Connecting CP violation from the TeV to the GeV scale

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Mostly based on: ``Renormalization Group Running of Dimension-Six Sources of P and T Violation”,

W. Dekens and J. de Vries, JHEP ’13

Hadronic Matrix Elements for Probes of CP Violation, 22 January 2015

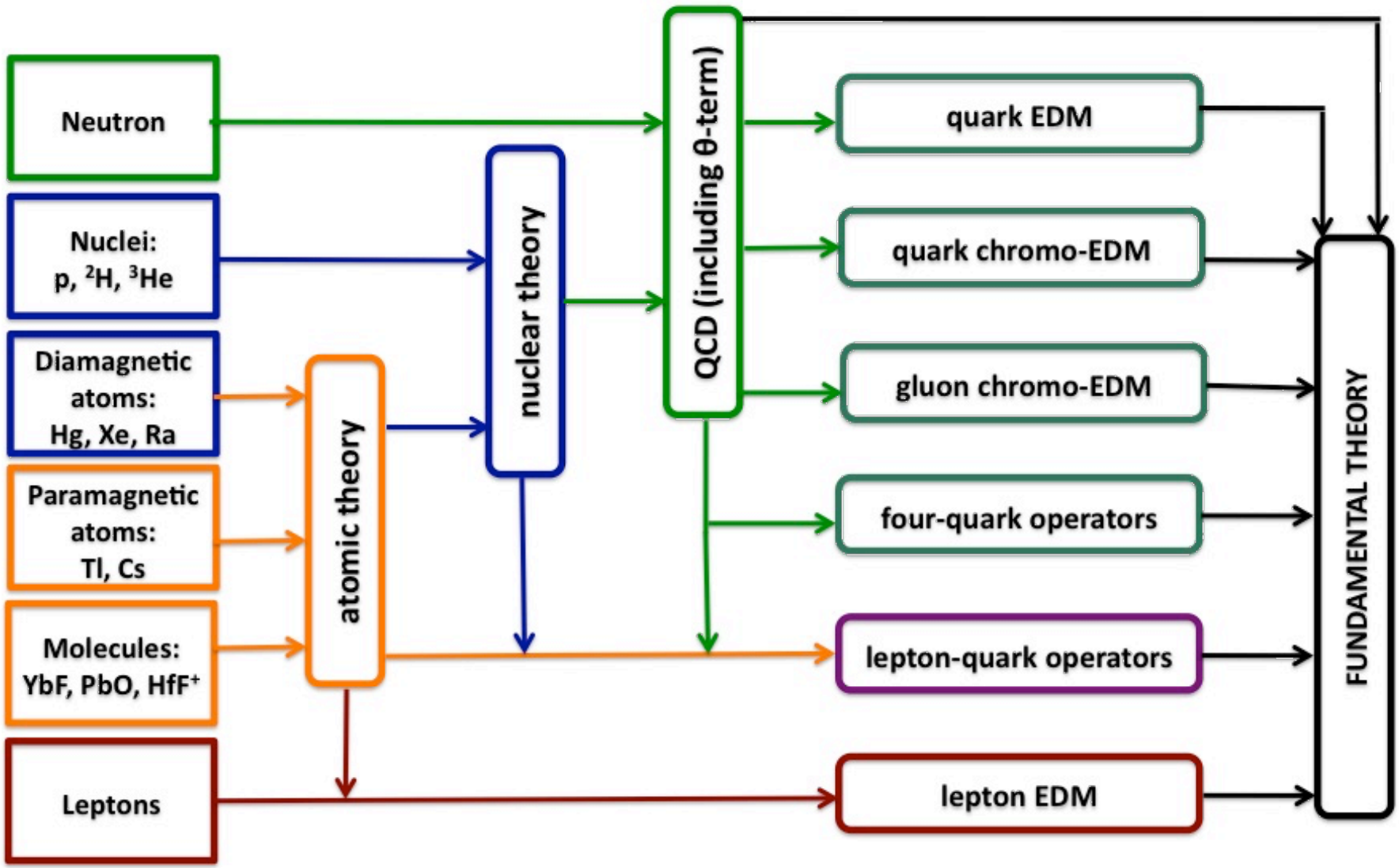
Outline of this talk

- **Part I: The relevant energy scales**

- Part II: Effective field theory framework
  - Dimension-six operators
  - Renormalization-group flow

- Part III: Matching to beyond-the-SM physic: which EFT operators actually appear and from what ?

Various energy scales



Separation of scales

Energy

M_{CP}

? TeV

$M_{EW} \sim v \sim M_{Z,W,H,t}$

100 GeV

$\Lambda_\chi \sim 2\pi F_\pi \sim M_N$

1 GeV

BSM physics

Integrate out heavy degrees of freedom

L_{EFF}

Renormalization-group evolution

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Integrate out heavy SM degrees of freedom

L'_{EFF}

Renormalization-group evolution

Bottom + charm quark

L''_{EFF}

End point of this talk

Separation of scales

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L''_{EFF}

End point of this talk

Here it gets really interesting…..
Main topic of this workshop

Separation of scales

Energy

$\Lambda_\chi \sim 2\pi F_\pi \sim M_N$

1 GeV

L''_{EFF}

Nonperturbative methods: lattice, SD, QCD sum rules

$F_\pi \sim m_\pi$

100 MeV

Hadronic Lagrangian (Chiral EFT)

Hadronic and nuclear EDMs and other CP-odd observables

$\alpha_{\rm em} m_e$

1 keV

Atomic/Molecular observables
Schiff theorem

Main questions now:

1) What **set of CP-odd operators*** should we consider right above the QCD phase transition ?

What is L_{EFF} around 1-2 GeV ?

2) How does this low-energy Lagrangian **connect** to possible BSM physics living at much higher scales?

* In this talk the QCD theta term is not considered. Strong CP problem assumed to be 'solved'.

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 (e.g. hierarchy problem)
- Relations between observables

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

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Effective Field Theory

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

- No relation between low-energy constants
- Many operators

Describing the unknown

Beyond-the-Standard Model (BSM) physics

Basically two methods of describing unknown high-energy physics

Models **Effective Field Theory**

Of course not mutually exclusive !

Models

Match *

EFT operators

Do this once and for all !

Lower energies

A little bit on this later

Main topic now

* Assuming no new light degrees of freedom

Outline of this talk

- Part I: Overview of the relevant energy scales

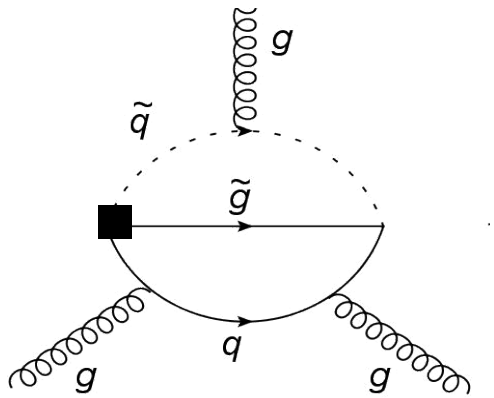
- **Part II: Effective field theory framework**
  - **Dimension-six operators**
  - **Renormalization-group flow**

- Part III: Matching to beyond-the-SM physic: which EFT operators actually appear and from what ?

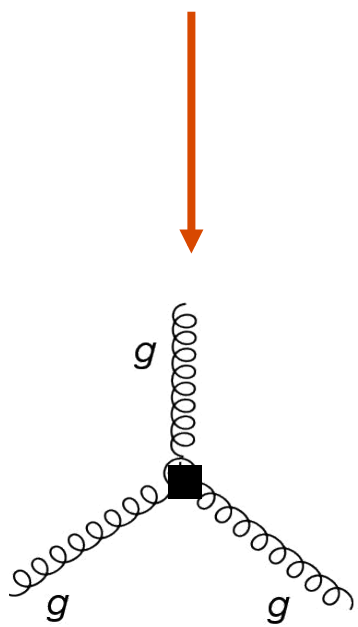
A systematic approach

Pospelov & Ritz, AOP '05

- Assume any BSM physics lives at scales >> M_{EW}



■ = CP-violating vertex



$$\propto \frac{1}{M_{CP}^2}$$

A systematic approach

Buchmuller & Wyler NPB '86
Gradzkowski et al JHEP '10

- Assume any BSM physics lives at scales >> M_{EW}
- Match right below M_{CP} to full set of EFT operators

1) Degrees of freedom: Full SM field content

2) Symmetries: Lorentz, SU(3)xSU(2)xU(1)

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$$L_{new} = \cancel{\frac{1}{M_{CP}} L_5} + \frac{1}{M_{CP}^2} L_6 + \cdots$$

The only dimension-5 operator is not relevant for hadronic EDMs.

How many EFT operators?

- **Full list** of dim-6 operators constructed:

Buchmuller & Wyler NPB '86
Gradzkowski et al JHEP '10

From the abstract of Gradzkowski et al :

"Assuming baryon number conservation, we find 15 + 19 + 25 = 59 independent operators …. "

Not that bad…..

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"Assuming baryon number conservation, we find 15 + 19 + 25 = 59 independent operators …. "

Not that bad….. But…..

*"Assuming baryon number conservation, we find 15 + 19 + 25 = 59 independent operators (**barring flavour structure**)…"*

Including flavour structure makes the list blow up

$$(\bar{u}_i \gamma_\mu u_j)(\bar{d}_k \gamma_\mu d_l) + \text{h.c.} \sim 3^4$$

Terms **with independent constants**

Total: 2499 operators of which 1149 are CP-odd

Alonso et al, JHEP '14

Trimming the list

Dekens & JdV JHEP '13

- We are interested in hadronic CPV

    1) CP-violating operators only…..
    2) No leptons…
    3) Consider light quarks only.
    4) No strange quarks at first.

- 1) and 2) are obvious for this context, but 3) and 4) not so much:

Trimming the list

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- 1) and 2) are obvious for this context, but 3) and 4) not so much:

Models exist where CPV in heavy-quark operators is important

For instance MSSM with large tan β, Demir et al NPB '04

The role of strange quarks in hadronic EDMs is under debate

Fuyuto et al PRD '13
Hisano et al PRD '12
Dall & Ritz, HI '13

Nevertheless: for most models the assumptions are reasonable

Counting the operators

- **Dipole operators: 2 color-EDMs**

$$\tilde{\Gamma}_u \, \bar{q}_L \sigma^{\mu\nu} t^a u_R \, G^a_{\mu\nu} \, \tilde{\varphi} + \tilde{\Gamma}_d \, \bar{q}_L \sigma^{\mu\nu} t^a u_R \, G^a_{\mu\nu} \, \varphi$$

In most models: $\tilde{\Gamma}_q \sim y_q \tilde{d}_q \qquad \tilde{d}_q \sim \frac{1}{M^2_{\rm CP}}$

SM Yukawa coupling

Exceptions exist with $y_t \sim 1$ instead ! e.g. McKeen et al, PRD '13

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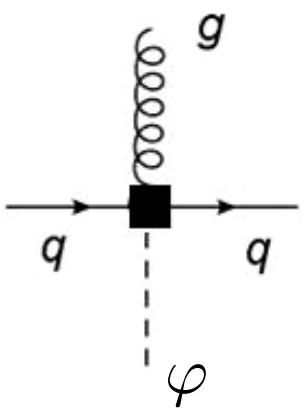
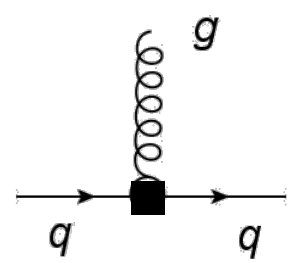
SM Yukawa coupling



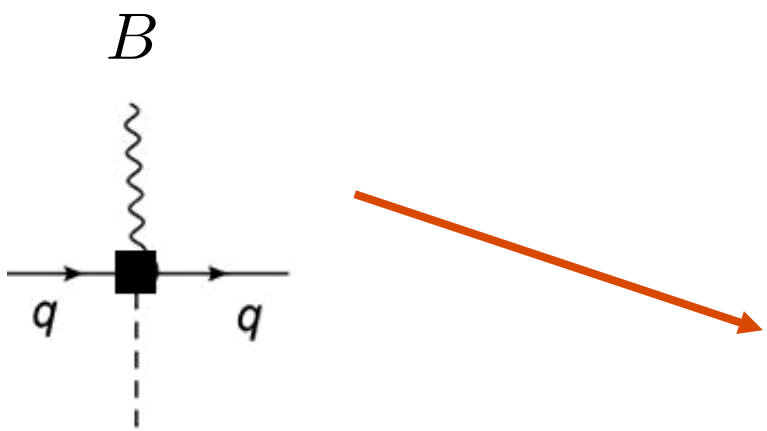
$$\sqrt{2}\varphi = (0 \;\; v + h)^T$$

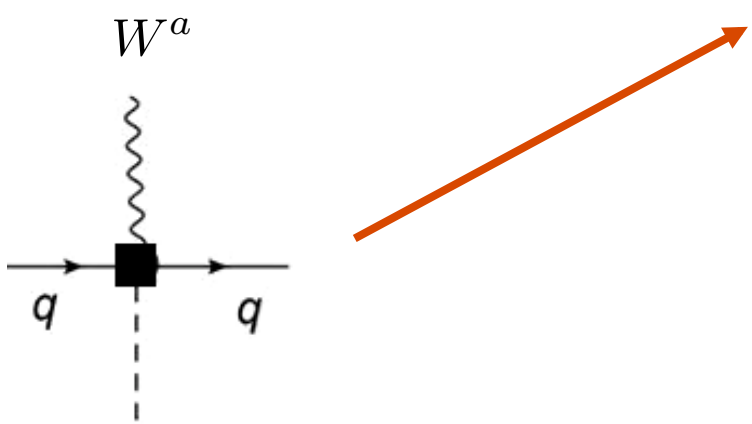


$$\sum_{u,d} m_q \tilde{d}_q \left(\bar{q}\sigma^{\mu\nu}\gamma^5 t^a q\right) G^a_{\mu\nu}$$

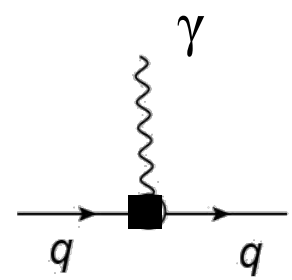
Counting the operators

- Dipole operators: 2 color-EDMs **+ 2 EDMs (+ 2 weak-EDMs)**

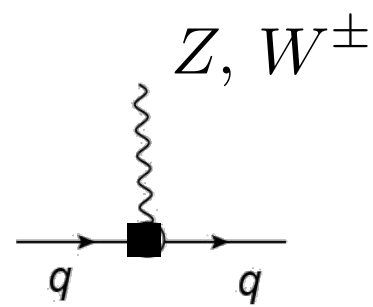




Quark EDM



Quark weak-EDMs



Induce small contributions to quark EDMs at lower energies

Counting the operators

- Dipole operators: 2 color-EDMs + 2 EDMs (+ 2 weak-EDMs)
- Higgs-quark: **2 Yukawa** + 1 LR

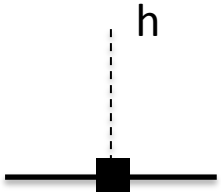
$$\varphi^\dagger\varphi\,(Y^u\,\bar{q}_L\tilde{\varphi}u_R + Y^d\,\bar{q}_L\varphi d_R + \text{h.c.})$$

typically $Y_q \sim \frac{y_q}{M_{CP}^2}$

e.g. in most 2HDM and LR models

Mass terms absorb in SM parameters, remainder:

$$\sum_{u,d}(v^2\text{Im}Y^q)(\bar{q}i\gamma^5 q)h$$

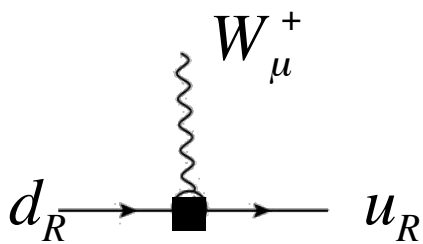


CP-odd quark-higgs coupling

Counting the operators

- Dipole operators: 2 color-EDMs + 2 EDMs (+ 2 weak-EDMs)
- Higgs-quark: 2 Yukawa **+ 1 LR**

$$\Xi\, \bar{u}_R \gamma^\mu d_R \, (\tilde{\varphi}^\dagger i D_\mu \varphi) + \text{h.c.} \longrightarrow \Xi v^2 g \, (\bar{u}_R \gamma^\mu d_R \, W_\mu^\pm + \text{h.c.})$$



A **right-handed** coupling to the W boson

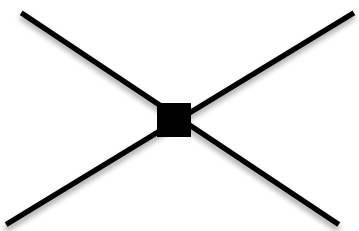
Ng & Tulin PRD '12
JdV et al '12

Counting the operators

Ramsey-Musolf & Su Phys. Rep. '08

- Dipole operators: 2 color-EDMs + 2 EDMs (+ 2 weak-EDMs)
- Higgs-quark: 2 Yukawa + 1 LR
- **Four-quark operators: 2**

Only **two** gauge-invariant **four-quark** interactions
(u, d quarks only)



$$\Sigma_1 \left(\bar{u}_L u_R \, \bar{d}_R d_L - \bar{d}_L u_R \, \bar{u}_R d_L \right) + h.c.$$

$$\Sigma_8 \left(\bar{u}_L \lambda^a u_R \, \bar{d}_R \lambda^a d_L - \bar{d}_L \lambda^a u_R \, \bar{u}_R \lambda^a d_L \right) + h.c.$$

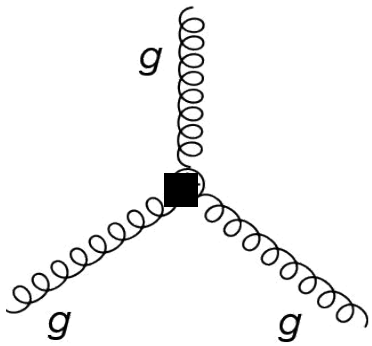
Don't insist on SU(2) gauge symmetry -> 10 four-quark operators!

Hisano et al. PLB '12

Counting the operators

- Dipole operators: 2 color-EDMs + 2 EDMs (+ 2 weak-EDMs)
- Higgs-quark: 2 Yukawa + 1 LR
- Four-quark operators: 2
- **Pure gauge: 1 (+ 1)**

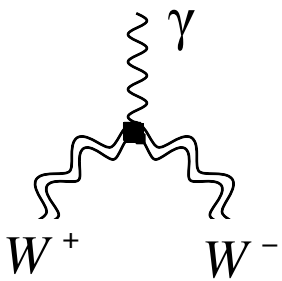
$$d_W f^{abc} G^a G^b \tilde{G}^c$$



Weinberg operator / gluon chromo-EDM

Weinberg PRL '89
Braaten et al PRD '90

$$d_{\text{weak}} \epsilon^{ijk} W^i W^j \tilde{W}^k$$



Induces lepton and quark EDMs at lower energy

Rujula et al NPB '91
Dekens et al JHEP '13

Counting the operators

- Dipole operators: 2 color-EDMs + 2 EDMs (+ 2 weak-EDMs)
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- Pure gauge: 1 (+ 1)
- **Gauge-Higgs 1 (+ 3)**

Rujula et al NPB '91
McKeen et al, PRD '12
Fan & Reece, JHEP '13
Dekens & JdV JHEP '13

$$(\theta' G^a \tilde{G}^a + \theta'_W W^i \tilde{W}^i + \theta'_B B \tilde{B})\varphi^\dagger \varphi + \theta_{WB} W^i \tilde{B} \left(\varphi^\dagger \tau^i \varphi\right)$$

Higgs-less terms absorb in SM theta terms (not discussed here), remainder:

- CP-odd gluon-gluon-Higgs coupling
- CP-odd gamma-gamma-Higgs, gamma-Z-Higgs, W-W-gamma

Counting the operators

- Dipole operators: 2 color-EDMs + 2 EDMs (+ 2 weak-EDMs)
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- Total: 11 (+6) operators with **independent** coupling constants
  (+ operators with strangeness or heavier flavours)

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How do these operators manifest at energies ~ 1 GeV ?

EFT operators (M_{CP})

Renormalization group equations

EFT operators (1 GeV)

The quark EDM: RGE 101

The easiest example is a quark EDM

$$\mathcal{L} = \sum_{u,d} C_q \, m_q \bar{q} \sigma^{\mu\nu} \gamma^5 q \, e F_{\mu\nu}$$

Anomalous dimension: $$\frac{\mathrm{d}C_q}{d \ln \mu} = \Gamma_q C_q$$

$$\Gamma_q = \left(\frac{\alpha_s}{4\pi}\right) \gamma_q^{(0)} + \left(\frac{\alpha_s}{4\pi}\right)^2 \gamma_q^{(1)} + \ldots$$

Leading order solution: $$C_q(m) = \left(\frac{\alpha_s(M_{CP})}{\alpha_s(m)}\right)^{\gamma_q/2\beta_0} C_q(M_{CP})$$

QCD beta function $\beta_0 = (11 - 2n_f)/3$

Changes after a quark threshold

$$n_f \to n_f - 1$$

The quark EDM: RGE 101

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Callan-Symanzik equation:

Operator with n_Ψ quark fields, n_G gluon fields

$$\gamma = \frac{\partial}{\partial \ln \mu} \left(\frac{n_\psi}{2} \delta_\psi + \frac{n_G}{2} \delta_G - \delta_{CT} \right) - \gamma_m$$

Quark field-strength renormalization

Gluon field-strength renormalization

The quark EDM: RGE 101

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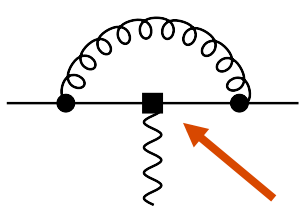
Quark field-strength renormalization

Gluon field-strength renormalization

All textbooks quantities except the counter term. Here we just need to calculate:

δ_{CT} ~ 

= no scale dependence

$$\frac{\partial}{\partial \ln \mu} (\delta_{CT}) = 0$$

qEDM operator

The quark EDM: RGE 101

Degrassi et al JHEP '05

$$\gamma_q = \frac{\partial}{\partial \ln \mu}(\delta_\Psi) - \gamma_m = (2+6)C_2(N) = \frac{32}{3} \qquad C_2(N) = \frac{N^2-1}{2N}$$

quark mass dependence dominates

Since anomalous dimension > 0, the qEDM gets suppressed:

For instance: $C_q(1\,\mathrm{GeV}) = 0.39\, C_q(1\,\mathrm{TeV})$

Modest suppression. Original paper Arnowitt et al, '90 has a sign mistake leading to an 1/0.39 ~ 2.6 enhancement!

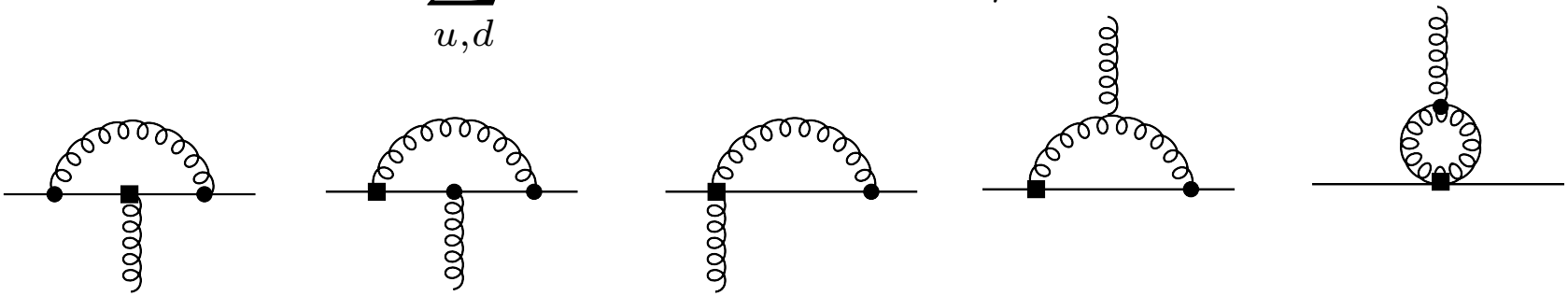
This is still quite often erroneously used.

The quark CEDM: RGE 102

Braaten et al PRL '90

Need to find the anomalous dimension of

$$\sum_{u,d} \tilde{C}_q \, m_q (\bar{q}\sigma^{\mu\nu}\gamma^5 t^a q) \, G^a_{\mu\nu}$$



$$\gamma_{\tilde{q}} = 16C_2 - 4N - \beta_0 = \frac{2n_f - 5}{3}$$

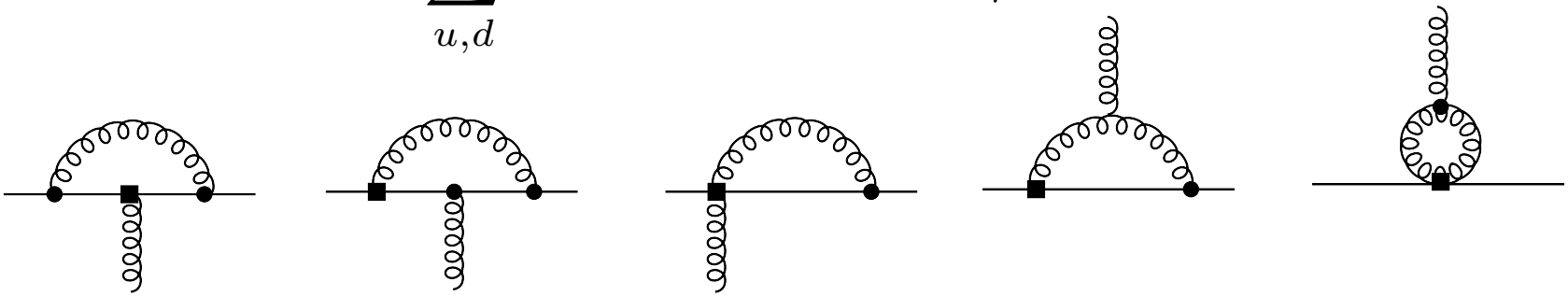
So > 0, for three or more quarks

The quark CEDM: RGE 102

Need to find the anomalous dimension of

Braaten et al PRL '90

$$\sum_{u,d} \tilde{C}_q \, m_q (\bar{q}\sigma^{\mu\nu}\gamma^5 t^a q) \, G^a_{\mu\nu}$$



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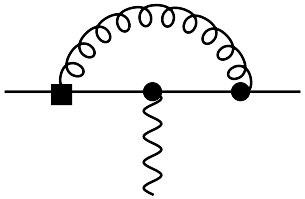
Degrassi et al JHEP '05

Plus mixing to quark EDM !



$$\gamma_{q\tilde{q}} = \frac{8C_2}{g_s}\frac{1}{Q_q}$$

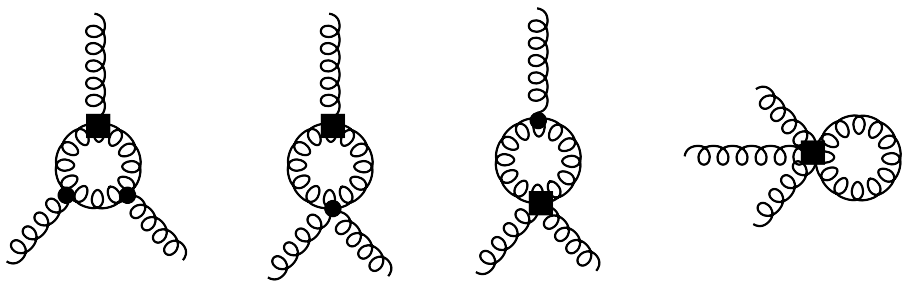
quark charge

The Weinberg operator

Braaten et al PRL '90
Rujula et al NPB '91

$$\frac{C_W}{6} f^{abc} \tilde{G}^a_{\mu\nu} G^{\mu,b}_{\rho} G^{\nu\rho,c}$$

Tedious calculation:

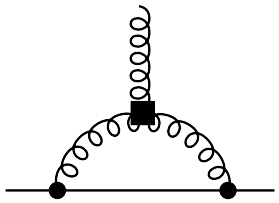


$$\gamma_W = N + 2n_f$$

So > 0 !

Sign mistake in original papers!

Mixing to quark CEDM



$$\gamma_{\tilde{q}W} = -2N$$

Dipoles combined

Numerical solution of the three dipole operators (same for strange quarks)

$\mathcal{O}(\alpha_s^2)$

$$C_q(1\,\mathrm{GeV}) = 0.39\,C_q(1\,\mathrm{TeV}) + 0.37\,\tilde{C}_q(1\,\mathrm{TeV}) - 0.072\,C_W(1\,\mathrm{TeV})$$

$$\tilde{C}_q(1\,\mathrm{GeV}) = \qquad + 0.88\,\tilde{C}_q(1\,\mathrm{TeV}) - 0.29\,C_W(1\,\mathrm{TeV})$$

$$C_W(1\,\mathrm{GeV}) = \qquad + 0.33\,C_W(1\,\mathrm{TeV})$$

1) **Diagonal terms are all suppressed**

2) Suppressions are moderate

3) Mixing is important, e.g. if qCEDM at low energy then also qEDM (unless cancellations….)

* 2-loop running in Degrassi et al, JHEP ’05 , O(10%) corrections to LO running

Weinberg enhancement ?

The Weinberg operator gets suppressed

$$C_W(1\ \mathrm{GeV}) = 0.33\, C_W(1\ \mathrm{TeV})$$

Arnowitt et al, PRD '90 , instead report **an enhancement** ~ 3.30.

Weinberg enhancement ?

The Weinberg operator gets suppressed

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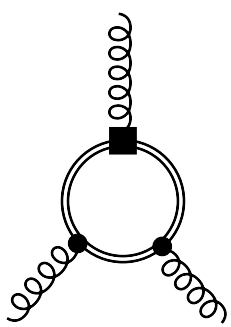
Consequence of their SUSY model:

- $C_W(M_{CP})$ generated at two-loop level
- Heavy-quark CEDMs at the one-loop level.
- Both are proportional to the same CP-odd phase: **Model dependent!**
- Large threshold contributions to C_W(mb, mc)



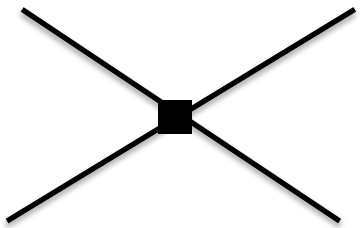
$$C_W(m_b) = -\frac{\alpha_s(m_b)}{8\pi}\frac{\tilde{C}_b(m_b)}{m_b}$$

Kamenik et al PRD '13
Sala, JHEP '14

Four-quark operators

Those were the 'standard' dipole operators

The other structures that appear at low energy are four-quark operators



Sometimes claimed they are not important

Argument: $C_{FQ}(\bar{u}u)(\bar{d}i\gamma^5 d)$

2 Chirality flips

Effectively dimension 8: $C_{FQ} \sim \frac{y_u y_d}{M_{CP}^2} = \frac{m_u m_d}{v^2 M_{CP}^2}$

However, there are exceptions !

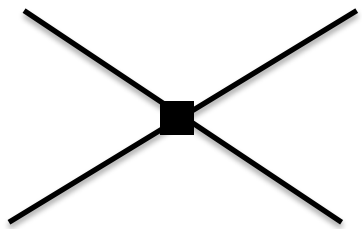
Four-quark operators

Ramsey-Musolf & Su Phys. Rep. '08

There are **two gauge- and chiral-invariant four-quark** interactions

Energy

M_{CP}



$$\Sigma_1 \left(\bar{u}_L u_R \; \bar{d}_R d_L - \bar{d}_L u_R \; \bar{u}_R d_L \right) + h.c.$$

$$\Sigma_8 \left(\bar{u}_L \lambda^a u_R \; \bar{d}_R \lambda^a d_L - \bar{d}_L \lambda^a u_R \; \bar{u}_R \lambda^a d_L \right) + h.c.$$

Λ_χ

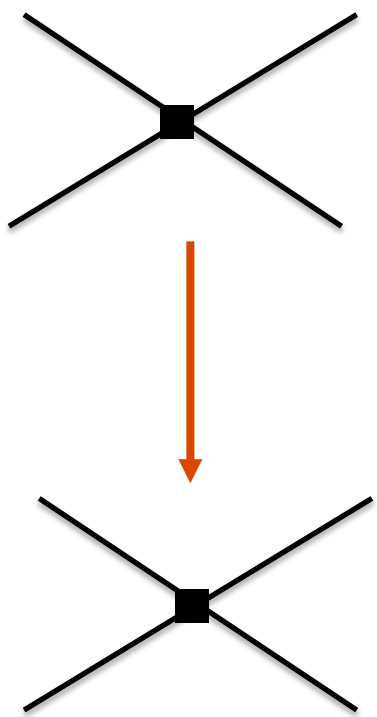
Four-quark operators

Ramsey-Musolf & Su Phys. Rep. '08

There are **two gauge- and chiral-invariant four-quark** interactions

Energy

M_{CP}



Λ_χ

$$\Sigma_1 \left(\bar{u}_L u_R \; \bar{d}_R d_L - \bar{d}_L u_R \; \bar{u}_R d_L\right) + h.c.$$

$$\Sigma_8 \left(\bar{u}_L \lambda^a u_R \; \bar{d}_R \lambda^a d_L - \bar{d}_L \lambda^a u_R \; \bar{u}_R \lambda^a d_L\right) + h.c.$$

Quite strong QCD enhancement
(*closed under RGE*):

Dekens & JdV, JHEP '13

$$\Sigma_1(1\,\mathrm{GeV}) = \; 7.2\,\Sigma_1(1\,\mathrm{TeV}) + 0.66\,\Sigma_8(1\,\mathrm{TeV})$$

$$\Sigma_8(1\,\mathrm{GeV}) = -3.7\,\Sigma_1(1\,\mathrm{TeV}) + 0.69\,\Sigma_8(1\,\mathrm{TeV})$$

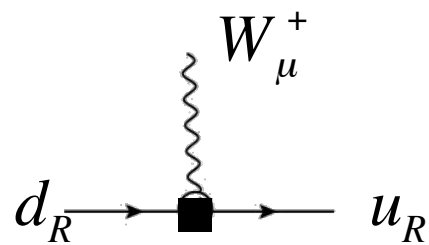
The color-singlet operator
dominates at low energies

Induced four-quark operators

Energy

M_{CP}

$$\Xi\, \bar{u}_R \gamma^\mu d_R \left(\tilde{\varphi}^\dagger i D_\mu \varphi\right) + \text{h.c.} \longrightarrow \Xi v^2 g \left(\bar{u}_R \gamma^\mu d_R W_\mu^\pm + \text{h.c.}\right)$$

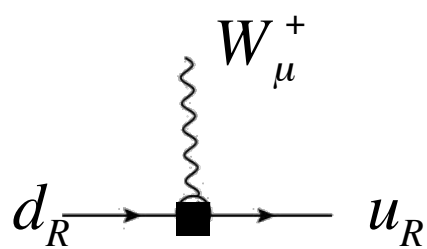


A **right-handed** coupling to the W boson

Trivial : $\gamma_{WR} = 0$

$$\Xi(M_W) = \Xi(M_{CP})$$

M_W



Induced four-quark operators

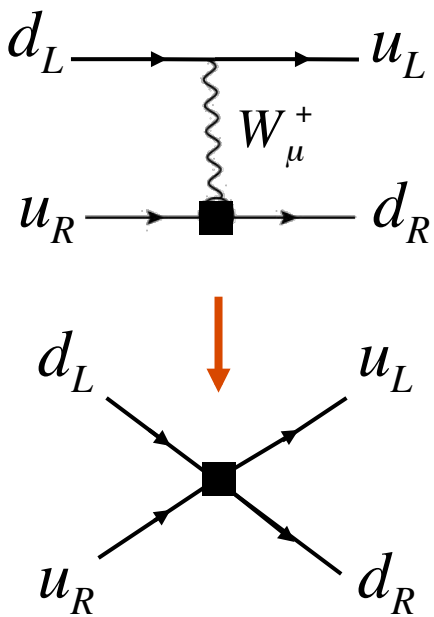
Ng & Tulin PRD '12
JdV et al AOP '12

Energy

M_W

$< M_W$

Λ_χ



$$\Xi v^2 g \left(\bar{u}_R \gamma^\mu d_R W_\mu^\pm + \text{h.c.}\right)$$

Integrate out W boson

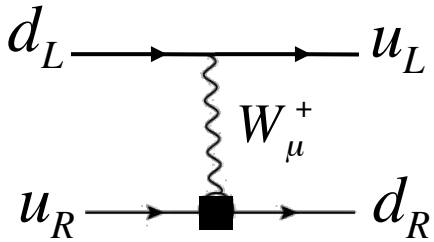
$$L = i\Xi(\bar{u}_R \gamma_\mu d_R)(\bar{u}_L \gamma_\mu d_L) + \text{h.c.}$$

Induced four-quark operators

Ng & Tulin PRD '12
JdV et al AOP '12

Energy

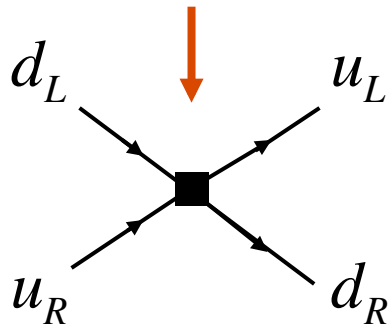
M_W



$$\Xi v^2 g\,(\bar{u}_R \gamma^\mu d_R\, W^\pm_\mu + \text{h.c.})$$

Integrate out W boson

$< M_W$



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

RGE

New structure!

Λ_χ

$$L = i\Xi\,[1.1(\bar{u}_R\gamma_\mu d_R)(\bar{u}_L\gamma_\mu d_L) + 1.4(\bar{u}_R\gamma_\mu t^a d_R)(\bar{u}_L\gamma_\mu t^a d_L)] + \text{h.c.}$$

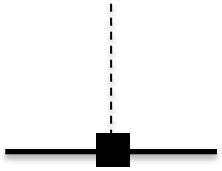
So two additional four-quarks terms (FQLR operators) at low energies (one independent coupling)

Suppressed four-quark operators

Energy

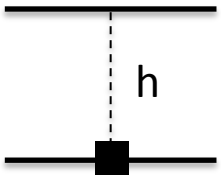
M_{CP}

$$\sum_{u,d}(v^2 Y^q)(\bar{q}i\gamma^5 q)h$$



CP-odd quark-higgs coupling

M_{EW}



Induces additional FQ structures

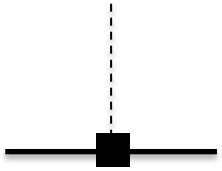
Λ_χ

Suppressed four-quark operators

Energy

M_{CP}

$$\sum_{u,d}(v^2 Y^q)(\bar{q}i\gamma^5 q)h$$



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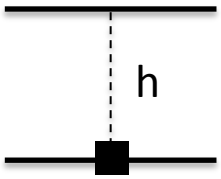

Induces additional FQ structures

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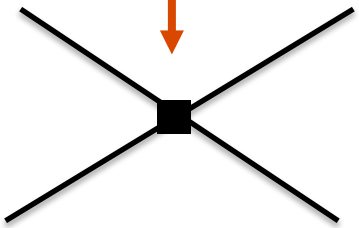


Λ_χ

Hisano et al. PLB '12

Dekens & JdV. JHEP '13

Induces 6 new FQ structures. Not nice….

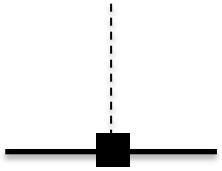
$$C_{FQ} \sim \frac{v^2 Y_q y_q}{m_H^2} \sim y_q Y_q \qquad y_q \sim 10^{-4}$$

Suppressed four-quark operators

Energy

M_{CP}

$$\sum_{u,d}(v^2 Y^q)(\bar{q}i\gamma^5 q)h$$



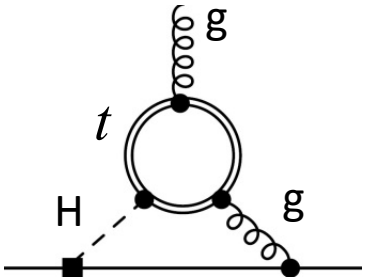
CP-odd quark-higgs coupling

Fortunately !

Barr & Zee PRL '90

Chang et al, PRD '92

M_{EW}



Much more efficient:

$$\tilde{C}_q(m_t) \sim -\frac{\alpha_s(m_t)}{32\pi^3}\frac{v}{m_q}Y^q \sim Y^q$$

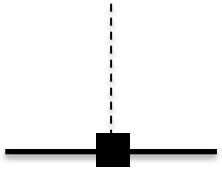
Λ_χ

Suppressed four-quark operators

Energy

M_{CP}

$$\sum_{u,d}(v^2 Y^q)(\bar{q}i\gamma^5 q)h$$



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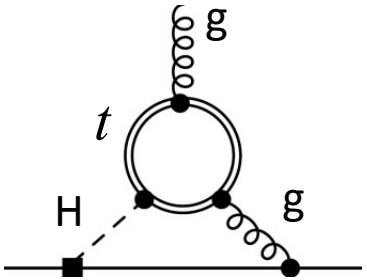


Much more efficient:

$$\tilde{C}_q(m_t) \sim -\frac{\alpha_s(m_t)}{32\pi^3}\frac{v}{m_q}Y^q \sim Y^q$$

At low energies induces hadronic EDMs
2-3 orders larger than FQ terms

Λ_χ

Conclusion: the 6 additional FQ operators can be neglected !

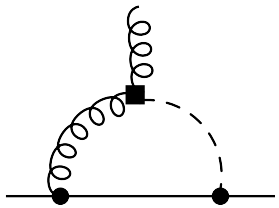
Heavy-quark Yukawa's treated similarly

Finally gauge-Higgs

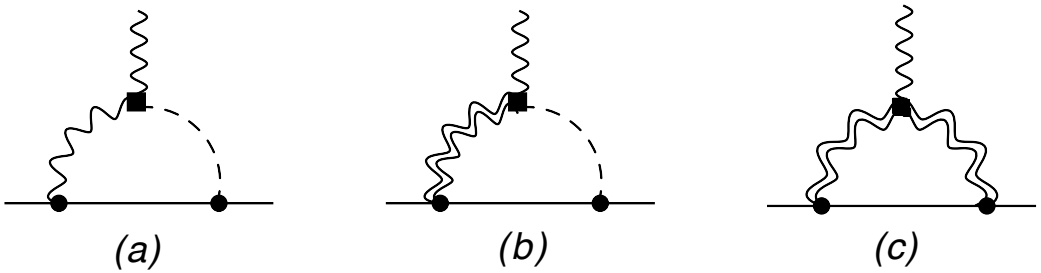
Briefly :

$$(\theta' G^a \tilde{G}^a + \theta'_W W^i \tilde{W}^i + \theta'_B B \tilde{B})\varphi^\dagger \varphi + \theta_{WB} W^i \tilde{B} \left(\varphi^\dagger \tau^i \varphi\right)$$

Dekens, JdV JHEP '13
Grojean, Jenkins JHEP '13



θ' Induces a quark chromo-EDM



Induce fermion EDMs

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Dekens, JdV JHEP '13
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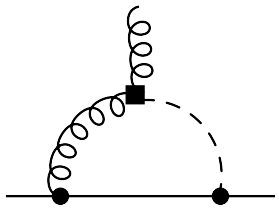

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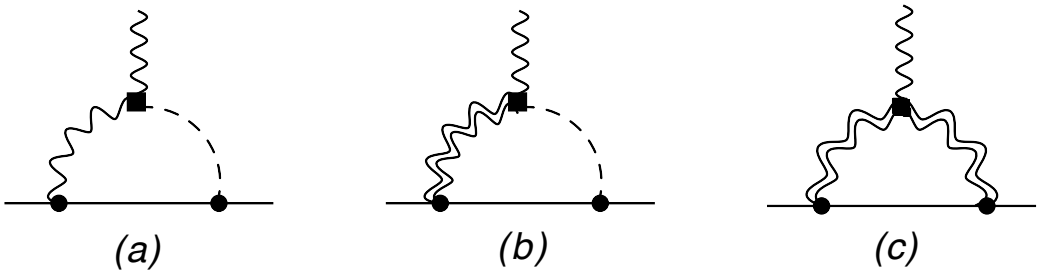

Induce fermion EDMs

Linear combination of $\theta'_W,\ \theta'_B,\ \theta'_{WB}$ modifies the $h \to \gamma\gamma$ rate

However, eEDM bound strongly limits these operators.
nEDM (via quark EDM) less strong limit.

Demir, Pospelov,Ritz PRD '12
Fan & Reece JHEP '13

After the dust settles…

1) What **set of CP-odd operators** should we consider right above the QCD phase transition ?

What is L_{EFF} around 1-2 GeV ?

After the dust settles…

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What is L_{EFF} around 1-2 GeV ?

L_{EFF} consists of:

- Quark EDM up, down, (strange)
- Quark chromo-EDM up, down, (strange)
- Weinberg operator
- 2 chiral invariant four-quark operators
- One combination of a 'left-right' four-quark operator

Form very constrained

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Form very constrained

The operators have **different chiral symmetry** properties.

JdV et al, AOP '12
Bsaisou et al, '14

Induce different hadronic Lagrangians and different EDM hierarchy.

See Emanuele Mereghetti's talk

Bounds and scales

Use the neutron* EDM bound (**big uncertainty for some operators: that's why we are here !**)

Dekens, JdV JHEP '13

Dimensionless couplings

	$M_{\mathcal{T}} = 1\,\mathrm{TeV}$	$M_{\mathcal{T}} = 10\,\mathrm{TeV}$
$(M_{\mathcal{T}}^2) d_{u,d}\,(M_{\mathcal{T}})$	$\leq \{1.8,\ 1.8\} \cdot 10^{-3}$	$\leq \{2.1,\ 2.1\} \cdot 10^{-1}$
$(M_{\mathcal{T}}^2) \tilde{d}_{u,d}\,(M_{\mathcal{T}})$	$\leq \{1.9,\ 0.91\} \cdot 10^{-3}$	$\leq \{1.7,\ 0.94\} \cdot 10^{-1}$
$(M_{\mathcal{T}}^2) d_W\,(M_{\mathcal{T}})$	$\leq 5.6 \cdot 10^{-5}$	$\leq 7.0 \cdot 10^{-3}$
$(M_{\mathcal{T}}^2) \mathrm{Im}\,\Sigma_1\,(M_{\mathcal{T}})$	$\leq 3.2 \cdot 10^{-5}$	$\leq 2.3 \cdot 10^{-3}$
$(M_{\mathcal{T}}^2) \mathrm{Im}\,\Sigma_8\,(M_{\mathcal{T}})$	$\leq 3.3 \cdot 10^{-4}$	$\leq 2.4 \cdot 10^{-2}$
$(M_{\mathcal{T}}^2) \mathrm{Im}\,\Xi_1\,(M_{\mathcal{T}})$	$\leq 1.7 \cdot 10^{-4}$	$\leq 1.7 \cdot 10^{-2}$
$(M_{\mathcal{T}}^2) \mathrm{Im}\,Y'^{u,d}\,(M_{\mathcal{T}})$	$\leq \{8.9,\ 8.9\} \cdot 10^{-5}$	$\leq \{7.9,\ 7.9\} \cdot 10^{-3}$
$(M_{\mathcal{T}}^2) \theta'\,(M_{\mathcal{T}})$	$\leq 2.4 \cdot 10^{-3}$	$\leq 1.5 \cdot 10^{-1}$

* Hg EDM bound gives stronger limits for some operators (e.g. quark CEDM) but also suffers from larger theoretical uncertainty

Engel et al, PNPP '13

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Dekens, JdV JHEP '13

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$(M_{\mathcal{T}}^2) \theta'\,(M_{\mathcal{T}})$	$\leq 2.4 \cdot 10^{-3}$	$\leq 1.5 \cdot 10^{-1}$

So 1 TeV seems 'unnatural' but note loop factors. For instance:

$$M_{CP}^2 \tilde{d}_q \sim \frac{\alpha_s}{4\pi} \sin\phi_{CP} \sim 10^{-2} \sin\phi_{CP} \longrightarrow \sin\phi_{CP} \leq 10^{-1}$$

The interpretation is model dependent

Bounds and scales

Use the neutron EDM bound (**big uncertainty for some operators: that's why we are here !**)

Dekens, JdV JHEP '13

'electroweak suppressed operators'

Dimensionless couplings

	$M_{\not{T}} = 1\,\text{TeV}$	$M_{\not{T}} = 10\,\text{TeV}$
$(M_{\not{T}}^2)C_B\,(M_{\not{T}})$	$\leq 8.1 \cdot 10^{-2}$	≤ 4.6
$(M_{\not{T}}^2)C_W\,(M_{\not{T}})$	$\leq 1.9 \cdot 10^{-2}$	≤ 1.1
$(M_{\not{T}}^2)C_{WB}\,(M_{\not{T}})$	$\leq 1.3 \cdot 10^{-2}$	≤ 0.74
$(M_{\not{T}}^2)C_{dW}\,(M_{\not{T}})$	≤ 0.11	≤ 11
$(M_{\not{T}}^2)C_{Wu,d}\,(M_{\not{T}})$	$\leq \{1.0,\, 0.84\} \cdot 10^{-2}$	$\leq \{0.53,\, 0.45\}$
$(M_{\not{T}}^2)C_{Zu,d}\,(M_{\not{T}})$	$\leq \{5.3,\, 2.8\} \cdot 10^{-2}$	$\leq \{2.7,\, 1.4\}$

First 4 operators better bound by eEDM

Outline of this talk

- Part I: Overview of the relevant energy scales

- Part II: Effective field theory framework
  - Dimension-six operators
  - Renormalization-group flow

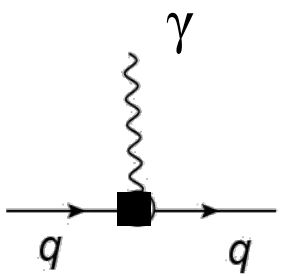
- **Part III: Matching to beyond-the-SM physics: which EFT operators actually appear and from what?**

What dim-6 operators appear most often?

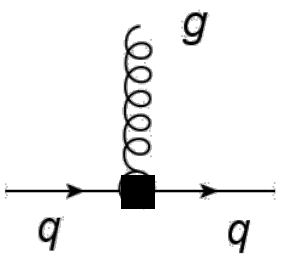
Or: which hadronic matrix elements are probably more relevant ?

Most likely the ‘standard’ three operators (modulo theta term):

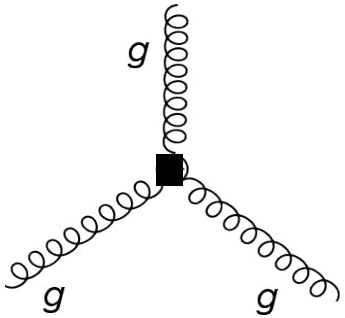
These (or a subset) dominate at low energies in most BSM models.



Quark EDM



Quark chromo-EDM



Weinberg operator

The dipole hierarchy

What about their hierarchy ?

Seems unanswerable. Very model and parameter dependent !

Some viable MSSM variants that soften the 'SUSY CP problem'

Pospelov-Ritz AOP '05
Abel & Lebedev, JHEP '06

The dipole hierarchy

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Some viable MSSM variants that soften the 'SUSY CP problem'

Pospelov-Ritz AOP '05
Abel & Lebedev, JHEP '06

1) Heavy SUSY spectrum with scale > 1 TeV and tan beta >= 5

qCEDM dominates due to one-loop diagrams.
*Thus **qEDM + qCEDM** at low energies*

McKeen et al, PRD '13

Kizikuri & Oshimo PRD '92

2) Heavy first two generation sfermions >10 TeV

One-loop suppressed: mainly *Weinberg operator induced at 2loop.*
*Thus mostly **Weinberg + qCEDM** at low energies.*

3) 'Split SUSY': Also third generation heavy

Arkani-Hamed et al, NPB '05
Giudice & Romanino, PLB '06

*Now gaugino BZ loops induce a qEDM. So only **qEDM** at low energies*

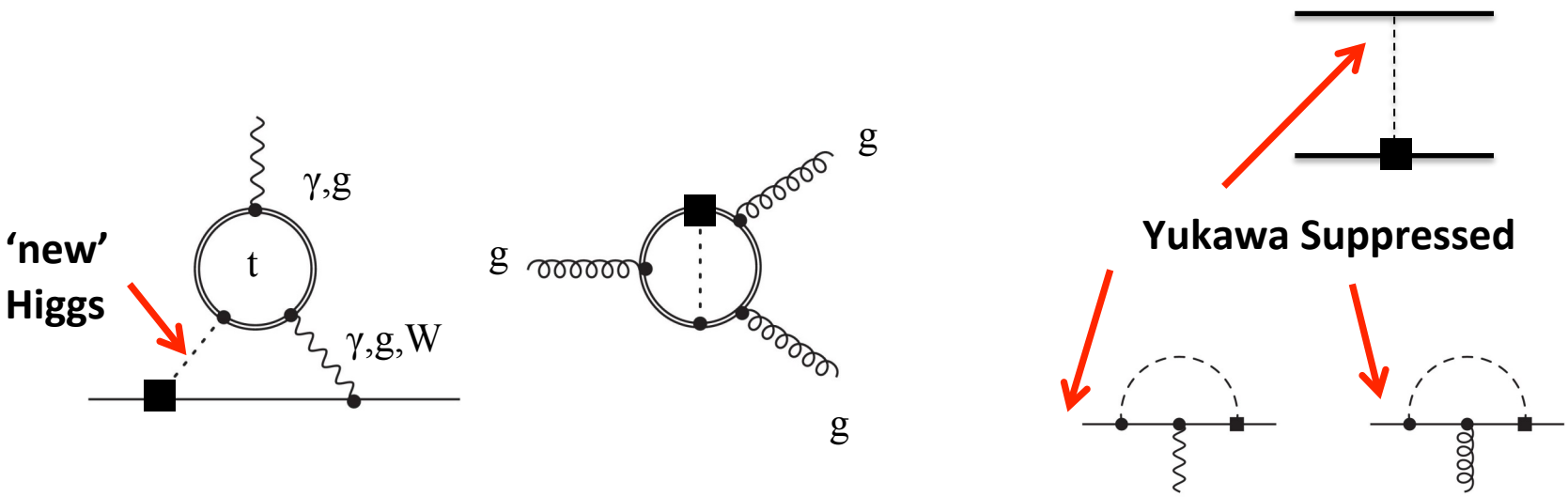
The dipole hierarchy

Pich & Jung JHEP '13
Dekens et al JHEP '14
Inoue et al PRD '14
Cheung et al JHEP '14

Similar in 2-Higgs-Doublet Models, some very recent work:

Additional Higgs fields with **CP-violation** in potential and/or Yukawa couplings.

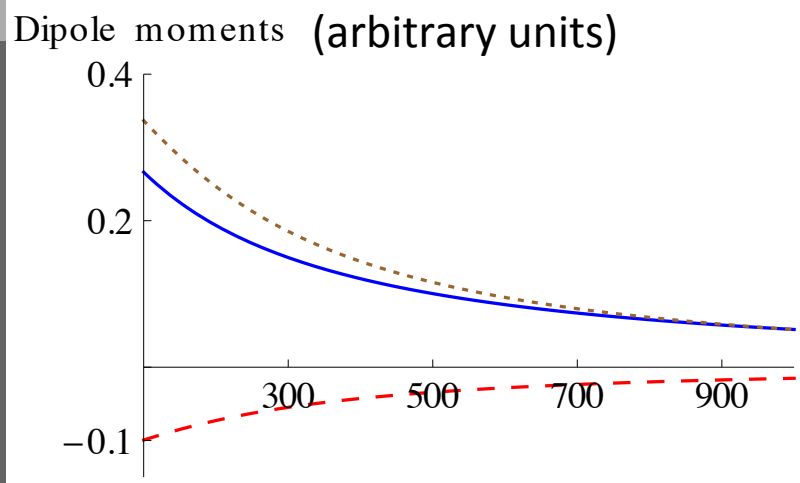
Quark (C)EDMs and Weinberg induced via Barr-Zee diagrams

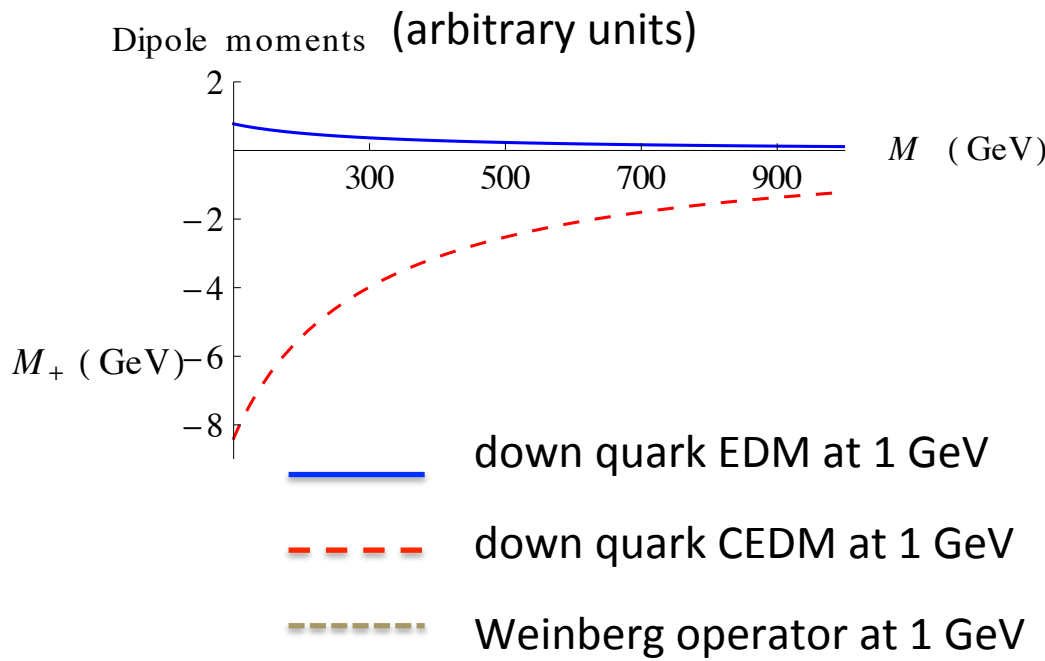


The dipole hierarchy

Here a **very specific** version of the 'aligned 2HDM'

Pich & Jung JHEP '13





Hierarchy of dipole operators depends on model details

Plots from Dekens et al JHEP '14

Four-quark operators

Senjanovic & Mohapatra PRD'75
Mohapatra et al NPB '08

What about the other operators ?

The 'left-right' four-quark operators appear in **left-right symmetric** models

E.g: ***the minimal left-right symmetric model***

- Based on unbroken Parity symmetry at high energies
- Gauge group: $SU_R(2) \times SU_L(2) \times SU_c(3) \times U(1)$ + additional Higgs fields
- Additional **heavy** right-handed gauge bosons W_R^{+-} and Z_R

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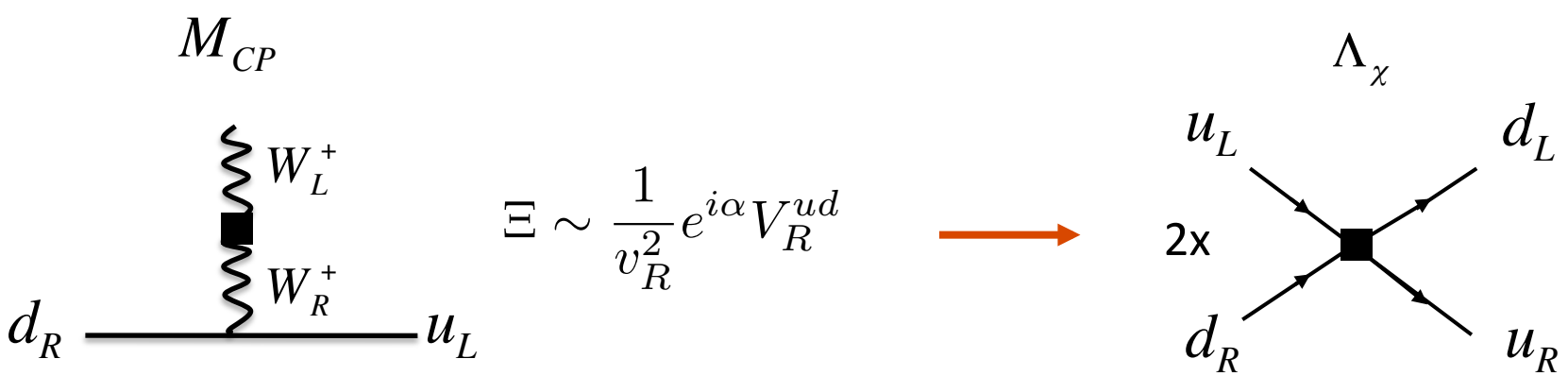


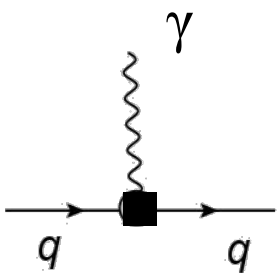
Quark (C)EDMs only appear at loop level and are **suppressed**

An et al, JHEP '10

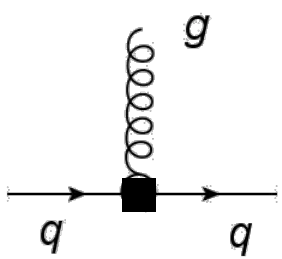
Just a taste…

By **no means** exhaustive analysis….. Clear that EDMs probe large classes of models

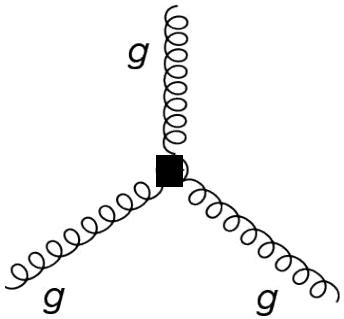
For hadronic EDM purposes: BSM physics is described by a relatively small set of operators around 1 GeV



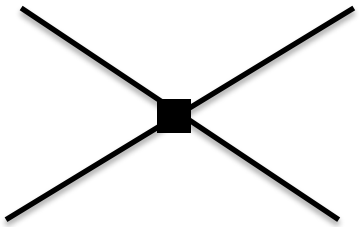
Quark EDM



Quark chromo-EDM



Weinberg operator



`Left-right' + 2 chiral-invariant FQ terms

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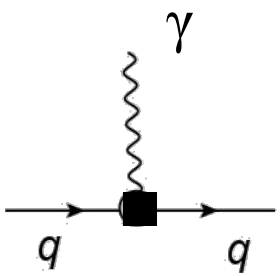
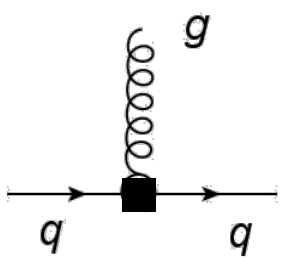


Quark EDM



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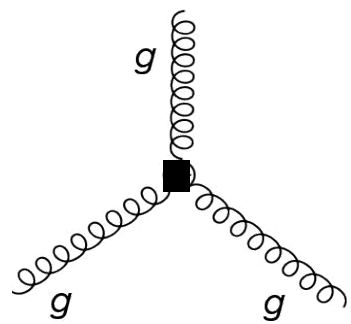

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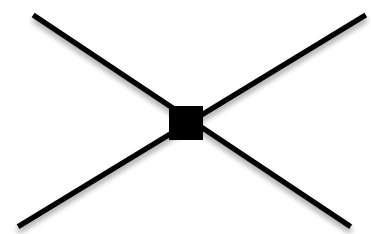
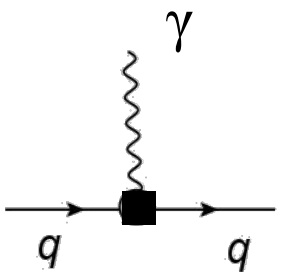


`Left-right' + 2 chiral-invariant FQ terms

- Connection established to **general operator set** at high energies
- This general set can be matched to specific beyond-the-SM models
- Strong bounds from EDM experiments

Bridging the gap



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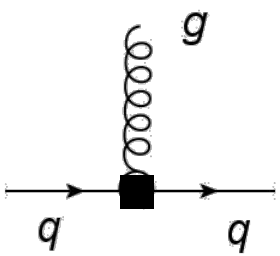

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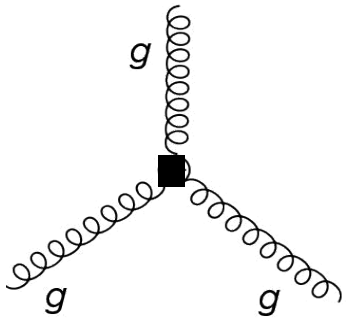
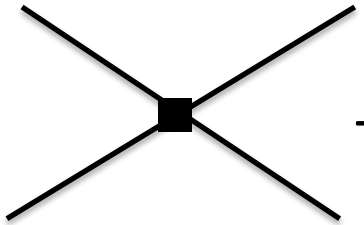


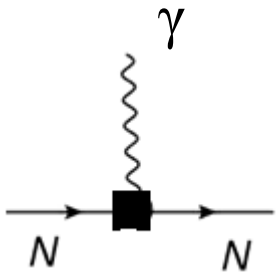
Weinberg operator



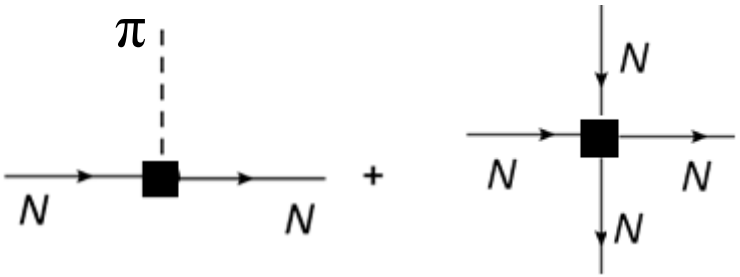
+ theta term

`Left-right' + 2 chiral-invariant FQ terms

Challenge of this workshop



Nucleon EDMs



CP-odd nuclear forces