Intersections of BSM phenomenology and QCD for New Physics Searches
INT, Oct 1 2015

EFTs for new physics
(non-standard CPV Higgs couplings)

Vincenzo Cirigliano
Los Alamos National Laboratory

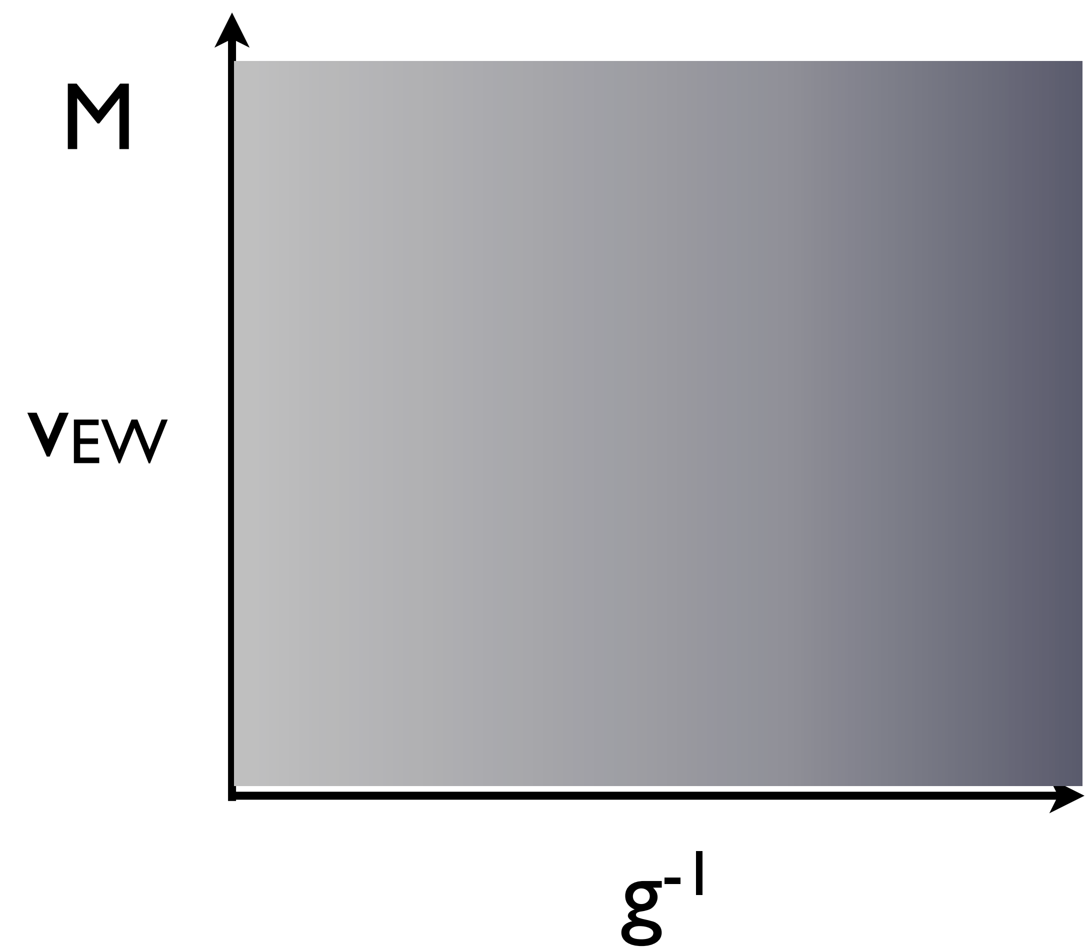
Outline

- EFTs for new physics
  - General considerations
- Worked example: non-standard CPV Higgs couplings
  - Framework: RGE, matrix elements
  - Direct (LHC) and indirect (EDMs) constraints
- Conclusions

EFTs for new physics

The quest for "new physics"

- The SM is remarkably successful, but can't be the whole story
  $\Rightarrow$ new degrees of freedom (Light & weakly coupled? Heavy? Both?)



The quest for “new physics”

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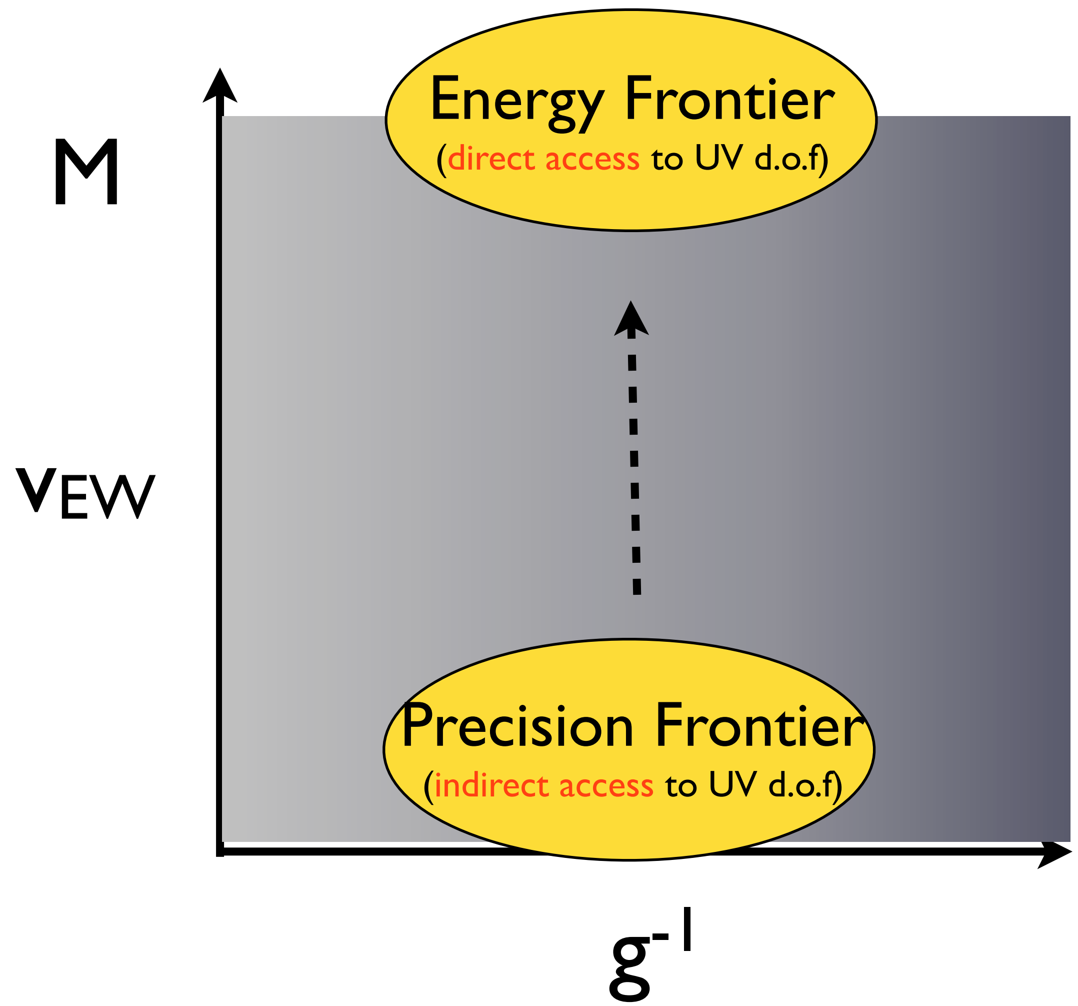
- Two laboratory strategies



- Both frontiers needed to reconstruct $\mathcal{L}_{BSM}$

The quest for "new physics"

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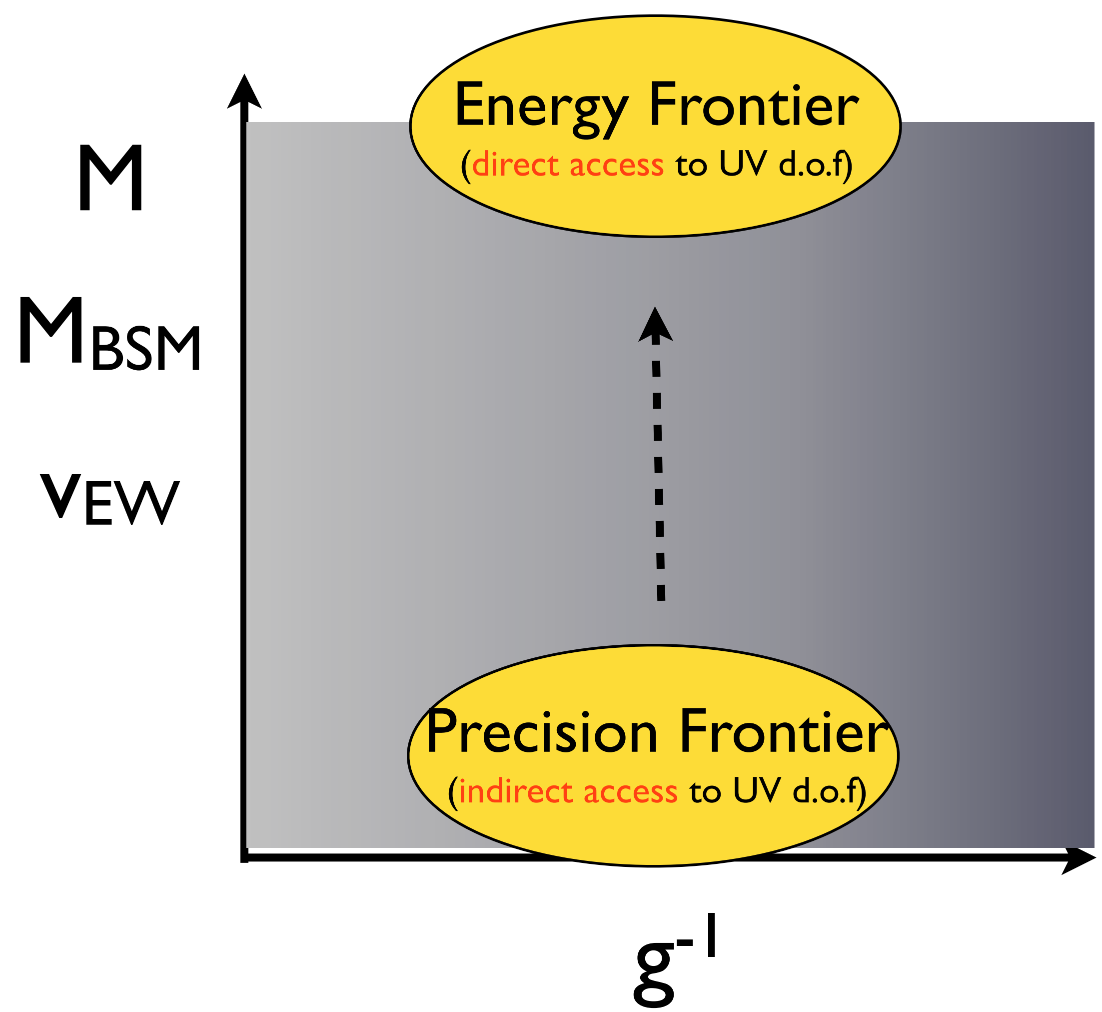
  ⇒ new degrees of freedom (Light & weakly coupled? Heavy? Both?)

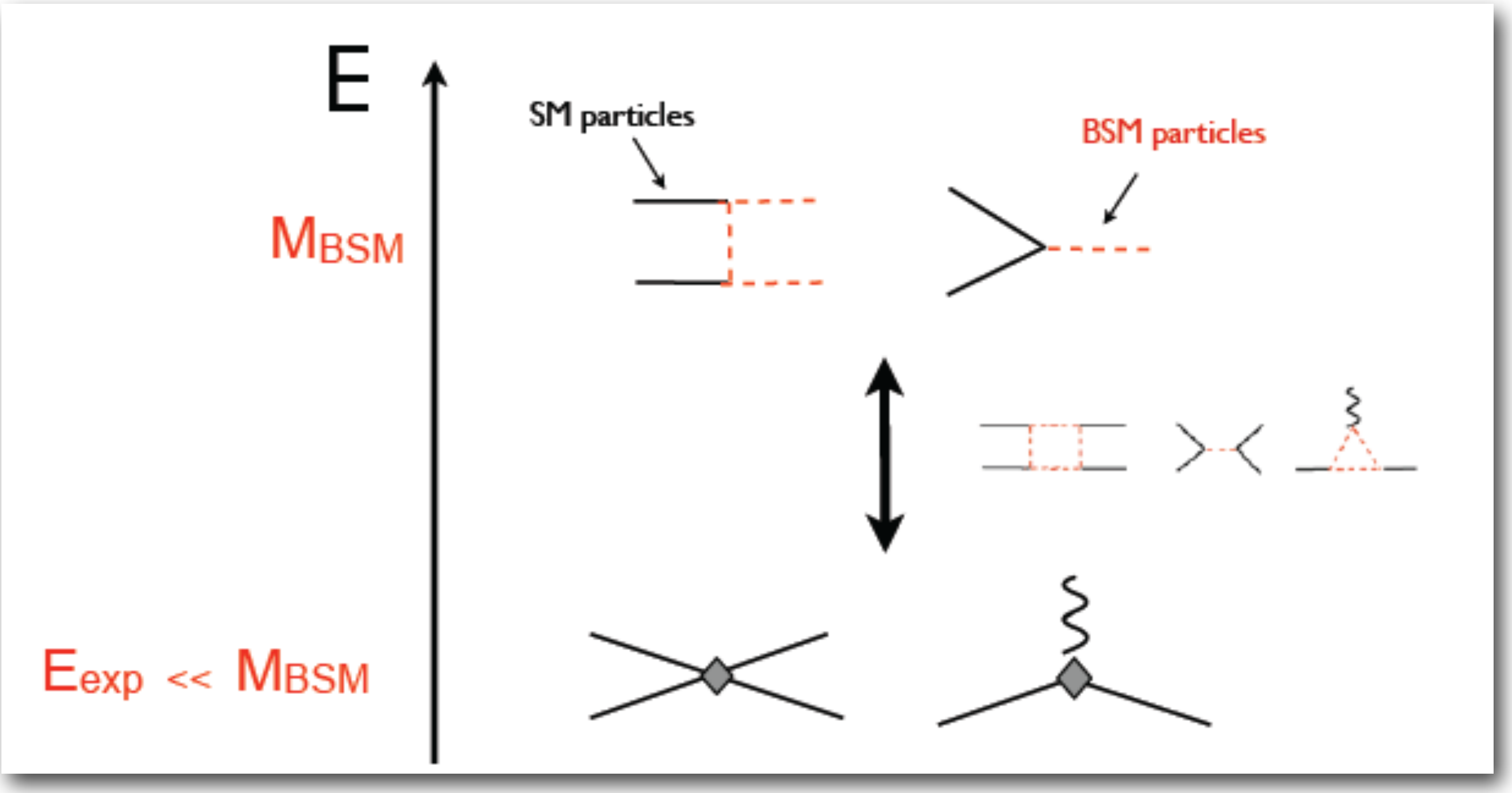
- Two laboratory strategies

In this talk discuss probing UV new physics, using EFT



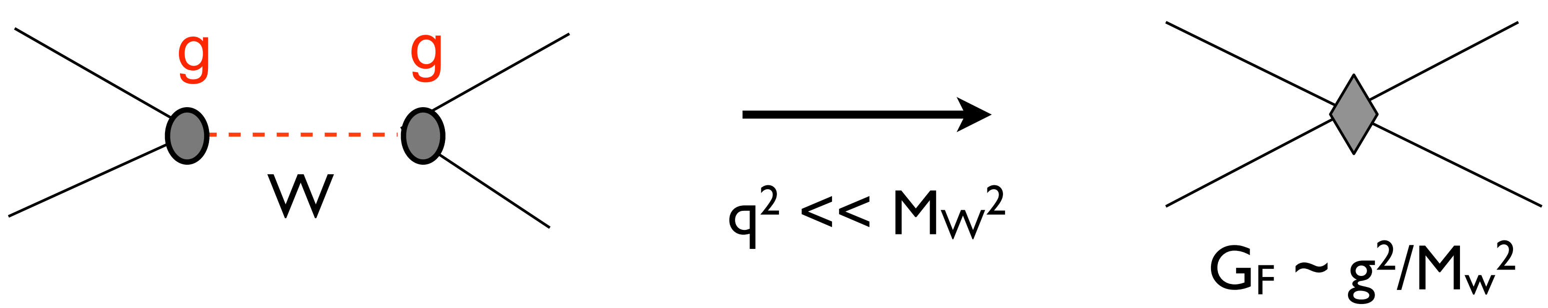
- Both frontiers needed to reconstruct $\mathcal{L}_{BSM}$

Heavy new physics and EFT



- At energy scales $E << M_{BSM}$, new physics shows up in local operators

Familiar example:



- Each UV model generates its own pattern of operators: experiments at $E << M_{BSM}$ can discover and tell apart new physics scenarios

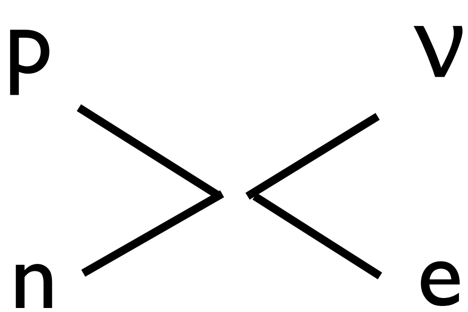
Why use EFTs for new physics

- General framework encompassing classes of models
- Efficient and rigorous tool to analyze experiments at different scales (from collider to table-top)
- The steps below UV matching apply to *all* models
- Very useful diagnosing tool in this “pre-discovery” phase :)
- Inform model building (success story is SM itself**)

EFT and UV models approaches are not mutually exclusive

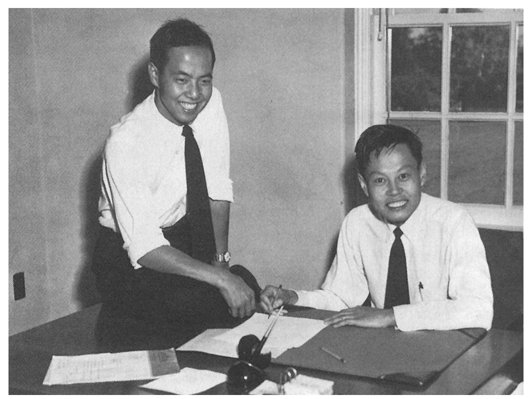
**EFT for β-decays and the making of the SM

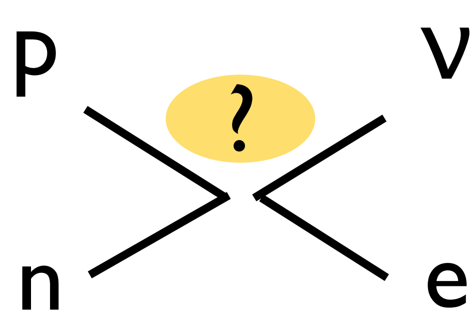
Fermi, 1934



Current-current, parity conserving

Lee and Yang, 1956





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

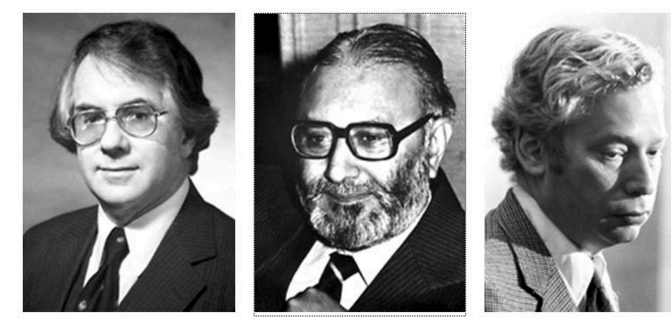
Parity violating: VA, SP, ...

Feynman & Gell-Mann, 1958
Marshak & Sudarshan

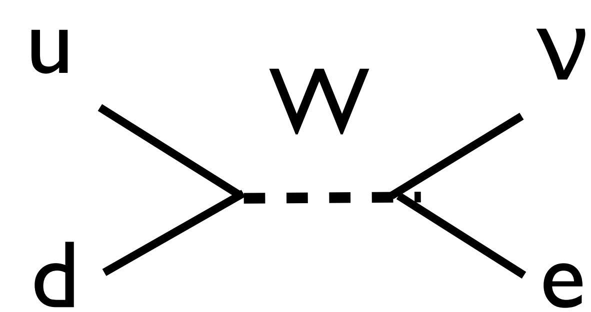
It's (V-A)*(V-A) !!

"V-A was the key"
S.Weinberg

Glashow, Salam, Weinberg



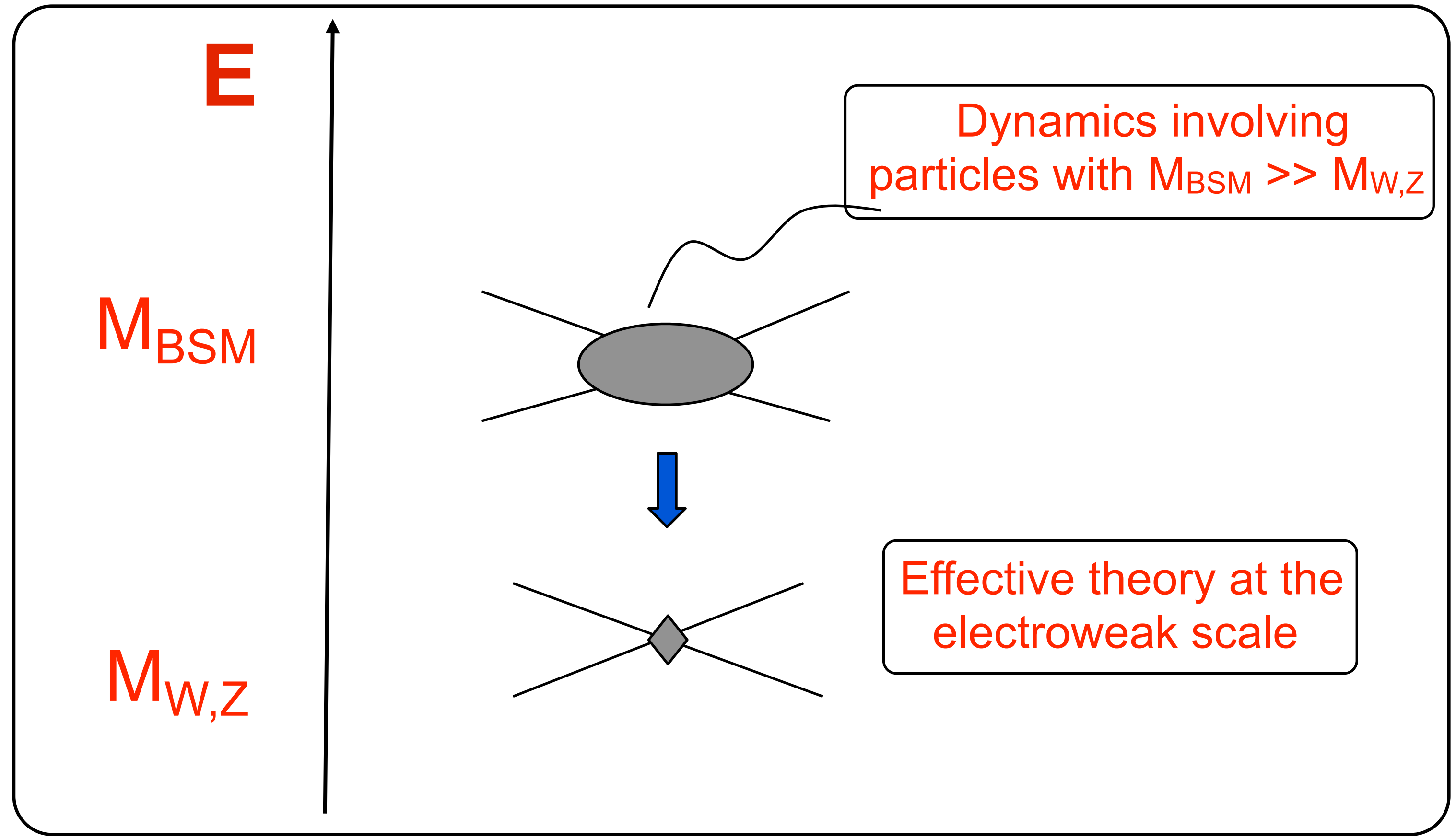
Sheldon Lee Glashow   Abdus Salam   Steven Weinberg



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

BSM EFT framework

- Assume existence of new particles with $M_{BSM} >> G_F^{-1/2} \sim v$
- Degrees of freedom: SM fields (+ possibly ν_R)



- Symmetries and their realization:
  - B, L, CP, flavor typically not enforced
  - SM gauge group:
    - Elementary Higgs: h ∈ EW doublet with EW GB (long. $W^{\pm}$ and Z)
    - Composite Higgs: h is GB associated with strong dynamics

Buchalla et al, 1307.5017, and refs therein

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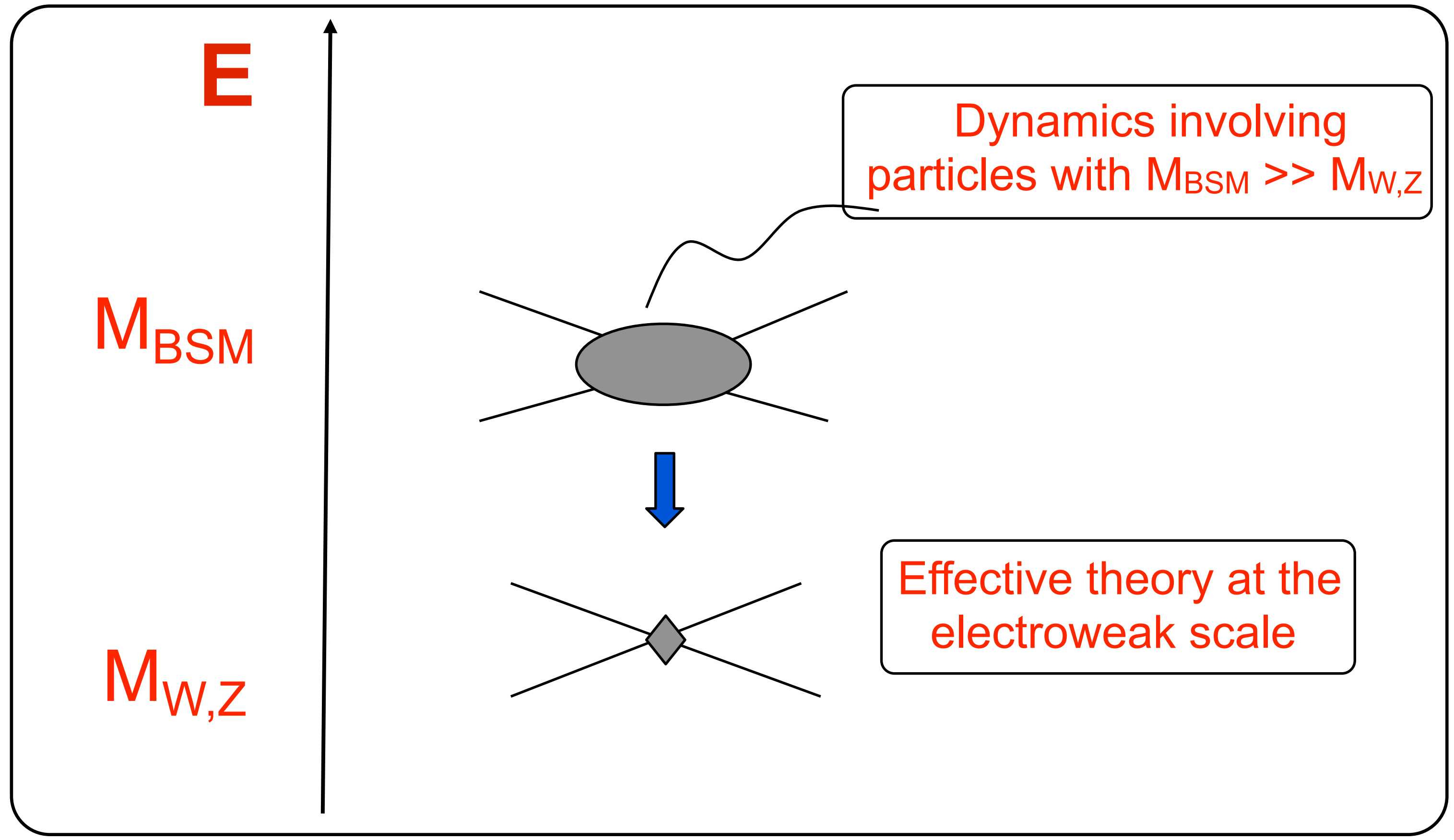


- Here focus on linear-realization: $\varphi = \frac{1}{\sqrt{2}}\, e^{-i(\phi_a/v)T_a} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$

- EFT expansion in E/M_{BSM}, M_W/M_{BSM}

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

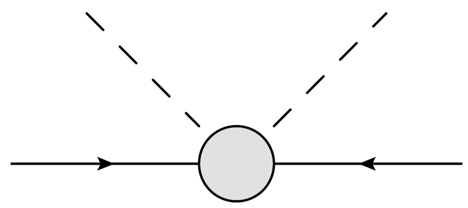
[$\Lambda \leftrightarrow M_{BSM}$]

Quick overview of $\mathcal{L}_{\text{eff}}$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

- Dim 5: one L-violating operator → Majorana mass for neutrinos

Weinberg 1979



$$\frac{1}{\Lambda}\frac{g^{ij}}{2}(\bar{L}_L^{ci} i\sigma_2 H)(H^T i\sigma_2 L_L^j) \longrightarrow m_\nu^{ij} = \frac{v^2}{\Lambda} g^{ij}$$

Key questions in neutrino physics revolve around this operator

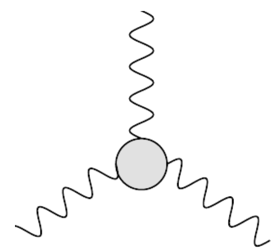
Quick overview of $\mathcal{L}_{eff}$

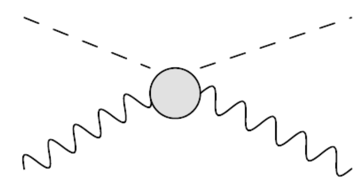
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

- Dim 6: *many* operators, affect many processes
- 59 operators (2499 including family indices)

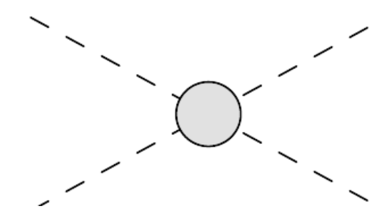
Weinberg 1979
Wilczek-Zee1979
Buchmuller-Wyler 1986, ...
Grzadkowski-Iskrzynksi-Misiak-Rosiek, 2010
Manohar-Trott, 2013

No fermions

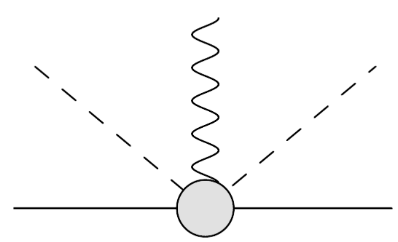




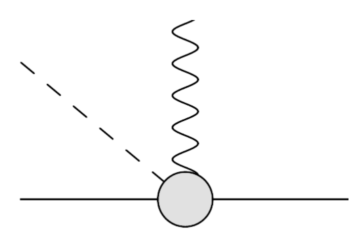
H-V-V



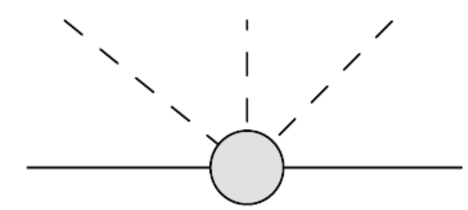
Two fermions



$V\text{-}f_{L,R}\text{-}f_{L,R}$: vector

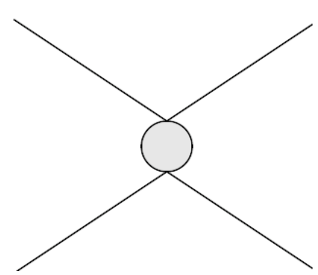


$V\text{-}f_L\text{-}f_R$: dipole



$H\text{-}f_L\text{-}f_R$

Four fermions



Quick overview of $\mathcal{L}_{eff}$

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- Several examples at this meeting
- Lepton Flavor Violation (E. Passemar)
- EDMs (M.J. Ramsey-Musolf, A. Walker-Loud, J. de Vries)
- Weak decays (J. M. Camalich and M. Gonzalez-Alonso)
- ΔB=1,2 (E. Shintani, M. Buchcoff)
- ...

Quick overview of $\mathcal{L}_{eff}$

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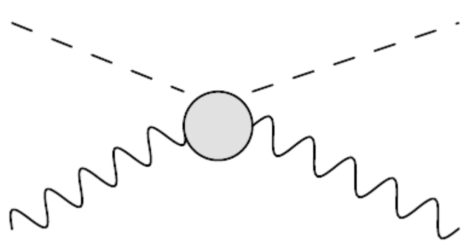
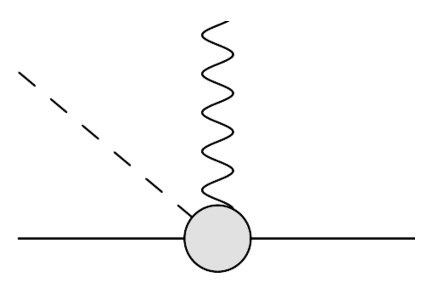
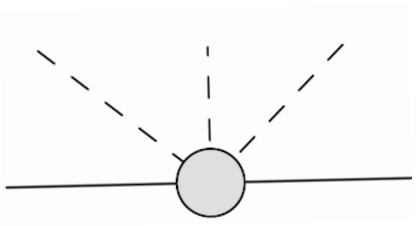


H-g-g



H-q_L-q_R-g: dipole



H-q_L-q_R: scalar

In this talk focus on CPV Higgs couplings to quarks and gluons

Non-standard CP-violating Higgs couplings

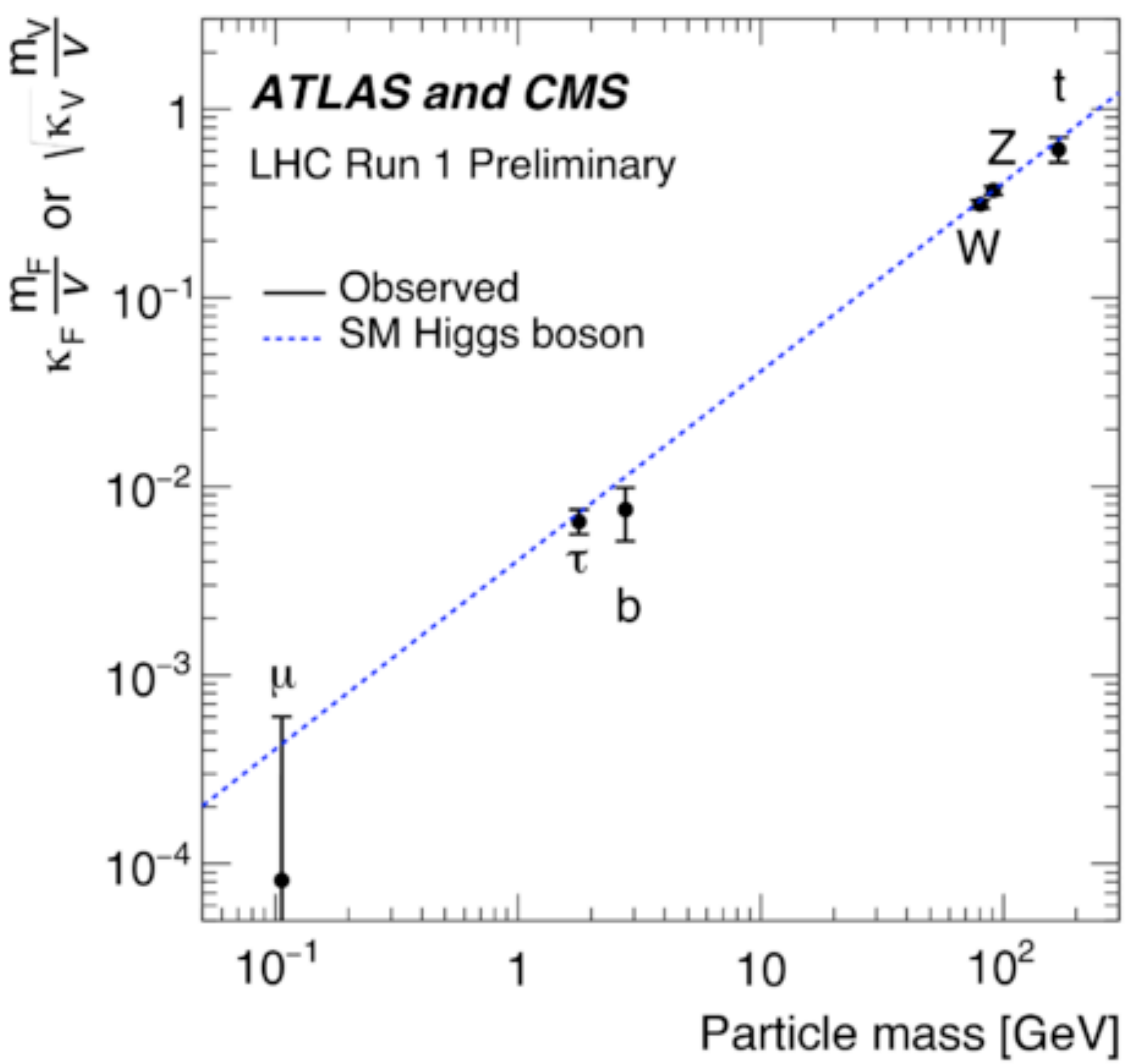
Based on

Y.T. Chien, VC, W. Dekens, J. de Vries, E. Mereghetti

1510.xxxx

Non-standard Higgs couplings?

- Higgs discovery: milestone for fundamental interactions
- So far, Higgs properties are compatible with the Standard Model: signal strengths $\mu \equiv \sigma_{obs}/\sigma_{SM}$ compatible with $\mu=1$

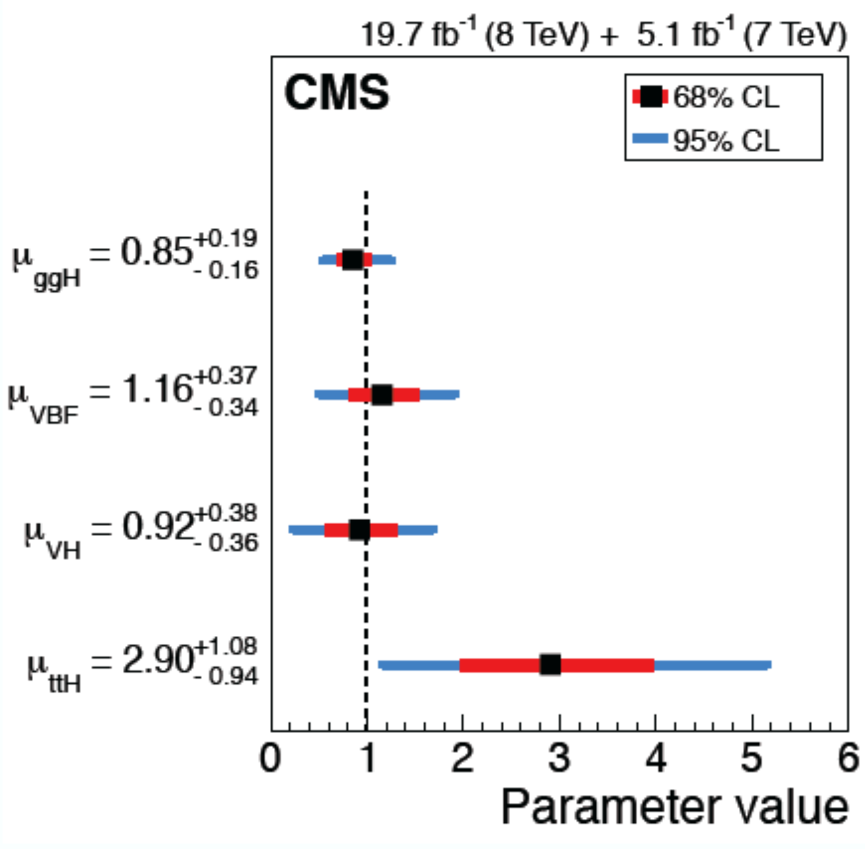


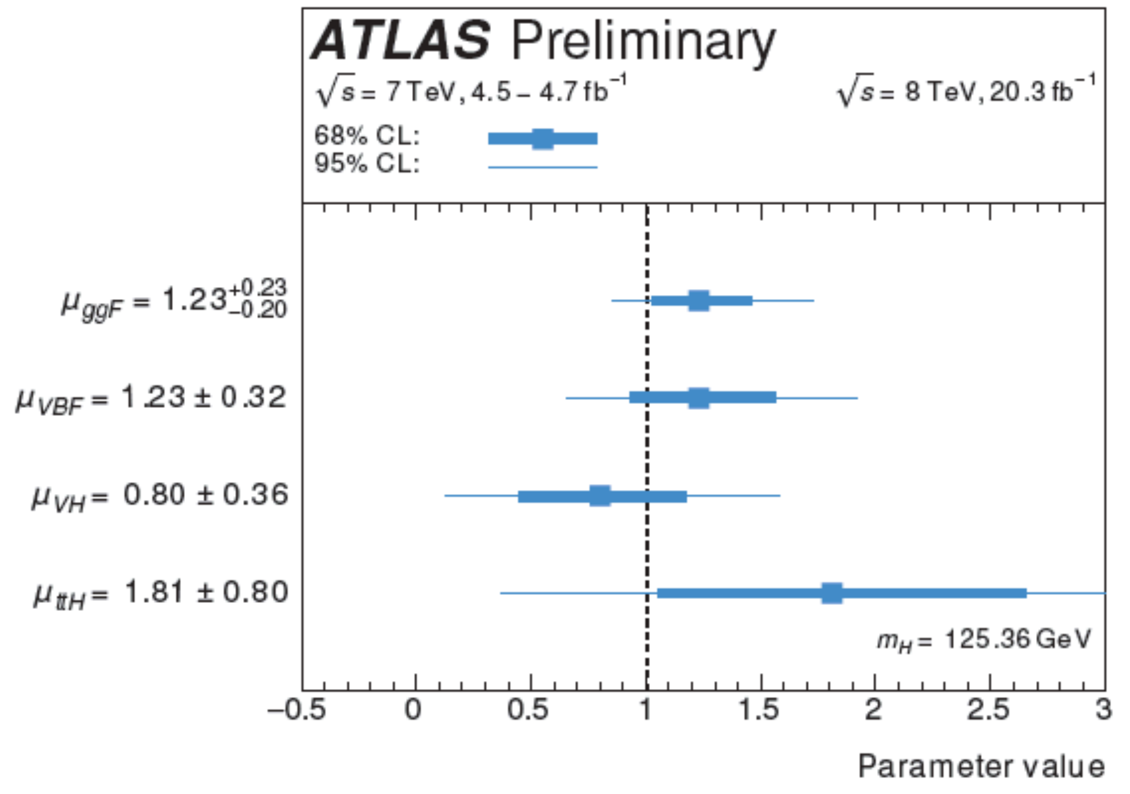
- Couplings to W, Z, γ,g and t, b, τ known at 20-30% level
- But couplings to light flavors much less constrained
- Still room for deviations: is this the SM Higgs? Key question at LHC Run 2 & important target for low energy experiments

CPV Higgs couplings

- Subsets of CPV interactions studied in the literature
- Wish to study CPV couplings systematically, through

  (1) LHC: Higgs production ($\mu \equiv \sigma_{obs}/\sigma_{SM}$)





CPV Higgs couplings

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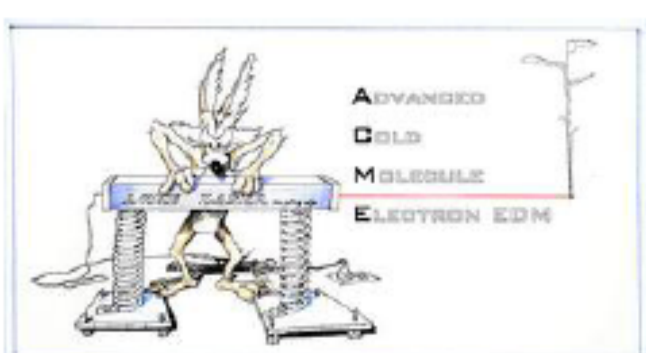
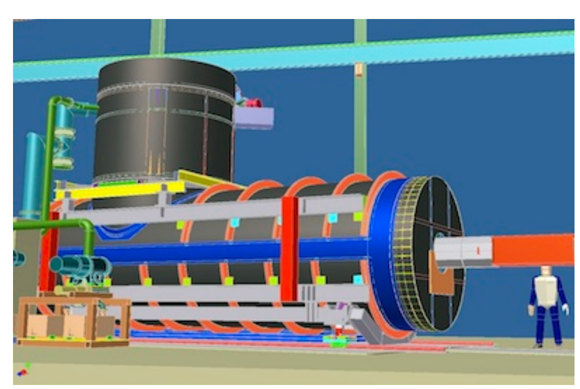
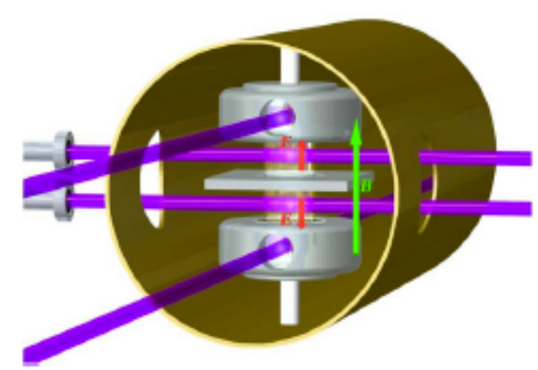
  (2) Low-energy: EDMs (expect strong constraints)

	d_e	d_n	$d_{p,D}$	$d_{\rm Hg}$	$d_{\rm Xe}$	$d_{\rm Ra}$
current limit	$8.7 \cdot 10^{-29}$	$2.9 \cdot 10^{-26}$	x	$2.6 \cdot 10^{-29}$	$5.5 \cdot 10^{-27}$	$4.2 \cdot 10^{-22}$
expected limit	$5.0 \cdot 10^{-30}$	$1.0 \cdot 10^{-28}$	$1.0 \cdot 10^{-29}$	$1.0 \cdot 10^{-29}$	$5.0 \cdot 10^{-29}$	$1.0 \cdot 10^{-27}$

(e cm)







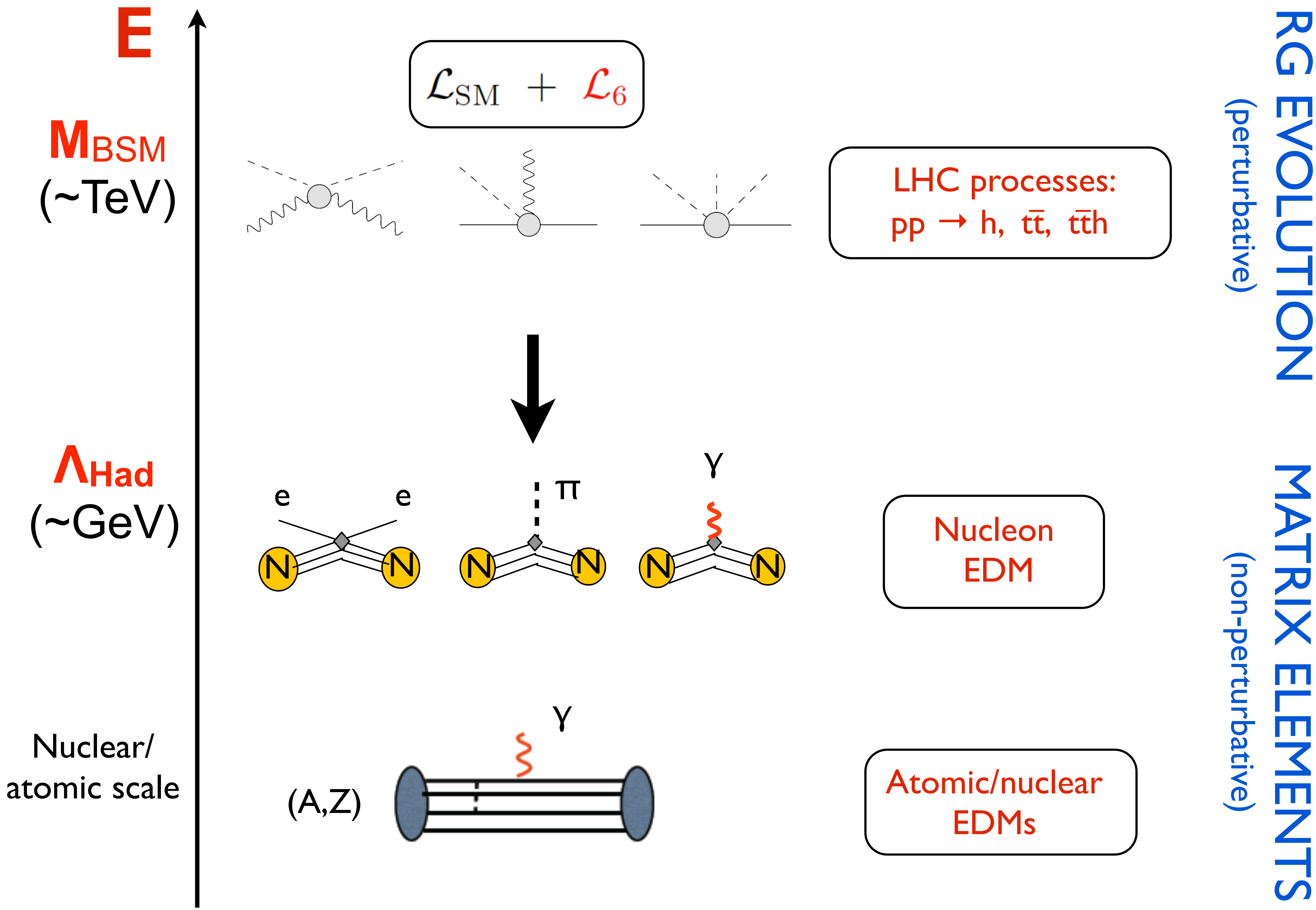
CPV Higgs couplings

- Subsets of CPV interactions studied in the literature
- Wish to study CPV couplings systematically, through
  - (1) LHC: Higgs production ($\mu \equiv \sigma_{obs}/\sigma_{SM}$)
  - (2) Low-energy: EDMs (expect strong constraints)
- Start at scale M_{BSM} with CPV Higgs couplings to quarks and gluons

$$\mathcal{L}_6 = -\,\theta' \frac{\alpha_s}{16\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} (\varphi^\dagger \varphi) \; + \; \sqrt{2}\varphi^\dagger\varphi \, (\bar{q}_L Y'_u \, u_R \, \tilde{\varphi} \; + \; \bar{q}_L Y'_d \, d_R \, \varphi)$$

$$-\frac{g_s}{\sqrt{2}} \bar{q}_L \, \sigma \cdot G \, \tilde{\Gamma}_u \, u_R \, \frac{\tilde{\varphi}}{v} \; - \; \frac{g_s}{\sqrt{2}} \bar{q}_L \, \sigma \cdot G \, \tilde{\Gamma}_d \, d_R \, \frac{\varphi}{v} + \text{h.c.}$$

Connecting $\mathcal{L}_6$ to LHC and EDMs



RG Evolution

μ = 1 TeV, in the quark mass basis

$$\mathcal{L}_6^{CPV} = -v\theta' \frac{\alpha_s}{8\pi} h G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + v^2 \mathrm{Im}\, Y'_q \, \bar{q} i\gamma_5 q \, h - \frac{i}{2} \tilde{d}_q \, g_s \, \bar{q}\sigma\cdot G\gamma_5 q \left(1 + \frac{h}{v}\right) + O(h^2)$$

μ = 1 GeV

$$\mathcal{L}_6^{CPV} \to -m_* \bar{\theta} \sum_{q=u,d,s} \bar{q} i\gamma_5 q - \frac{i}{2} \sum_{f=e,u,d,s} d_f \, eQ_f \, \bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2} \sum_{q=u,d,s} \tilde{d}_q \, g_s \, \bar{q}\sigma\cdot G\gamma_5 q + d_W \frac{g_s}{6} f_{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu}$$

- High-scale operators contribute to EDMs through mixing into light quark (C)EDMs and d_W
- Extend operator basis to take this into account (d_q, d_W)
- Low-scale couplings involve linear combinations of high scale ones
- Assume Peccei-Quinn is at work

- Evolution equations & mixing structure

$$\mu\frac{d}{d\mu}\begin{pmatrix} d_q/m_q \\ \tilde{d}_q/m_q \\ d_W \\ \mathrm{Im}\,Y_q' \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F-4N_C & 2N & 0 & -1/4\pi^2 \\ 0 & 0 & N_C+2n_f+\beta_0 & 0 & 0 \\ 0 & -30C_F(\frac{m_q}{v})^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}(\frac{m_q}{v})^2 & 0 & 0 & 0 \end{pmatrix}\cdot\begin{pmatrix} d_q/m_q \\ \tilde{d}_q/m_q \\ d_W \\ \mathrm{Im}\,Y_q' \\ \theta' \end{pmatrix}$$

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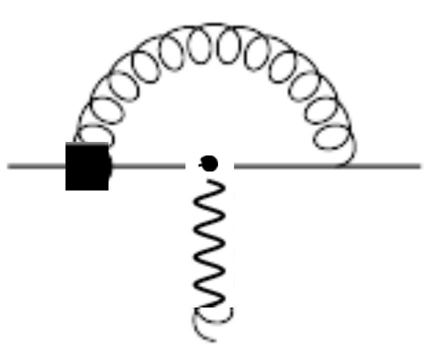
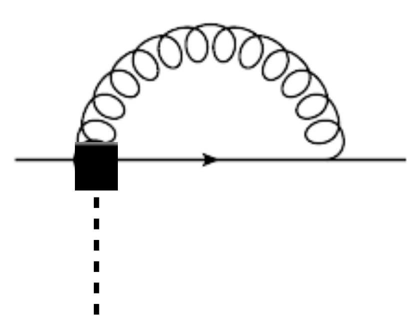
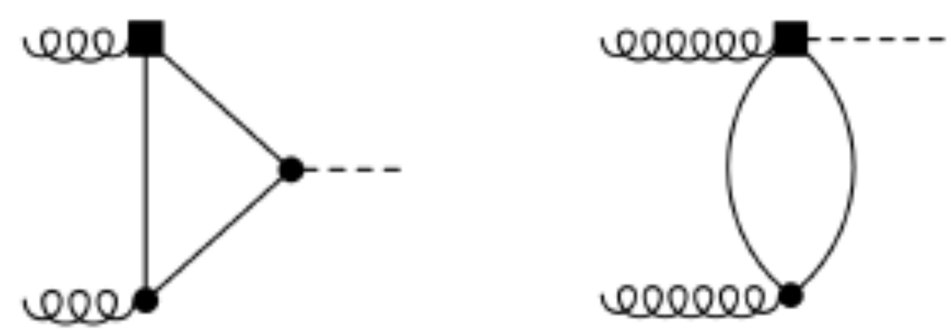
- CEDM insertions:



d_q/m_q



$\mathrm{Im}\,Y_q'$

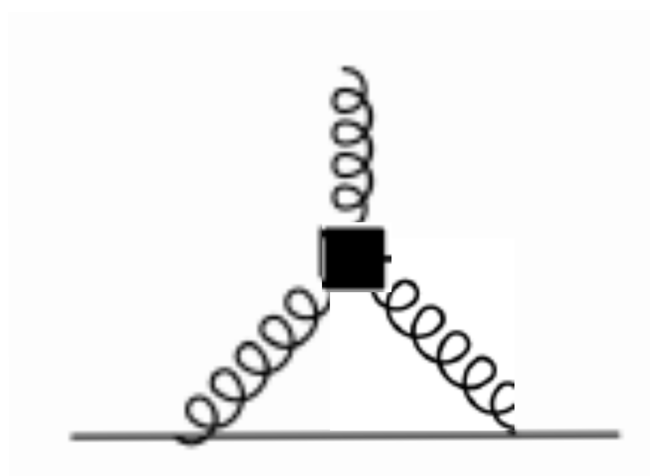


θ'

- Evolution equations & mixing structure

$$\mu\frac{d}{d\mu}\begin{pmatrix} d_q/m_q \\ \tilde{d}_q/m_q \\ d_W \\ \mathrm{Im}\,Y'_q \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F-4N_C & 2N & 0 & -1/4\pi^2 \\ 0 & 0 & N_C+2n_f+\beta_0 & 0 & 0 \\ 0 & -30C_F(\frac{m_q}{v})^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}(\frac{m_q}{v})^2 & 0 & 0 & 0 \end{pmatrix}\cdot\begin{pmatrix} d_q/m_q \\ \tilde{d}_q/m_q \\ d_W \\ \mathrm{Im}\,Y'_q \\ \theta' \end{pmatrix}$$

- Weinberg insertions:

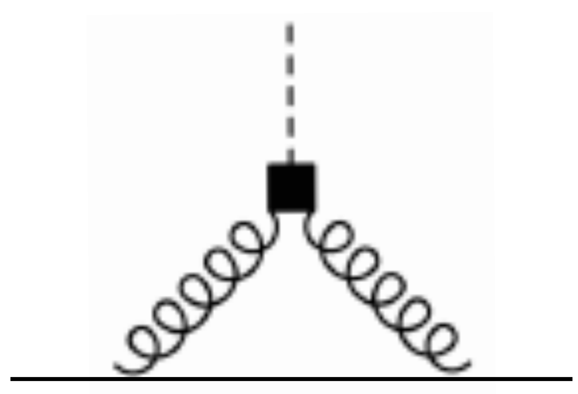


$\tilde{d}_q/m_q$

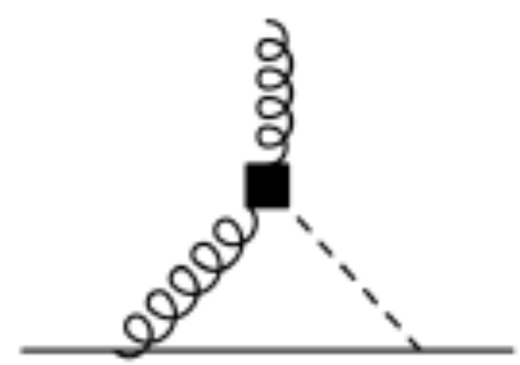
- Evolution equations & mixing structure

$$\mu\frac{d}{d\mu}\begin{pmatrix} d_q/m_q \\ \tilde{d}_q/m_q \\ d_W \\ \mathrm{Im}\,Y_q' \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F-4N_C & 2N & 0 & -1/4\pi^2 \\ 0 & 0 & N_C+2n_f+\beta_0 & 0 & 0 \\ 0 & -30C_F(\frac{m_q}{v})^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}(\frac{m_q}{v})^2 & 0 & 0 & 0 \end{pmatrix}\cdot\begin{pmatrix} d_q/m_q \\ \tilde{d}_q/m_q \\ d_W \\ \mathrm{Im}\,Y_q' \\ \theta' \end{pmatrix}$$

- θ' insertions:



$\mathrm{Im}\,Y_q'$

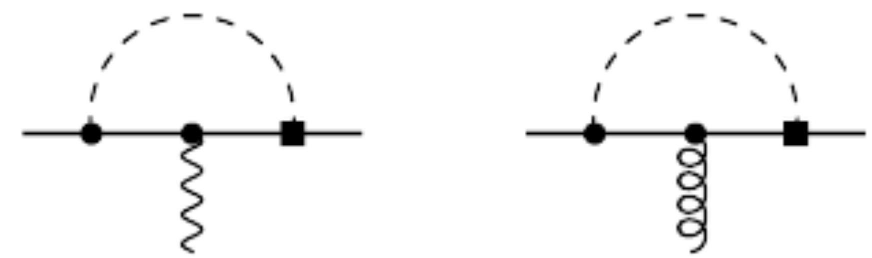


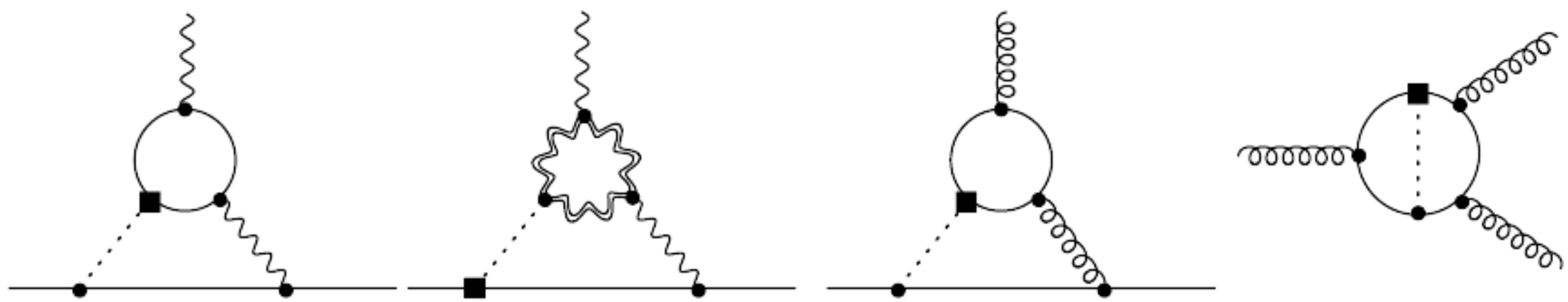
$\tilde{d}_q/m_q$

Threshold effects

- At μ= m_t, m_h, $m_{W,Z}$ integrate out t, h, W, Z:

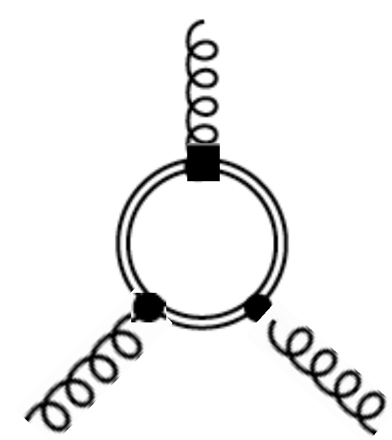
$$\mathrm{Im}\, Y'_q \;\Rightarrow\; d_q/m_q \quad \tilde{d}_q/m_q \quad d_W \quad d_e$$





- At μ= $m_{t,b,c}$:

$$\tilde{d}_q/m_q \;\Rightarrow\; d_W$$



Matrix Elements: status

- A lot (but not everything) can be learned from chiral symmetry considerations
- Need dynamical calculation: QCD sum rules, ... , Lattice QCD
- Lattice QCD should play an increasingly important role:
    - θ-term: long-known challenge
    - BSM operators: recently got on the "radar"

See Talks by J. de Vries,
T. Bhattacharya, G. Schierholz,   A. Walker-Loud

Matrix Elements: status

- Nucleon EDMs from BSM operators: $d_{n,p}\left[d_{u,d,s};\ \tilde{d}_{u,d,s};\ d_W\right]$

	$d_u(1\,\mathrm{GeV})$	$d_d(1\,\mathrm{GeV})$	$d_s(1\,\mathrm{GeV})$
d_n	-0.22 ± 0.03	0.74 ± 0.07	0.0077 ± 0.01
d_p	0.74 ± 0.07	-0.22 ± 0.03	0.0077 ± 0.01

Bhattacharya et al
1506.04196, 1506.06411

Lattice QCD: 10% for u,d, bound for s

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Lattice QCD: 10% for u,d, bound for s

	$e\,\tilde{d}_u(1\,\text{GeV})$	$e\,\tilde{d}_d(1\,\text{GeV})$	$e\,\tilde{d}_s(1\,\text{GeV})$	$e\,d_W(1\,\text{GeV})$
d_n	-0.55 ± 0.28	-1.1 ± 0.55	xxx	$\pm(50 \pm 40)$ MeV
d_p	1.30 ± 0.65	0.60 ± 0.30	xxx	$\mp(50 \pm 40)$ MeV

Pospelov-Ritz
hep-ph/0504231
and refs therein

QCD Sum Rules (50%) QCD Sum Rules + NDA (~100%)

For LQCD prospects, see T. Bhattacharya's talk

- πNN couplings

$$\bar{g}_0 = (5 \pm 10)(\tilde{d}_u + \tilde{d}_d)\,\mathrm{fm}^{-1} \;, \qquad \bar{g}_1 = (20^{+40}_{-10})(\tilde{d}_u - \tilde{d}_d)\;\mathrm{fm}^{-1}$$

QCD Sum Rules: Pospelov-Ritz hep-ph/0504231 and refs therein

- Deuteron

$$d_D \;=\; (0.94 \pm 0.01)(d_n + d_p) + \left[(0.18 \pm 0.02)\,\bar{g}_1\right] e\,\mathrm{fm}\;,$$

Basiou et al. 1411.5804
de Vries et al, 1109.3604

- Diamagnetic atoms

$$d_A \;=\; \mathcal{A}_A\, S_A$$
$$S_A \;=\; (a_0\,\bar{g}_0 + a_1\,\bar{g}_1)\, e\,\mathrm{fm}^3 \;+\; (\alpha_n\, d_n + \alpha_p\, d_p)\,\mathrm{fm}^2$$

$\alpha_n = 1.9 \pm 0.1 \qquad \alpha_p = 0.20 \pm 0.06$ Dimitriev and Sen'kov 2003

	Atomic screening $\mathcal{A}(\mathrm{fm}^{-2})$	Best values of $a_{0,1}$		Estimated ranges of $a_{0,1}$	
		a_0	a_1	a_0	a_1
^{129}Xe	$(0.33 \pm 0.05) \cdot 10^{-4}$	-0.10	-0.076	$\{-0.063, -0.63\}$	$\{-0.038, -0.63\}$
^{199}Hg	$-(2.8 \pm 0.6) \cdot 10^{-4}$	0.13	± 0.25	$\{0.063, 0.63\}$	$\{-0.38, 1.14\}$
^{225}Ra	$-(7.7 \pm 0.8) \cdot 10^{-4}$	-19	76	$\{-12.6, -76\}$	$\{51, 303\}$

Engel et al 1303.2371

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QCD Sum Rules:
Pospelov-Ritz
hep-ph/0504231
and refs therein

- Deuteron

Basiou et al.

Take home message: in most cases O(1) uncertainties,
in some cases not even the sign is known

$$\alpha_n = 1.9 \pm 0.1 \qquad \alpha_p = 0.20 \pm 0.06$$

Dimitriev and Sen'kov 2003

	Atomic screening $\mathcal{A}(\mathrm{fm}^{-2})$	Best values of $a_{0,1}$		Estimated ranges of $a_{0,1}$	
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Engel et al
1303.2371

Matrix Elements: strategy

- To study impact these uncertainties, we obtain bounds on non-standard couplings with different treatments of theoretical input

1. Central: use central value matrix elements
2. RFit ("Range-Fit"): vary matrix elements in their allowed theoretical ranges; minimize chi-squared (= pick weakest bound)

Matrix Elements: strategy

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1. Central: use central value matrix elements
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3. RFit+: RFit with improved uncertainties in matrix elements

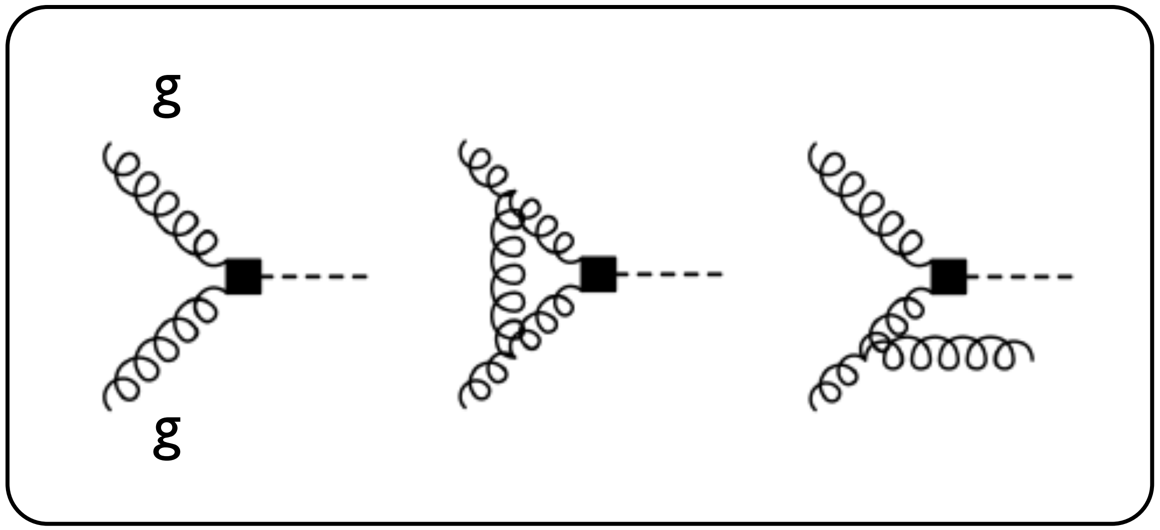
$d_{n,p}[\tilde{d}_{u,d}]$	$d_{n,p}[d_s]$ $d_{n,p}[d_W]$ $\bar{g}_{0,1}[\tilde{d}_{u,d}]$ $S_{\rm Hg}[\bar{g}_{0,1}]$
25%	50%

Concrete (albeit challenging) target for Lattice QCD and nuclear structure calculations

Representative case: θ′

$$\mathcal{L}_6^{CPV} \supset -v\theta' \frac{\alpha_s}{8\pi} h\, G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

LHC: Higgs production via gluon fusion



$$\mu_{ggF} = \frac{\sigma^{SM}_{ggF} + \sigma^{\theta'}_{ggF}}{\sigma^{SM}_{ggF}} = 1 + (2.28 \pm 0.01)\ \left(v^2\theta'\right)^2$$

Cross-section known to N2LO:
10% error largely cancels in the ratio

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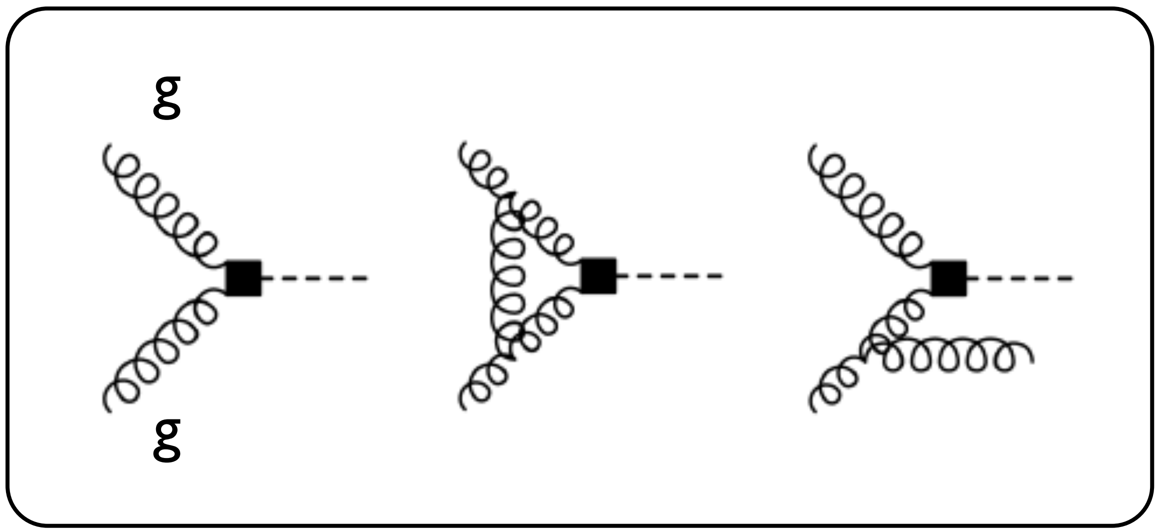

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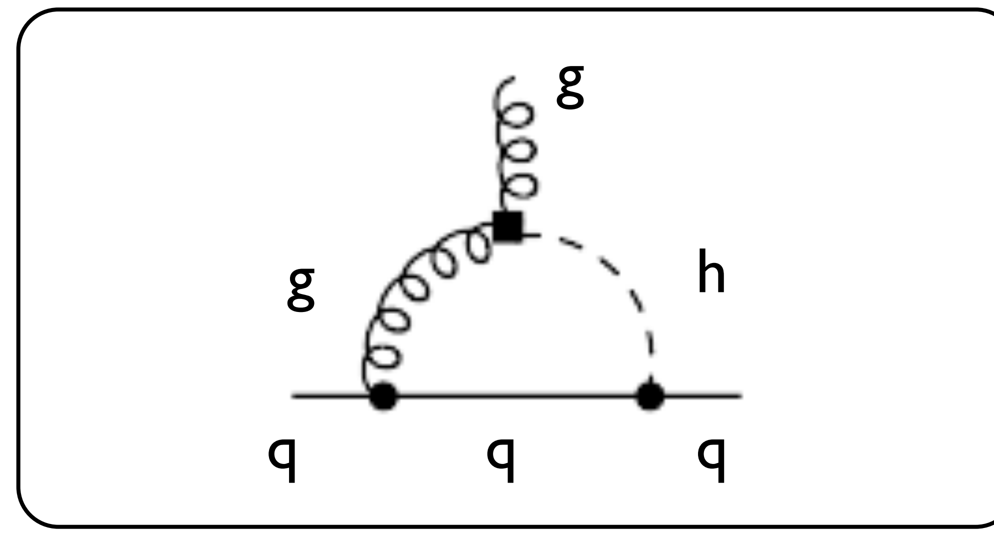
Low Energy: quark (C)EDM + Weinberg



$$\Lambda_\chi = 1\ \text{GeV} \qquad M_{\rm BSM} = 1\ \text{TeV}$$

$$(d_q/m_q)(\Lambda_\chi) = 1.4 \times 10^{-4}\, Q_q\, \theta'(M_{\rm BSM})$$

$$(\tilde{d}_q/m_q)(\Lambda_\chi) = 1.7 \times 10^{-4}\, \theta'(M_{\rm BSM})$$

$$d_W(\Lambda_\chi) = -7.3 \times 10^{-6}\, \theta'(M_{\rm BSM})$$

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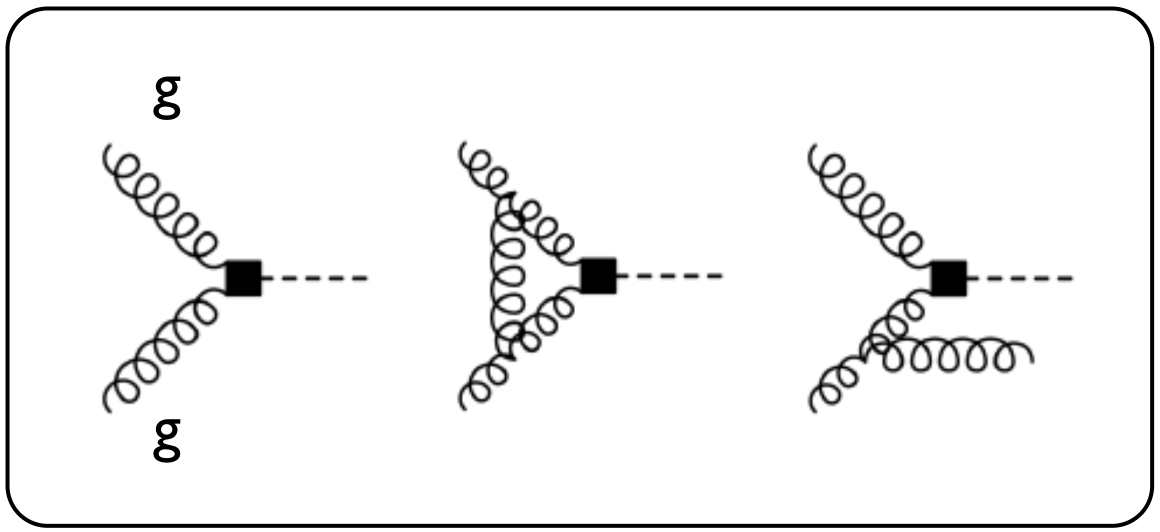

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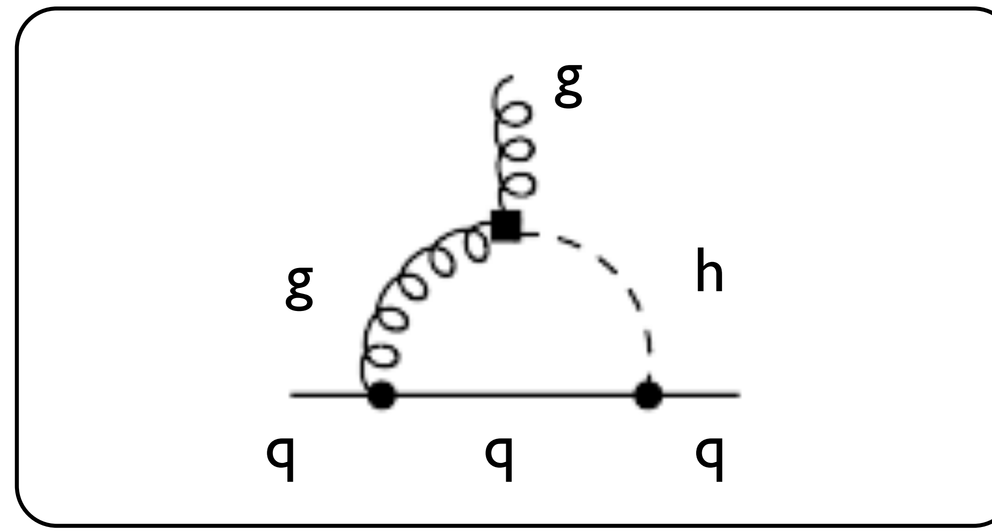

Current experiments

$v^2\theta'$	d_n	d_{Hg}	d_n, d_{Hg} (comb)	LHC (CMS)
Central	0.06	0.04	0.04	0.27
RFit	0.23	x	0.23	0.27
RFit+			0.05	0.27

Bounds on couplings at the scale $\mu = M_{BSM} = 1\,\text{TeV}$

Representative case: θ′

$$\mathcal{L}_6^{CPV} \supset -v\theta' \frac{\alpha_s}{8\pi} h\, G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- General features (that apply to all operators):
  1. RFit: ^{199}Hg bounds disappears, n bound much weaker ⇒ EDM and LHC bounds much closer
  2. RFit+: bounds comparable to "central" (no cancellations). Exploit the full constraining power of experiments

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- Impact of improved theory, improved experiments, and both

	$v^2\,\theta'$
Current	0.23
Current+Th.	0.052
$d_n + d_{\mathrm{ThO}}$	$8.0 \cdot 10^{-4}$
$d_n + d_{\mathrm{ThO}}$+Th.	$3.3 \cdot 10^{-4}$
$d_{\mathrm{Xe}} + d_{\mathrm{Ra}}$	0.14
$d_{\mathrm{Xe}} + d_{\mathrm{Ra}}$+Th.	0.011
$d_p + d_D$	$3.1 \cdot 10^{-5}$
$d_p + d_D$+Th.	$2.2 \cdot 10^{-5}$
LHC Run 1	0.27
LHC Run 2	0.20

	Current	Projected
d_e	$8.7 \cdot 10^{-29}$	$5.0 \cdot 10^{-30}$
d_n	$2.9 \cdot 10^{-26}$	$1.0 \cdot 10^{-28}$
$d_{p,D}$	x	$1.0 \cdot 10^{-29}$
d_{Hg}	$2.6 \cdot 10^{-29}$	$1.0 \cdot 10^{-29}$
d_{Xe}	$5.5 \cdot 10^{-27}$	$5.0 \cdot 10^{-29}$
d_{Ra}	$4.2 \cdot 10^{-22}$	$1.0 \cdot 10^{-27}$

(e cm)

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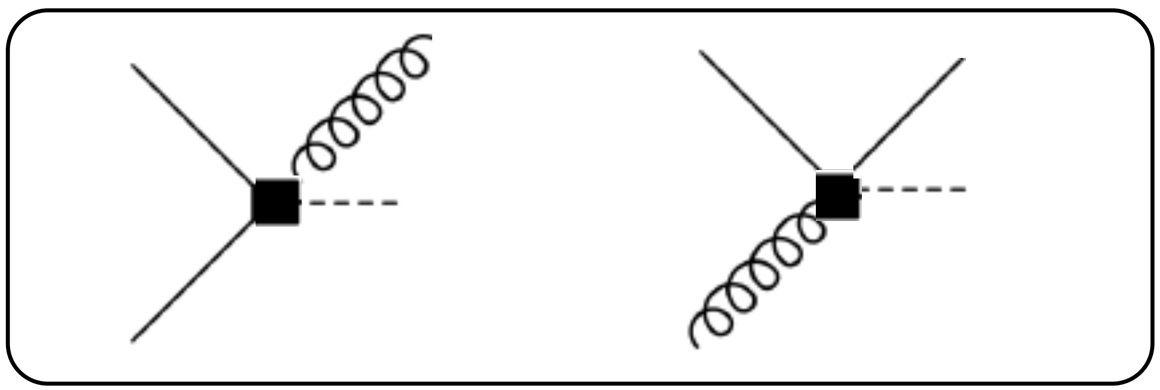
- Improved EDM matrix elements can have bigger impact than additional measurements
- Improved EDM matrix elements: enough to beat LHC Run 1 & 2
- LHC Run 2 sensitivity not great: ratio $\sigma_{\theta'}/\sigma_{SM}$ ~ constant with $\sqrt{s}$

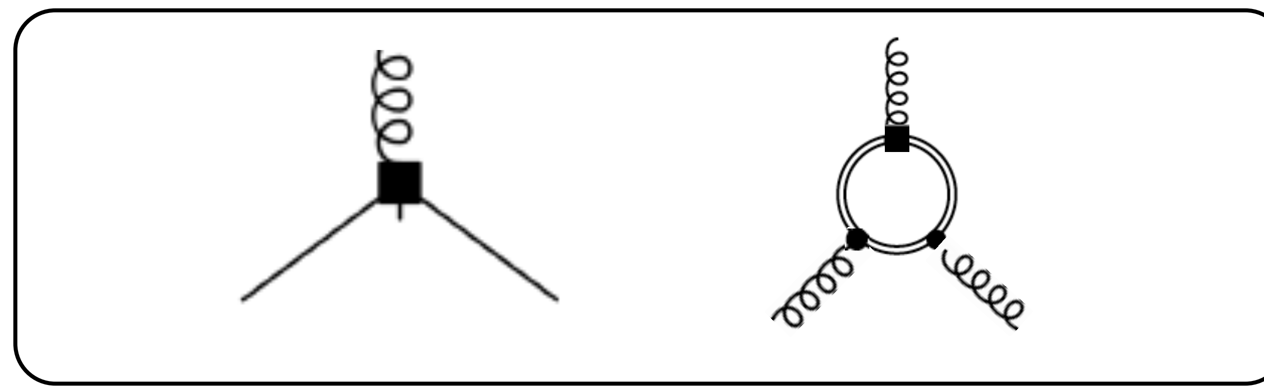
Signatures of other operators

- $\tilde{d}_q$ for $q \neq t$:

LHC: Higgs (+ jet) production



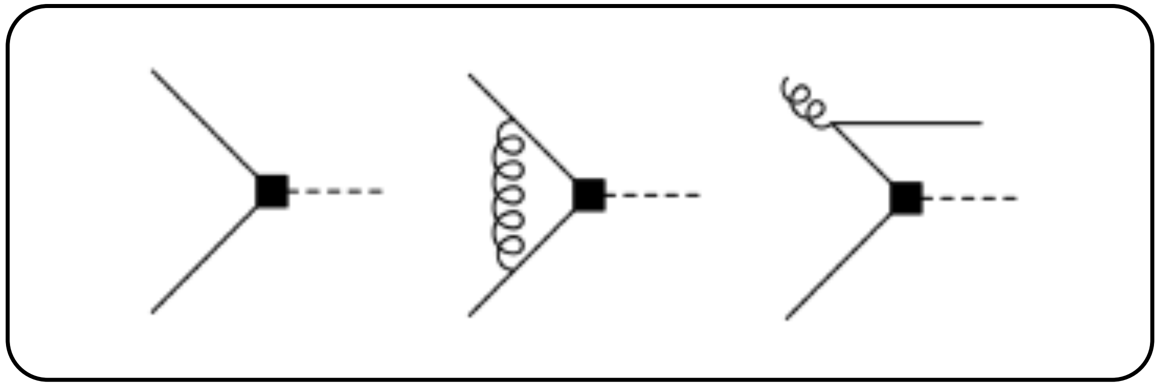
Low Energy: quark (C)EDM, Weinberg



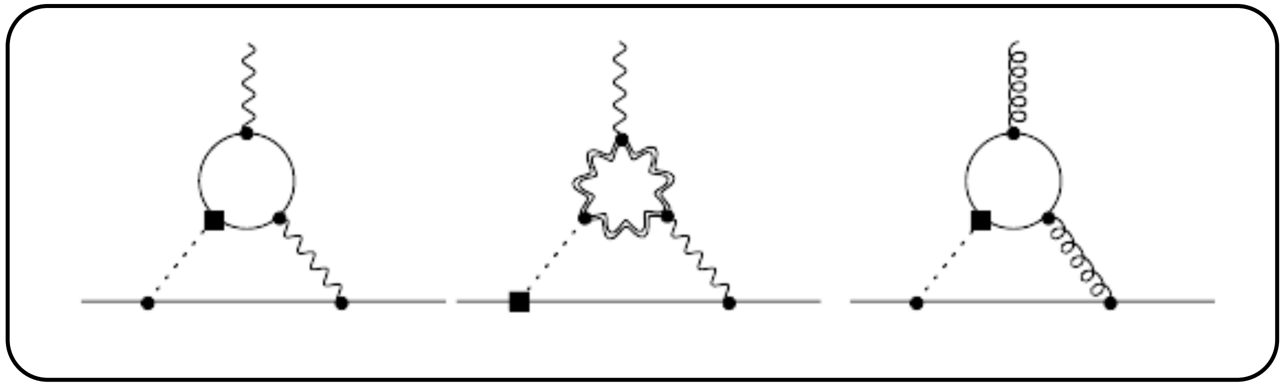
- LHC constraints from $pp \to h$ at the level of $v\tilde{d}_q$~4-20%
- EDM (d_n) bounds stronger by 4-6 orders of magnitude!

- ## Pseudoscalar Yukawas q≠t

LHC: Higgs production

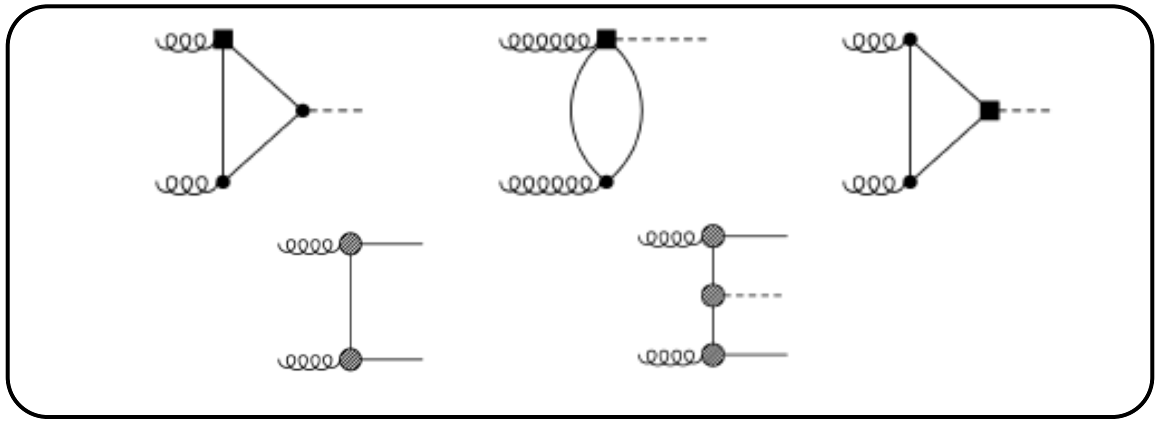


Low Energy: quark (C)EDM, Weinberg, *and* d_e



- ## Top pseudoscalar Yukawa and CEDM

LHC: pp → h (via ggF), $t\bar{t}$, $t\bar{t}h$



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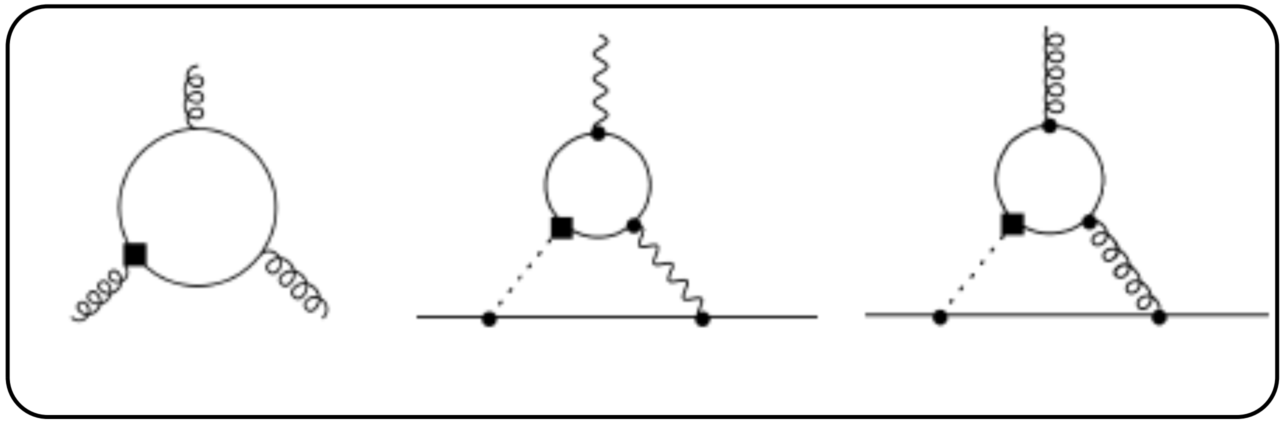

Summary table 1

	$v^2 \mathrm{Im}\, Y'_u$	$v^2 \mathrm{Im}\, Y'_d$	$v^2 \mathrm{Im}\, Y'_c$	$v^2 \mathrm{Im}\, Y'_s$	$v^2 \mathrm{Im}\, Y'_t$	$v^2 \mathrm{Im}\, Y'_b$	$v^2\, \theta'$	$v^2 \tilde{d}_t / m_t$
Current EDMs	$2.8 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	$6.3 \cdot 10^{-3}$	0.42	$7.8 \cdot 10^{-3}$	0.041	0.23	$4.1 \cdot 10^{-2}$
LHC Run 1	$0.6 \cdot 10^{-2}$	$0.7 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$15 \cdot 10^{-2}$	$3.8 \cdot 10^{-2}$	0.27	$5.2 \cdot 10^{-2}$

- Complementarity of EDMs and LHC:
  - Currently, best bounds on Higgs couplings come from combination of EDMs and LHC
  - For $Y'_{b,t}$ ThO (electron) provides strongest EDM constraint

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- Bounds correspond to effective scales varying from 1 to 200 TeV

	$v^2 \mathrm{Im}\, Y'_u$	$v^2 \mathrm{Im}\, Y'_d$	$v^2 \mathrm{Im}\, Y'_c$	$v^2 \mathrm{Im}\, Y'_s$	$v^2 \mathrm{Im}\, Y'_t$	$v^2 \mathrm{Im}\, Y'_b$	$v^2\, \theta'$	$v^2 \tilde{d}_t / m_t$
Λ (TeV)	145	200	3.1	2	2.8	1.2	0.5	1.2

- Pseudoscalar Yukawas in units of SM Yukawa m_q/v:

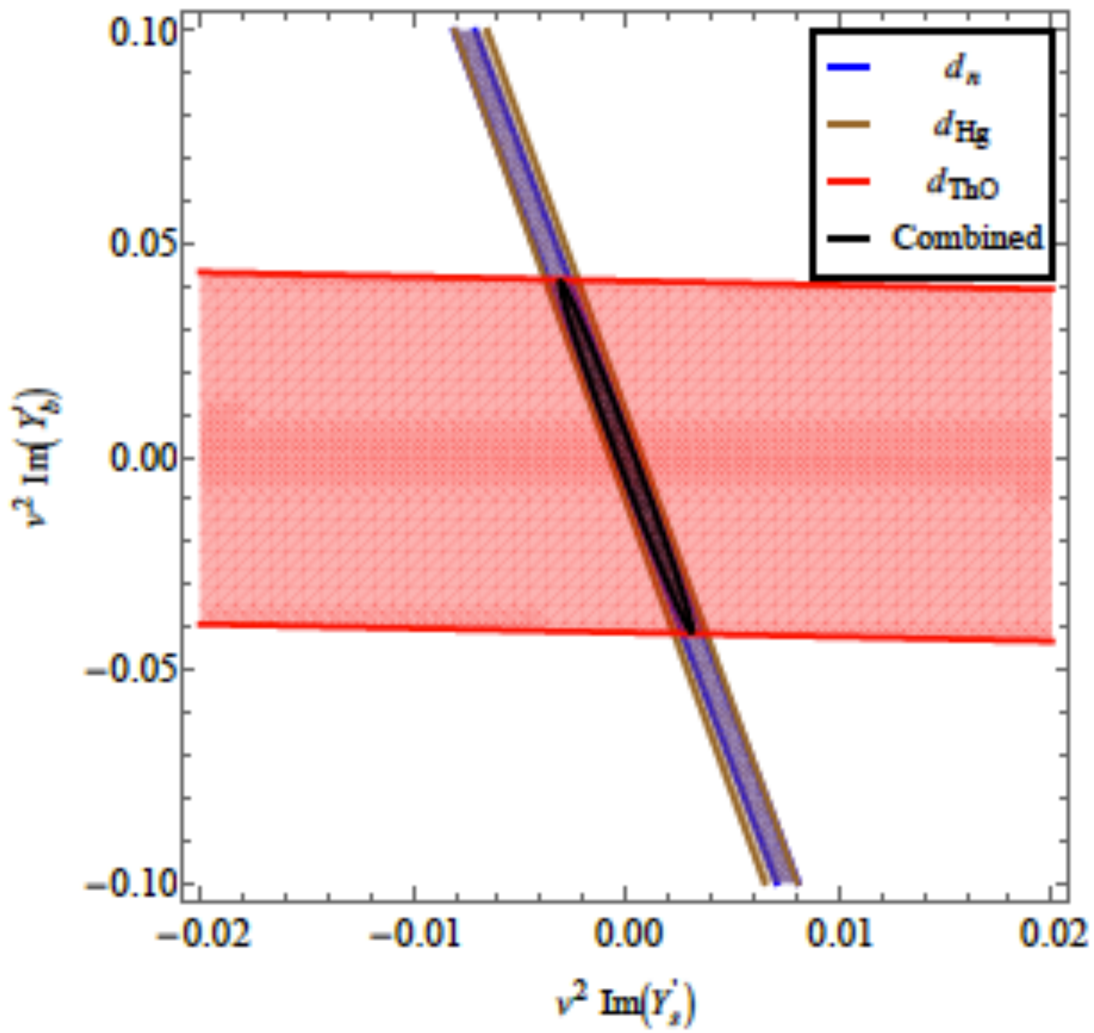
$$\mathcal{L} = \frac{m_q}{v} \tilde{\kappa}_q \; \bar{q} i \gamma_5 q \; h$$

$\tilde{\kappa}_u$	$\tilde{\kappa}_d$	$\tilde{\kappa}_s$	$\tilde{\kappa}_c$	$\tilde{\kappa}_b$	$\tilde{\kappa}_t$
0.45	0.11	58	2.3	3.6	0.01

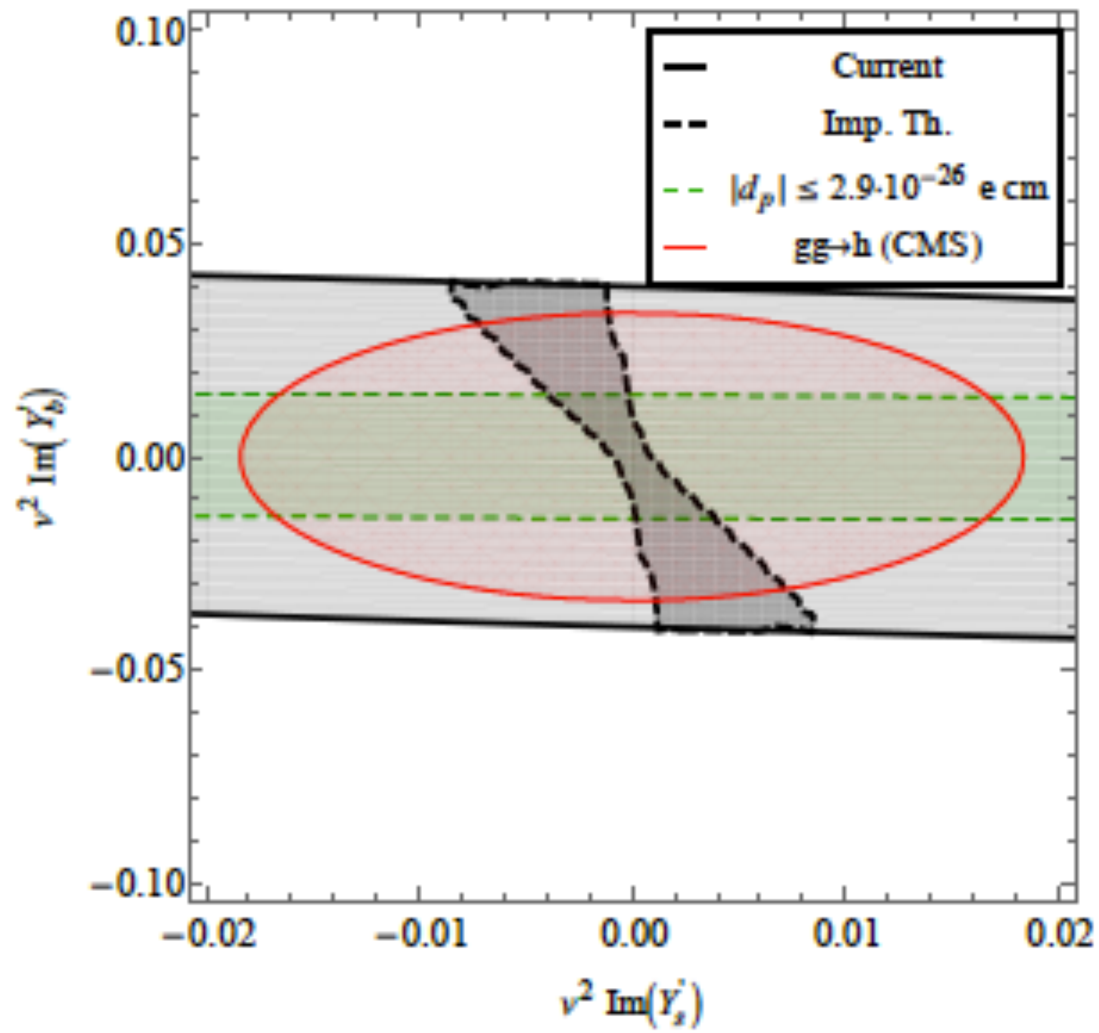
Examples of complementarity

- Two-coupling analysis: Y'_b - Y'_s

Central



RFit



LHC (or improved theory) removes unconstrained direction

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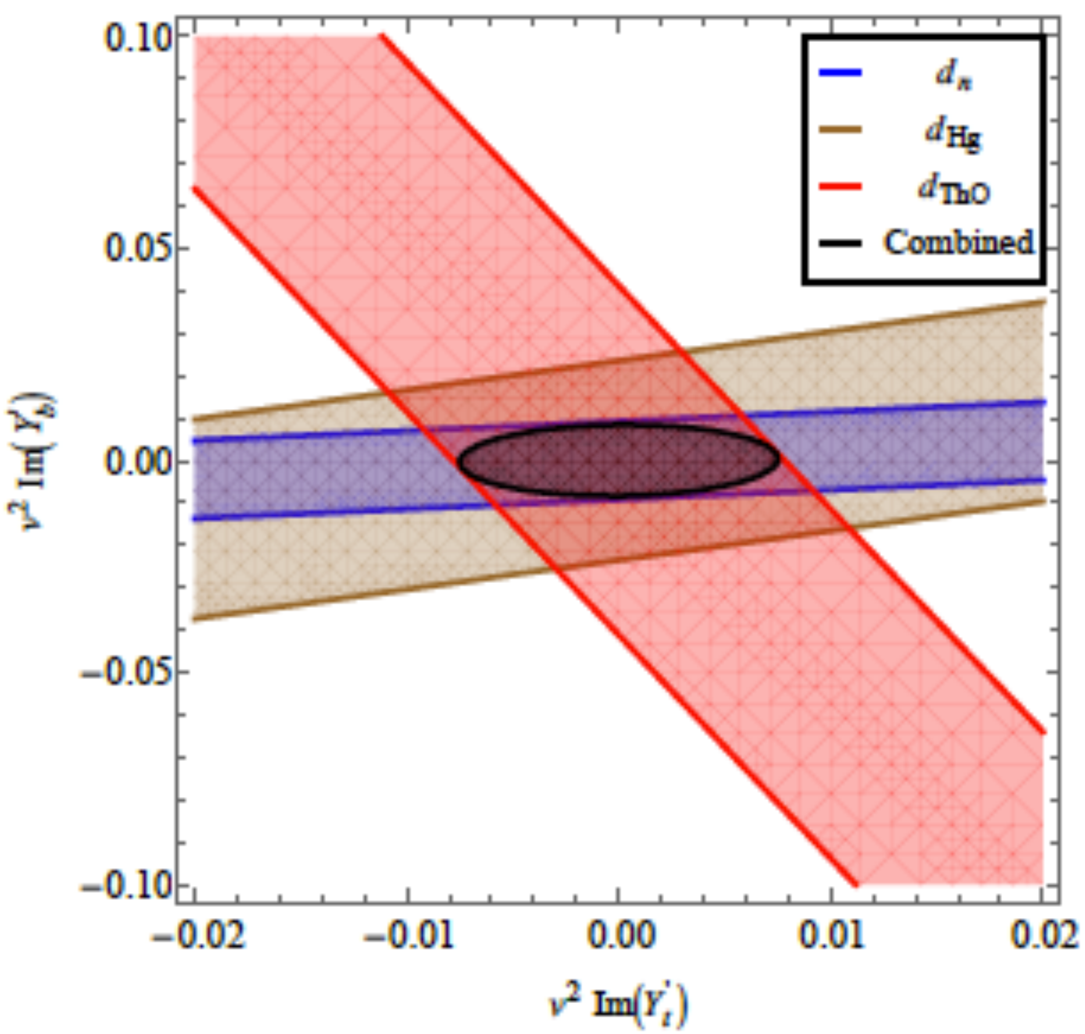

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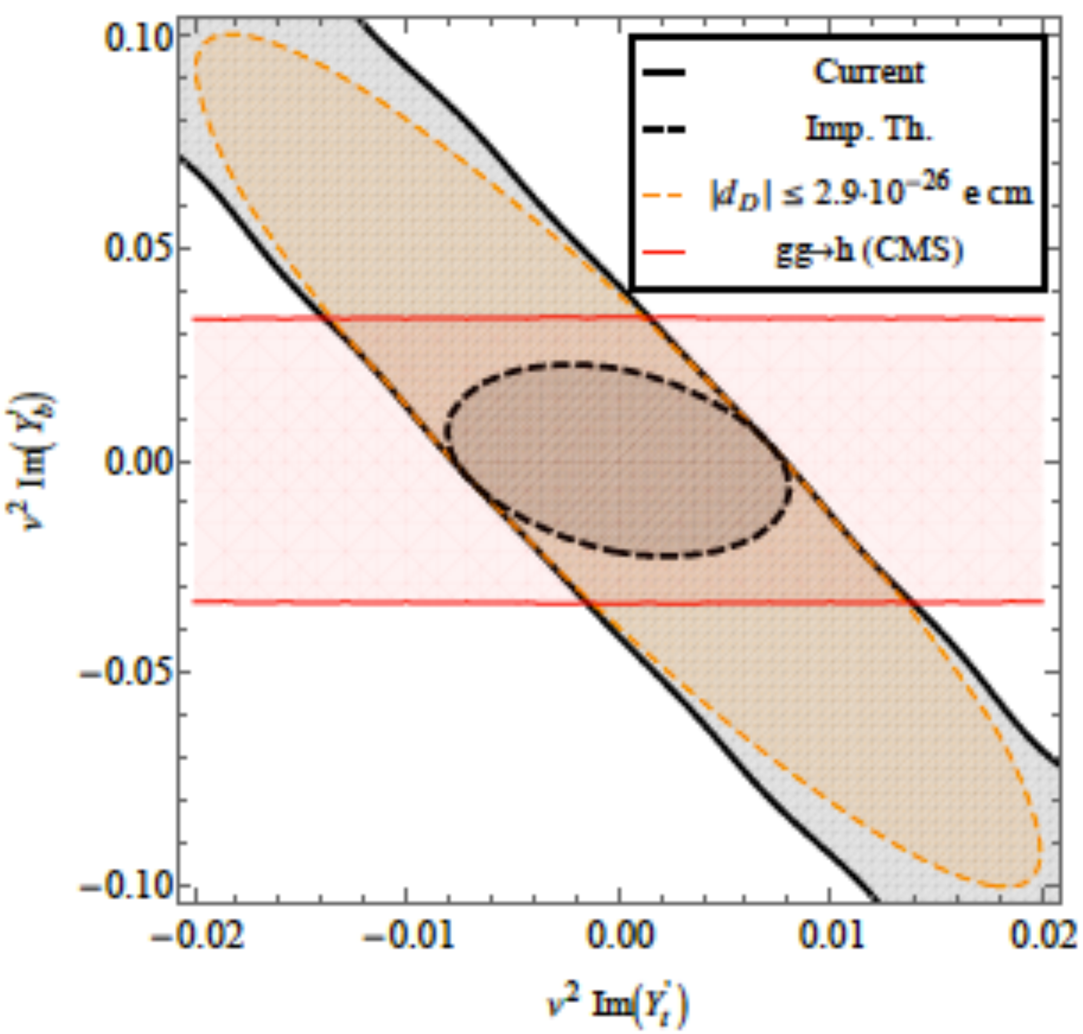

LHC (or improved theory) removes unconstrained direction

Summary table 2

- Improved theory, improved experiments, and both

	$v^2 \mathrm{Im}\, Y'_u$	$v^2 \mathrm{Im}\, Y'_d$	$v^2 \mathrm{Im}\, Y'_c$	$v^2 \mathrm{Im}\, Y'_s$	$v^2 \mathrm{Im}\, Y'_t$	$v^2 \mathrm{Im}\, Y'_b$	$v^2\, \theta'$	$v^2 \tilde{d}_t / m_t$
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Current+Th.	$1.9 \cdot 10^{-6}$	$9.7 \cdot 10^{-7}$	$2.2 \cdot 10^{-3}$	$8.7 \cdot 10^{-4}$	$7.8 \cdot 10^{-3}$	0.011	0.052	$1.5 \cdot 10^{-3}$
$d_n + d_{\mathrm{ThO}}$	$9.5 \cdot 10^{-9}$	$5.1 \cdot 10^{-9}$	$2.3 \cdot 10^{-5}$	0.024	$2.4 \cdot 10^{-4}$	$2.4 \cdot 10^{-3}$	$8.0 \cdot 10^{-4}$	$1.8 \cdot 10^{-4}$
$d_n + d_{\mathrm{ThO}}$+Th.	$7.0 \cdot 10^{-9}$	$3.6 \cdot 10^{-9}$	$8.4 \cdot 10^{-6}$	$3.5 \cdot 10^{-6}$	$1.7 \cdot 10^{-4}$	$8.9 \cdot 10^{-5}$	$3.3 \cdot 10^{-4}$	$9.5 \cdot 10^{-6}$
$d_{\mathrm{Xe}} + d_{\mathrm{Ra}}$	$1.3 \cdot 10^{-6}$	$3.4 \cdot 10^{-7}$	$6.3 \cdot 10^{-3}$	0.41	$7.8 \cdot 10^{-3}$	0.040	0.14	$2.3 \cdot 10^{-2}$
$d_{\mathrm{Xe}} + d_{\mathrm{Ra}}$+Th.	$1.6 \cdot 10^{-7}$	$9.4 \cdot 10^{-7}$	$2.2 \cdot 10^{-3}$	$8.7 \cdot 10^{-4}$	$6.1 \cdot 10^{-3}$	$8.1 \cdot 10^{-3}$	0.011	$1.5 \cdot 10^{-3}$
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LHC Run 2	$0.7 \cdot 10^{-2}$	$0.8 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$	$12 \cdot 10^{-2}$	$3.6 \cdot 10^{-2}$	0.21	$4.0 \cdot 10^{-2}$

Summary table 2

- Improved theory, improved experiments, and both

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$d_{\mathrm{Xe}} + d_{\mathrm{Ra}}$	$1.3 \cdot 10^{-6}$	$3.4 \cdot 10^{-7}$	$6.3 \cdot 10^{-3}$	0.41	$7.8 \cdot 10^{-3}$	0.040	0.14	$2.3 \cdot 10^{-2}$
$d_{\mathrm{Xe}} + d_{\mathrm{Ra}}$+Th.	$1.6 \cdot 10^{-7}$	$9.4 \cdot 10^{-7}$	$2.2 \cdot 10^{-3}$	$8.7 \cdot 10^{-4}$	$6.1 \cdot 10^{-3}$	$8.1 \cdot 10^{-3}$	0.011	$1.5 \cdot 10^{-3}$
$d_p + d_D$	$1.9 \cdot 10^{-10}$	$2.1 \cdot 10^{-10}$	$2.2 \cdot 10^{-6}$	0.13	$2.3 \cdot 10^{-5}$	0.014	$3.1 \cdot 10^{-5}$	$7.7 \cdot 10^{-6}$
$d_p + d_D$+Th.	$1.5 \cdot 10^{-10}$	$1.8 \cdot 10^{-10}$	$8.4 \cdot 10^{-7}$	$1.7 \cdot 10^{-7}$	$1.8 \cdot 10^{-5}$	$8.2 \cdot 10^{-6}$	$2.2 \cdot 10^{-5}$	$9.0 \cdot 10^{-7}$
LHC Run 1	$0.6 \cdot 10^{-2}$	$0.7 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$15 \cdot 10^{-2}$	$3.8 \cdot 10^{-2}$	0.27	$5.2 \cdot 10^{-2}$
LHC Run 2	$0.7 \cdot 10^{-2}$	$0.8 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$	$12 \cdot 10^{-2}$	$3.6 \cdot 10^{-2}$	0.21	$4.0 \cdot 10^{-2}$

- Impact of improved experiments:
  - Constraints from EDMs scale linearly with EDM sensitivity
  - LHC Run 2 unimpressive sensitivity: σ_{BSM}/σ_{SM} does not grow with $\sqrt{s}$ (except for $\tilde{d}_t$)

Summary table 2

- Improved theory, improved experiments, and both

	$v^2 \mathrm{Im}\, Y_u'$	$v^2 \mathrm{Im}\, Y_d'$	$v^2 \mathrm{Im}\, Y_c'$	$v^2 \mathrm{Im}\, Y_s'$	$v^2 \mathrm{Im}\, Y_t'$	$v^2 \mathrm{Im}\, Y_b'$	$v^2\, \theta'$	$v^2 \tilde{d}_t / m_t$
Current EDMs	$2.8 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	$6.3 \cdot 10^{-3}$	0.42	$7.8 \cdot 10^{-3}$	0.041	0.23	$4.1 \cdot 10^{-2}$
Current+Th.	$1.9 \cdot 10^{-6}$	$9.7 \cdot 10^{-7}$	$2.2 \cdot 10^{-3}$	$8.7 \cdot 10^{-4}$	$7.8 \cdot 10^{-3}$	0.011	0.052	$1.5 \cdot 10^{-3}$
$d_n + d_{\mathrm{ThO}}$	$9.5 \cdot 10^{-9}$	$5.1 \cdot 10^{-9}$	$2.3 \cdot 10^{-5}$	0.024	$2.4 \cdot 10^{-4}$	$2.4 \cdot 10^{-3}$	$8.0 \cdot 10^{-4}$	$1.8 \cdot 10^{-4}$
$d_n + d_{\mathrm{ThO}}$+Th.	$7.0 \cdot 10^{-9}$	$3.6 \cdot 10^{-9}$	$8.4 \cdot 10^{-6}$	$3.5 \cdot 10^{-6}$	$1.7 \cdot 10^{-4}$	$8.9 \cdot 10^{-5}$	$3.3 \cdot 10^{-4}$	$9.5 \cdot 10^{-6}$
$d_{\mathrm{Xe}} + d_{\mathrm{Ra}}$	$1.3 \cdot 10^{-6}$	$3.4 \cdot 10^{-7}$	$6.3 \cdot 10^{-3}$	0.41	$7.8 \cdot 10^{-3}$	0.040	0.14	$2.3 \cdot 10^{-2}$
$d_{\mathrm{Xe}} + d_{\mathrm{Ra}}$+Th.	$1.6 \cdot 10^{-7}$	$9.4 \cdot 10^{-7}$	$2.2 \cdot 10^{-3}$	$8.7 \cdot 10^{-4}$	$6.1 \cdot 10^{-3}$	$8.1 \cdot 10^{-3}$	0.011	$1.5 \cdot 10^{-3}$
$d_p + d_D$	$1.9 \cdot 10^{-10}$	$2.1 \cdot 10^{-10}$	$2.2 \cdot 10^{-6}$	0.13	$2.3 \cdot 10^{-5}$	0.014	$3.1 \cdot 10^{-5}$	$7.7 \cdot 10^{-6}$
$d_p + d_D$+Th.	$1.5 \cdot 10^{-10}$	$1.8 \cdot 10^{-10}$	$8.4 \cdot 10^{-7}$	$1.7 \cdot 10^{-7}$	$1.8 \cdot 10^{-5}$	$8.2 \cdot 10^{-6}$	$2.2 \cdot 10^{-5}$	$9.0 \cdot 10^{-7}$
LHC Run 1	$0.6 \cdot 10^{-2}$	$0.7 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$15 \cdot 10^{-2}$	$3.8 \cdot 10^{-2}$	0.27	$5.2 \cdot 10^{-2}$
LHC Run 2	$0.7 \cdot 10^{-2}$	$0.8 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$	$12 \cdot 10^{-2}$	$3.6 \cdot 10^{-2}$	0.21	$4.0 \cdot 10^{-2}$

- Impact of improved EDM matrix elements:
  - Can strengthen bounds more than new EDM measurements
  - Put *current* EDM bounds beyond reach of LHC Run 2 cross-section sensitivity

Conclusions

- EFT is very useful tool to study high-scale BSM physics
- Worked example: bounds on CPV Higgs-quark and Higgs-gluon couplings, through EDMs and Higgs production at the LHC
- Uncertainty in matrix elements strongly affects EDM constraints. Quantified improvements needed to exploit EDM searches

$d_{n,p}[\tilde{d}_{u,d}]$ — 25%

$d_{n,p}[d_s]$ $d_{n,p}[d_W]$ $\bar{g}_{0,1}[\tilde{d}_{u,d}]$ $S_{\rm Hg}[\bar{g}_{0,1}]$ — 50%

Challenging goal for Lattice QCD and Nuclear Structure

- Current best bounds come from combination of LHC and EDMs
- Future: EDMs will have major impact on pinning down Higgs couplings

Outlook

Anticipating discoveries at LHC Run 2 and next generation EDMs, prepare for their interpretation:

- Study collider observables with linear sensitivity to CPV couplings
- Extend analysis to Higgs operators that involve EW gauge bosons
- Linear vs non-linear EFT realization: testable differences?

Backup slides

Dependence on θ-term

- Recent progress in Lattice QCD calculations

  - Nucleon EDMs

$$d_{n,p}\,[\bar{\theta};\ d_{u,d,s};\ \tilde{d}_{u,d,s};\ c_w;\ c_{4q}]$$

  - Pion-nucleon CP-odd couplings

$$\bar{g}_{0,1}\,[\bar{\theta};\ \tilde{d}_{u,d,s};\ c_w;\ c_{4q}]$$

RECENT PROGRESS

$$\frac{d_n}{\bar{\theta}} = -3.8(2)_{\rm stat}(9)_{\rm fit}\ 10^{-3}\, e\,{\rm fm}$$

Guo et al., 1502.02295

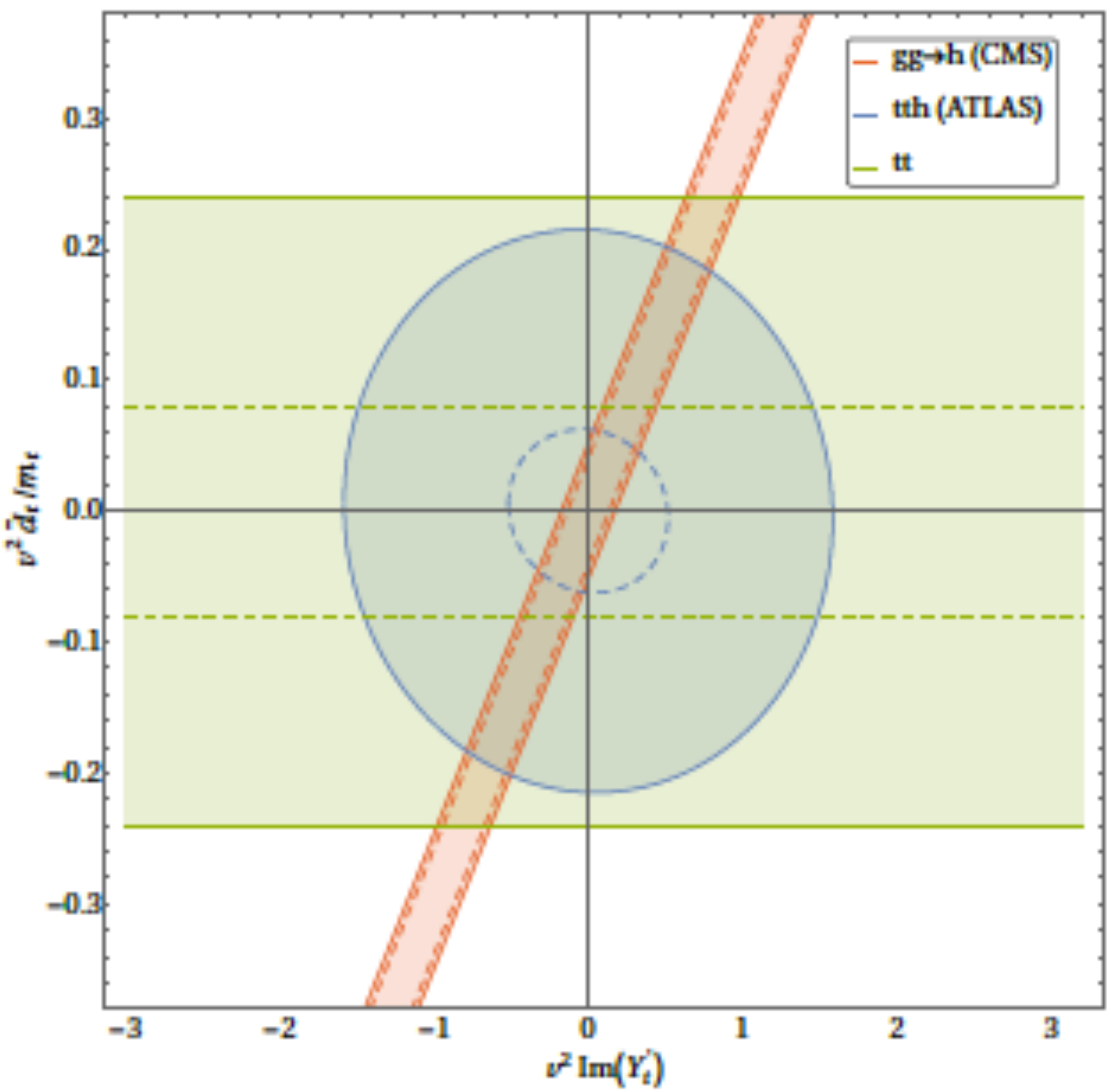
$$\frac{d_n}{\bar{\theta}} = -2.7(1.2)\ 10^{-3}\ e\,{\rm fm}$$

Akan et al., 1406.2882
Fit to Shintani et al, POS (Lat 2013) 298

$$\frac{\bar{g}_0}{F_\pi} = (15 \pm 2)\cdot 10^{-3}\sin\bar{\theta}$$

Mereghetti, van Kolck 1505.06272 with input from A. Walker-Loud, '14; Borsanyi et al, '14.

Top CPV couplings



Zoom in