EXA 2017, Vienna, September 11-15 2017

Theoretical aspects of precision measurements with neutrons

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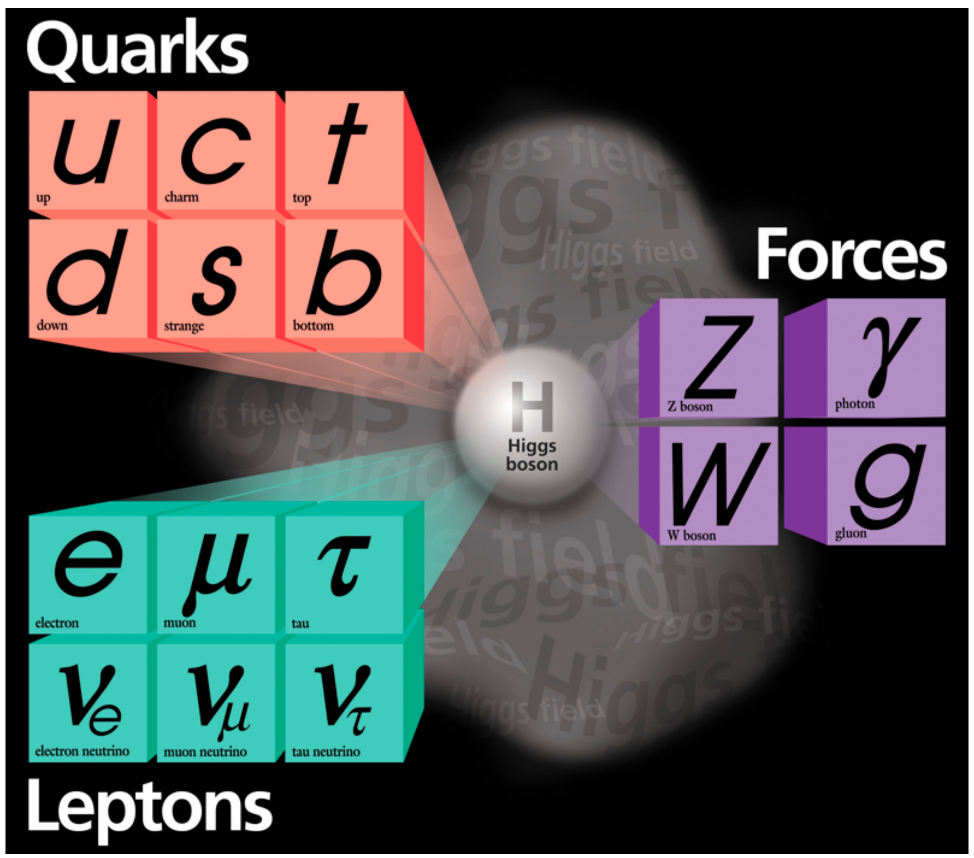
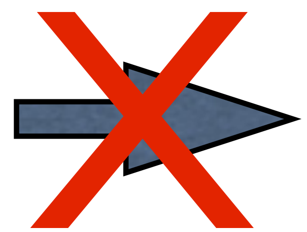
Outline

- Introduction — searching for new physics with neutrons
- Precision beta decay measurements
- Neutron EDM:
  - Higgs properties
  - High scale supersymmetry

New physics: why?

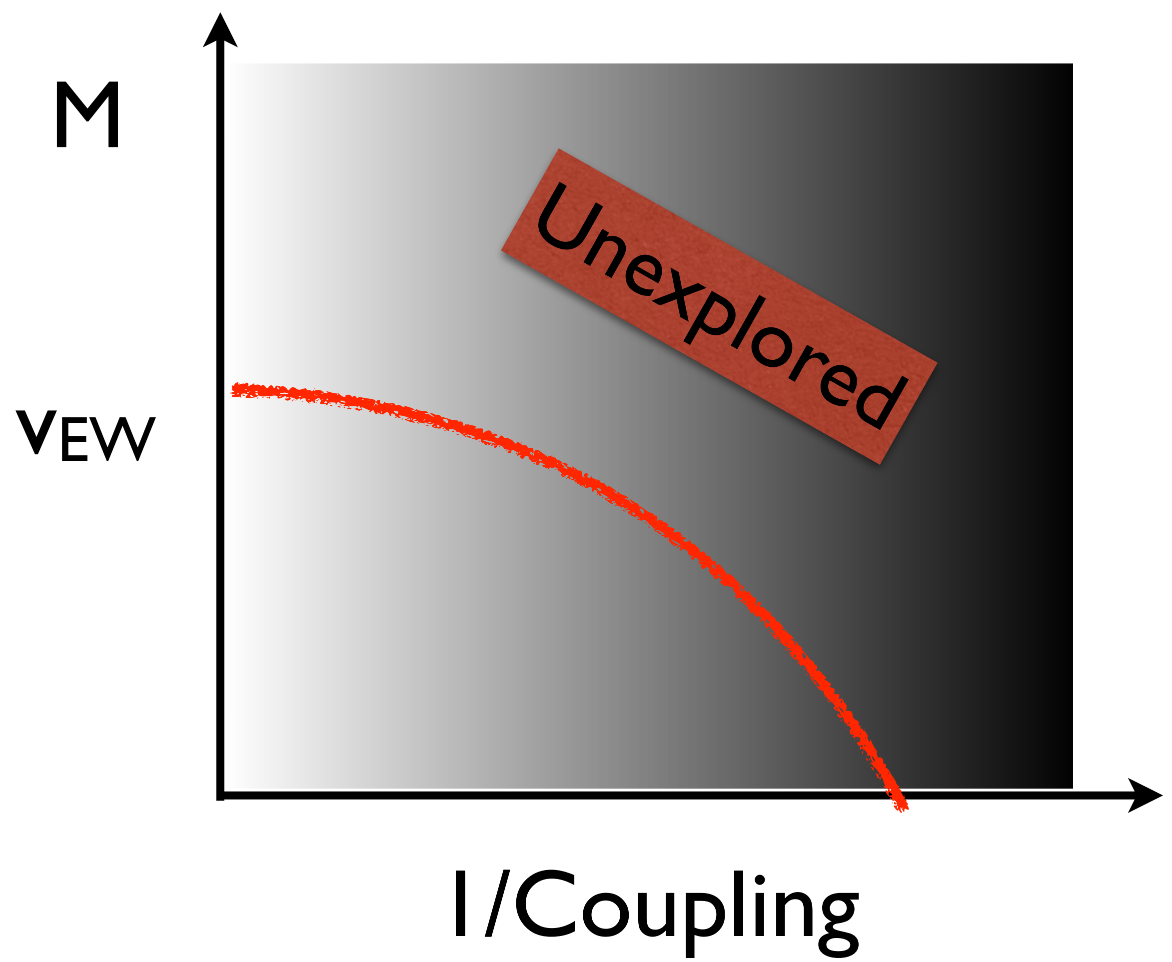
- The SM is remarkably successful, but it’s probably not the whole story





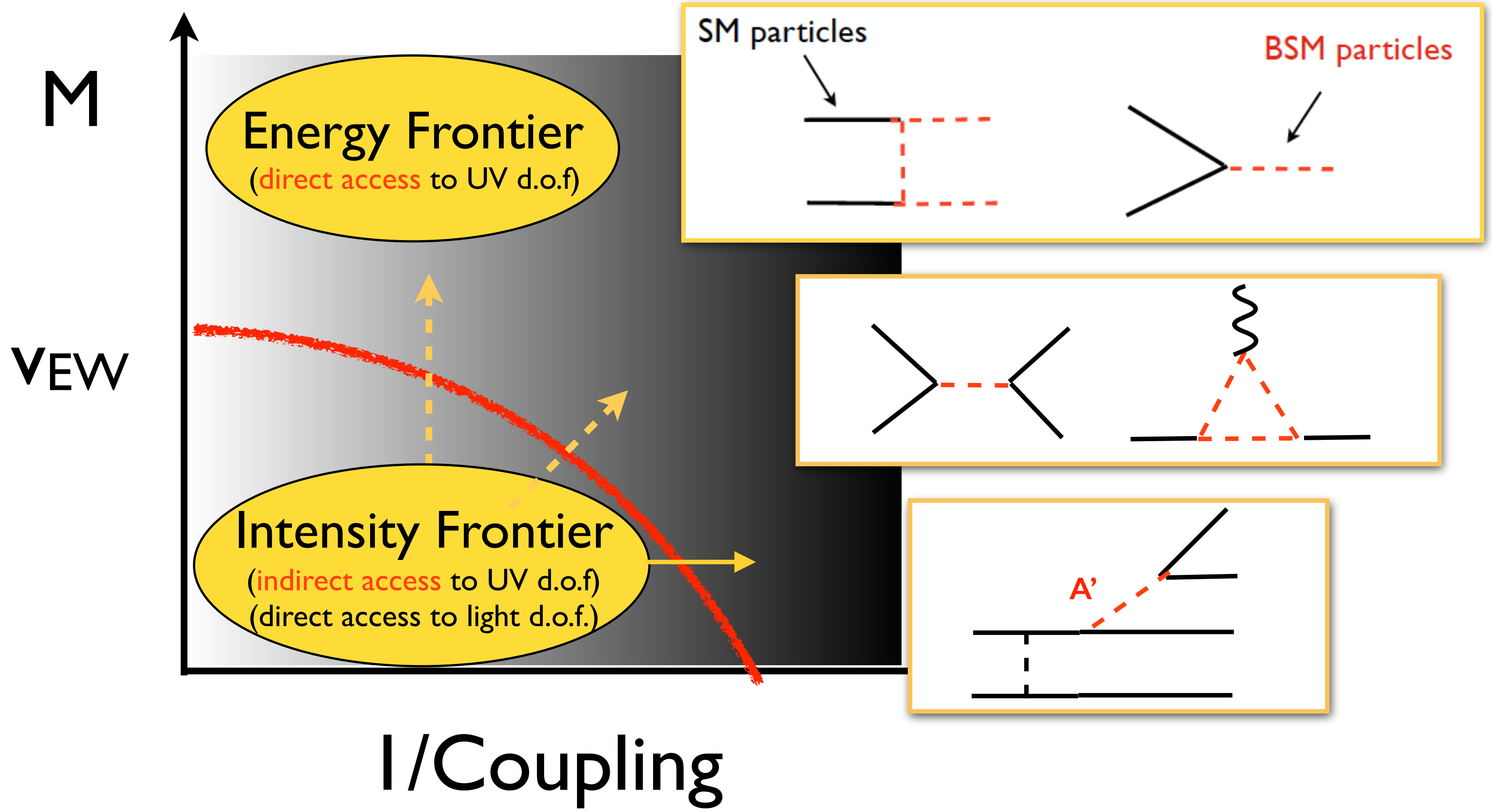
New physics: where?

- New degrees of freedom: Heavy? Light & weakly coupled?



New physics: where?

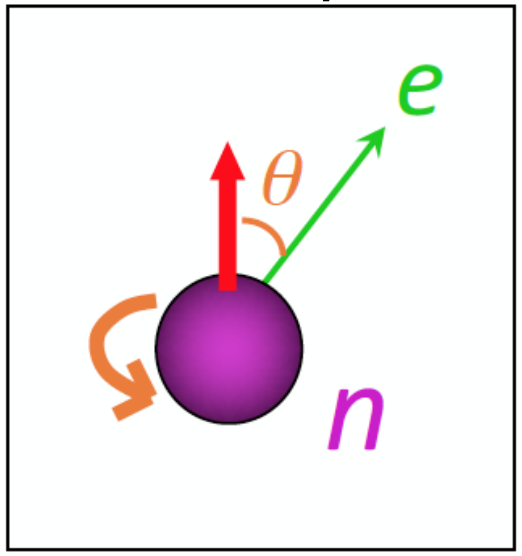
- New degrees of freedom: Heavy? Light & weakly coupled?
- Two complementary paths to probe $\mathcal{L}_{BSM}$



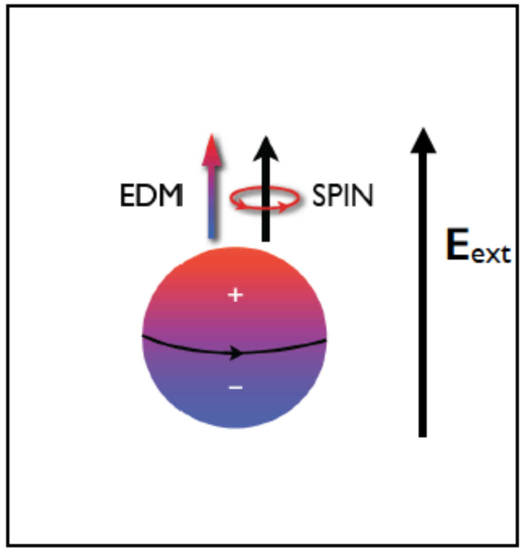
Role of neutrons

- Neutron physics at the forefront of the intensity frontier → vibrant world-wide program

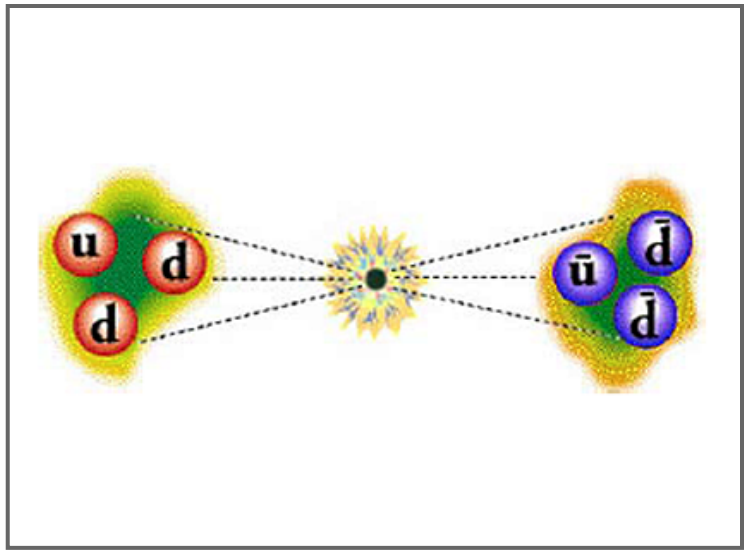
n decay



nEDM



n-nbar oscillations



Structure of weak interactions

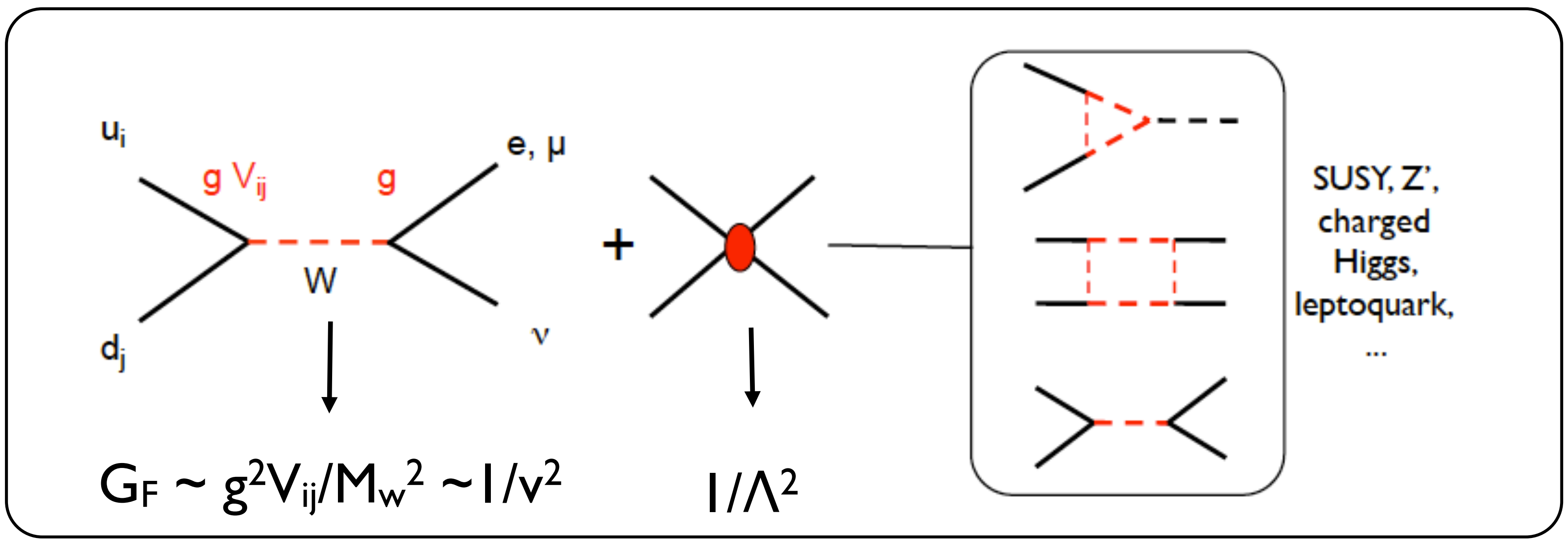
P,T, & CP violation

Baryon number violation

Precision neutron decay and new physics

β-decays in the SM and beyond

- In the SM, W exchange ⇒ V-A currents, universality



Λ ~ mass scale of new particles

- BSM: sensitive to tree-level and loop corrections from large class of models → "broad band" probe of new physics

Effective Lagrangian at E~GeV

- New physics effects are encoded in ten quark-level couplings

$$\begin{aligned}
\mathcal{L}_{CC} = & -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[(1+\epsilon_L) \; \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
& + \epsilon_R \; \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
& + \epsilon_S \; \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d \\
& - \epsilon_P \; \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
& + \epsilon_T \; \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.} \\
& + \quad \epsilon_i \longrightarrow \tilde{\epsilon}_i \qquad (1-\gamma_5)\nu_\ell \longrightarrow (1+\gamma_5)\nu_\ell
\end{aligned}$$

$$\epsilon_i \;, \tilde{\epsilon}_i \sim (M_W/\Lambda)^2$$

Linear sensitivity to ε_i (interference with SM)

Quadratic sensitivity to $\tilde{\varepsilon}_i$ (interference suppressed by m_ν/E)

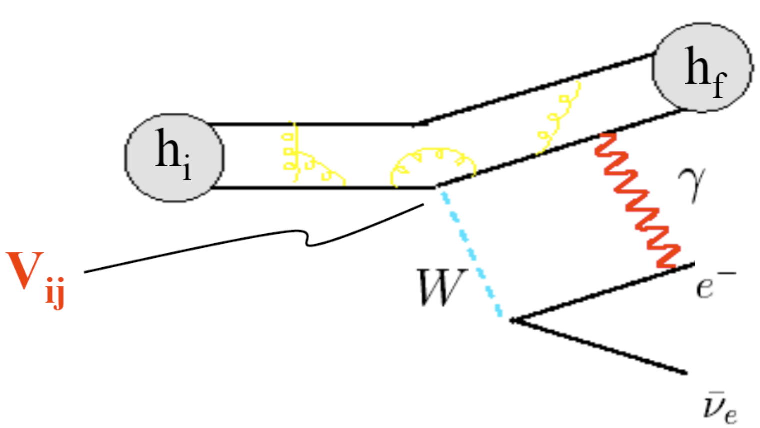
Probing the ε_α

- Two classes of observables:

  1. Total decay rates: probe V, A ($\varepsilon_{L,R}$) via extraction of V_{ud}, V_{us}

$$\Gamma_k = (G_F^{(\mu)})^2 \times |\bar{V}_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\delta_{RC}) \times F_{\rm kin}$$

Channel-dependent effective CKM element



$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\rm CKM}(\epsilon_i)$$

Probing the ε_α

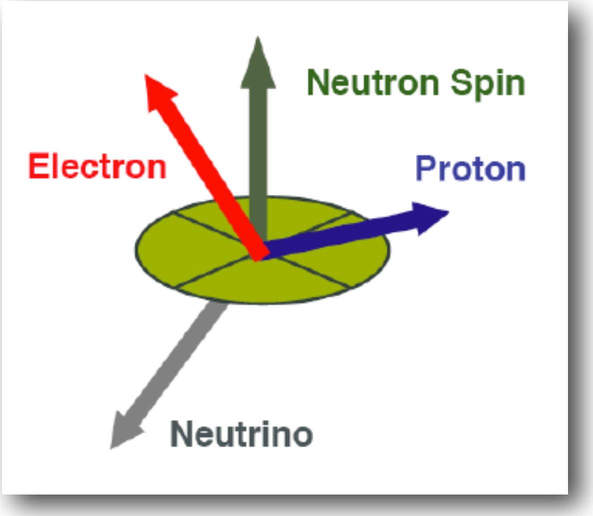
- Two classes of observables:

1. Total decay rates: probe V, A ($\varepsilon_{L,R}$) via extraction of V_{ud}, V_{us}

2. Differential distributions (n, nuclei): probe non V-A structures

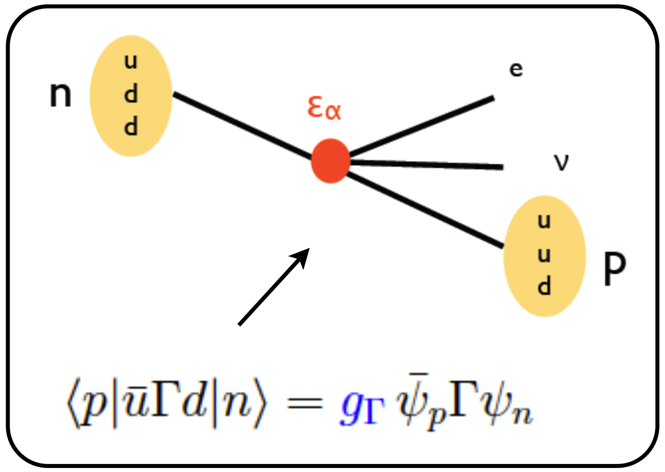
$$d\Gamma \propto F(E_e)\left\{1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + \langle\vec{J}\rangle\cdot\left[\,A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + \cdots\right]\right\}$$

Lee-Yang, 1956 Jackson-Treiman-Wyld 1957



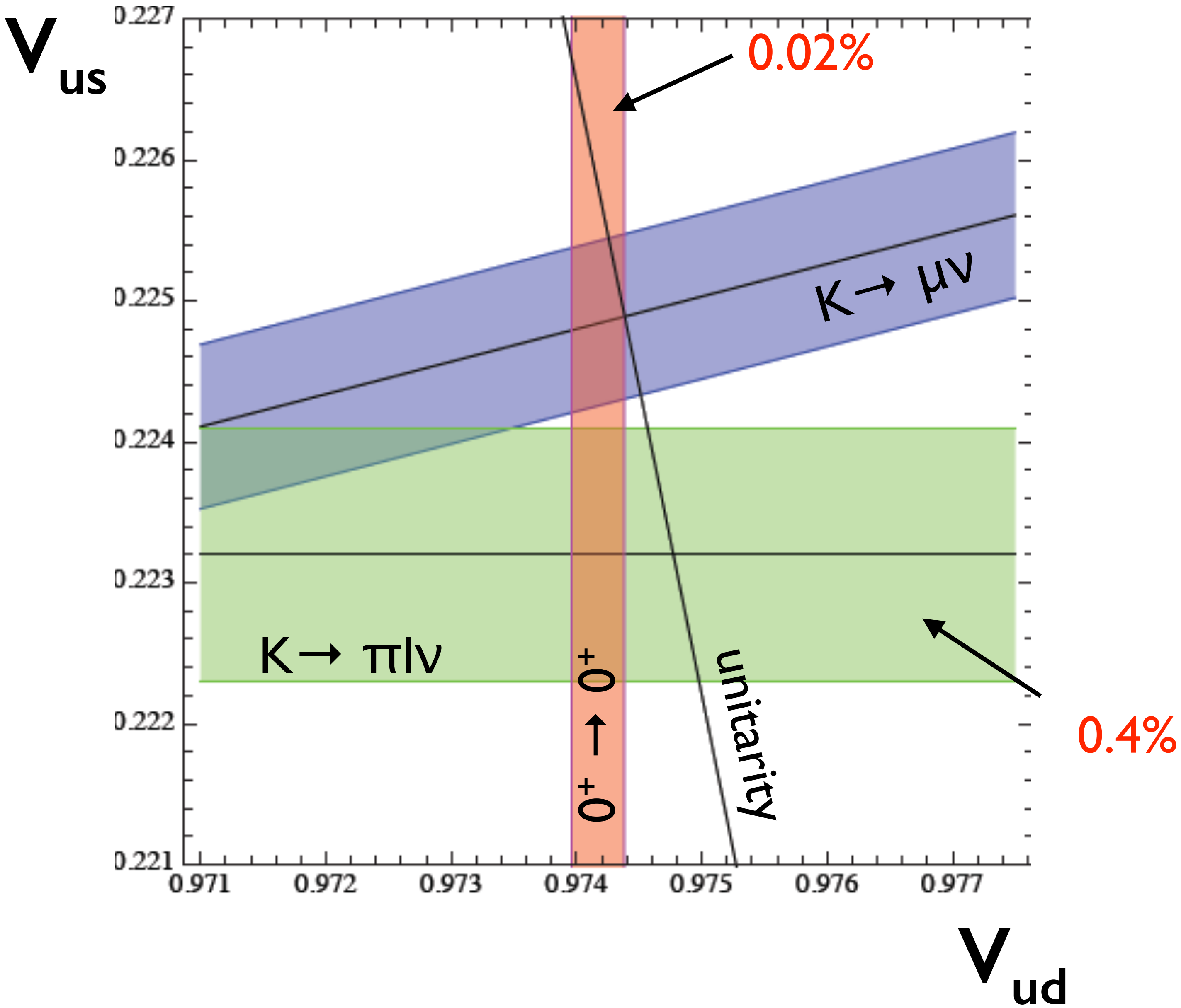
$a(g_A, g_\alpha\varepsilon_\alpha)$, $A(g_A, g_\alpha\varepsilon_\alpha)$, $B(g_A, g_\alpha\varepsilon_\alpha)$, …
isolated via suitable experimental asymmetries

Theory input: $g_{V,A,S,T}$



CKM unitarity test

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)$$



Hardy-Towner 1411.5987
FLAVIANET report 1005.2323
Lattice QCD input from FLAG 1607.00299

V_{us} from $K \to \mu\nu$

$\Delta_{\rm CKM} = -(4 \pm 5) * 10^{-4}$ 0.9σ

$\Delta_{\rm CKM} = -(12 \pm 6) * 10^{-4}$ 2.1σ

V_{us} from $K \to \pi l \nu$

Worth a closer look: at the level of the best LEP EW precision tests

Impact of neutrons

- n decay can provide independent extraction of V_{ud} @ 0.02%

$$V_{ud} = \left[\frac{4908.7(1.9)\ s}{\tau_n \, (1 + 3 g_A^2)} \right]^{1/2}$$

Marciano, Sirlin 2006

$\delta\tau_n \sim 0.35$ s

$\delta\tau_n/\tau_n \sim 0.04$ %

Cold beam & Ultra Cold Neutrons

UCNτ @ LANL: $\tau_n \sim 877.7(7)(3)$s

1707.01817

$\delta g_A/g_A \sim 0.1(0.2)\% * \rightarrow 0.025\%$

($\delta a/a$, $\delta A/A \sim 0.1\%$)

PERC, Nab, UCNA+, ...

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PERC, Nab, UCNA+, ...

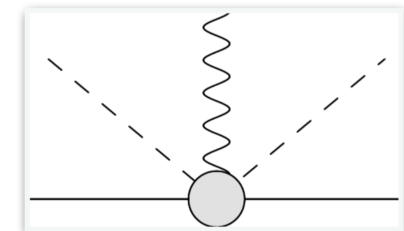
- V_{ud} (n) and V_{ud} ($0^+ \rightarrow 0^+$) sensitive to different new physics: not a "duplicate" measurement

$$\frac{\bar{V}_{ud}|_n}{\bar{V}_{ud}|_{0^+}} = 1 + c_S\,\epsilon_S + c_T\,\epsilon_T$$

c_S, c_T ~O(1)

Probing $\varepsilon_{L,R}$ couplings

- Assume $\varepsilon_{L,R}$ are induced by gauge vertex corrections at high scale

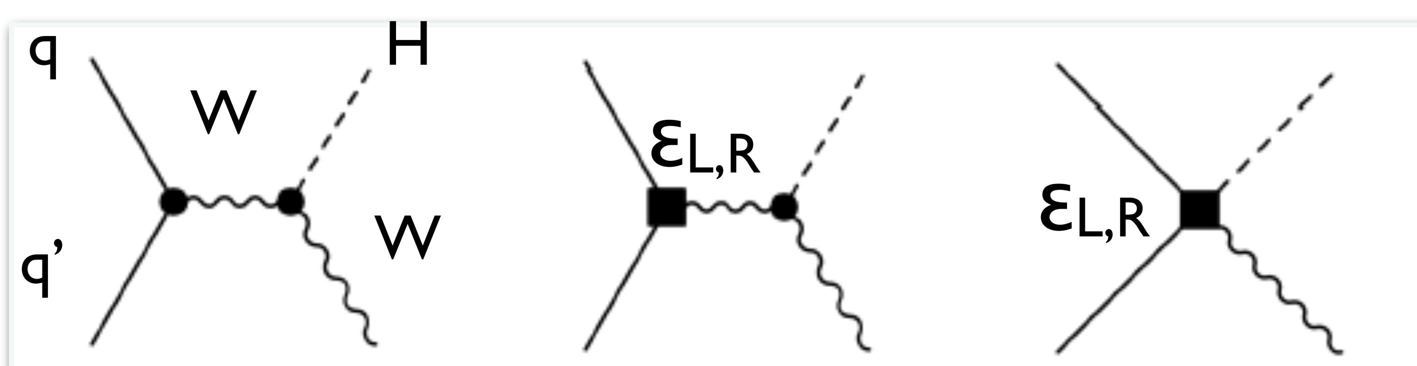


$$\varphi^\dagger \tau^a D_\mu \varphi \;\; \bar{q}_L \tau^a \gamma^\mu q_L$$

$$\varphi^T \epsilon D_\mu \varphi \;\; \bar{u}_R \gamma^\mu d_R$$

- Low energy probes:
    - $\Delta_{CKM} \propto \varepsilon_L + \varepsilon_R$
    - $\delta\Gamma_{(\pi \to \mu\nu)} \propto \varepsilon_L - \varepsilon_R$ [f_π from LQCD]
    - Neutron decay correlations (A, a, B) → $\lambda = g_A (1 - 2\,\varepsilon_R)$

- LHC (if Λ > few TeV): associated Higgs + W production



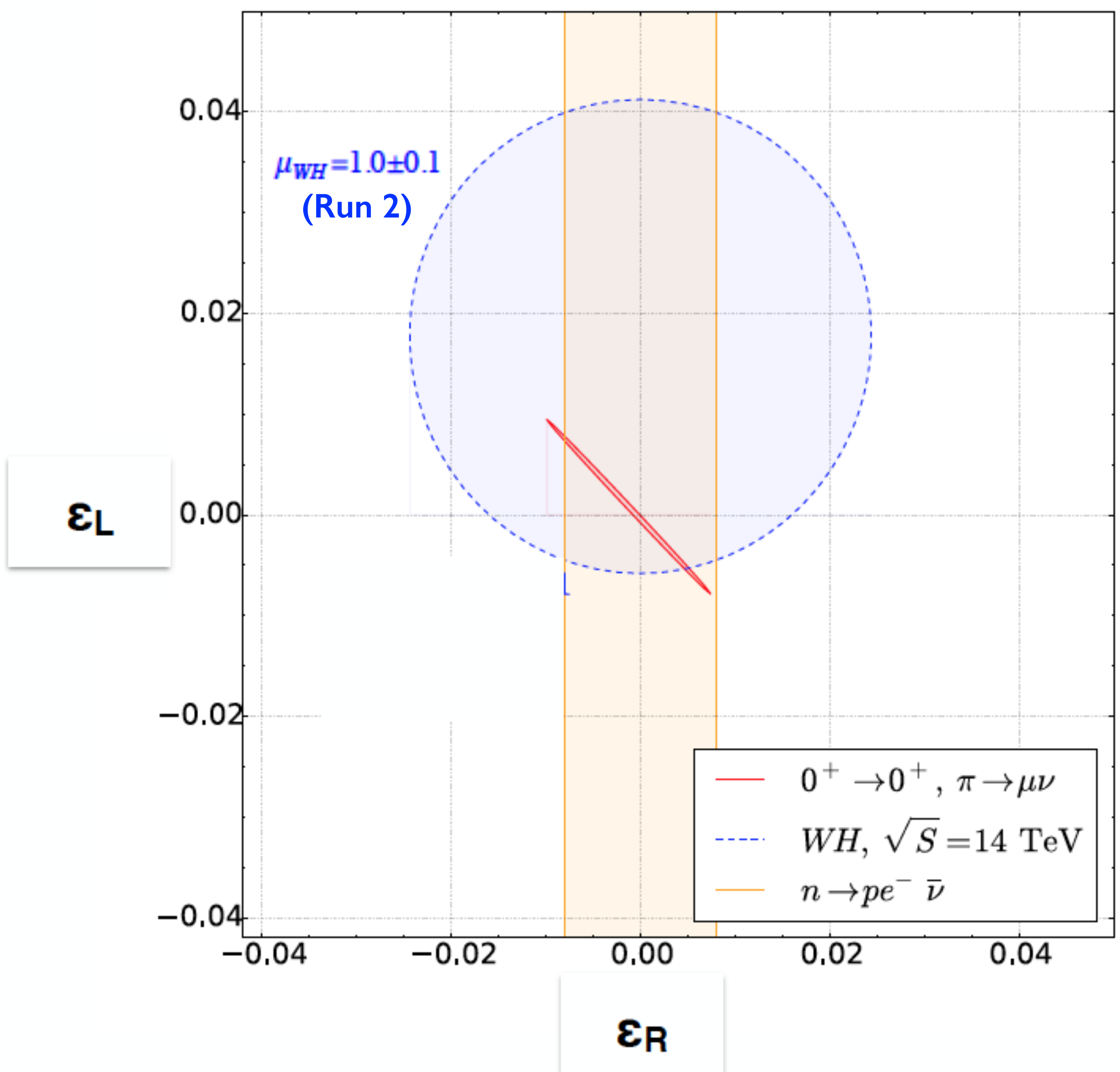
Probing $\varepsilon_{L,R}$ couplings

1703.04751: S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti

Neutron decay constraint controlled by LQCD error on g_A

Here use CalLat 1704.01114 g_A = 1.285(17)

Updated plot courtesy of E. Mereghetti

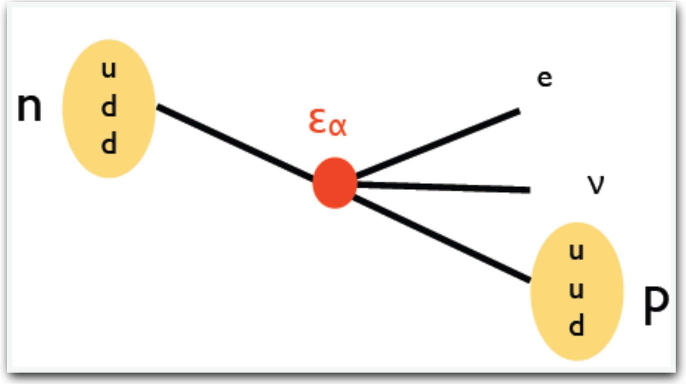


- Low-E measurements more constraining than collider
- Neutron decay (λ) + LQCD: competitive sensitivity to ε_R

Probing non V-A ($\epsilon_{S,T}$) couplings

- π, neutron & nuclear decays:
  - Current: $b(0^+ \to 0^+)$ [ϵ_S] ; $\pi \to e \nu \gamma$ [ϵ_T]
  - Future: b_n, B_n [$\epsilon_{S,T}$] @ 10^{-3}; b_{GT} [ϵ_T](^{6}He, ...) @10^{-3}

$n \to p\, e\, \nu$



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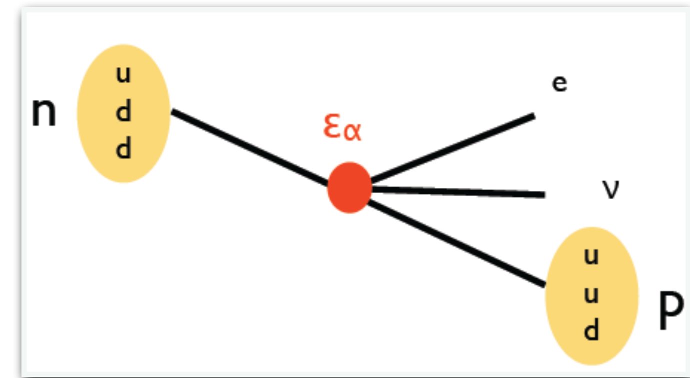
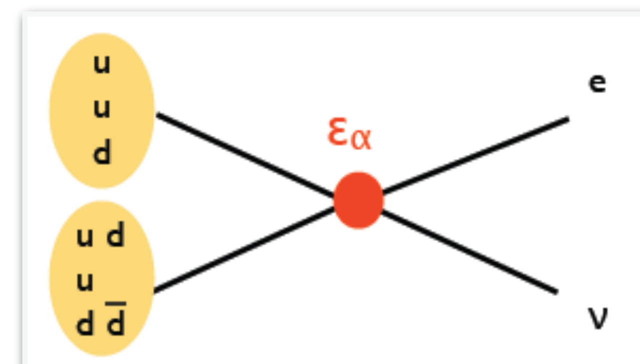
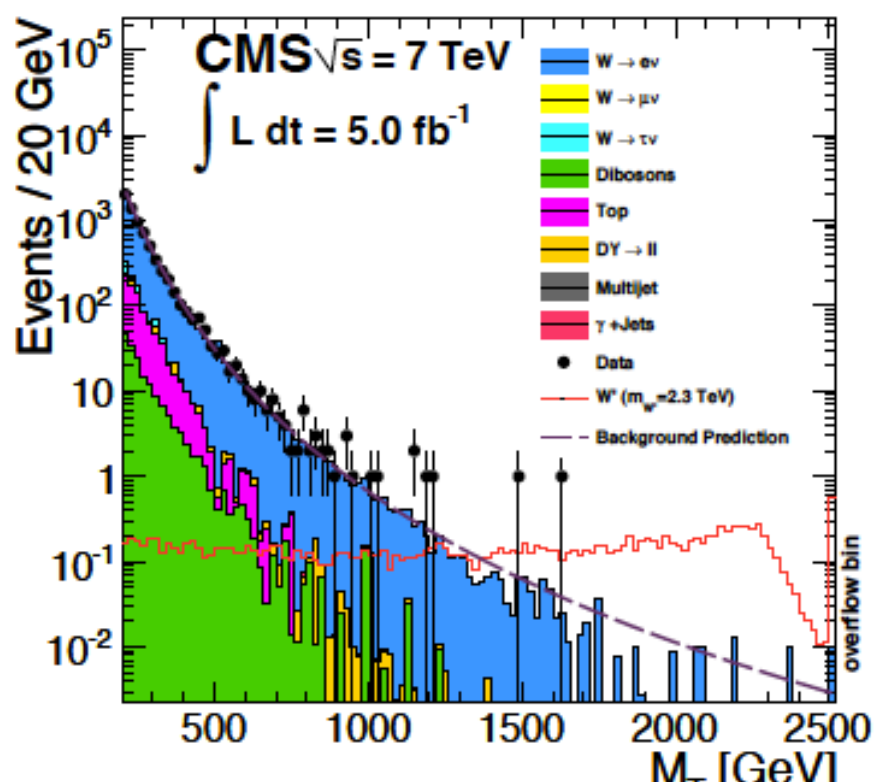


$pp \to e\,\nu + X$



- Collider: for heavy new mediators probe *same* $\varepsilon_{S,T}$

$$m_T \equiv \sqrt{2E_T^e E_T^\nu (1 - \cos\Delta\phi_{e\nu})}$$



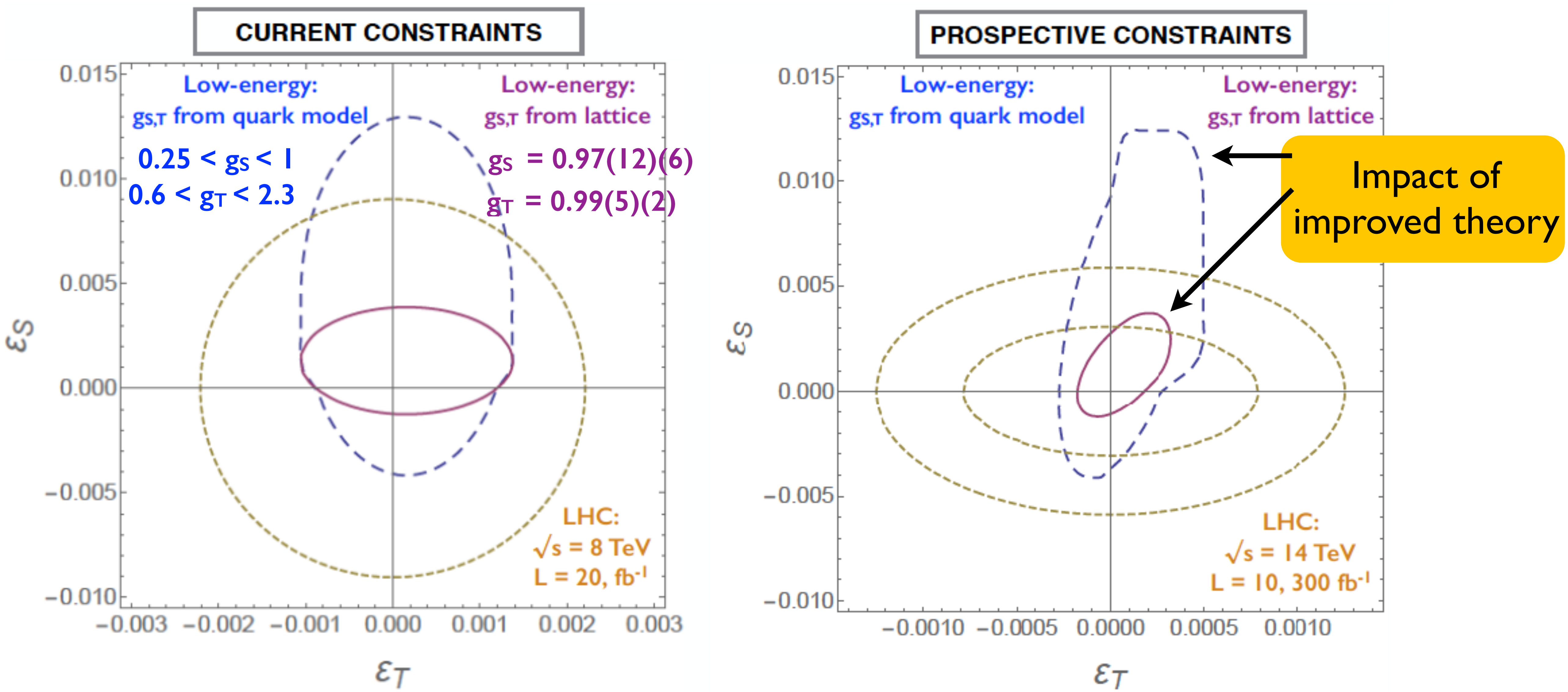
T. Bhattacharya et al, 1110.6448

VC, Gonzalez-Alonso, Graesser, 1210.4553

Probing non V-A ($\varepsilon_{S,T}$) couplings

Bhattacharya, et al 1606.07049

$\varepsilon_{S,T}$ @ μ= 2 GeV (MS-bar)



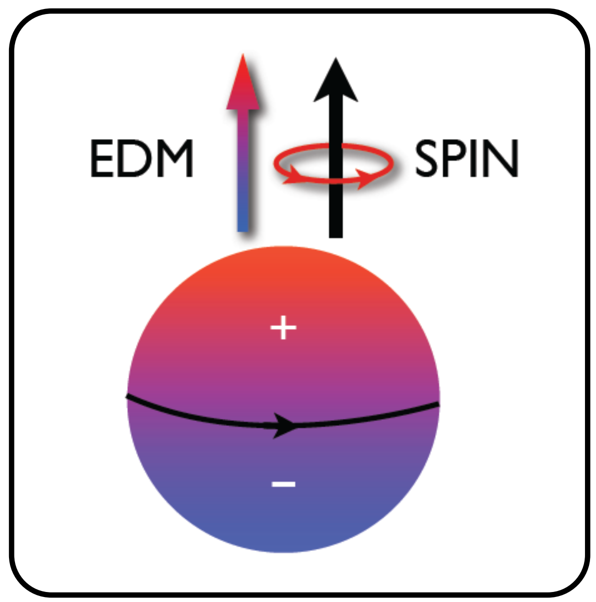
Probing mass scales $\Lambda_{S,T} \sim$ 5-10 TeV

Neutron EDM in the LHC era**

**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

EDMs and symmetry breaking

- EDMs of *non-degenerate* systems violate P and T: $\mathcal{H} \sim d\,\vec{J} \cdot \vec{E}$



$$\vec{d} = \sum_i q_i\,\vec{r}_i$$

$$\vec{d} = d\,\vec{J}$$

- CPT invariance $\Rightarrow$ nonzero EDMs imply CP violation

EDMs as probes of new physics

1. Essentially free of SM "background" (CKM) *1

EDMs in $e \cdot cm$

System	current	projected	SM (CKM)
e	$\sim 10^{-28}$	10^{-29}	$\sim 10^{-38}$
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	$\sim 10^{-29}$	10^{-30}	$\sim 10^{-33}$
^{129}Xe	$\sim 10^{-27}$	10^{-29}	$\sim 10^{-33}$
^{225}Ra	$\sim 10^{-23}$	10^{-26}	$\sim 10^{-33}$
...	...		...

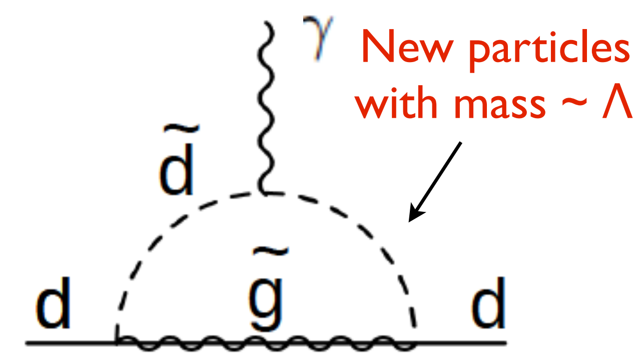
*1 Observation would signal new physics or a tiny QCD θ-term (< 10^{-10}).
Multiple measurements can disentangle the two effects.
In the rest of the discussion assume that θ relaxes to zero dynamically (Peccei-Quinn)

EDMs as probes of new physics

1. Essentially free of SM "background" (CKM) *1

2. Sensitive to high scale BSM physics (Λ~10-100 TeV)

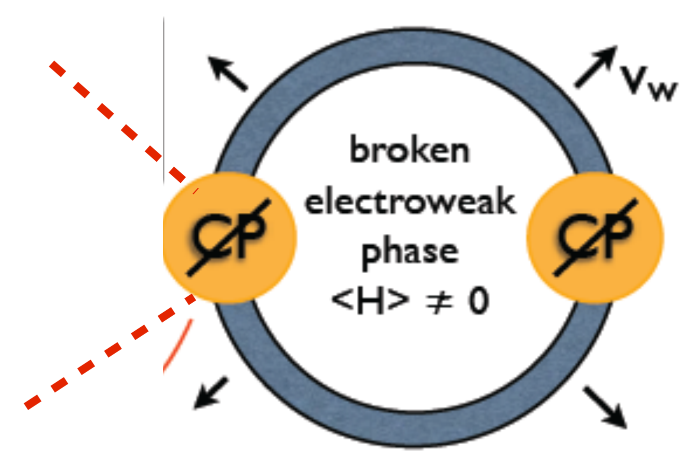
$$d_n \propto \frac{m_q}{\Lambda^2}\, e\, \phi_{CP}$$



3. Probe key ingredient of baryogenesis

Sakharov '67

- B violation
- C and CP violation
- Departure from equilibrium*



Effective Lagrangian at E~GeV

- New physics effects encoded in local operators with couplings ~1/Λ²

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

Electric and chromo-electric dipoles of fermions

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

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

Gluon chromo-EDM (Weinberg operator)

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

Semileptonic and 4-quark

Neutron EDM

- Neutron EDM from BSM operators is poorly known.
  This strongly dilutes the constraining power of measurements

Pospelov-Ritz hep-ph/0504231 and refs therein

$\mu \simeq 1$ GeV

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

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

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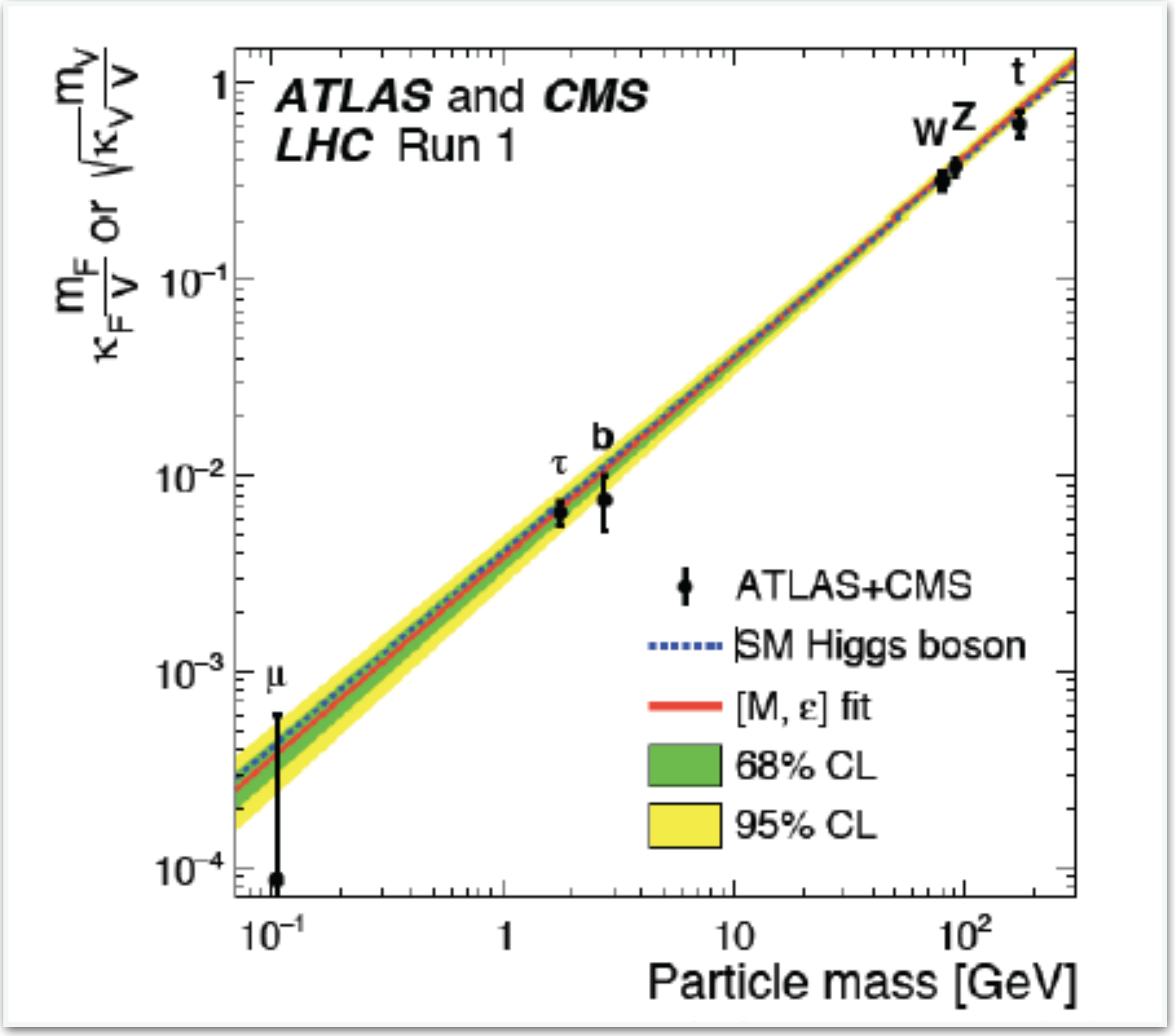
QCD Sum Rules (50%) QCD Sum Rules + NDA (~100%)

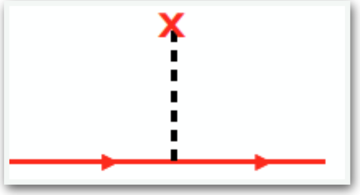
- Recent development: matrix elements from LQCD
  - quark EDM: tensor charges @ 10% [✔]
  - quark CEDM [ongoing (LANL, BNL)]
  - Weinberg & 4q [future]

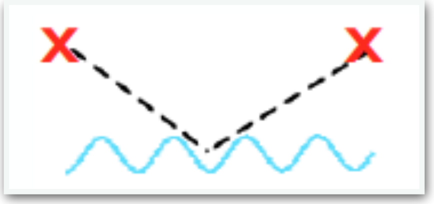
Bhattacharya, VC, Gupta, Lin, Yoon, PRL 115 (2015) 212002 [1506.04196]

EDMs and CPV Higgs couplings

- So far, Higgs properties are compatible with SM expectations



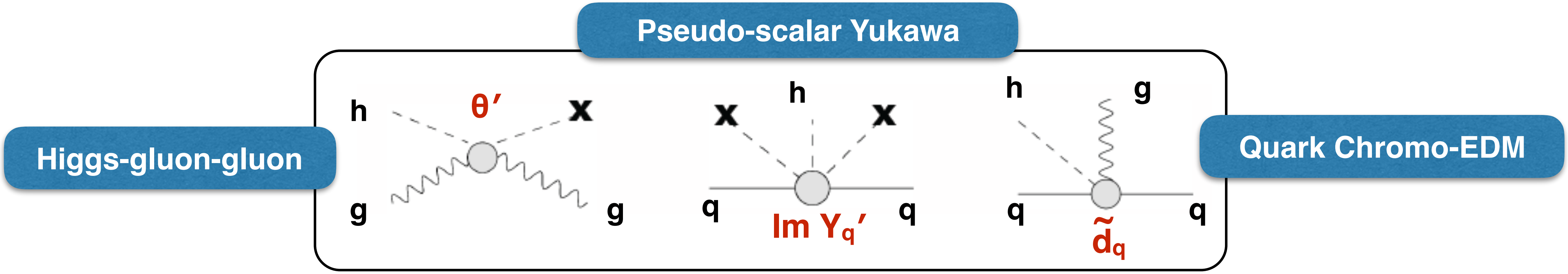




- Still room for deviations: is this the SM Higgs? Key question at LHC Run 2

- EDMs can help constraining non-standard CPV Higgs couplings

CPV Higgs couplings to quarks and gluons



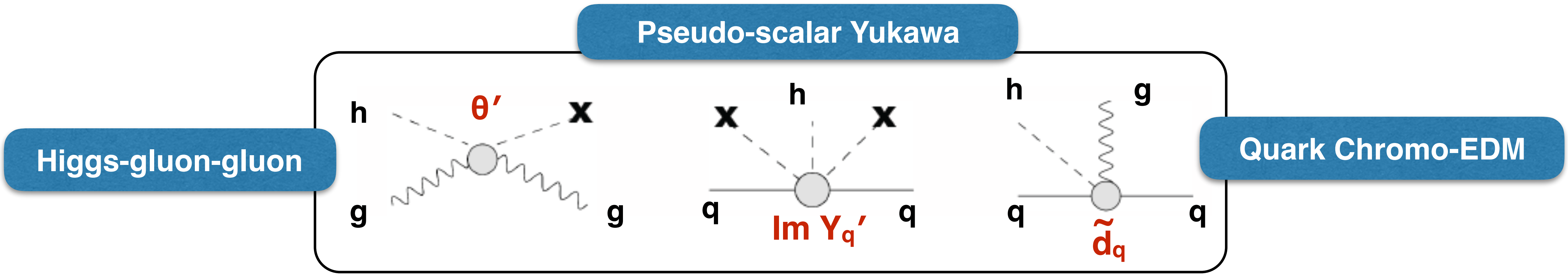
- A handful of leading ($1/\Lambda^2$) gauge-invariant couplings

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

$$\theta', \mathrm{Im}Y'_q \sim \frac{1}{\Lambda^2} \qquad \tilde{d}_q \sim \frac{v}{\Lambda^2}$$

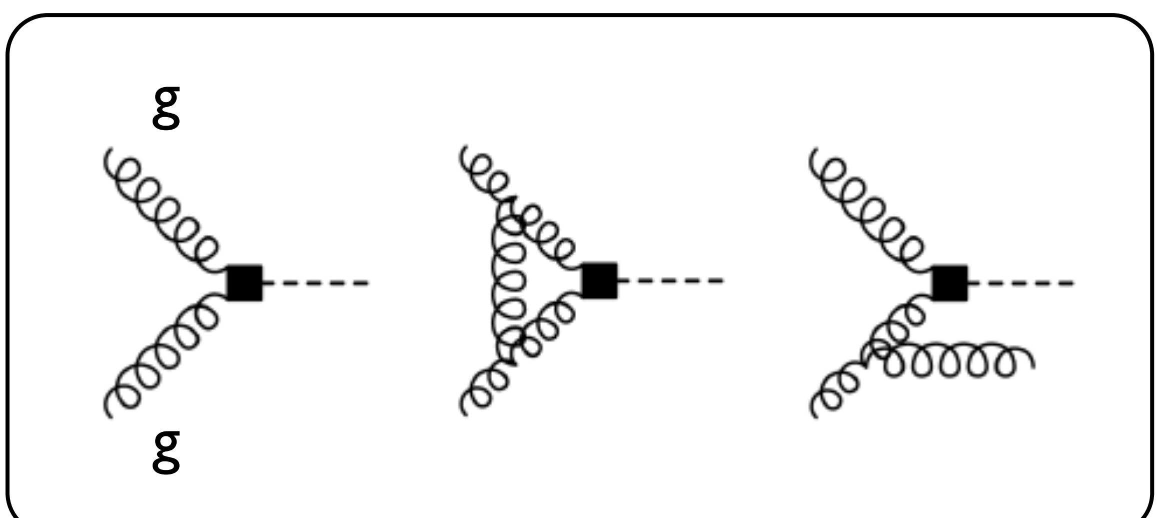
Y.-T. Chien, V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

CPV Higgs couplings to quarks and gluons

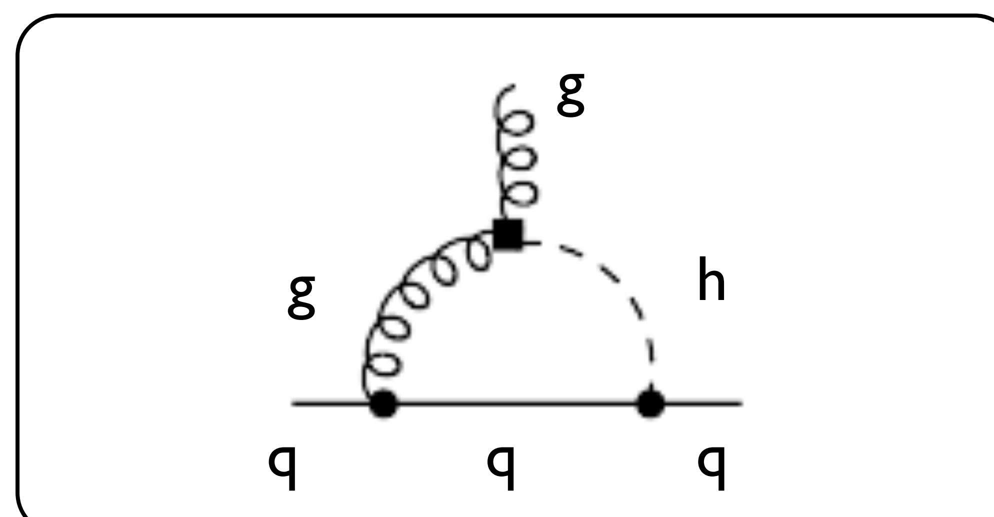


- Signatures of various operators: Higgs-gluon-gluon (θ′)

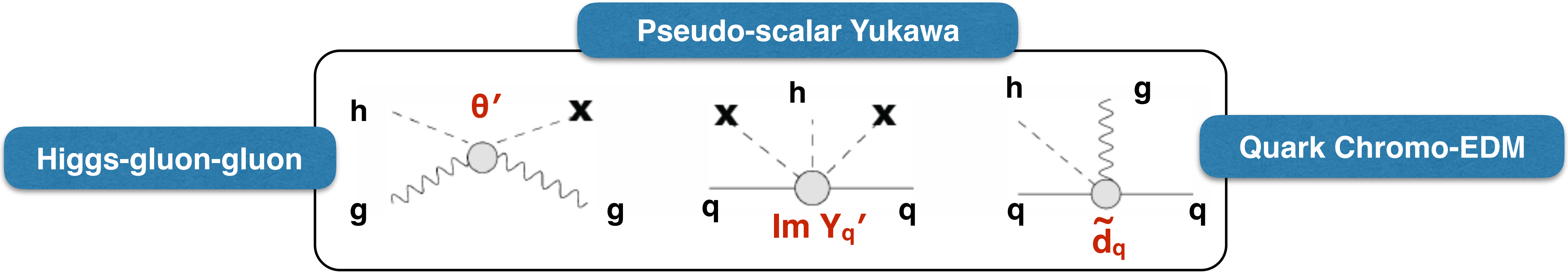
LHC: Higgs production via gluon fusion



Low Energy: quark (C)EDM + Weinberg

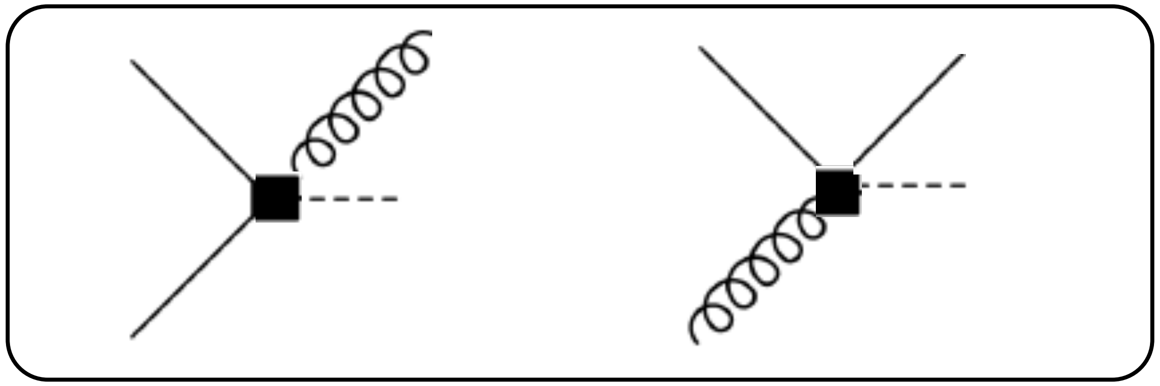


CPV Higgs couplings to quarks and gluons

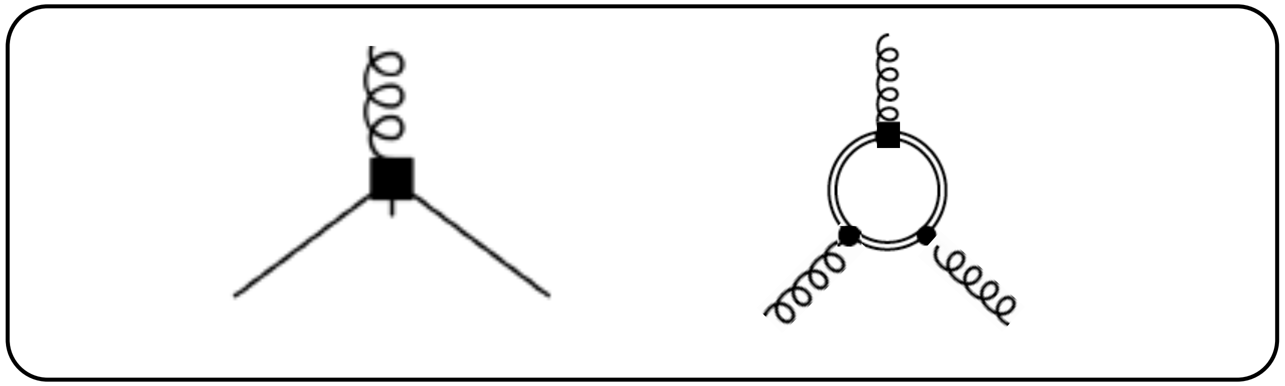


- Signatures of various operators: $\tilde{d}_q$ for $q \neq t$

LHC: Higgs (+ jet) production



Low Energy: quark (C)EDM, Weinberg



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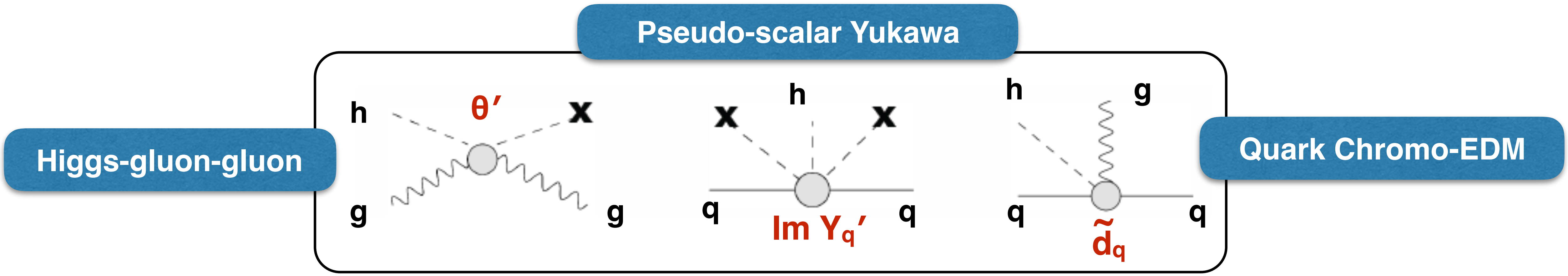
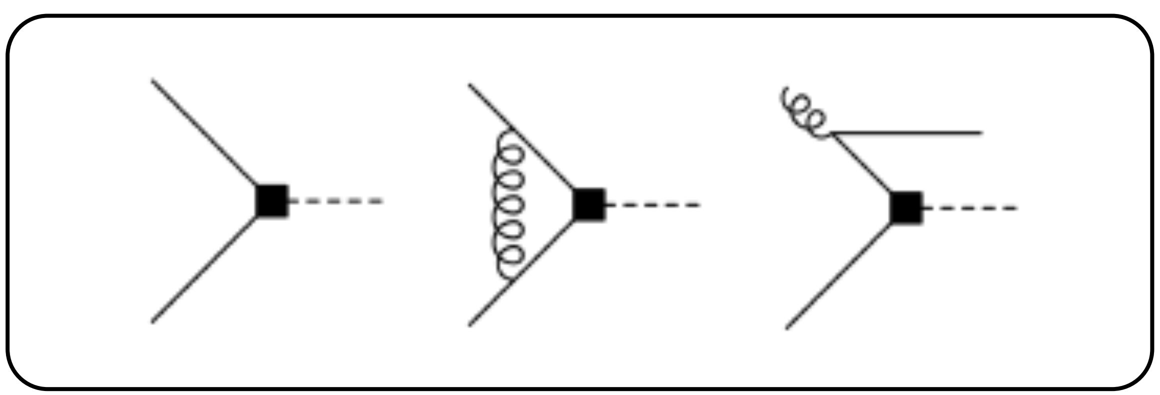
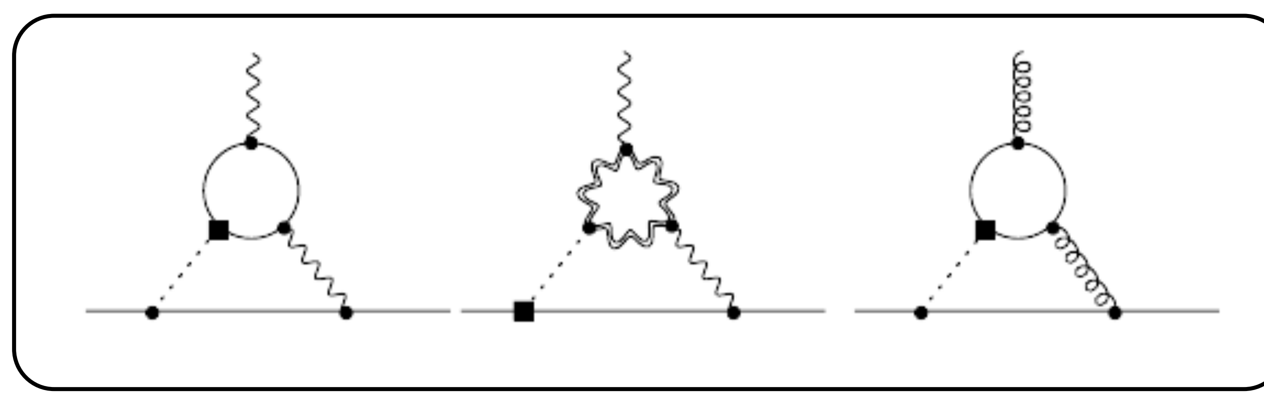


- Signatures of various operators: pseudoscalar Yukawas q≠t

LHC: Higgs production



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

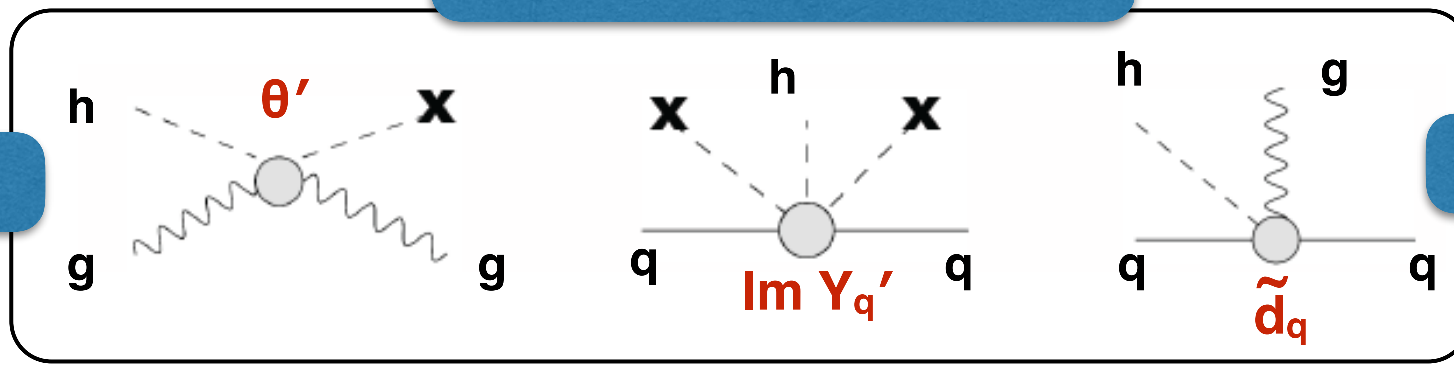


CPV Higgs couplings to quarks and gluons

Pseudo-scalar Yukawa

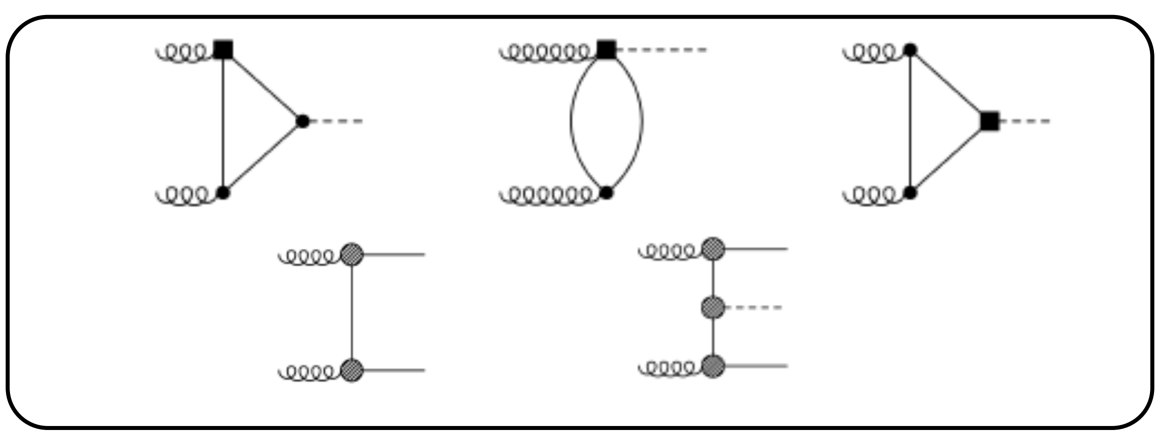
Higgs-gluon-gluon

Quark Chromo-EDM

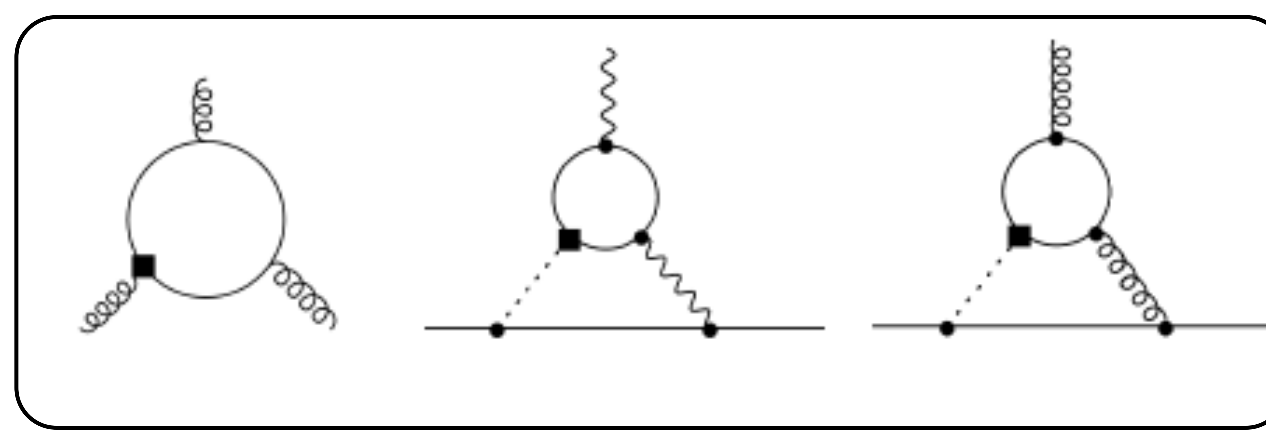


- Signatures of various operators: top pseudo-scalar Yukawa and CEDM

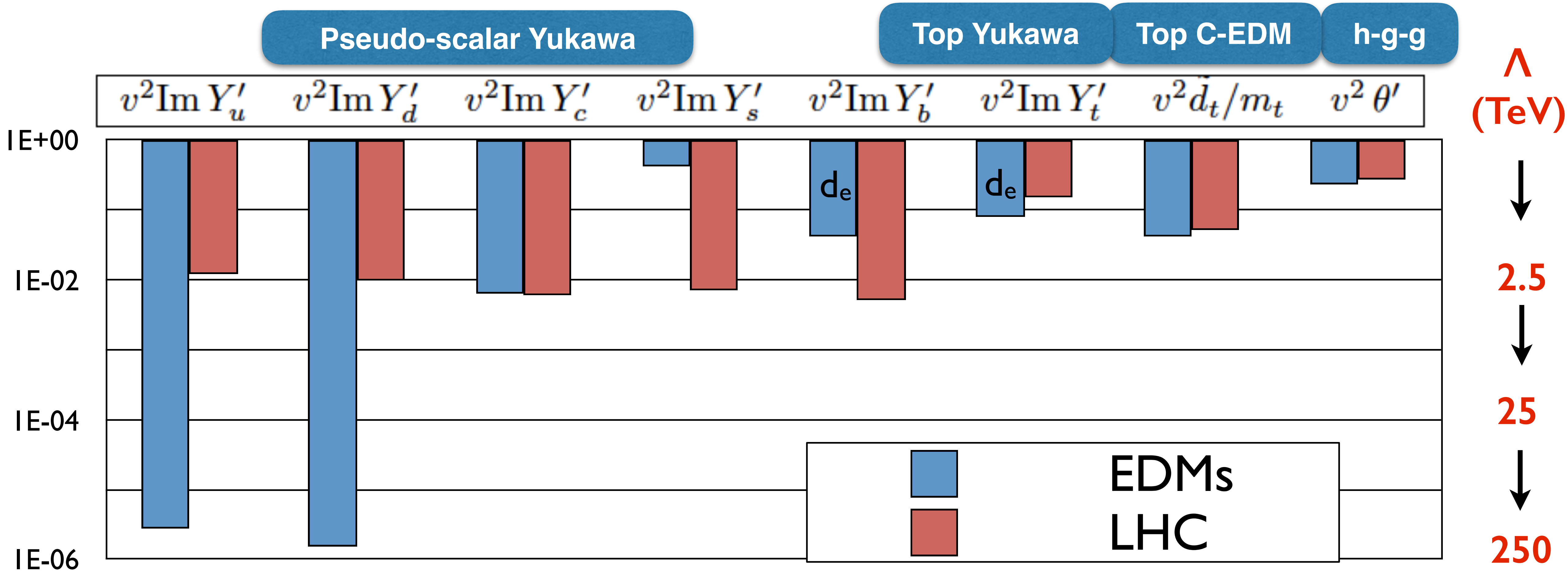
LHC: pp → h (via ggF), $t\bar{t}$, $t\bar{t}h$



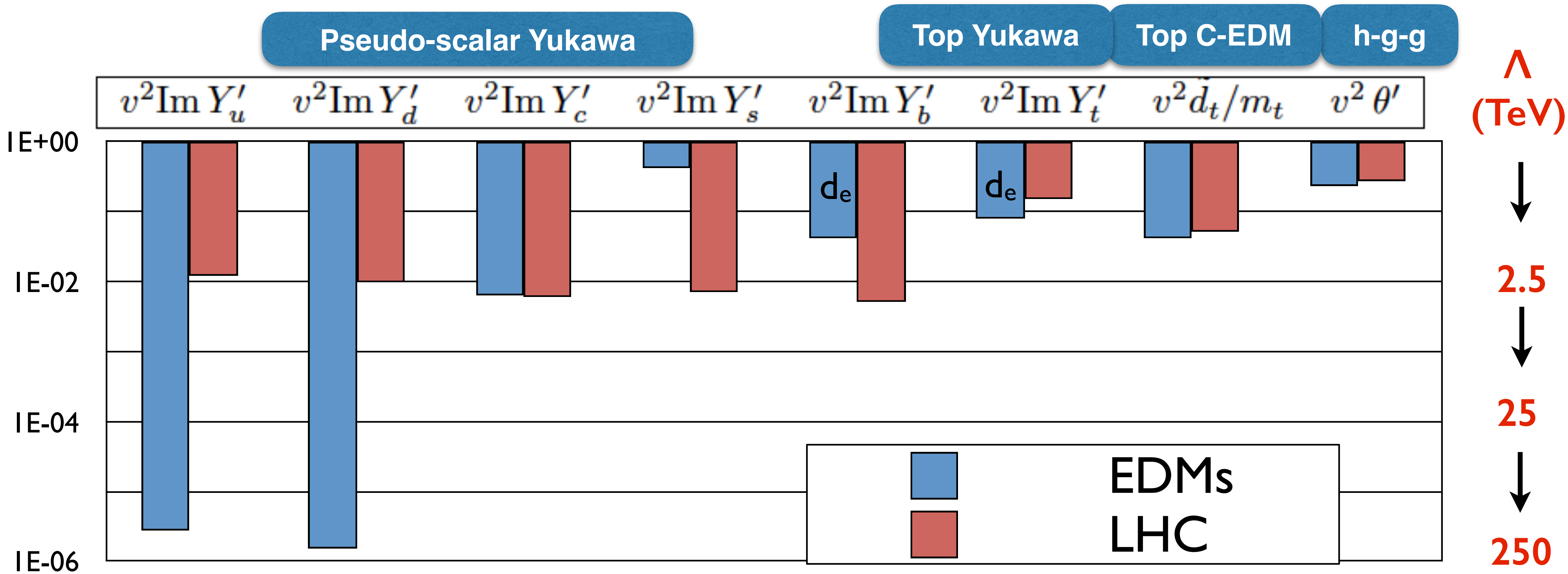
Low Energy: quark (C)EDM, Weinberg, *and* d_e



Bounds

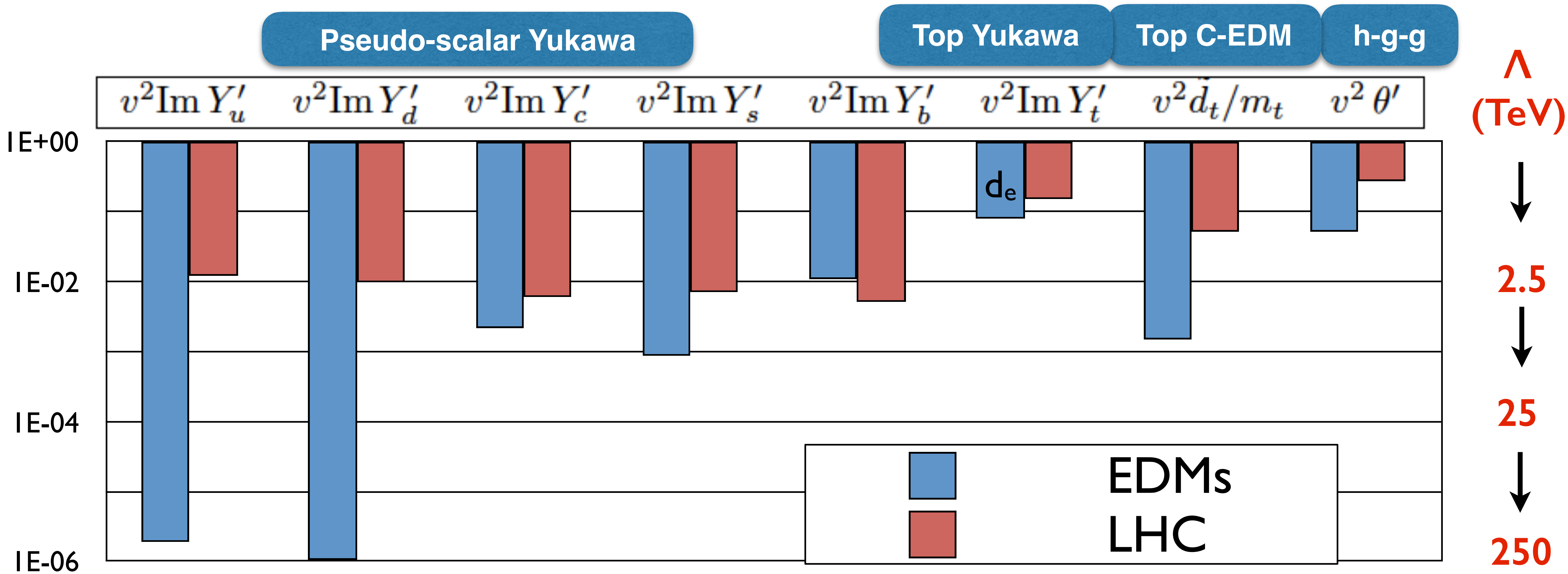

Pseudo-scalar Yukawa
Top Yukawa
Top C-EDM
h-g-g
$v^2 \mathrm{Im}\, Y'_u$
$v^2 \mathrm{Im}\, Y'_d$
$v^2 \mathrm{Im}\, Y'_c$
$v^2 \mathrm{Im}\, Y'_s$
$v^2 \mathrm{Im}\, Y'_b$
$v^2 \mathrm{Im}\, Y'_t$
$v^2 \tilde{d}_t / m_t$
$v^2\, \theta'$
1E+00
1E-02
1E-04
1E-06
d_e
d_e
EDMs
LHC
Λ
(TeV)
2.5
25
250

Bounds



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

Bounds



- Much stronger impact of neutron EDM with reduced uncertainties

$d_{n,p}[\tilde{d}_{u,d}]$ — 25%

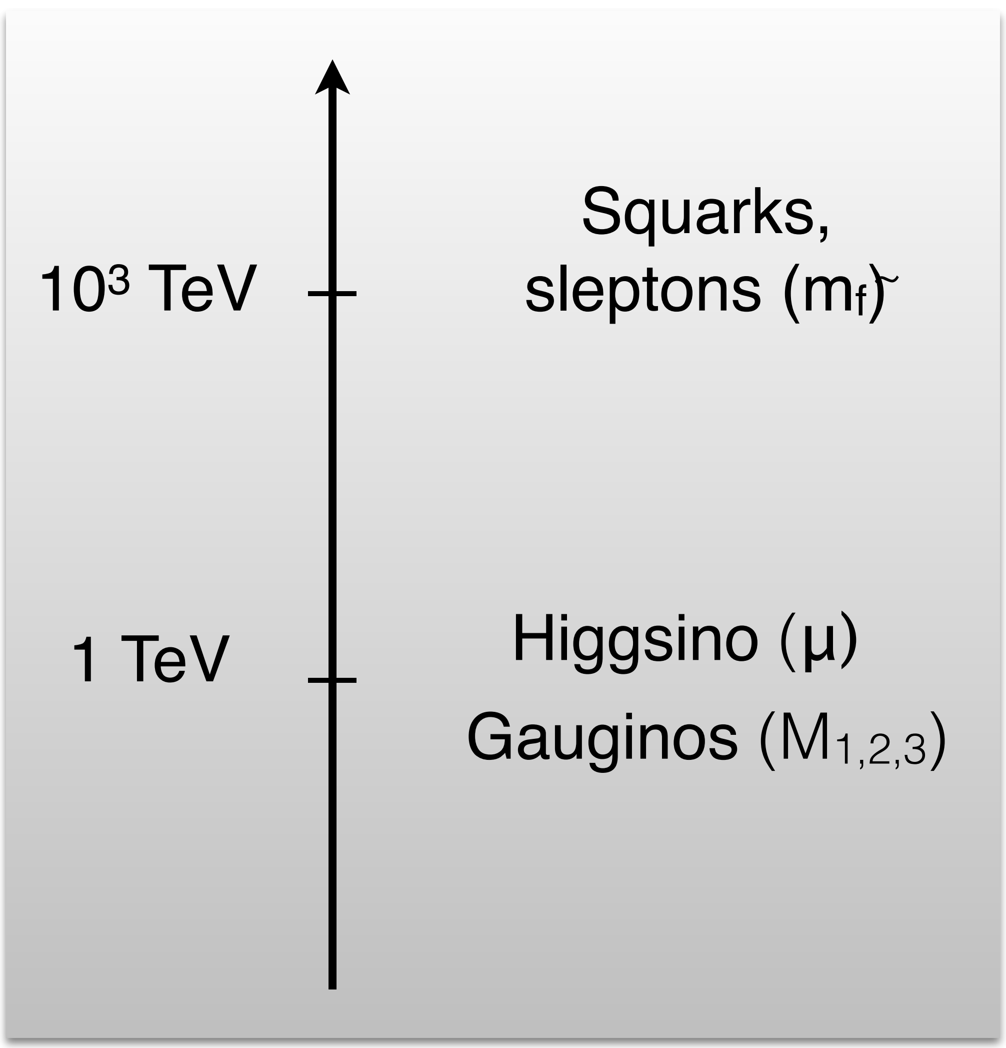
$d_{n,p}[d_s]$ $\quad d_{n,p}[d_W]$ — 50%

- Target for Lattice QCD in the 5-year time scale

EDMs in high-scale SUSY models

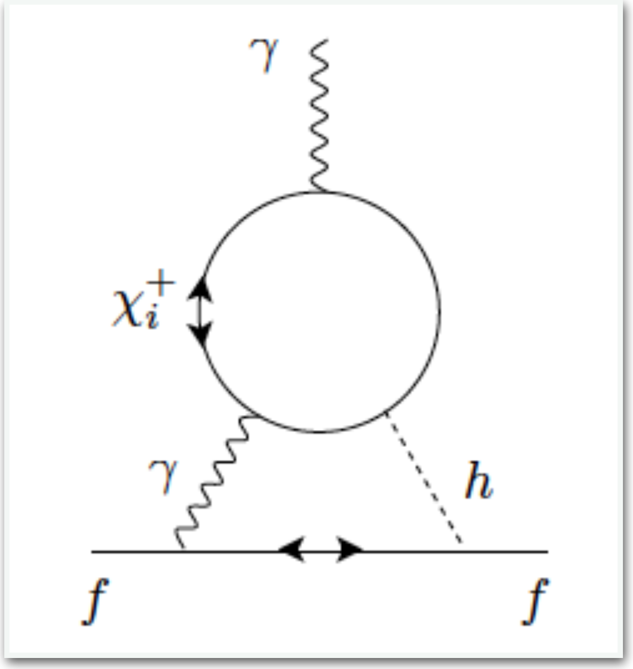
- Higgs mass + absence of other signals point to heavy super-partners
- "Split-SUSY": retain gauge coupling unification and DM candidate

Arkani-Hamed, Dimopoulos 2004, Giudice, Romanino 2004, Arkani-Hamed et al 2012, Altmannshofer-Harnik-Zupan 1308.3653, …

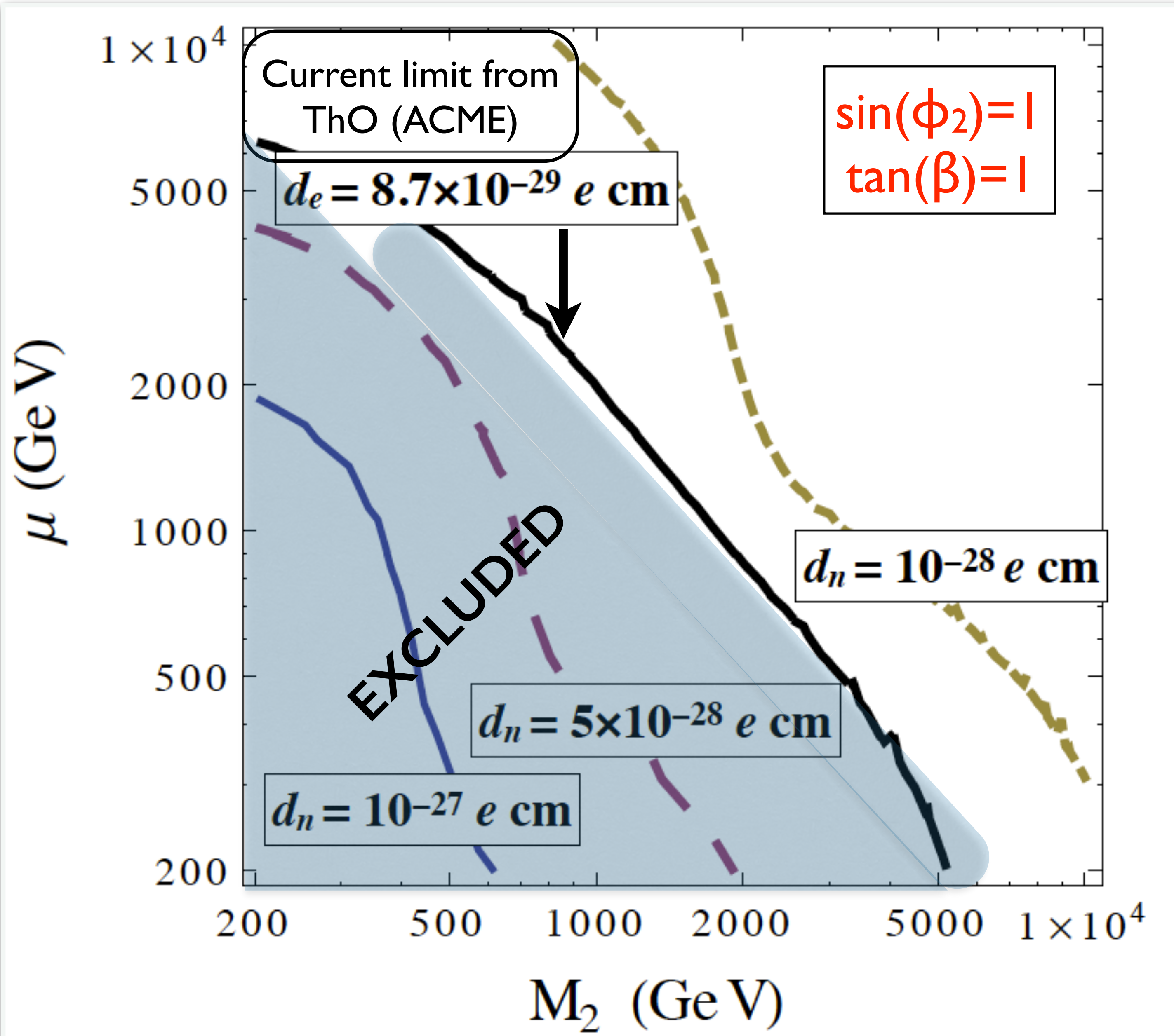


EDMs among a handful of observables capable of probing such high scales

Same CPV phase controls d_e, $d_n[d_q]$



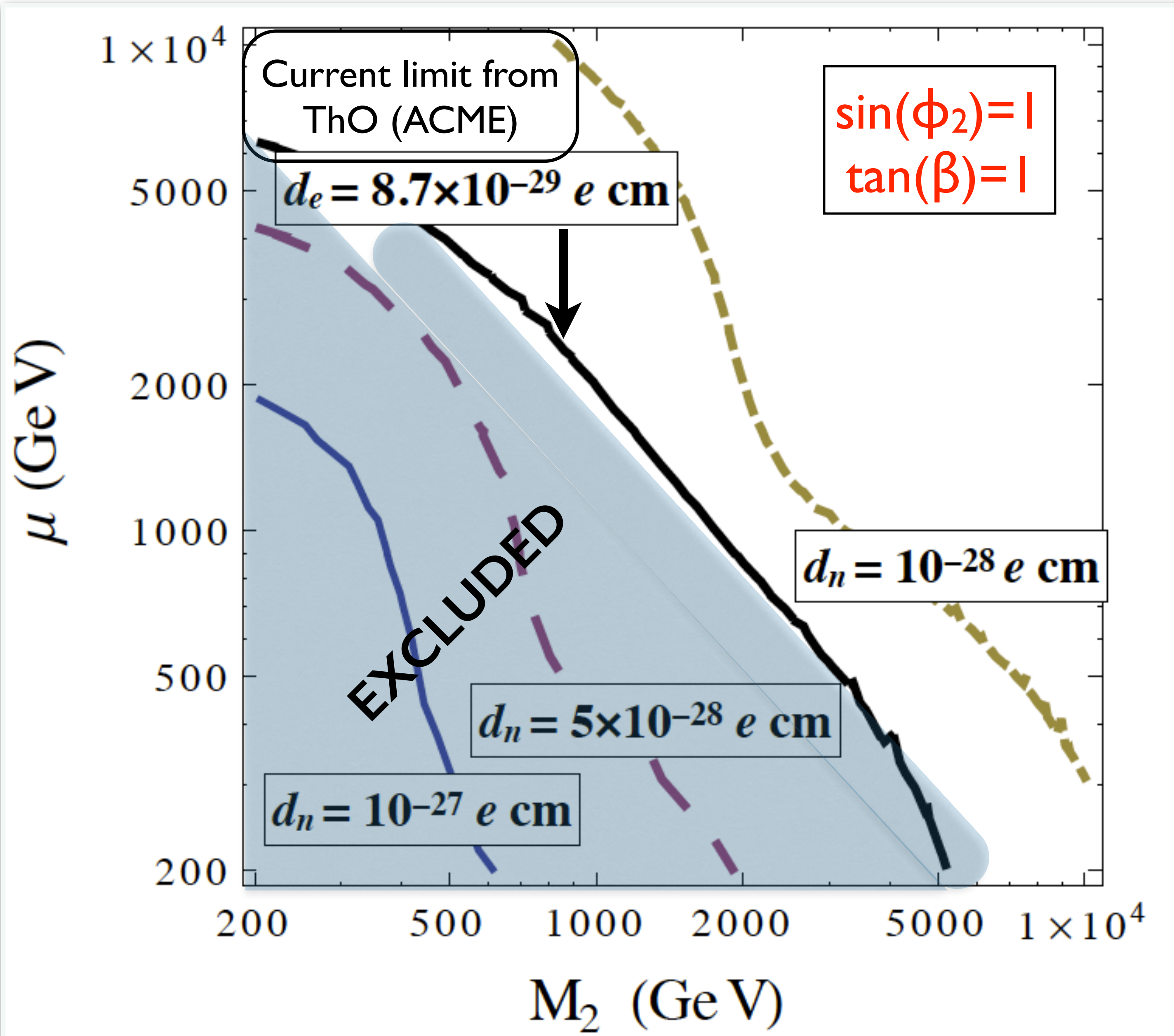
EDMs in high-scale SUSY models



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

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

EDMs in high-scale SUSY models



- 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
- Split-SUSY can be falsified by current nEDM searches

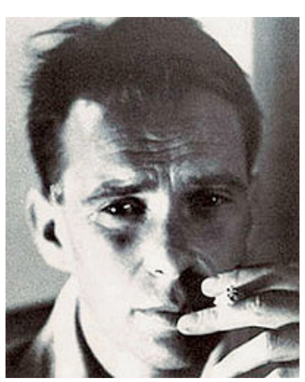
Bhattacharya, VC, Gupta, Lin, Yoon
Phys. Rev. Lett. 115 (2015) 212002 [1506.04196]

Example of model diagnosing enabled by multiple measurements (e,n) and controlled theoretical uncertainty

Conclusions

- Precision neutron experiments provide strong probes of new physics
- Neutron decay:
  - Measurements of lifetime ($\delta\tau_n/\tau_n \sim 0.04$ %) and decay correlations (@ $\leq 0.1\%$) are a "broad band" BSM probe
  - In "heavy BSM" case, discovery window exists well into the LHC era (ε_L-ε_R and ε_S-ε_T plots)
- Neutron EDM: powerful probe of new sources of CP violation
  - Strong constraints on CPV Higgs couplings (better than LHC)
  - Sensitivity to high-scale BSM scenarios (example: split SUSY)

Thank you!



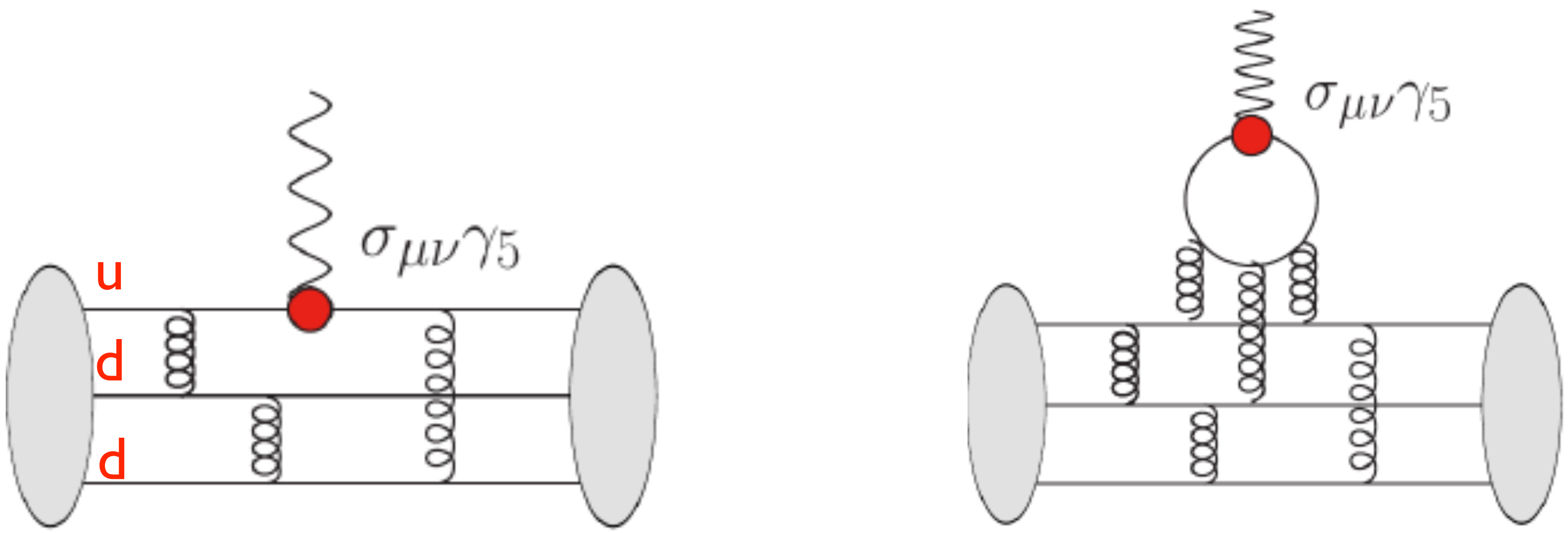
A drawing by
Bruno Touschek

Backup

Neutron EDM from quark EDM

- Quarks couple directly to photon (in a CP-odd way)

$$\mathcal{L} = -\frac{i}{2} \sum_{q=u,d,s} d_q \, \bar{q} \sigma_{\mu\nu} \gamma_5 q \, F^{\mu\nu}$$



Neutron EDM from quark EDM

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$$\mathcal{L} = -\frac{i}{2} \sum_{q=u,d,s} d_q \, \bar{q}\sigma_{\mu\nu}\gamma_5 q \, F^{\mu\nu}$$

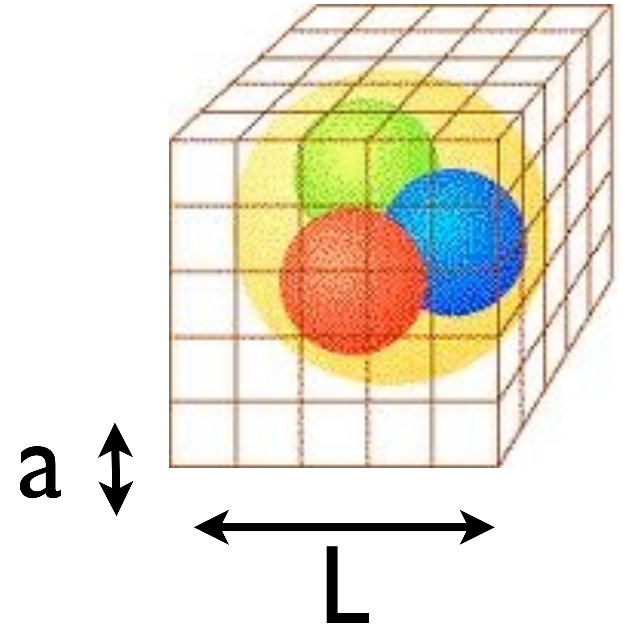
- Problem "factorizes": need so-called tensor charge of the neutron

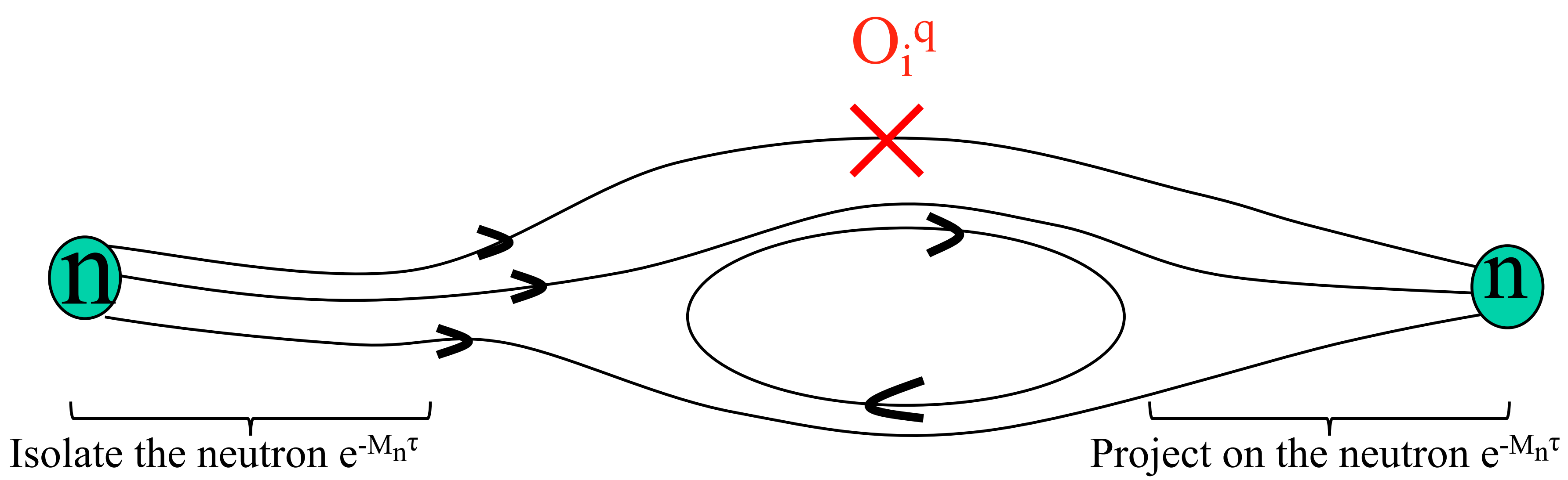
$$d_N = d_u \, g_T^{(N,u)} + d_d \, g_T^{(N,d)} + d_s \, g_T^{(N,s)}$$

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

Neutron EDM from quark EDM

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





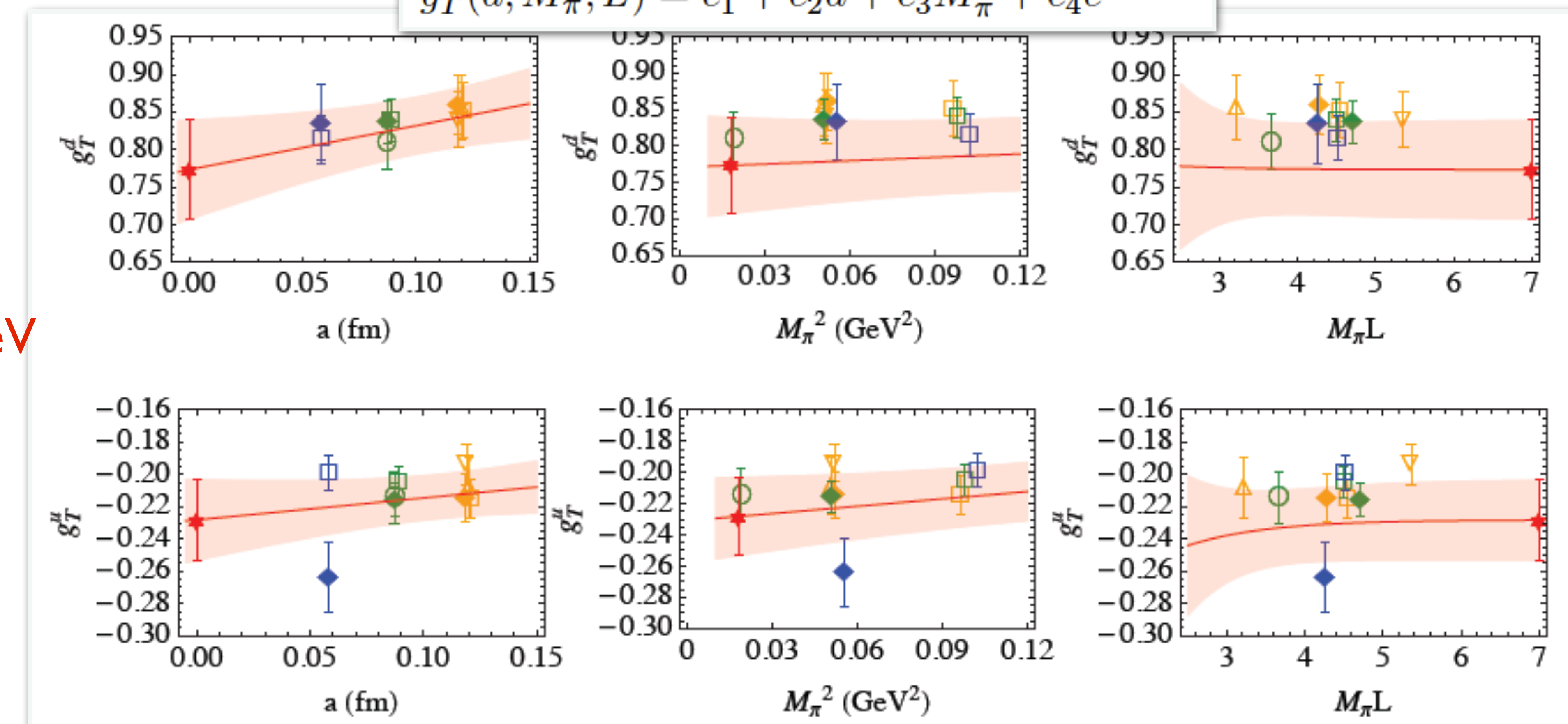
- Do it on many little universes with different m_q, a, V

Neutron EDM from quark EDM

$g_T^{(n,u)} = -0.23(3)$ $g_T^{(n,d)} = 0.77(7)$ $g_T^{(s)} = 0.008(9)$

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

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



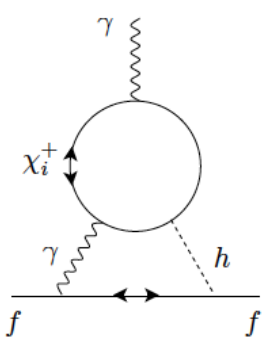
Bhattacharya, VC, Gupta, Lin, Yoon, PRL 115 (2015) 212002 [1506.04196]

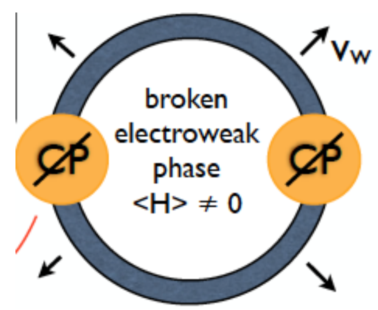
O(10%) error including all systematics: excited states, continuum, quark masses, volume

Ongoing efforts by LANL, BNL, LBL groups to tackle other operators

EDMs and baryogenesis models

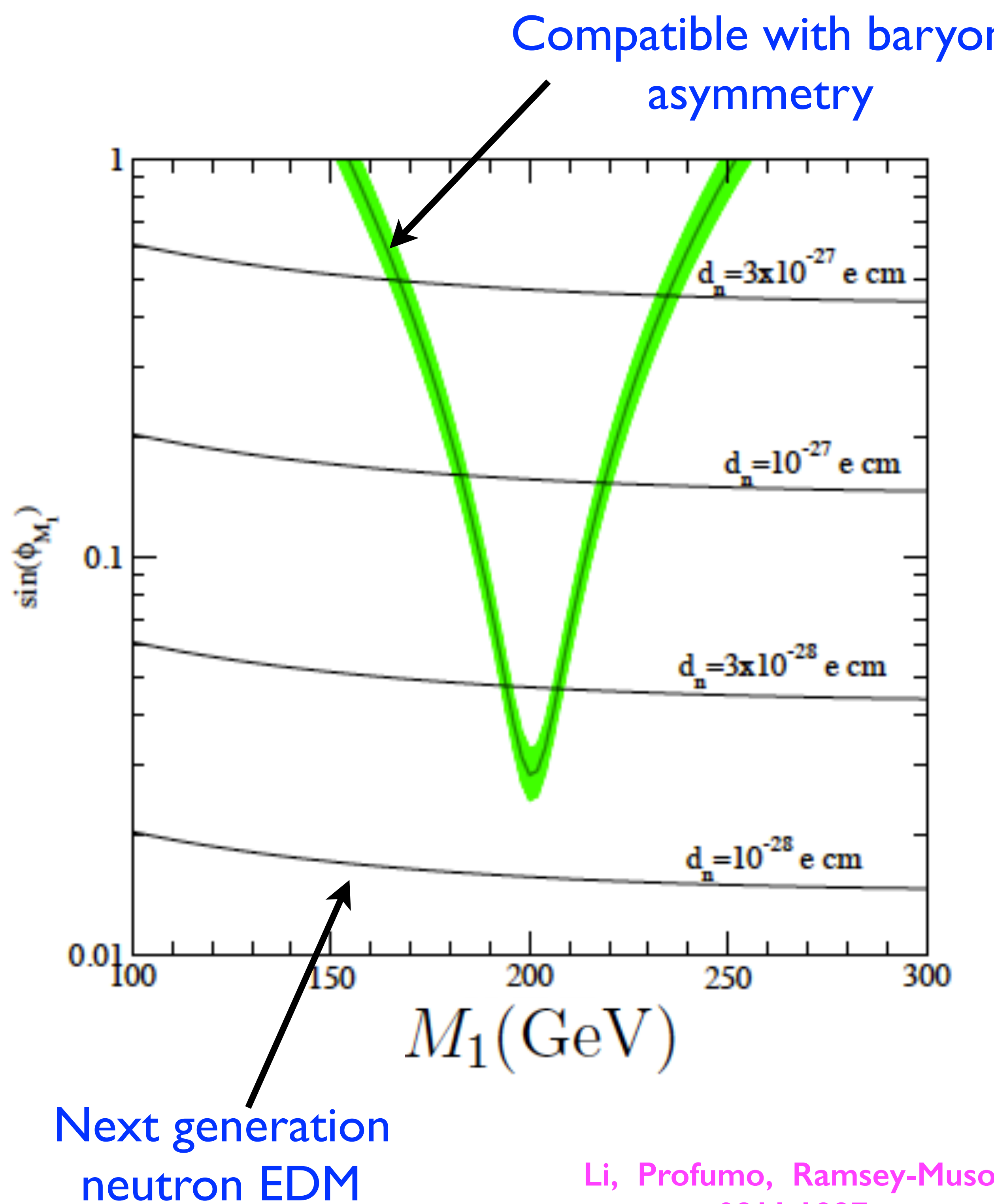
- In Supersymmetry, CPV phases appearing in the gaugino-higgsino mixing contribute to both baryogenesis and EDM





- In *this model*, successful baryogenesis implies a "guaranteed signal" for EDMs

- Within reach of planned experiments, with caveat that "constant EDM" lines shift due to hadronic uncertainties!



Li, Profumo, Ramsey-Musolf 0811.1987
Cirigliano, Li, Profumo, Ramsey-Musolf, 0910.4589

CKM unitarity test

	V	V,A	A
V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e \nu)$	$n \to p e \bar{\nu}$	$\pi \to \mu \nu$
V_{us}	$K \to \pi l \nu$	$\Lambda \to p e \bar{\nu}, \ldots$	$K \to \mu \nu$

- Currently, the most precise input comes from pure V or A channels
  - V: nuclear decays and semi-leptonic K decays
  - A: leptonic decays → V_{us} / V_{ud} (need f_K/f_π)

Hardy-Towner1411.5987

FLAVIANET report 1005.2323

Lattice QCD input from FLAG 1607.00299

Beta decays and new physics models

- Model → set overall size and pattern of effective couplings
- Beta decays can play very useful diagnosing role
- Qualitative picture: "DNA matrix"

	ε_L	ε_R	ε_P	ε_S	ε_T
LRSM	x	✓	x	x	x
LQ	✓	x	✓	✓	✓
2HDM	x	x	✓	✓	x
MSSM	✓	✓	✓	✓	✓

YOUR FAVORITE MODEL ... ...

Can be made quantitative