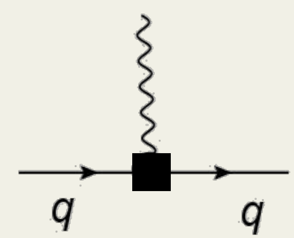
$$d_w\ f^{abc}\varepsilon^{\mu\nu\alpha\beta}\ G^a_{\alpha\beta}G^b_{\mu\lambda}\ G^{c\ \lambda}_{\nu}$$

-

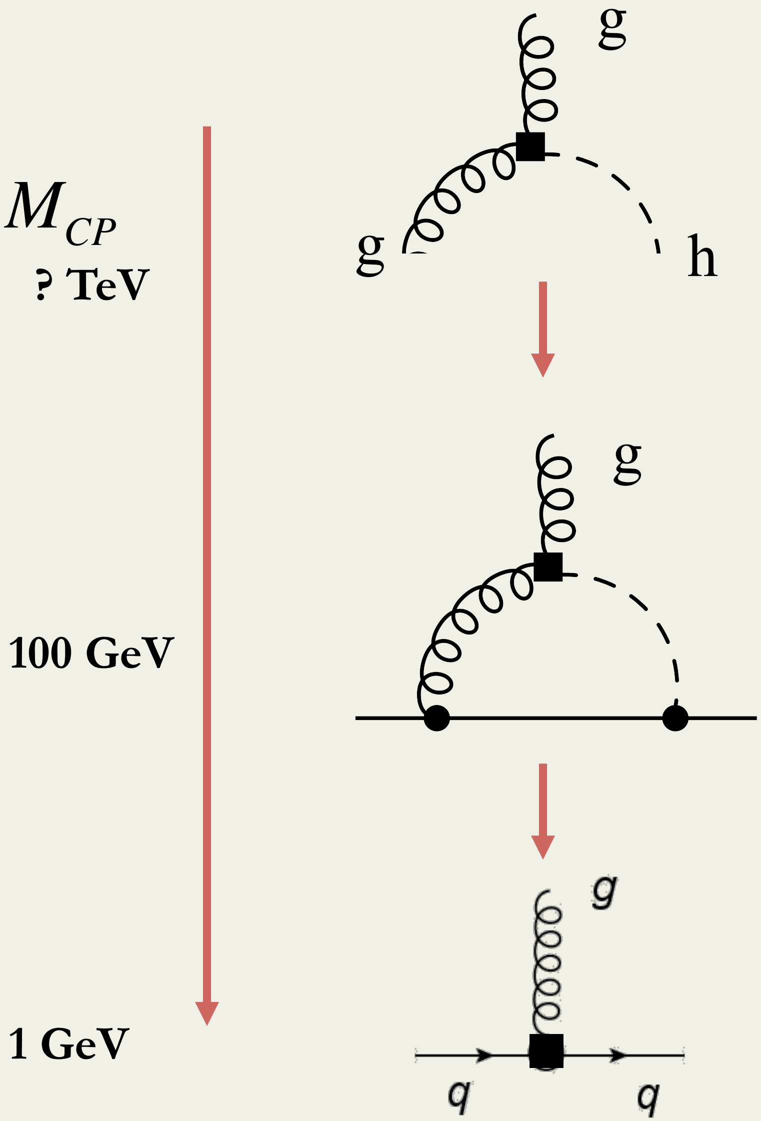
1 GeV







Anomalous gauge/higgs couplings



Search at the same time at LHC.

One example: $\theta' H^2 G\tilde{G}$

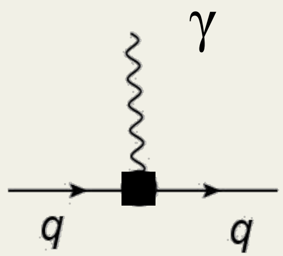
a) Probed at LHC (affects gluon fusion)

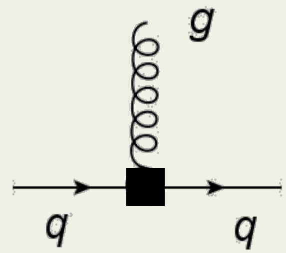
b) Induces quark chromo-EDM

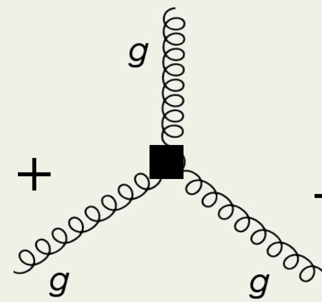
Similar for **Higgs-photon/Z/W** operators

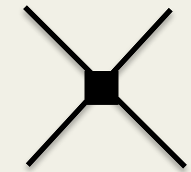
Many more… But when the dust settles…..

Few GeV

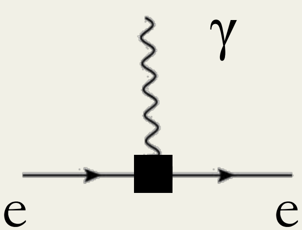
QCD
(θ -term)
+


Quark EDM
+


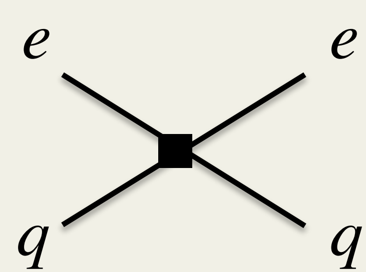
Quark C-EDM
+


Gluon C-EDM
+

Four-quark operators

(semi-)leptonic interactions



Electron EDM



- Any BSM model with additional CP-violation can be described at low energies by O(10) CPV operators (**integrated out the high-energy details !**)
- Different BSM model, different relevant operators

Intermediate summary

- Parametrized BSM CP violation in terms of **dim6** operators
- Evolved them to lower energies to ~ 1 GeV
- Several operators left: theta, (C)EDMs, Weinberg, Four-fermion
- **Important:** different BSM models -> different EFT operators

Intermediate summary

- Parametrized BSM CP violation in terms of **dim6** operators
- Evolved them to lower energies to ~ 1 GeV
- Several operators left: theta, (C)EDMs, Weinberg, Four-fermion
- **Important:** different BSM models -> different EFT operators

1. Standard Model: only **theta** has a chance to be measured
2. 2-Higgs doublet model: **quark+electron EDM, CEDMs, Weinberg** (exact hierarchy depends on detail of models)
3. Split SUSY: only **electron + quark EDMs** (ratio fixed)
4. Left-right symmetric models: **FQ operators**, way smaller (C)EDMs
5. …...

- **Can EDMs compete with high-energy experiments ?**
- **can we unravel these scenarios with EDMs ?**

Example: CP violation in the Higgs sector

- The Standard Model has a 'minimal' Higgs sector
- Only 1 Higgs doublet
- Mass ~ Yukawa,   real diagonal mass → real diagonal Yukawa (boring…)

Example: CP violation in the Higgs sector

- The Standard Model has a 'minimal' Higgs sector
- Only 1 Higgs doublet
- Mass ~ Yukawa, real diagonal mass → real diagonal Yukawa (boring…)

- In many models there are more Higgses (SUSY, LR, 2HDM, ...)
- Imagine 2 scalars: φ_1 is the SM Higgs, φ_2 is a new one

$$y_1 \bar{\Psi}_L \Psi_R \varphi_1 + y_2 \bar{\Psi}_L \Psi_R \varphi_2 + \lambda_{12} (\varphi_1)^3 \varphi_2 + \cdots + h.c.$$

- We can always make y_1 real, but then y_2 will be complex...

Example: CP violation in the Higgs sector

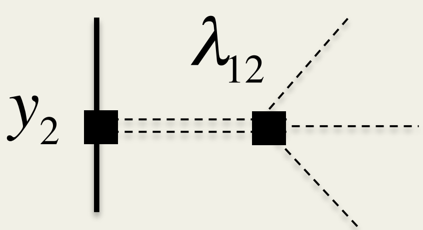
- The Standard Model has a 'minimal' Higgs sector
- Only 1 Higgs doublet
- Mass ~ Yukawa, real diagonal mass → real diagonal Yukawa (boring…)

- In many models there are more Higgses (SUSY, LR, 2HDM, ...)
- Imagine 2 scalars: φ_1 is the SM Higgs, φ_2 is a new one

$$y_1\, \bar{\Psi}_L \Psi_R \varphi_1 + y_2\, \bar{\Psi}_L \Psi_R \varphi_2 + \lambda_{12} (\varphi_1)^3 \varphi_2 + \cdots + h.c.$$

- We can always make y_1 real, but then y_2 will be complex...

- **LHC** tells us: if there is another scalar it is **heavy,** integrate it out!

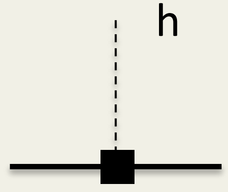


$$L = Y_{new}\, \bar{\Psi}_L \Psi_R \varphi_1 (\varphi_1 \varphi_1^*) \qquad Y_{new} = \frac{y_2 \lambda_{12}}{M_{\varphi 2}^2}$$

Example: CP violation in the Higgs sector

- So: forget high-energy details and look at dim-6 EFT operator

$$L = Y_{new}\ \bar{\Psi}_L \Psi_R \varphi_1 (\varphi_1 \varphi_1^*) \qquad Y_{new} \propto \frac{1}{\Lambda^2}$$



- Y_{new} is complex → CP-violating Higgs-quark couplings
- Very interesting for baryogenesis

- How do we measure this ? Very popular at the LHC recently

Atwood et al. '92; Choudhury et al, '12
Baumgart et al, '13; Bernreuther et al, '15, '15
Biswal et al, '13; Hioki et al, '13, '15
Aguilar-Saavedra et al, '15; Bramante et al, '14
Englert et al, '14; Rindani et al, '15
Gaitan et al, '15; Cordero-Cid et al, '08

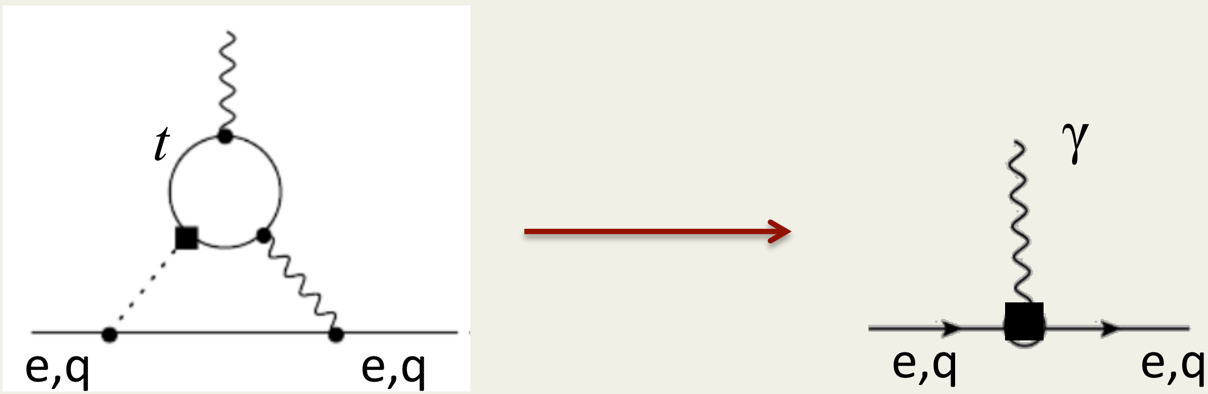
Fael et al, '13; Bouzas et al, '12, '13
Röntsch et al, '15; Grzadkowski et al, '08
Gonzalez-Sprinberg, '11; Drobnak et al, '10, '12
Cao et al, '15; Schulze et al, '16
Brod et al, '13; Dolan et al, '14
Demartin et al, '14, '15; Kobakhidze et al, '14

Khatibi et al, '14
Chen et al, '15
Buckley et al, '15

- But what about low-energy constraints ?
- How do we measure Higgs properties at low energy ?

Loops, loops, and loops

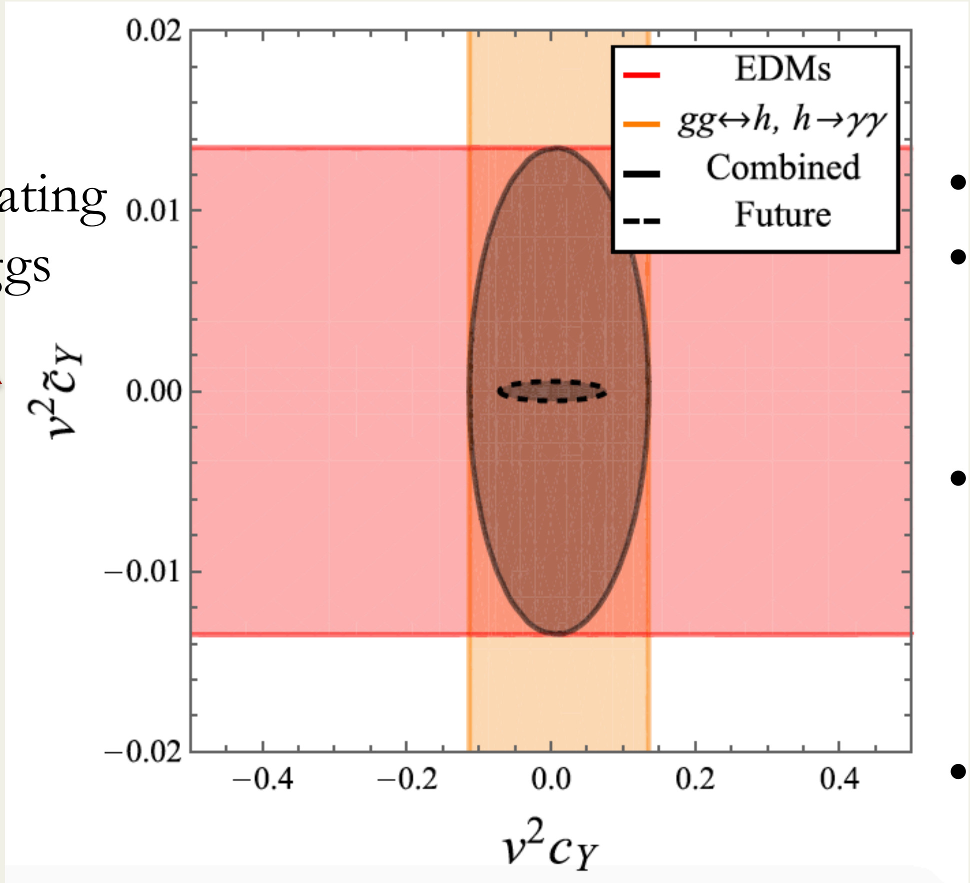
- Quantum corrections involving Higgs particles affect properties of leptons and nucleons



- Top-Higgs coupling induces a 2-loop electron/quark EDM
- The electron/neutron EDM limit constraints the size of top-Higgs CPV

Testing the SM

CP-violating top-Higgs



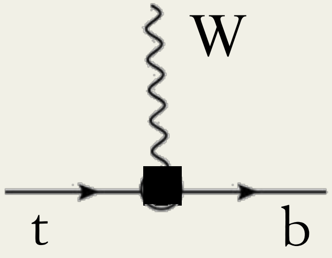
CP-conserving top-Higgs

- So EDM limit CPV at 1% !
- While CP-even Yukawa still can vary by 15% from SM
- **This rules out various models of baryogenesis that requires ~ 10% CPV**
- Main message: low- and high-energy experiments are complementary

Modifying the top-bottom-W vertex

- In the SM, we only have a left-handed vector top-bottom-W vertex
- In BSM might have right-handed or tensor couplings
- Example: the dimension-six operator

$$+\bar{q}_L C_W^t \sigma^{\mu\nu} \tau \cdot W_{\mu\nu} u_R \tilde{\varphi}$$

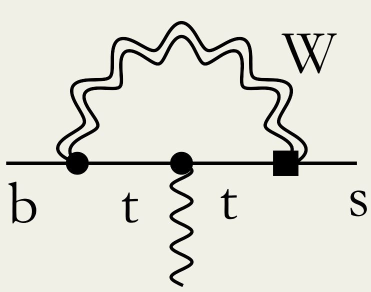


- Measure at colliders, flavor physics, and EDMs (complementary)

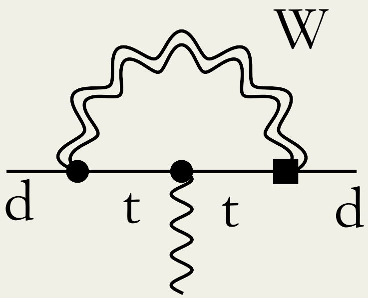
- EFT framework allows one to connect these experiments

Indirect constraints

- Known constraints from low-energy experiments



$(b \rightarrow s\,\gamma)$

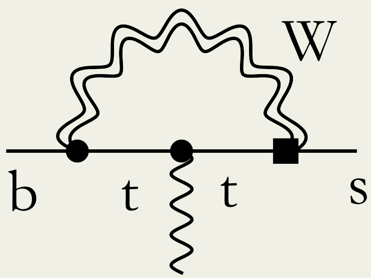


Neutron EDM

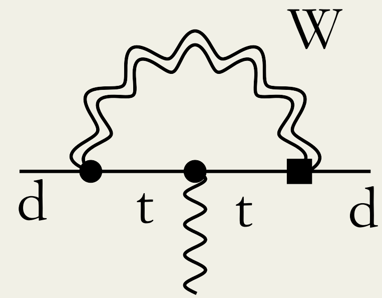
- Bound from neutron EDM, too weak ~ $|V_{td}|^2$

Indirect constraints

- Known constraints from low-energy experiments



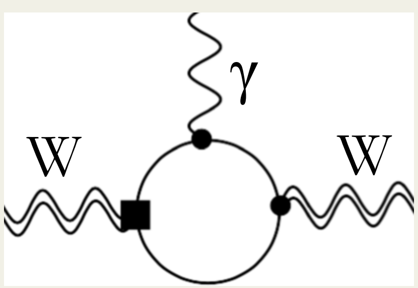
(b → s γ)



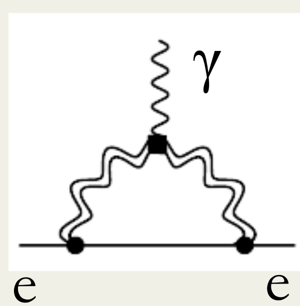
Neutron EDM

- Bound from neutron EDM, too weak ~ $|V_{td}|^2$

Step 1: induce CPV WW-photon



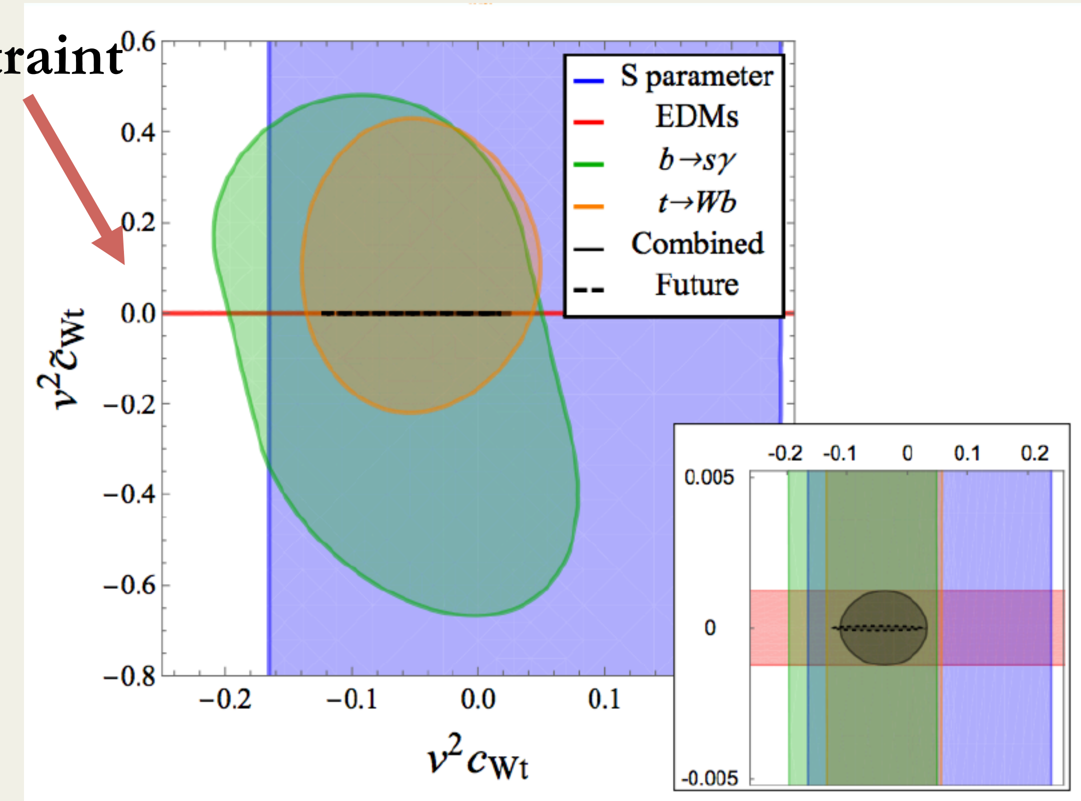
Step 2: induce fermion EDMs



- **Use eEDM constraint!**
- **No CKM suppression**
- **Two loop**

Top-bottom-W constraints

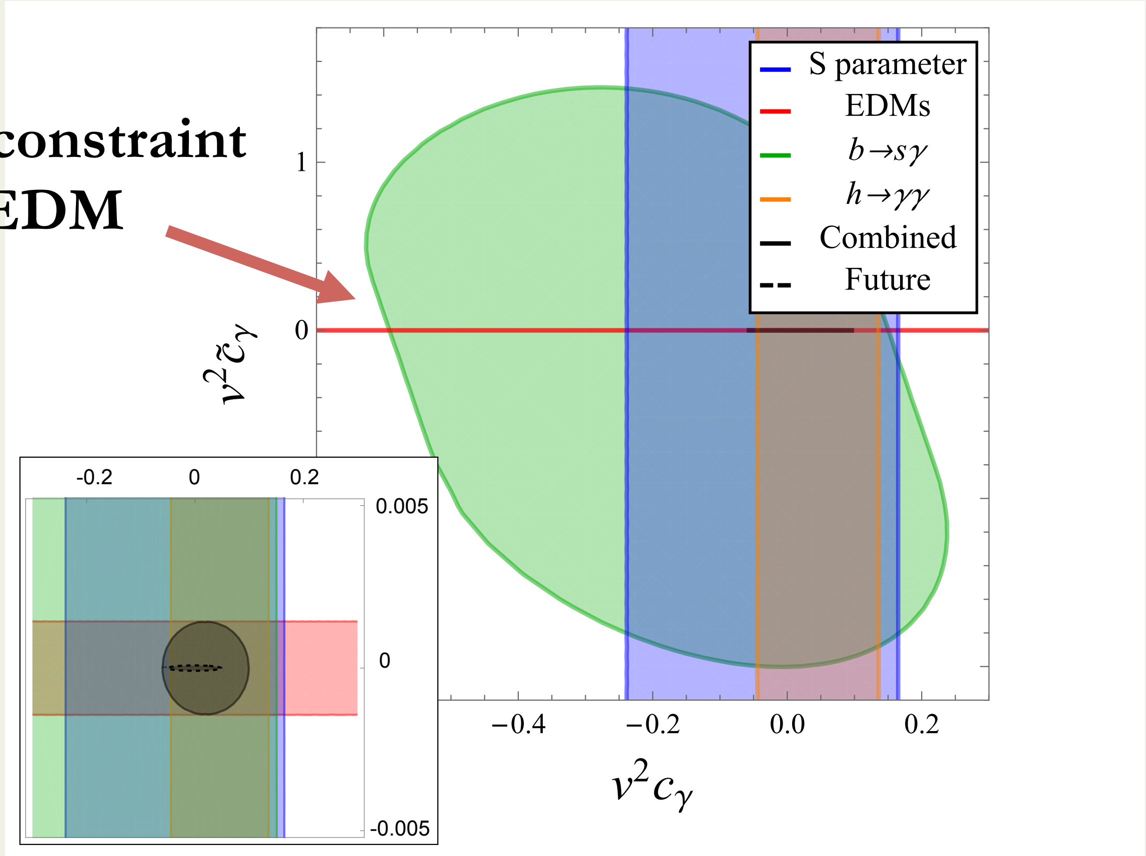
eEDM constraint



- **Again: best constraints by combining experiments !**

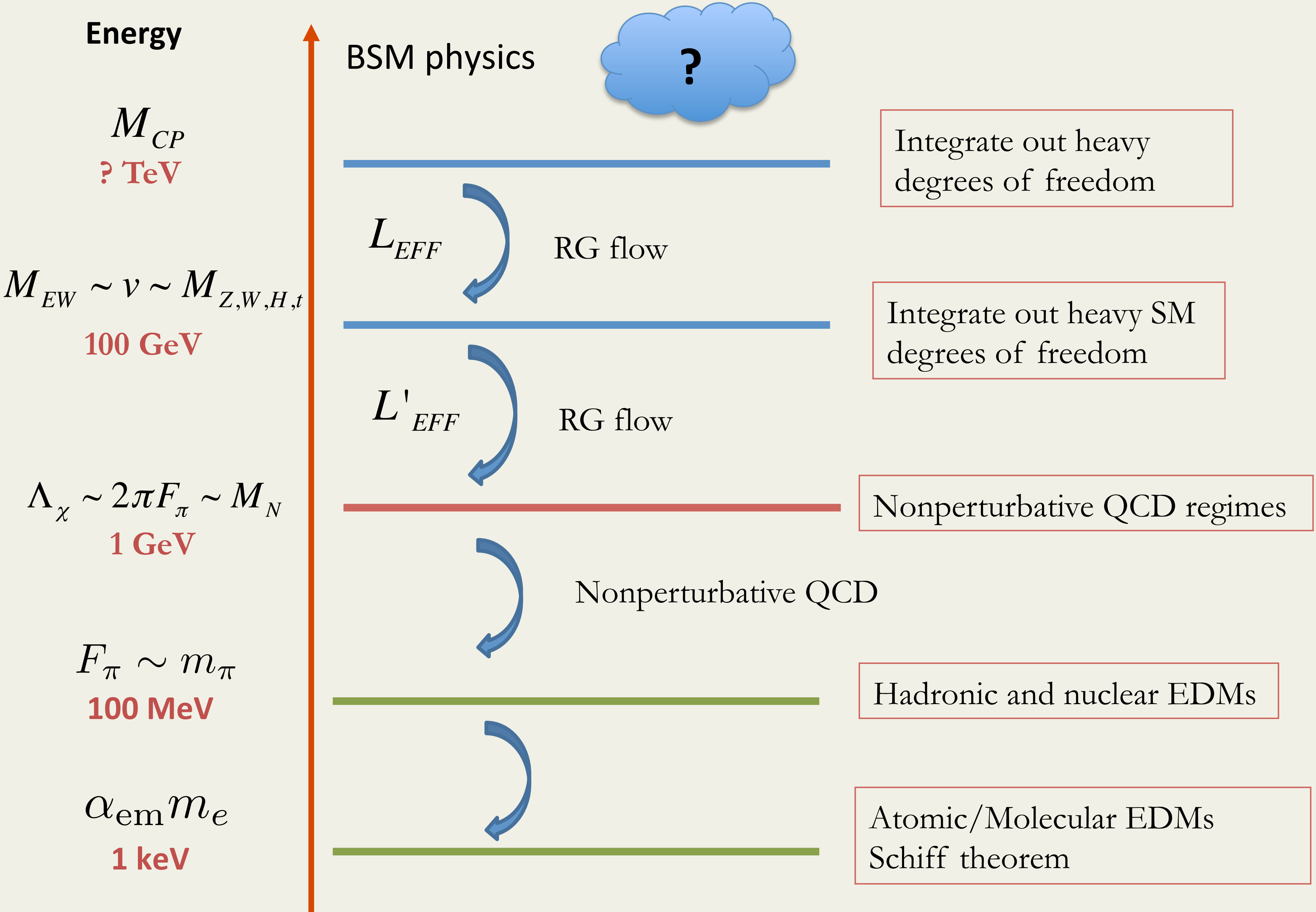
Top EDM constraints

eEDM constraint on top EDM

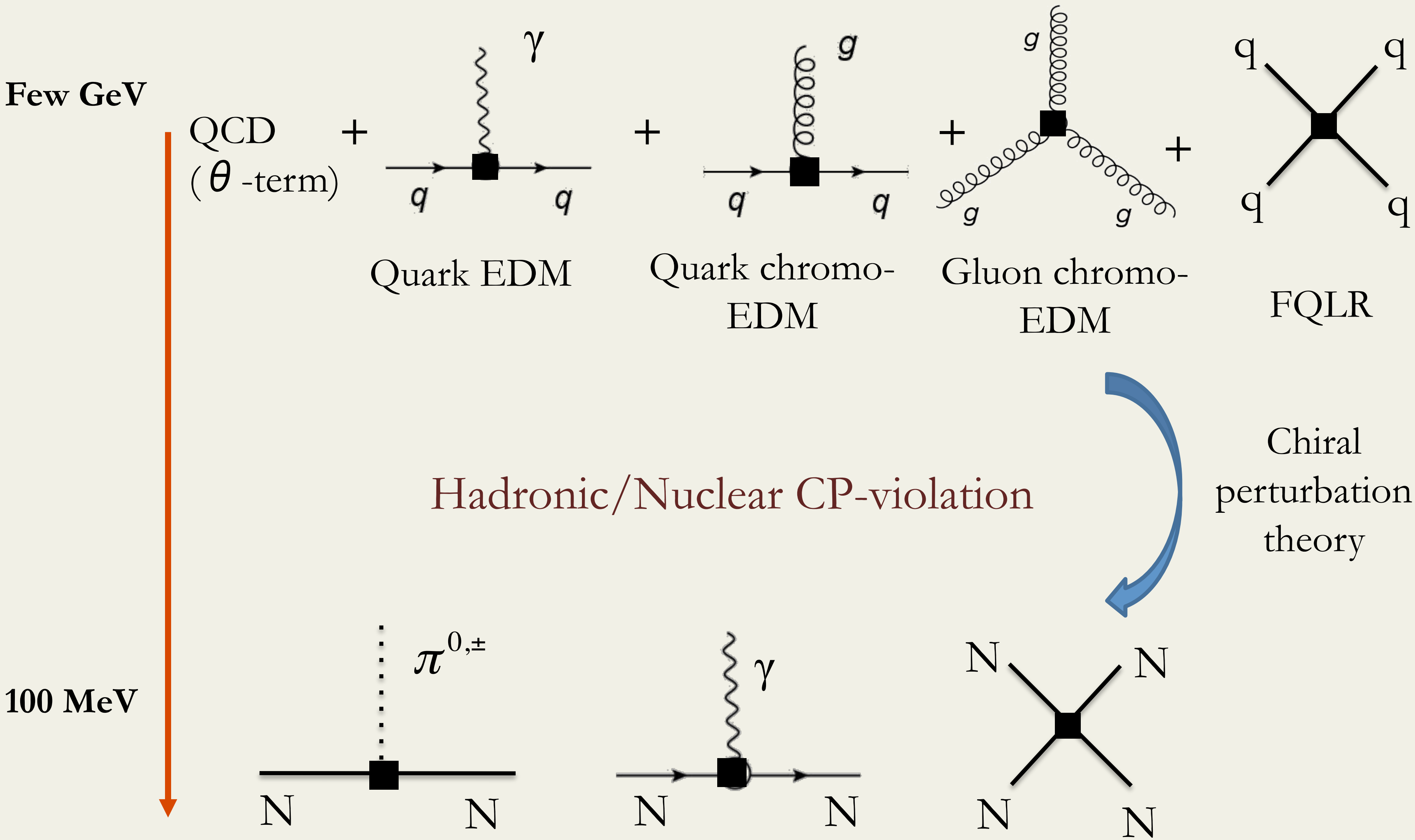


- Bound improves by **three** orders of magnitude
- top EDM < 5 x 10^{-20} e cm
- Run II LHC LHC sensitivity (pp → j + t + γ): $d_t < 10^{-17,-18}$ e cm
- **Again: best constraints by combining experiments !**

Separation of scales

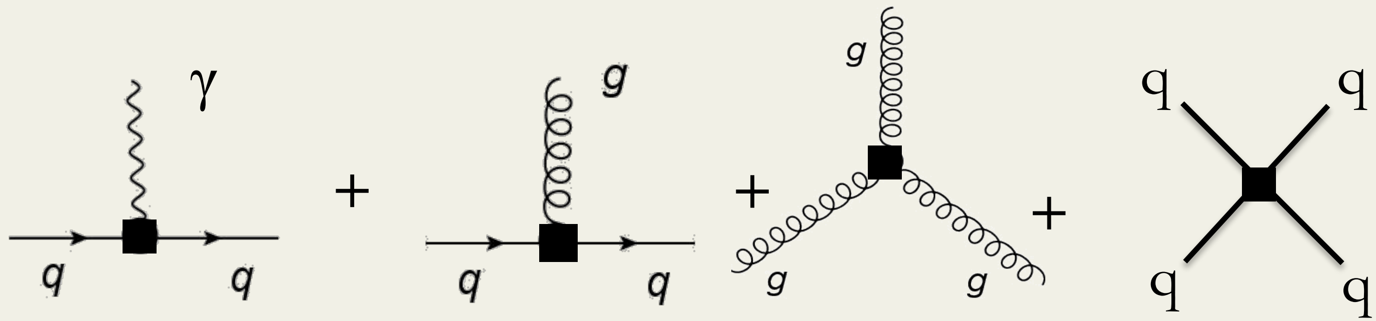


Onwards to hadronic CPV



ChiPT with CP violation

QCD
(θ-term) +



- They all break CP….
- But transform **differently** under chiral/isospin symmetry

↓

Different CP-odd hadronic Lagrangians

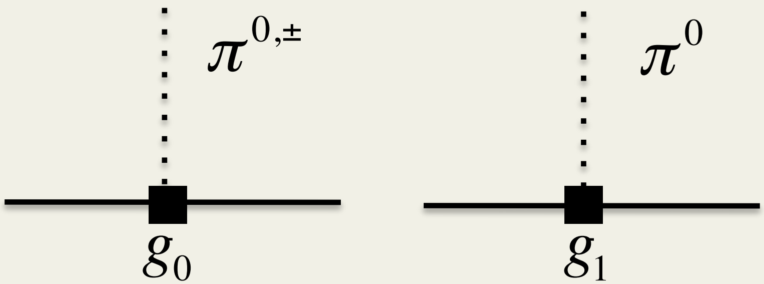
↓

Different hierarchy of EDMs

CP-violating pion-nucleon couplings

- 2 CP-odd structures

$$L = g_0\, \bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N + g_1\, \bar{N}\pi_3 N$$



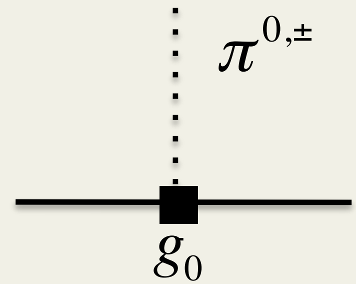
- θ -term conserves isospin! So g_1 is **suppressed**.

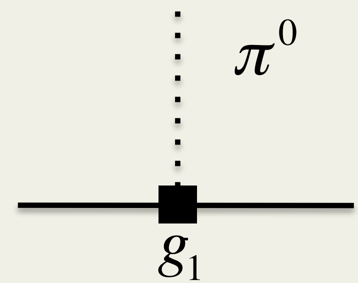
$$\frac{\bar{g}_1}{\bar{g}_0} = -(0.2 \pm 0.1)$$

CP-violating pion-nucleon couplings

- 2 CP-odd structures

$$L = g_0 \bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N + g_1 \bar{N}\pi_3 N$$

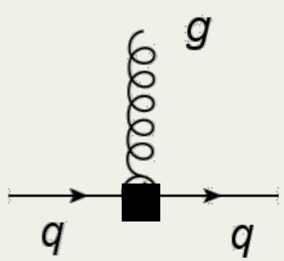




- θ -term conserves isospin! So g_1 is **suppressed**.

$$\frac{\bar{g}_1}{\bar{g}_0} = -(0.2 \pm 0.1)$$

- **Not** true for the **dimension-six qCEDM** !



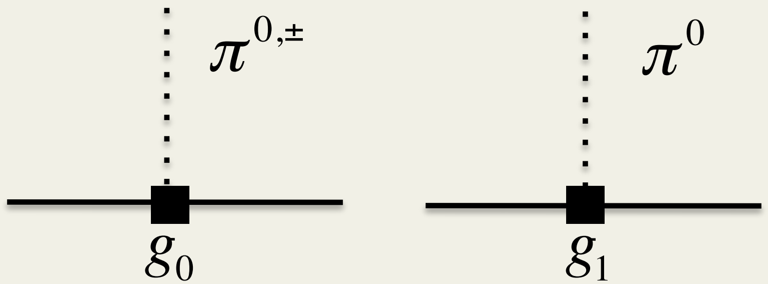
$$\bar{g}_0 = (5 \pm 10)(\tilde{d}_u + \tilde{d}_d)\,\mathrm{fm}^{-1} \qquad \bar{g}_1 = (20^{+20}_{-10})(\tilde{d}_u - \tilde{d}_d)\,\mathrm{fm}^{-1}$$

- Fairly large uncertainties. But generally: $|\bar{g}_1| \geq |\bar{g}_0|$

CP-violating pion-nucleon couplings

- 2 CP-odd structures

$$L = g_0\, \bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N + g_1\, \bar{N}\pi_3 N$$



- Four-quark left-right operator breaks isospin !

$$L = i\Xi(\bar{u}_R\gamma_\mu d_R)(\bar{u}_L\gamma_\mu d_L) + \text{h.c.}$$

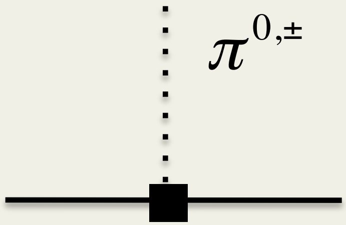
- ChPT gives ratio of couplings

$$\frac{\bar{g}_1}{\bar{g}_0} = -(68 \pm 25)$$

Back to pion-nucleon couplings

- 2 CP-odd structures

$$L = g_0\, \bar{N}\pi \cdot \tau N + g_1\, \bar{N}\pi_3 N$$



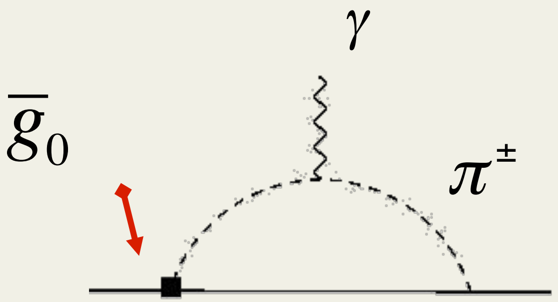
Key idea

- The theta-term and dim-6 operators all **break CP**
- **Different** CP-odd chiral Lagrangians, illustrated by ratios

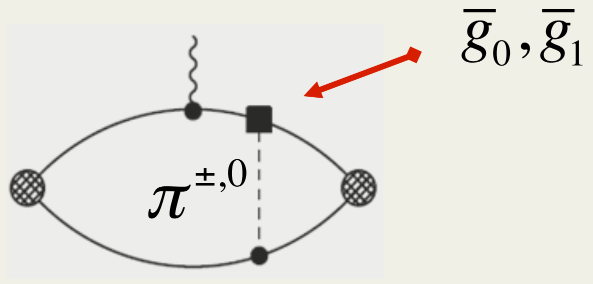
	Theta term	**Quark CEDMs**	**Four-quark operator**	**Quark EDM and Weinberg**
$\dfrac{\bar{g}_1}{\bar{g}_0}$	-0.2	≈ 1	50	**Both couplings are suppressed** !

- **But how to experimentally probe these ratios ?**

Probe these ratios with nuclear EDMs



Nucleon EDM



Nuclear EDM

- Tree-level: **no loop** suppression
- Orthogonal to nucleon EDMs, sensitive to different CPV structures

$$d_A = <\Psi_A \,\|\, \vec{J}_{\cancel{CP}} \,\|\, \Psi_A> \; + \; 2 <\Psi_A \,\|\, \vec{J}_{CP} \,\|\, \tilde{\Psi}_A>$$

$$(E - H_{PT})\,|\Psi_A> = 0$$
$$(E - H_{PT})\,|\tilde{\Psi}_A> = V_{\cancel{CP}}\,|\Psi_A>$$

- **All inputs from chiral EFT** ! Clear (and tested) power counting !

The chiral filter

Chiral filter

- Deuteron EDM results

$$d_D = 0.9(d_n + d_p) + \left[(0.18 \pm 0.02)\, \bar{g}_1 + (0.0028 \pm 0.0003)\, \bar{g}_0\right] e\ fm$$

- Error estimate from cut-off variations + higher-order terms

`	**Theta term**	**Quark CEDMs**	**Four-quark operator**	**Quark EDM and Weinberg**
$\left\lvert \frac{d_D - d_n - d_p}{d_n} \right\rvert$	0.5 ± 0.2	5 ± 3	20 ± 10	$\cong 0$

- Ratio suffers from hadronic (not nuclear!) uncertainties **(need lattice)**
- EDM ratio hint towards **underlying CP-odd operator**!

Unraveling models

Dekens et al '14

Theta term: quantitative predictions

$$d_n = -(3.9 \pm 1.0) \cdot 10^{-16} \theta \; e \; cm$$

$$d_D - d_n - d_p = -(0.89 \pm 0.3) \cdot 10^{-16} \theta \; e \; cm$$

$$d_{3He} - 0.9 d_n = (1.0 \pm 0.4) \cdot 10^{-16} \theta \; e \; cm$$

Left-right symmetry

$$\left| \frac{d_{2H}}{d_{n,p}} \right| = 20 \pm 10$$

$$d_{3He} = (0.8 \pm 0.1) d_D$$

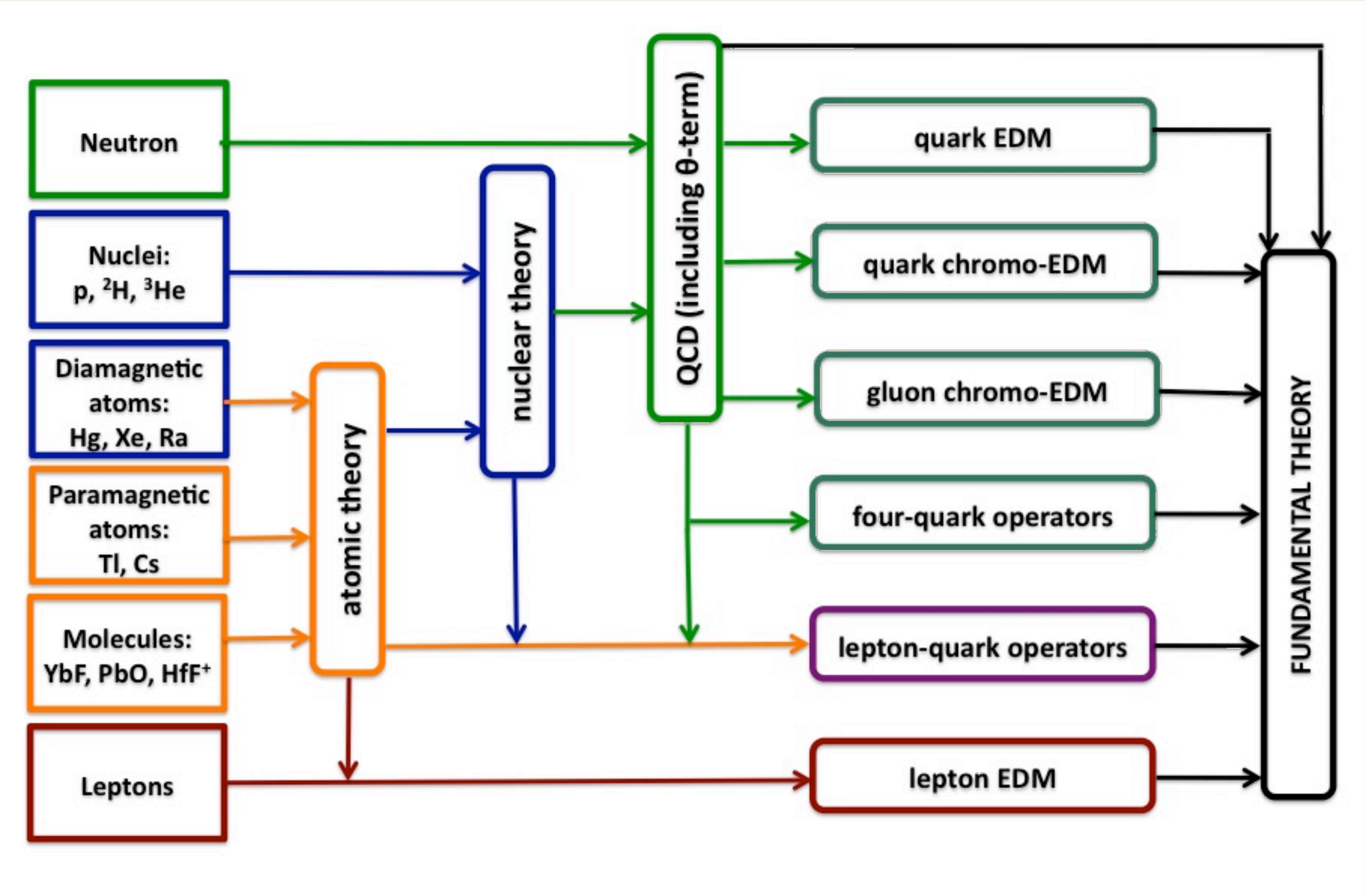
Identifying **2-Higgs Doublet Model** more difficult. Need lattice input.

$$|d_{3He}| \sim |d_D| \sim 5 \, |d_{n,p}|$$

Complementary info from electron EDM (assuming similar phases)

Theta: $\frac{d_e}{d_n} = 0$ **mLRSM:** $\frac{d_e}{d_n} \sim 10^{-4}$ **2HDM:** $\frac{d_e}{d_n} \sim 10^{-2}$

The EDM metromap



Conclusion/Summary/Outlook

EDMs

- ✓ CP-violation but no CKM contribution
- ✓ Probe of strong CP violation: QCD theta term
- ✓ Very powerful search for BSM physics (probe the highest scales)
- ✓ Heroic experimental effort and great outlook

Classes of EDM experiments

- ✓ Basically 4 'classes: neutron, paramagnetic, diamagnetic, storage rings
- ✓ Probe complementary sources of CP-violation
- ✓ Measurements in several classes → unravel CPV source

EFT framework

- ✓ Framework exists for CP-violation (EDMs) from 1st principles
- ✓ Keep track of **symmetries** (gauge/CP/chiral) from multi-Tev to atomic scales
- ✓ Can be nicely combined to LHC and flavor experiments ! **Complementary !**
- ✓ Still need much better theory control of hadronic and nuclear theory