“Symmetry Tests in Nuclei and Atoms”, KITP, September 19-23 2016

Electric Dipole Moments and new sources of CP violation

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- Bad news: one more talk on EDMs…
- Good news: it's the last one!

Outline

- Connecting EDMs to UV models of CPV (matrix elements)

- EDMs as probes of new sources of CPV in the LHC era**
    - Impact of EDMs on CP-violating Higgs couplings
    - Impact of EDMs on high-scale supersymmetry

**Two main results from the LHC, so far:
(1) There is a Higgs boson with m ~125 GeV and
(2) Everything else (if any) is quite heavier

Part 1: Framework

We love EDMs because:

1. Essentially free of SM “background” (CKM)*

2. Probe very high-scales (Λ~10-100 TeV)

$$d_n \propto \frac{m_q}{\Lambda^2} e\, \phi_{CP}$$

3. Probe key ingredient for baryogenesis (CPV in SM is insufficient)

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

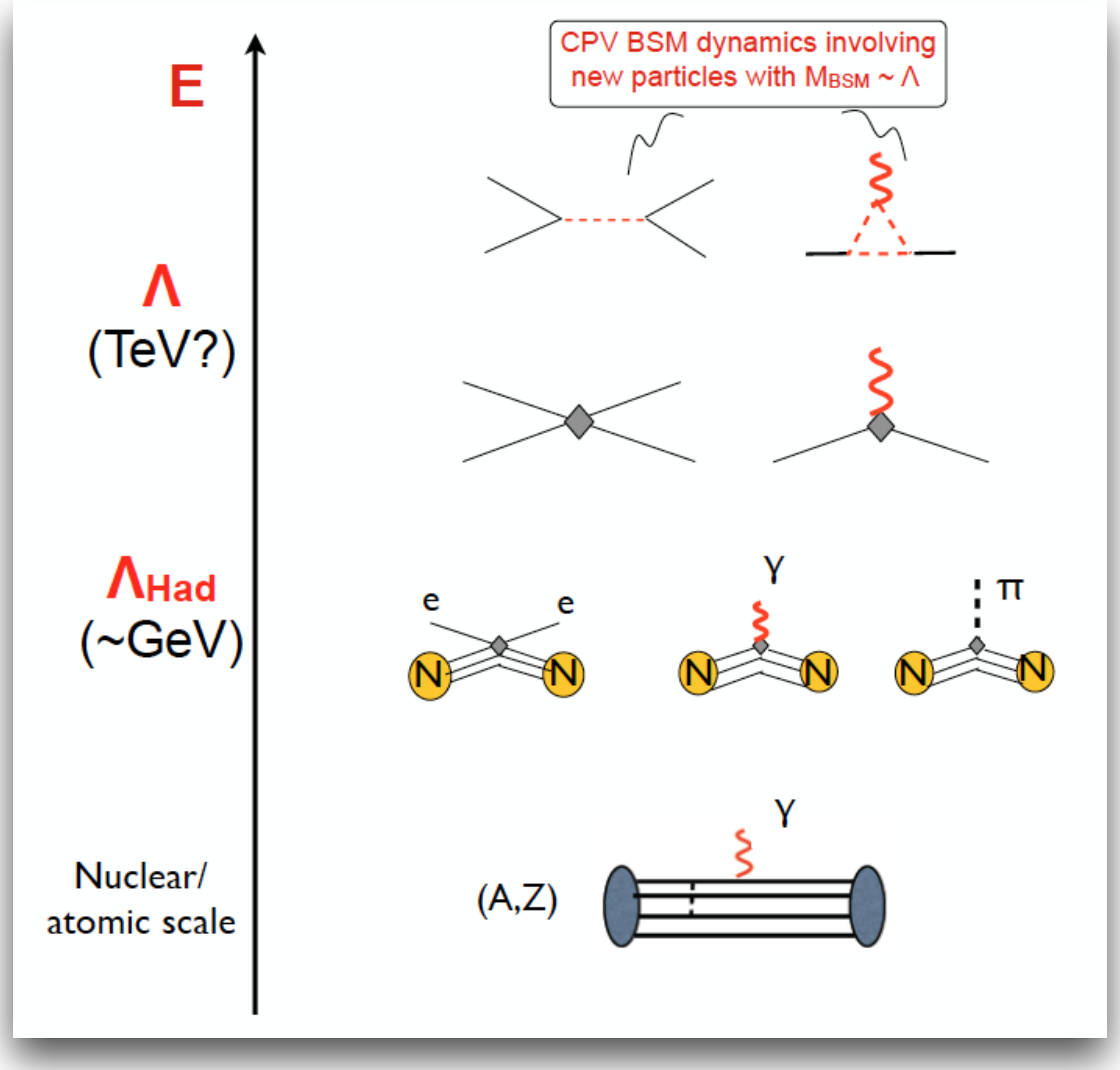
We hate EDMs because:

See talks by A. Ritz and J. de Vries

(framework)

See talks by C. Alexandrou, H.W. Lin, S. Syritsyn

(LQCD)



RG EVOLUTION (perturbative)

MATRIX ELEMENTS (non-perturbative)

Connecting EDMs to new physics is a challenging multi-scale problem: need RG evolution of effective couplings & hadronic / nuclear / molecular calculations of matrix elements

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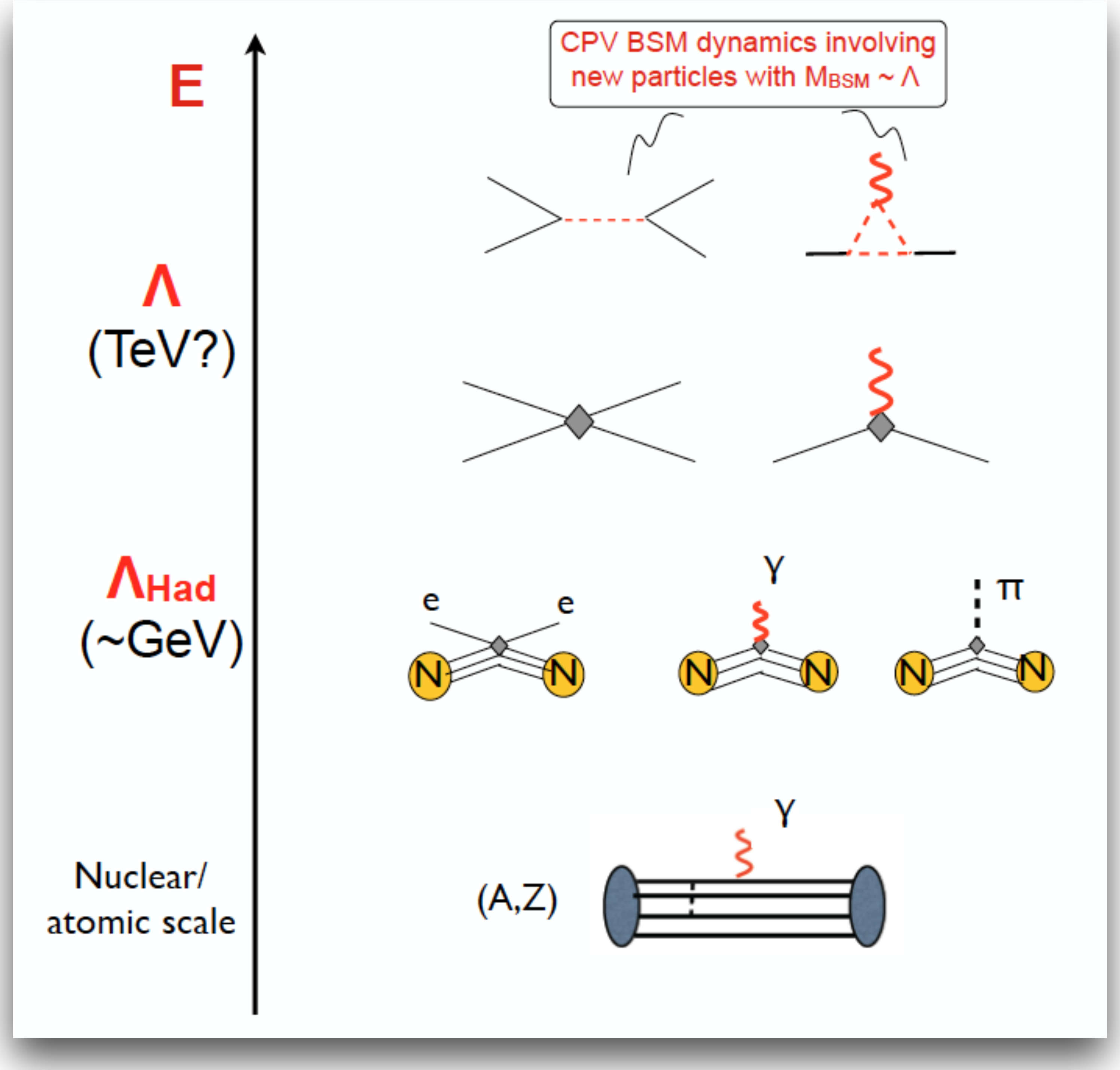

RG EVOLUTION (perturbative)

MATRIX ELEMENTS (non-perturbative)

Matrix element uncertainties strongly dilute constraining and model-discriminating power of impressive experimental searches

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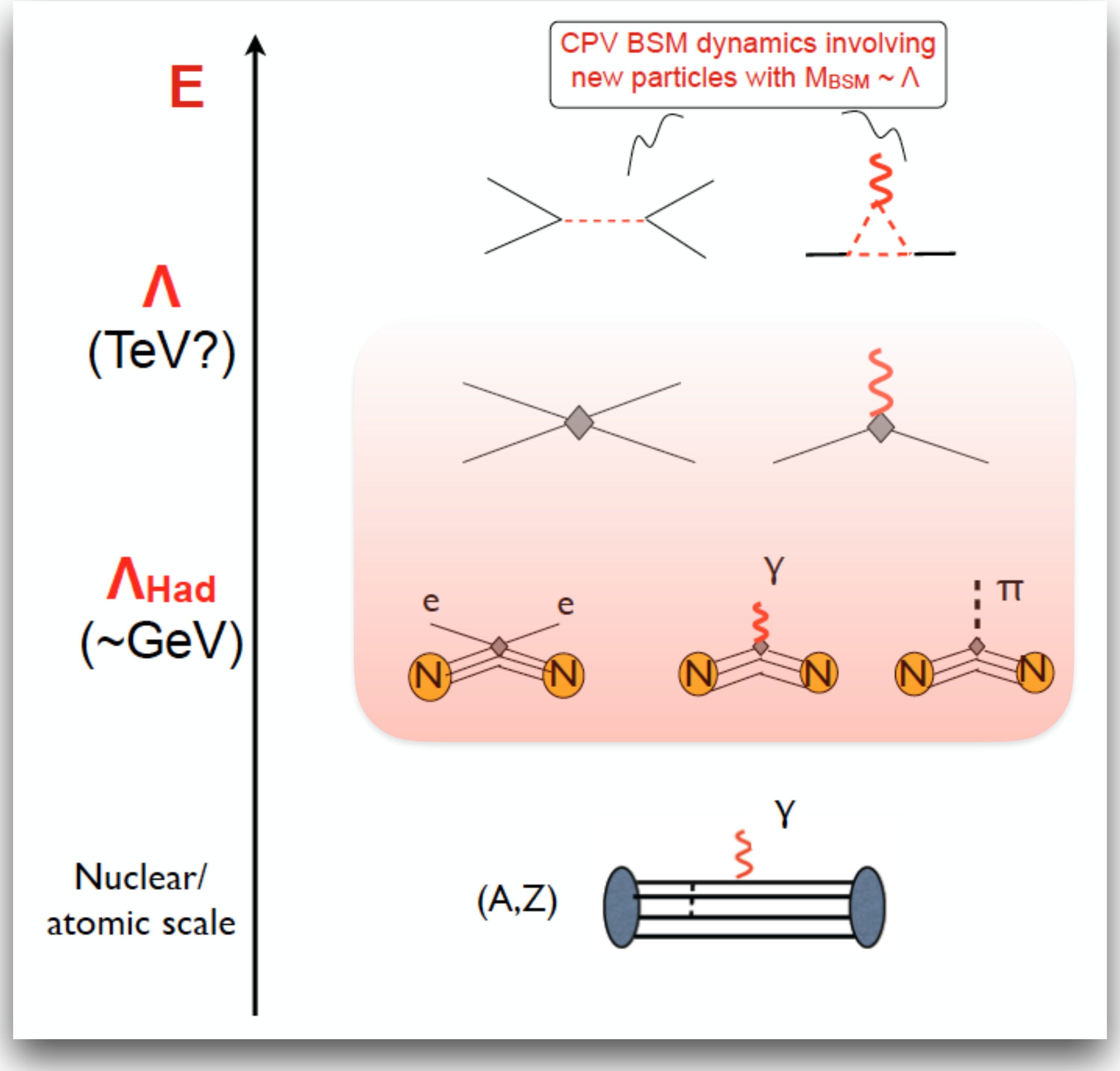


RG EVOLUTION

(perturbative)

MATRIX ELEMENTS

(non-perturbative)

Next: short summary on status and prospects for hadronic matrix elements

CPV at the hadronic level

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

Electric and chromo-electric dipoles of fermions

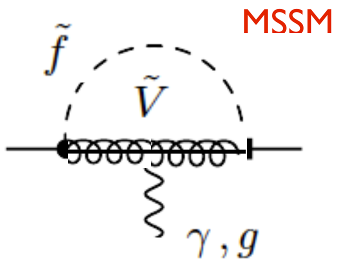
$$\boxed{d_f, \tilde{d}_q \sim \frac{v_{ew}}{\Lambda^2}}$$

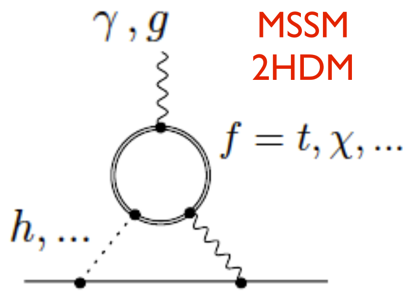
Gluon chromo-EDM (Weinberg operator)

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

Semileptonic and 4-quark

Generated by “integrating out” heavy particles and RG running, e.g:





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Matches onto leading pion-nucleon chiral EFT operators

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

Electron and Nucleon EDMs

T-odd P-odd pion-nucleon couplings

3π, short-range 4N and 2N2e coupling

LECs calculable in terms of quark couplings via appropriate matrix elements

Status of matrix elements (1)

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

Pospelov-Ritz hep-ph/0504231 and refs therein

$$\begin{aligned} d_n \; = \; & -(0.35 \pm 0.18) d_u + (1.4 \pm 0.7) d_d + (?\pm?) d_s \\ & -(0.55 \pm 0.28) e\tilde{d}_u - (1.1 \pm 0.55) e\tilde{d}_d \pm (50 \pm 40)\,\mathrm{MeV}\, e\, d_W \end{aligned}$$

μ=1 GeV

QCD Sum Rules (50%)

QCD Sum Rules + NDA (~100%)

- Matching with QCD sum rules: 50% → 200% uncertainties

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$$

μ=1 GeV

QCD Sum Rules (50%)

QCD Sum Rules + NDA (~100%)

- Matching with QCD sum rules: 50% → 200% uncertainties

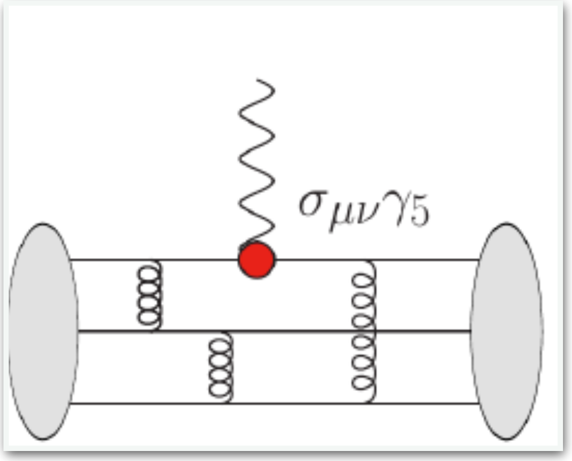
- Here Lattice QCD can play a major role:
  quark EDM [✔], quark CEDM [ongoing], Weinberg & 4q [future]

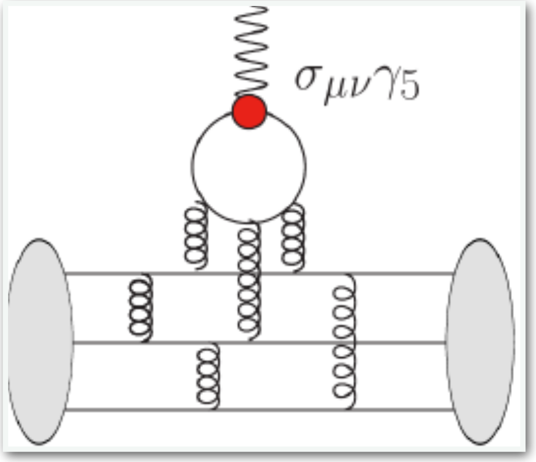
First step: $d_N[d_q]$ from LQCD

- Problem “factorizes”: need tensor charge of the nucleon

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

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





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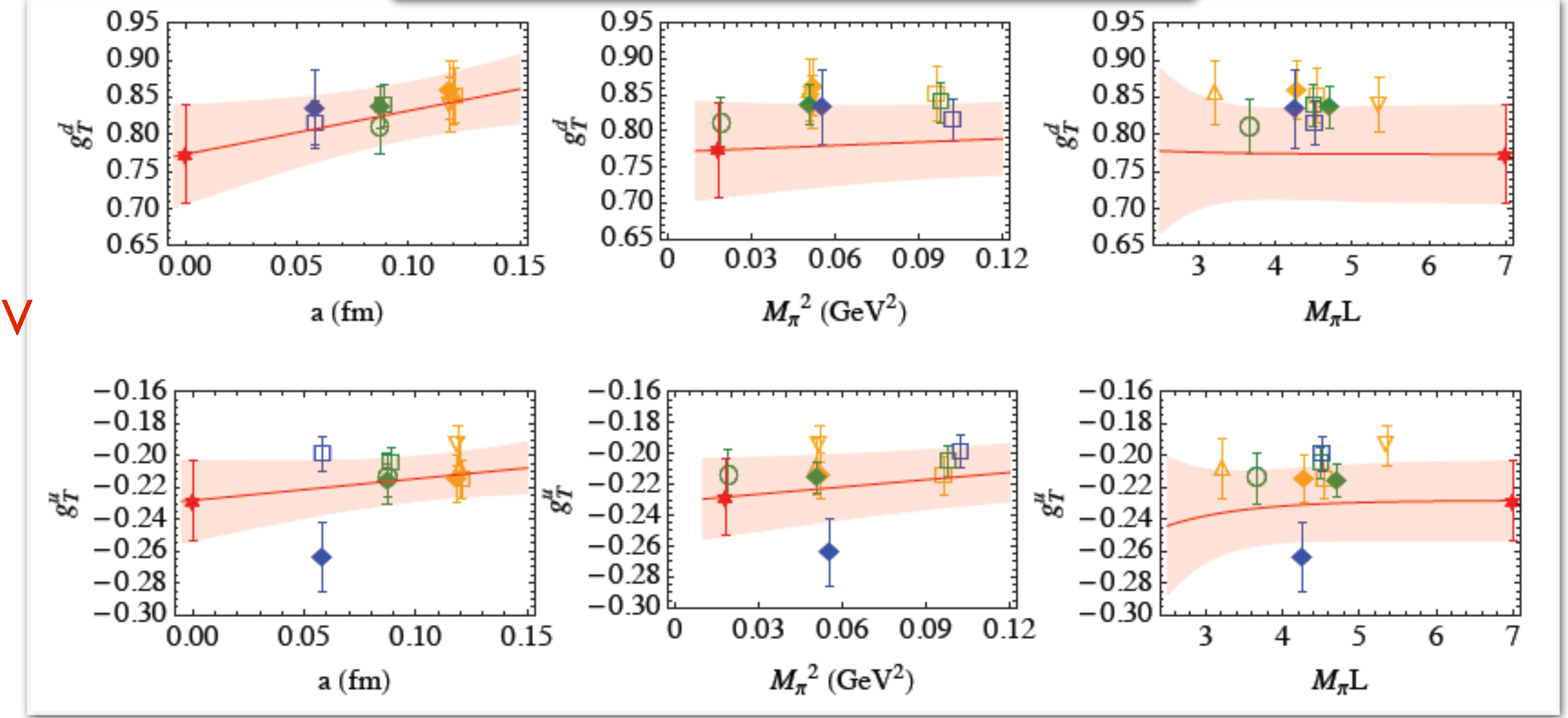
$$\langle N|\, \bar{q}\sigma_{\mu\nu}q\, |N\rangle \equiv g_T^{(N,q)}\; \bar{\psi}_N\sigma_{\mu\nu}\psi_N$$

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



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

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

See talk by H.W. Lin

O(10%) error including all systematics: excited states, continuum, quark masses, volume

First step: $d_N[d_q]$ from LQCD

- Problem “factorizes”: need tensor charge of the nucleon

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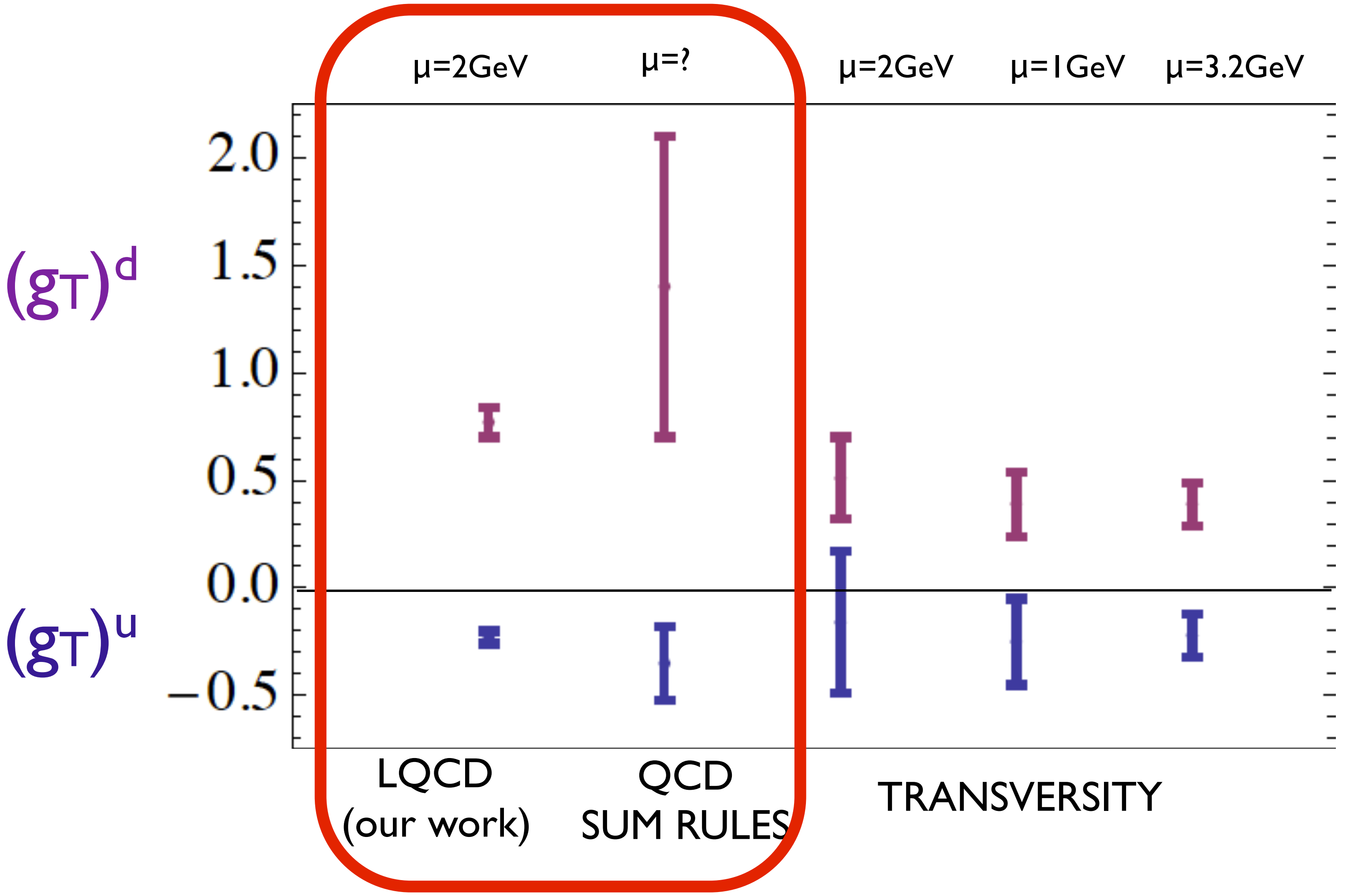
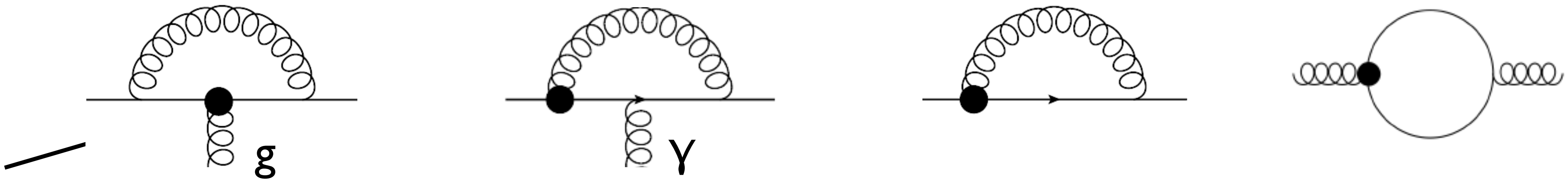
- Impact: smaller uncertainty (50% to 10%) and smaller central values



Ongoing: $d_N[\tilde{d}_q]$ from LQCD

- Study of UV divergences: mixing with pseudo-scalar density, qEDM, $mG\tilde{G}$, … → renormalization prescription suitable for LQCD



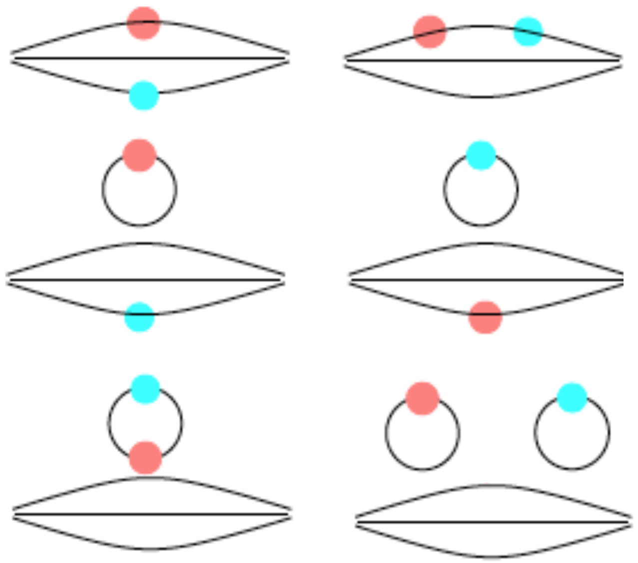
Bhattacharya, VC, Gupta, Mereghetti, Yoon, Phys. Rev. D92, 114026 [1502.07325]

- Extraction of nucleon EDM from appropriate correlation function

Requires in principle a 4-point function:

$$\boxed{\langle n| J_\mu^{\mathrm{EM}} \int d^4x \, O_i(x) \, |n\rangle}$$

See talk by S. Syritsyn



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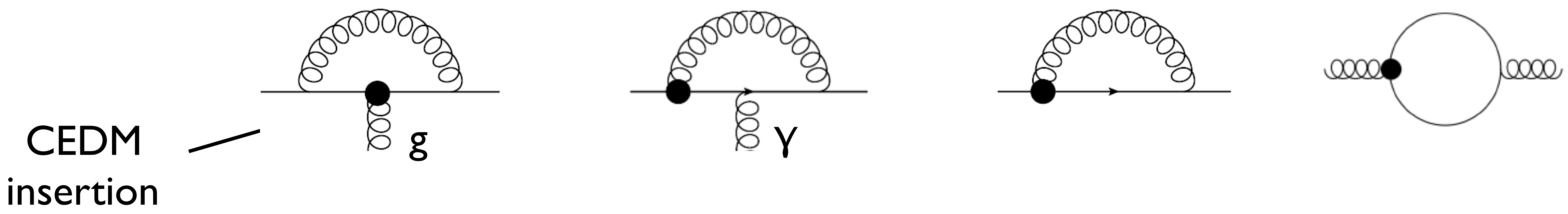
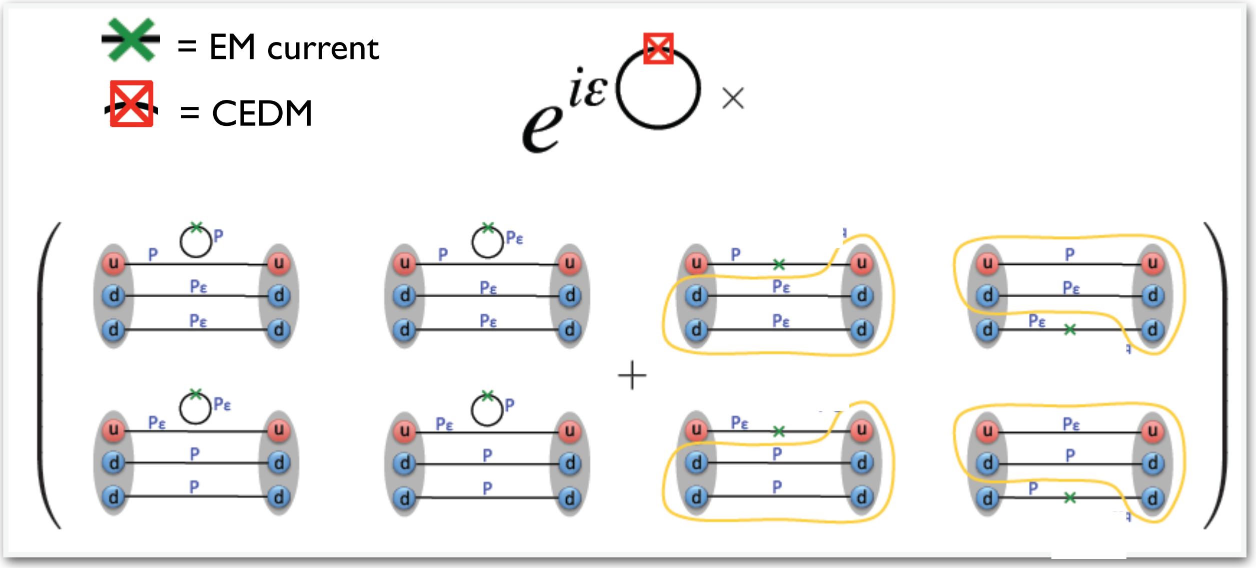


Bhattacharya, VC, Gupta, Mereghetti, Yoon, Phys. Rev. D92, 114026 [1502.07325]

- Alternative method: modify Dirac operator by adding term $i\varepsilon\sigma_{\mu\nu}\gamma_5 G^{\mu\nu}$ and compute 3-point function

T. Bhattacharya, V. Cirigliano, R. Gupta, E. Mereghetti, B. Yoon,
Proceedings of Science LATTICE 2015 (2016) 238
and Talk at Lattice 2016



Status of matrix elements (2)

- πNN couplings: O(1) uncertainties (from QCD sum rules)

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

Pospelov-Ritz hep-ph/0504231 and refs therein

Towards lattice QCD calculation: de Vries, Mereghetti, Walker-Loud

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Towards lattice QCD calculation: de Vries, Mereghetti, Walker-Loud

- Diamagnetic atoms: O(1) uncertainties from nuclear structure

$$d_{\mathrm{Hg}} = -(2.8 \pm 0.6)10^{-4}\left[(1.9 \pm 0.1)d_n + (0.20 \pm 0.06)d_p + \left(0.13^{+0.5}_{-0.07}\,\bar{g}_0 + 0.25^{+0.89}_{-0.63}\,\bar{g}_1\right)e\,\mathrm{fm}\right]$$

^{199}Hg, ^{129}Xe, ^{225}Ra

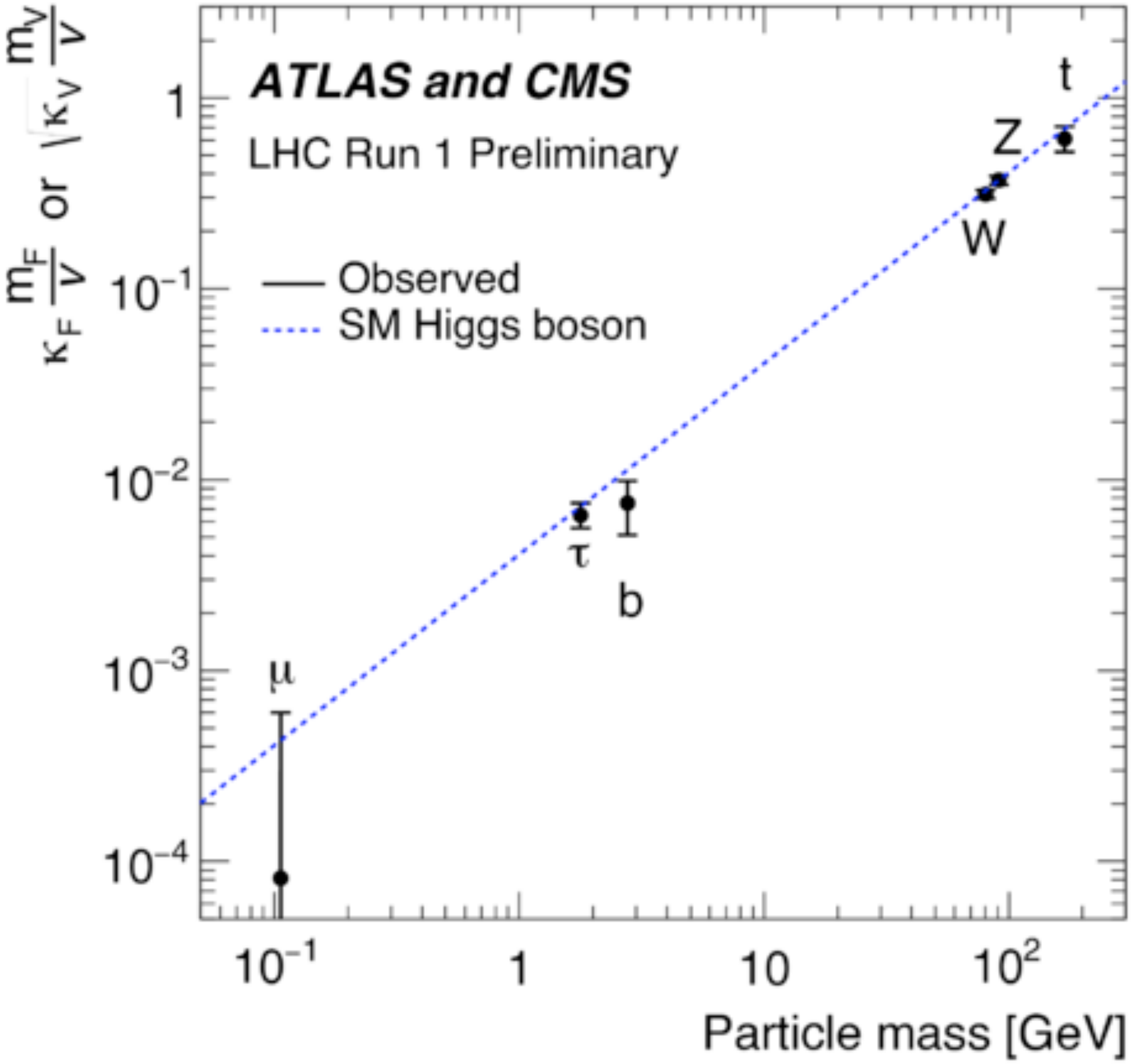
$$\begin{aligned} d_{\mathrm{Xe}} &= (0.33 \pm 0.05)10^{-4}\left(-0.10^{+0.037}_{-0.53}\,\bar{g}_0 - 0.076^{+0.038}_{-0.55}\,\bar{g}_1\right)e\,\mathrm{fm} \\ d_{\mathrm{Ra}} &= -(7.7 \pm 0.8)10^{-4}\left(-19^{+6.4}_{-57}\,\bar{g}_0 + 76^{+227}_{-25}\,\bar{g}_1\right)e\,\mathrm{fm} \end{aligned}$$

Engel, Ramsey-Musolf, van Kolck 1303.2371, and references therein

Part 2: EDMs in the LHC era

EDMs and Higgs couplings

- So far, Higgs properties are compatible with SM expectations



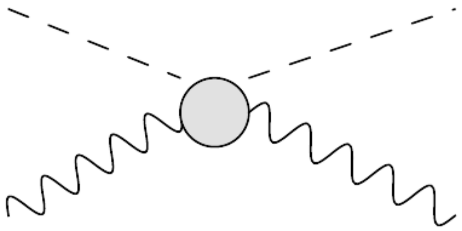
- Still room for deviations: is this the SM Higgs? Key question at LHC Run 2 & important goal for low energy experiments

- EDMs play an important role in pinning down non-standard CP-violating Higgs couplings

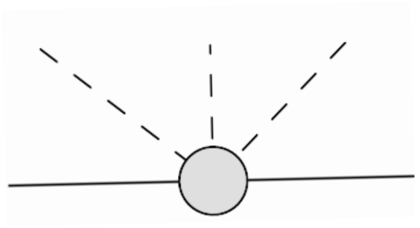
If Λ_{BSM} > TeV, EFT approach applicable to EDMs *and* colliders

- Several dim-6 operators in the “SM-EFT” involve CPV Higgs interactions

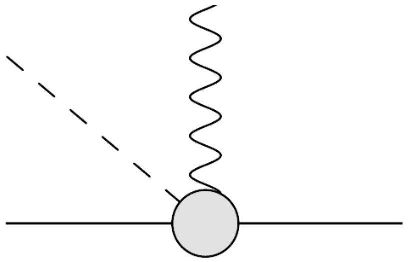
$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$



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



H-q_L-q_R: scalar



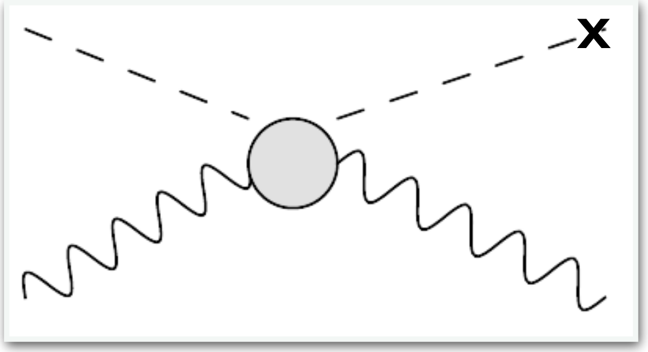
H-q_L-q_R-V: dipole

V = g, W^a, B

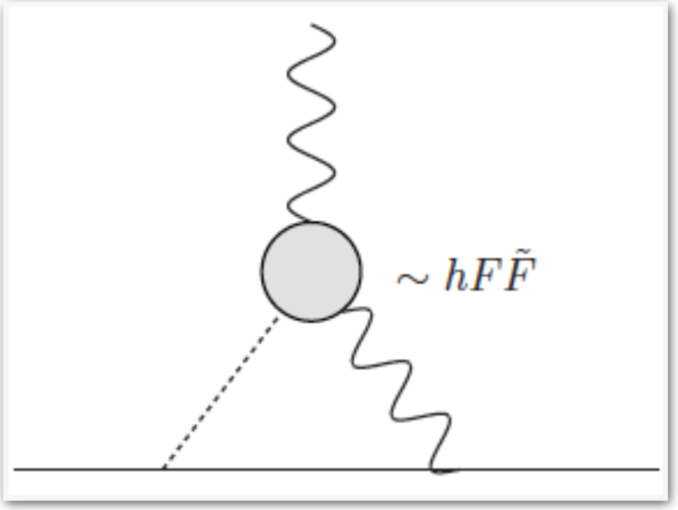
Higgs coupling to photons

- Leading (dim-6) CPV operator affects both Higgs decay and EDMs

$$\boxed{\mathcal{L} \supset c_{\gamma\gamma}\, v\, h\, F_{\mu\nu} \tilde{F}^{\mu\nu}}$$



$$c_{\gamma\gamma} \equiv \frac{1}{\Lambda^2_{\gamma\gamma}}$$



McKeen-Pospelov-Ritz 1208.4597 + ACME new limit

- eEDM ⇒ $\Lambda_{\gamma\gamma} > 100$ TeV and hence $\Gamma(h\to\gamma\gamma)/\Gamma(h\to\gamma\gamma)_{SM} - 1 \approx 10^{-5}$

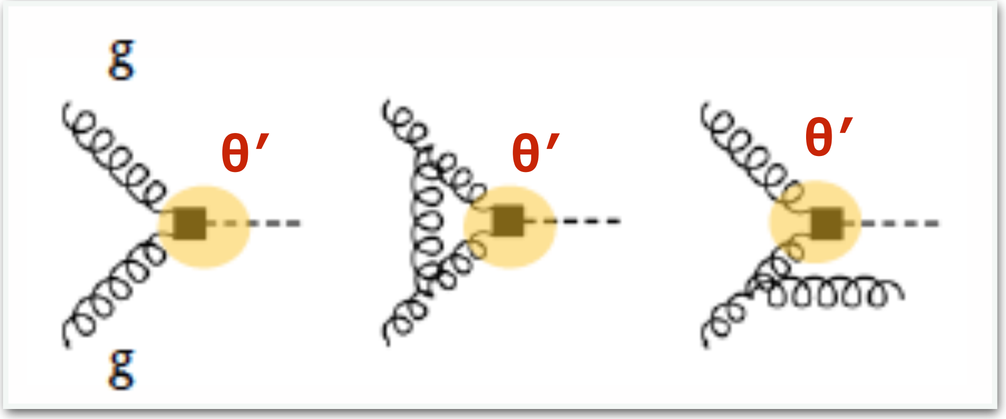
- Bound evaded by more elaborate model-building, involving for example (i) contribution to $d_e(\Lambda)$ that cancels effect of running;
  (ii) degenerate scalar sector (EFT not applicable)

Higgs coupling to gluons

- Leading operator affects both Higgs production and decay and EDMs

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

E.g.: Gluon Fusion at LHC



$$\mu_{ggF} = \frac{\sigma^{SM}_{ggF} + \sigma^{\theta'}_{ggF}}{\sigma^{SM}_{ggF}} :$$

$$= 1 + (2.28 \pm 0.01)\ \left(v^2\theta'\right)^2$$

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

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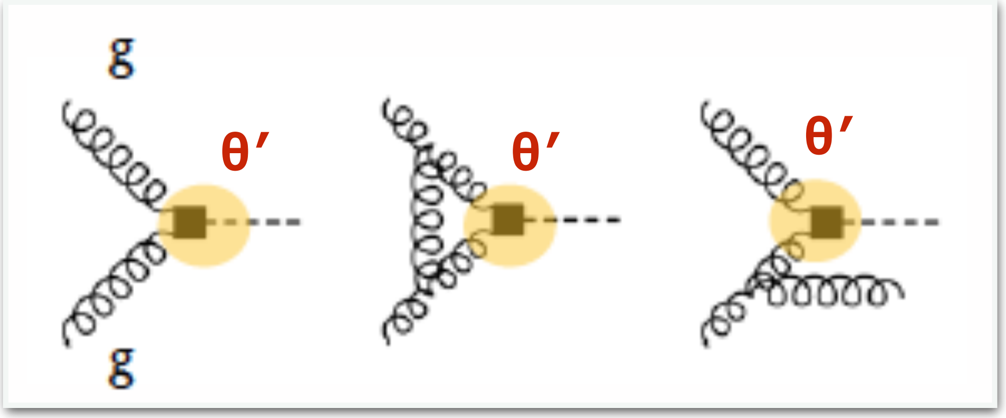
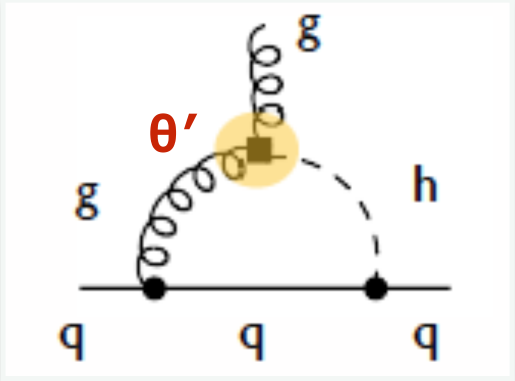


nEDM via quark chromo-EDM
(→ qEDM and Weinberg)



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

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

$$\begin{aligned} (d_q/m_q)(\Lambda_\chi) &= 1.4 \times 10^{-4}\, Q_q\, \theta'(M_{\text{BSM}}) \\ (\tilde{d}_q/m_q)(\Lambda_\chi) &= 1.7 \times 10^{-4}\, \theta'(M_{\text{BSM}}) \\ d_W(\Lambda_\chi) &= -7.3 \times 10^{-6}\, \theta'(M_{\text{BSM}}) \end{aligned}$$

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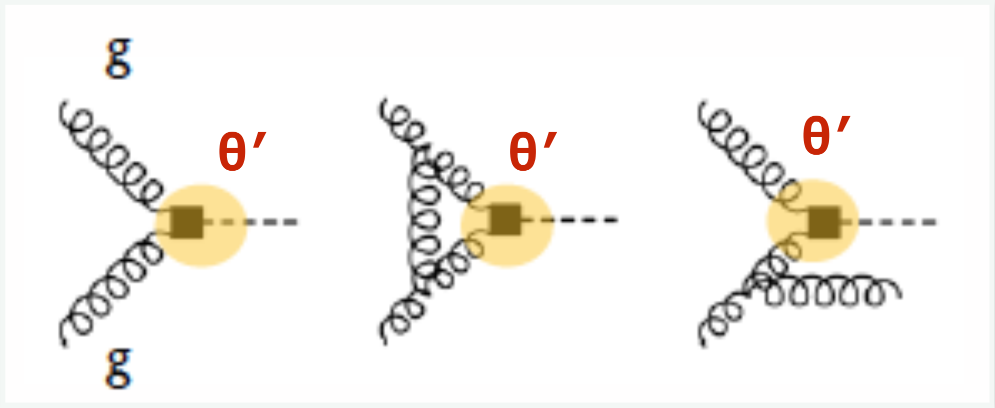

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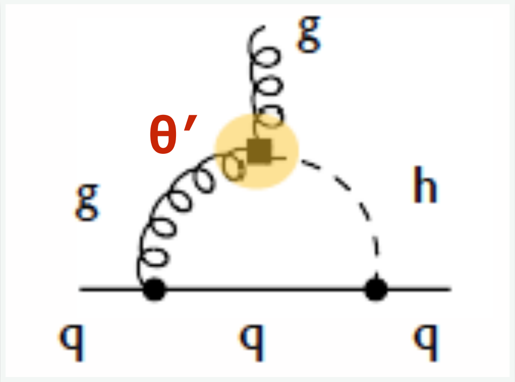

	d_n	d_{Hg}	d_n, d_{Hg} (comb)	LHC (CMS)
Central	0.06	0.04	0.04	0.27
Range	0.23	x	0.23	0.27

Bounds on $v^2\theta'$ at the scale Λ = 1TeV

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

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E.g.: Gluon Fusion at LHC

nEDM via quark chromo-EDM
(→ qEDM and Weinberg)

- Central: EDMs leave little room for observable deviation at LHC run 2
- Range: ^{199}Hg bounds disappears, n bound much weaker

	d_n	d_{Hg}	d_n, d_{Hg} (comb)	LHC (CMS)
Central	0.06	0.04	0.04	0.27
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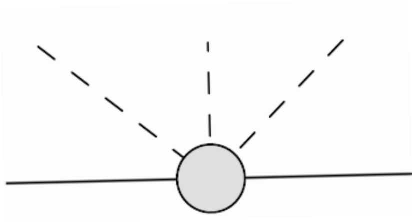
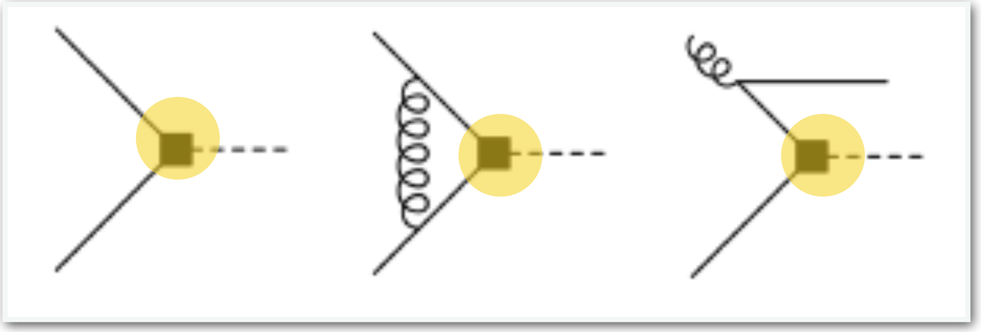
Yukawa couplings to quarks

- Pseudo-scalar Yukawa coupling (e.g. from dim-6 operator)

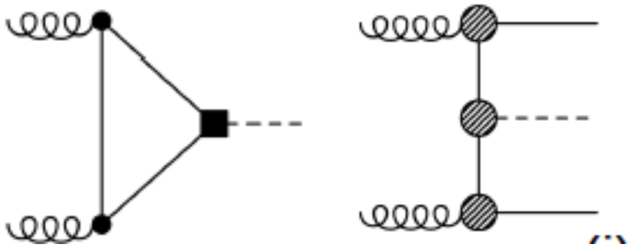
$$\boxed{\mathcal{L}_6^{CPV} \supset v^2 \mathrm{Im}\, Y_q' \, \bar{q} i \gamma_5 q \, h}$$



LHC: Higgs production



Top quark:



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

Brod Haisch Zupan 1310.1385 — third generation Yukawas

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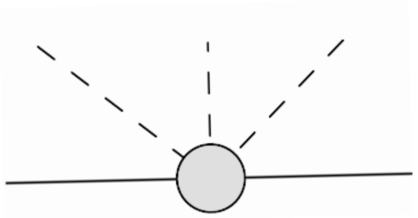

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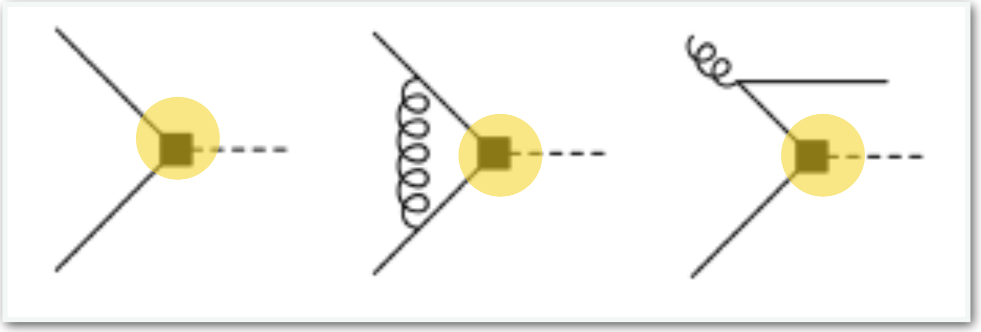
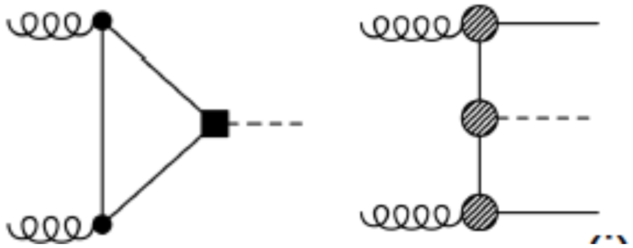
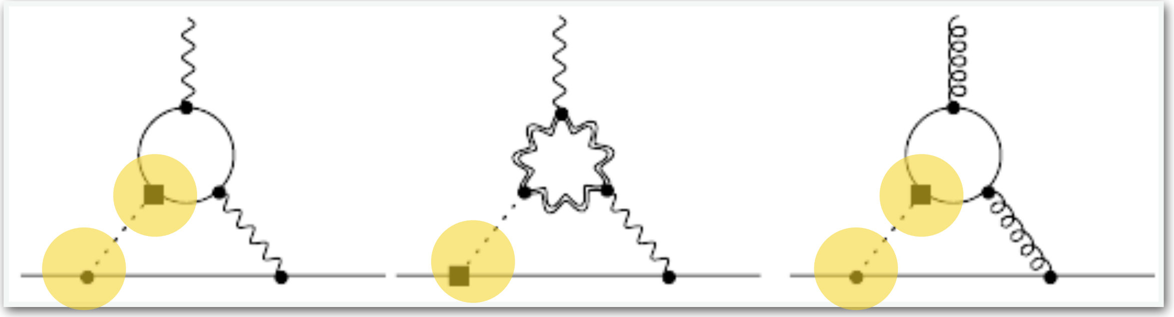
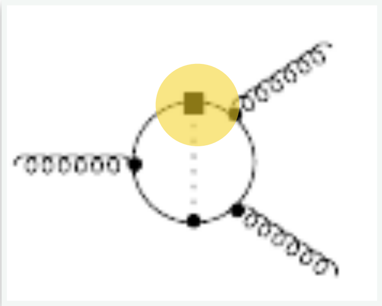


Top quark:



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

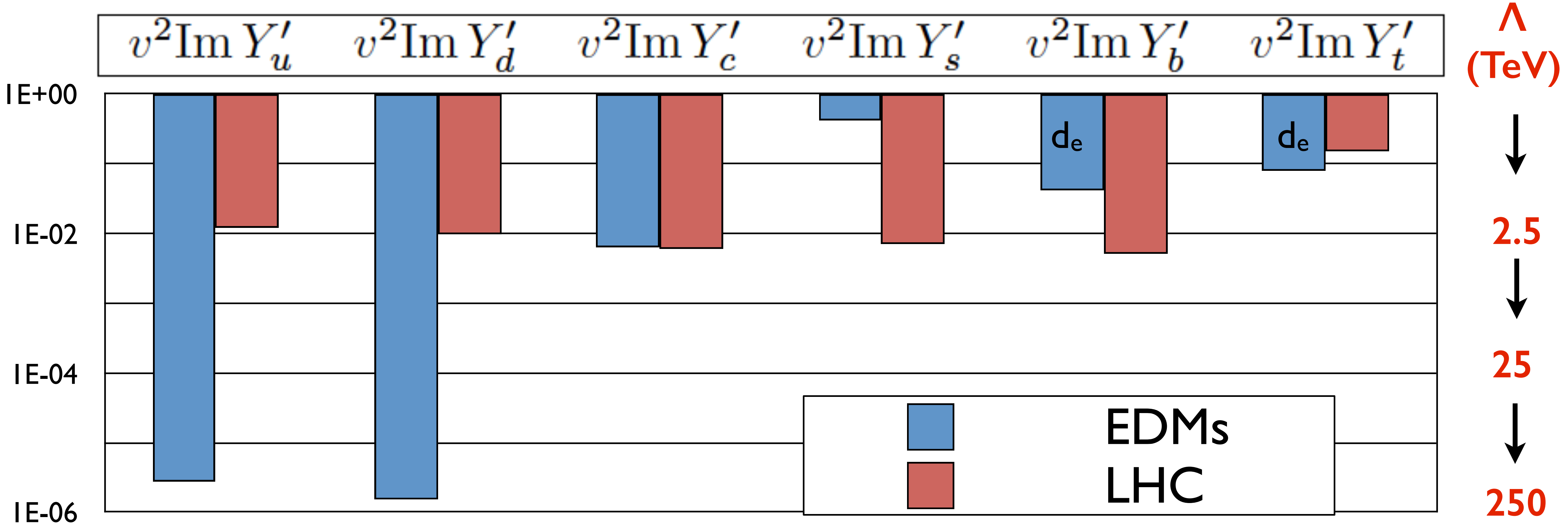




Y.-T. Chien, V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

Brod Haisch Zupan 1310.1385 — third generation Yukawas

Yukawa couplings to quarks

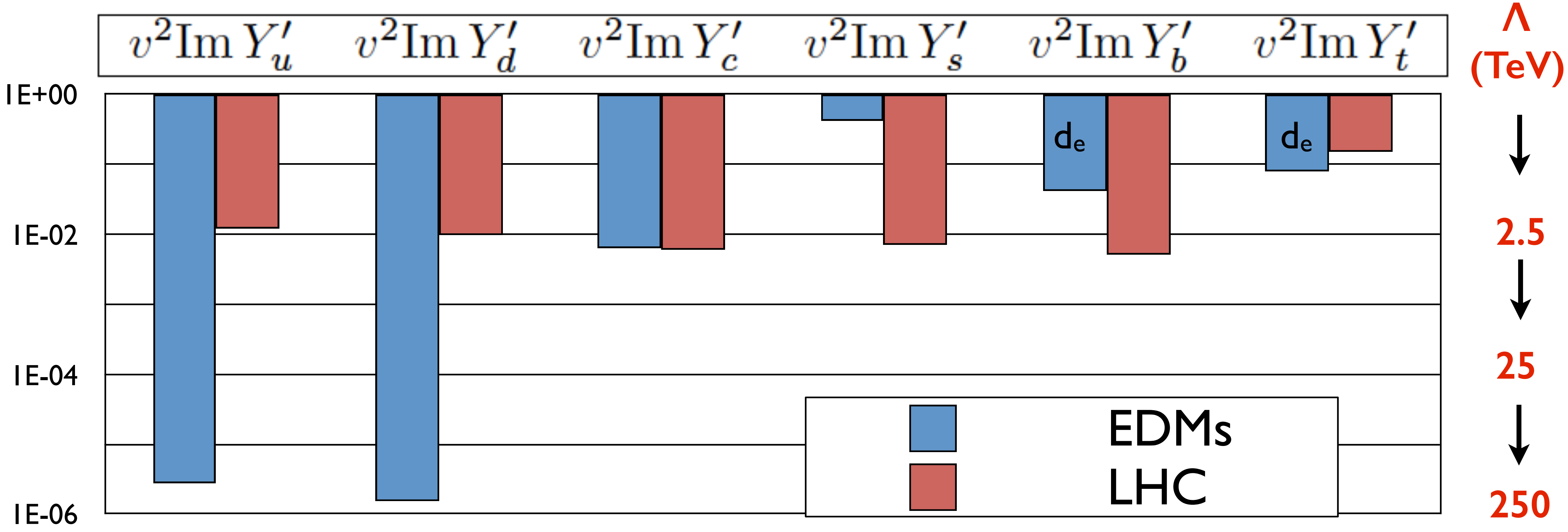


- Pseudo-scalar Yukawas in units of SM Yukawa m_q/v:

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

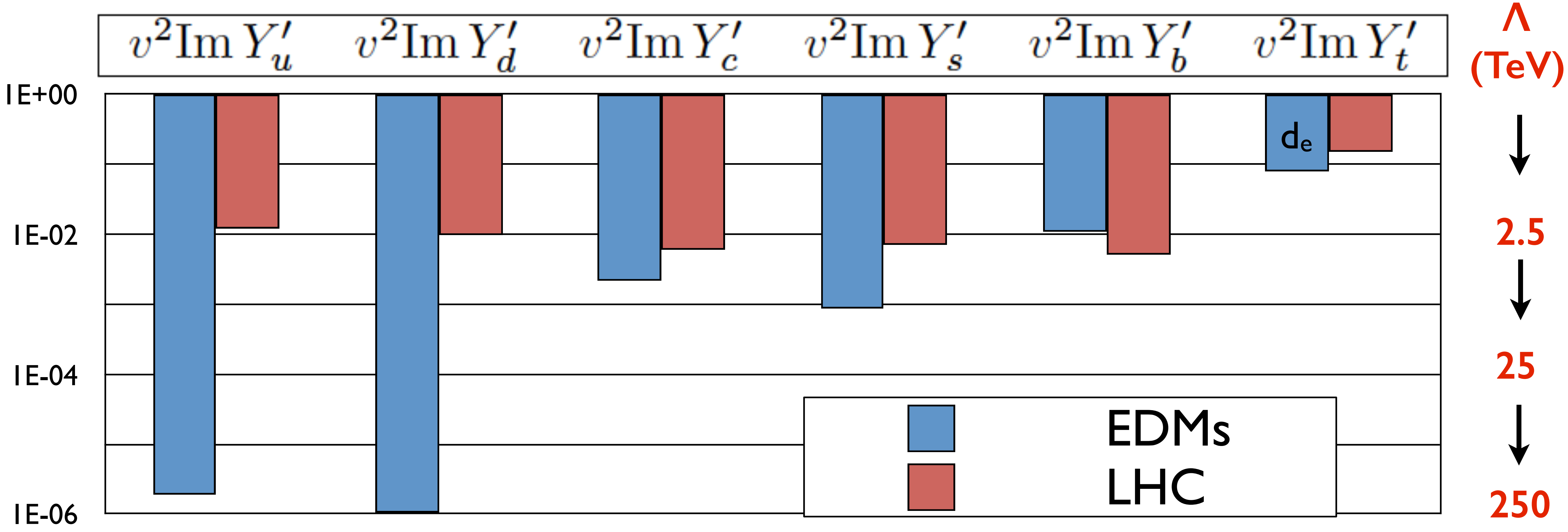
$\tilde{\kappa}_u$	$\tilde{\kappa}_d$	$\tilde{\kappa}_s$	$\tilde{\kappa}_c$	$\tilde{\kappa}_b$	$\tilde{\kappa}_t$
0.45	0.11	58	2.3	3.6	0.01

Yukawa couplings to quarks



- Future: factor of 2 at LHC; EDM constraints scale linearly
- Uncertainty in matrix elements strongly dilutes EDM constraints

Yukawa couplings to quarks



- Much stronger impact of n and ^{199}Hg EDM with reduced uncertainties

$$d_{n,p}[\tilde{d}_{u,d}] \quad d_{n,p}[d_s] \quad d_{n,p}[d_W] \quad \bar{g}_{0,1}[\tilde{d}_{u,d}] \quad S_A[\bar{g}_{0,1}]$$

25%

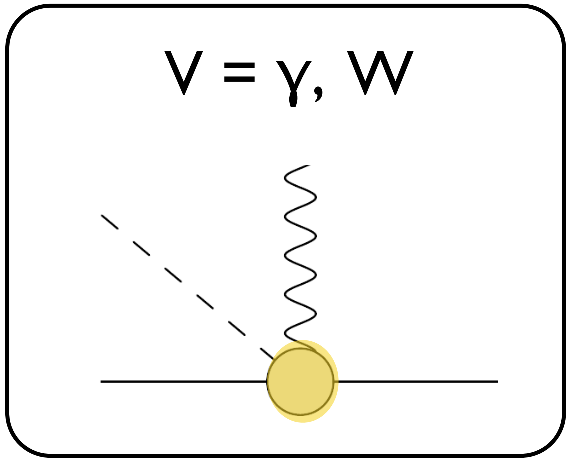
50%

- Challenging but realistic target for LQCD and nuclear structure

Higgs-top couplings

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

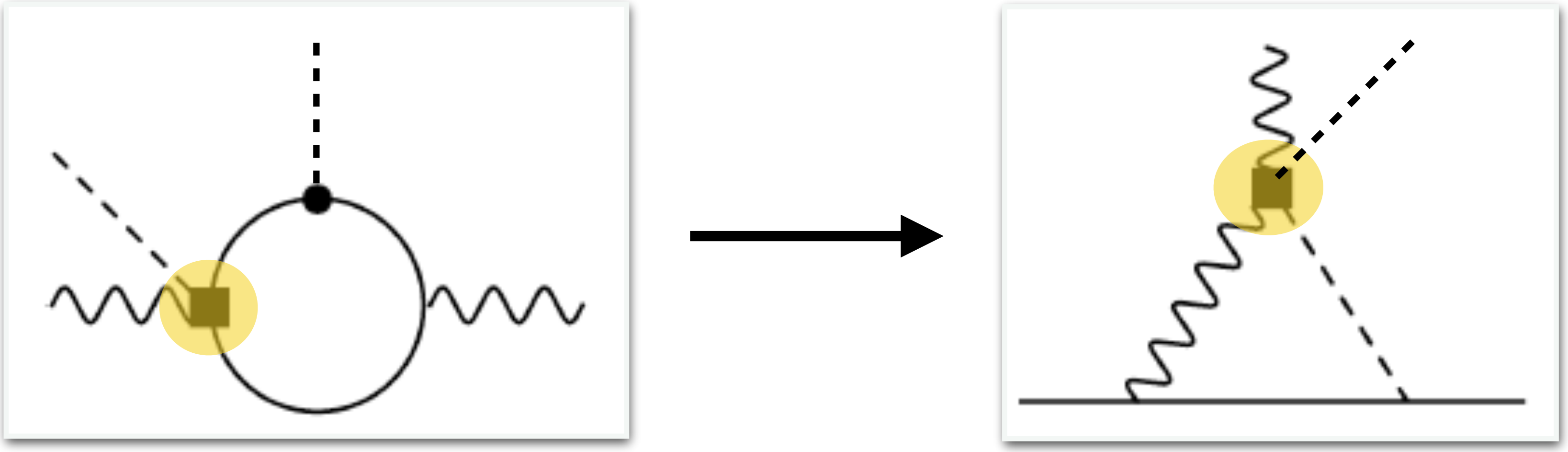
C_γ, C_{Wt}



H-t_L-t_R-V: EW top dipoles

- Impact of EDMs on top electroweak dipoles (γ,W) was overlooked

- C_γ, C_{Wt} affect eEDM and qEDMs via two-step mixing

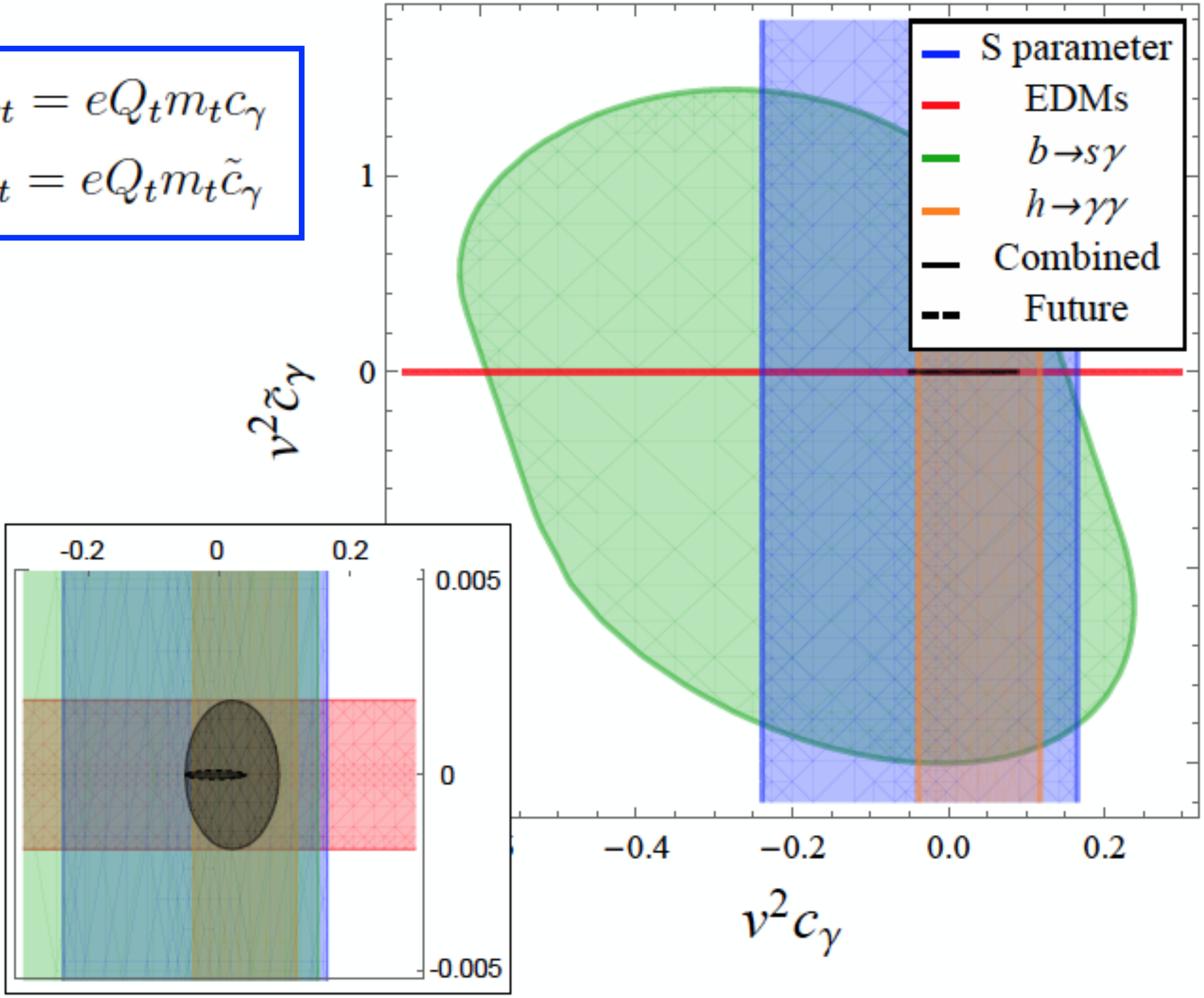


VC, W. Dekens, J. de Vries, E. Mereghetti 1603.03049

- EDM physics reach vs flavor and collider probes

$$C_\gamma = c_\gamma + i\,\tilde{c}_\gamma$$

$$\mu_t = eQ_t m_t c_\gamma$$
$$d_t = eQ_t m_t \tilde{c}_\gamma$$



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

No direct bounds

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

← Dominated by eEDM

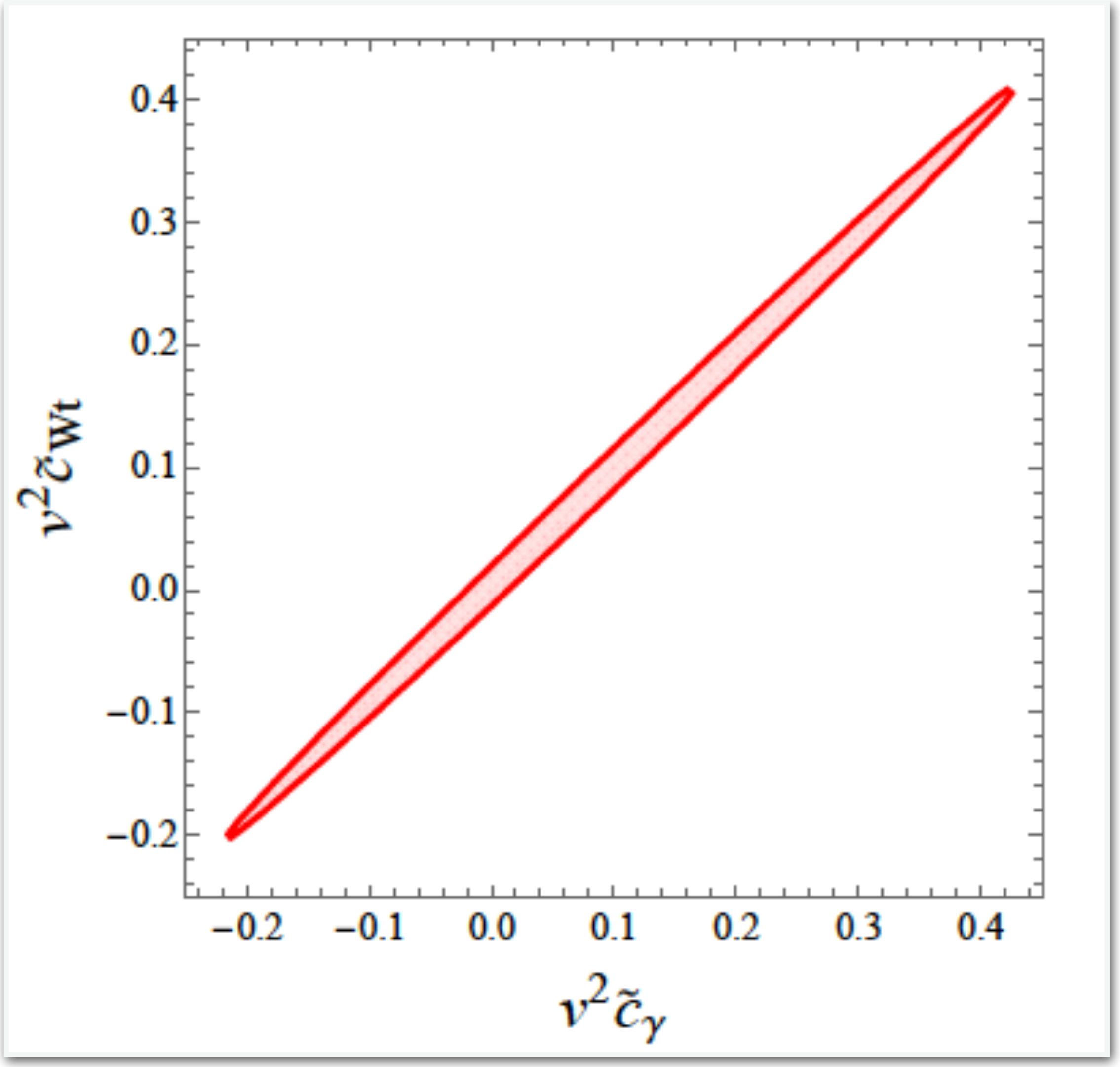
b → sγ bounds consistent with Kamenik-Papucci-Weiler 2011

LHC sensitivity (pp → jet t γ) and LHeC $d_t \sim 10^{-17}$ e cm [Fael-Gehrmann 13, Bouzas-Larios 13]

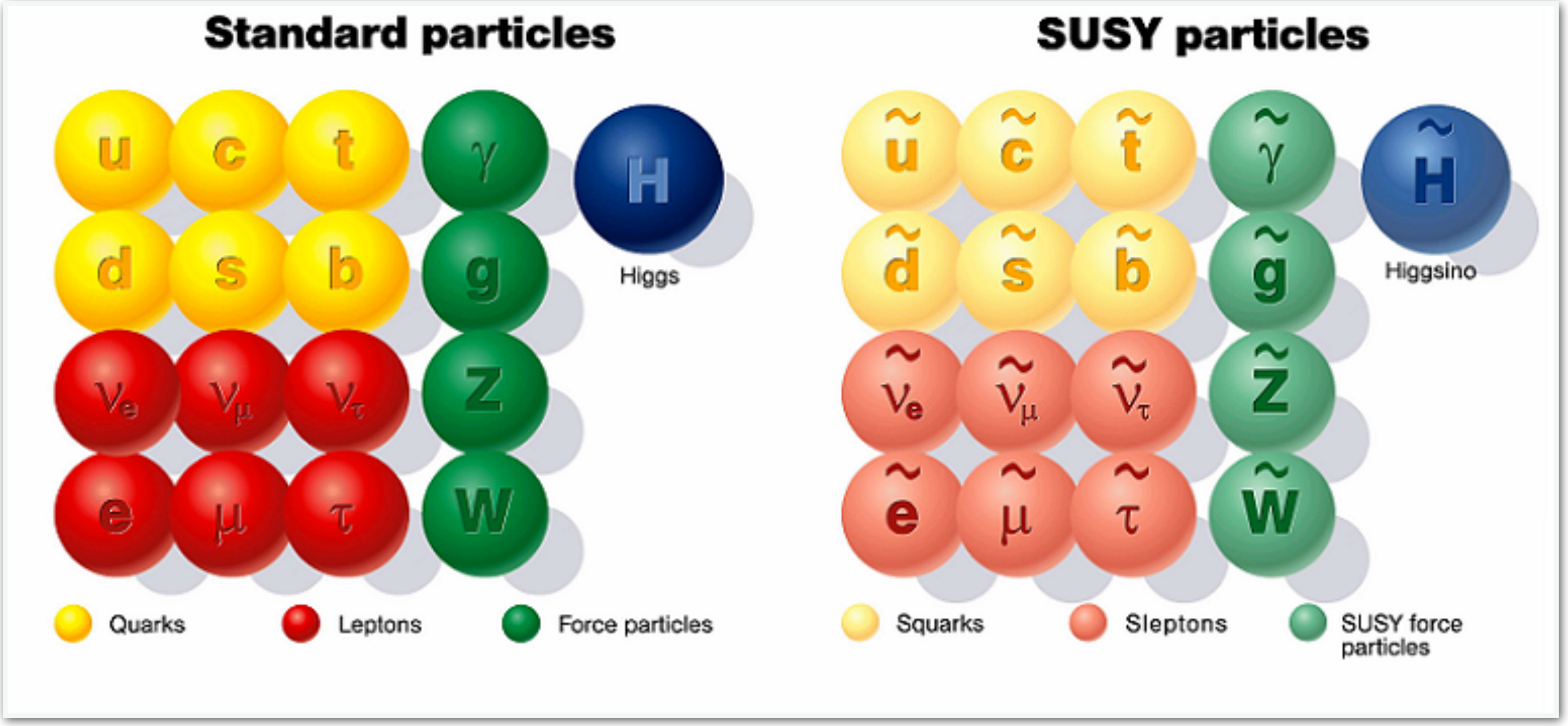
Discussion

- If new physics simultaneously generates several operators at the scale $\Lambda \sim M_{BSM}$, cancellations are possible
- Need to tune Wilson coefficients at the scale Λ (for example $d_e(\Lambda)$ or other top couplings) to cancel RG effects

- Possible, but non-trivial model building
- Still powerful constraints on the underlying model: they show up as correlations among the effective couplings



Probing high-scale SUSY

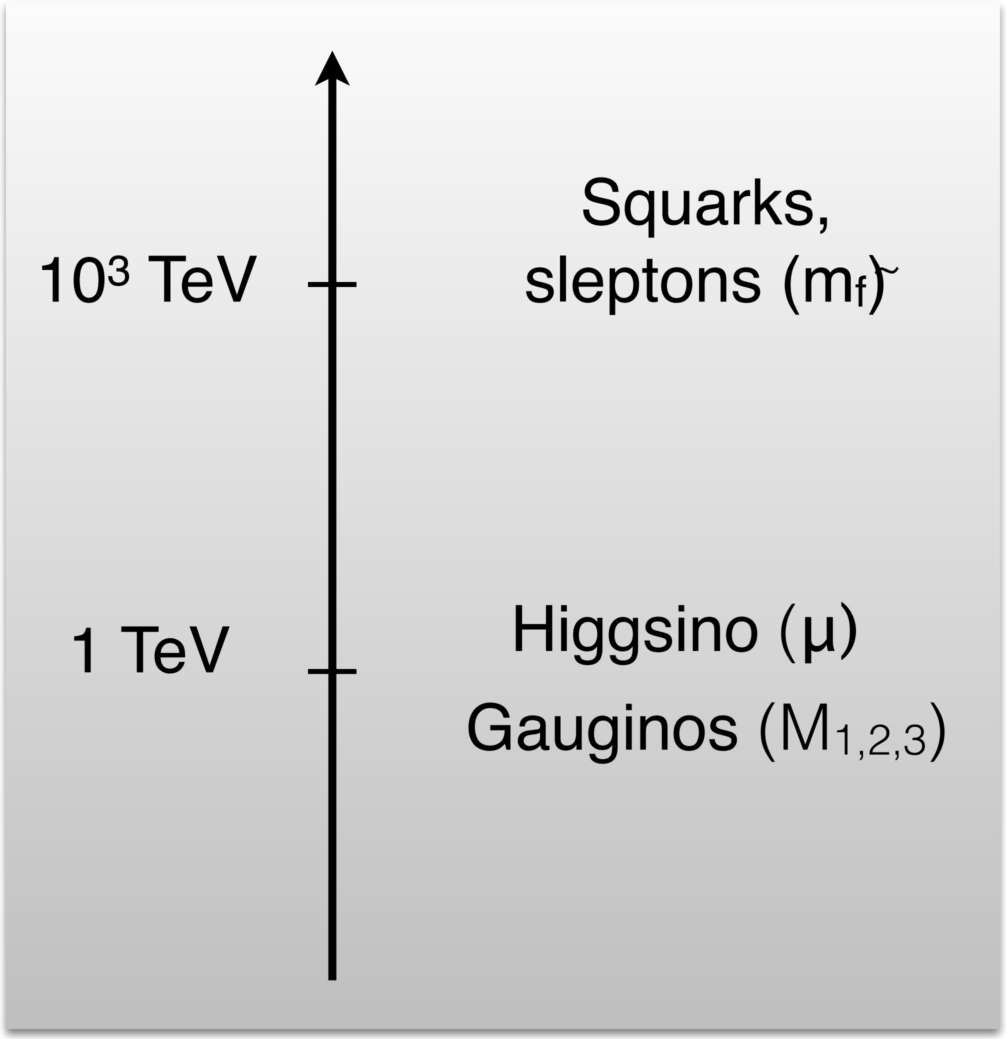


- Absence of direct signals and the observation of Higgs at 125 GeV put strong constraints on the spectrum of SUSY particles

Probing high-scale SUSY

- Higgs mass at ~125 GeV points to PeV-scale super-partners
- "Split-SUSY": retain gauge coupling unification and DM candidate

Arkani-Hamed, Dimopoulos 2004, Giudice, Romanino 2004,
Arkani-Hamed et al 2012, …



10^3 TeV

Squarks,
sleptons ($m_{\tilde{f}}$)

1 TeV

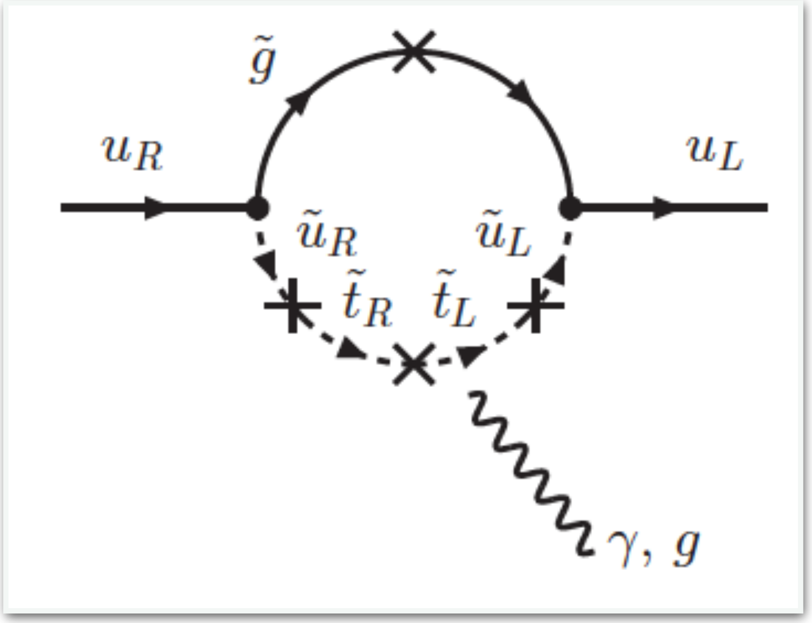
Higgsino (μ)

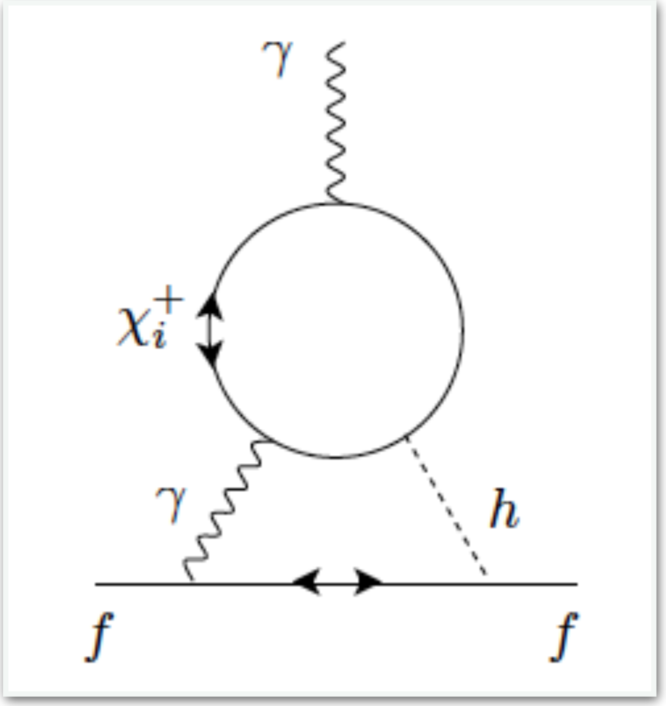
Gauginos ($M_{1,2,3}$)

EDMs among a handful of observables capable of probing such high scales

EDMs in split SUSY (1)

Altmannshofer-Harnik-Zupan 1308.3653





$$\tilde{d}_u \sim \frac{\alpha_s}{4\pi} \frac{m_t}{m_{\tilde{q}}^2} \frac{\mu M_3}{m_{\tilde{q}}^2} \delta^L_{ut} \delta^R_{tu} \sin\phi_u$$

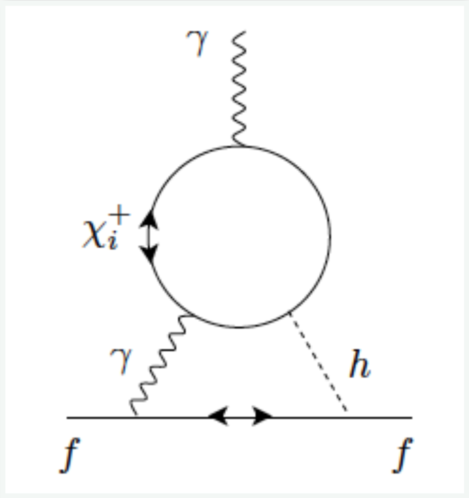
$$d_q \sim \frac{\alpha\, \alpha_w}{(4\pi)^2} \frac{m_q}{\mu M_2} \sin\phi_2$$

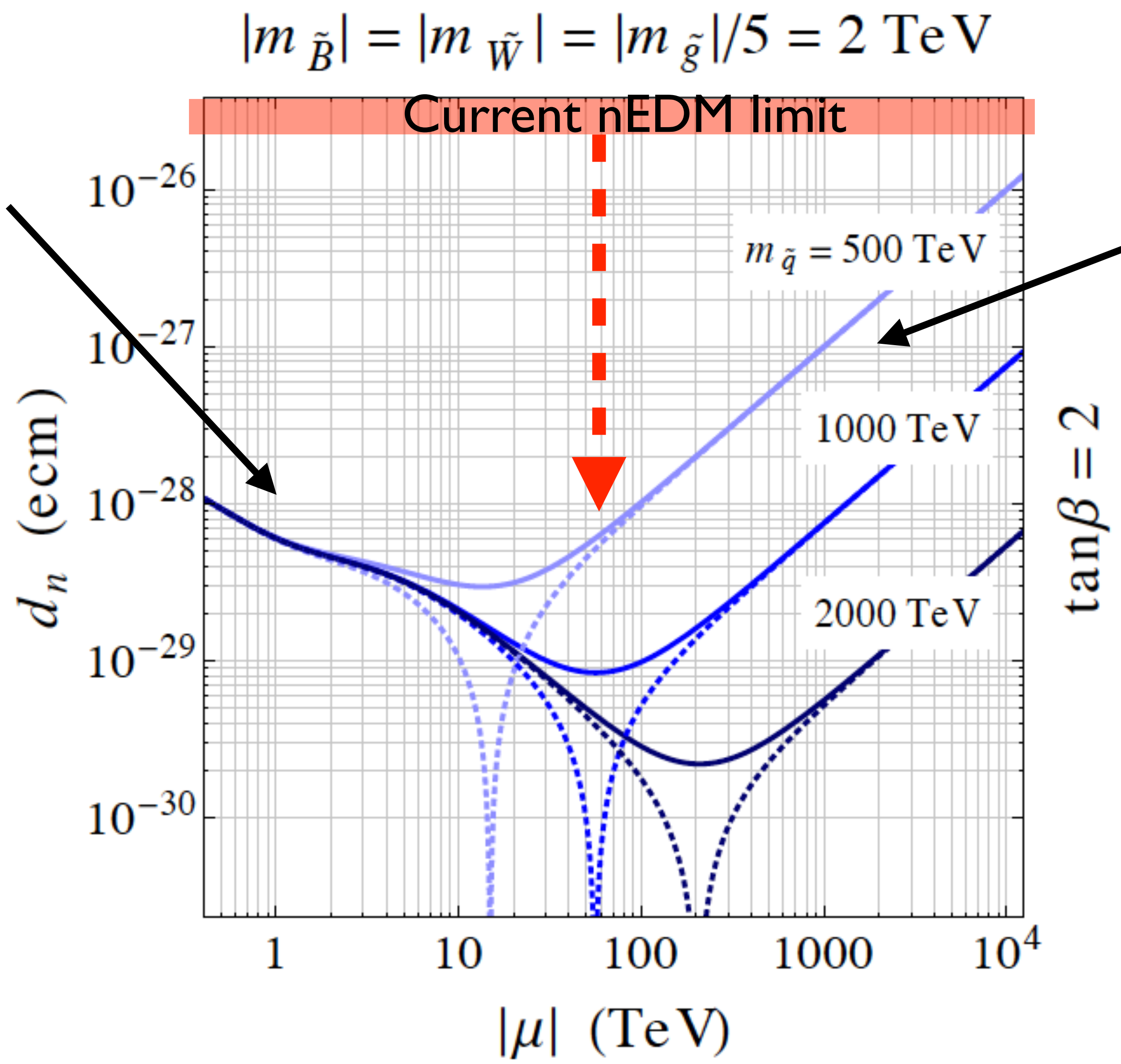
Quark EDMs and chromo-EDMs

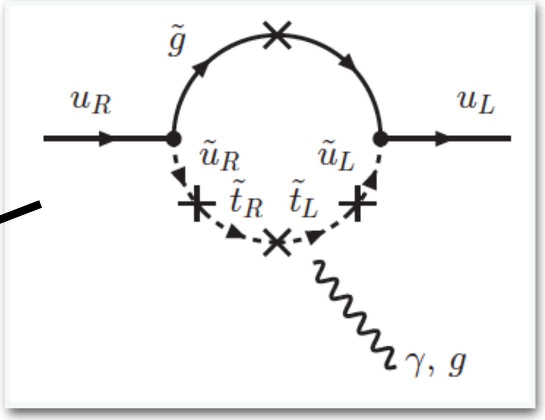
Only fermion EDMs

Relative importance controlled by Higgsino mass parameter |μ|

EDMs in split SUSY (1)







Maximal CPV phases.
Squark mixings fixed at 0.3

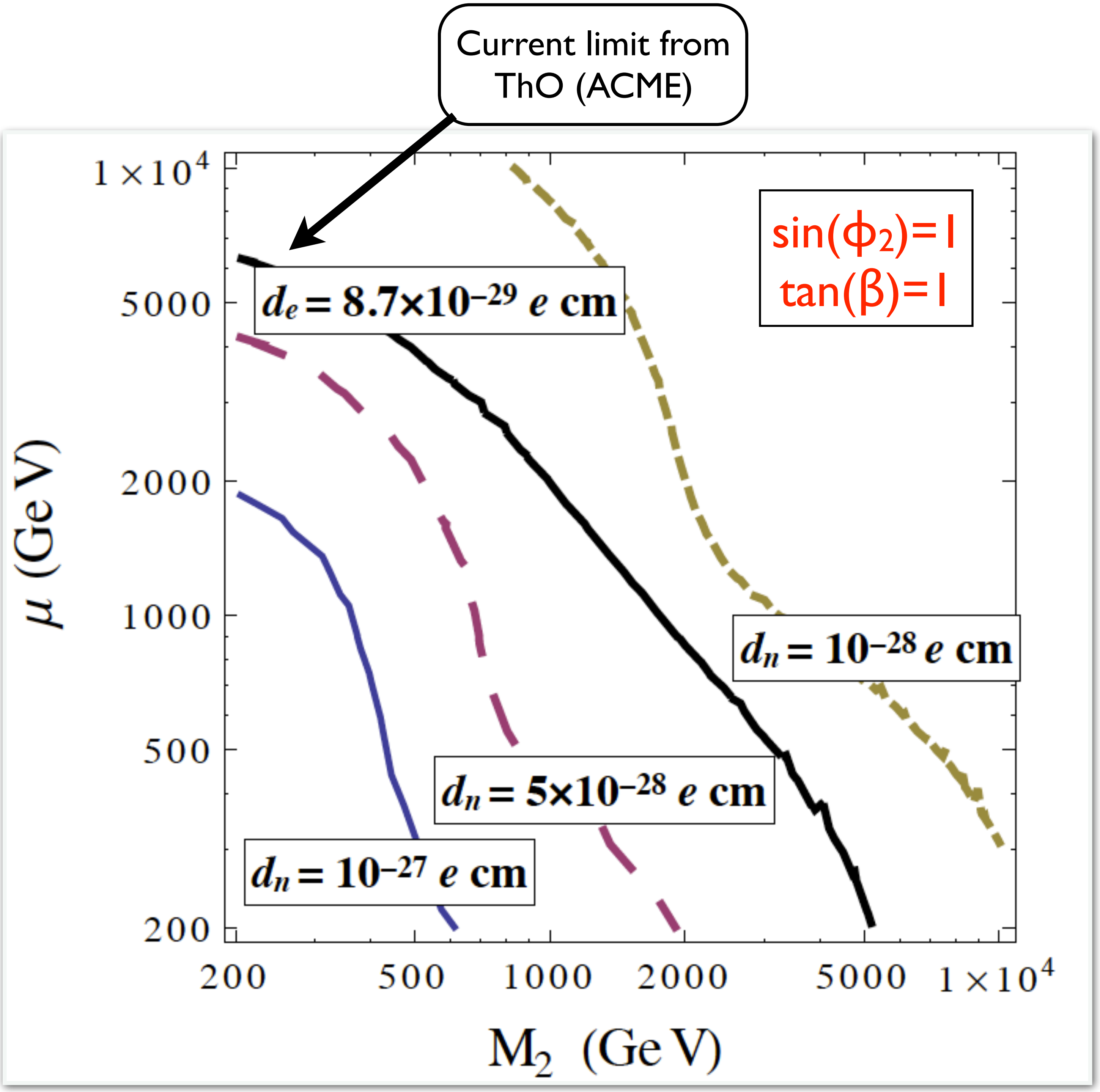
Altmannshofer-Harnik-Zupan
1308.3653

For $|\mu| < 10$ TeV, $m_{\tilde{q}} \sim 1000$ TeV, same CPV phase controls d_e, d_n

Distinctive correlations?

EDMs in split SUSY (2)

Both d_e and d_n within reach of current searches for M_2, μ <10 TeV



- Studying the ratio d_n / d_e *with precise matrix elements* → stringent upper bound $d_n < 4 \times 10^{-28}$ e cm

Bhattacharya, VC, Gupta, Lin, Yoon
Phys. Rev. Lett. 115 (2015) 212002 [1506.04196]

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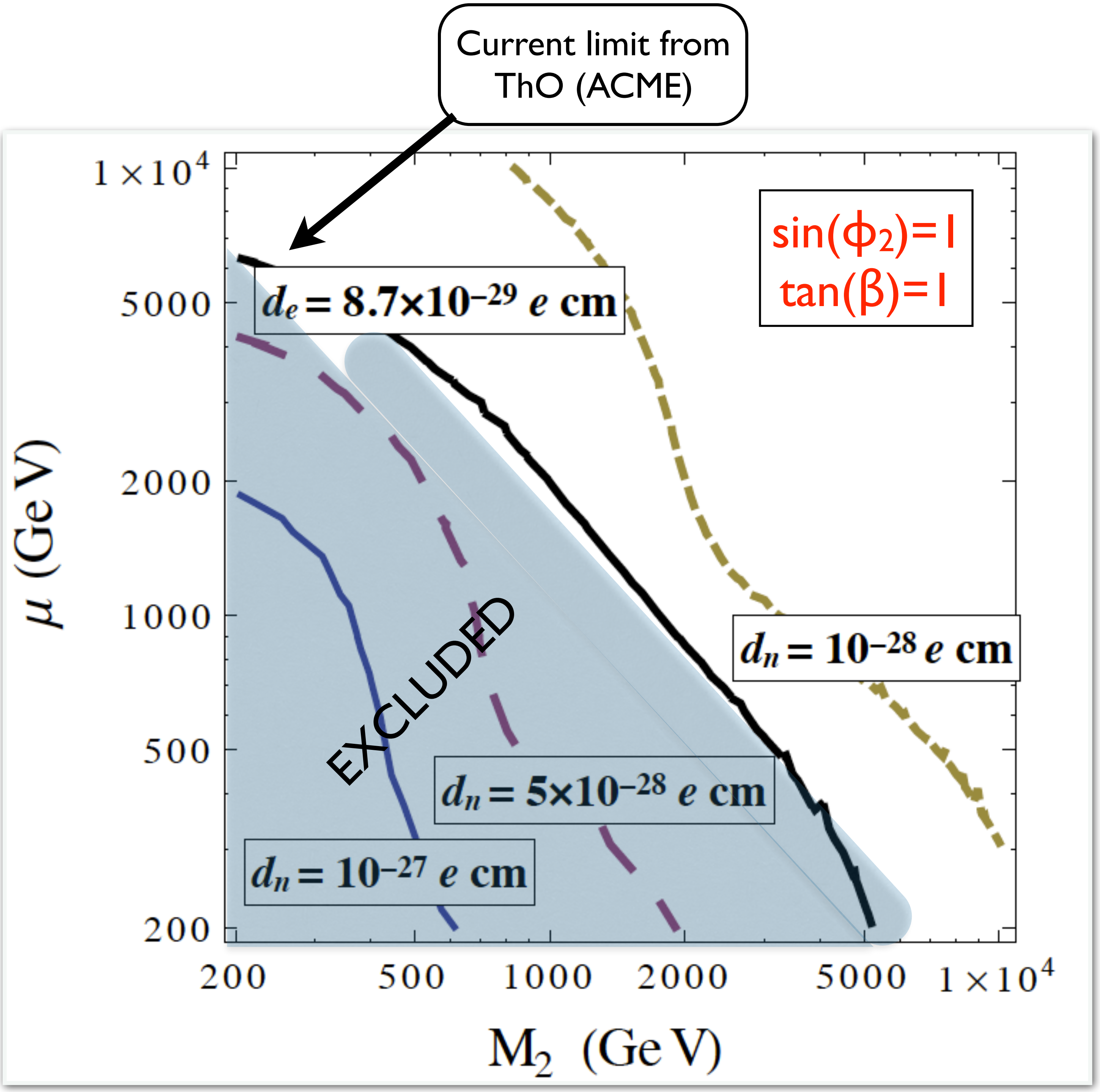

Current limit from ThO (ACME)

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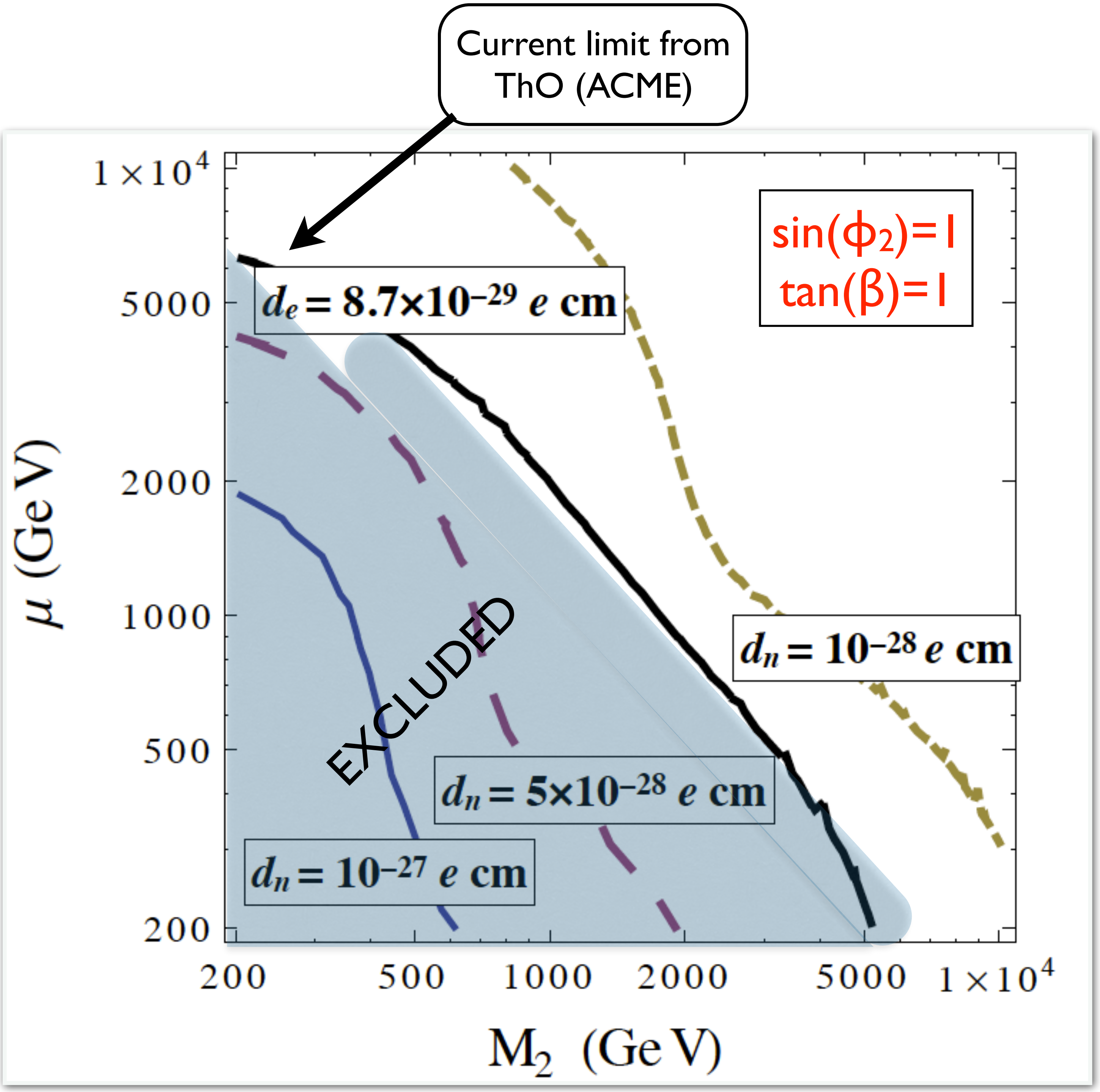

Current limit from ThO (ACME)

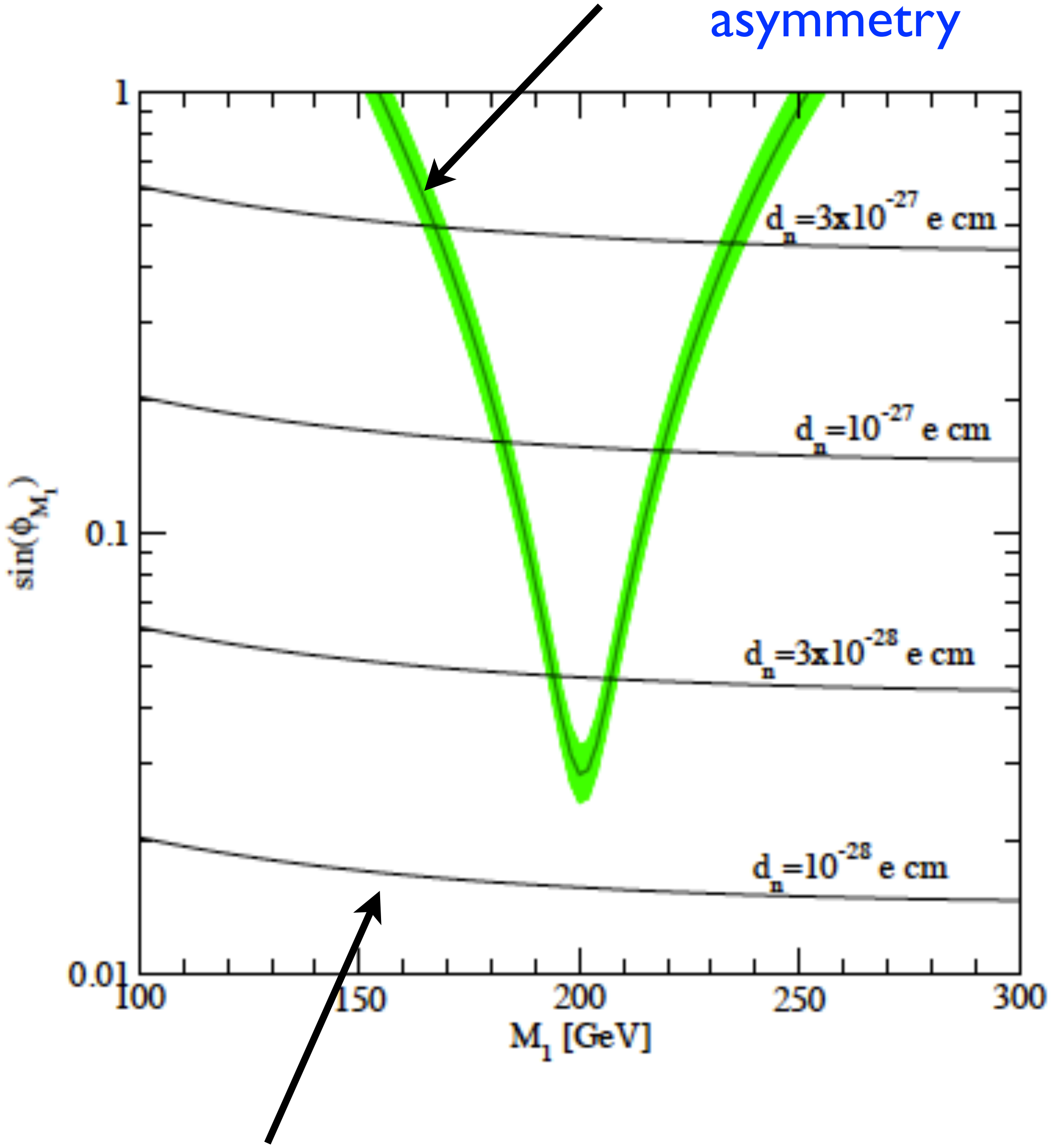
- Studying the ratio d_n/d_e *with precise matrix elements* → stringent upper bound $d_n < 4\times10^{-28}$ e cm
- Can be falsified by current nEDM searches
- Illustration of "improved matrix elements → enhanced model-discriminating power"

Bhattacharya, VC, Gupta, Lin, Yoon
Phys. Rev. Lett. 115 (2015) 212002 [1506.04196]

Impact on Baryogenesis: NMSSM

- CPV phases appearing in the gaugino-higgsino mixing contribute to both baryogenesis and EDM
- In *this model,* successful baryogenesis implies a “guaranteed signal” for EDMs
- Within reach of planned experiments?

Compatible with baryon asymmetry



Next generation neutron EDM

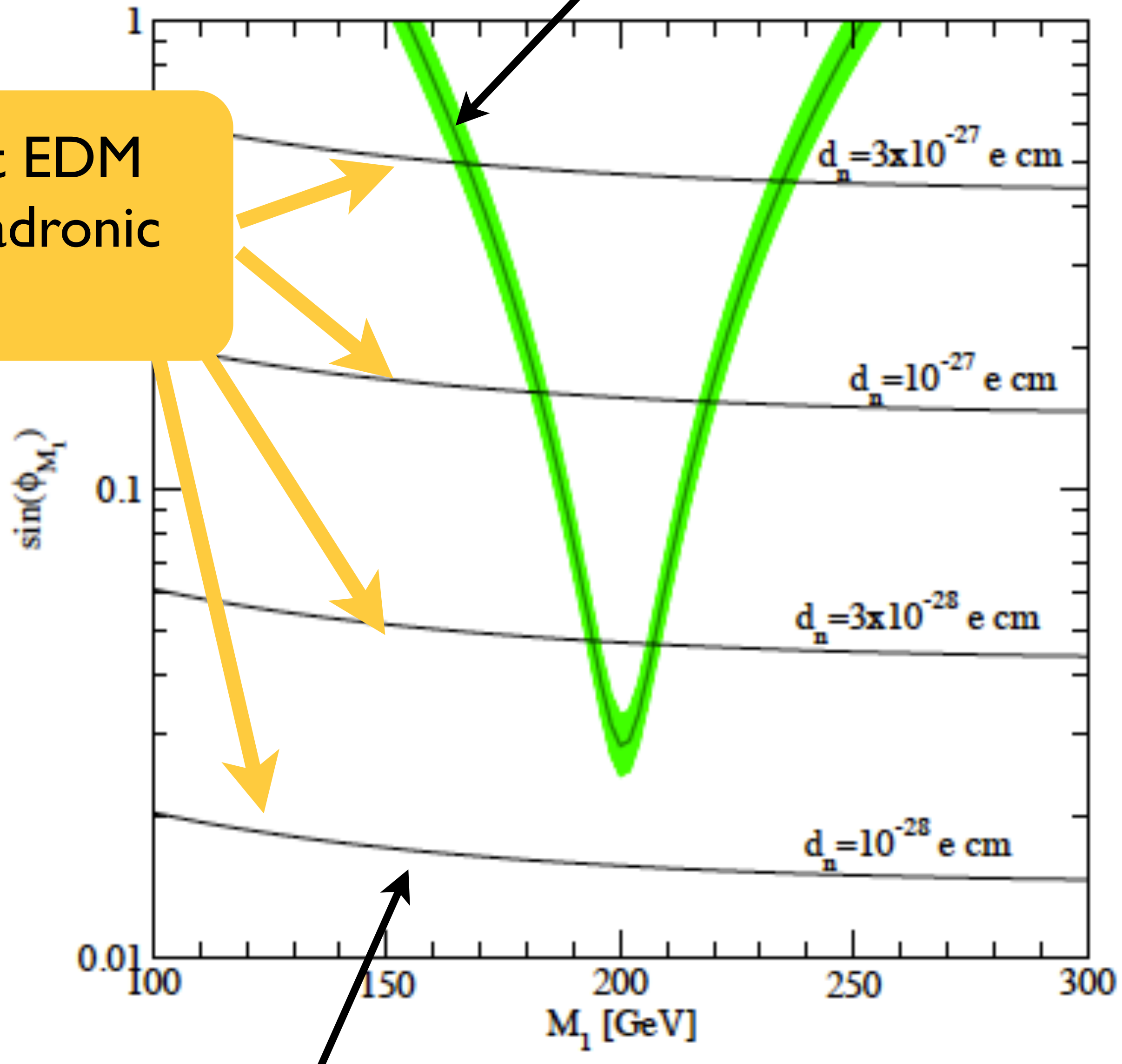
Li, Profumo, Ramsey-Musolf 2009-10

Impact on Baryogenesis: NMSSM

- CPV phases appearing in the gaugino-higgsino mixing contribute to bo baryogenesis an
- In *this model,* successful baryogenesis implies a "guaranteed signal" for EDMs
- Within reach of planned experiments?
- Again, this points to importance of controlling $d_n[d_q, \tilde{d}_q, d_W, ..]$ for tests of baryogenesis scenarios

But these "constant EDM lines" shift due to hadronic uncertainties!

Compatible with baryon asymmetry



Next generation neutron EDM

Li, Profumo, Ramsey-Musolf 2009-10

Conclusions

- EDMs are a powerful probe of new sources of CP violation
  - Stringent constraints on CPV couplings of Higgs and top quark
  - Great sensitivity to high-scale BSM scenarios (e.g. split SUSY)
  - …

- Interpretation of null (for now) or positive EDM searches requires bridging scales: from BSM to hadronic, nuclear, and atomic
  - Controlling theory uncertainties is essential to fully exploit the heroic experimental efforts (example: Higgs couplings)
  - LQCD can have big impact on hadronic matrix elements

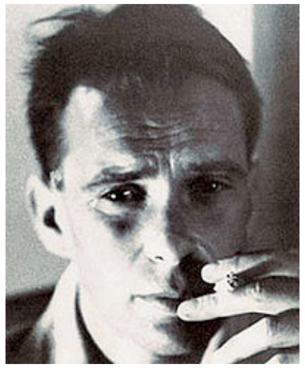
Outlook

EDMs will continue to play unique role in the next decade(s)

- May lead to the discovery of new physics (before colliders)
- Will have major impact on elucidating CP properties of new physics that might be discovered at LHC or future colliders
- If new physics exists only at very high scale, EDMs may be among few observables to probe it

These prospects strongly motivate the many experimental efforts and theory calculations to refine hadronic and nuclear matrix elements

Thank you!



A drawing by
Bruno Touschek