“Frontiers in Nuclear Physics”, KITP, September 13 2016

Nuclear Physics and the “New Standard Model”

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Los Alamos
NATIONAL LABORATORY
EST. 1943

Problem with “big picture” talks

Figure by Robert Bernstein (FNAL)

Leave out people’s work

Cover too much

I will do both…

Outline

- Introduction: the role of nuclear physics in the quest for new physics

- Tutorial: EFT approach to new physics & low-E landscape

- "Worked examples" (highlighting challenges & impact)
    - EDMs and CPV Higgs couplings
    - Precision β-decays and new CC interactions

The role of nuclear physics in the quest for new physics

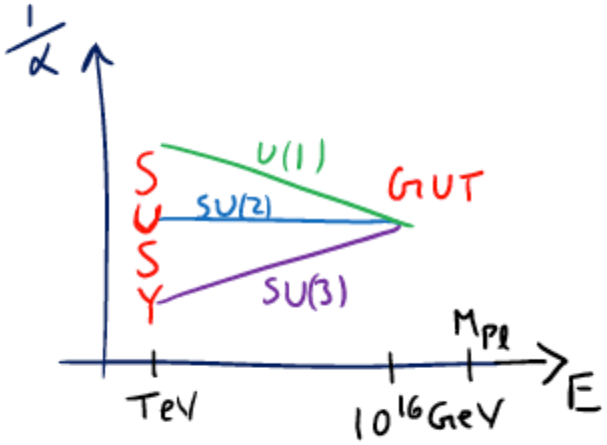
The quest for “new physics”

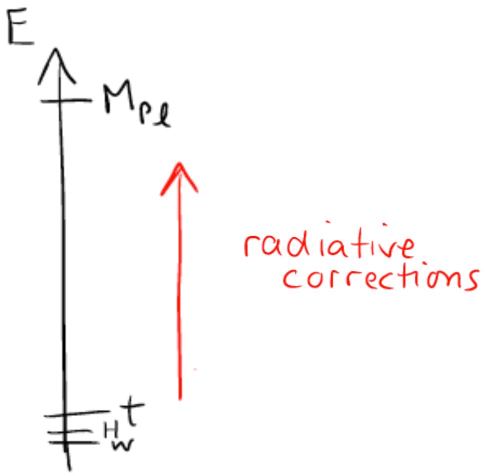
- The SM is remarkably successful, but can’t be the whole story

Empirical arguments

Theoretical arguments

Neutrino mass,
excess of matter over antimatter,
dark matter, dark energy

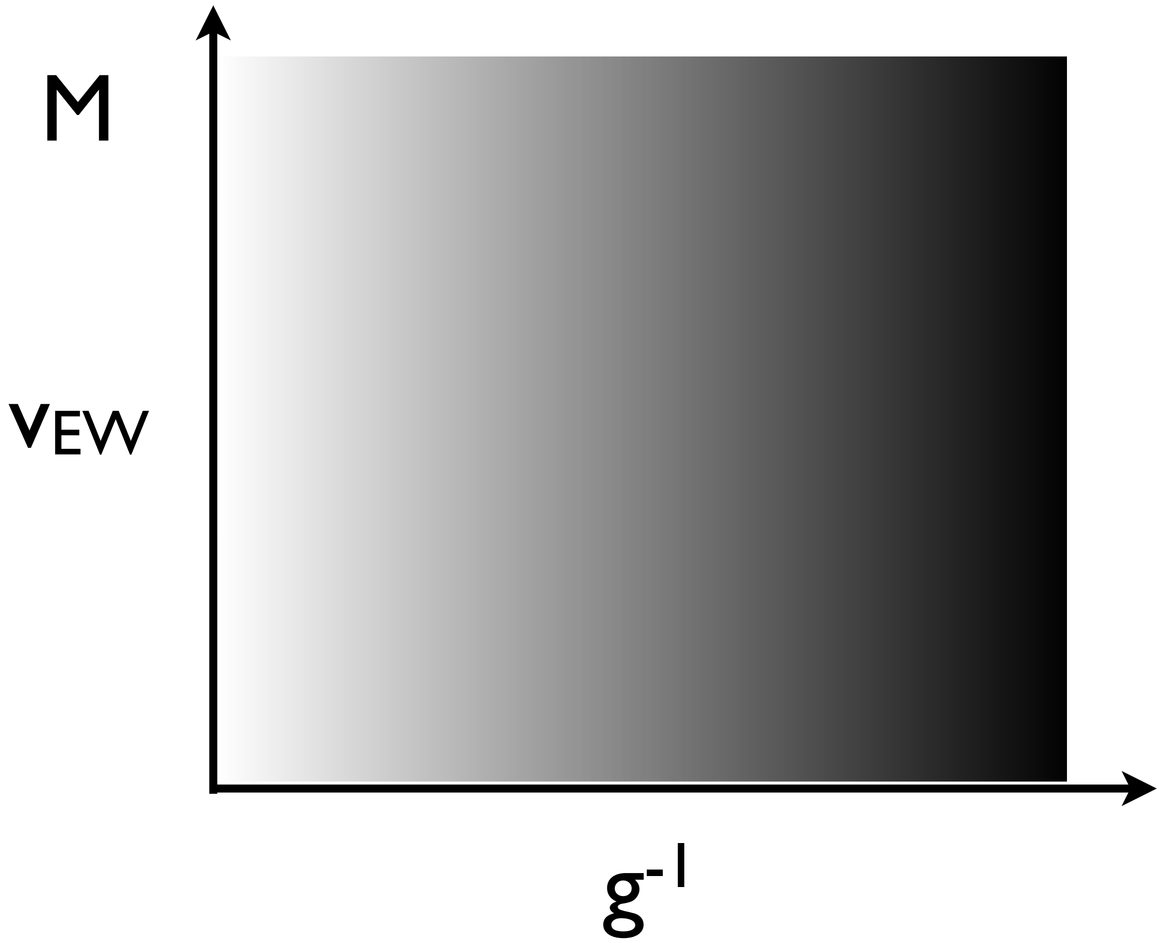




R. Sundrum
ICHEP 12

The quest for “new physics”

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



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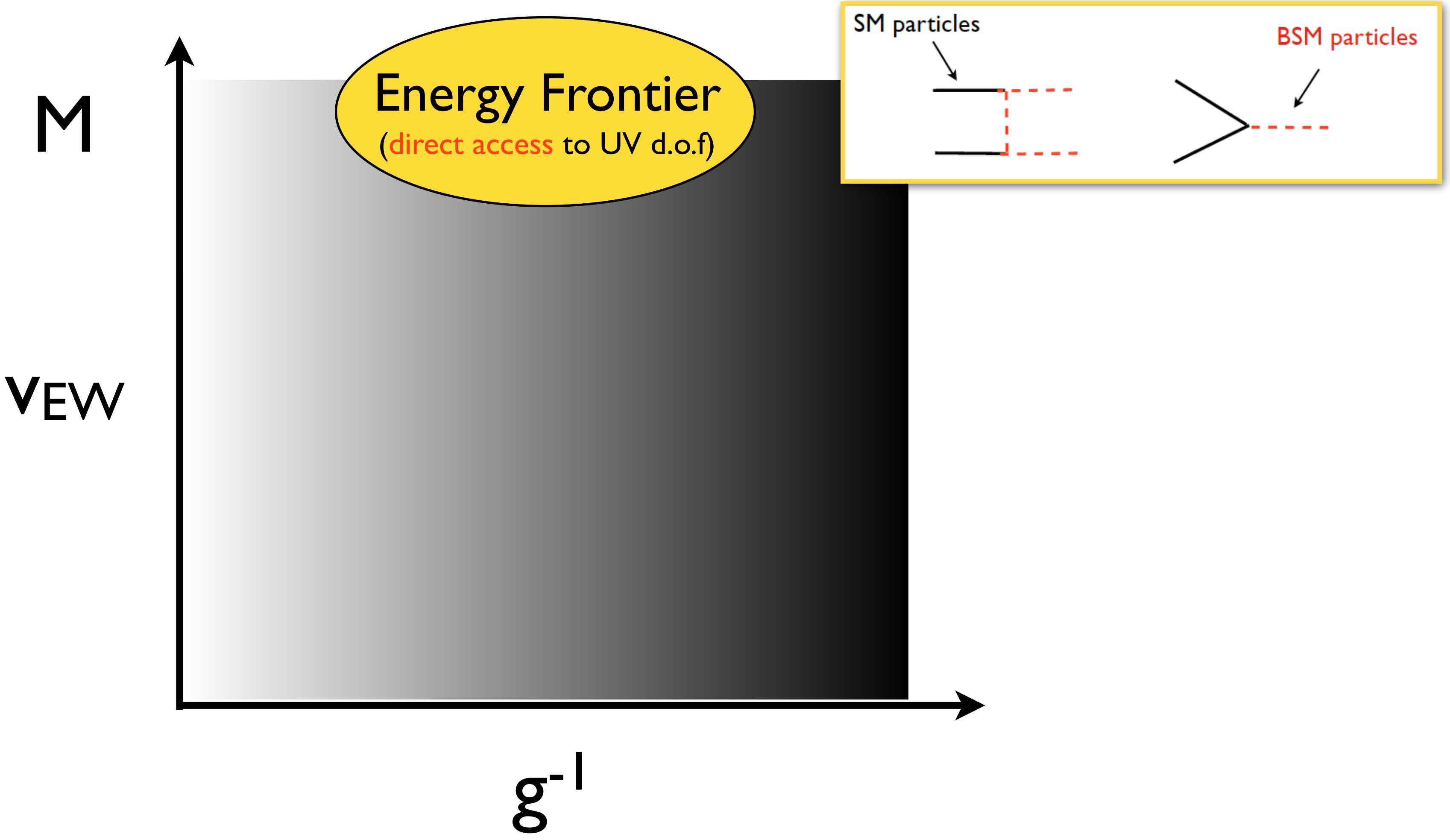

- Two approaches

The quest for "new physics"

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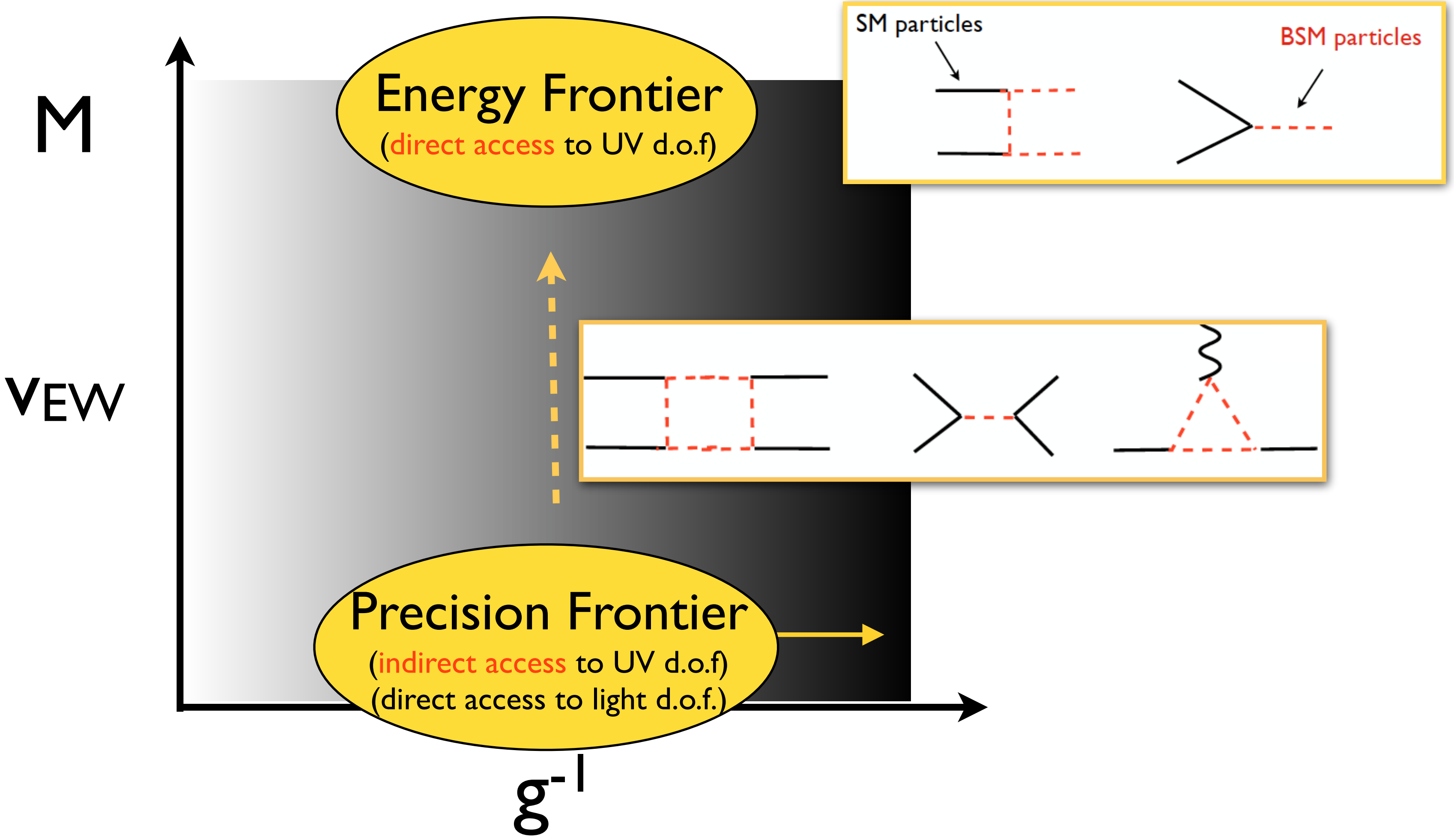

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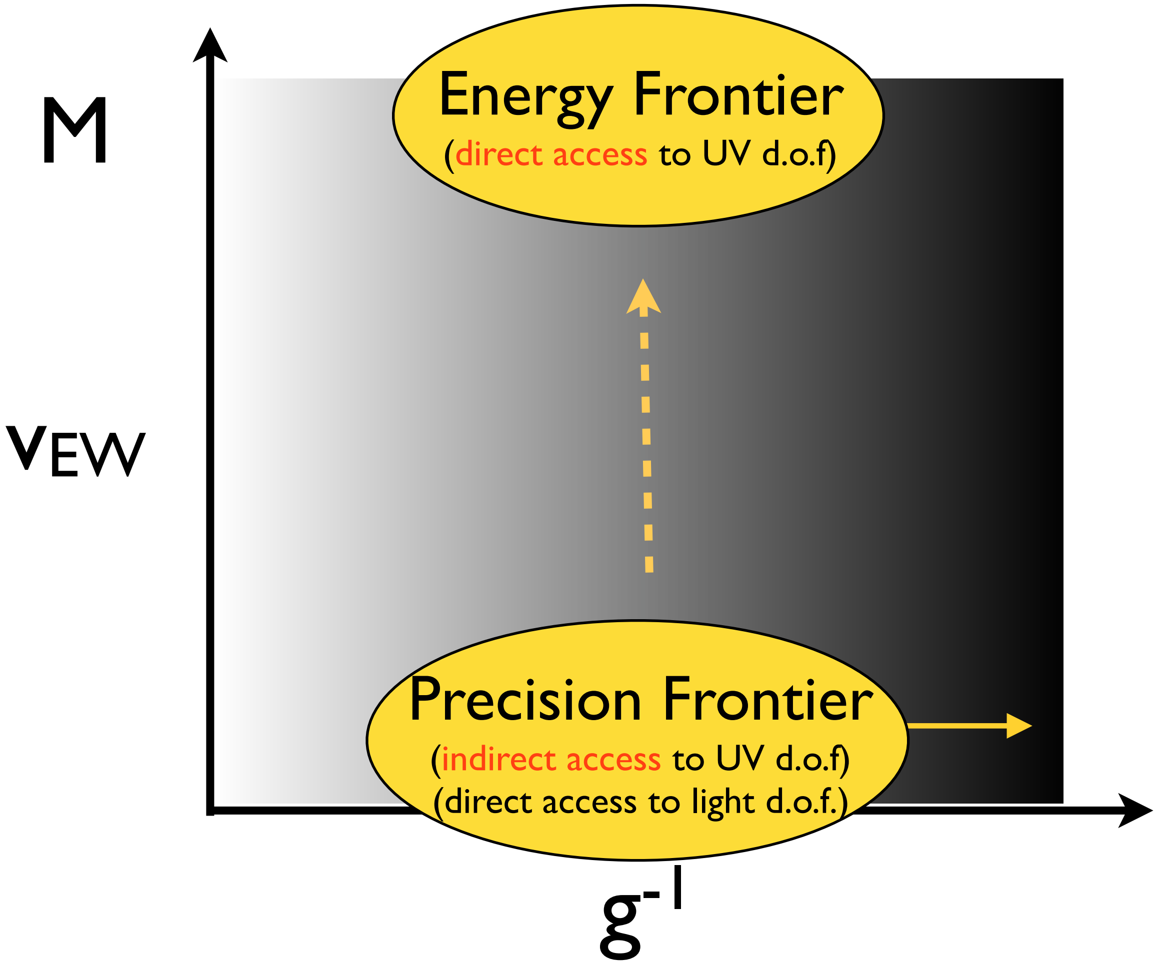

M

v_{EW}

g^{-1}

Energy Frontier
(direct access to UV d.o.f)

Precision Frontier
(indirect access to UV d.o.f)
(direct access to light d.o.f.)

- EWSB mechanism
- Direct access to heavy particles
- ...

- L and B violation
- CP violation (w/o flavor)
- Flavor: quarks, leptons
- Precision tests (heavy mediators)
- Dark matter detection, dark sectors
- …

- Two approaches, both needed to reconstruct BSM dynamics: structure, symmetries, and parameters of $\mathcal{L}_{BSM}$

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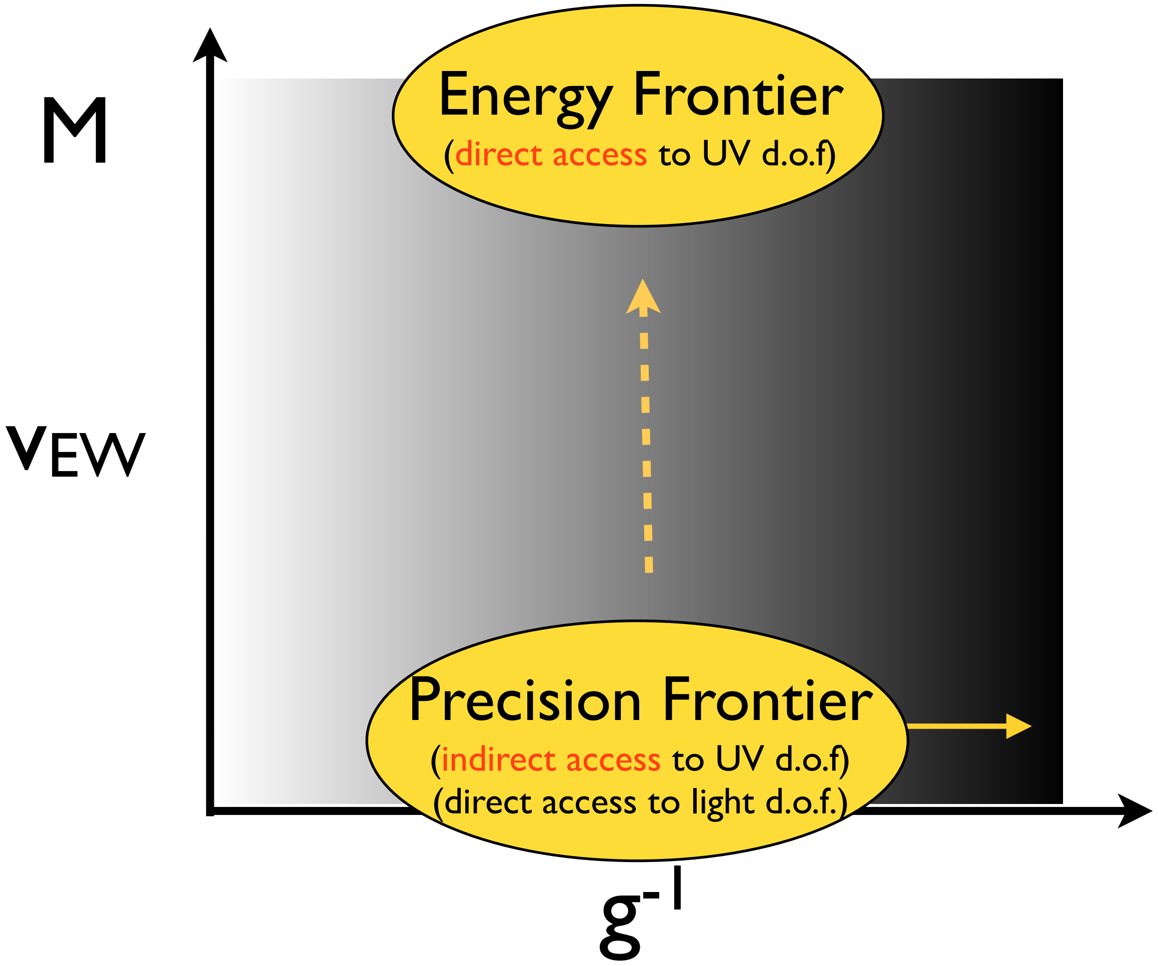

- EWSB mechanism
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- L and B violation
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- Flavor: quarks, leptons
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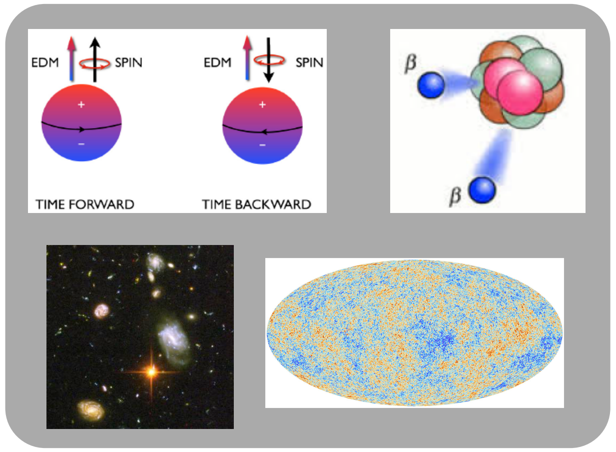
- …

- Nuclear Physics plays a prominent role at the Precision Frontier

Nuclear physics and “The new SM”

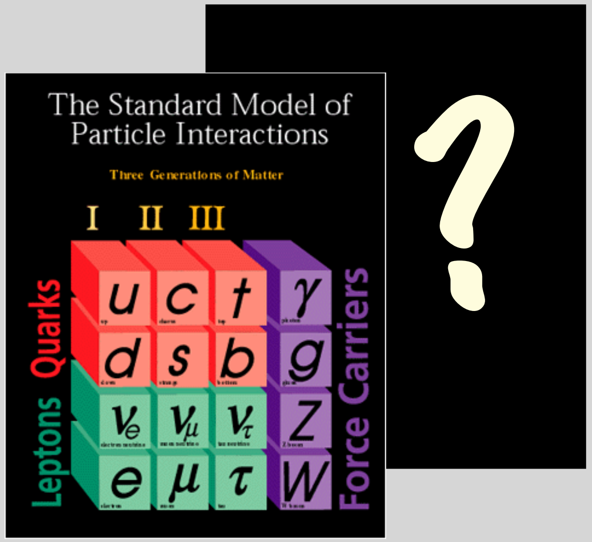
Broad vibrant program

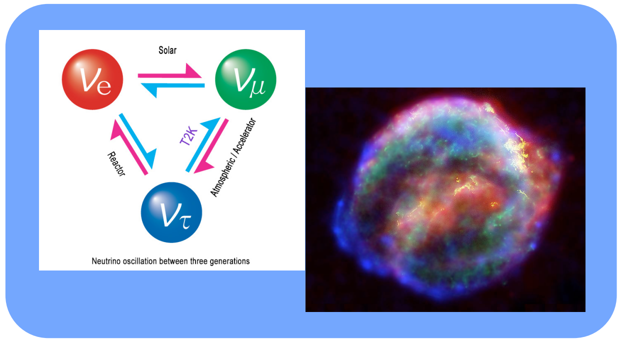
EDMs, 0νββ, KATRIN, …



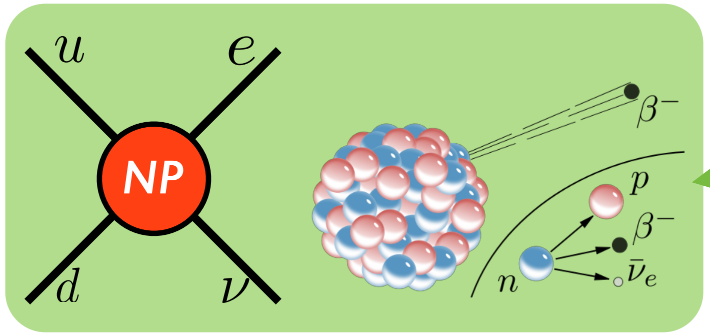
Broken symmetries
(CP, L, B) and
the Origin of Matter

New Standard Model



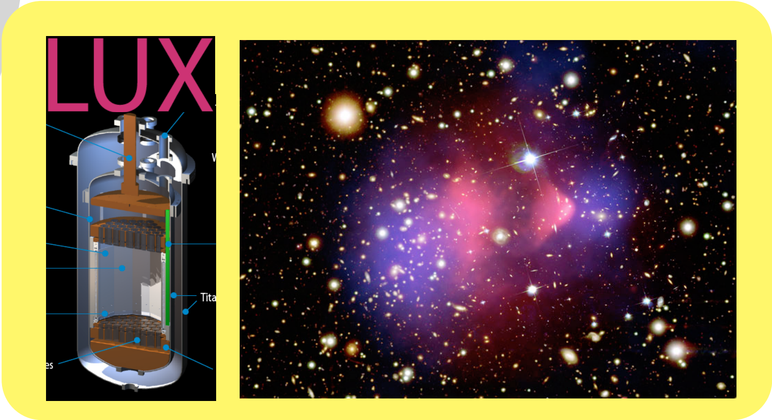


Nature and properties of
neutrinos, and their impact on
astrophysics and cosmology



Precision Measurements as probes
of New Particles and Interactions

β-decays, PVES, …



The Nuclear Physics of Dark Matter

Dark γ, Z, …

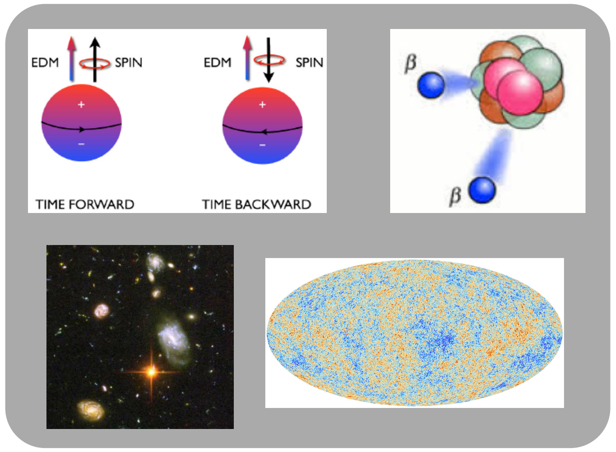
Nuclear physics and “The new SM”

Broad vibrant program

(in synergy with HEP)

EDMs, 0νββ, KATRIN, …

CPV ν oscillations (DUNE, …)



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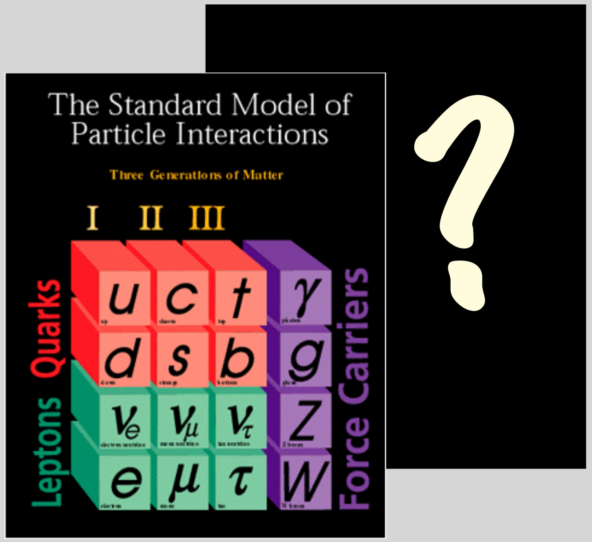

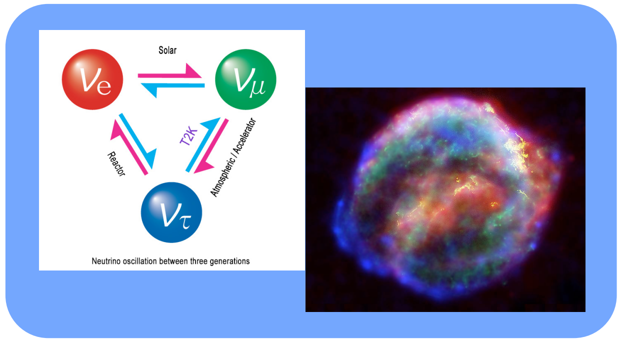

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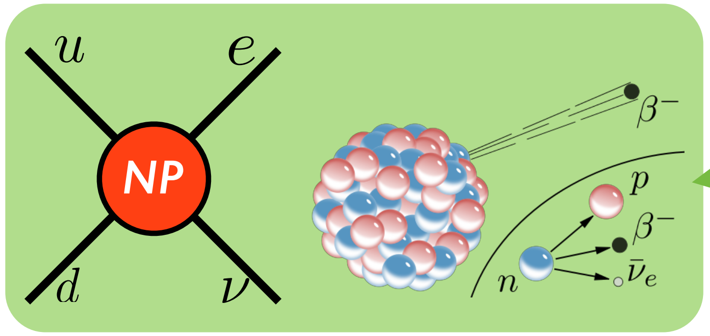

Precision Measurements as probes
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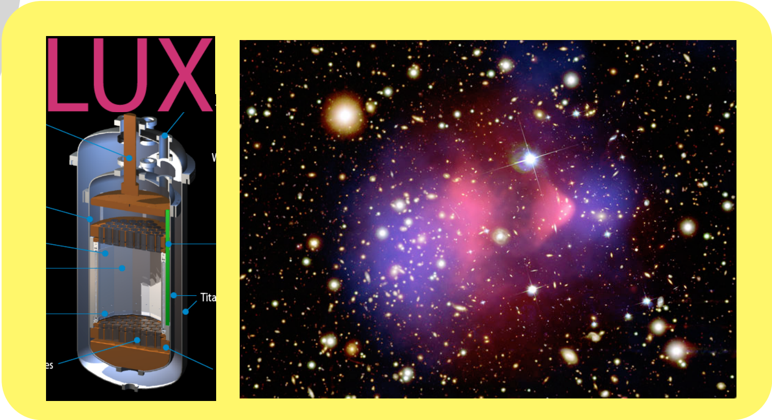
β-decays, PVES, … g-2

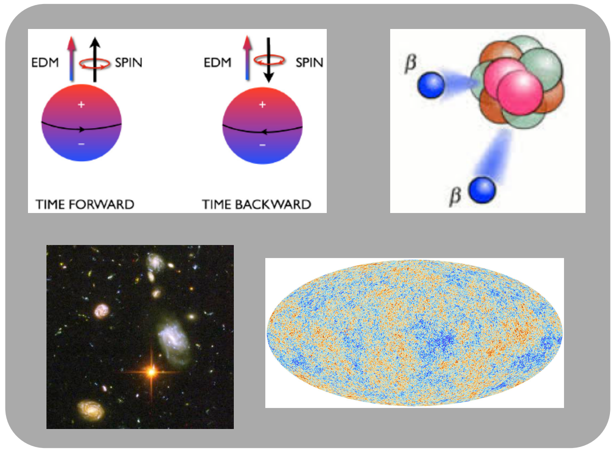


The Nuclear Physics of Dark Matter

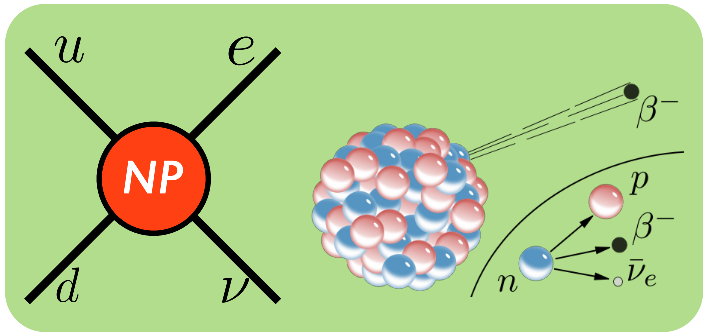
Dark γ, Z, …

Direct detection

Nuclear physics and “The new SM”



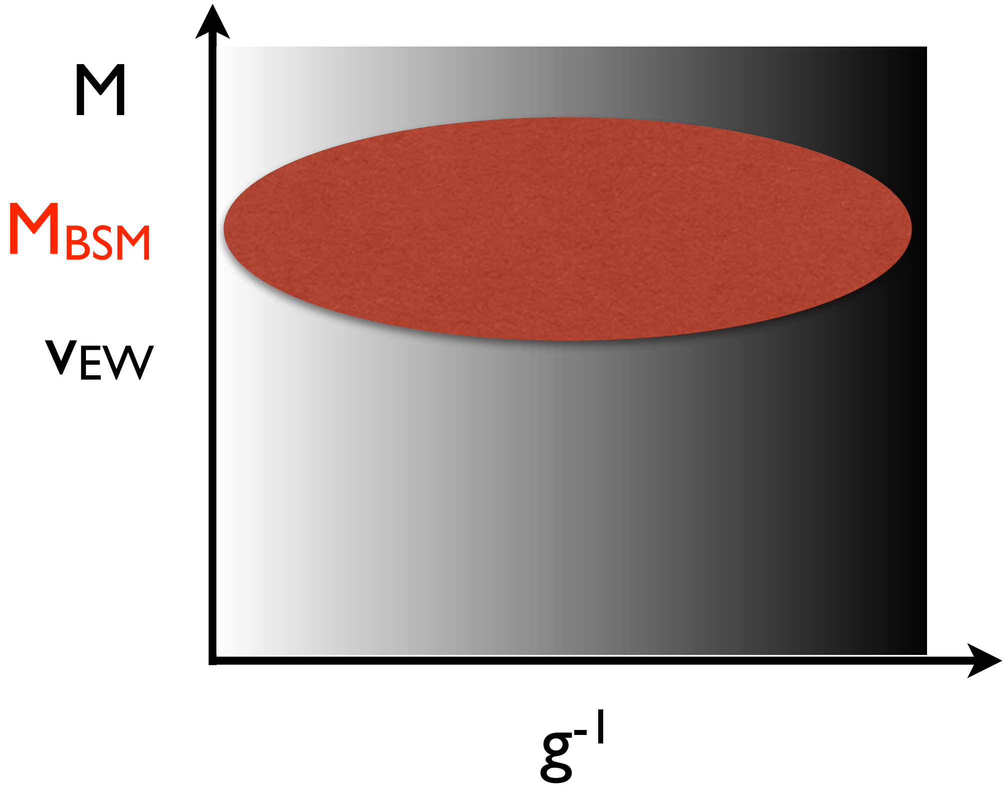
Broken symmetries (CP, L, B) and the Origin of Matter



Precision Measurements as probes of New Particles and Interactions

Most topics will be covered in great detail at the KITP conference on “Symmetry Tests in Nuclei and Atoms” next week

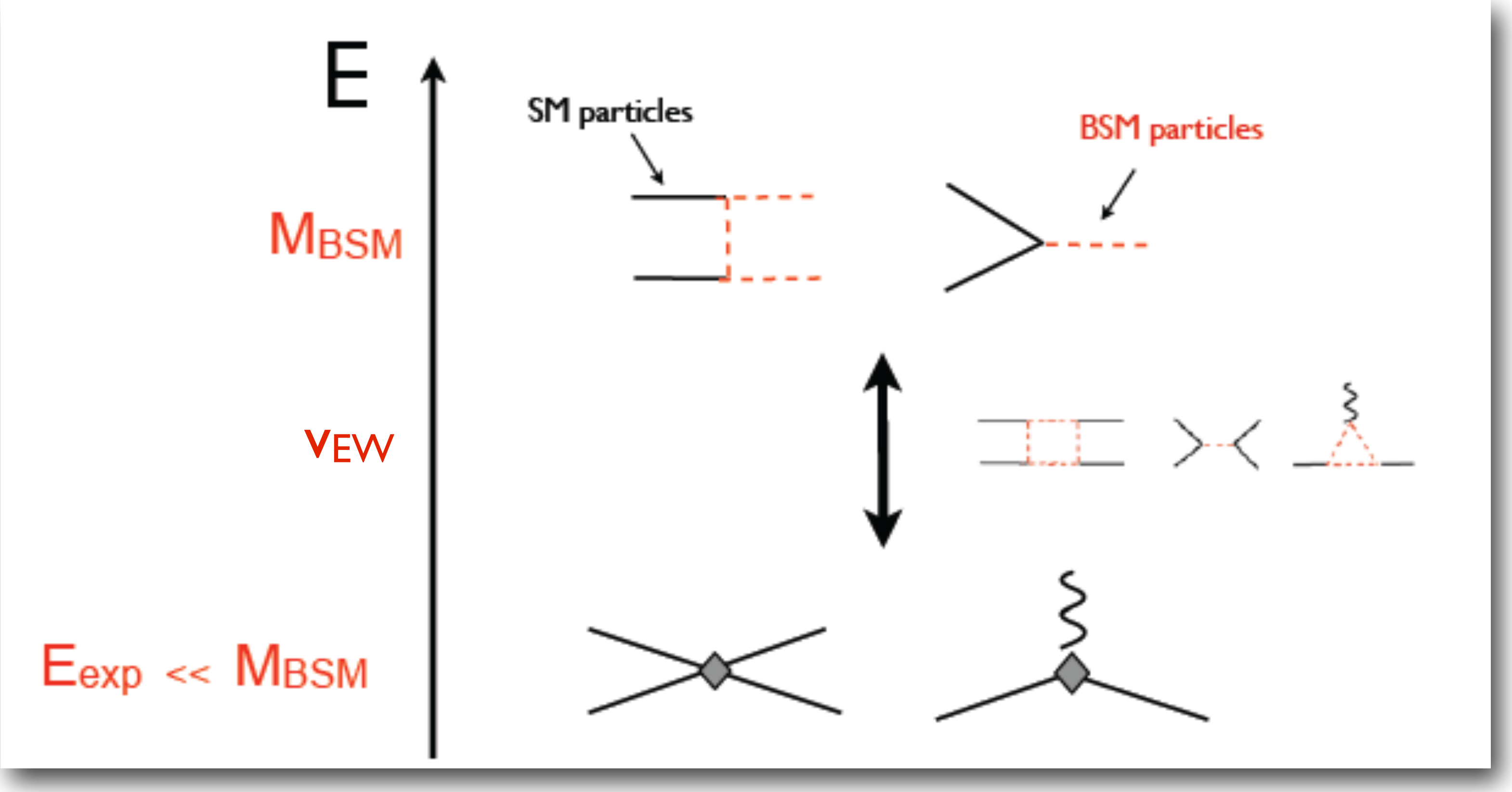
Toady I will discuss selected probes of “heavy” new physics ($M_{BSM} > v_{EW}$): will use EFT framework



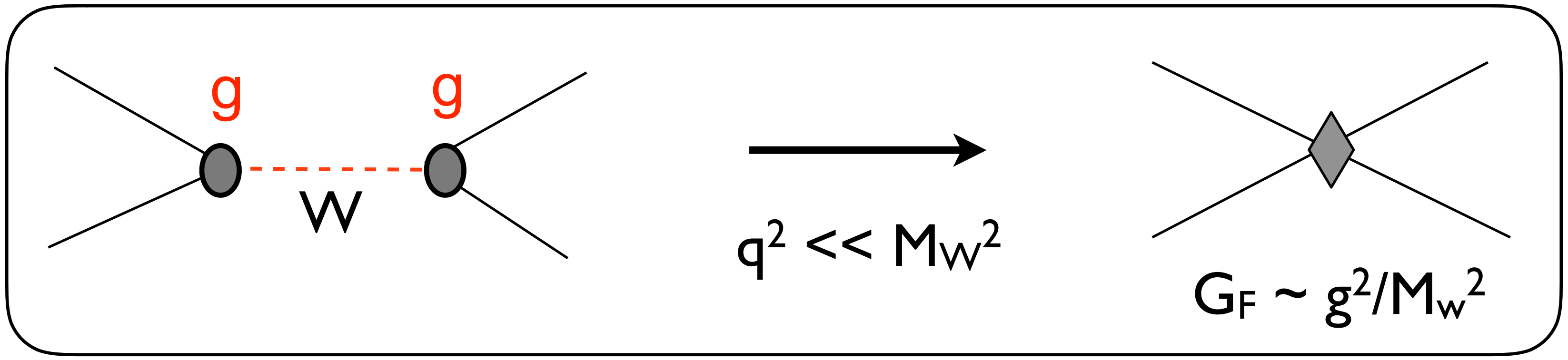
Tutorial: EFT approach to new physics & Low energy landscape

The low-energy footprints of $\mathcal{L}_{BSM}$

- At energy $E_{exp} << M_{BSM}$, new particles can be “integrated out”
- Generate new local operators with coefficients ~ $g^k/(M_{BSM})^n$



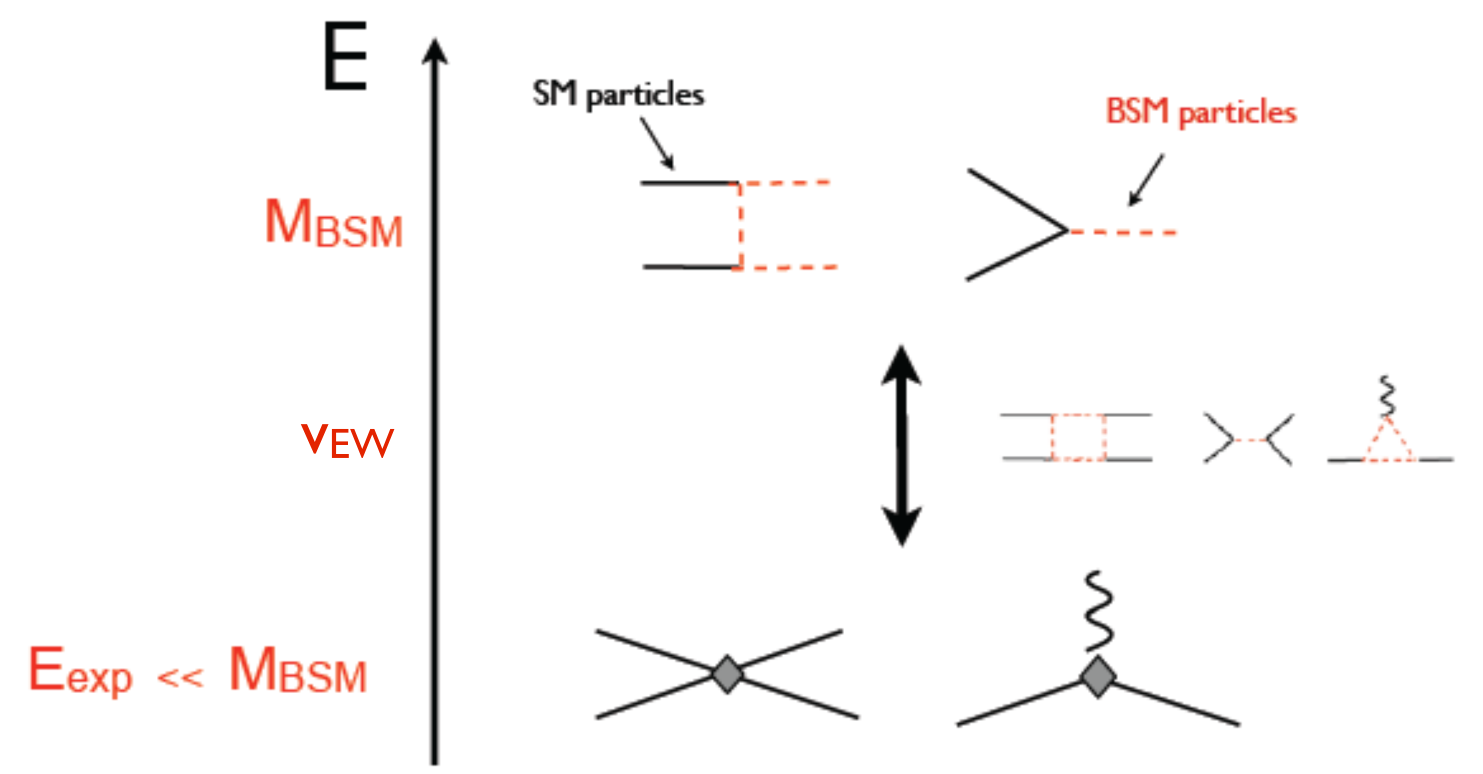
Familiar example:



Effective Field Theory emerges as a natural framework to analyze low-E implications of classes of BSM scenarios *and* inform model building

EFT framework

- Assume mass gap $M_{BSM} > G_F^{-1/2} \sim v_{EW}$
- Degrees of freedom: SM fields (+ possibly ν_R)
- Symmetries: SM gauge group; no flavor, CP, B, L



- EFT expansion in E/M_{BSM}, M_W/M_{BSM} [$O_i^{(d)}$ built out of SM fields]

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

$[\Lambda \leftrightarrow M_{BSM}]$ $C_i\ [g_{\rm BSM},\ M_a/M_b]$

Guided tour of $\mathcal{L}_{\text{eff}}$

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

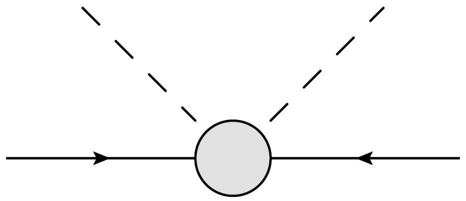
- Dim 5: only one operator

Weinberg 1979

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \quad \ell = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$\hat{O}_{\text{dim}=5} = \ell^T C \epsilon \varphi \, \varphi^T \epsilon \ell$$

$$C = i\gamma_2\gamma_0$$
$$\epsilon = i\sigma_2$$



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- Violates total lepton number $\ell \to e^{i\alpha}\ell \qquad e \to e^{i\alpha} e$
- Generates Majorana mass for L-handed neutrinos (after EWSB)

$$\frac{1}{\Lambda}\hat{O}_{\text{dim}=5} \xrightarrow{\langle\varphi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}} \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

- “See-saw”: $m_\nu \sim 1\,\text{eV} \;\to\; \Lambda \sim 10^{13}\,\text{GeV}$

Guided tour of $\mathcal{L}_{eff}$

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- Dim 5: only one operator

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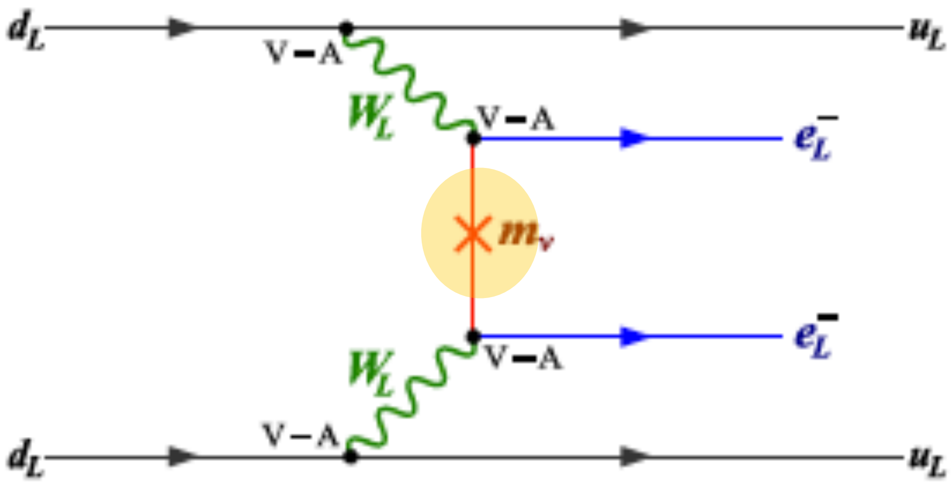
$$\hat{O}_{\rm dim=5} = \ell^T C \epsilon \varphi \, \varphi^T \epsilon \ell$$

- Mediates 0νββ, with $A \propto (m_\nu)_{ee}$



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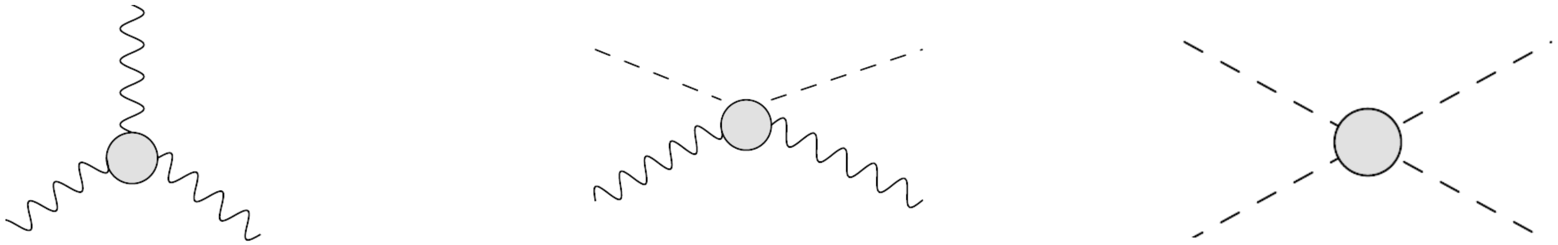
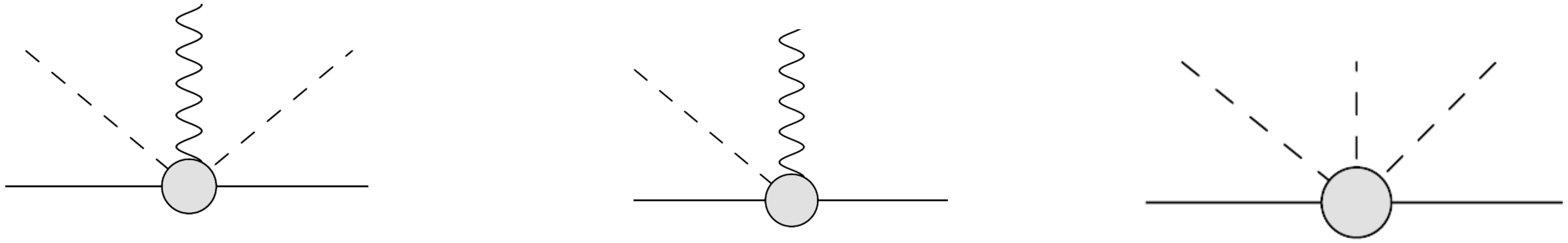
- Dim 6: affect *many* processes (59 structures not including flavor)

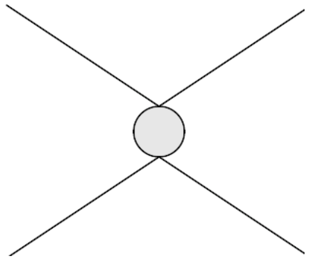
No fermions



Two fermions



Four fermions



Guided tour of $\mathcal{L}_{eff}$

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

- Dim 6: affect *many* processes
  - B violation
  - Gauge and Higgs boson couplings
  - CPV, LFV, qFCNC, ...
  - g-2, Charged Currents, Neutral Currents, ...

Weinberg 1979
Wilczek-Zee1979
Buchmuller-Wyler 1986, ...
Grzadkowski-Iskrzynksi-
Misiak-Rosiek (2010)

- EFT used beyond tree-level: one-loop anomalous dimensions known

Alonso, Jenkins, Manohar, Trott 2013

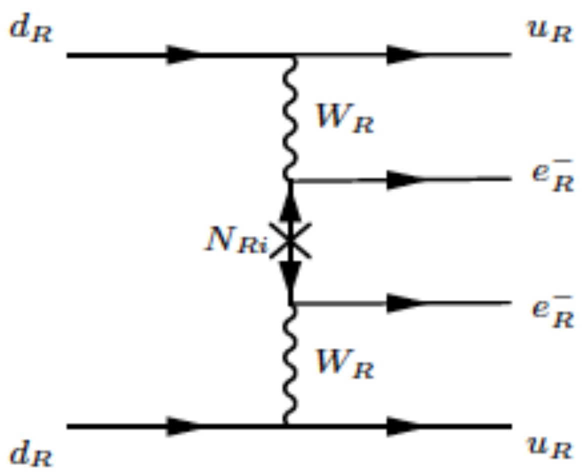
Guided tour of $\mathcal{L}_{eff}$

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

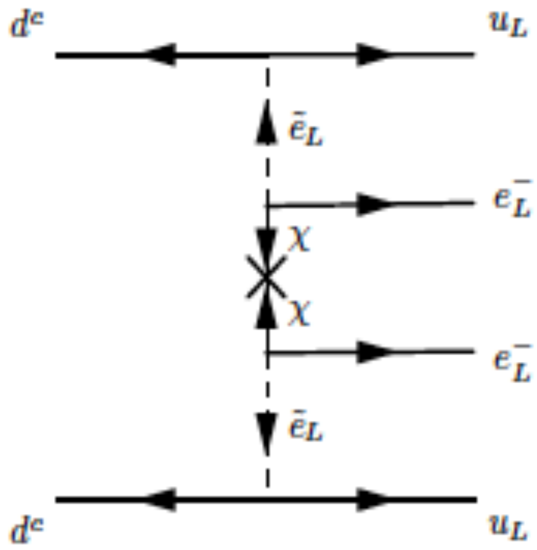
- Dim 9: ΔB=2 six-quark operators mediating n-nbar oscillations (see talk by S. Syritsyn); ΔL=2 operators contributing to 0νββ

$$\boxed{\frac{1}{\Lambda^5} \; \bar{q}q \, \bar{q}q \, \overline{e^c} e}$$

Prezeau, Ramsey-Musolf, Vogel 2003
Hirsch et al 2014
Graesser 2016



See talk by Evan Berkowitz

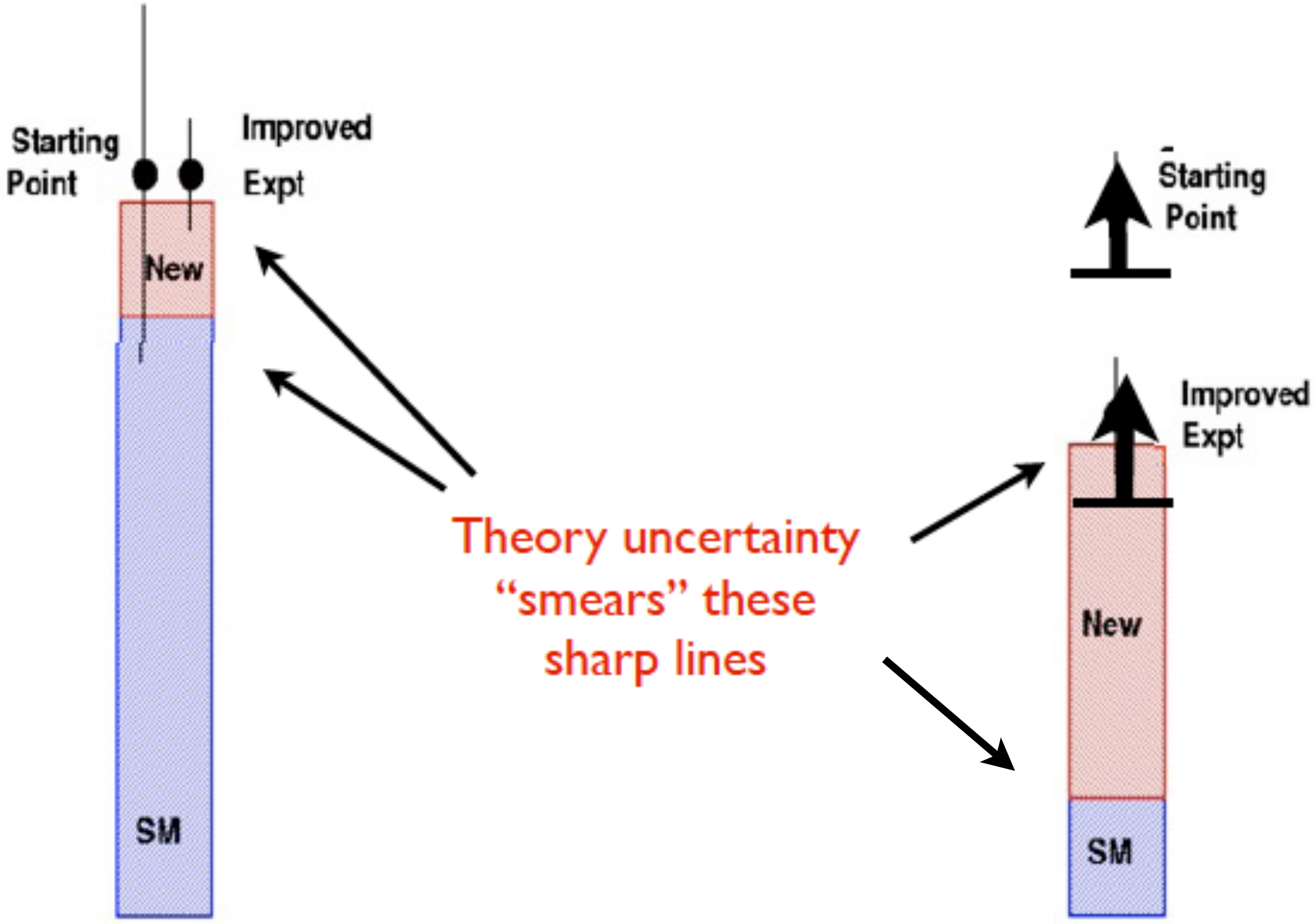


Two classes of probes

- Comment #1: $O_i^{(d)}$ can be roughly divided in two classes

(i) Those that give corrections to SM "allowed" processes: probe them with precision measurements (muon g-2, β-decays, Q_W, ...)

(ii) Those that violate (approximate) SM symmetries: mediate rare/forbidden processes (qFCNC, LFV, LNV, BNV, EDMs)



Theory uncertainty "smears" these sharp lines

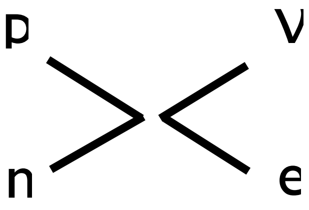
Figure copyright: David Mack

Discovering and diagnosing

- Comment #2: each UV model generates its own pattern of operators & couplings → different signatures in low-E experiments

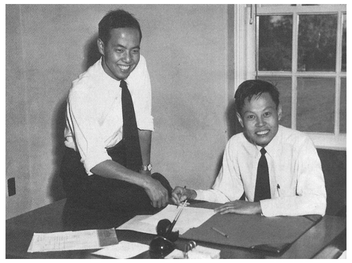
Therefore, low-E measurements can both discover BSM effects and discriminate among BSM scenarios (need more probes)

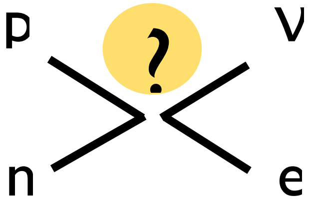
Fermi, 1934



Current-current,
parity conserving

Lee and Yang, 1956





Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

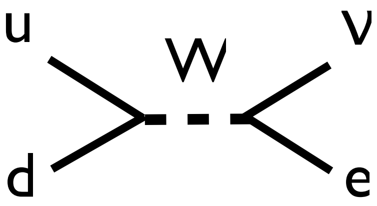
Feynman & Gell-Mann,
1958
Marshak & Sudarshan

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

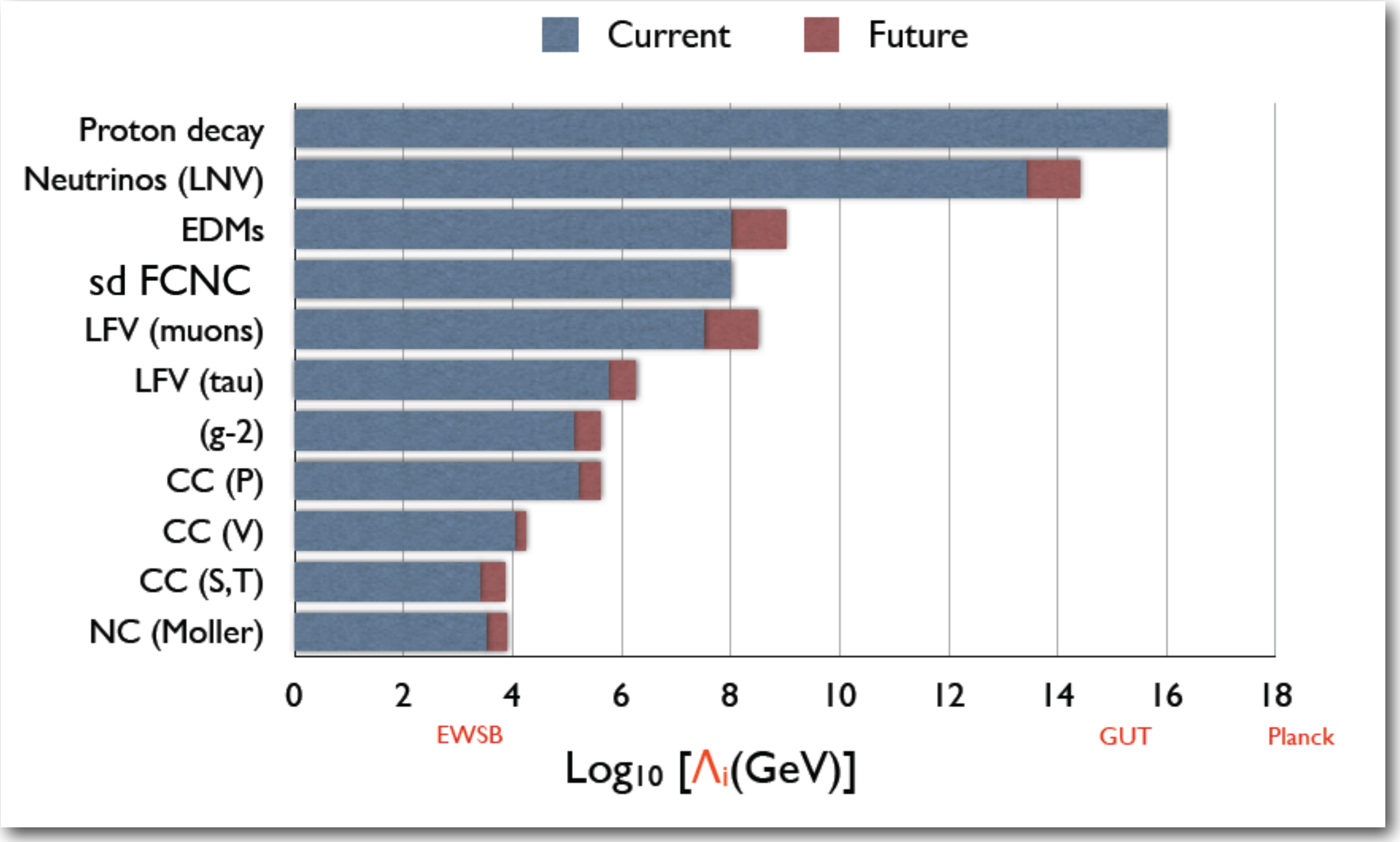
Physics reach at a glance

This equation at work

$$\boxed{\delta O_{\rm BSM}(\Lambda) \lesssim (O_{\rm exp} - O_{\rm SM})}$$

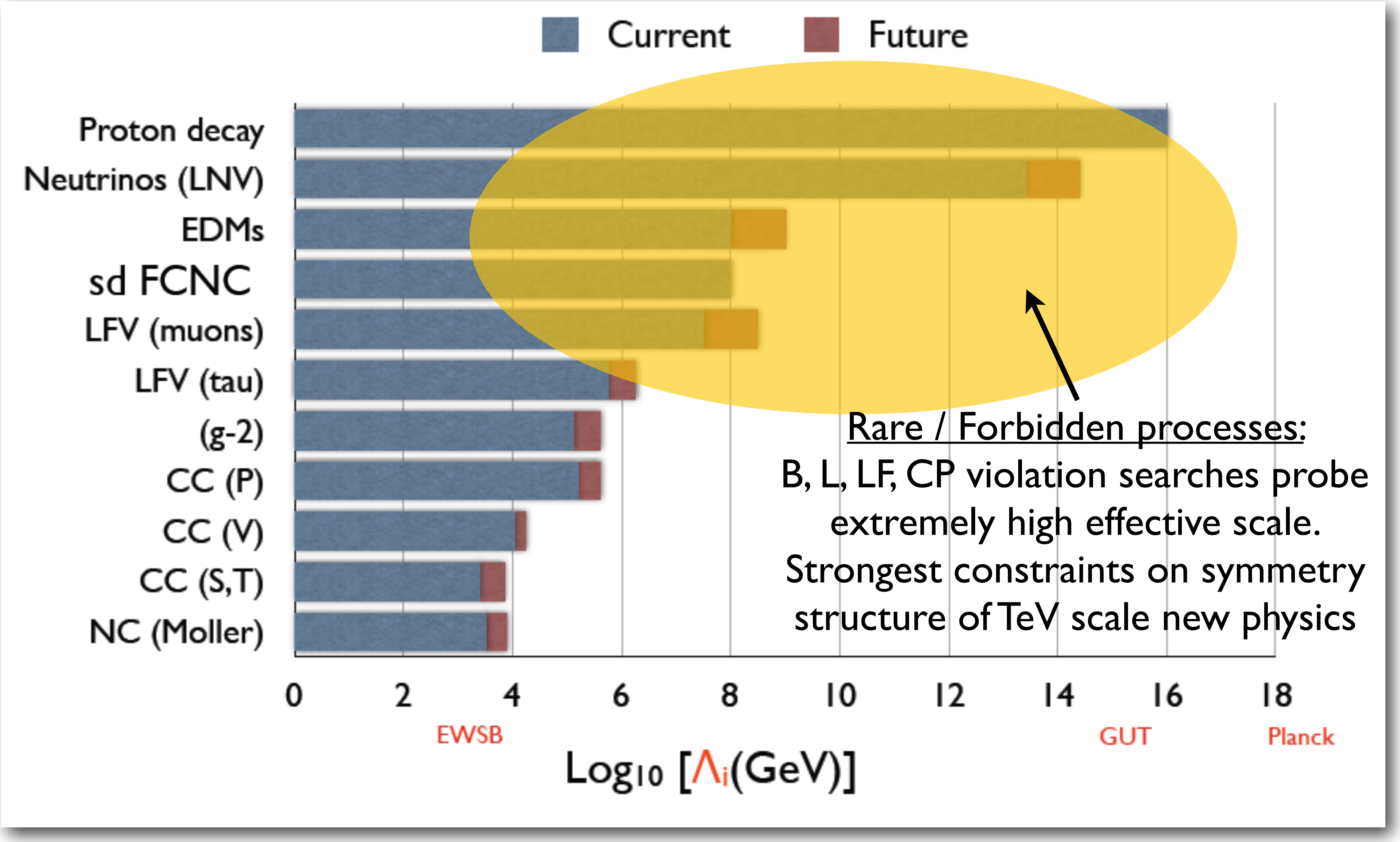
(for any observable *O*, $\delta O_{\rm BSM} \sim (v/\Lambda)^n$ $n=2,4,..$)

Physics reach at a glance



- Caveat: horizontal axis is $\Lambda/C^{(5)}$, $\Lambda/[C_i^{(6)}]^{1/2}$, ...
- So beware of couplings, loop factors, approximate symmetries

Physics reach at a glance



<u>Rare / Forbidden processes:</u>
B, L, LF, CP violation searches probe extremely high effective scale. Strongest constraints on symmetry structure of TeV scale new physics

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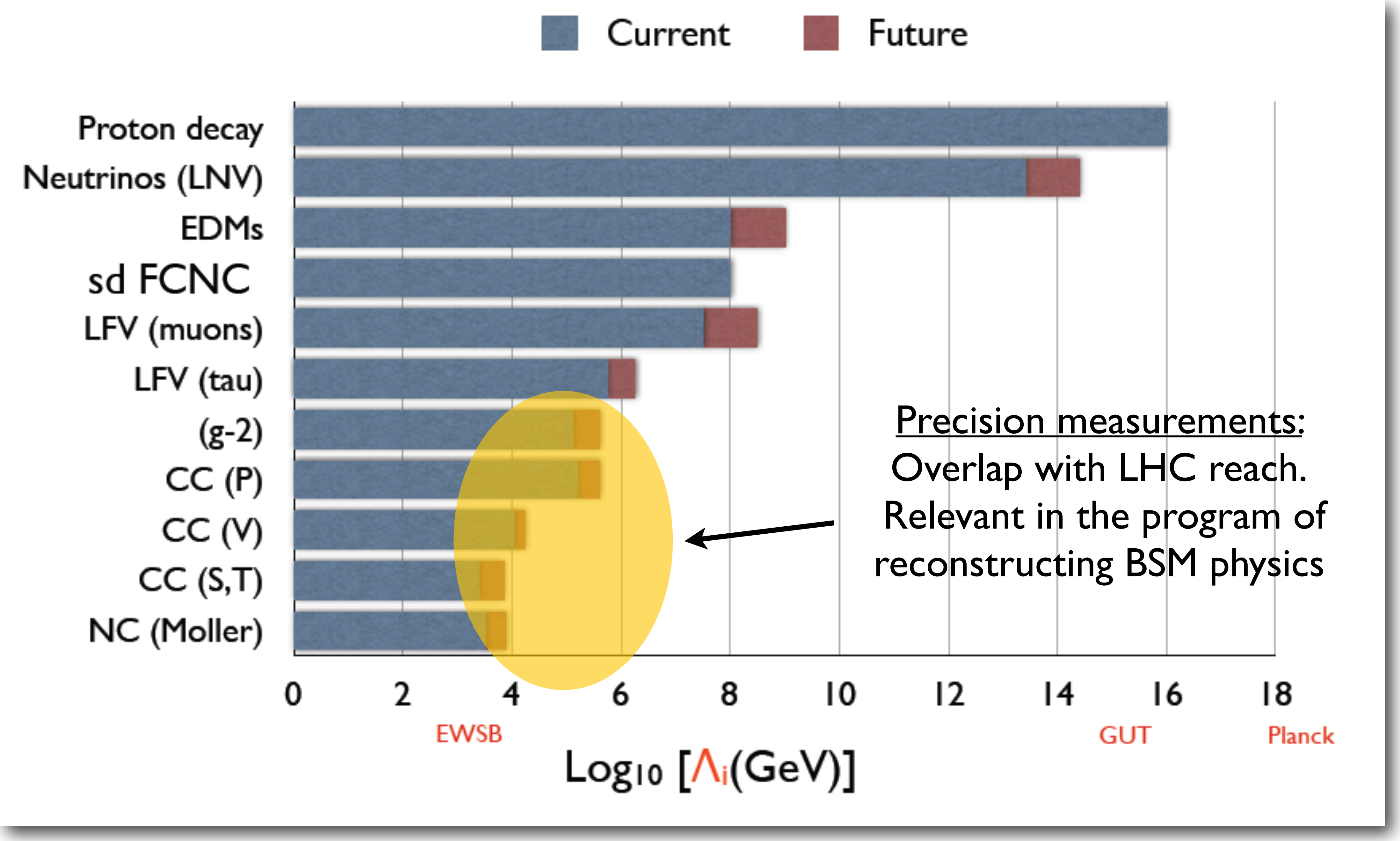
Physics reach at a glance



Precision measurements:
Overlap with LHC reach.
Relevant in the program of
reconstructing BSM physics

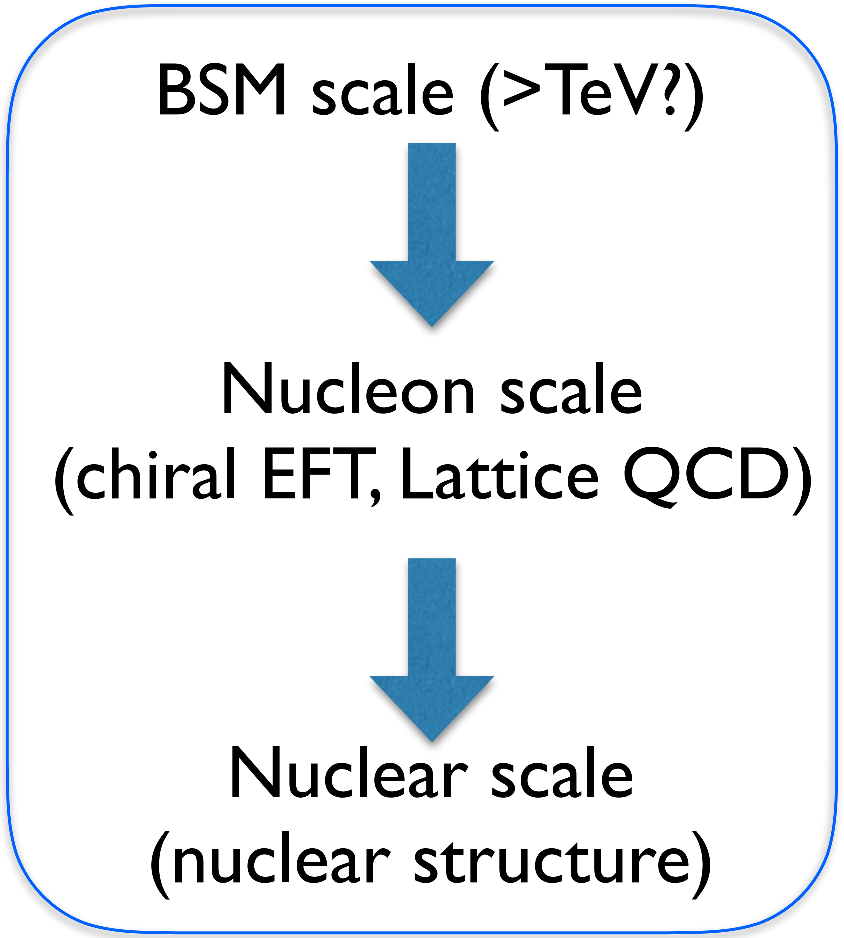
- Caveat: horizontal axis is $\Lambda/C^{(5)}, \ \Lambda/[C_i^{(6)}]^{1/2}$, ...
- So beware of couplings, loop factors, approximate symmetries

Promising but challenging

- Overarching challenge: interpreting experimental results (positive or null!) in terms of new physics models requires

1. Connecting physics at different scales: RGE (Note: steps below UV matching scale apply to all models)

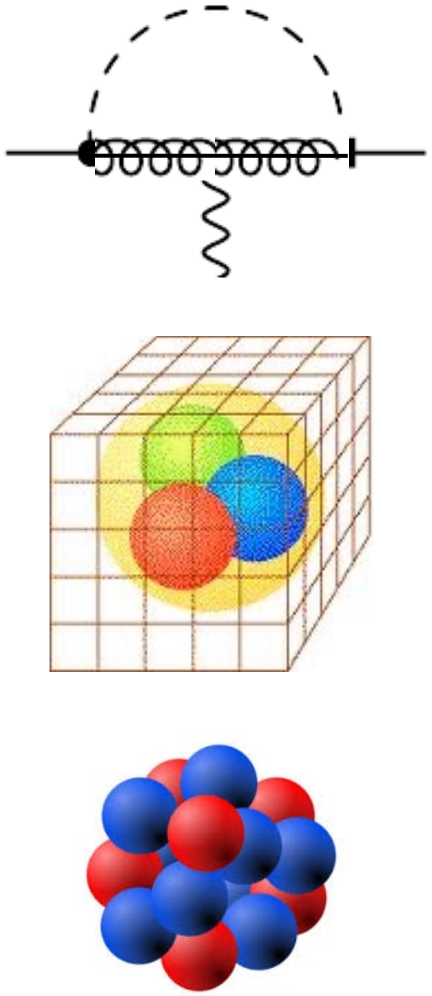
2. Computing hadronic & nuclear matrix elements with sufficient precision (depending on probe)



BSM scale (>TeV?)

Nucleon scale
(chiral EFT, Lattice QCD)

Nuclear scale
(nuclear structure)



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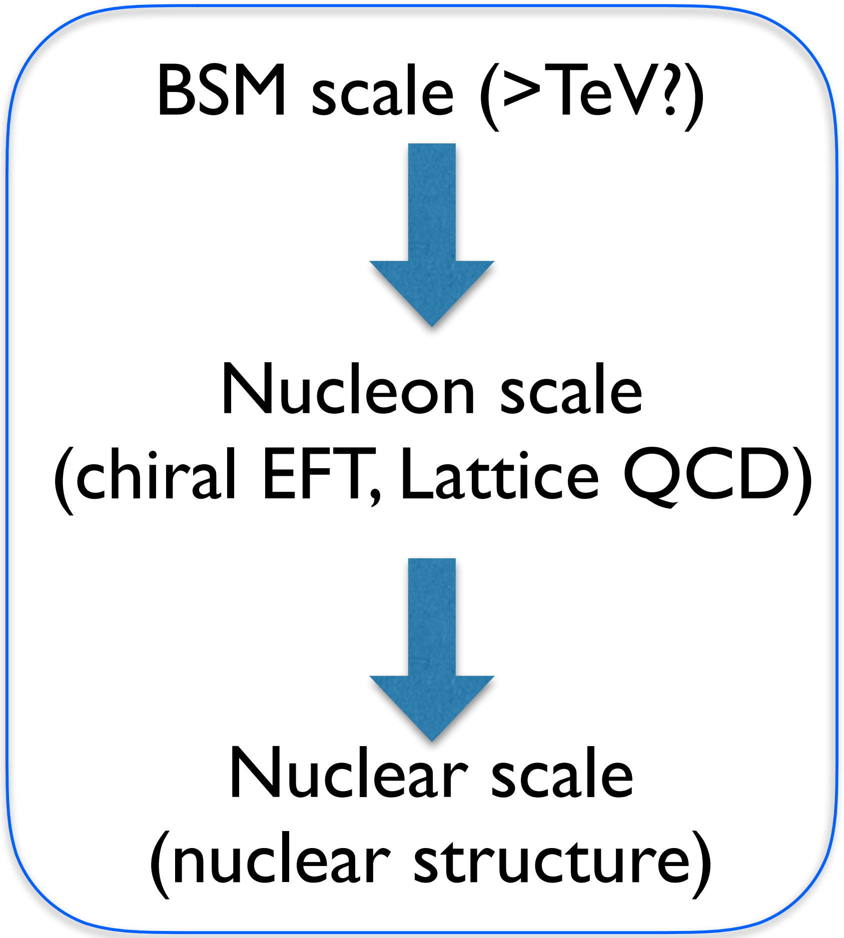

BSM scale (>TeV?)

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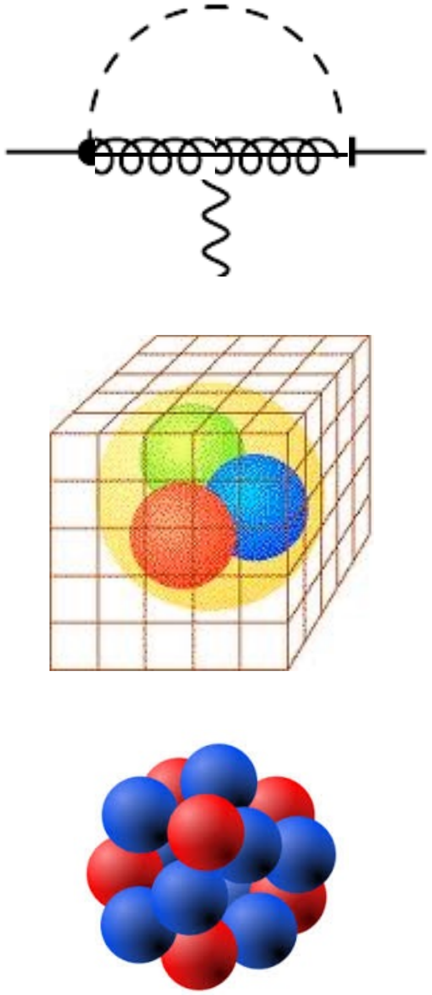
(chiral EFT, Lattice QCD)

Nuclear scale
(nuclear structure)



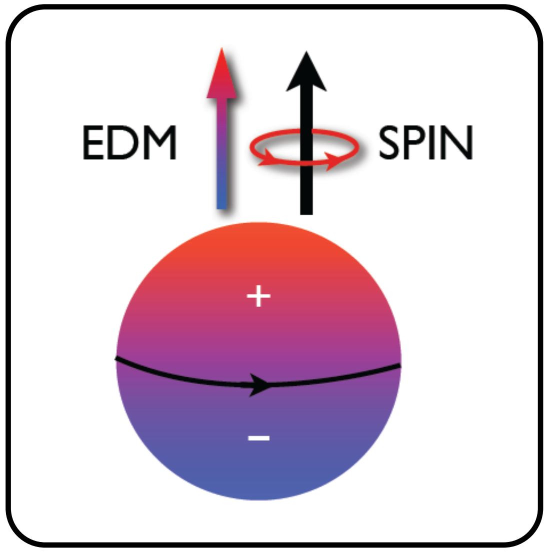
- Next, illustrate these points with two examples:
EDMs (symmetry test) and β decays (precision measurement)

Example #1:
Electric Dipole Moments

EDMs and symmetry breaking

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

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



P and T violation:

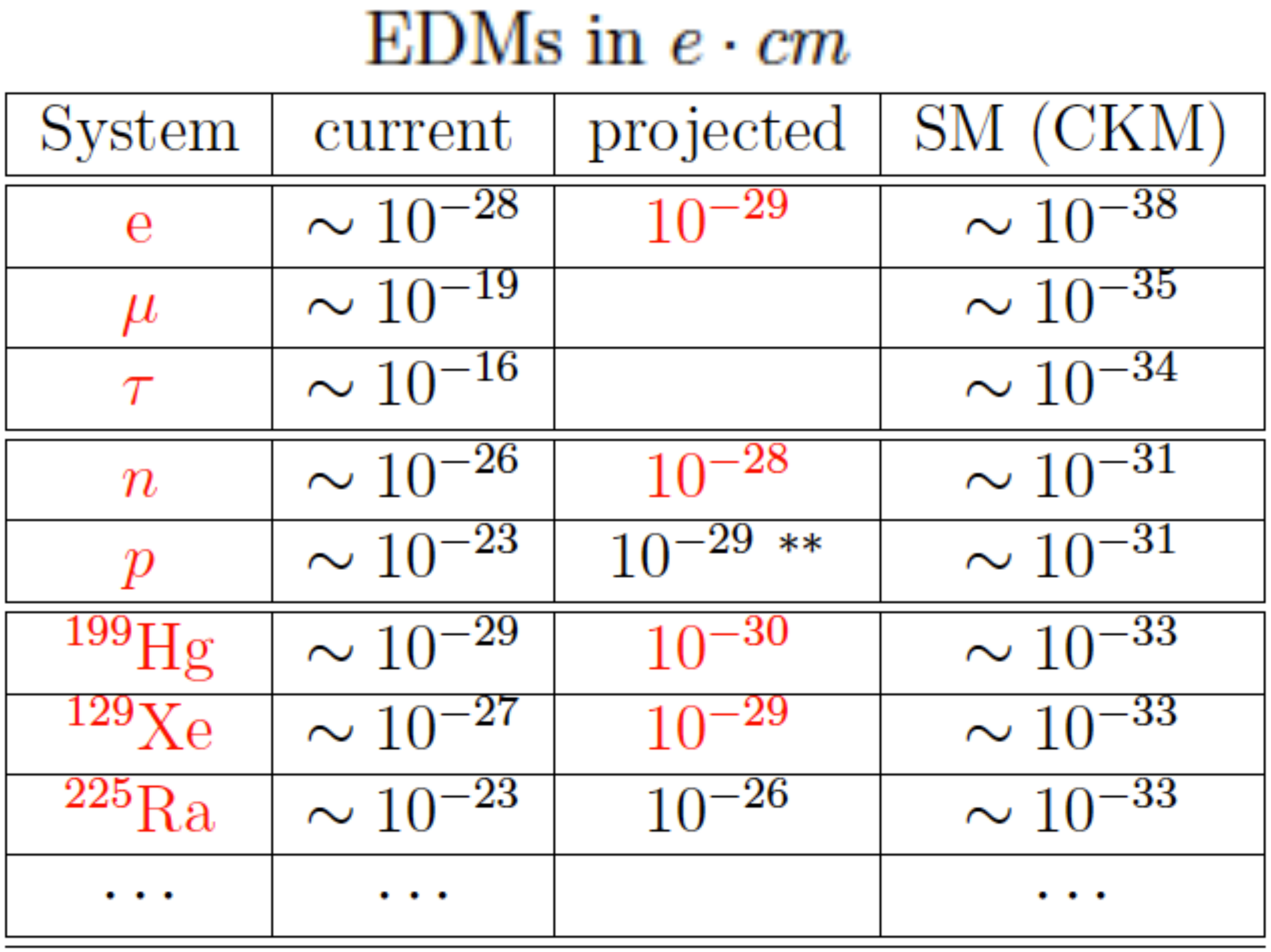
$\vec{d} \propto \vec{J}$

- Ongoing and planned searches in several systems

★ n, p
★ Light nuclei: d, t, h
★ Atoms: diamagnetic (^{129}Xe, ^{199}Hg, ^{225}Ra, ...);
paramagnetic (^{205}Tl, ...)
★ Molecules: YbF, ThO, ...

For more details see talk by Andreas Wirzba on Thursday

EDMs and new physics

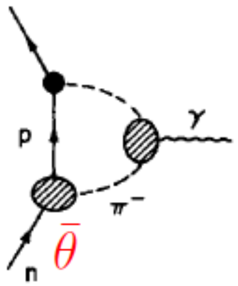


EDMs in $e \cdot cm$

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}	$\sim 10^{-33}$
$\cdots$	$\cdots$		$\cdots$

- Essentially free of SM "background" (CKM)*

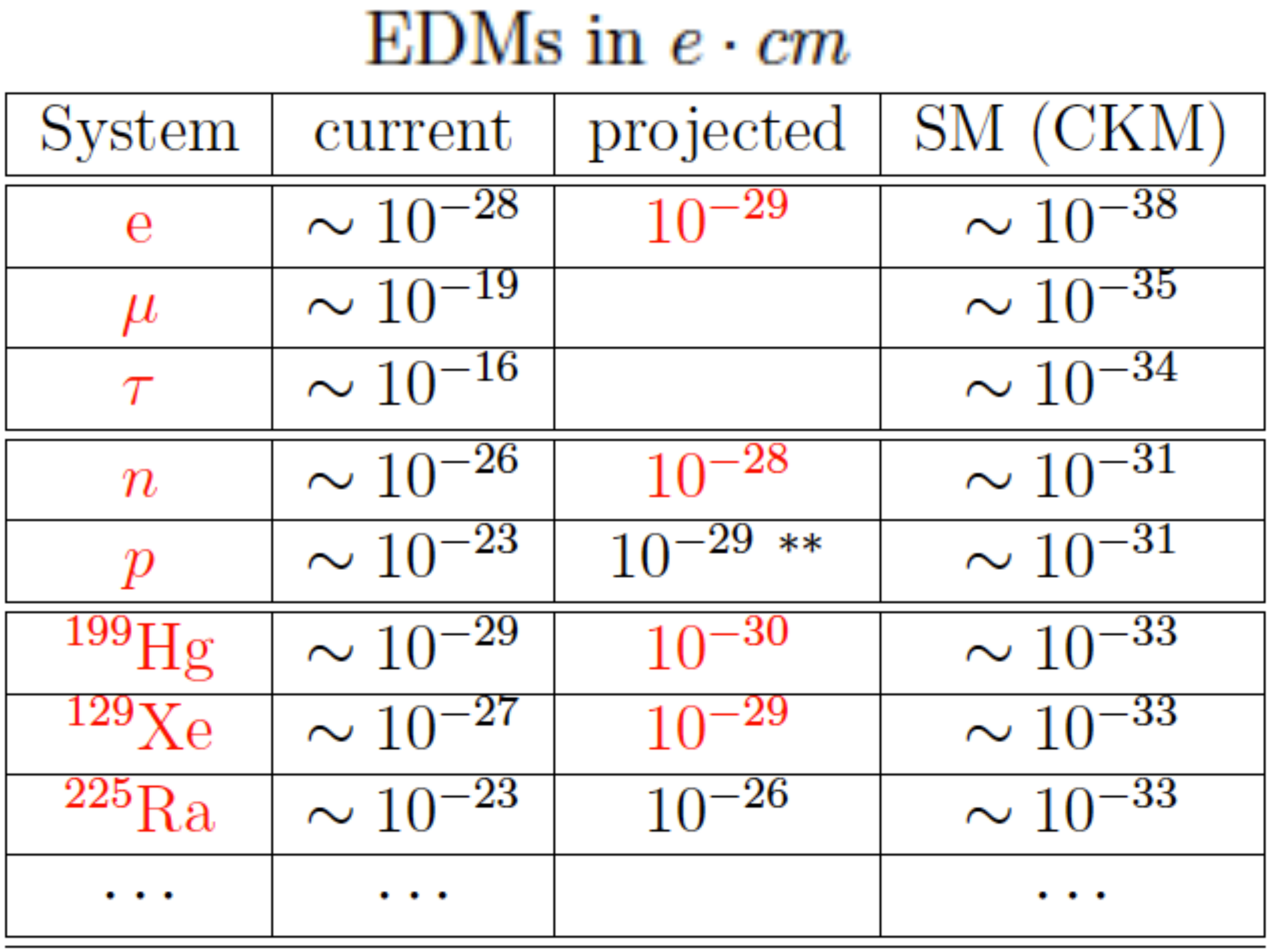
* Observation would signal new physics or a tiny QCD θ-term (< 10^{-9}). Multiple measurements can disentangle the two effects



$$d_n \sim \frac{m_*}{\Lambda^2_{\rm had}}\, e\,\bar{\theta} \sim 10^{-17}\,\bar{\theta}\, e{\rm cm}$$

Crewther, Di Vecchia, Veneziano, Witten 1979

EDMs and new physics



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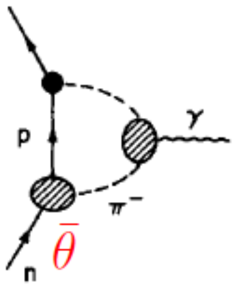
^{225}Ra	$\sim 10^{-23}$	10^{-26}	$\sim 10^{-33}$
$\cdots$	$\cdots$		$\cdots$

- Essentially free of SM "background" (CKM)*
- Probe very high-scales

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

- Probe ingredient for bayrogenesis (CPV in SM is insufficient)

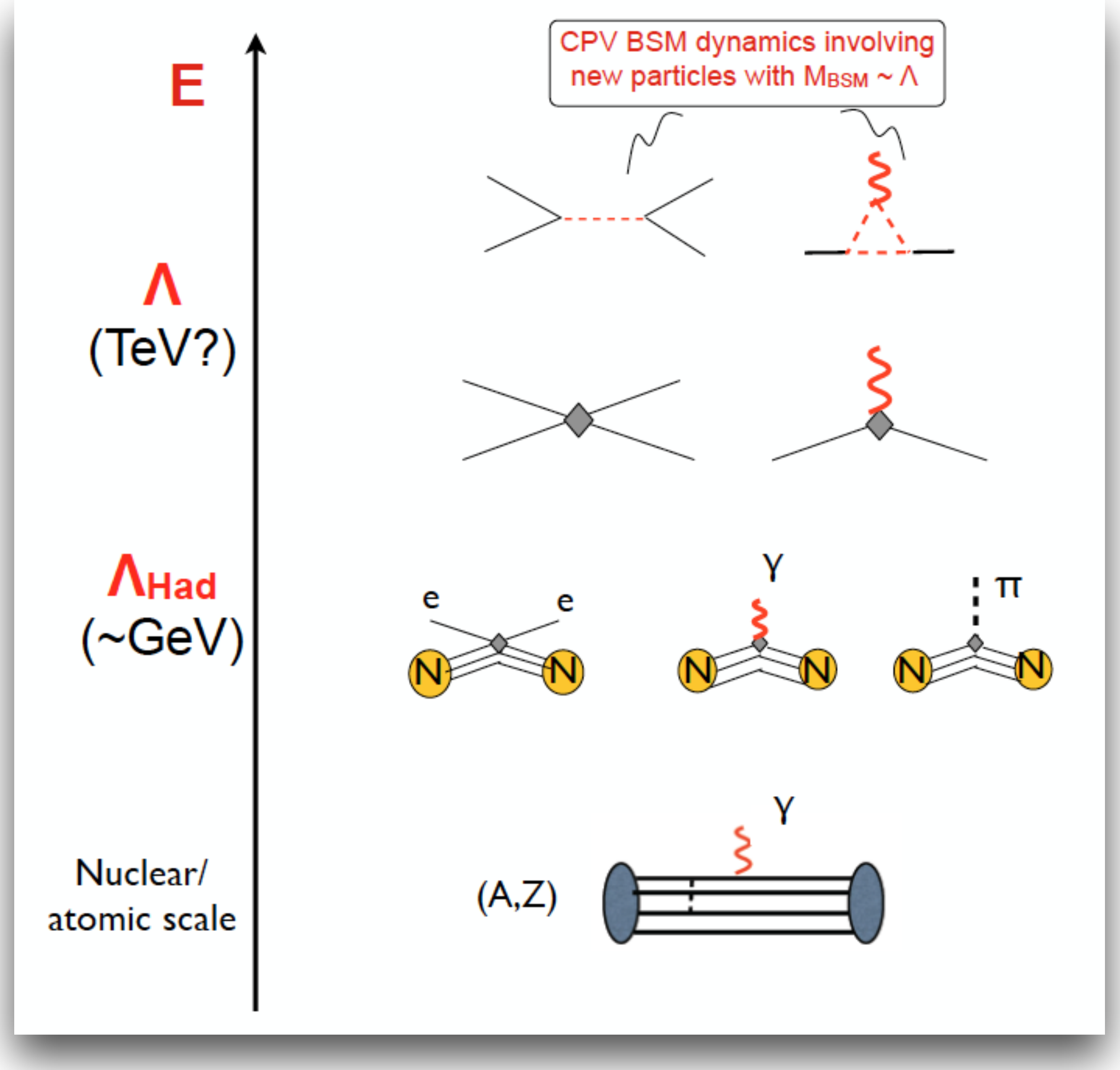
* Observation would signal new physics or a tiny QCD θ-term (< 10^{-9}). Multiple measurements can disentangle the two effects



$$d_n \sim \frac{m_*}{\Lambda^2_{\rm had}}\, e\, \bar{\theta} \sim 10^{-17}\, \bar{\theta}\, e{\rm cm}$$

Crewther, Di Vecchia, Veneziano, Witten 1979

Connecting EDMs to BSM CPV



- Multi-scale problem: need RG evolution of effective couplings & hadronic / nuclear / molecular calculations of matrix elements
- I discuss nucleon EDM — for nuclear EDMs see talk by Andreas Wirzba on Thursday

CPV at the quark-gluon level

- CPV at hadronic scale, induced by leading 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

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

J · E **J · E**

Gluon chromo-EDM (Weinberg operator)

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

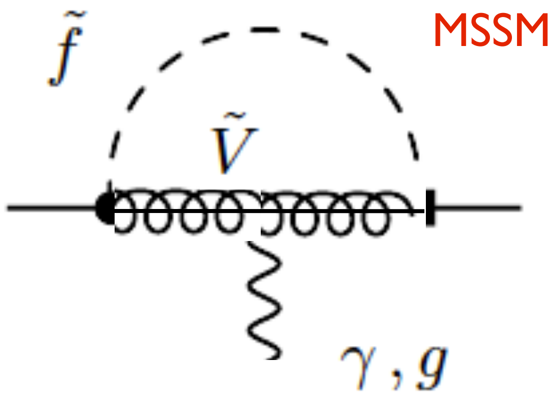
Semileptonic and 4-quark

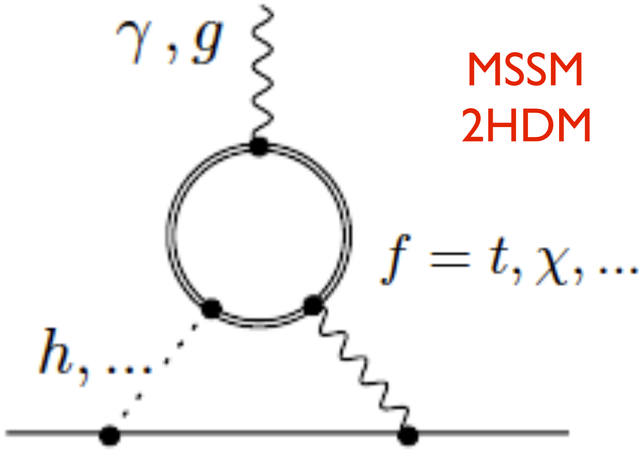
CPV at the quark-gluon level

- CPV at hadronic scale, induced by leading dim=6 operators

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

- Generated by a variety of BSM scenarios





→

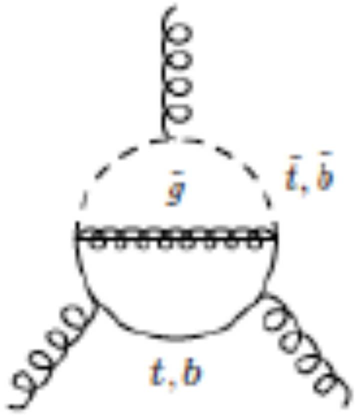
Quark EDM and
chromo-EDM

CPV at the quark-gluon level

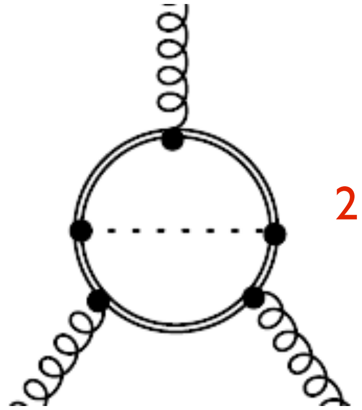
- CPV at hadronic scale, induced by leading dim=6 operators

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

- Generated by a variety of BSM scenarios



MSSM



2HDM

→

Weinberg operator

CPV at the quark-gluon level

- CPV at hadronic scale, induced by leading dim=6 operators

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

- Generated by a variety of BSM scenarios

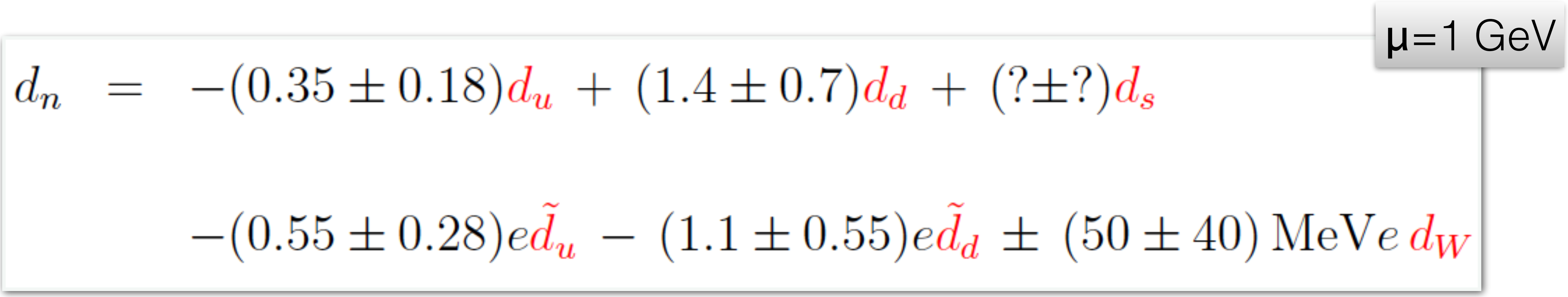
Operator mixing and threshold corrections →
EDM sensitivity to non-standard Higgs couplings (hVV, ...), heavy quark CPV, ...

CPV at the nucleon level

- CPV at hadronic scale, induced by leading dim=6 operators

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

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



μ=1 GeV

$$\begin{aligned} d_n \;&=\; -(0.35\pm0.18)d_u \;+\; (1.4\pm0.7)d_d \;+\; (?\pm?)d_s \\ &\quad -(0.55\pm0.28)e\tilde{d}_u \;-\; (1.1\pm0.55)e\tilde{d}_d \;\pm\; (50\pm40)\,\mathrm{MeV}\,e\,d_W \end{aligned}$$

Pospelov-Ritz hep-ph/0504231 and refs therein

- Here Lattice QCD can play a major role

First step: $d_N[d_q]$ from LQCD

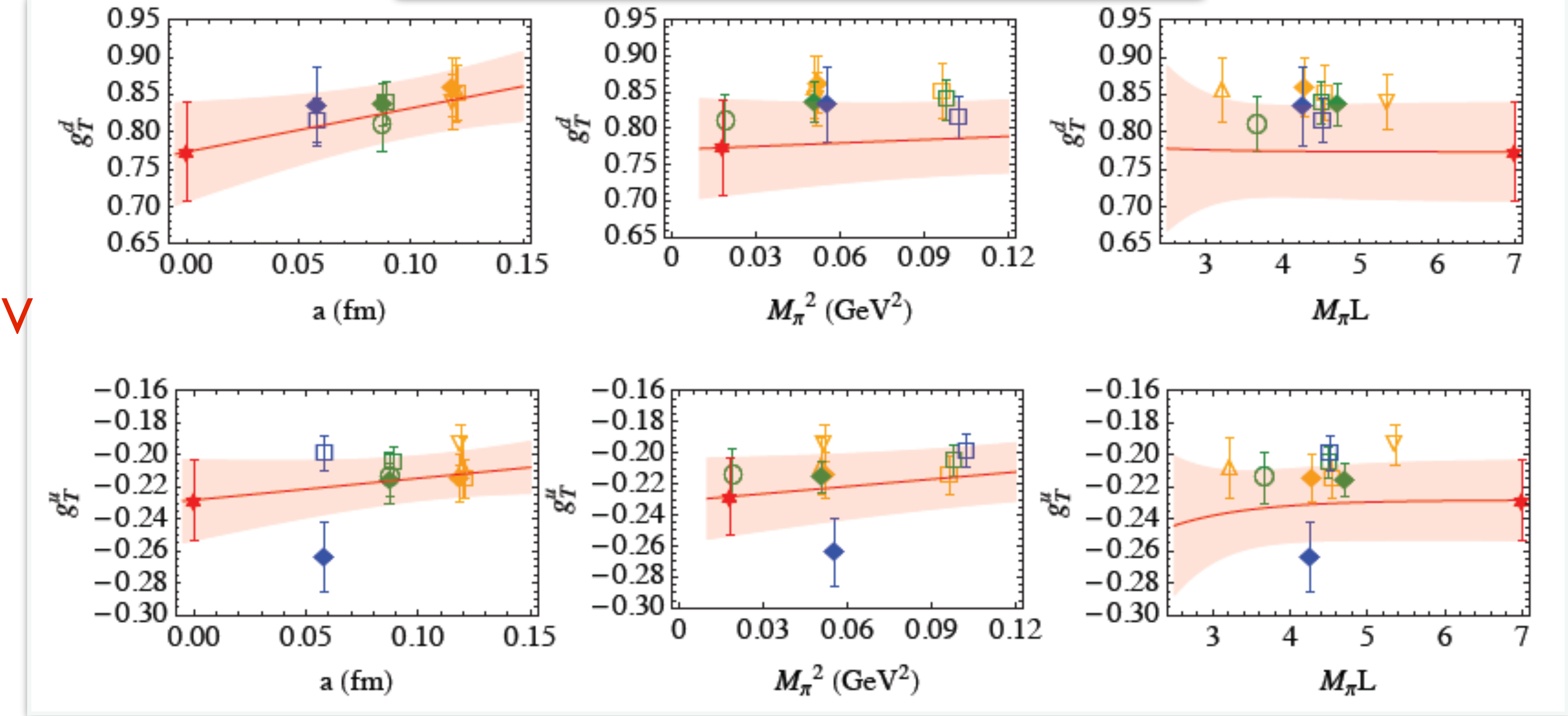
- Problem "factorizes": need tensor charge of the nucleon

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

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

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

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

First step: $d_N[d_q]$ from LQCD

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

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

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

- Improved matching using LQCD input

μ=1 GeV

$$\begin{aligned} d_n = & -(0.22 \pm 0.03) d_u + (0.74 \pm 0.07) d_d + (0.0077 \pm 0.01) d_s \\ & -(0.55 \pm 0.28) e\tilde{d}_u - (1.1 \pm 0.55) e\tilde{d}_d \pm (50 \pm 40) \,\mathrm{MeV}\, e \, d_W \end{aligned}$$

- Work in progress to compute $d_N[\tilde{d}_q]$ in LQCD

Bhattacharya, VC, Gupta, Mereghetti, Yoon, Phys. Rev. D92, 114026 [1502.07325],
Proceedings of Science LATTICE 2015 (2016) 238, [1601.02264]

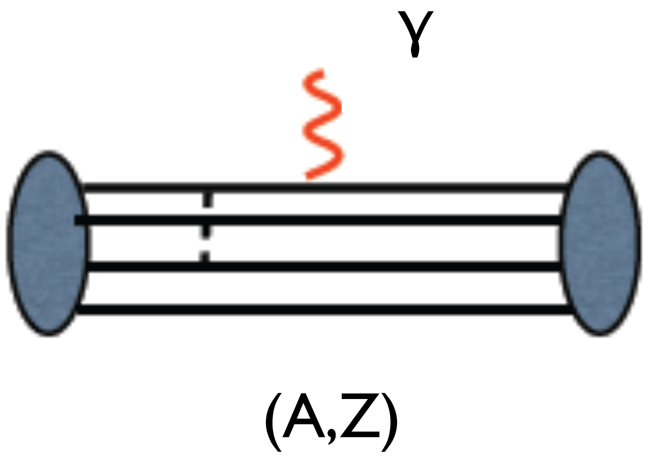
S. Syritsyn, LATTICE 2016

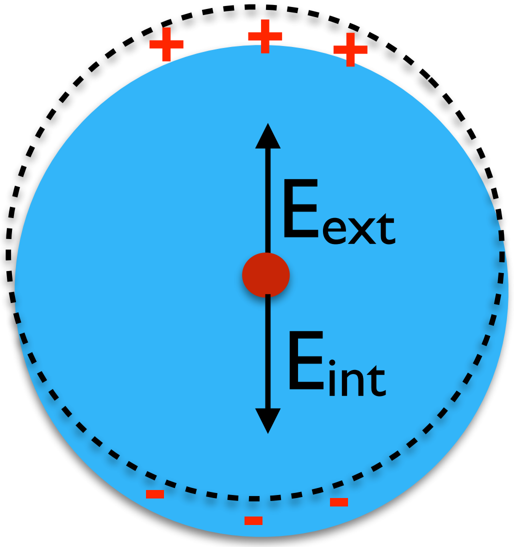
Beyond nucleon EDM

- Light ions (d,t,h): great progress with chiral EFT (EDMs in terms of d_N and πNN couplings)

Arizona-Groningen and Bonn-Julich groups: see 1505.06272 and 1412.5471

- Neutral atoms: need to work against Schiff's theorem
  - No atomic EDM due to d_e, d_{nucl} (charged constituents rearrange to screen the externally applied E_{ext})
  - Evaded by finite-size and relativistic effects

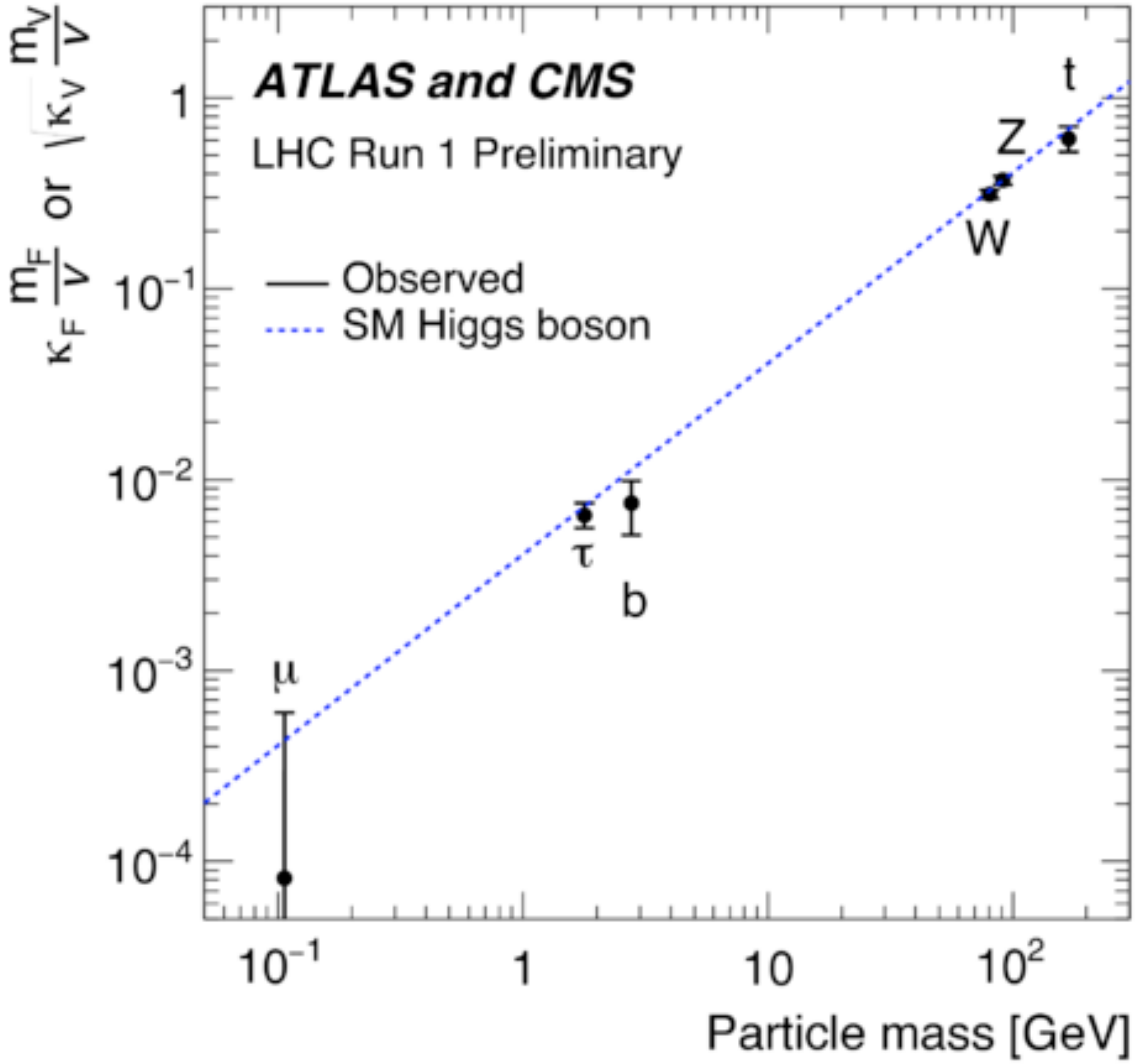




- Uncertainties: O(10%) in paramagnetic systems; O(few 100%) in diamagnetic systems

Impact on Higgs couplings

- So far, Higgs properties are compatible with SM expectations

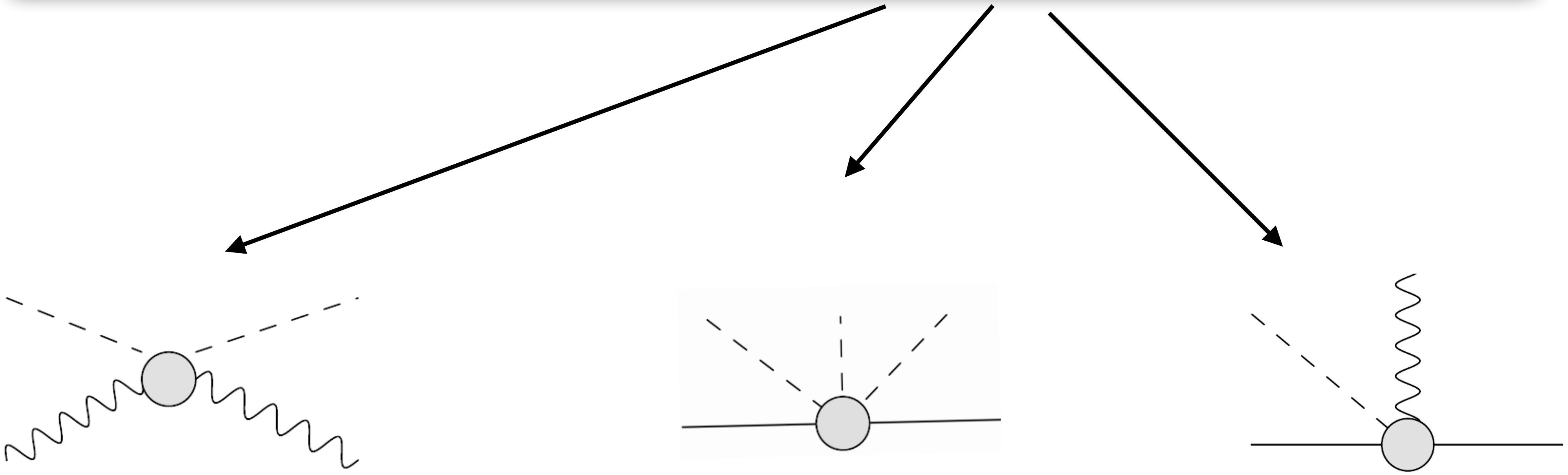


- Still room for deviations: is this the SM Higgs? Key question at LHC Run 2 & important goal for low energy experiments

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

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

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



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

H-q_L-q_R: scalar

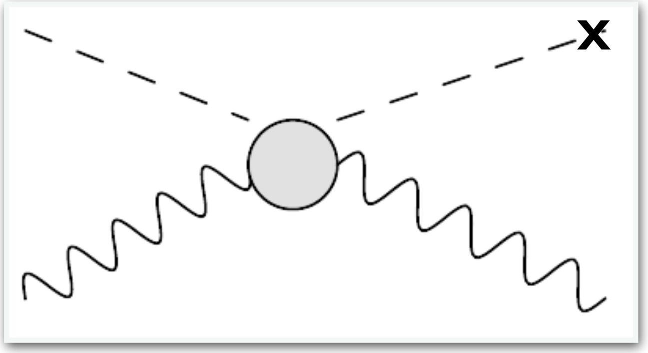
H-q_L-q_R-V: dipole

V = g, W^a, B

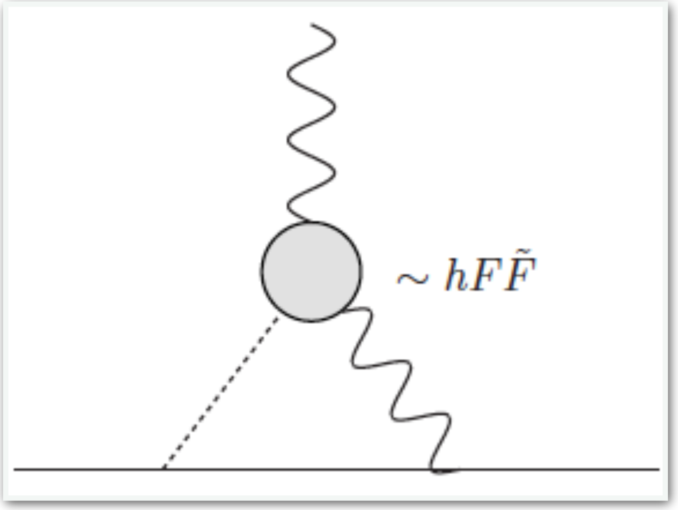
Higgs coupling to photons

- 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 $\Gamma(h\to\gamma\gamma)/\Gamma(h\to\gamma\gamma)_{SM} - 1 \approx 10^{-5}$

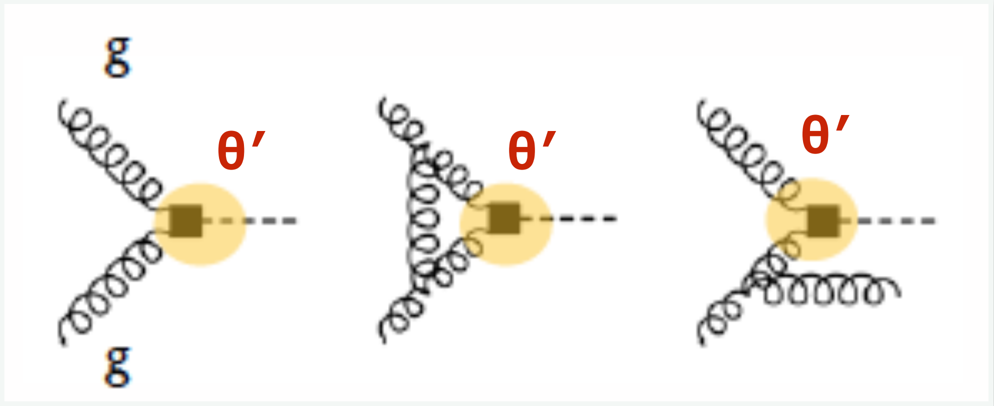
- Bound evaded by more elaborate model-building, involving for example (i) contribution to $d_e(\Lambda)$ that cancels effect of running; (ii) degenerate scalar sector (EFT not applicable)

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



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

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

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

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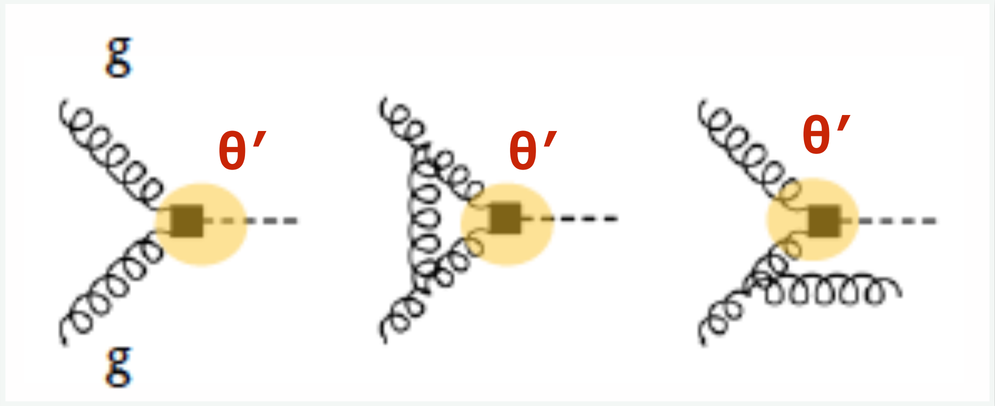
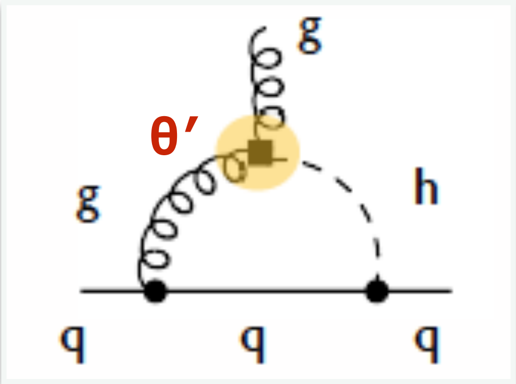


nEDM via quark chromo-EDM (→ qEDM and Weinberg)



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

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

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

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

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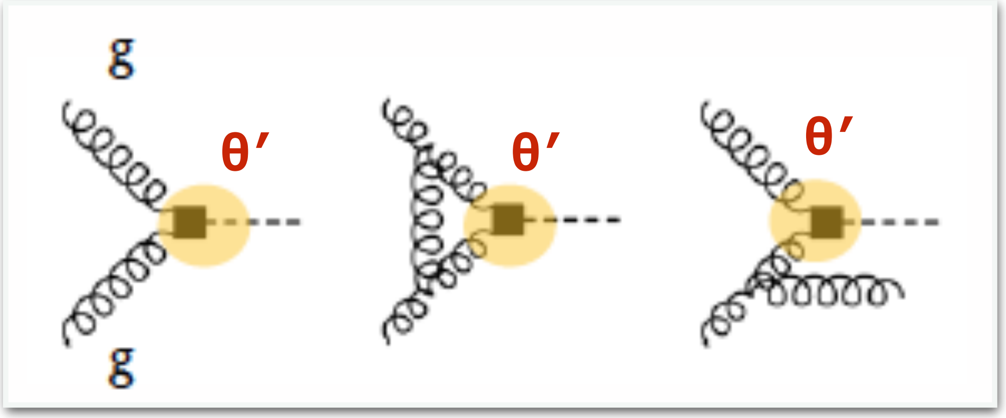

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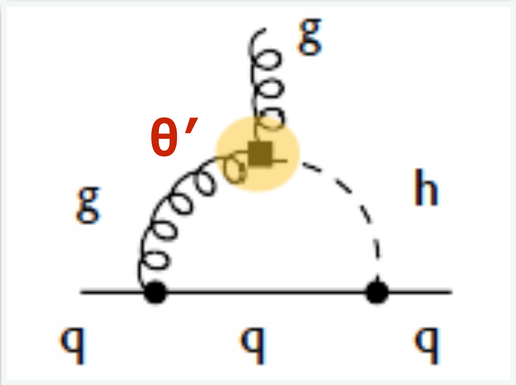

	d_n	d_{Hg}	d_n, d_{Hg} (comb)	LHC (CMS)
Central	0.06	0.04	0.04	0.27
Range	0.23	x	0.23	0.27

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

- 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
Range	0.23	x	0.23	0.27

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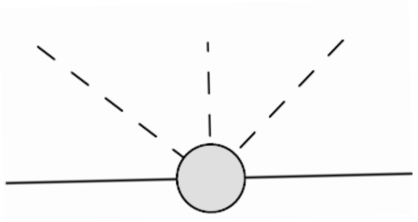
Y.-T. Chien,VC, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

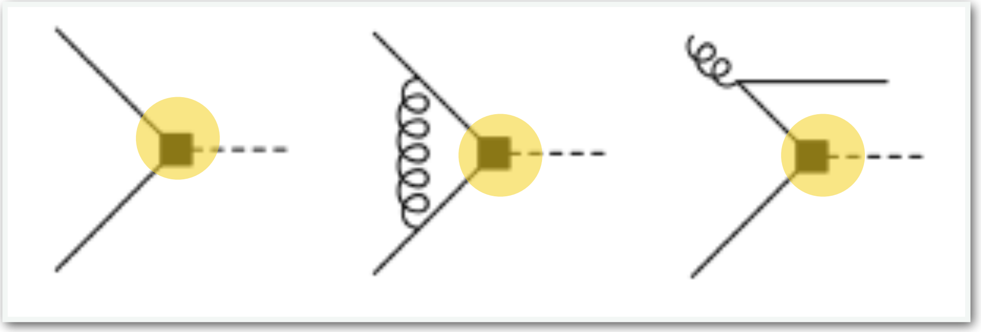
Yukawa couplings to quarks

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

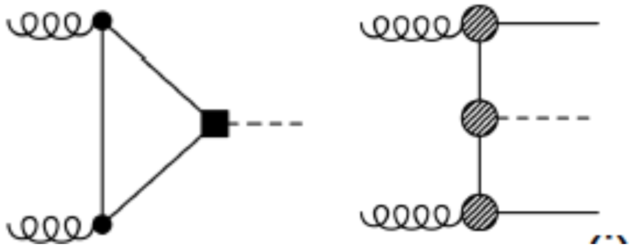
$$\boxed{\mathcal{L}_6^{CPV} \supset v^2 \mathrm{Im}\, Y'_q \, \bar{q} i \gamma_5 q \, h}$$



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

Yukawa couplings to quarks

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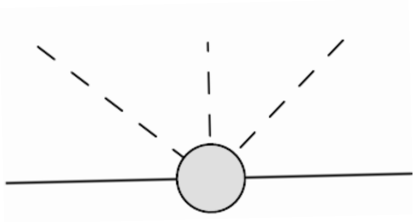
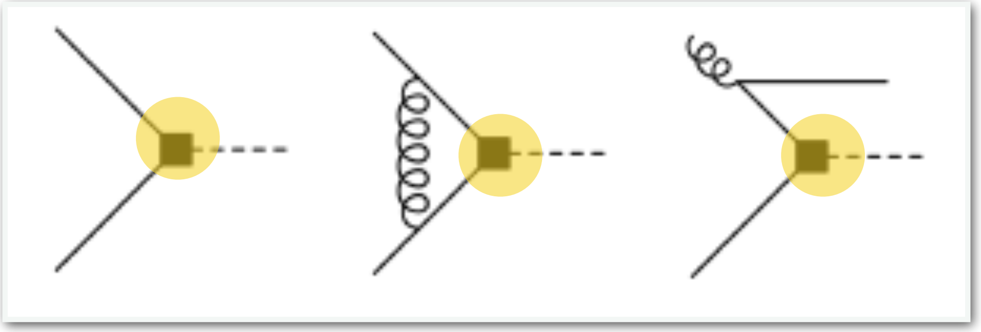
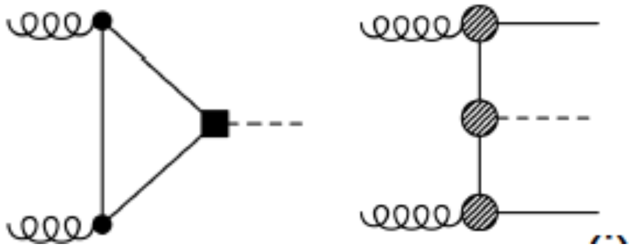


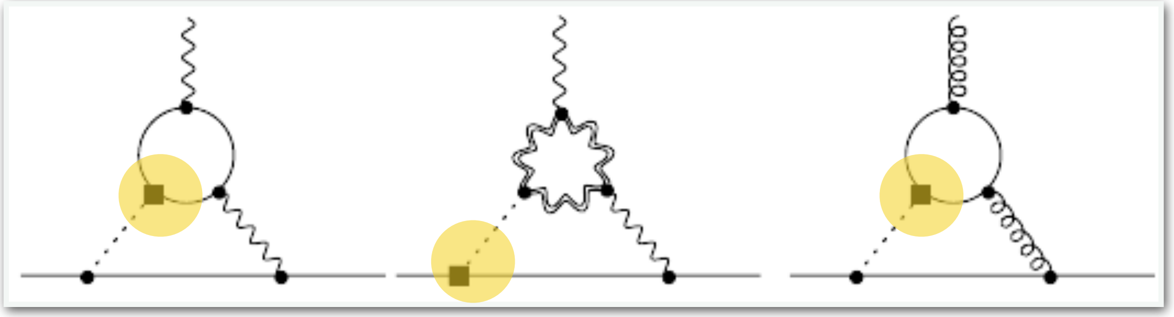
LHC: Higgs production

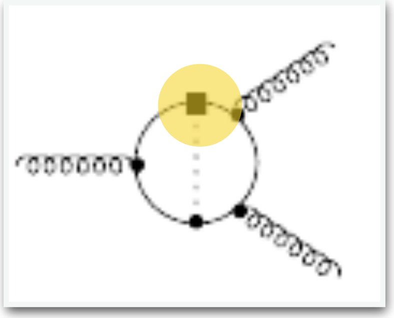


Top quark:



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

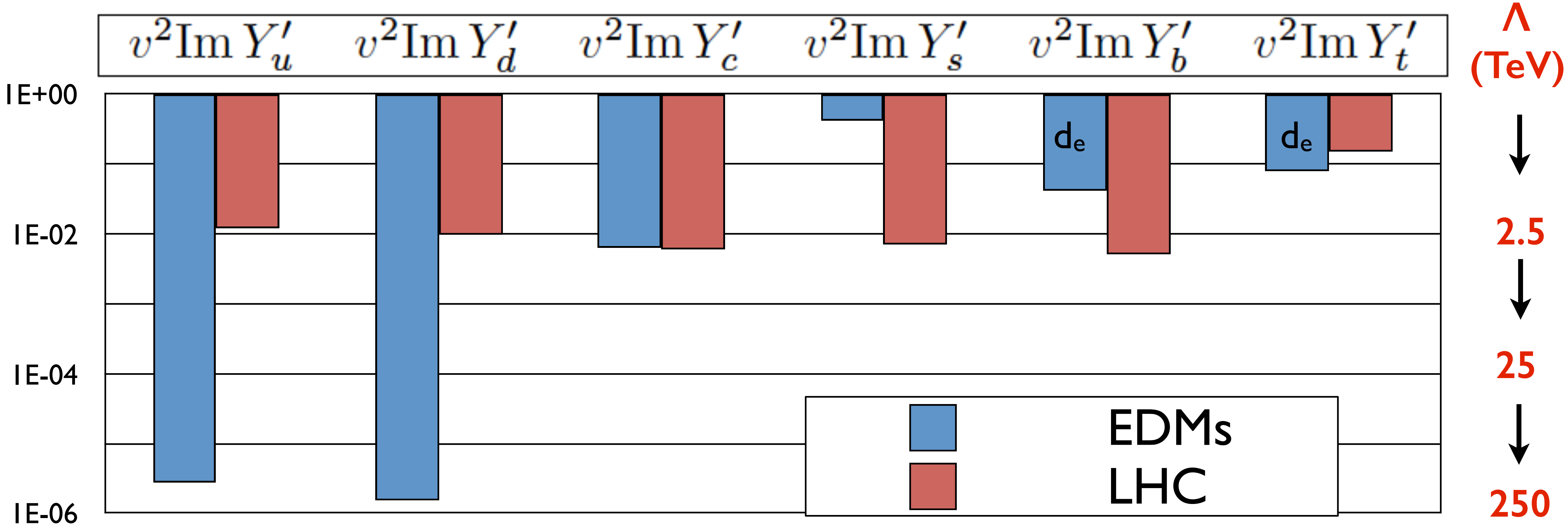




Y.-T. Chien, V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

Brod Haisch Zupan 1310.1385 — third generation Yukawas

Yukawa couplings to quarks

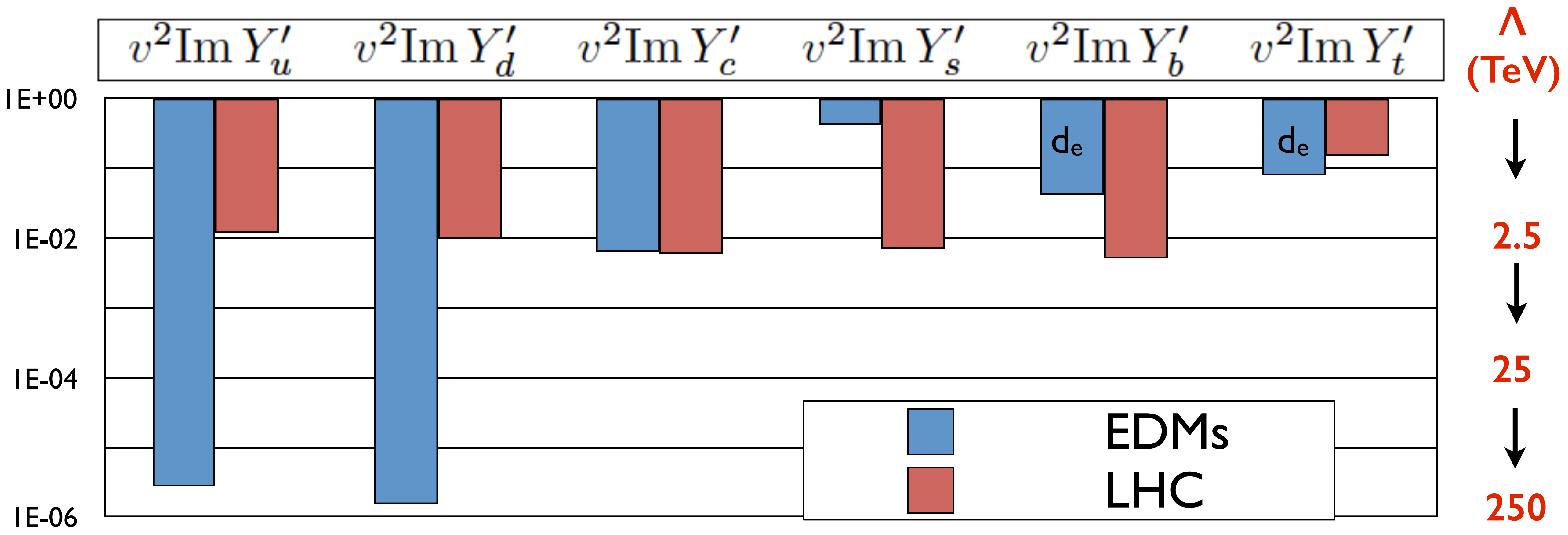


- Pseudo-scalar Yukawas in units of SM Yukawa m_q/v:

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

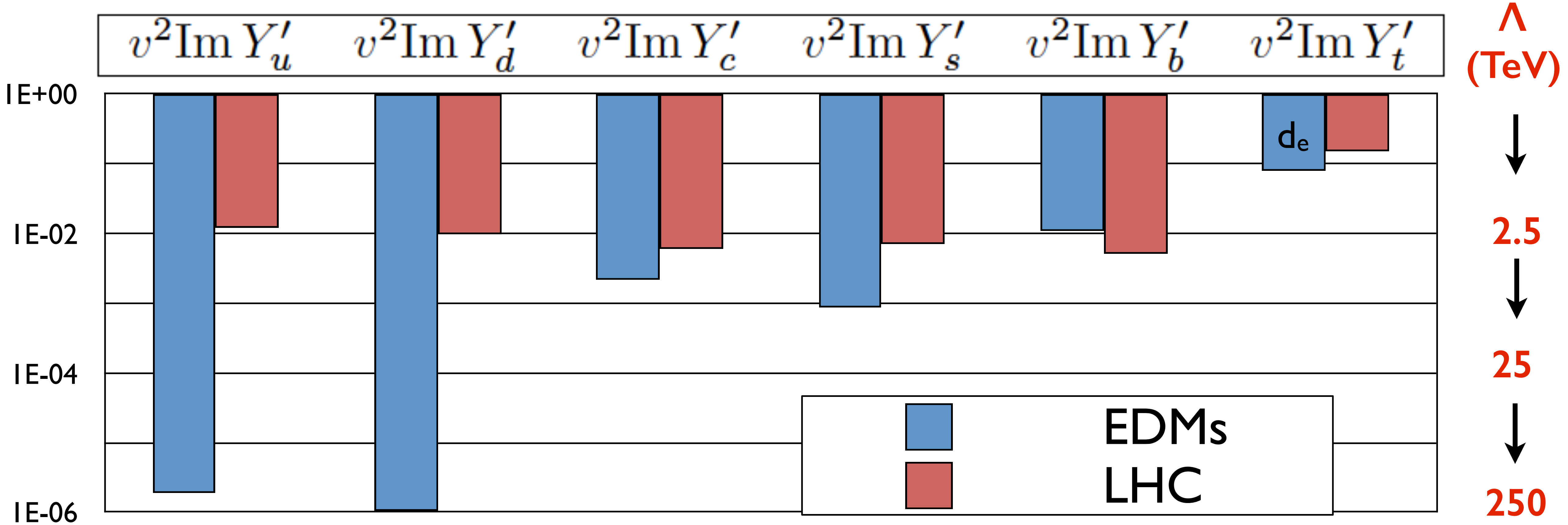
$\tilde{\kappa}_u$	$\tilde{\kappa}_d$	$\tilde{\kappa}_s$	$\tilde{\kappa}_c$	$\tilde{\kappa}_b$	$\tilde{\kappa}_t$
0.45	0.11	58	2.3	3.6	0.01

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

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

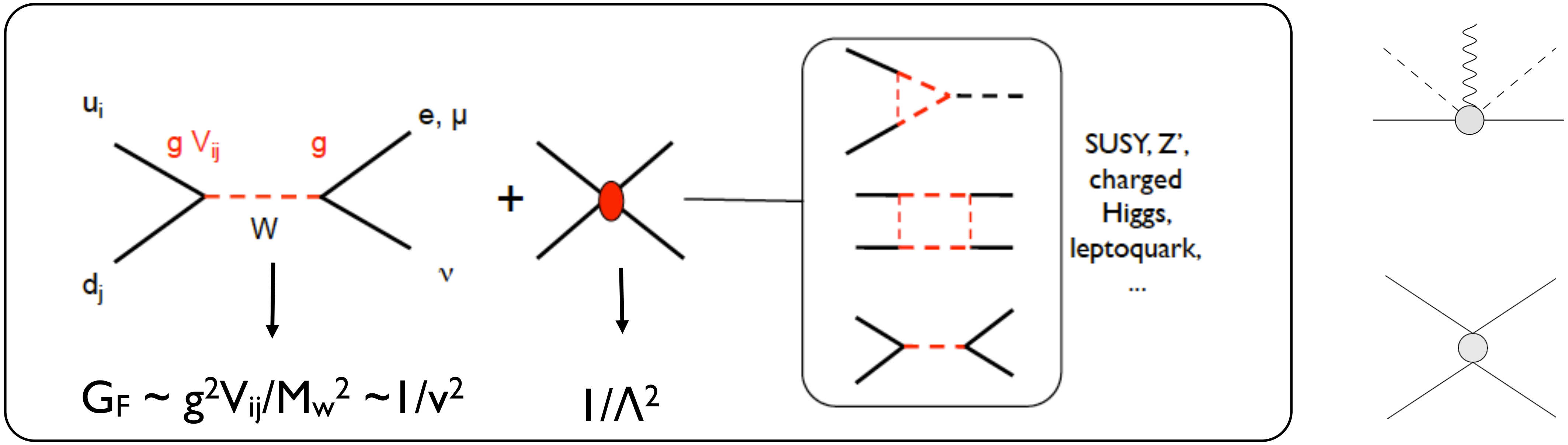
25% 50%

- Challenging but realistic target for LQCD and nuclear structure

Example #2:
Precision beta decays

β-decays and BSM physics

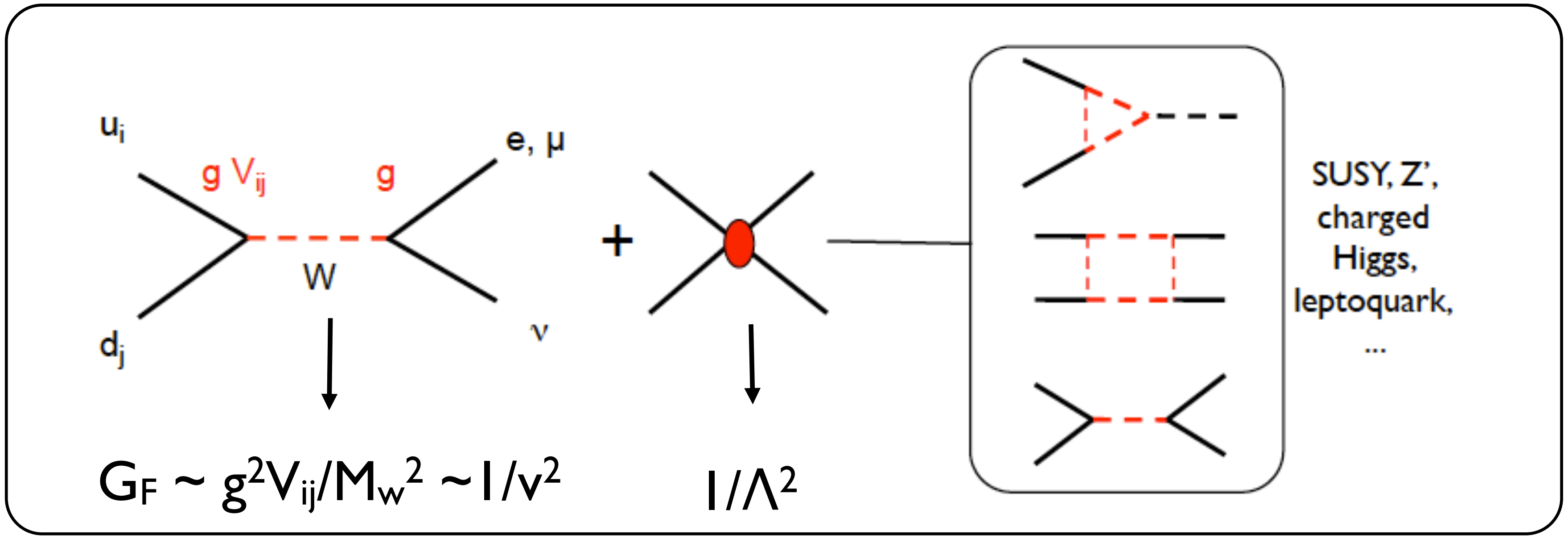
- In the SM, W exchange (V-A, universality)



- Broad band sensitivity to BSM physics
- Experimental and theoretical precision at or approaching 0.1% level
  Probe effective scale Λ in the 5-10 TeV range

β-decays and BSM physics

- In the SM, W exchange (V-A, universality)



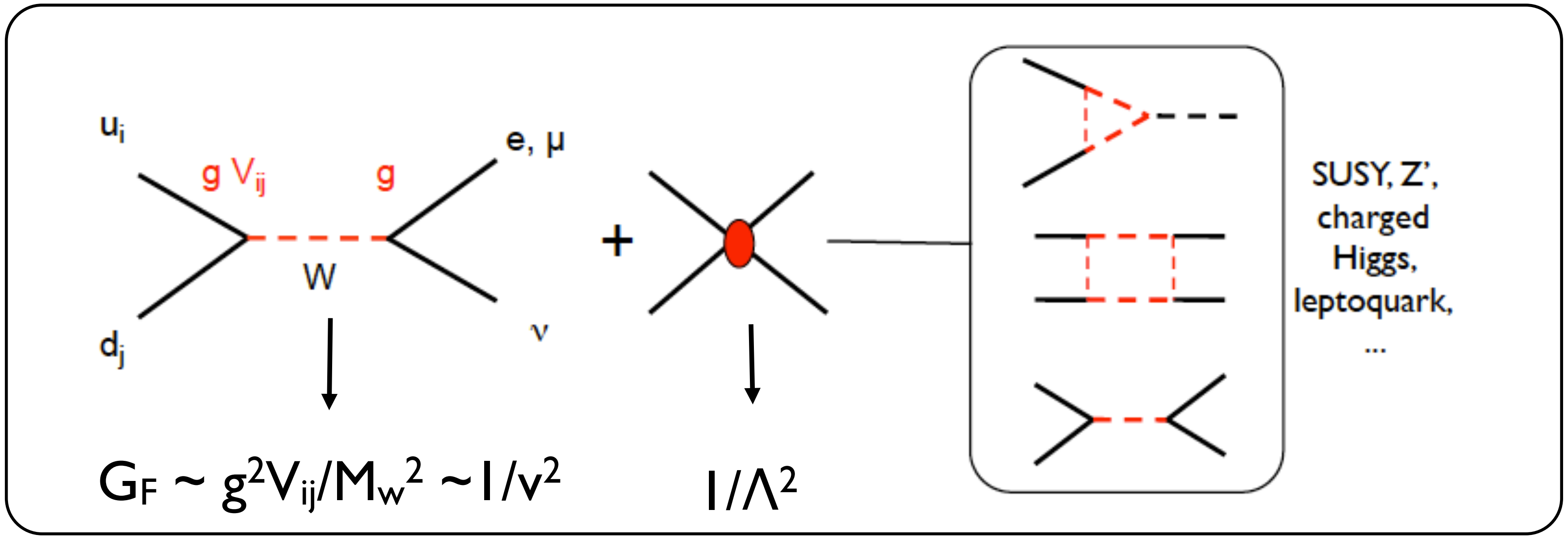
E << Λ $\quad \downarrow \quad \epsilon_\Gamma \sim (M_W/\Lambda)^2$

$$\boxed{\mathcal{L}_{\rm SM} - \frac{G_F V_{ud}}{\sqrt{2}} \sum_\Gamma \left[\epsilon_\Gamma \; \bar\ell \Gamma \nu_L \cdot \bar u \Gamma d \; + \; \tilde\epsilon_\Gamma \; \bar\ell \Gamma \nu_R \cdot \bar u \Gamma d\right]}$$

Ten effective couplings $\qquad \Gamma = L, R, S, P, T$

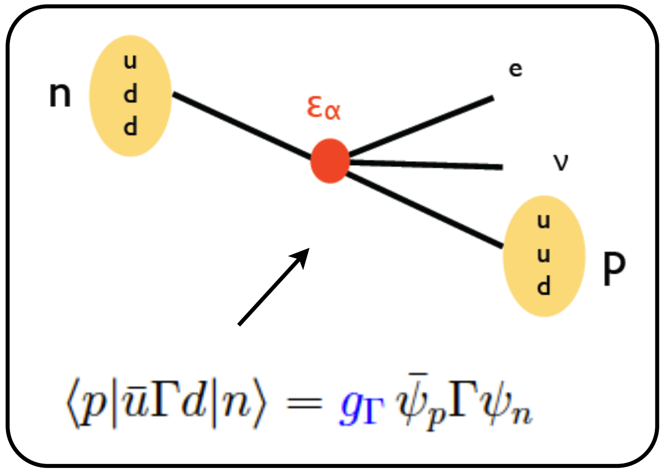
β-decays and BSM physics

- In the SM, W exchange (V-A, universality)



- To connect experiment to (B)SM couplings, need radiative corrections + hadronic & nuclear matrix elements

Example: $g_{V,A,S,T,P}$

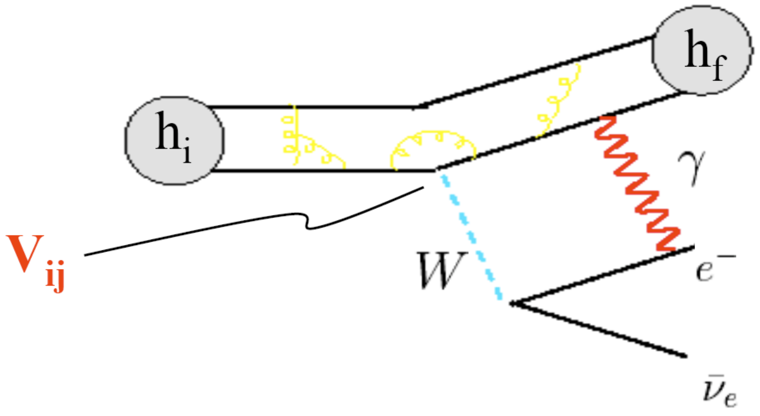


$$\langle p|\bar{u}\Gamma d|n\rangle = g_\Gamma\, \bar{\psi}_p \Gamma \psi_n$$

CKM unitarity test

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

Channel-dependent
effective CKM element



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

CKM unitarity test

- V_{ud} from $0^+ \rightarrow 0^+$ nuclear β decays

$$\frac{1}{t} = \frac{G_\mu^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} f(Q)\ (1+RC) \longrightarrow f\,t\ (1+RC) = \frac{2984.48(5)\ s}{|V_{ud}|^2}$$

CKM unitarity test

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$$(1+RC) = (1-\delta_C)\,(1+\delta_R)\,(1+\Delta_C)$$

$$\langle f|\tau_+|i\rangle = \sqrt{2}\,(1-\delta_C/2)$$

Coulomb distortion

of wave-functions

$$\delta_C \sim 0.5\%$$

Towner-Hardy

Ormand-Brown

Ab initio methods?

Nucleus-dependent

rad. corr.

(Z, E^{max} ,nuclear structure)

$$\delta_R \sim 1.5\%$$

Sirlin-Zucchini ‘86

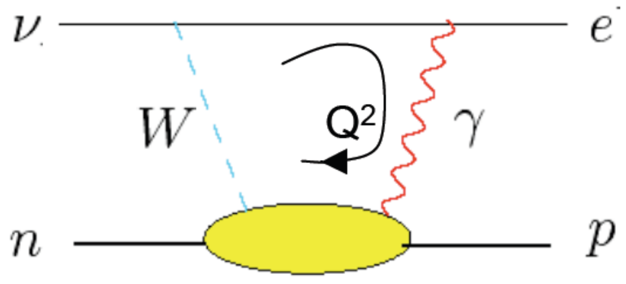
Jaus-Rasche ‘87

Nucleus-independent

short distance rad. corr.

$$\Delta_R \sim 2.4\%$$

Marciano-Sirlin ‘06

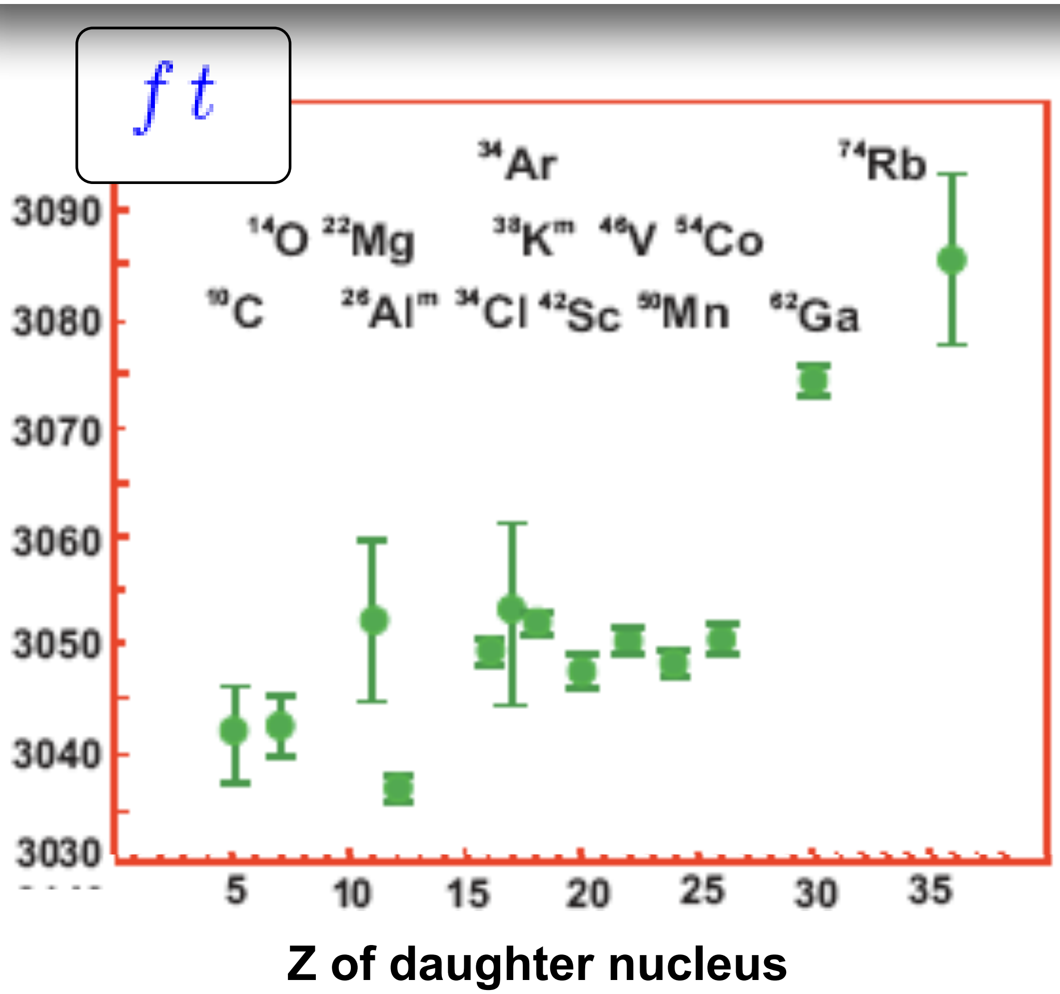


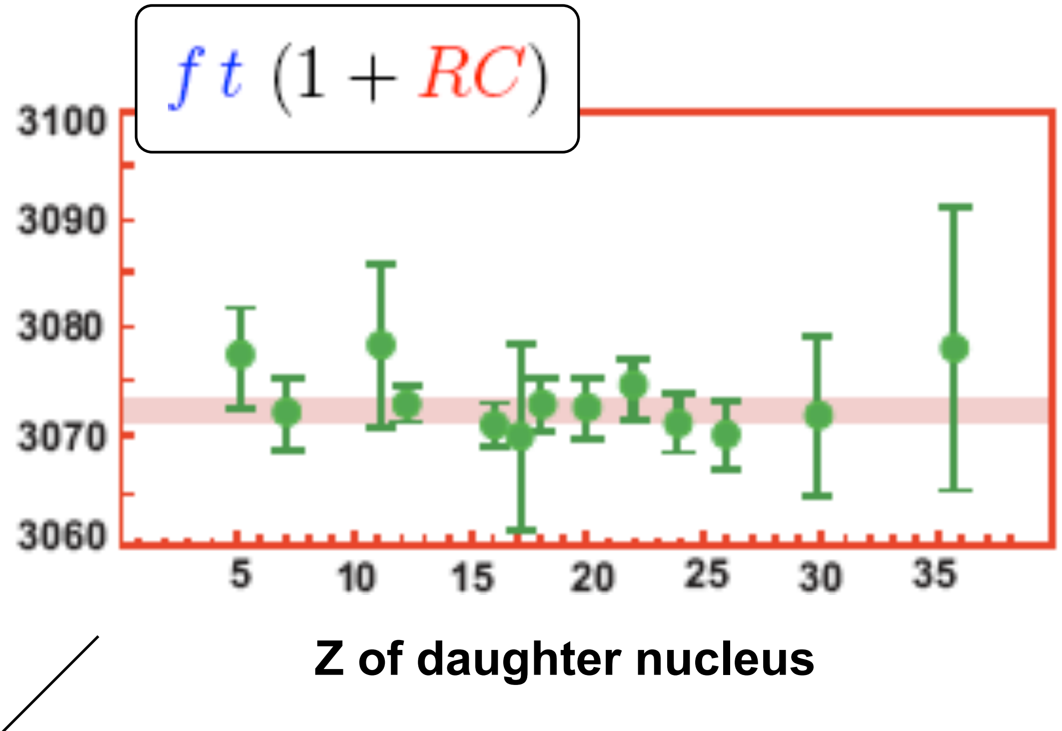
Lattice QCD?

CKM unitarity test

- V_{ud} from $0^+ \rightarrow 0^+$ nuclear β decays

$$\frac{1}{t} = \frac{G_\mu^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2}\, f(Q)\,(1+RC) \longrightarrow f\,t\,(1+RC) = \frac{2984.48(5)\ s}{|V_{ud}|^2}$$



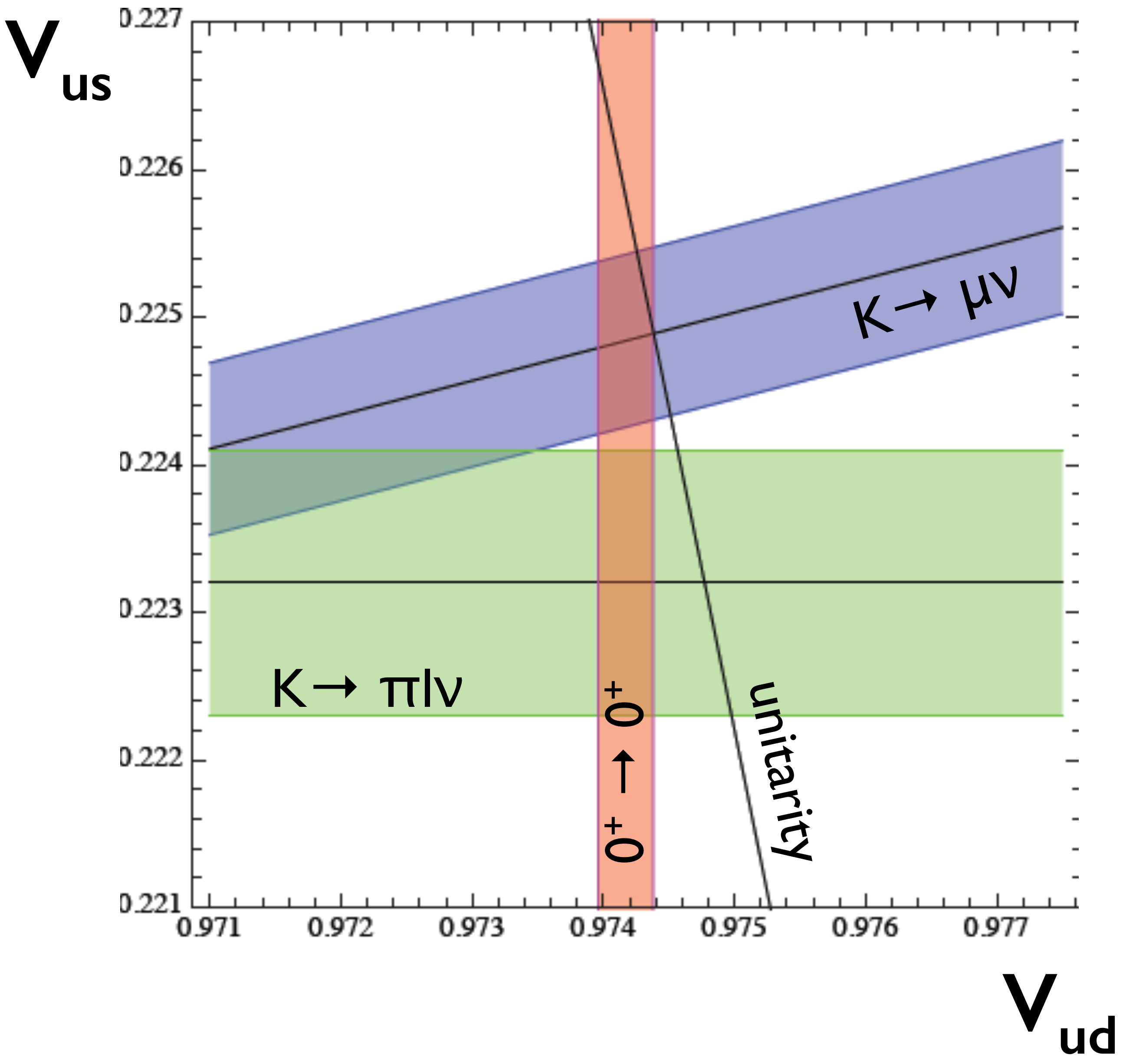


$$\boxed{V_{ud} = 0.97417\,(21)}$$

Townwer-Hardy 2014

CKM unitarity test

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



V_{us} from K→ μν

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

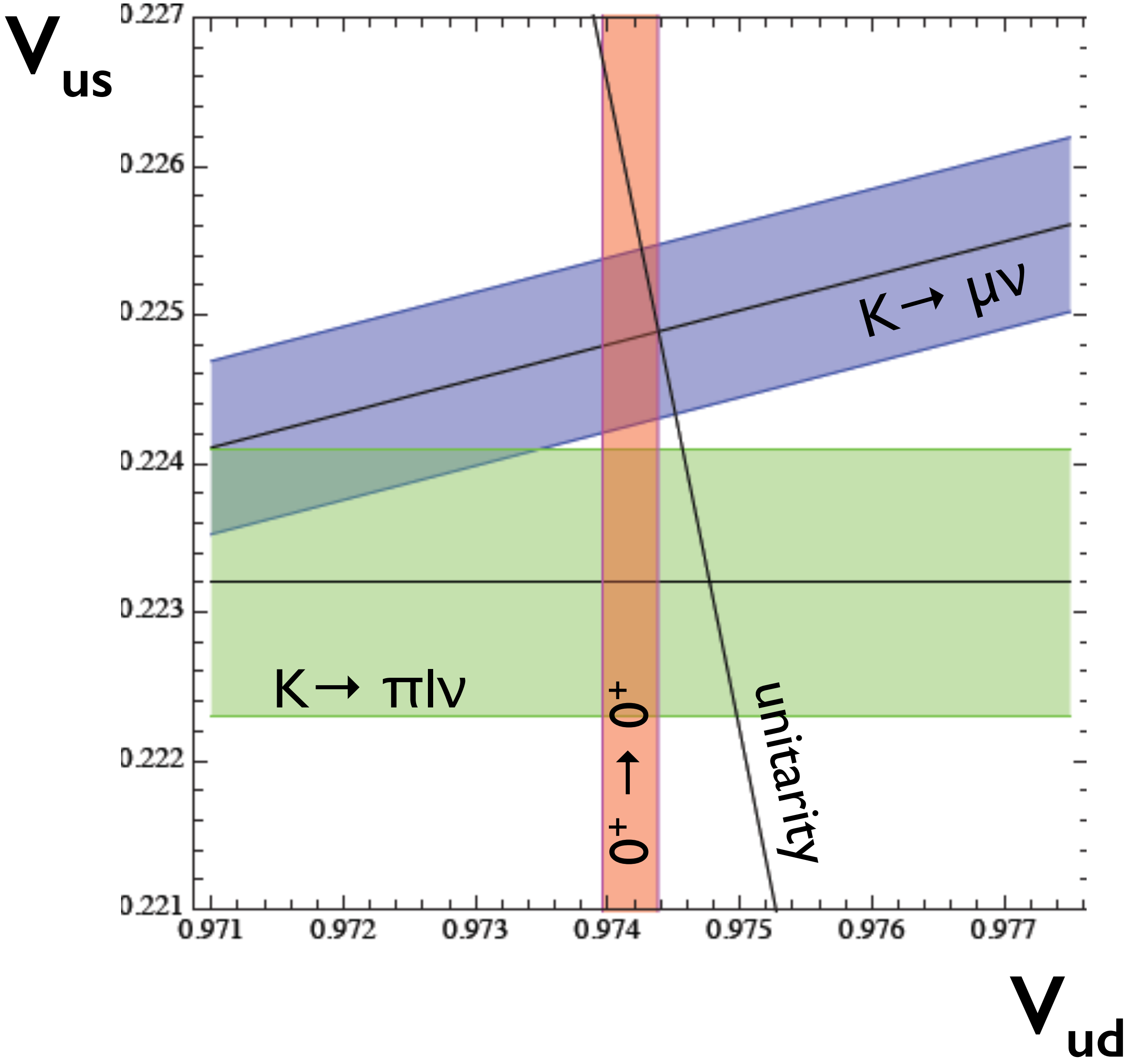
$\Delta_{\mathrm{CKM}} = -(12 \pm 6) * 10^{-4}$ 2.1σ

V_{us} from K→ πlν

- No longer perfect agreement:
  - New physics?
  - Underestimated th. errors? [Δ_R, δ_C (A,Z), $\langle\pi|V|K\rangle$, F_K/F_π]

CKM unitarity test

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



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V_{us} from K→ πlν

- No longer perfect agreement:
  - New physics?
  - Underestimated th. errors?
    [Δ_R, δ_C (A,Z), <π |V|K>, F_K/F_π]

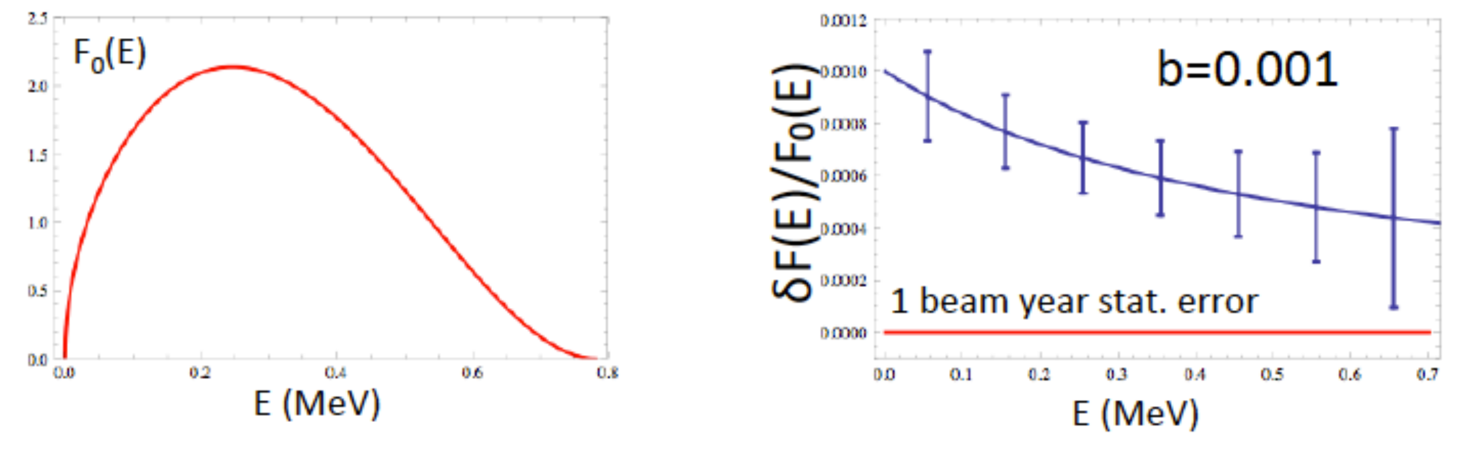
Worth a closer look: at the level of the best LEP EW precision tests

Spectrum and decay correlations

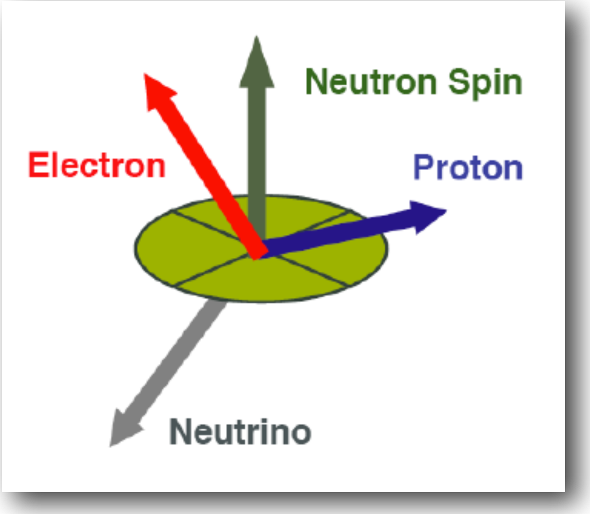
$$d\Gamma \propto F(E_e)\left\{1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + \langle\vec{J}\rangle\cdot\left[\,A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + \cdots\right]\right\}$$

Lee-Yang, Jackson-Treiman-Wyld

Example: Beta spectrum and
effect of "b" in neutron decay



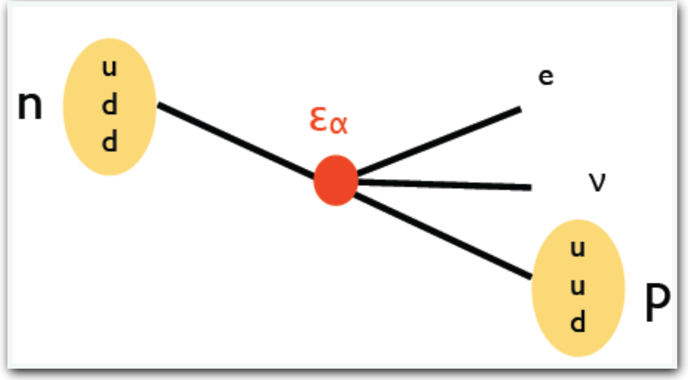
$a(\varepsilon_\alpha)$, $A(\varepsilon_\alpha)$, $B(\varepsilon_\alpha)$, ...
isolated via suitable
experimental asymmetries



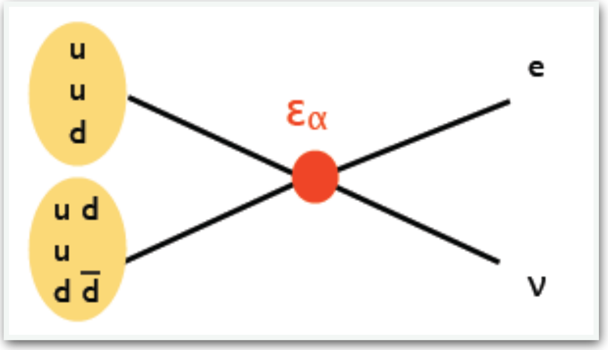
Spectrum and decay correlations

b, B @ 0.1%, probe ε_S and ε_T deeper than the LHC (for heavy BSM)

n → p e ν



LHC: pp → e ν + X



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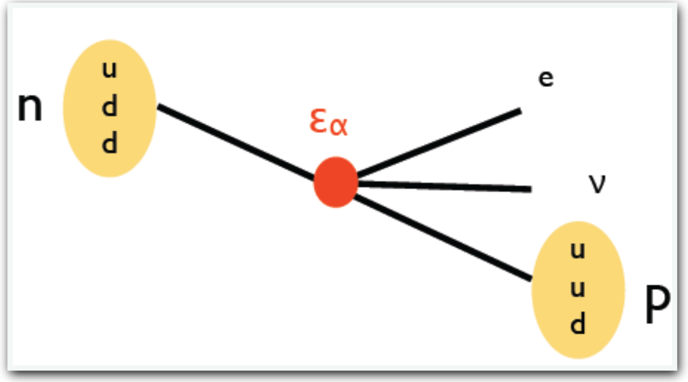
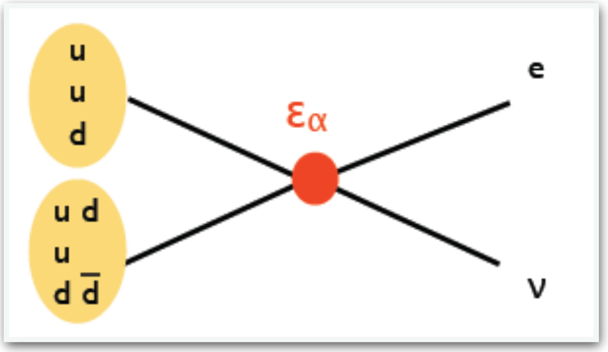
$n \rightarrow p\, e\, \nu$

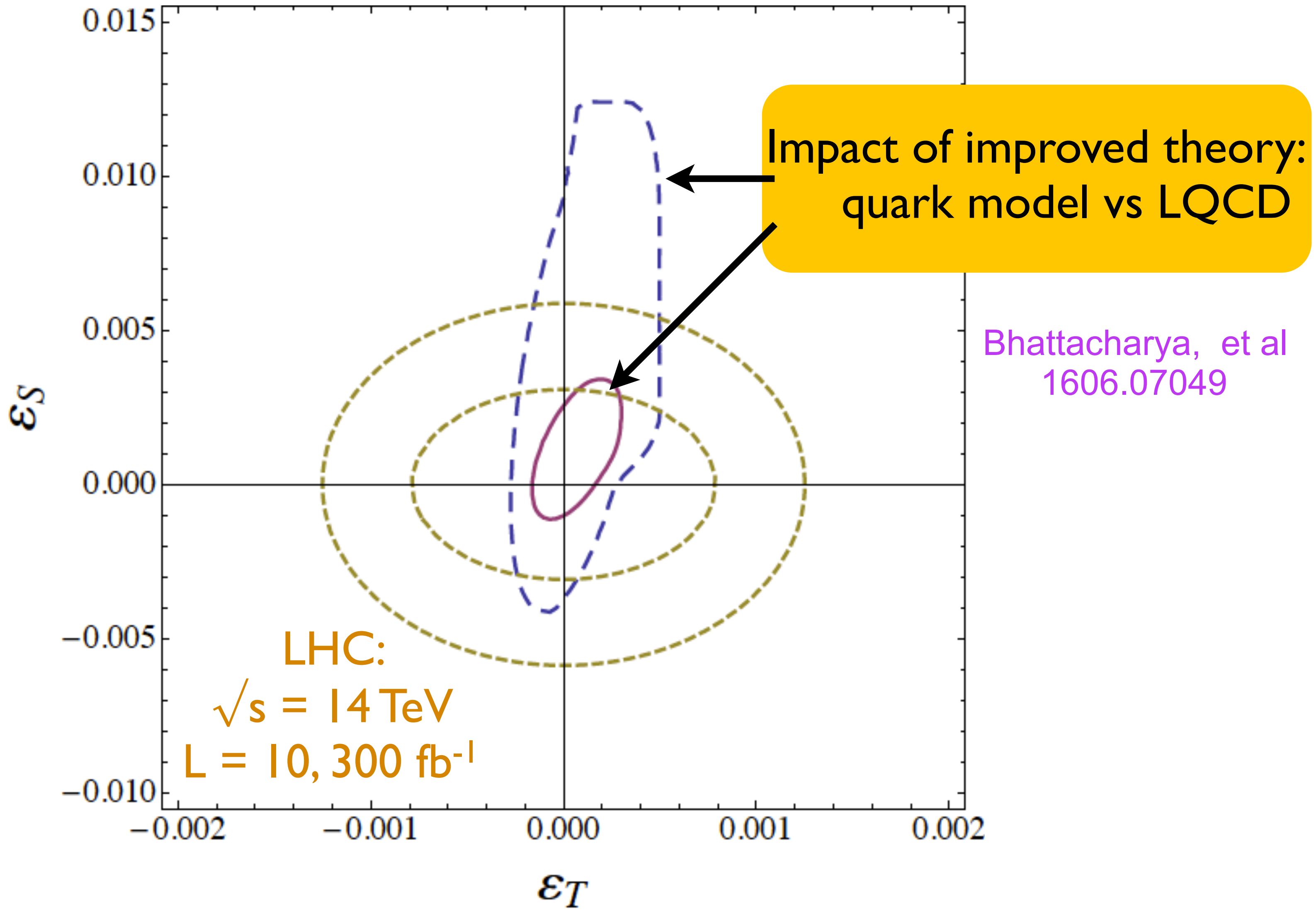


LHC: $pp \rightarrow e\, \nu + X$



Future b (n, ^{6}He) @ 0.1%

Current b($0^+ \rightarrow 0^+$): Hardy & Towner 1411.5987



Impact of improved theory: quark model vs LQCD

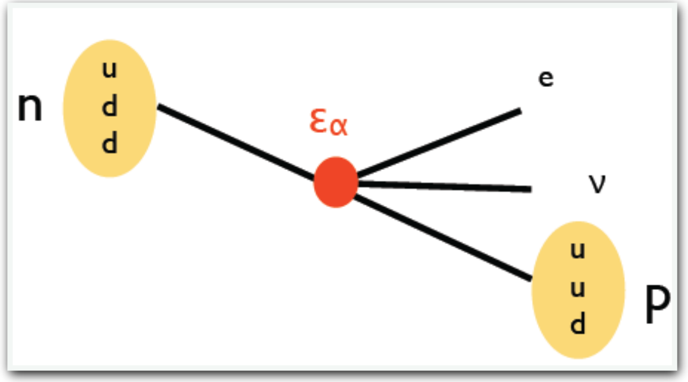
LHC: $\sqrt{s}$ = 14 TeV L = 10, 300 fb^{-1}

Bhattacharya, et al 1606.07049

Spectrum and decay correlations

b, B @ 0.1%, probe ε_S and ε_T deeper than the LHC (for heavy BSM)

n → p e ν



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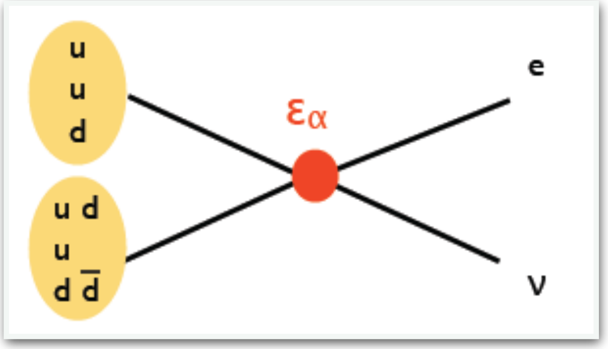

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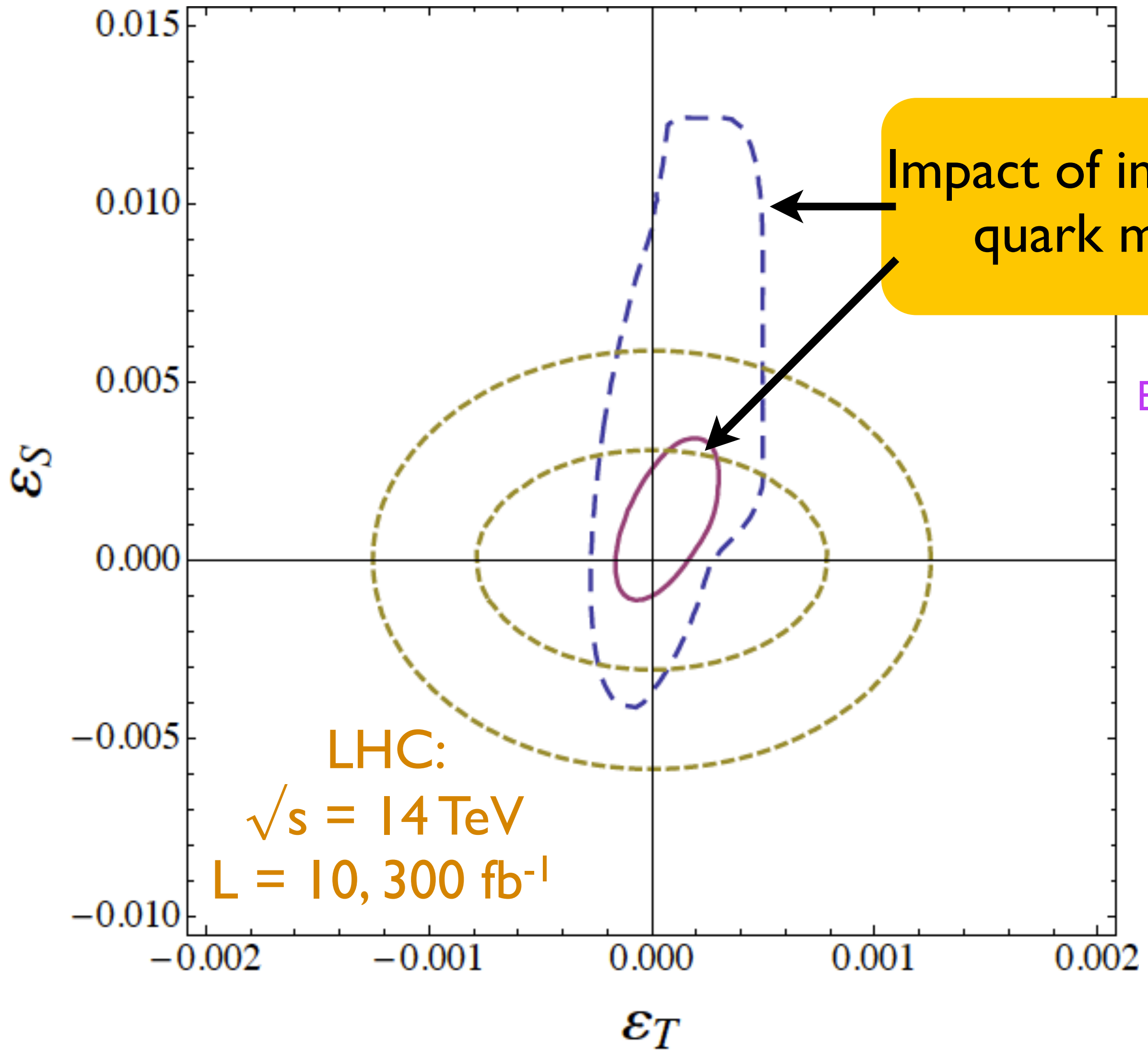


Impact of improved theory:
quark model vs LQCD

Bhattacharya, et al
1606.07049

Theory OK for neutron decay.

What about ^{6}He and other nuclei of experimental interest?

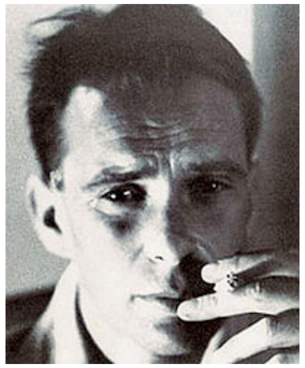
Conclusions

- Precision measurements and searches for rare / forbidden processes can discover and help disentangling BSM dynamics
- Broad and vibrant field: our best chance to see new physics in the short-term if M_{BSM} > few TeV
- Illustrated impact and challenges in two examples: EDMs, β decays
- Overarching challenge: maximizing impact of experimental searches requires controlled uncertainties on hadronic and nuclear matrix elements
- Specific challenges: see next page

Specific challenges

EDMs	"Desirable" precisions: Nucleon EDM from quark CEDM and Weinberg operator @ 25%; Pion-nucleon coupling from qCEDM @ 50%; Schiff moment @ 50%
β decays	Recoil, radiative, and isospin-breaking corrections: one- and multi-nucleon level. QED on the lattice (mesons and nucleons)
0νββ	Nuclear matrix elements: "standard mechanism" (dim-5) and dim-9 mechanism with controlled errors. Interface of lattice and nuclear structure.
ν-nucleus scattering	Energy-dependent cross sections for neutrinos and antineutrinos with controlled errors. What precision is required for DUNE to be successful?
Dark Matter	Connect DM-quark to DM-nucleus: RG evolution; chiral EFT matching, nuclear responses. Work out matching to phenomenologically interesting cases (heavy WIMP)
…	…

Thank you!



A drawing by
Bruno Touschek