New Opportunities for Fundamental Physics Research with Radioactive Molecules
Virtual Meeting
June 28 - July 2, 2021

Electric Dipole Moments as probes of New Physics

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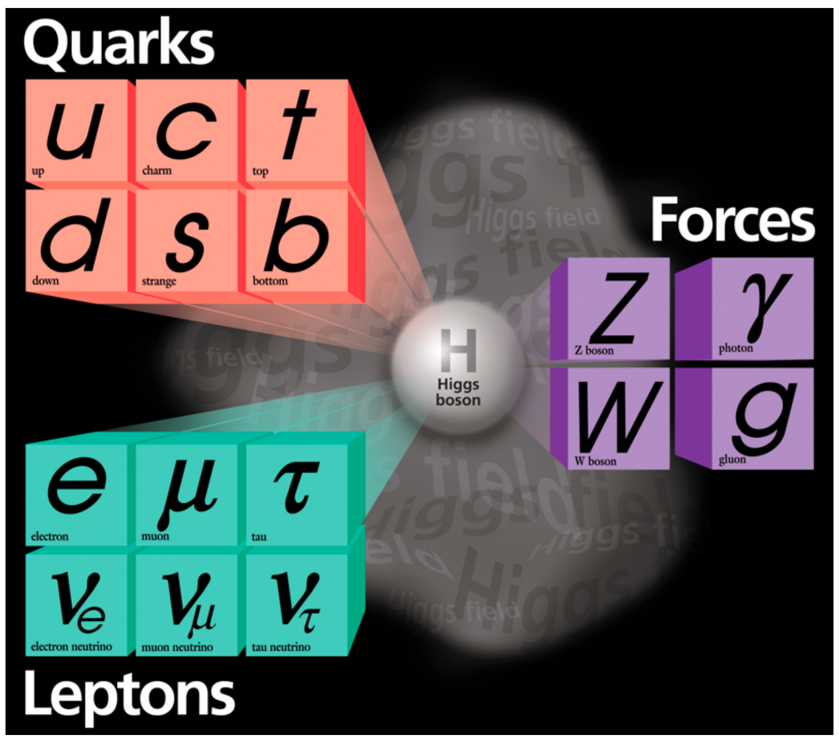
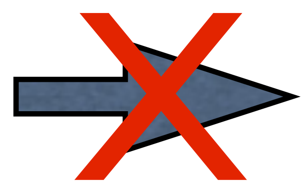
LA-UR-21-26015

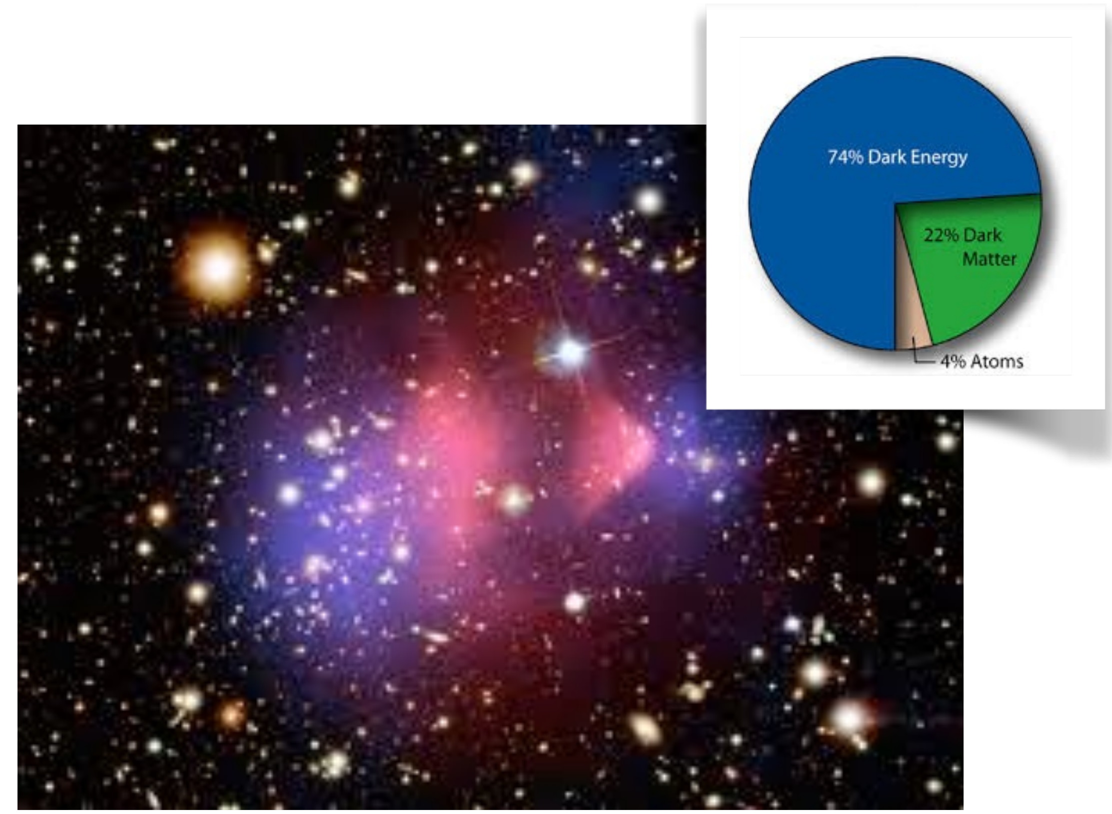
Outline

- The quest for new physics and the special role of EDMs
- Connecting EDMs to underlying sources of CP violation
    - EFT framework
    - Nucleon EDM in lattice QCD
- (Selected topics in) EDM phenomenology in the LHC era
    - Non-standard CP-violating Higgs couplings

New physics: why?





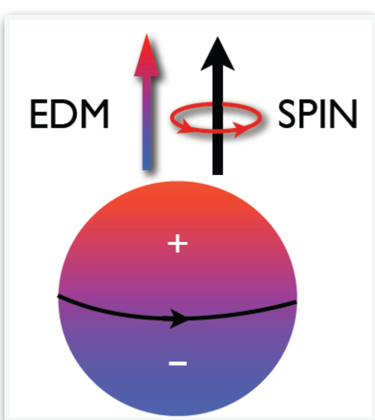


No Matter, no Dark Matter, no Dark Energy

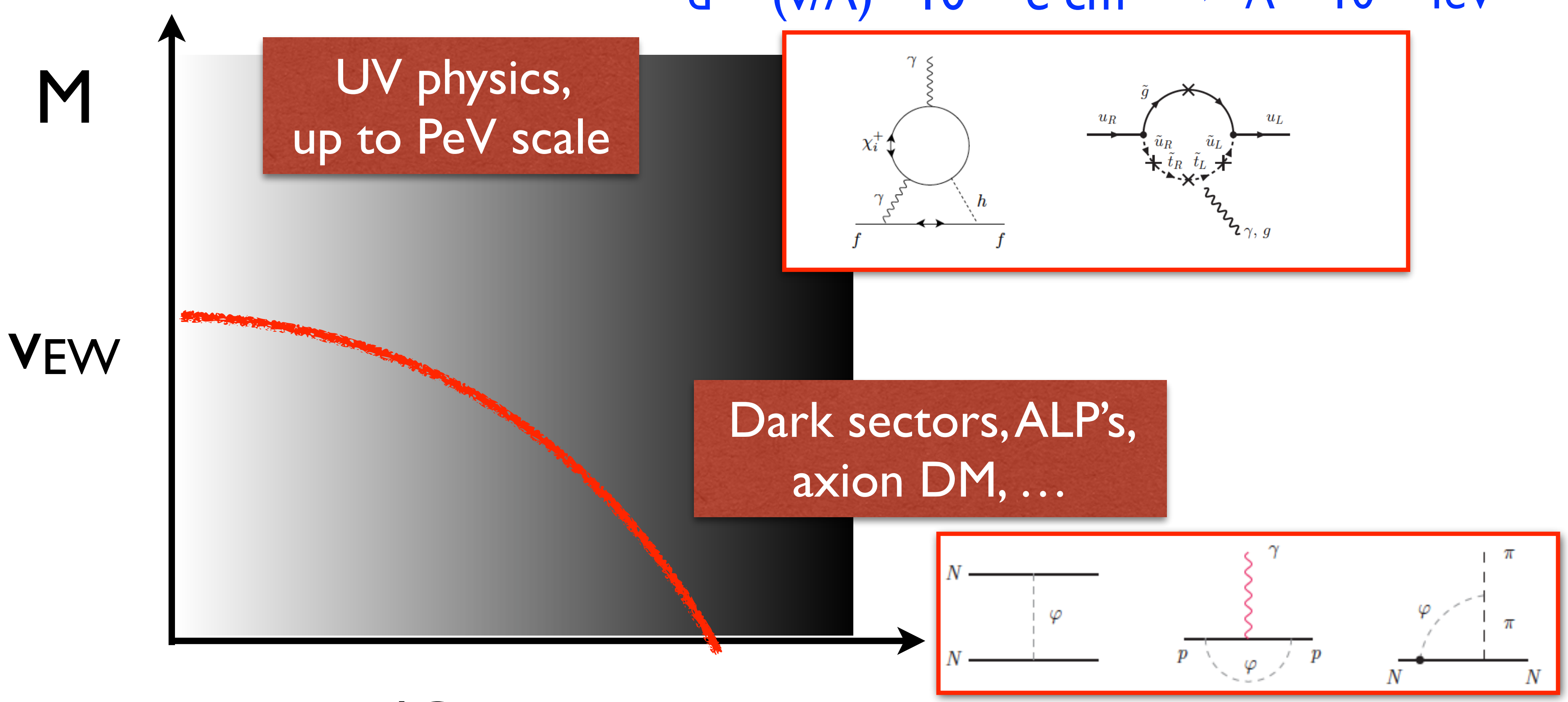
While remarkably successful in explaining phenomena over a wide range of energies, the SM is probably not the whole story

Special role of EDMs

- Probe P *and* T symmetry violation (CP) in flavor diagonal transitions: (i) highly suppressed in SM; (ii) sensitive to broad spectrum of new physics; (iii) possibly related to baryon asymmetry in the universe



$d \sim (v/\Lambda)^2\ 10^{-22}$ e cm $\rightarrow\ \Lambda \sim 10^{2\text{-}3}$ TeV



Dzuba, Flambaum, Samsonov, Stadnik, 1805.01234
Abel et al., 1708.06367
LeDall, Pospelov, Ritz 1505.01865
Mantry, Pitschmann, Ramsey-Musolf 1401.7339
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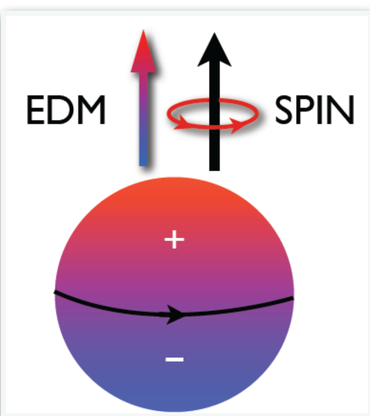

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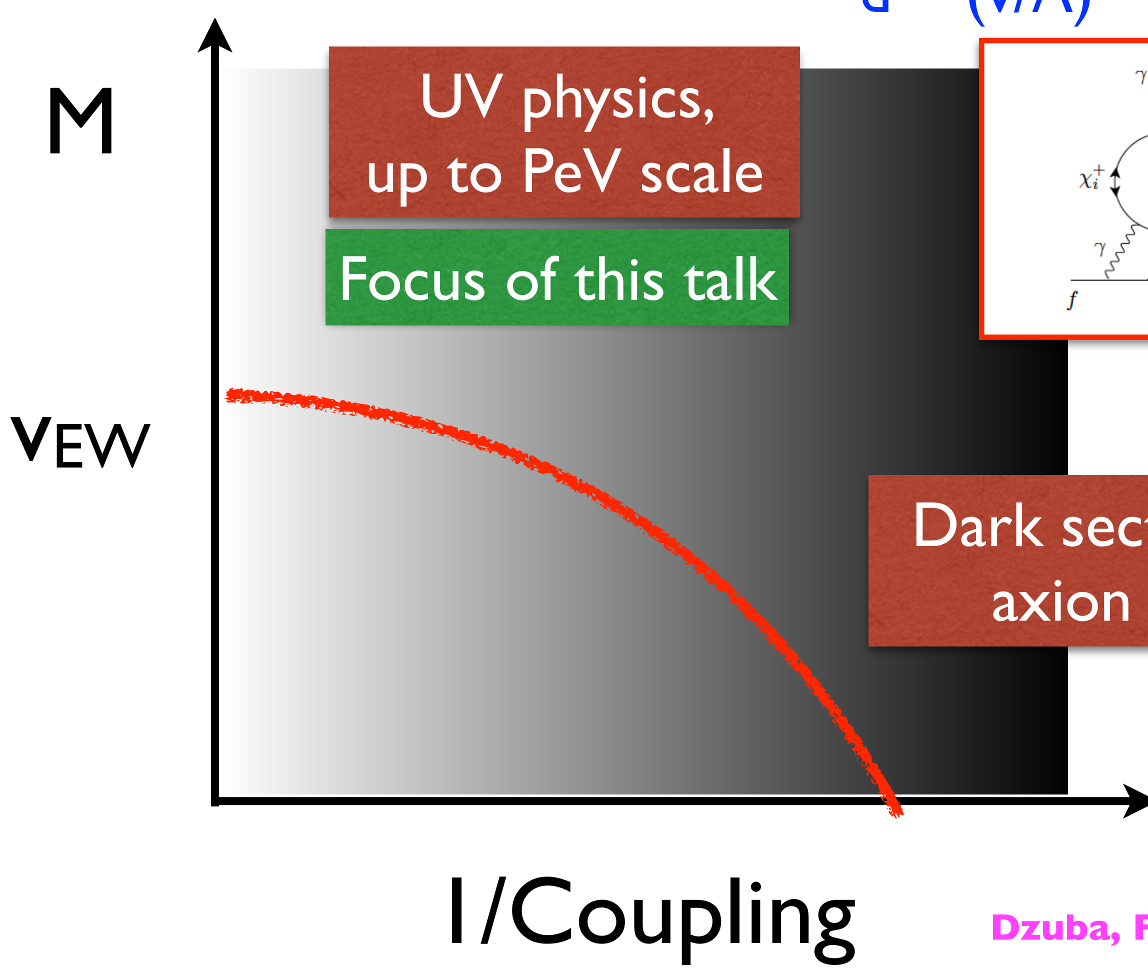

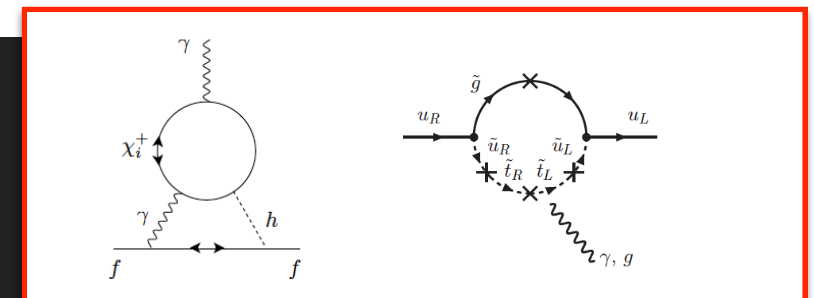

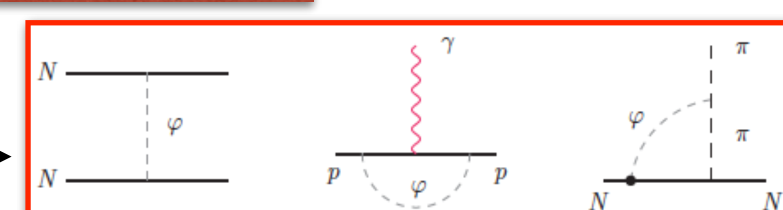

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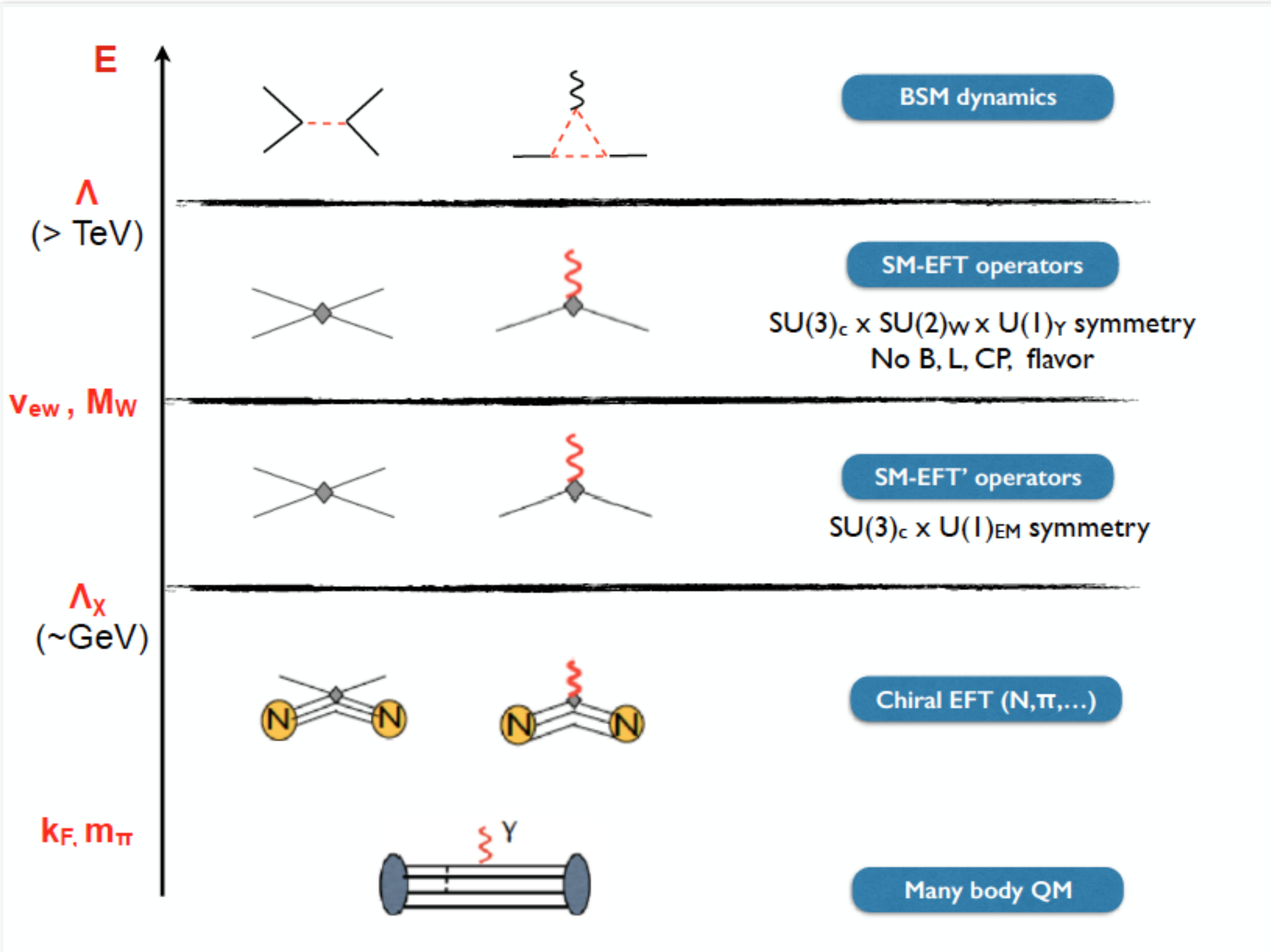
Connecting EDMs to underlying sources of CPV

Connecting scales

To connect UV physics to nuclei & atoms, use multiple EFTs



$$\mathcal{L}_{\rm BSM}$$

$$\downarrow$$

$$\mathcal{L}_{\rm SM} + \sum_{\alpha} \frac{c_\alpha}{\Lambda^2} O_\alpha + \ldots$$

$$\downarrow$$

$$\tilde{\mathcal{L}}_{\rm SM} + \sum_{\beta} \tilde{c}_\beta \, \tilde{O}_\beta$$

Connecting scales

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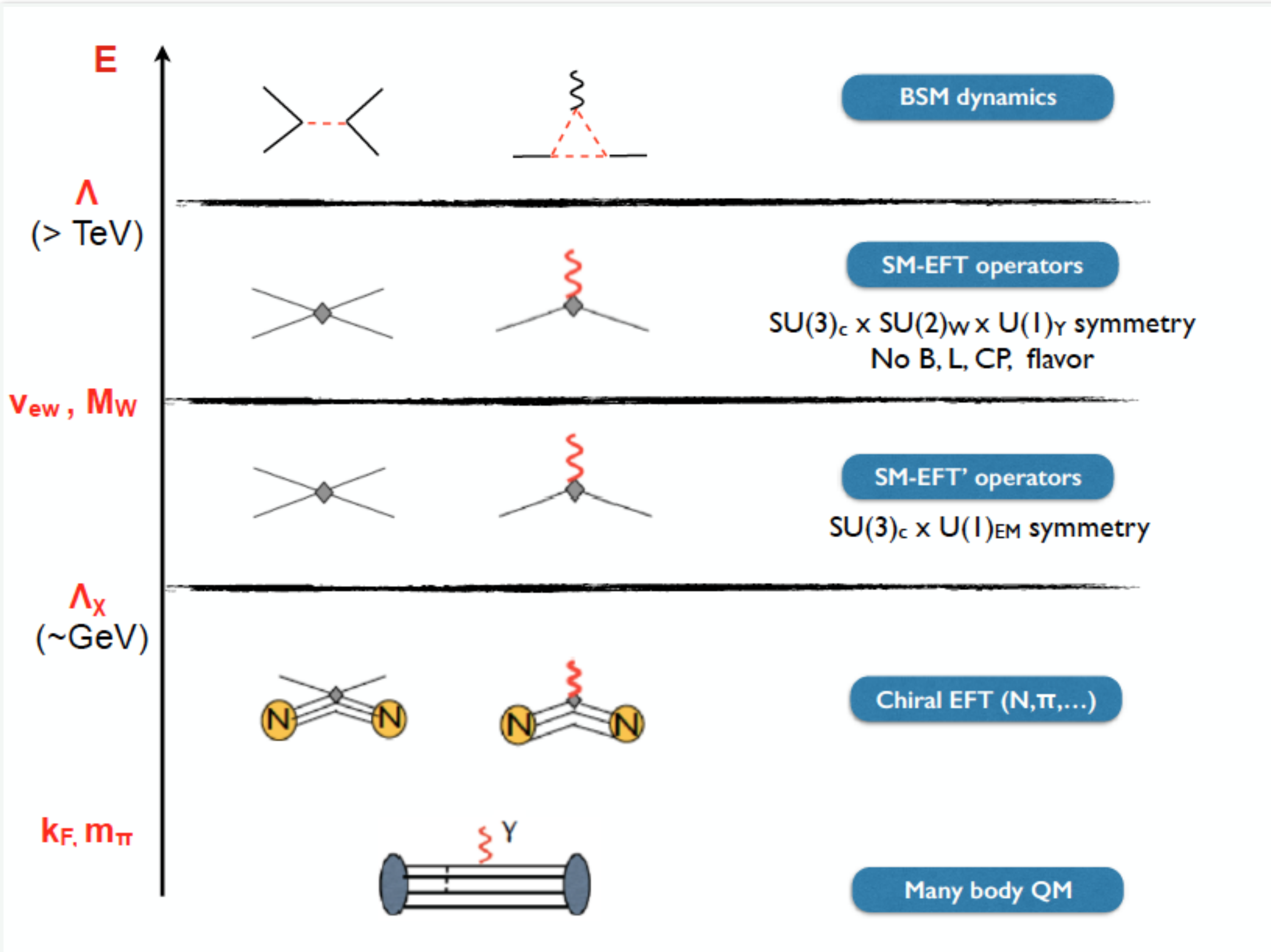


$$\mathcal{L}_{\rm BSM}$$

↓ Perturbative

$$\mathcal{L}_{\rm SM} + \sum_\alpha \frac{c_\alpha}{\Lambda^2} O_\alpha + \ldots$$

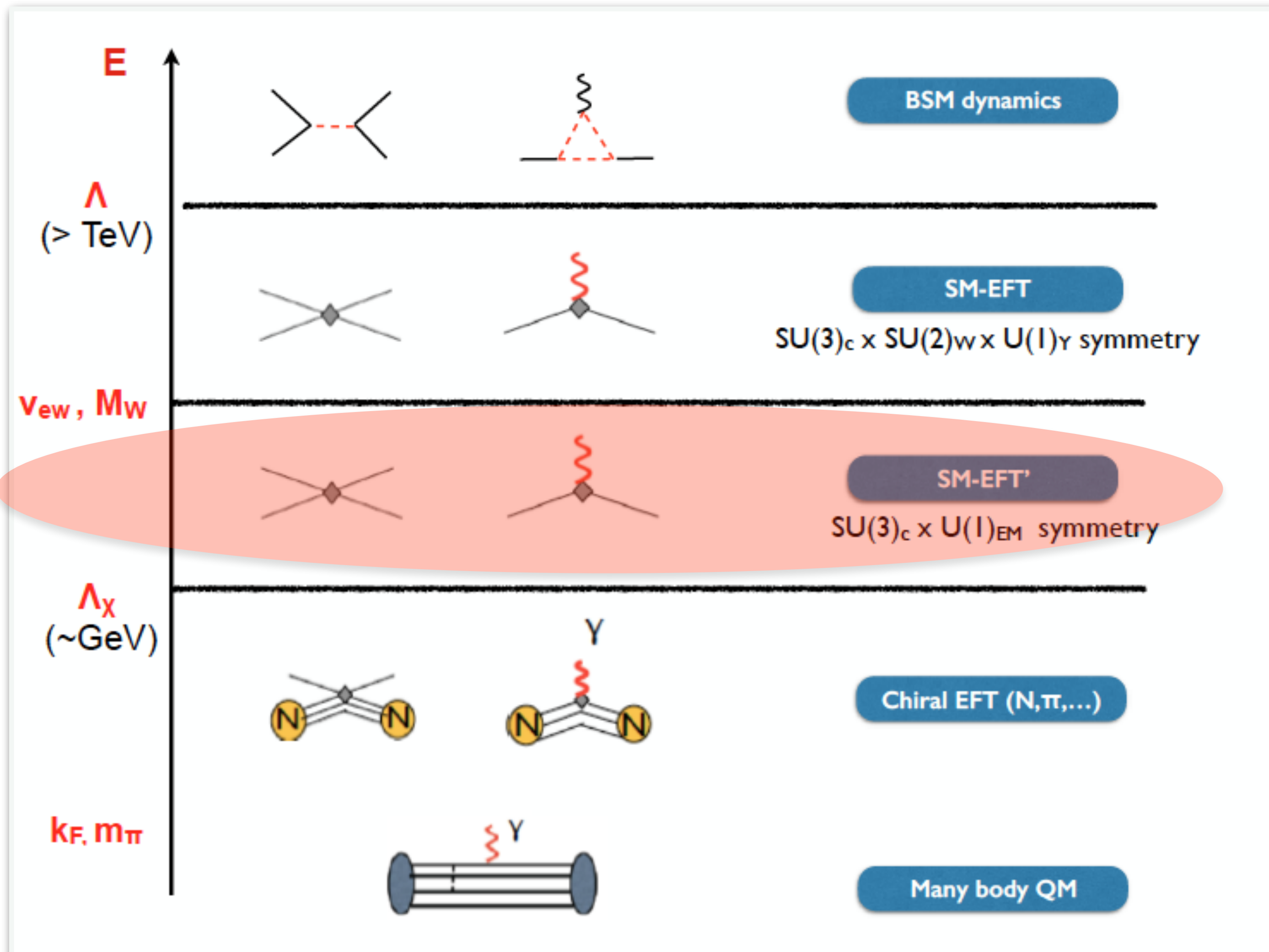
$\tilde{c}_\beta [c_\alpha]$ ↓ Non-perturbative

$$\tilde{\mathcal{L}}_{\rm SM} + \sum_\beta \tilde{c}_\beta \tilde{O}_\beta$$

↓ Non-perturbative

$$d_A [\tilde{c}_\beta [c_\alpha]]$$

CPV at the quark-gluon level



$$\mathcal{L}_{\rm BSM}$$

Perturbative

$$\mathcal{L}_{\rm SM} + \sum_\alpha \frac{c_\alpha}{\Lambda^2} O_\alpha + \ldots$$

CPV at the quark-gluon level

- At E ~GeV, Standard Model CPV in QCD theta term and CKM phase

$$\mathcal{L}_4^{CPV} = -\bar{\theta}\frac{g_s^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} - \left(\frac{g_2}{2\sqrt{2}}W_\mu^+\ \bar{u}_i\gamma^\mu(1-\gamma_5)V_{ij}d_j + \mathrm{h.c.}\right)$$

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$$\bar{\theta} = \theta - \text{ArgDet}(\mathcal{M}_q)$$

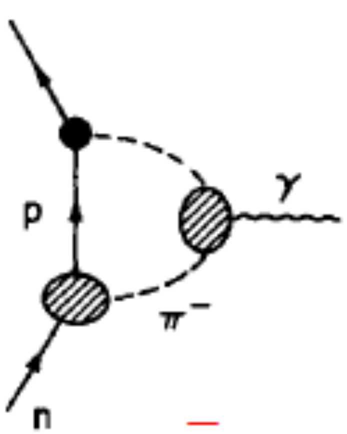
$\sim B_c \cdot E_c$

Baluni 1979
Crewther, Di Vecchia, Veneziano, Witten 1979

$$-m_* \,\bar{\theta}\, \bar{q}\, i\gamma_5 q$$

$\sim \sigma \cdot (p_f - p_i)$

$$m_* = \frac{1}{\sum_i (1/m_i)} \simeq \frac{m_u m_d}{m_u + m_d}$$



$\bar{\theta}$

$$d_n \sim \frac{m_*}{\Lambda_{\text{had}}^2} e\bar{\theta} \sim 10^{-17}\,\bar{\theta}\, e\text{cm} \quad \rightarrow \quad |\bar{\theta}| < 10^{-9}$$

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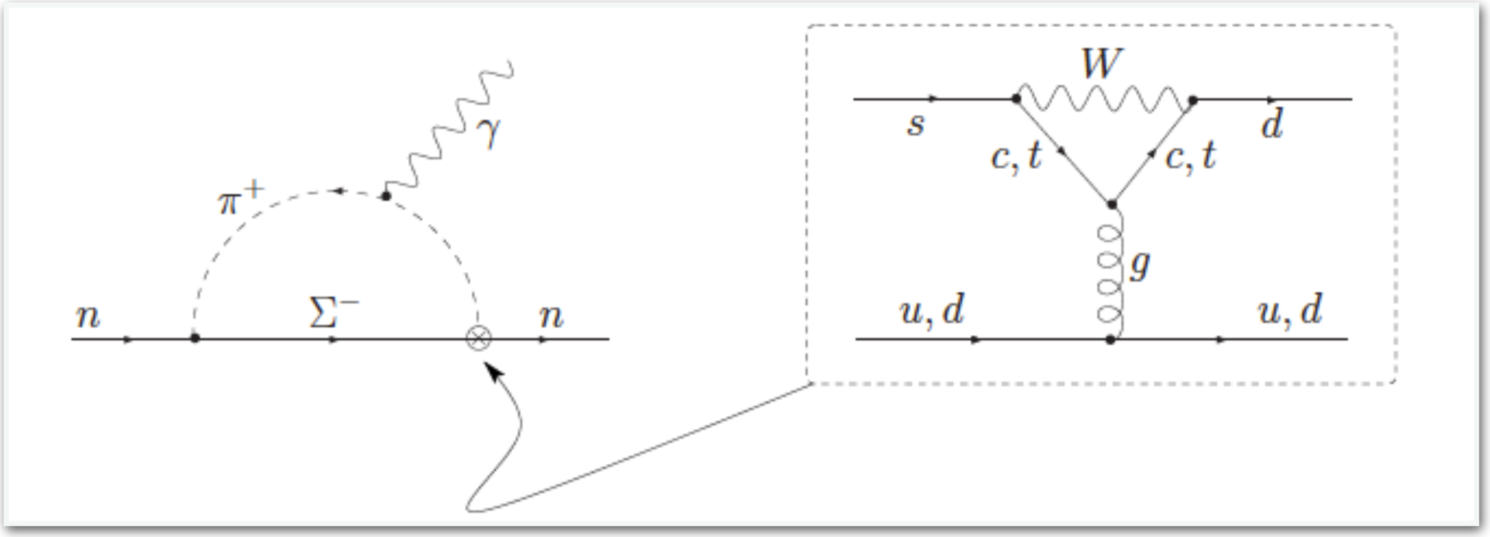

Dominant contribution to nEDM

$d_n \sim 10^{-31}$ e cm

...

Pospelov-Ritz hep-ph/0504231

C.Y. Seng 1411.1476

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EDMs in $e \cdot cm$

Th0 → e

System	current limit	projected	SM (CKM)
e	$\sim 10^{-29}$	$\sim 5\times 10^{-30}$	$\sim 10^{-38}$
μ	$\sim 10^{-19}$		$\sim 10^{-35}$
τ	$\sim 10^{-16}$		$\sim 10^{-34}$
n	$\sim 10^{-26}$	10^{-28}	$\sim 10^{-31}$
p	$\sim 10^{-23}$	10^{-29}	$\sim 10^{-31}$
^{199}Hg	$\sim 6\times 10^{-30}$	10^{-30}	$\sim 10^{-33}$
^{129}Xe	$\sim 10^{-27}$	10^{-29}	$\sim 10^{-33}$
^{225}Ra	$\sim 10^{-23}$	10^{-26}	$\sim 10^{-33}$
...	...		...

For a recent review see: Chupp, Fierlinger, Ramsey-Musolf, Singh, 1710.02504

* Observation would signal new physics or a tiny QCD θ-term (< 10^{-10}).
Multiple measurements can disentangle the two effects

CPV at the quark-gluon level

- At E ~GeV, leading BSM effects encoded in handful of dim-6 operators

$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\, \bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q\, g_s\, \bar{q}\sigma\cdot G\gamma_5 q + d_W \frac{g_s}{6} G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

Electric and chromo-electric dipoles of fermions

$$d_f, \tilde{d}_q \sim \frac{v_{ew}}{\Lambda^2}$$

$\mathbf{J\cdot E}$ $\mathbf{J\cdot E_c}$

Gluon chromo-EDM (Weinberg operator)

$$d_W \sim \frac{1}{\Lambda^2}$$

Semileptonic and 4-quark

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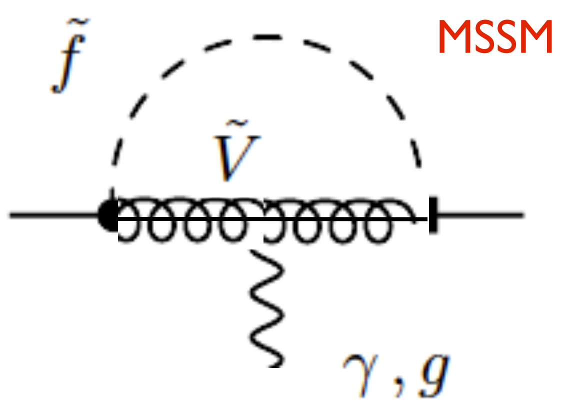
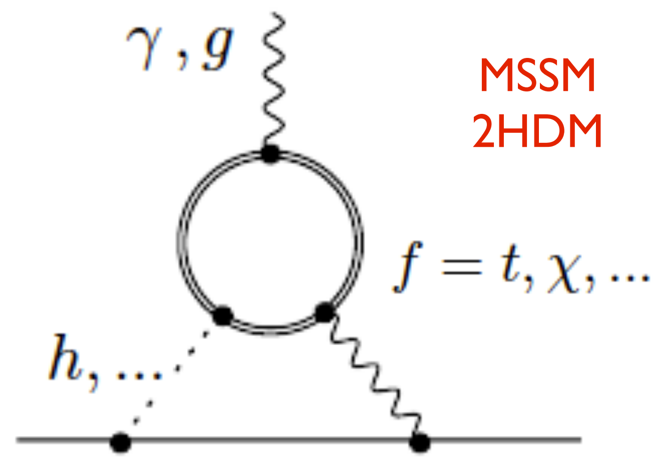
- Generated by a variety of BSM scenarios





→ Quark EDM and chromo-EDM

Matching at high scale Λ

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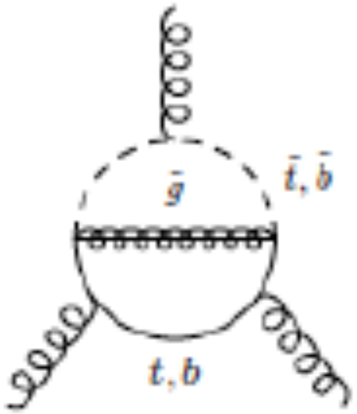
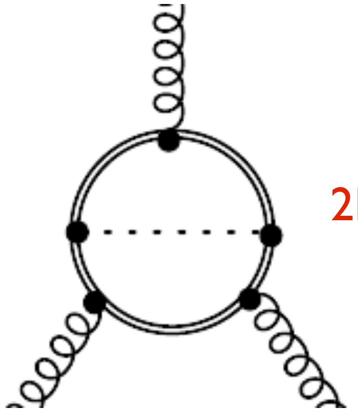


MSSM



2HDM

→ Weinberg operator

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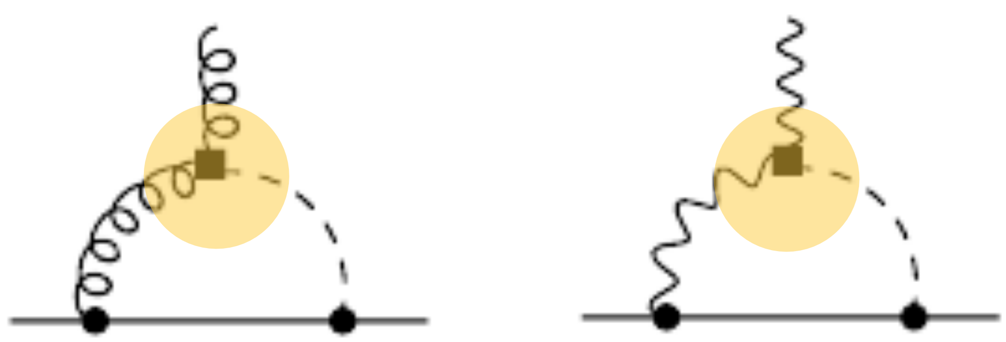
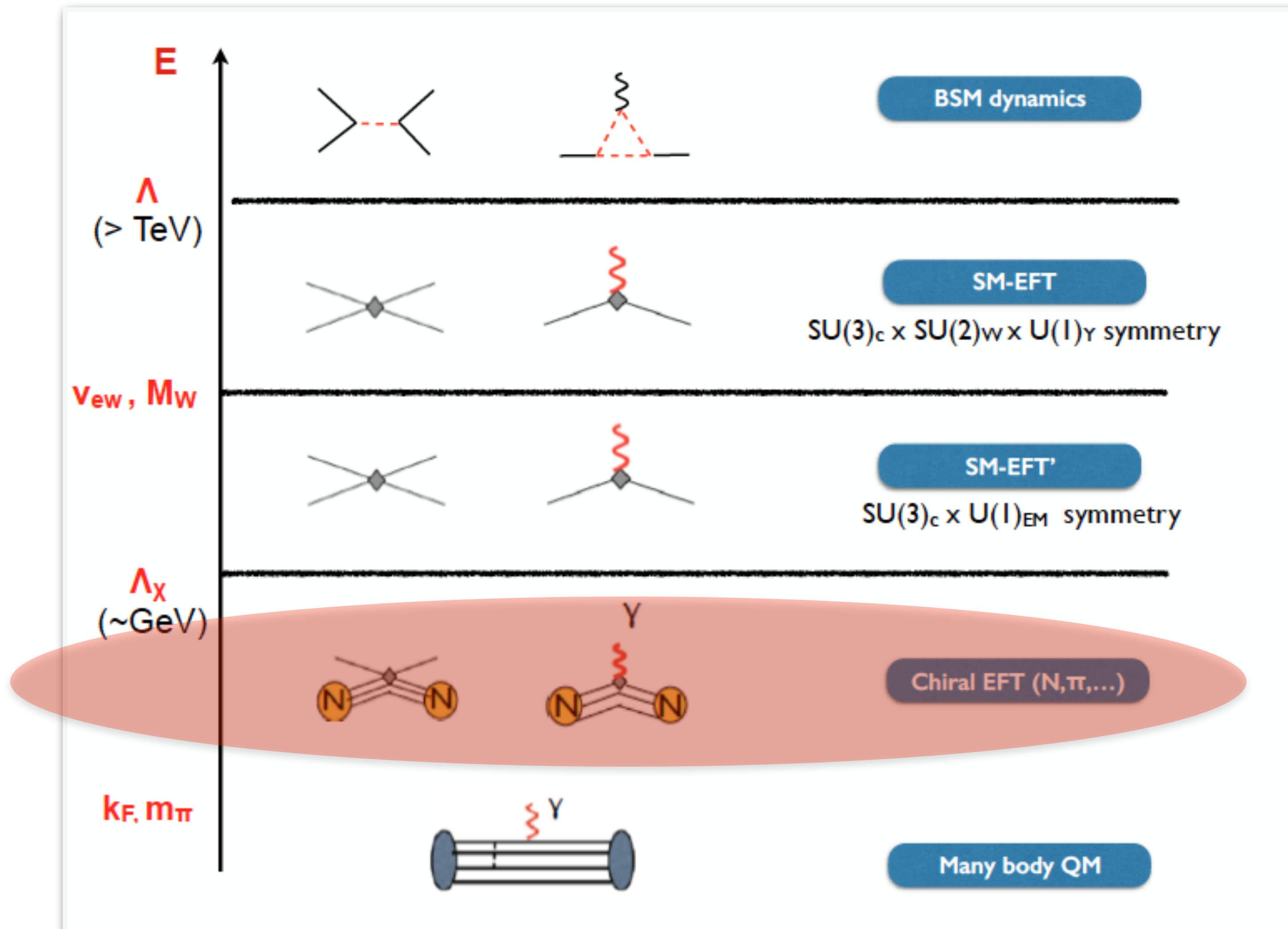


Operator mixing (quantum effects) between Λ and weak scale

CPV at the hadronic level



$$\mathcal{L}_{\rm SM} + \sum_\alpha \frac{c_\alpha}{\Lambda^2} O_\alpha + \ldots$$

$$\tilde{c}_\beta [c_\alpha]$$

Non-perturbative

$$\tilde{\mathcal{L}}_{\rm SM} + \sum_\beta \tilde{c}_\beta \, \tilde{O}_\beta$$

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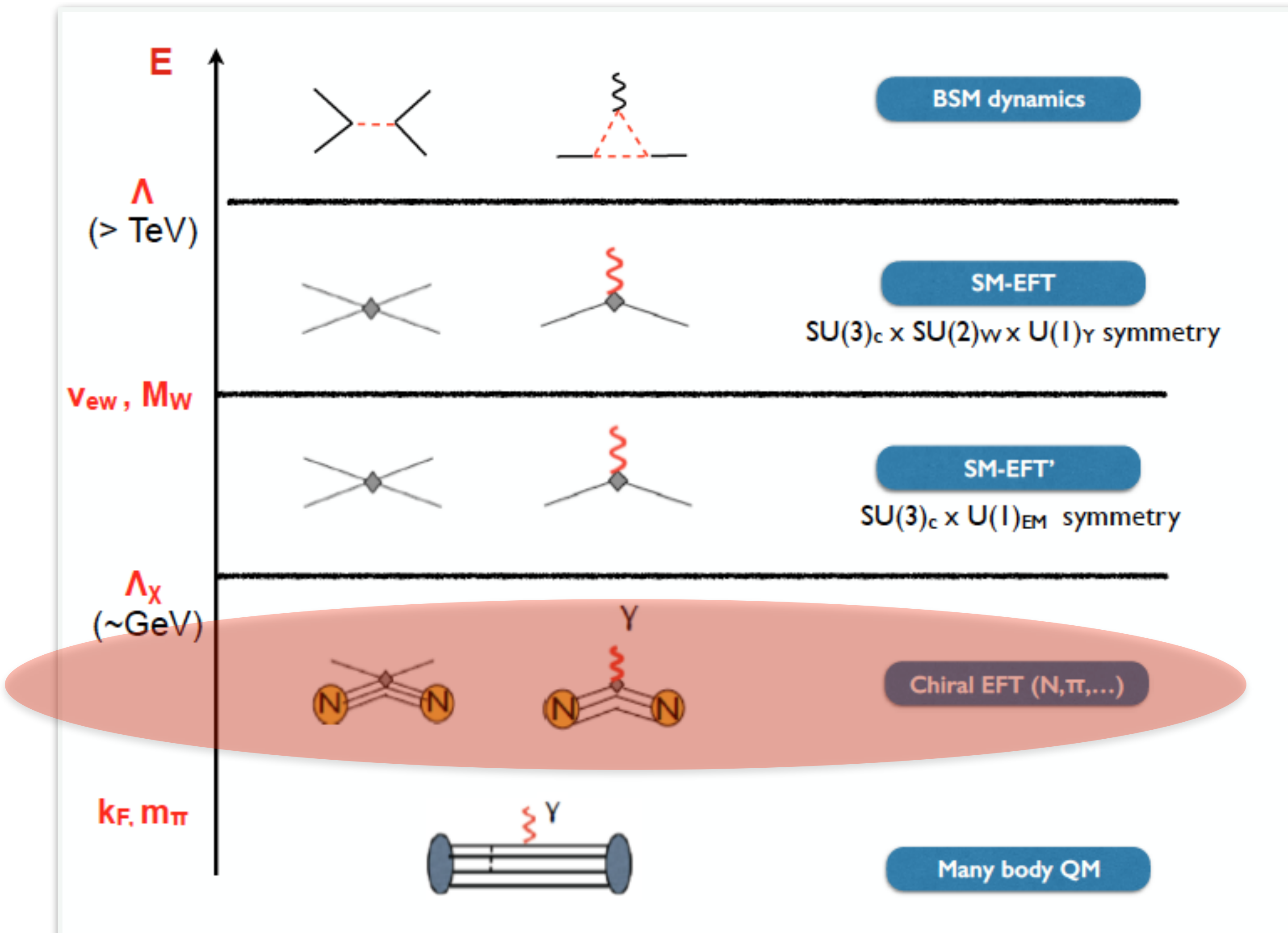

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$$\tilde{\mathcal{L}}_{\rm SM} + \sum_\beta \tilde{c}_\beta \, \tilde{O}_\beta$$

- At E ~ Λ_χ ~ m_N ~ GeV, map CPV Lagrangian onto π, N operators with same chiral properties
- Organize expansion according to power counting in Q/Λ_χ (Q ~ k_F ~ m_π)

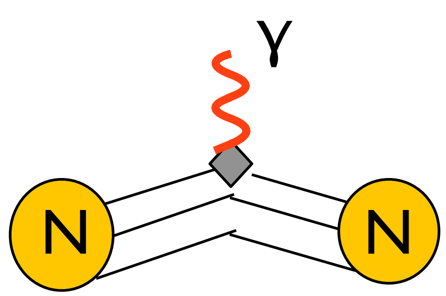
de Vries, Mereghetti, Timmermans, van Kolck, 1212.0990, ...

CPV at the hadronic level

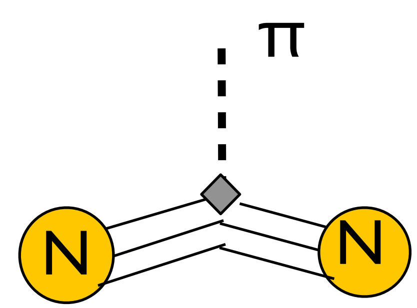
- Leading pion-nucleon CPV interactions characterized by few LECs

$$\tilde{\mathcal{L}}_{\rm CPV} = -\frac{i}{2}\sum_{i=n,p,e} d_i\,\bar{\psi}_i\,\sigma\cdot F\gamma_5\,\psi_i - \bar{N}\left[\bar{g}_0\,\vec{\tau}\cdot\vec{\pi} + \bar{g}_1\,\pi^0\right]N + \dots$$

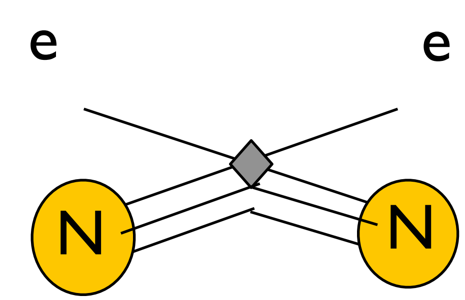
Electron and Nucleon EDMs



T-odd P-odd pion-nucleon couplings



Short-range 4N and 2N2e coupling



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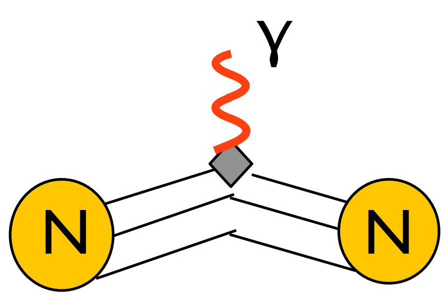

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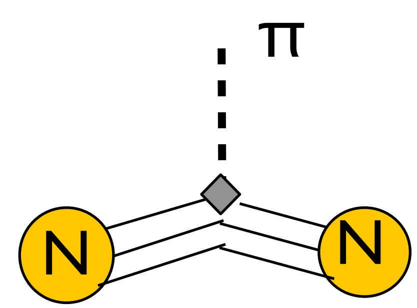

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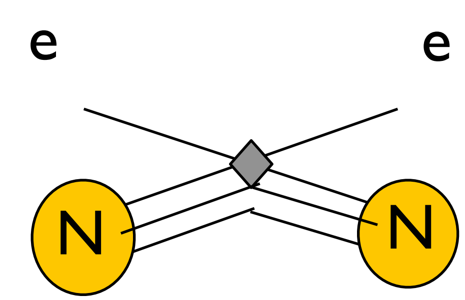
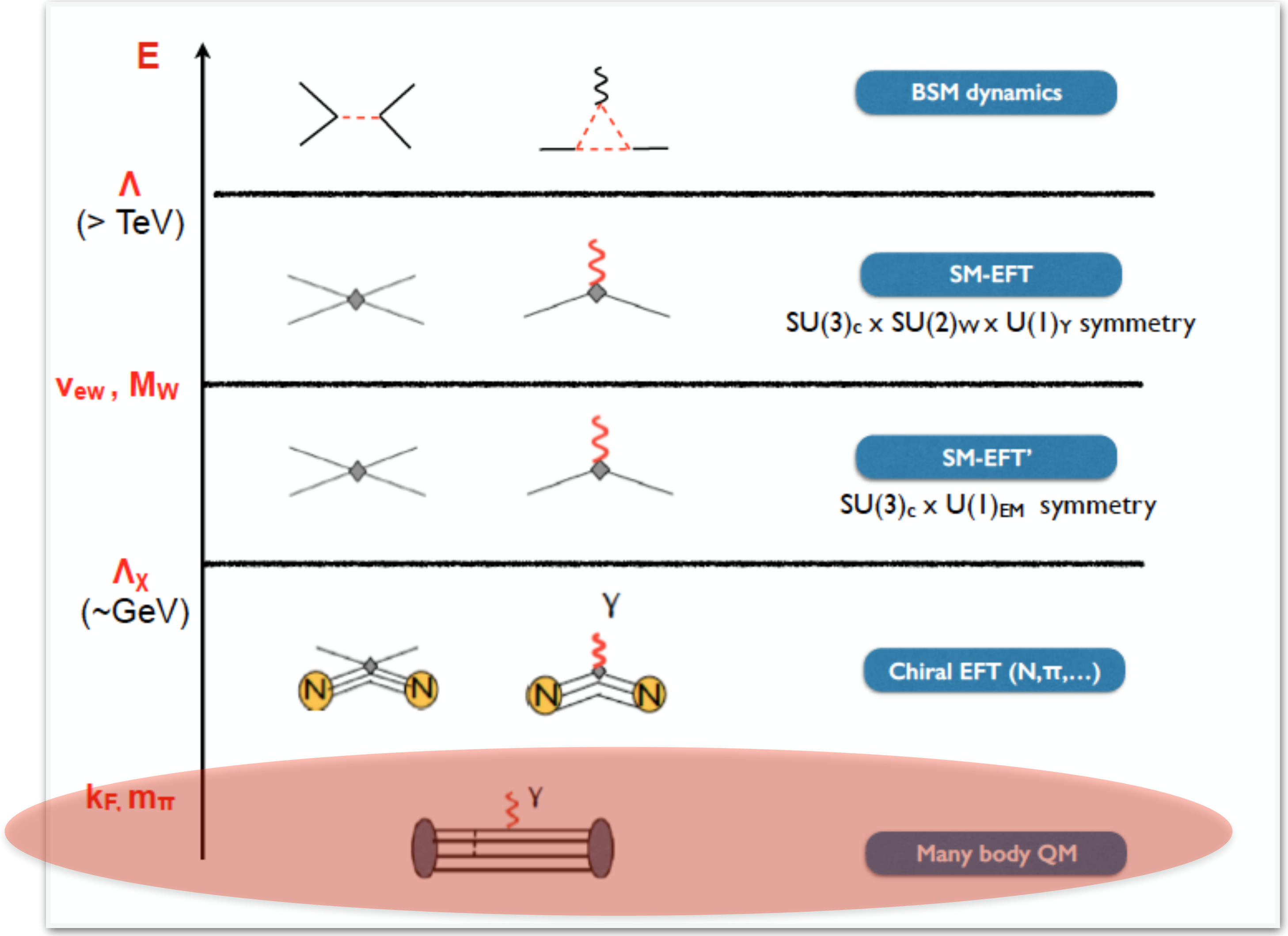


$d_N[d_q]$ and 2N2e couplings known at 10% level (lattice QCD)

Other $d_N[c_\alpha] \quad \bar{g}_{0,1}[c_\alpha] \quad \ldots$ O(1) uncertainty

CP Violation at atomic level



$$\tilde{\mathcal{L}}_{SM} + \sum_\beta \tilde{c}_\beta \, \tilde{O}_\beta$$

Non-perturbative

$$d_A[\tilde{c}_\beta[c_\alpha]]$$

See other theory talks at this meeting

Summary: the "EDM matrix"

Hadronic scale effective couplings

(B)SM sources of CP violation

$i \in$ {n, p, …, ThO, …, ^{199}Hg}

$$d_i = \sum_j \alpha_{ij} \, \tilde{c}_j \, [\{c\}]$$

α_{ij}
Nuclear and atomic / molecular matrix elements

$$\tilde{c}_j = \sum_k \beta_{jk} \, c_k$$

β_{jk}
Hadronic matrix elements

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α_{ij} Nuclear and atomic / molecular matrix elements

$$\tilde{c}_j = \sum_k \beta_{jk} \, c_k$$

β_{jk} Hadronic matrix elements

- To constrain & disentangle new CPV sources need multiple probes
- Many of the coefficients α_{ij} and β_{jk} are currently poorly known:
  - *need both* α's and β's to connect EDMs to new physics [c_k's]
  - major challenge for theorists

Nucleon EDM from lattice QCD

Neutron EDM master formula

$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\, \bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q\, g_s\, \bar{q}\sigma\cdot G\gamma_5 q + d_W \frac{g_s}{6} G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

Lattice QCD

μ=2GeV

$$\begin{aligned} d_n &= O(10^{-3}) \times \bar{\theta}\, e\, \mathrm{fm} \\ &\quad -(0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d + (0.0027 \pm 0.016) d_s \\ &\quad -(0.55 \pm 0.28) e\tilde{d}_u - (1.1 \pm 0.55) e\tilde{d}_d \pm (50 \pm 40)\, \mathrm{MeV}\, e\, d_W \end{aligned}$$

QCD Sum Rules
(50% error estimate)

Pospelov-Ritz hep-ph/0504231 and refs therein

Older QCD Sum Rules + NDA (~100%)
New QCD SR → (25 ±13) e MeV d_W

Haisch-Hala 1909.08955

Status of Lattice QCD calculations

- Recent development: nucleon EDM from Lattice QCD
  - Theta term (MSU, ETMC, LANL) — Dragos, Luu, Shindler, deVries, Yousif, 1902.03254; Alexandrou et al, 2011.01084; Bhattacharya et al. 2101.07230
  - quark EDM: tensor charges @ 10% (LANL) — Bhattacharya et al. 1506.04196 & 1808.07597
  - quark CEDM (ongoing: BNL, LANL, MSU) — M. Abramczyk et al., 1701.07792; S. Syritsyn, T. Izubuchi, H. Ohki 1810.03721
  - gluon CEDM (ongoing: LANL, MSU) — M. Rizik, A. Shindler, C. Monahan, 1810.05637
  - 4-quark: { }

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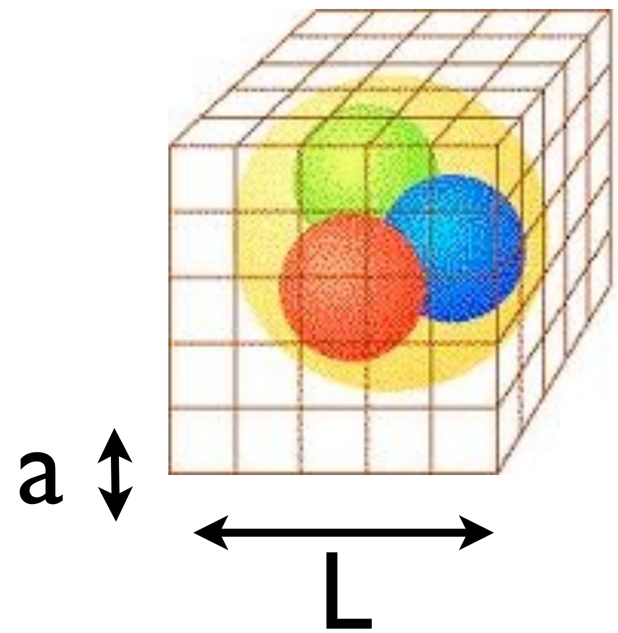
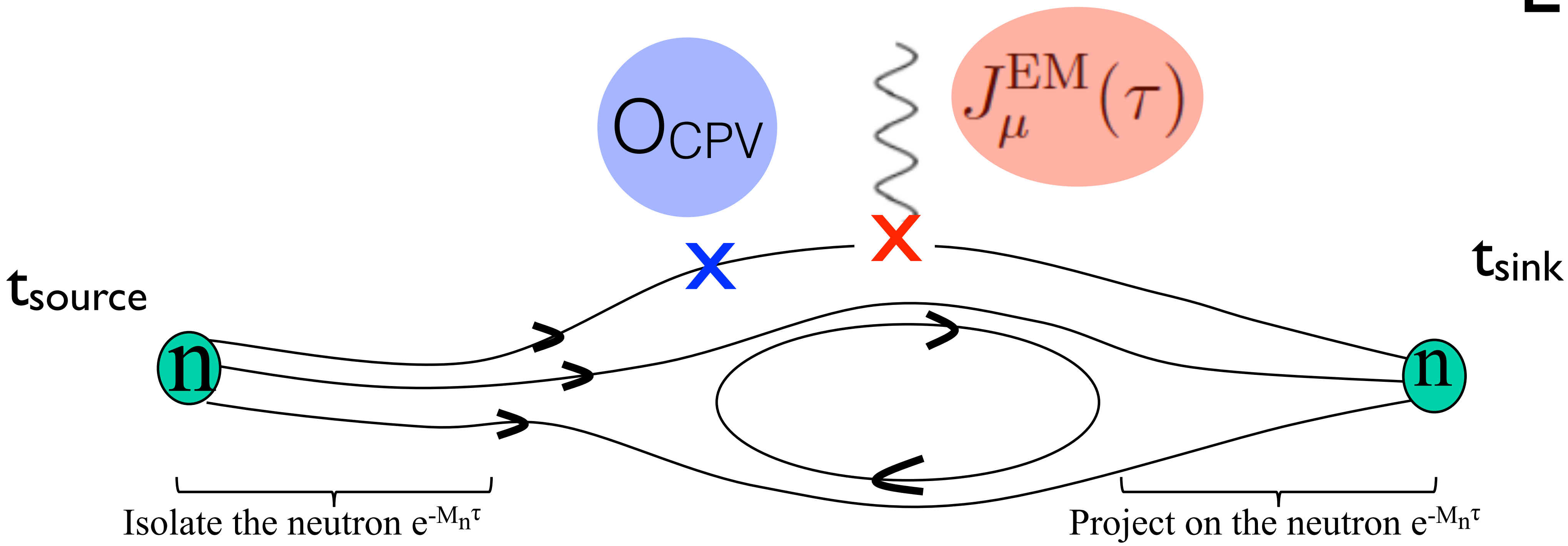
Basics of lattice methodology

- Discretize space-time into a finite Euclidean lattice (a,V) → perform Monte Carlo integration of the path integral



- Compute appropriate correlation functions:



- Systematics: remove excited state contamination; extrapolate to physical point by doing calculation in universes with different m_q, a, V

Neutron EDM from theta term

Bhattacharya, VC, Gupta, Mereghetti, Yoon, 2101.07230

- For each 'universe', isolate ground state $<n|\, J_{EM}\, |n>$ from 3-point function with different t_{source} , t_{sink}, τ

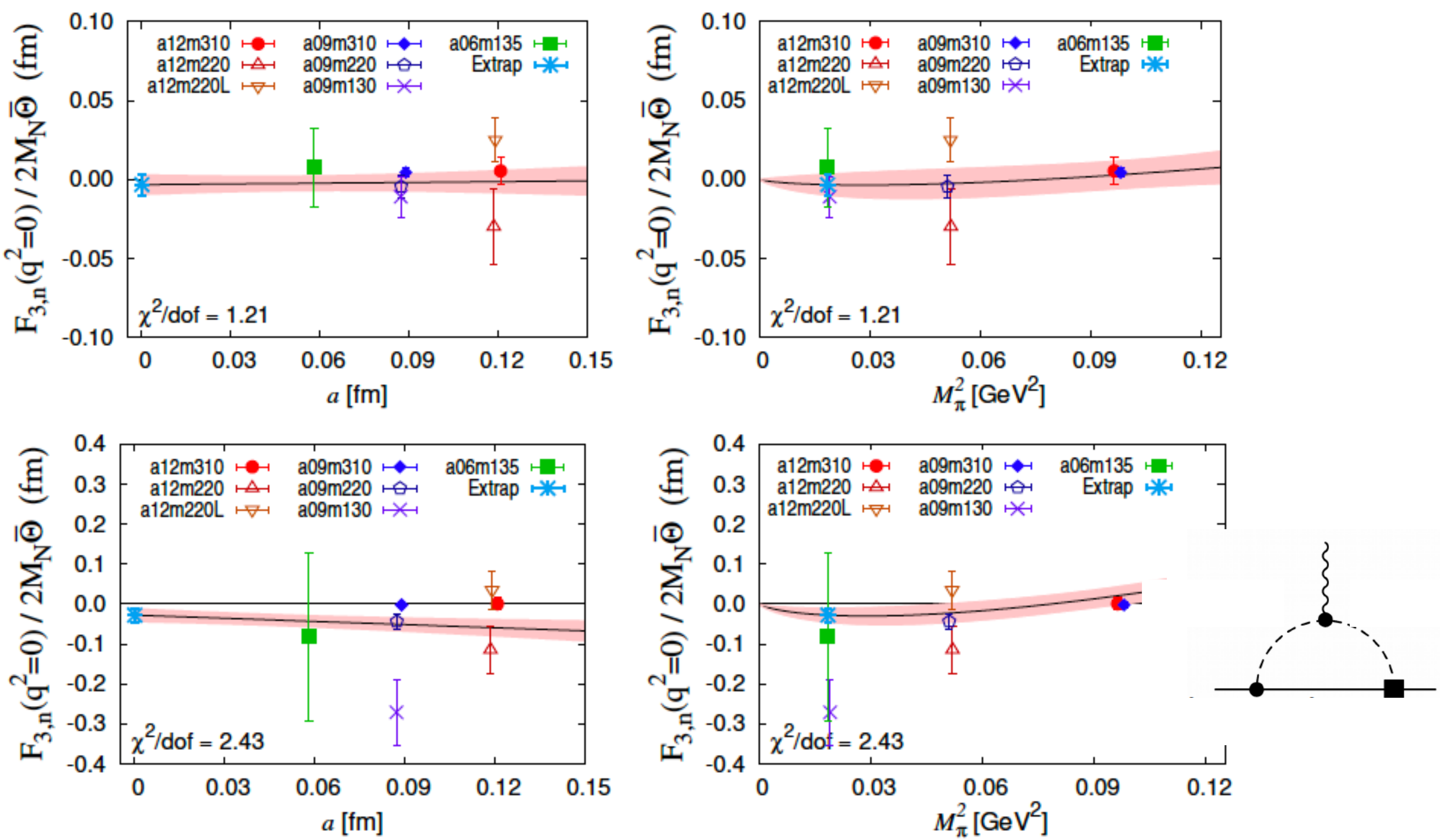
- Extract CPV electric dipole form factor $F_3(q^2)$ and take $q^2 \to 0$ limit (linear or chiral EFT fit)

- Take chiral-continuum limit (m_q, a) by combining results from various universes

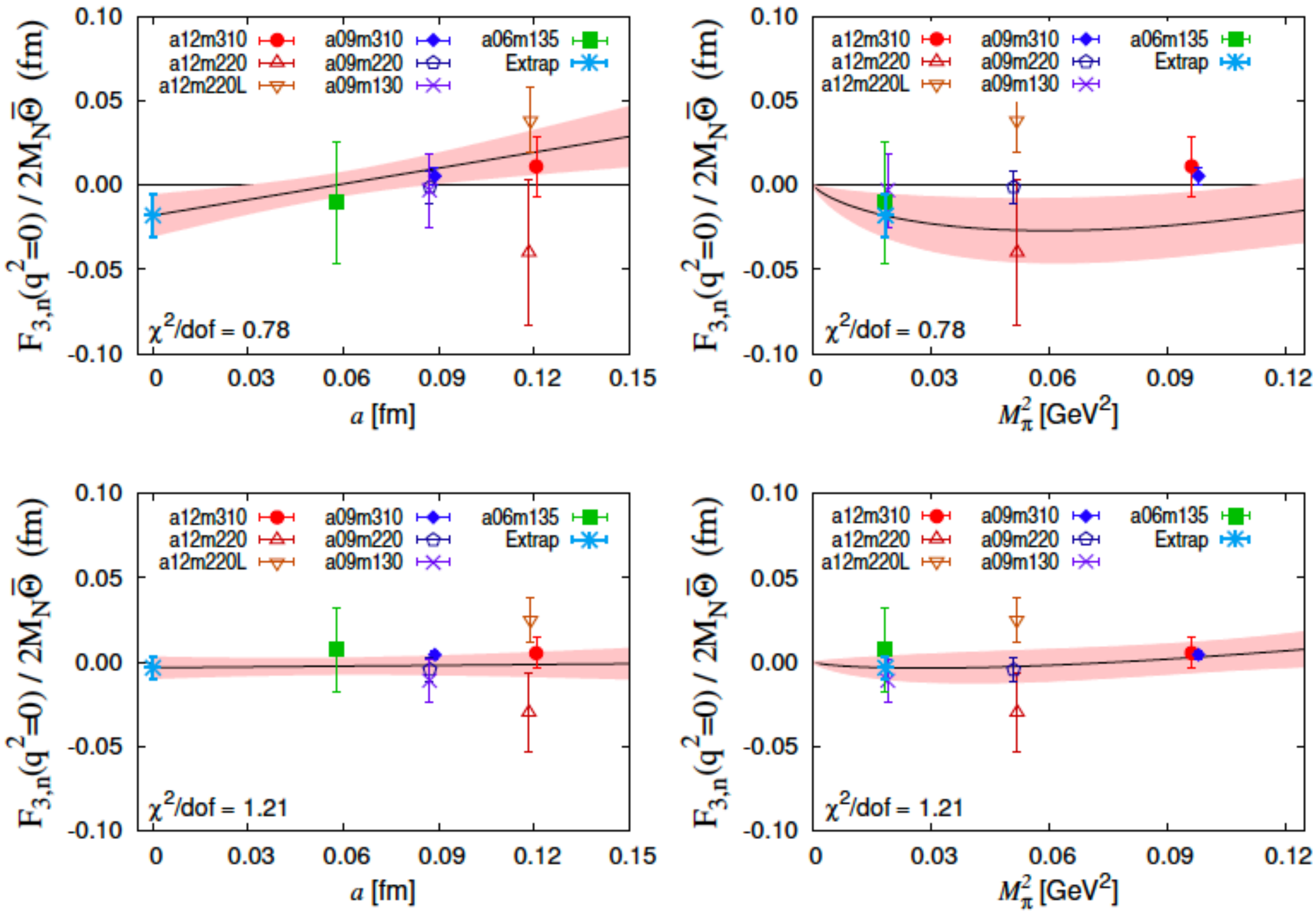
$$d_n(a, M_\pi) \;=\; c_1 M_\pi^2 + c_{2L} M_\pi^2 \ln\left(\frac{M_\pi^2}{M_N^2}\right) + c_3 a$$

Dependence on excited state assumptions

- Order of magnitude difference depending on assumption about lowest excited state: from fit to 2-pt function or Nπ, as suggested by chiral EFT



Dependence on q^2 extrapolation



Linear q^2 fit

Chiral q^2 fit

Theta term summary

Statistical ↘ ↙ Extrapolation

2101.07230	This Work	$d_n = -0.003(7)(20)$
	This Work with $N\pi$	$d_n = -0.028(18)(54)$
2011.01084	ETMC	$\lvert d_n \rvert = 0.0009(24)$
1902.03254	Dragos et al.	$d_n = -0.00152(71)$
1810.03721	Syritsyn et al.	$d_n \approx 0.001$

$\times\ \bar{\theta}\ e\,\mathrm{fm}$

- LANL approach: more statistics needed to have better control on excited states, q^2, and chiral-continuum extrapolation

Theta term summary

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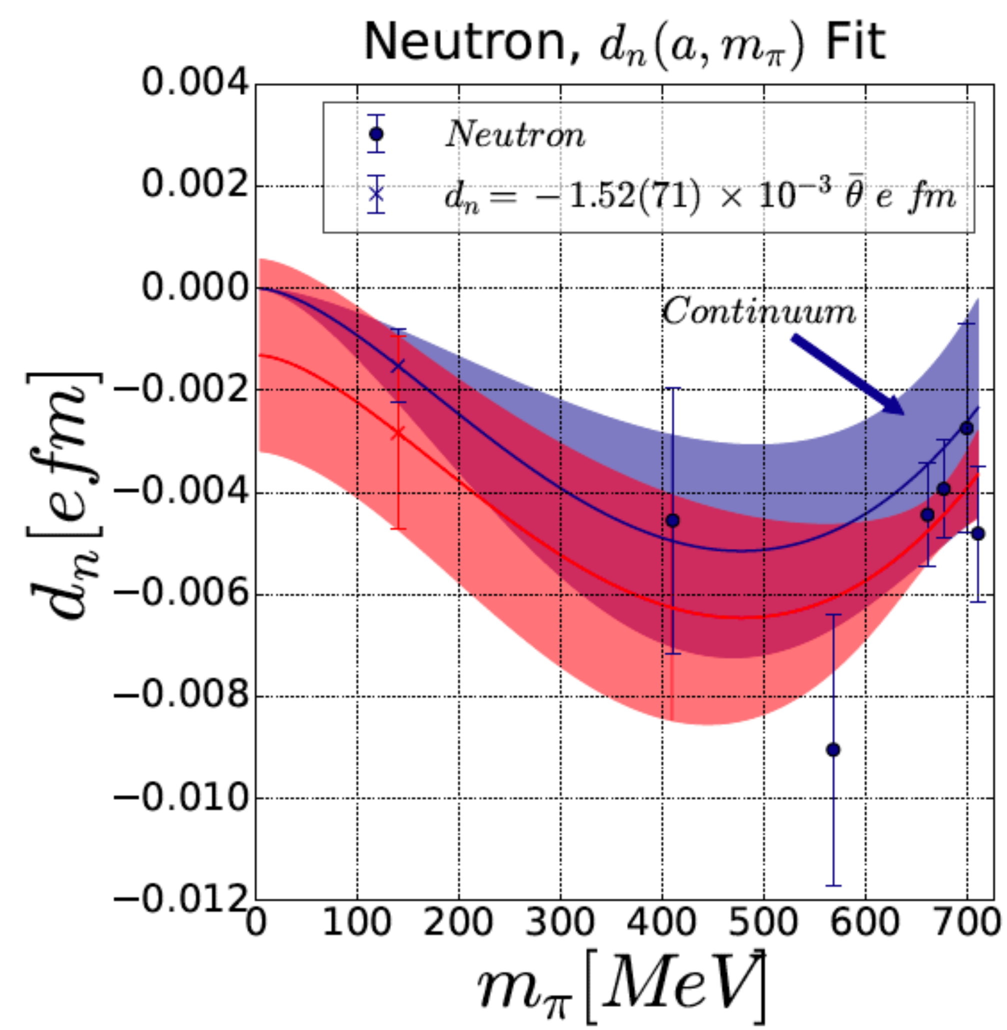
- LANL approach: more statistics needed to have better control on excited states, q^2, and chiral-continuum extrapolation

- Dragos et al. have most precise result (50%), based on m_π > 400 MeV. More data at lower pion mass will improve precision

Dragos, Luu, Shindler, deVries, Yousif, 1902.03254



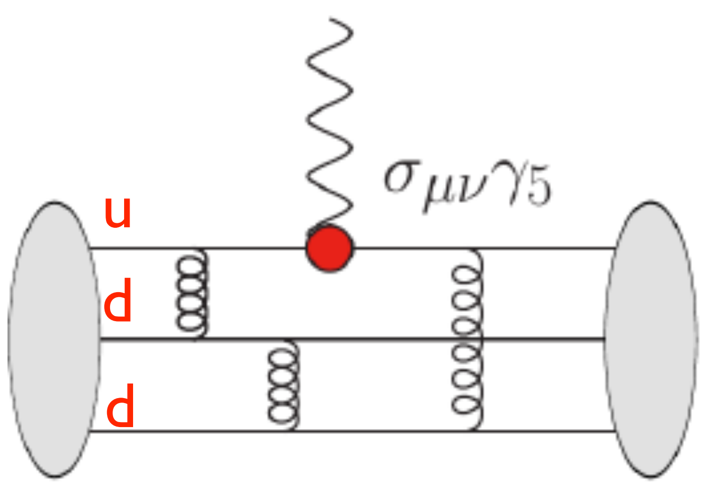
Neutron EDM from quark EDM

- Problem "factorizes": need tensor charge of the nucleon

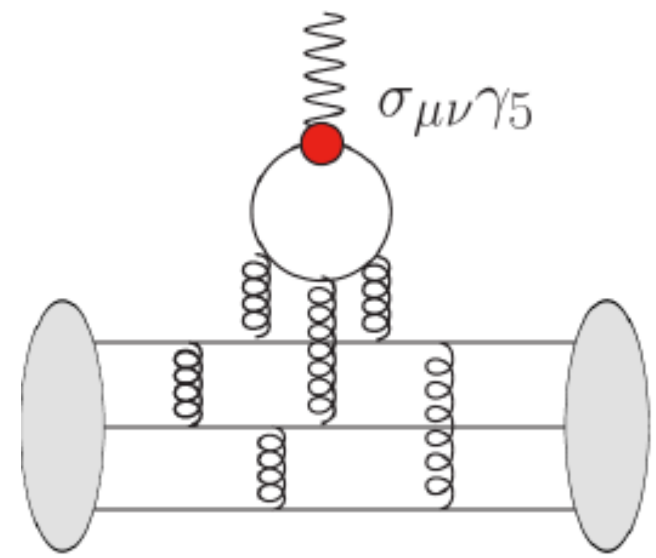
$$\mathcal{L} = -\frac{i}{2} \sum_{q=u,d,s} d_q \, \bar{q} \sigma_{\mu\nu} \gamma_5 q \, F^{\mu\nu} \quad \longrightarrow \quad d_N = d_u \, g_T^{(N,u)} + d_d \, g_T^{(N,d)} + d_s \, g_T^{(N,s)}$$

** Use $\sigma_{\mu\nu}\gamma_5 \propto \epsilon_{\mu\nu\alpha\beta}\,\sigma^{\alpha\beta}$

$$\langle N | \bar{q} \sigma_{\mu\nu} q \, | N \rangle \equiv g_T^{(N,q)} \; \bar{\psi}_N \sigma_{\mu\nu} \psi_N$$



"connected"



"disconnected"

(dominates the error)

Neutron EDM from quark EDM

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$$\mathcal{L} = -\frac{i}{2} \sum_{q=u,d,s} d_q \; \bar{q}\sigma_{\mu\nu}\gamma_5 q \, F^{\mu\nu} \quad \rightarrow \quad d_N = d_u \, g_T^{(N,u)} + d_d \, g_T^{(N,d)} + d_s \, g_T^{(N,s)}$$

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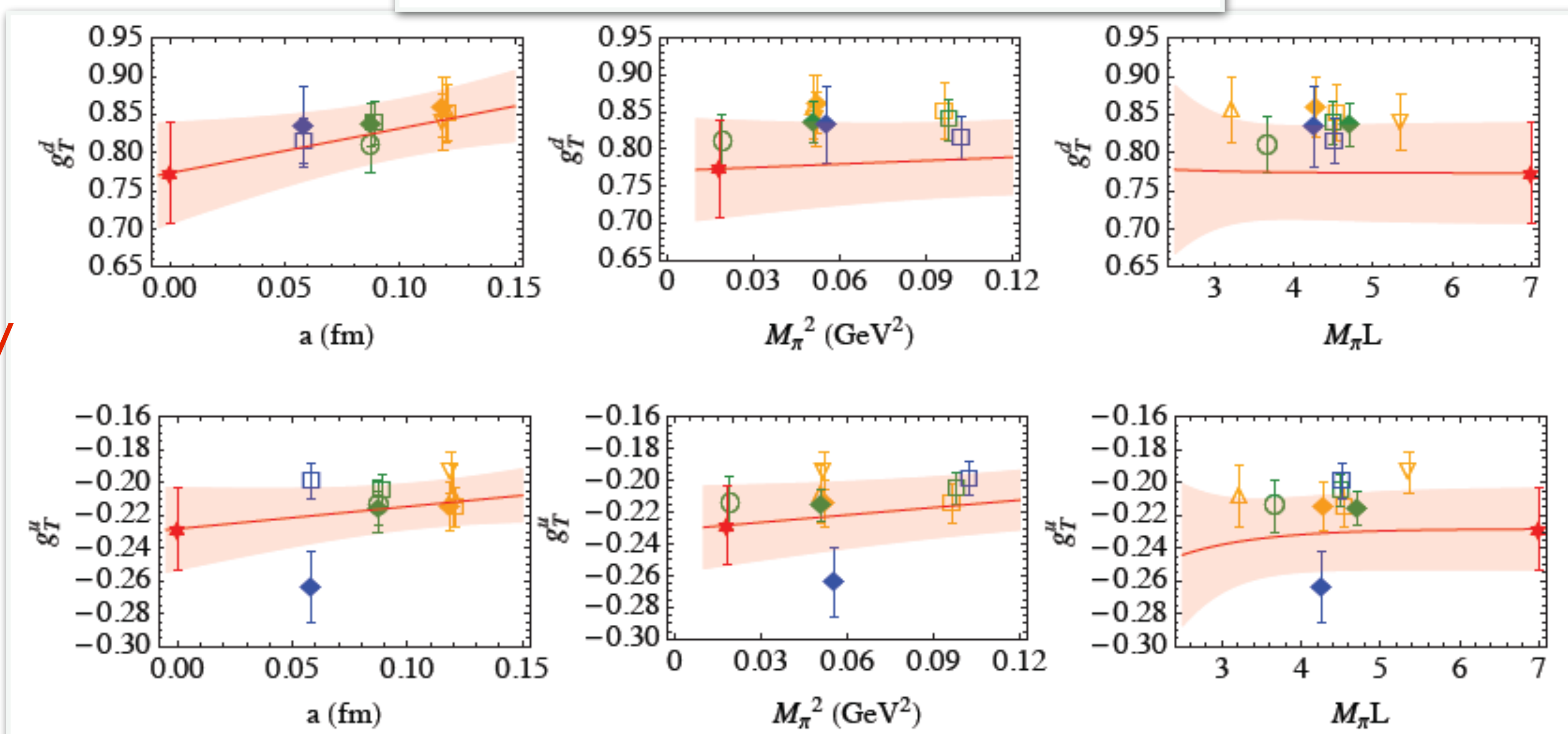
$$\langle N|\,\bar{q}\sigma_{\mu\nu}q\,|N\rangle \equiv g_T^{(N,q)} \; \bar{\psi}_N \sigma_{\mu\nu} \psi_N$$

$$g_T(a, M_\pi, L) = c_1 + c_2 a + c_3 M_\pi^2 + c_4 e^{-M_\pi L}$$

$\overline{\text{MS}}$ @ 2 GeV



Bhattacharya, VC, Gupta, Lin, Yoon, PRL 115 (2015) 212002 [1506.04196]

&

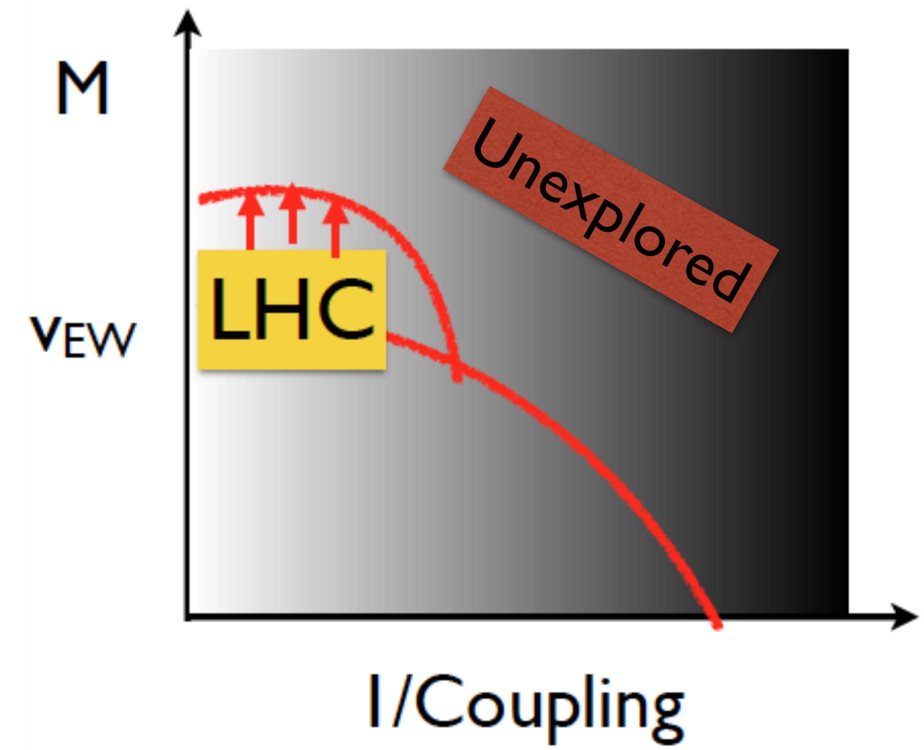
1808.07597

O(10%) error including all systematics

EDMs and non-standard Higgs couplings

EDMs in the LHC era

- LHC output so far:
  - Higgs boson @ 125 GeV
  - Everything else is quite heavier (or very light)

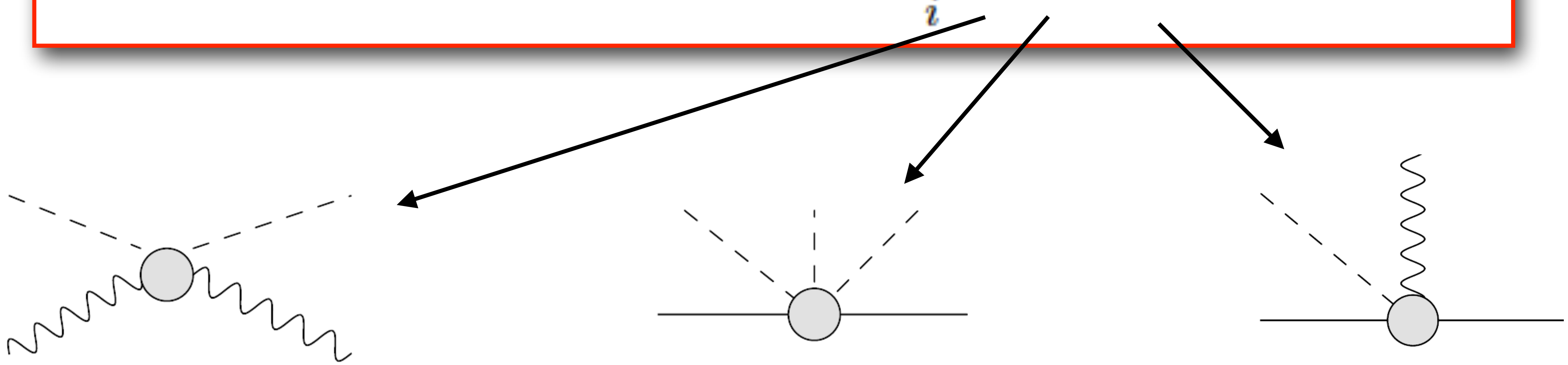


- *EDMs more relevant than ever:*
  - Strongest constraints of non-standard CPV Higgs couplings
  - One of few observables probing PeV scale supersymmetry
  - Strong constraints on weak scale baryogenesis models

EDMs and CPV Higgs couplings

- Leading ($1/\Lambda^2$) CP-violating BSM interactions involving the Higgs:

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



H-H-V-$\tilde{V}$
$F_{\mu\nu} \tilde{F}^{\mu\nu} \sim$ **E · B**

H-q_L-q_R: pseudo-scalar
Yukawa coupling ~ **σ** · (**p_f** -**p_i**)

H-q_L-q_R-V: dipole ~ **σ · E**
V = g, W^a, B

EDMs and CPV Higgs couplings

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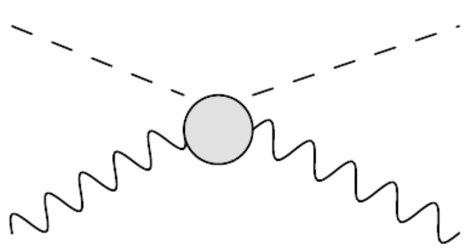


H-H-V-$\tilde{V}$

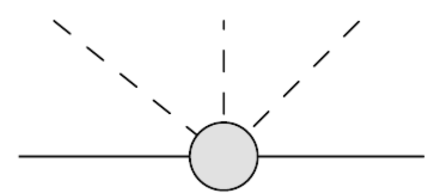
$F_{\mu\nu} \tilde{F}^{\mu\nu} \sim$ **E · B**

McKeen-Pospelov-Ritz 1208.4597

...

VC, Crivellin,, Dekens, de Vries, Hoferichter, Mereghetti, 1903.03625, Phys. Rev. Lett. 123, 051801 (2019)

...



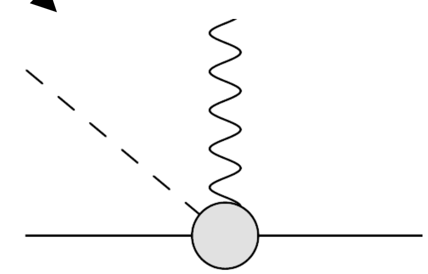
H-q_L-q_R: pseudo-scalar Yukawa coupling ~ **σ · (p_f -p_i)**

Brod Haisch Zupan 1310.1385

Chien-VC-Dekens-de Vries-Mereghetti, 1510.00725

Brod-Stamou, 1812.12303

...



H-q_L-q_R-V: dipole ~ **σ · E**

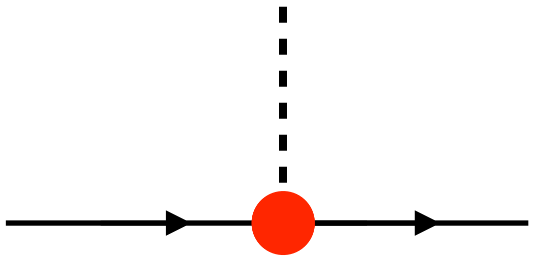
V = g, W^a, B

VC-Dekens-de Vries-Mereghetti, 1603.03049

Fuyuto & Ramsey-Musolf 1706.08548

...

Yukawa couplings to quarks



$$\mathcal{L}_6^{CPV} \supset \sum_q v^2\, \mathrm{Im}\, Y'_q\, \bar{q} i\gamma_5 q\, h$$

Pseudo-scalar coupling **σ** · (**p**$_f$ -**p**$_i$) is zero in the Standard Model

Y.-T. Chien, VC, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

Brod Haisch Zupan 1310.1385

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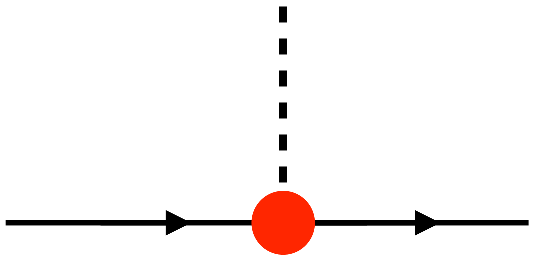

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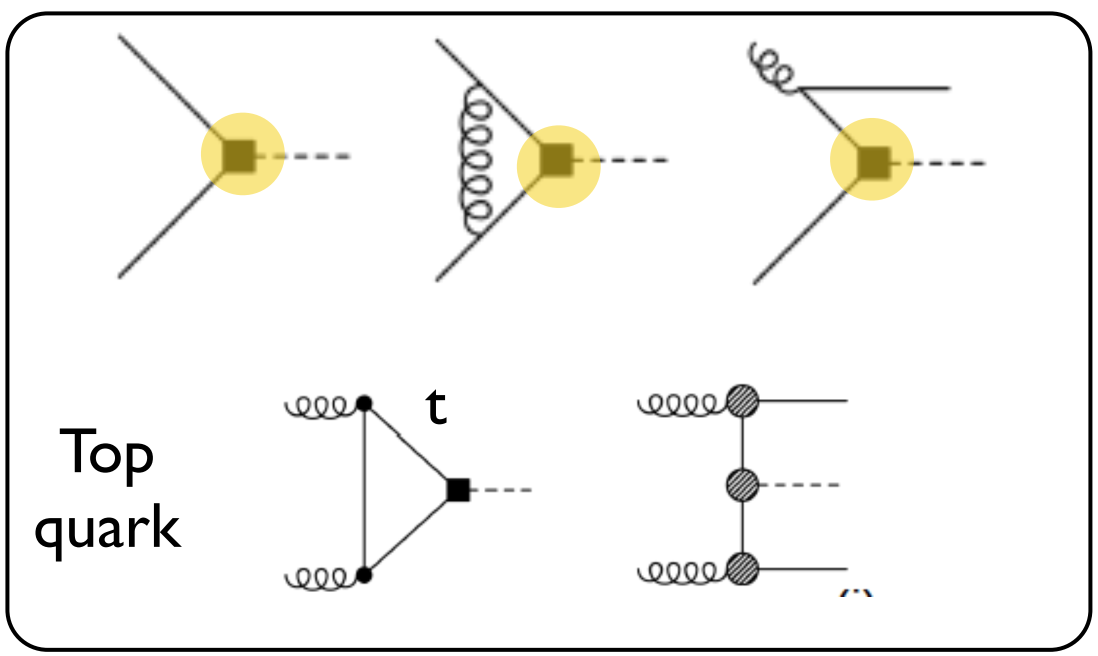
Pseudo-scalar coupling $\sigma \cdot (\mathbf{p_f} - \mathbf{p_i})$ is zero in the Standard Model

LHC: Higgs production & decay



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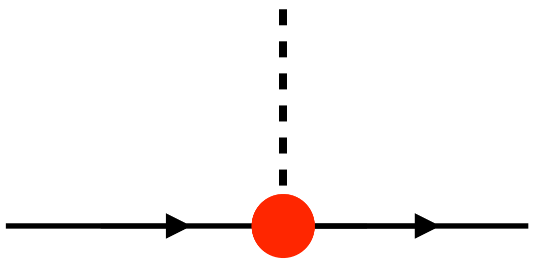

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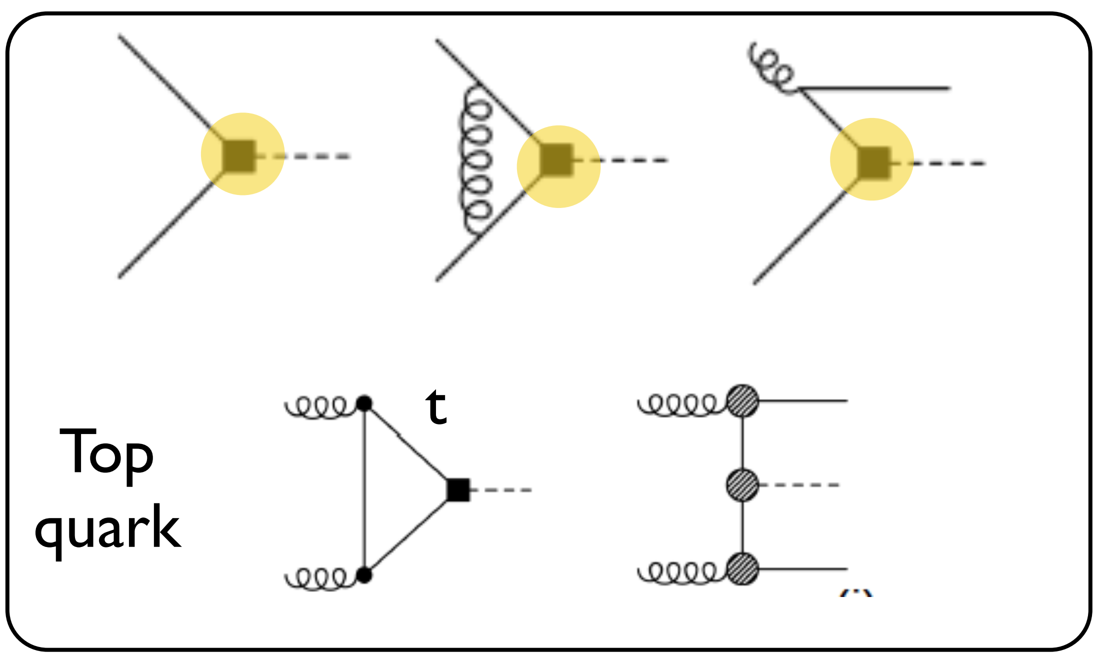
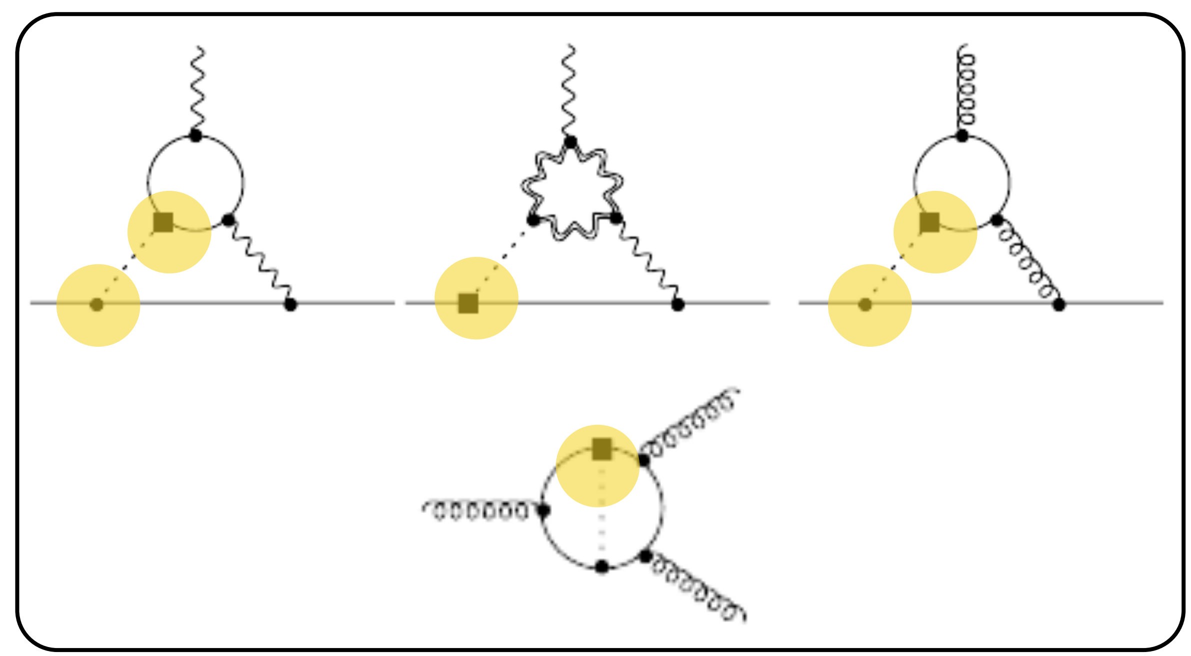


Low Energy: induce electron, neutron, mercury EDM



Y.-T. Chien, VC, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

Brod Haisch Zupan 1310.1385

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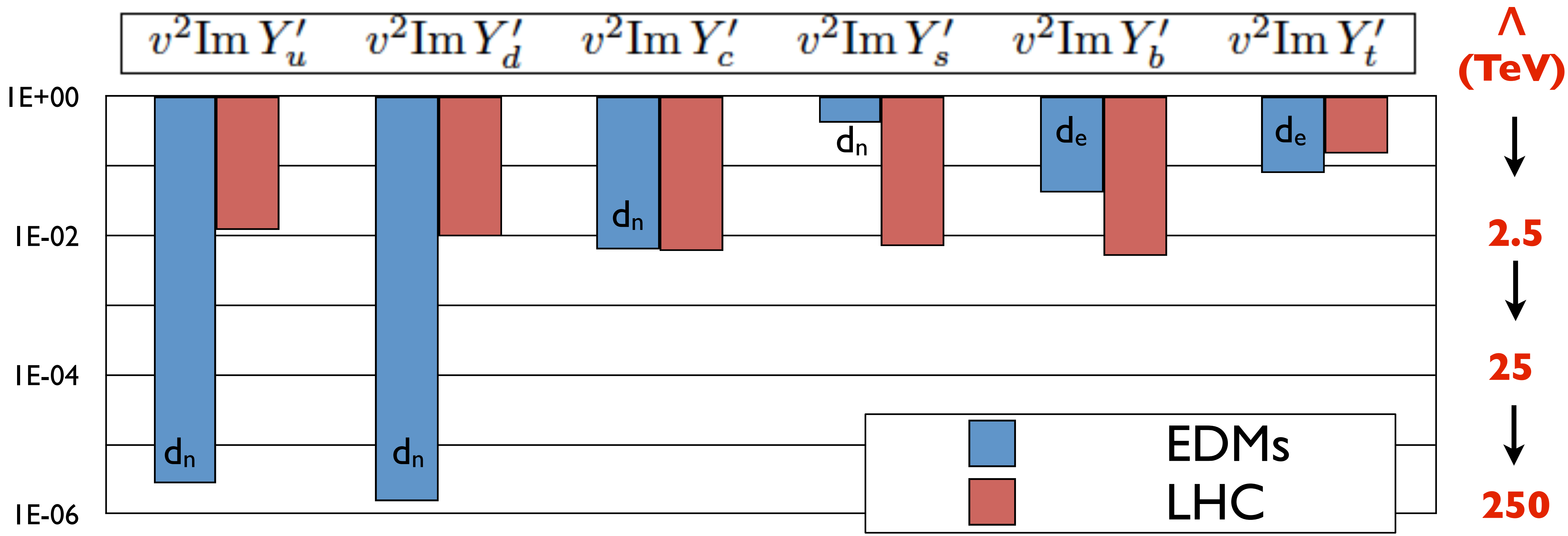
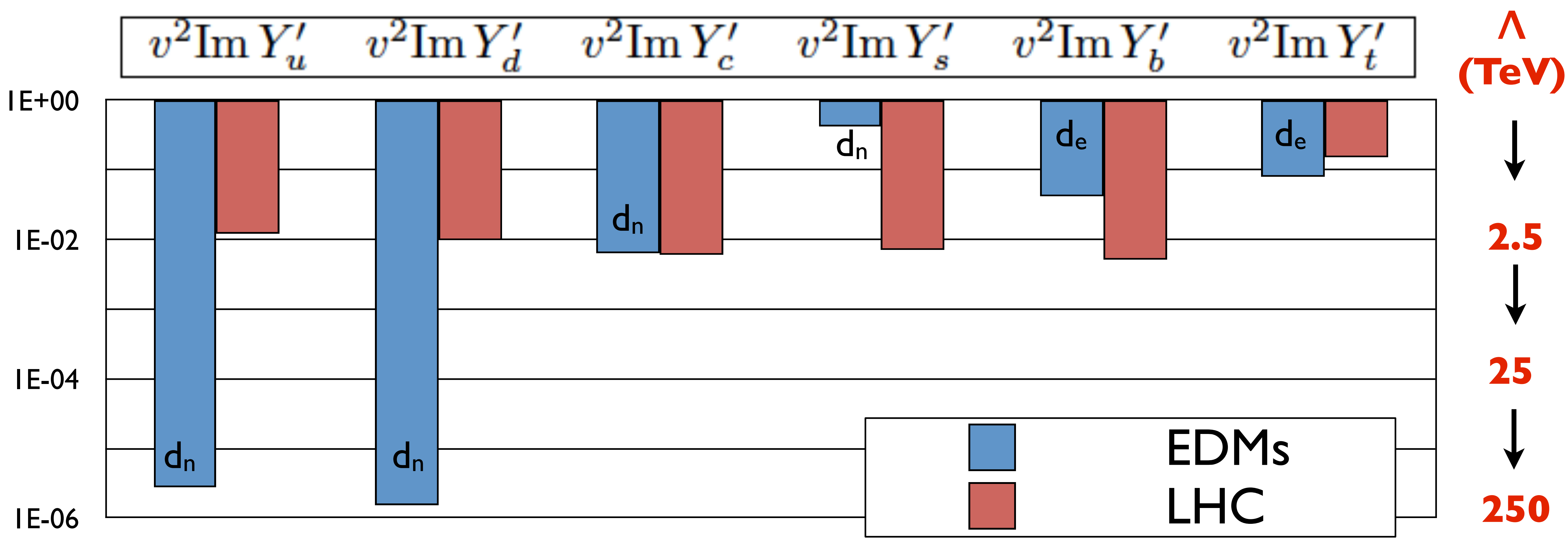


Y.-T. Chien, VC, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

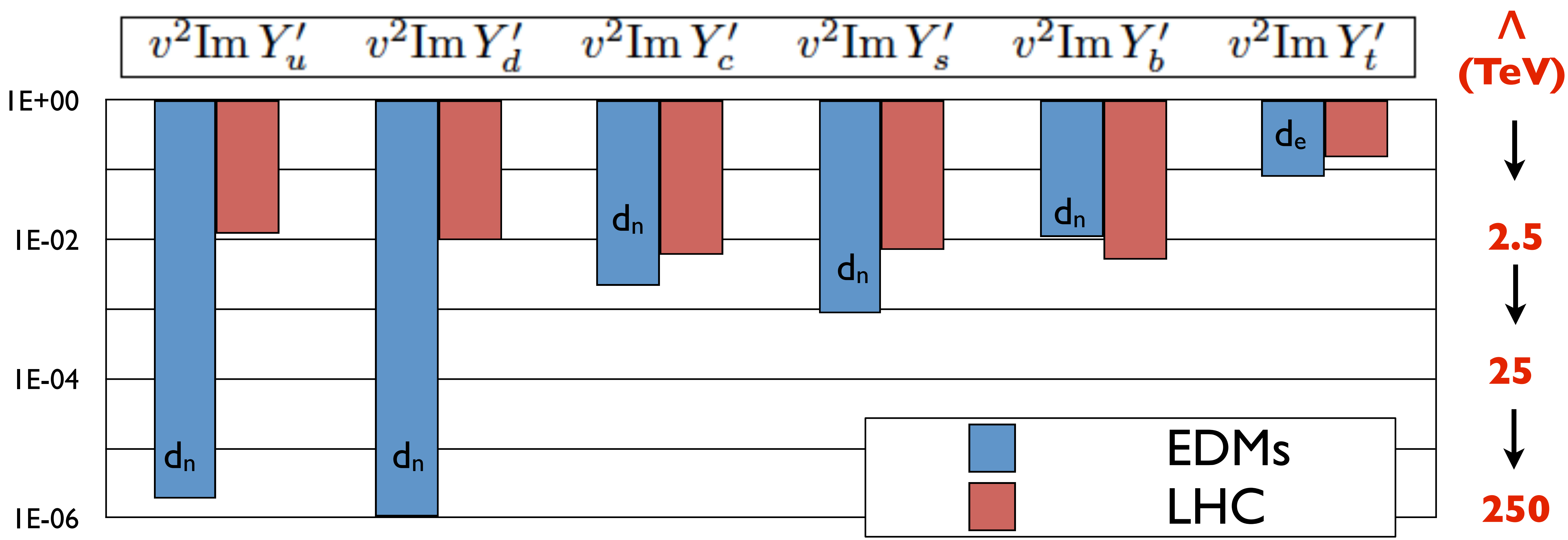
Yukawa couplings to quarks



- EDMs are teaching us something about the Higgs!
- Future: factor of 2 at LHC; EDM constraints scale linearly
- Uncertainty in matrix elements strongly dilutes EDM constraints

Y.-T. Chien, VC, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

Yukawa couplings to quarks



- Much stronger impact of nEDM with reduced uncertainties

$d_{n,p}[\tilde{d}_{u,d}]$ 25%

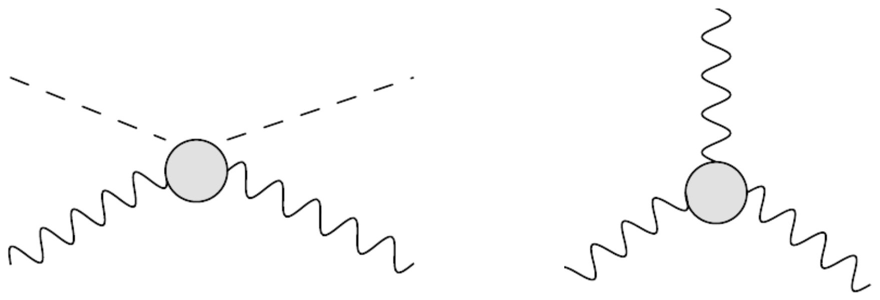
$d_{n,p}[d_W]$ 50%

Target for Lattice QCD in the 5-year time scale

- Experiment at 5 x 10^{-27} e cm and improved matrix elements will make nEDM the strongest probe for all couplings

Higgs-gauge CPV couplings

- Dominant sources of CPV (together with VVV) in so-called *universal theories*



Peskin-Takeuchi, PRL 65, 964 (1990)
Barbieri-Pomarol-Rattazzi-Strumia hep-ph/0405040
Wells-Zhang, 1510.08462

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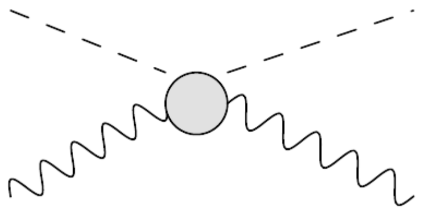

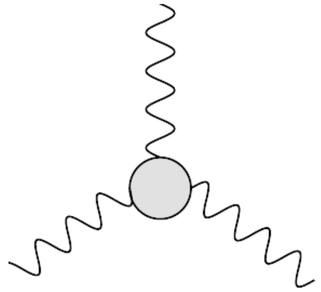

Peskin-Takeuchi, PRL 65, 964 (1990)
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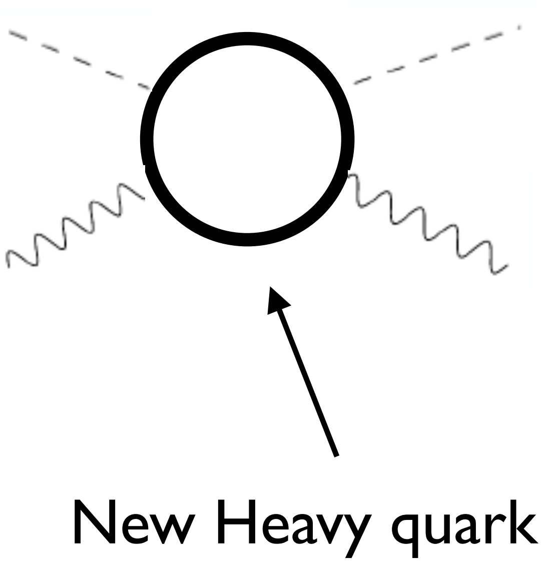
Example

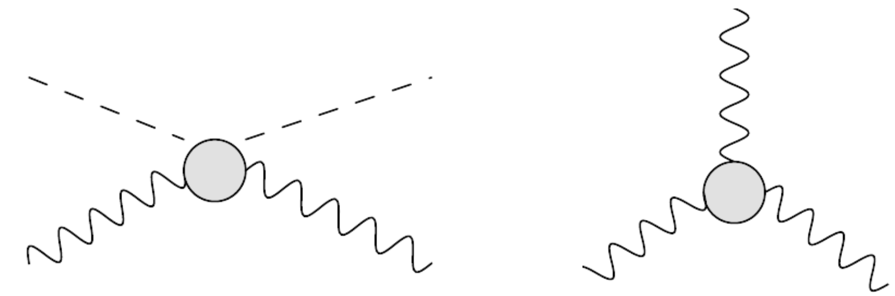


"Universal theories"

- New physics couples to SM bosons, and / or to fermions through SM currents
- Consistent framework to analyze EW precision tests (oblique corrections, etc)
- Evade flavor constraints (Minimal Flavor Violation is automatic), scale can be low

Higgs-gauge CPV couplings

- Dominant sources of CPV (together with VVV) in so-called *universal theories*



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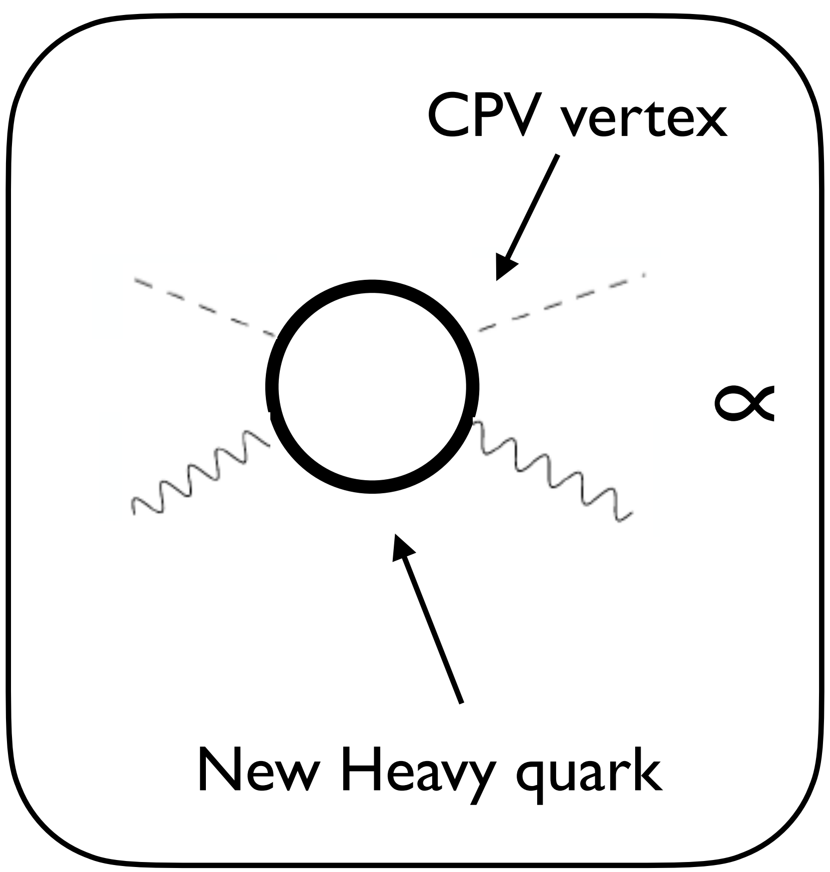

$\propto \quad F_{\mu\nu} \tilde{F}^{\mu\nu} \sim \mathbf{E} \cdot \mathbf{B}$

Ferreira-Fuks-Sanz-Sengupta
Eur. Phys. J. C (2017) 77:675

Higgs-gauge CPV couplings

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Peskin-Takeuchi, PRL 65, 964 (1990)
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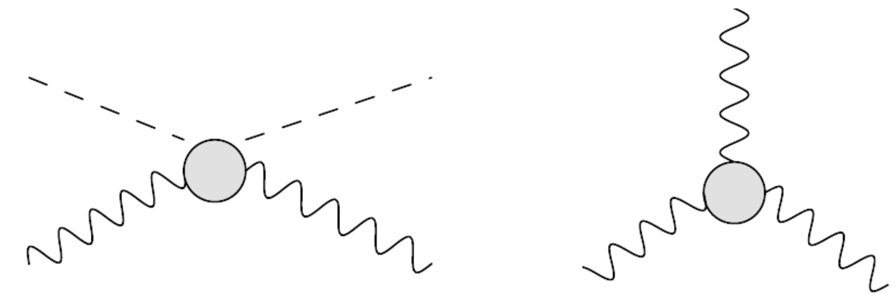


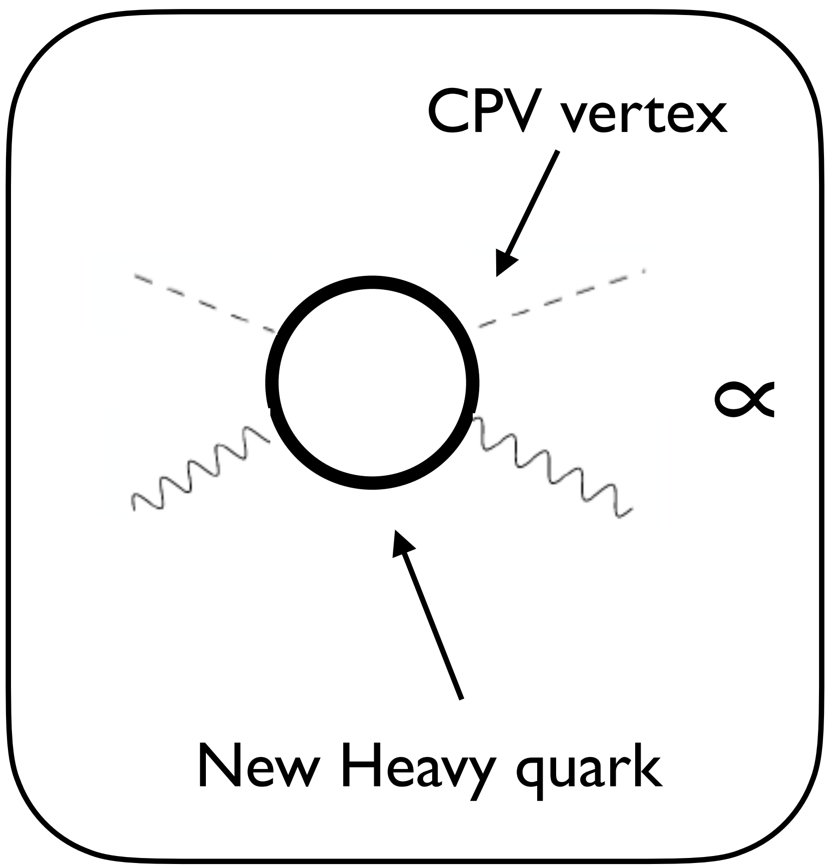
H-H-V-$\tilde{V}$ V-V-$\tilde{V}$

$v^2\, C_{\varphi\tilde{B}}$ $v^2\, C_{\tilde{W}}$

$v^2\, C_{\varphi\tilde{W}}$ $v^2\, C_{\tilde{G}}$

$v^2\, C_{\varphi\tilde{W}B}$

$v^2\, C_{\varphi\tilde{G}}$



$\propto$ $F_{\mu\nu}\,\tilde{F}^{\mu\nu} \sim \mathbf{E}\cdot\mathbf{B}$

Ferreira-Fuks-Sanz-Sengupta
Eur. Phys. J. C (2017) 77:675

Six CPV couplings at $O(1/\Lambda^2)$

Higgs-gauge CPV couplings

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Peskin-Takeuchi, PRL 65, 964 (1990)
Barbieri-Pomarol-Rattazzi-Strumia hep-ph/0405040
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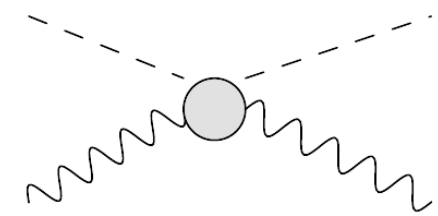
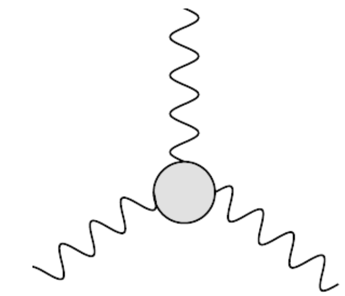
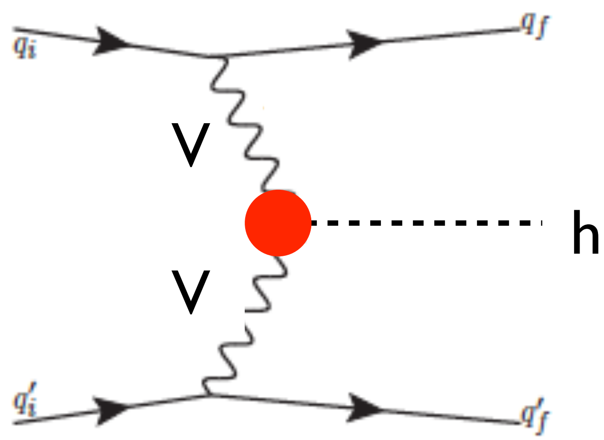


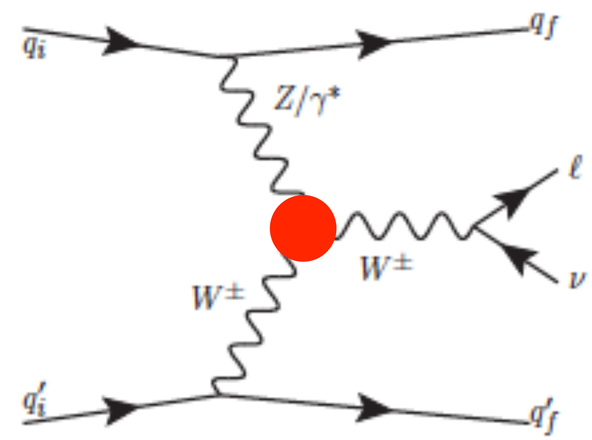
H-H-V-$\tilde{V}$



V-V-$\tilde{V}$

- Induce CPV angular distributions in pp → h +2 jets, pp → V +2 jets, …



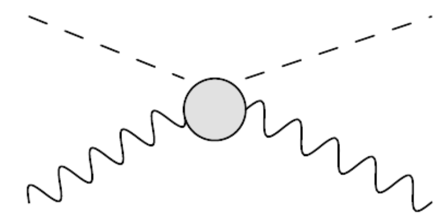


Angular distribution of the two jets ($\Delta\Phi_{jj}$) contains information about CP structure of the VVh vertex.
Triple products of quark momenta appear, e.g. $\mathbf{p} \cdot (\mathbf{q} \times \mathbf{k})$

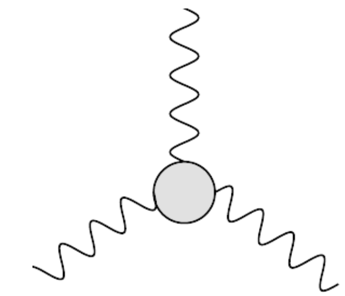
Higgs-gauge CPV couplings

- Dominant sources of CPV (together with VVV) in so-called *universal theories*

Peskin-Takeuchi, PRL 65, 964 (1990)
Barbieri-Pomarol-Rattazzi-Strumia hep-ph/0405040
Wells-Zhang, 1510.08462



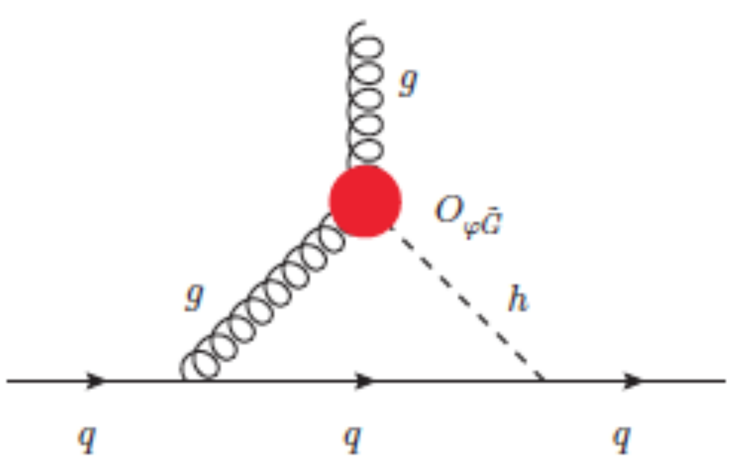
H-H-V-$\tilde{V}$

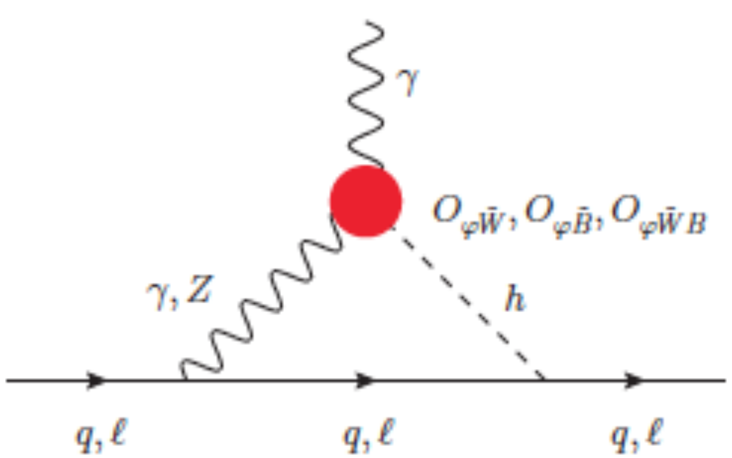


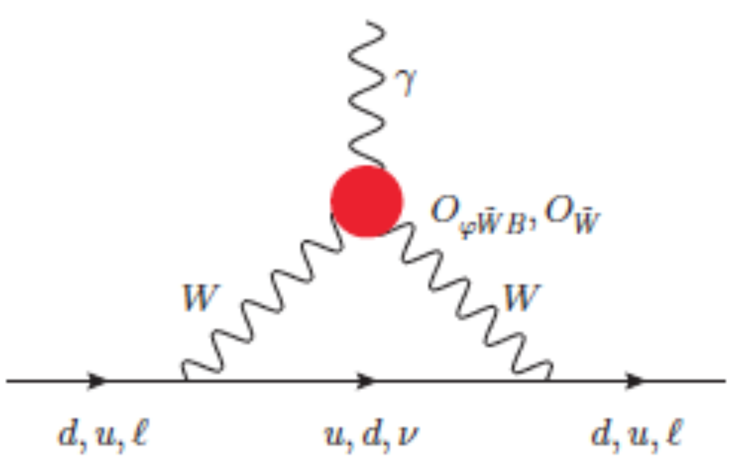
V-V-$\tilde{V}$

- Induce CPV angular distributions in pp → h +2 jets, pp → V +2 jets, …

- Induce light fermions (chromo)-EDMs at the 1-loop level

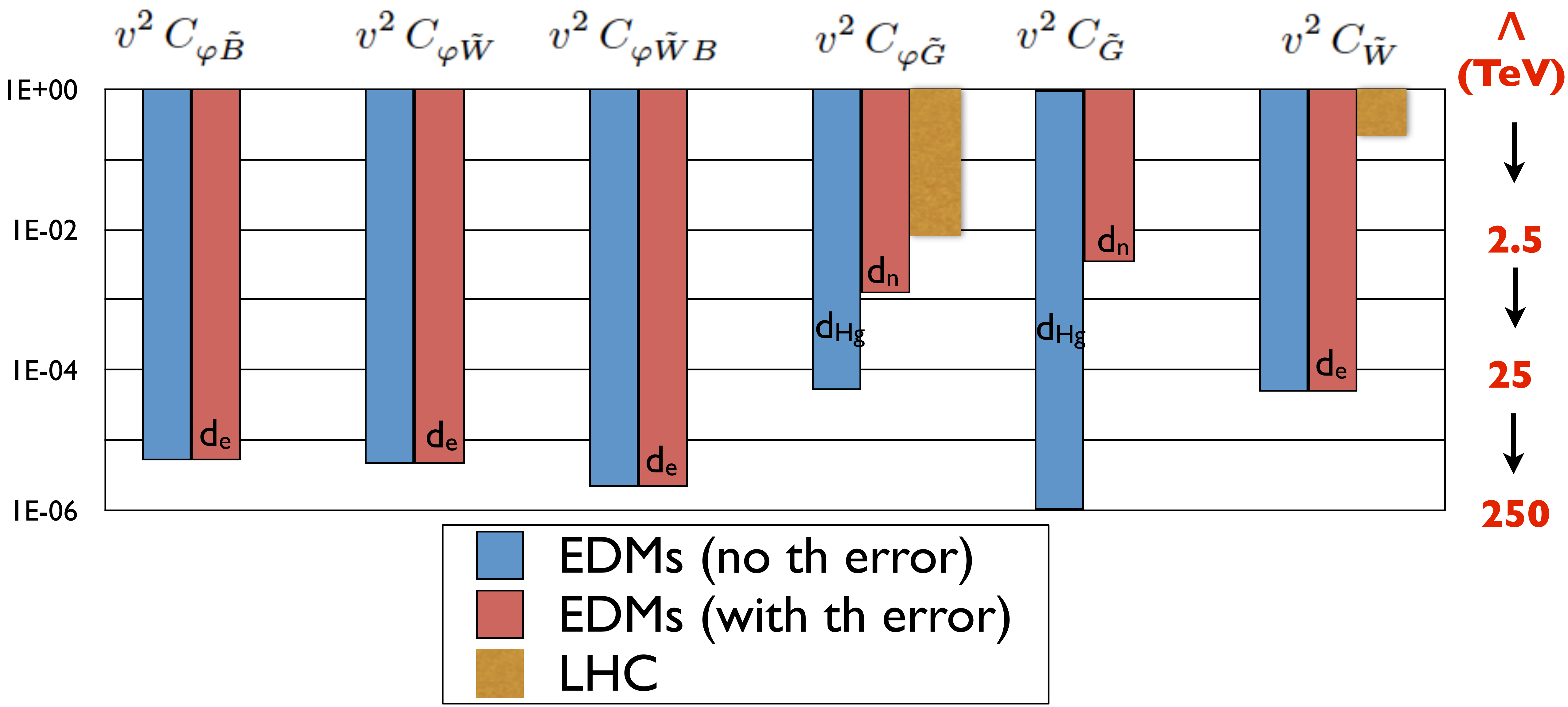






Higgs-gauge CPV couplings

- *Current* constraints, "turning on" one coupling at a time: EDMs vs LHC



VC, A. Crivellin, W. Dekens, J. de Vries, M. Hoferichter, E. Mereghetti, 1903.03625, Phys. Rev. Lett. 123, 051801 (2019)

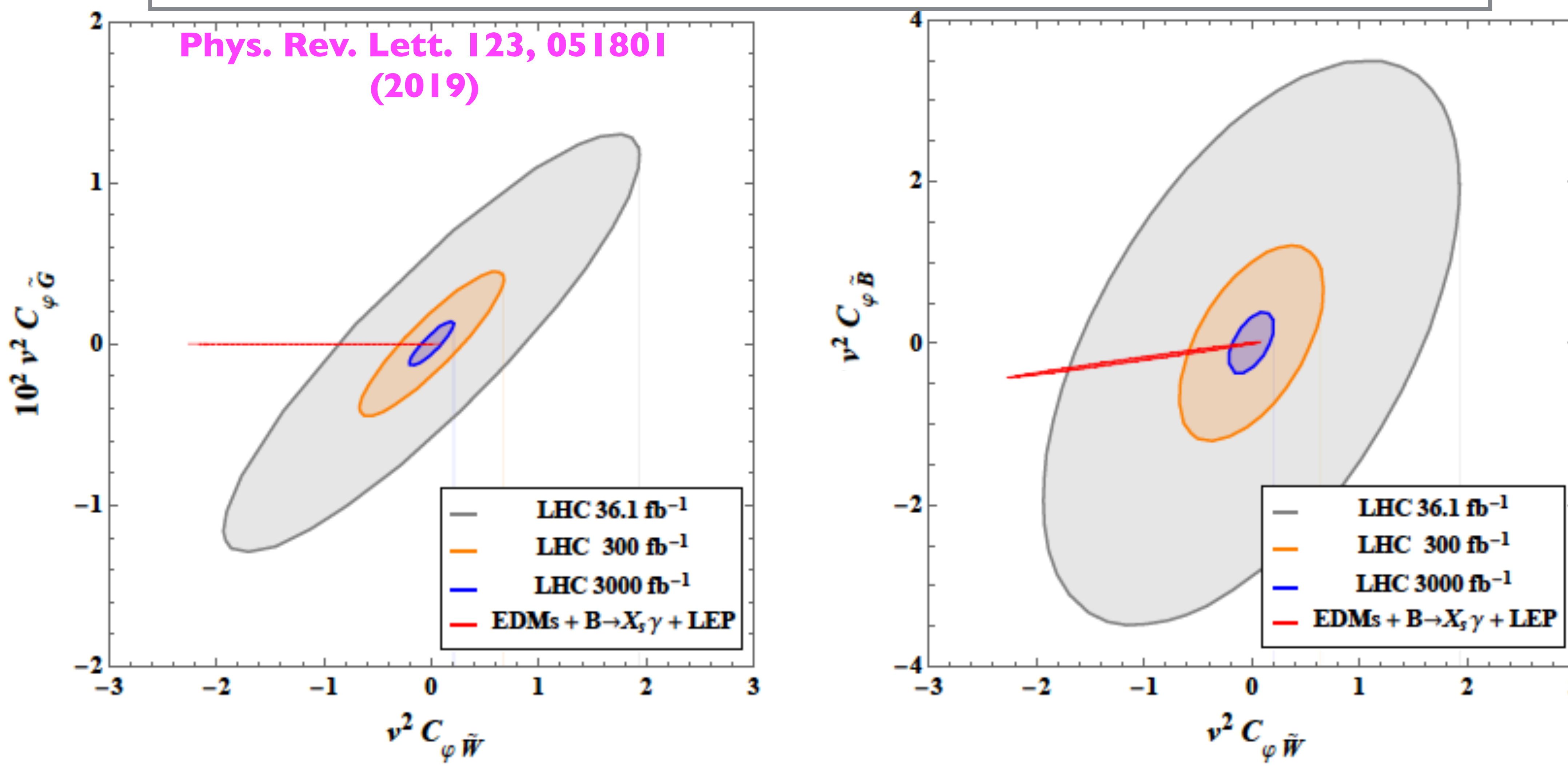
LHC limits from : ATLAS, 1703.04362 & Bernlochner et al., 1808.06577

Higgs-gauge CPV couplings

- *Prospective* constraints, turing on all couplings: low-energy vs LHC

$|d_{n,p,d,Ra}| < 10^{-27}$ e cm + improved theory errors

Phys. Rev. Lett. 123, 051801 (2019)



95% CL

LHC projections from Bernlochner et al., 1808.06577

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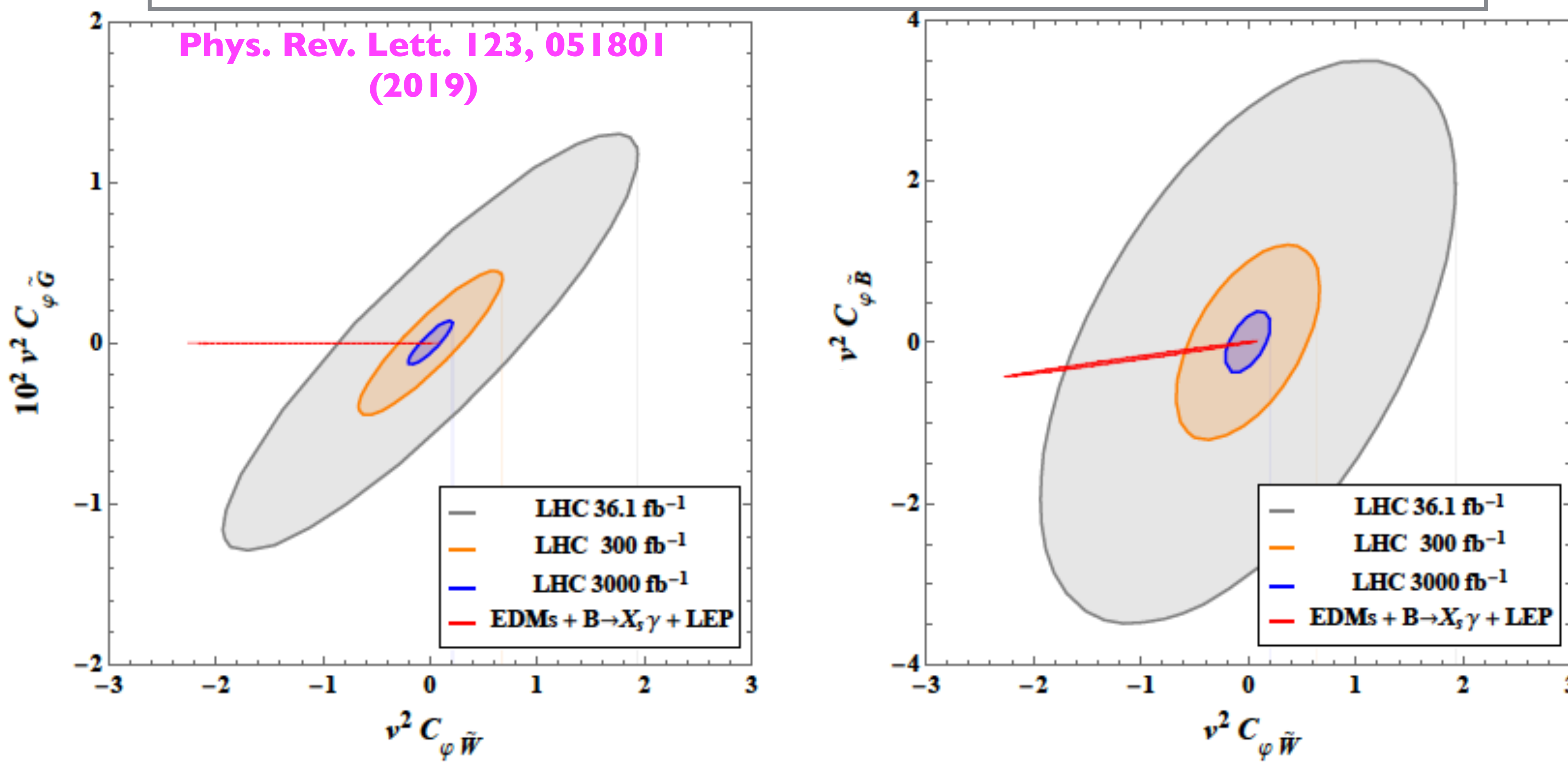


95% CL

LHC projections from Bernlochner et al., 1808.06577

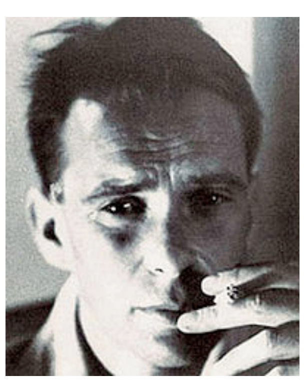
Low-energy measurements have far stronger constraining power → highly correlated allowed regions. Distinctive pattern that could be probed at the high-luminosity LHC

Summary

- Interpretation of null (for now) or positive EDM searches requires bridging scales: from BSM to hadronic, nuclear, atomic, molecular
  - Reducing theory uncertainties is essential
  - Lattice QCD can have big impact on hadronic matrix elements

- EDMs are a powerful probe of new sources of CP violation
  - Discussed stringent constraints on CPV couplings of the Higgs
  - More generally, if new physics exists only at very high scale, EDMs may be among a handful of observables able to probe it

Thank you!



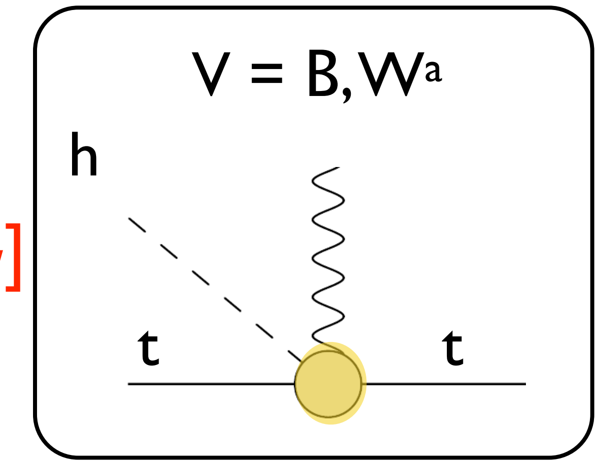
A drawing by
Bruno Touschek

Backup

Higgs-top couplings

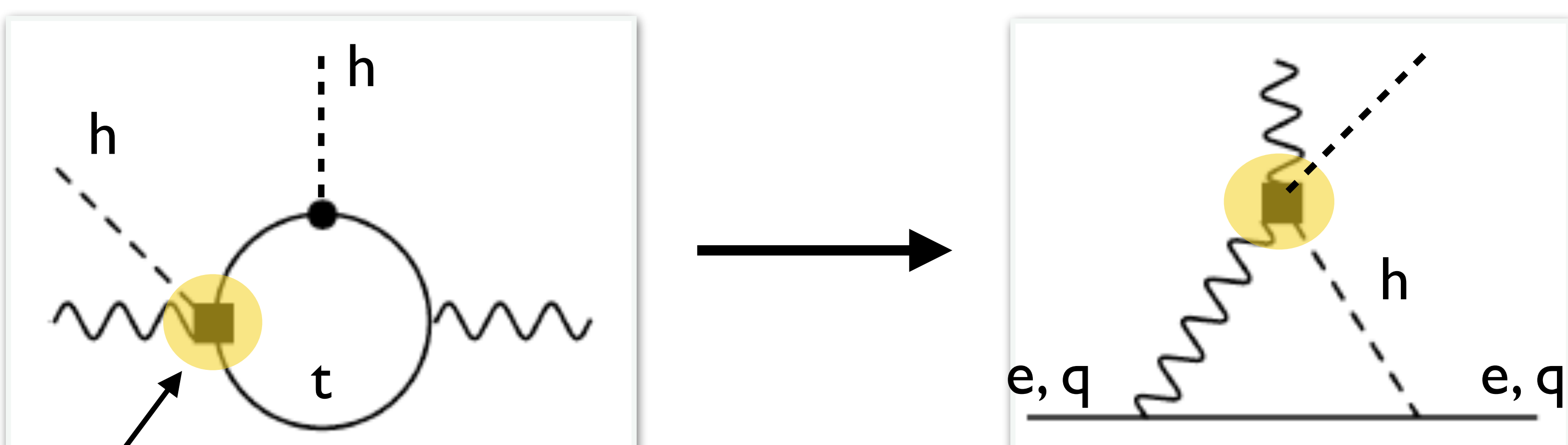
- Top quark particularly interesting: strongest coupling to Higgs; largest deviations from SM in several BSM scenarios; LHC is a top factory

C_Y [C_B, C_W]



H-t_L-t_R-V: EW top dipoles

- Top quark EDM affects the eEDM and qEDMs via two-step mixing

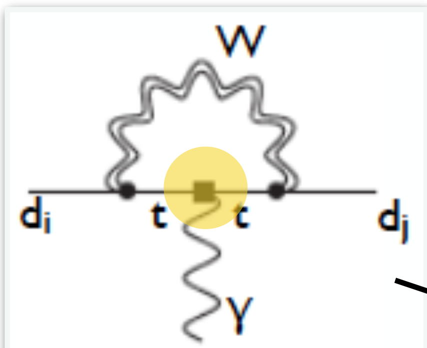


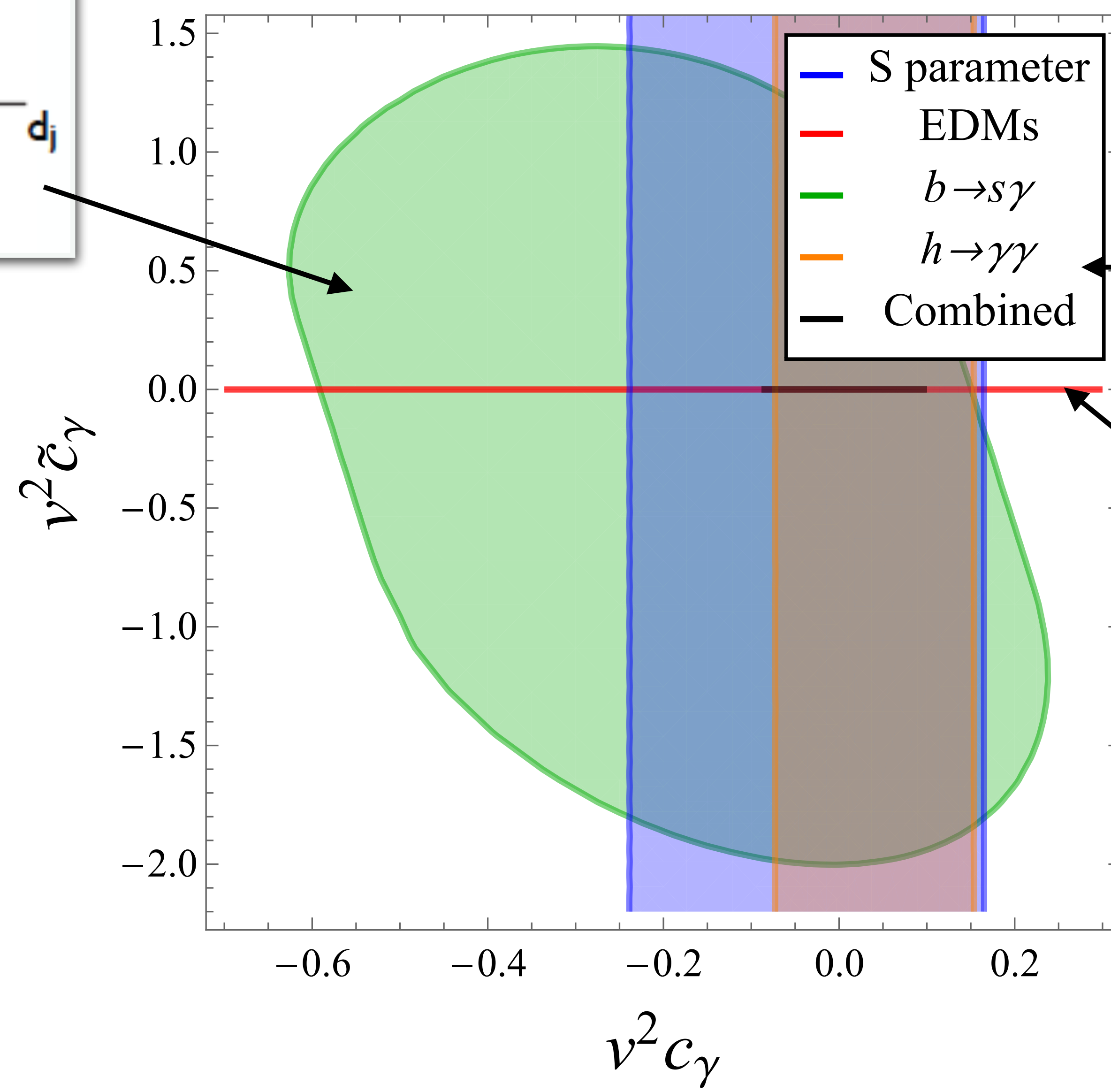
Im(C_Y)

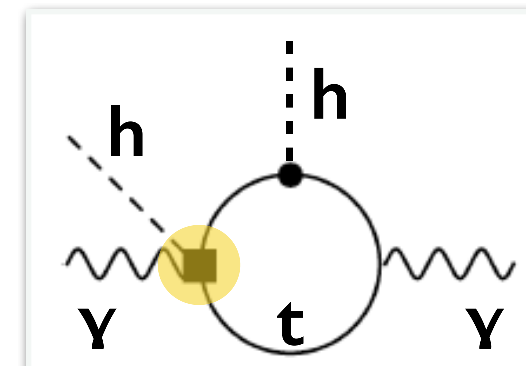
VC, W. Dekens, J. de Vries, E. Mereghetti 1603.03049
Fuyuto and Ramsey-Musolf 1706.08548

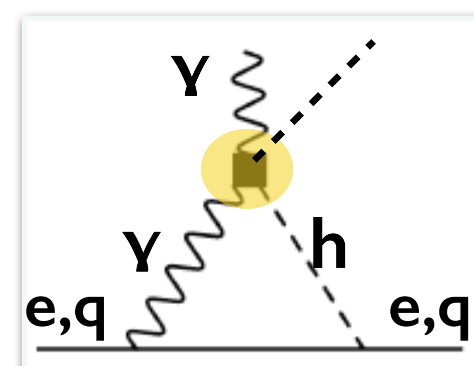
Higgs-top couplings

- EDM vs flavor and collider constraints









Top EDM
$d_t = eQ_t m_t \tilde{c}_\gamma$

Top MDM $\mu_t = eQ_t m_t c_\gamma$

VC, W. Dekens, J. de Vries, E. Mereghetti 1603.03049

Higgs-top couplings

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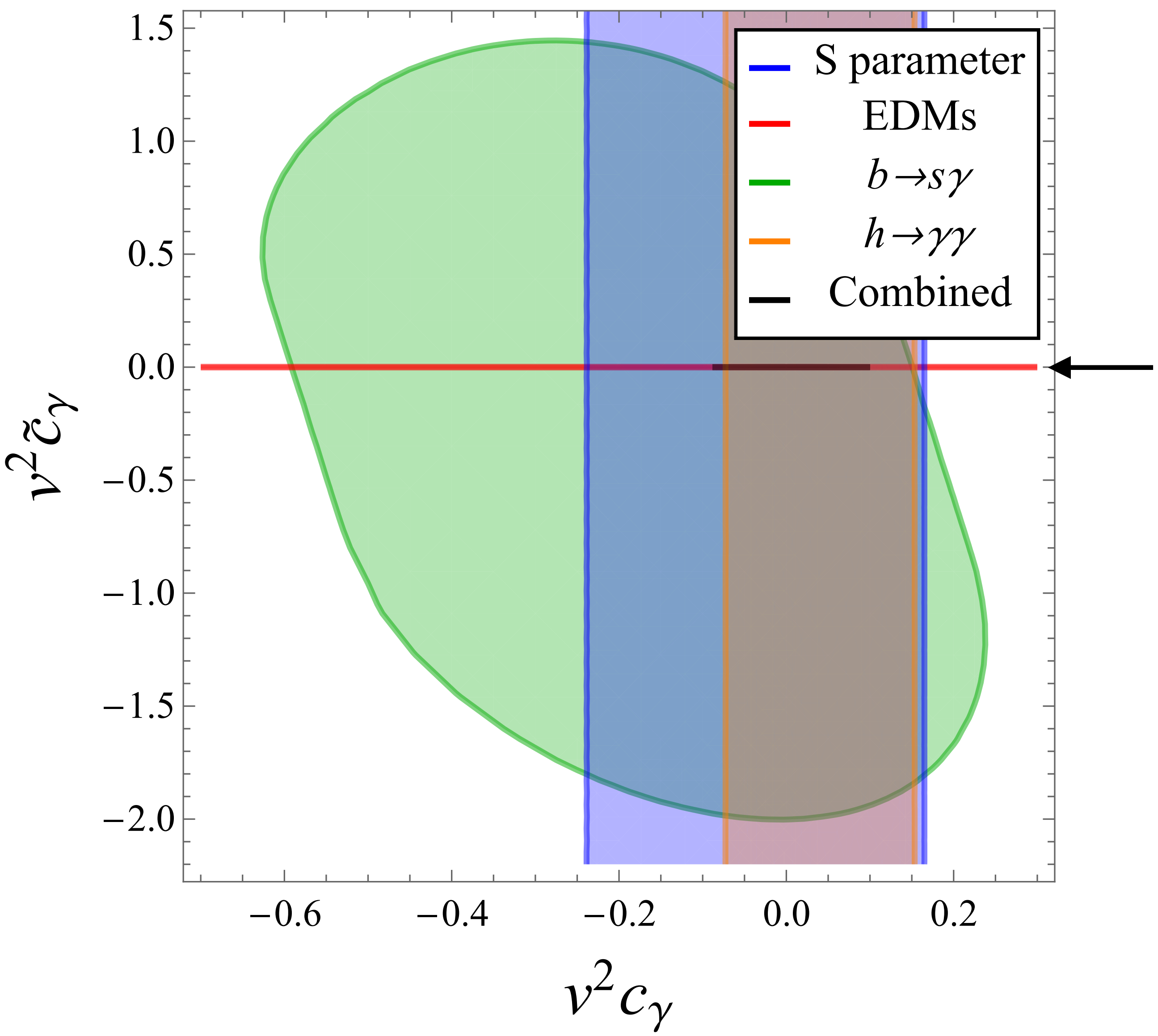


Top MDM $\mu_t = eQ_t m_t c_\gamma$

Bound on top EDM improved by three orders of magnitude: $|d_t| < 5 \times 10^{-20}$ e cm

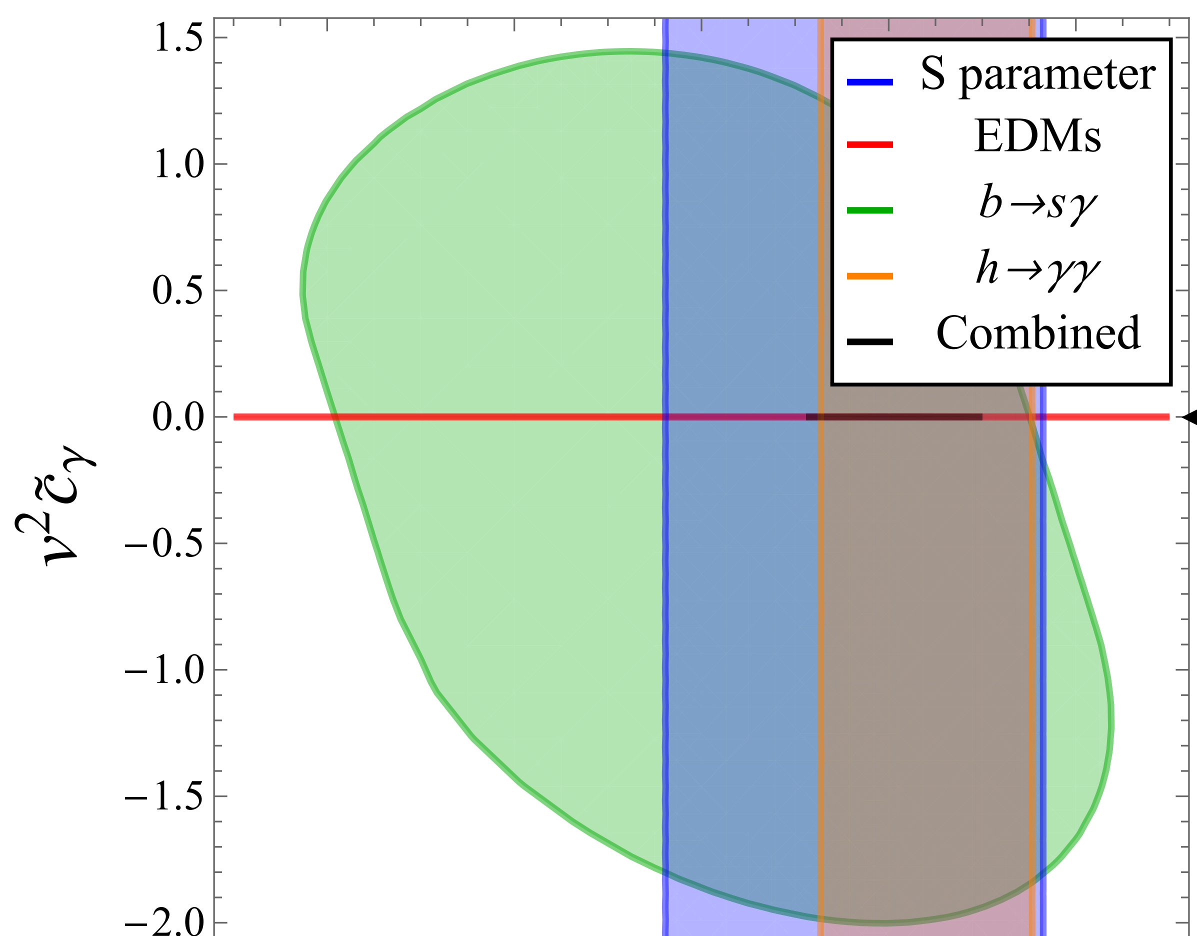
Dominated by eEDM

1000x stronger than direct LHC sensitivity ($pp \to$ jet t γ) [Fael-Gehrmann 13, Bouzas-Larios 13]

VC, W. Dekens, J. de Vries, E. Mereghetti 1603.03049

Higgs-top couplings

- EDM vs flavor and collider constraints



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Top EDM
$d_t = eQ_t m_t \tilde{c}_\gamma$

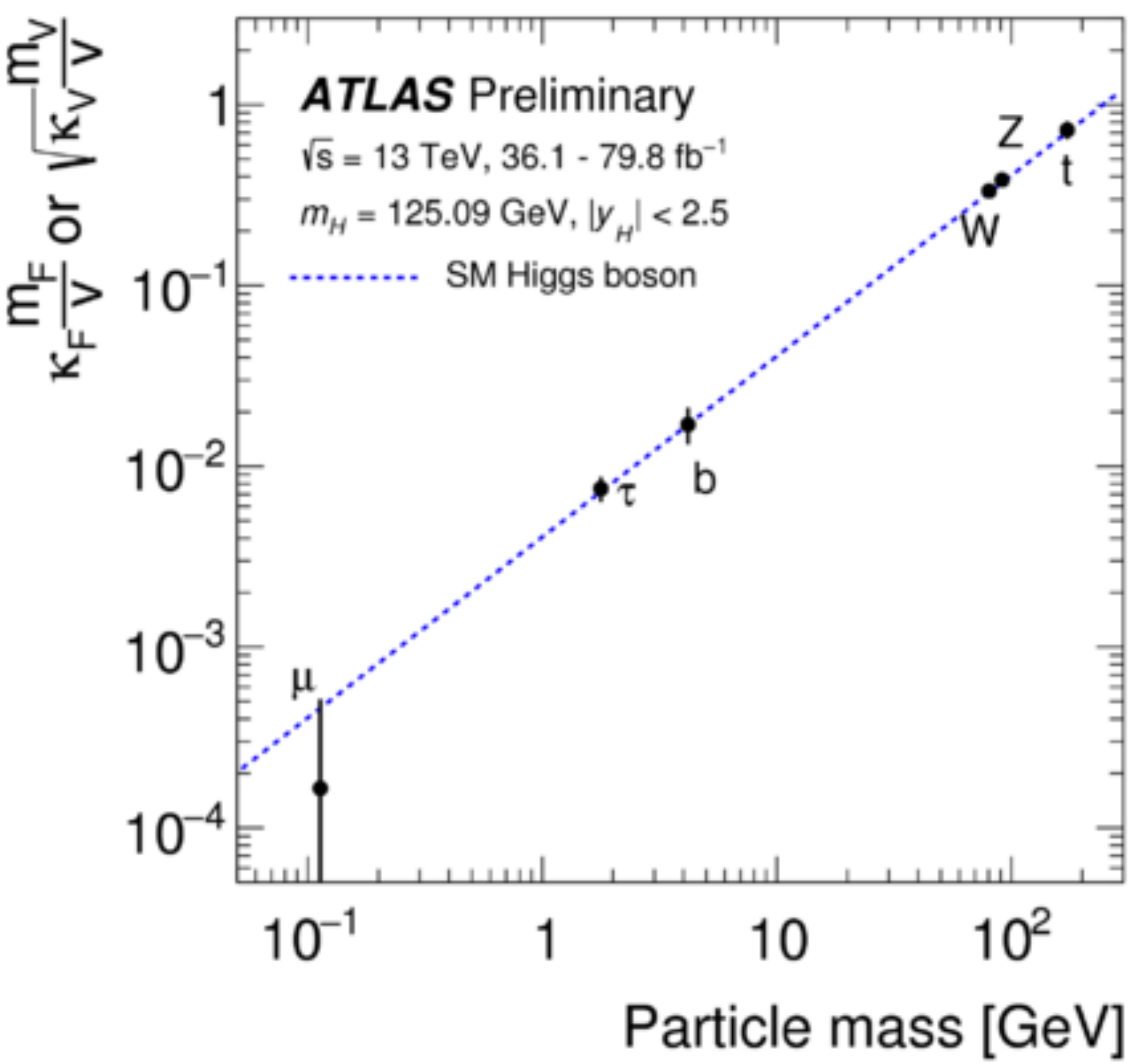
After ACME-II, bound on top EDM becomes stronger by a factor ~8

Top MDM $\mu_t = eQ_t m_t c_\gamma$

de Vries, E. Mereghetti 1603.03049

EDMs and CPV Higgs couplings

- So far, Higgs properties are compatible with SM expectations

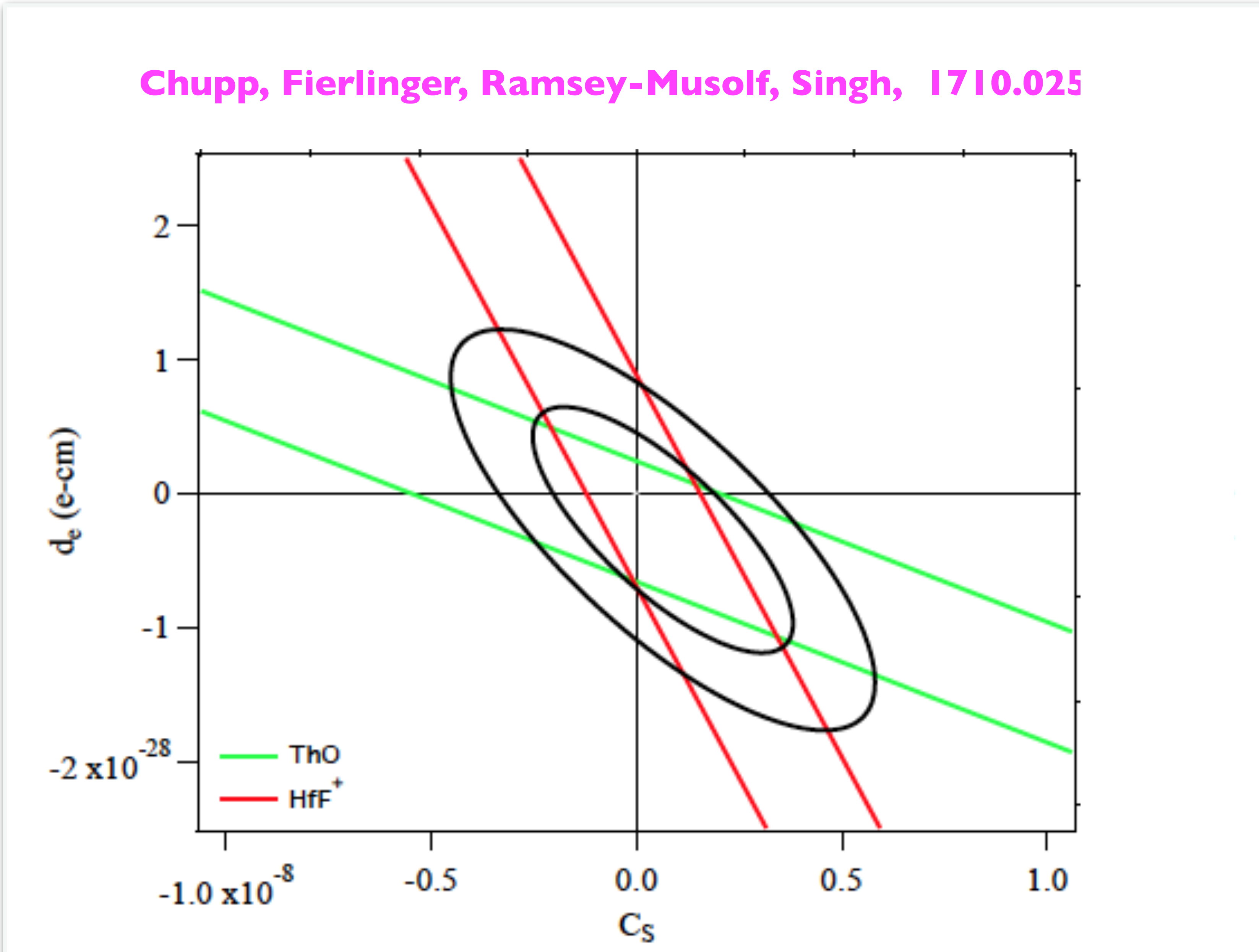


- Still room for deviations: is this the SM Higgs? Key question at LHC Run 2, 3

- EDMs can help constraining non-standard CPV Higgs couplings

Example: paramagnetic systems

- Constraints on $\tilde{c}_j$ (d_e and C_S) → connection to c_k's is relatively simple



$$\mathcal{L}_S = -\frac{G_F}{\sqrt{2}} \bar{e} i \gamma_5 e \, \bar{N} \left[C_S^{(0)} + C_S^{(1)} \tau_3 \right] N \qquad C_S \equiv C_S^{(0)} + \left(\frac{Z-N}{Z+N} \right) C_S^{(1)}$$