Testing the SM(EFT) at low- and high-energy

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Los Alamos
NATIONAL LABORATORY
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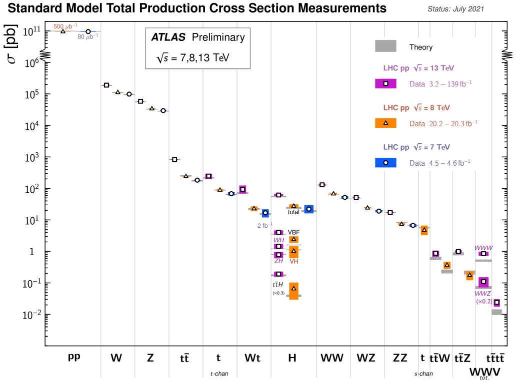
Finding new physics: the energy frontier

1. collide protons at high energy, and see what comes out

- create new particles **and/or**
  study their effects on rare processes

Finding new physics: the energy frontier



ATLAS, Standard Model Public Results

1. collide protons at high energy, and see what comes out

- create new particles **and/or**
  study their effects on rare processes

Finding new physics: the precision frontier

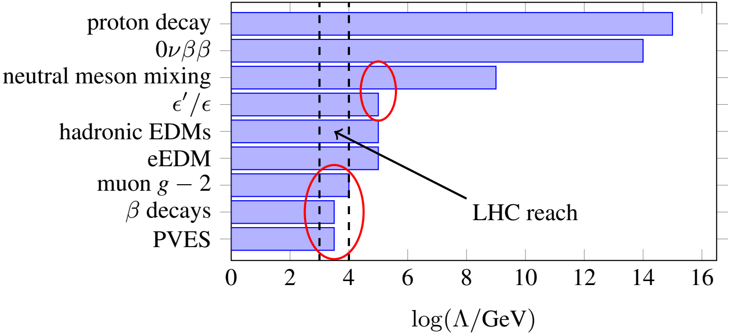
Majorana
demonstrator

2. search for tiny indirect effects,
   with no (very precisely known) SM background

- electric dipole moments
- kaon physics
- rare B decays, $b \to s\gamma$

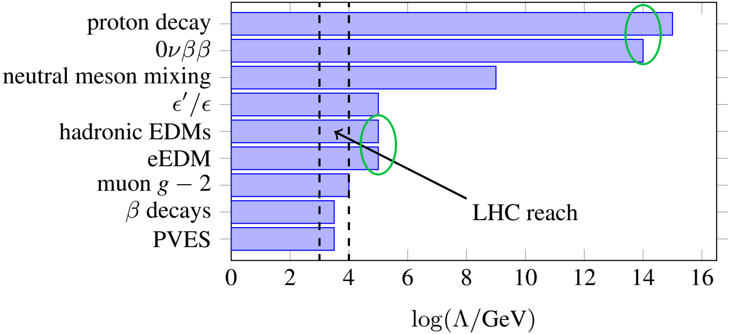
- muon and electron $g-2$
- neutrinoless double β decay
- lepton flavor violation $\mu \to e\gamma$

Finding new physics: the precision frontier



1. observables w. SM background
   need precise SM background to claim discovery

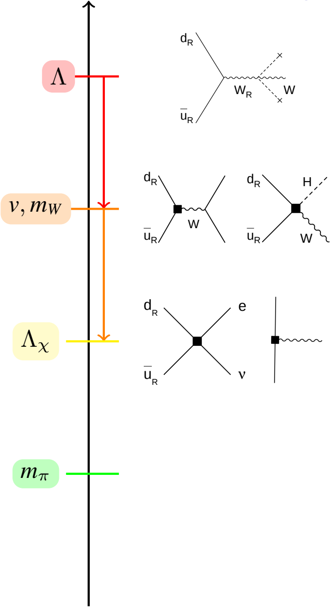
Finding new physics: the precision frontier



1. observables w. SM background
   need precise SM background to claim discovery
2. observables w/o (w. negligible) SM background
   need precision to extract microscopic symmetry violation params ($\bar{\theta}$, $m_{\beta\beta}$,...)

competitive/complementary to energy frontier.
What can we learn from the complementary?

Connecting the SMEFT with low-energy probes



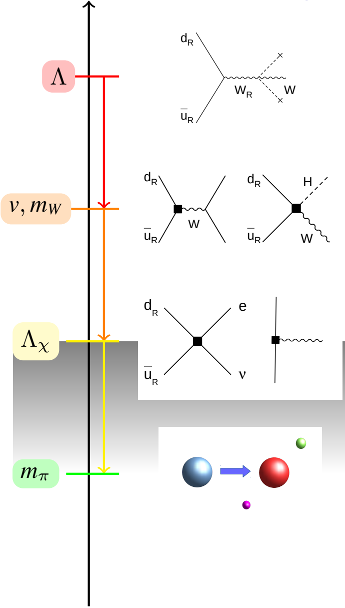
new physics $\Lambda \gg v$

SM-EFT operators

$SU(3)_c \times U(1)_{\text{em}}$ operators

perturbative matching
integrate out heavy SM d.o.f.

Connecting the SMEFT with low-energy probes



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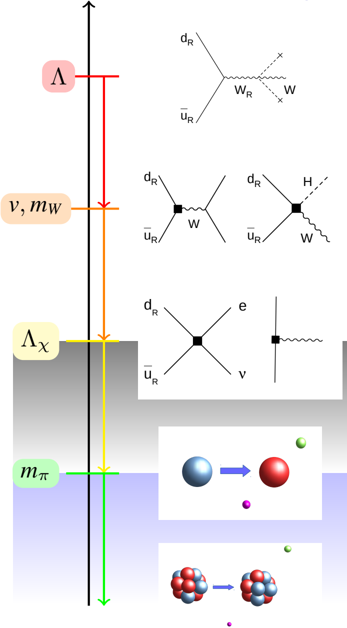
$SU(3)_c \times U(1)_{\text{em}}$ operators

non perturbative QCD

Chiral Effective Theory

Connecting the SMEFT with low-energy probes



new physics $\Lambda \gg v$

SM-EFT operators

$SU(3)_c \times U(1)_{\rm em}$ operators

non perturbative QCD

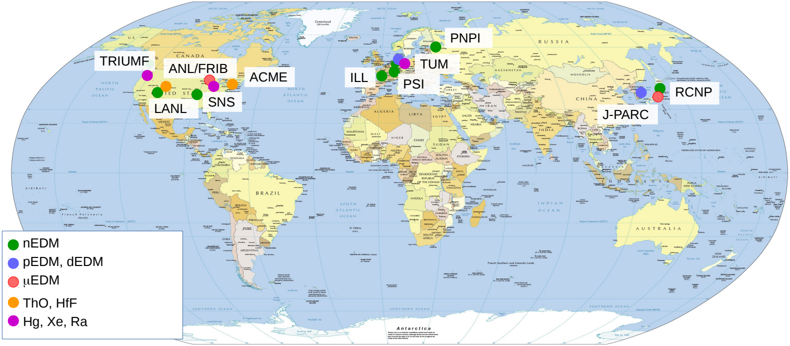
Chiral Effective Theory

strong nuclear interactions

Many body

Electric dipole moments and BSM CP violation

EDM experiments worldwide

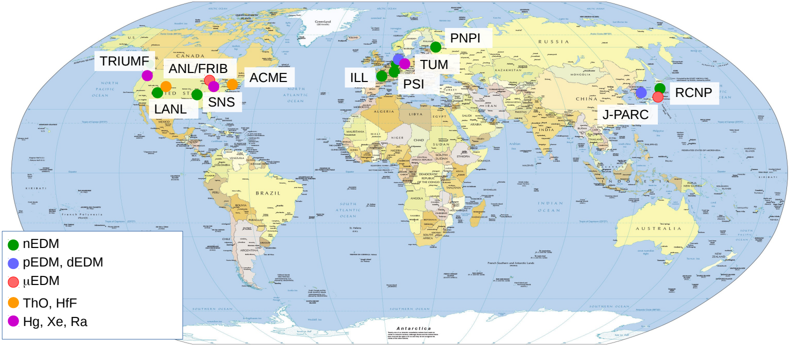


- EDMs probe CP-violation beyond the SM
- large worldwide experimental program

$$\begin{array}{llll} d_e & < 1.0 \cdot 10^{-16}\ e\ \text{fm} & d_n & < 1.8 \cdot 10^{-13}\ e\ \text{fm} \\ d_{^{225}\text{Ra}} & < 1.2 \cdot 10^{-10}\ e\ \text{fm} & d_{^{199}\text{Hg}} & < 6.2 \cdot 10^{-17}\ e\ \text{fm} \end{array}$$

$\Lambda_{\text{naive}} \sim$ 10-100 TeV

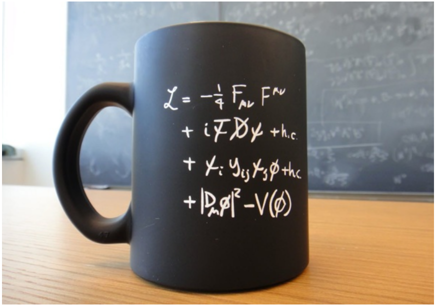
EDM experiments worldwide



- goals for the next EDM generation

$$\begin{array}{llll}
d_e & < 1.0 \cdot 10^{-17}\, e\ \mathrm{fm} & d_n & < 1.0 \cdot 10^{-15}\, e\ \mathrm{fm} \\
d_d & < 1.0 \cdot 10^{-16}\, e\ \mathrm{fm} & d_{^{225}\mathrm{Ra}} & < 1.0 \cdot 10^{-14}\, e\ \mathrm{fm} \\
d_p & < 1.0 \cdot 10^{-16}\, e\ \mathrm{fm} & & d_{^{3}\mathrm{He}}/d_p ?
\end{array}$$

CP violation in the SM(EFT)



- two CPV sources in SM

$$\mathcal{L}_{\text{CPV}}^{(4)} = -\theta \frac{g_s^2}{64\pi^2} \varepsilon^{\alpha\beta\mu\nu} G_{\mu\nu} G_{\alpha\beta} + \bar{u}_L^i \left[V_{\text{CKM}}\right]_{ij} \gamma^\mu d_L^j W_\mu$$

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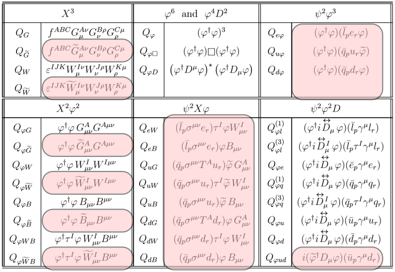
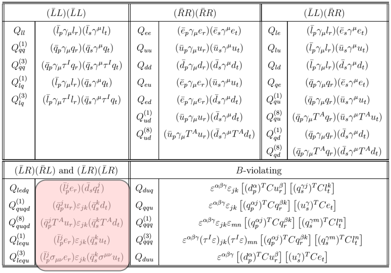


X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$



$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu \tau^I q_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu \tau^I l_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
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$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Grzadkowski *et al.* ‘10

- two CPV sources in SM

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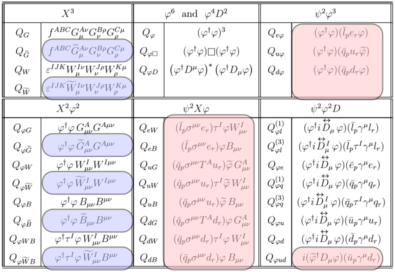
- 53 (1350) CP-even, 23 (1149) CP-odd dimension-6 operators ($\mathcal{O}(v^2/\Lambda^2)$)

  Buchmuller & Wyler ‘86, Weinberg ‘89, de Rujula *et al.* ‘91, Grzadkowski *et al.* ‘10 . . .

CP violation in the SM(EFT)



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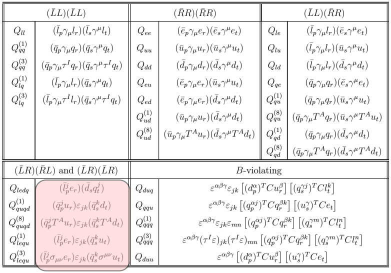

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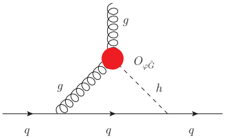
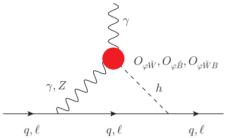
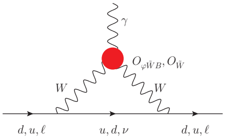
- focus on bosonic operators

  arise in “universal theories”, evade flavor bounds

Matching & running to low energy







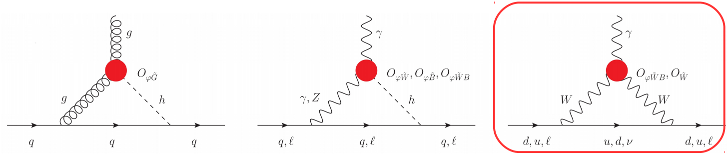
- $C_{\varphi\tilde{W}}, C_{\varphi\tilde{W}B}, C_{\varphi\tilde{B}}$ and $C_{\tilde{W}} \Longrightarrow$ lepton & quark EDM @ 1 EW loop

$$\tilde{c}_{\gamma}^{(e,q)} \sim \frac{\alpha_{\text{em}}}{4\pi} C_{\tilde{X}} \sim \left\{10^{-2} C_{\varphi\tilde{X}}, 10^{-3} C_{\tilde{W}}\right\}$$

- gluonic operators $\Longrightarrow$ qCEDM and gCEDM @ $\mathcal{O}(\alpha_s)$

$$\left\{\tilde{c}_g^{(q)}, C_{\tilde{G}}\right\} \sim 10^{-1} \times \{C_{\varphi\tilde{G}}, C_{\tilde{G}}\},$$

Matching & running to low energy



- $C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{W}B}$, $C_{\varphi\tilde{B}}$ and $C_{\tilde{W}}$ $\Longrightarrow$ lepton & quark EDM @ 1 EW loop

$$\tilde{c}_{\gamma}^{(e,q)} \sim \frac{\alpha_{\rm em}}{4\pi} C_{\tilde{X}} \sim \left\{ 10^{-2} C_{\varphi\tilde{X}}, 10^{-3} C_{\tilde{W}} \right\}$$

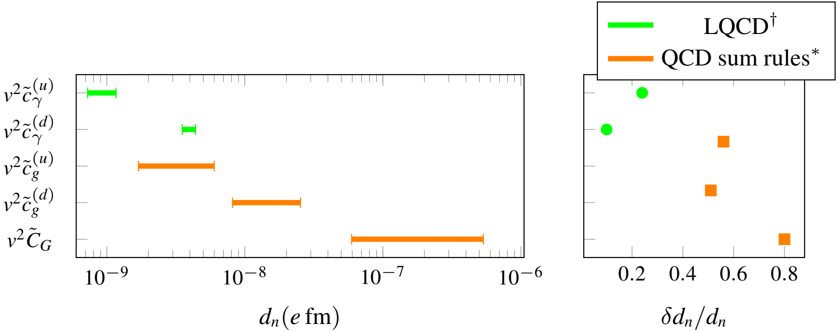
- gluonic operators $\Longrightarrow$ qCEDM and gCEDM @ $\mathcal{O}(\alpha_s)$

$$\left\{ \tilde{c}_g^{(q)}, C_{\tilde{G}} \right\} \sim 10^{-1} \times \left\{ C_{\varphi\tilde{G}}, C_{\tilde{G}} \right\},$$

- $C_{\varphi\tilde{W}B}$ and $C_{\tilde{W}}$ match on flavor-changing dipoles $\Longrightarrow$ $B \to X_s\gamma$, $K_L \to \pi^0 e^+ e^-$
- **but** same flavor & chiral structure as SM (GIM mechanism, . . .)

SM-like, weak bounds from flavor

From quarks to hadrons. Nucleon EDM matrix elements



† FLAG '21

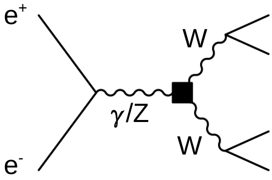
* Pospelov and Ritz, '05, Haisch and Hala, '19

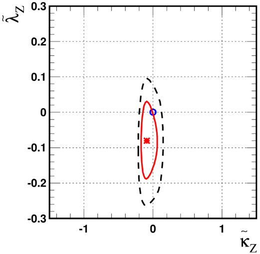
- small error on the eEDM and ThO precession frequency

$$d_e = e m_e \tilde{c}_e^{(\gamma)} \sim 1.7 \cdot 10^{-9} (v^2 \tilde{c}_e^{(\gamma)})\, e\,\mathrm{fm}$$

- tensor charges control qEDMs
- large (uncontrolled) errors on purely hadronic operators

Collider constraints. LEP





Delphi Collaboration, ‘08

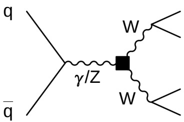
- $C_{\varphi\tilde{W}B}$ and $C_{\tilde{W}}$ map into anomalous $WW\gamma$ and WWZ couplings
- W polarization measurements at LEP2

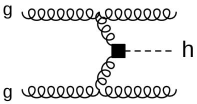
$$\tilde{\kappa}_Z = -0.12^{+0.06}_{-0.04} \qquad \tilde{\lambda}_Z = -0.09^{+0.07}_{-0.07}$$

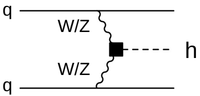
sensitive to EW scale physics

- not sensitive to Higgs, gluon couplings

Collider constraints. LHC







Many more possibilities @ LHC

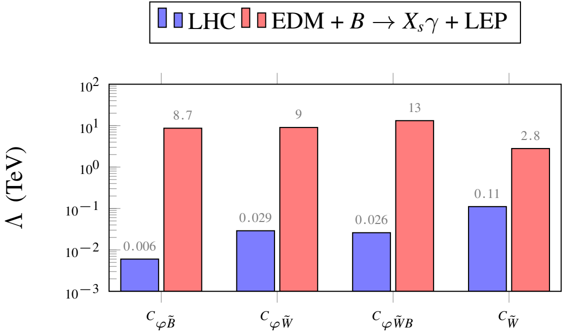
- EW physics

  $pp \to WW,\ WZ$

- Higgs production
  $pp \to h$, $pp \to h + 2j$,
- & Higgs decays
  $h \to \gamma\gamma$, $h \to \gamma Z$, $h \to ZZ^* \to 4l$
- use only LHC observables sensitive to CP-violation

LHC already competitive with LEP!

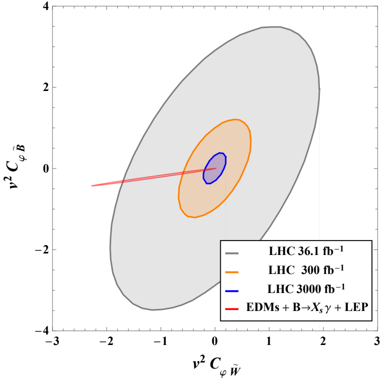
Constraints on weak gauge-Higgs operators



$$C_X = \frac{1}{(4\pi\Lambda)^2}$$

- low-energy observables not affected by large theory uncertainties
- eEDM dominates single coupling analysis
- collider not competitive

Constraints on weak gauge-Higgs operators



marginalized

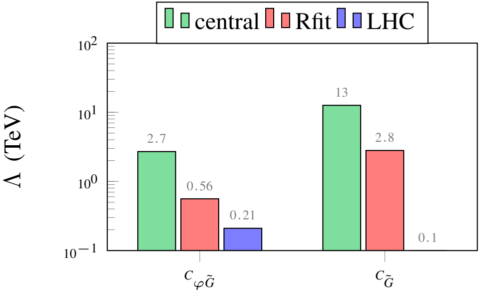
V. Cirigliano, A. Crivellin *et al*, ‘19

LHC projections of Bernlochner *et al*, ‘18

- EDMs constrain 2 directions
  d_n, d_{Hg} and d_{Ra} largely degenerate
- need LEP, $B \to X_s\gamma$ or LHC to close free directions

strong correlations to avoid EDMs

Constraints on gluonic operators



"central":
no theory errors

"Rfit":
vary ME in allowed th. ranges

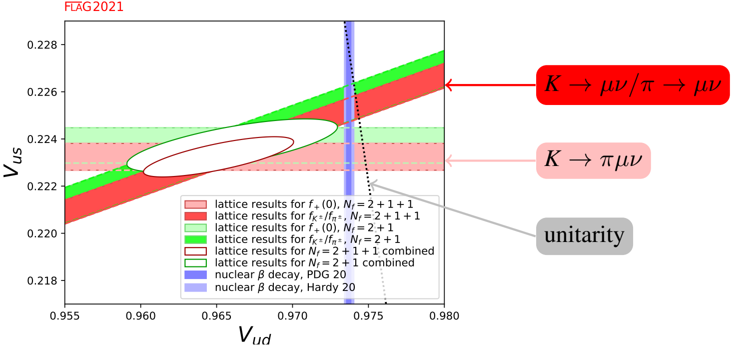
- depend strongly on treatment of hadronic uncertainties
- limits on $C_{\varphi\tilde{G}}$, $C_{\tilde{G}}$ weaker by factor ~ 20

need improved LQCD & nuclear theory calculations

- study more CPV observables at colliders?

The Cabibbo anomaly and non-standard charged-currents

The Cabibbo anomaly



$K \to \mu\nu / \pi \to \mu\nu$

$K \to \pi\mu\nu$

unitarity

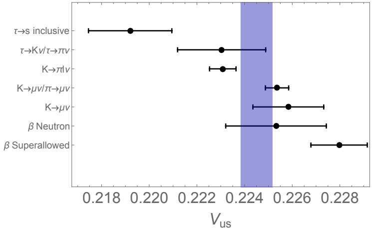
- improved radiative corrections to $0^+ \to 0^+$ Fermi decays

C. Y. Seng, M. Gorchtein, H. Patel, M. Ramsey-Musolf, ‘18;
A. Czarnecki, W. Marciano, A. Sirlin, ‘19; J. C. Hardy and I. S. Towner, ‘20

- high-precision lattice QCD calculations of f_K/f_π and $f_+(0)$

$$\Delta = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = (2.1 \pm 0.6) \cdot 10^{-3}$$

Fitting the Cabibbo anomaly in LEFT



V. Cirigliano, D. Diaz-Calderon, A. Falkowski, M. Gonzalez-Alonso, A. Rodriguez-Sanchez, ‘21

- most general charged-current Lagrangian at low-energy

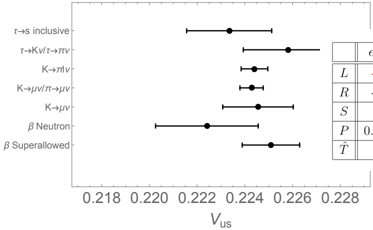
$$\mathcal{L}_{\text{LEFT}} = -\frac{4G_F}{\sqrt{2}} V_{ud_j} \times \Big\{ \bar{\ell}_L \gamma_\mu \nu_L \Big[\Big(1+\epsilon_L^{\ell j}\Big) \bar{u}_L \gamma^\mu d_{Lj} + \epsilon_R^{\ell j}\, \bar{u}_R \gamma^\mu d_{Rj} \Big]$$

$$+ \frac{1}{2}\epsilon_S^{\ell j}\; \bar{\ell}_R \nu_L\, \bar{u} d_j - \frac{1}{2}\epsilon_P^{\ell j}\; \bar{\ell}_R \nu_L\, \bar{u}\gamma_5 d_j + \epsilon_T^{\ell j}\; \bar{\ell}_R \sigma_{\mu\nu} \nu_L\, \bar{u}_R \sigma^{\mu\nu} d_{Lj} \Big\} + \text{h.c.}$$

- can be fit by new left- or right-handed charged-currents

$$\Lambda \sim 3.5 - 7\ \text{TeV}$$

Fitting the Cabibbo anomaly in LEFT



	$\epsilon_X^{de} \times 10^3$	$\epsilon_X^{se} \times 10^3$	$\epsilon_X^{d\mu} \times 10^3$	$\epsilon_X^{s\mu} \times 10^3$	$\epsilon_X^{d\tau} \times 10^3$	$\epsilon_X^{s\tau} \times 10^3$
L	-0.79(25)	-0.6(1.2)	0.40(87)	0.5(1.2)	5.0(2.5)	-18.2(6.2)
R	-0.62(25)	-5.2(1.7)	-0.62(25)	-5.2(1.7)	-0.62(25)	-5.2(1.7)
S	1.40(65)	-1.6(3.2)	x	-0.51(43)	-6(16)	-270(100)
P	0.00018(17)	-0.00044(36)	-0.015(32)	-0.032(64)	1.7(2.5)	10.4(5.5)
$\hat{T}$	0.29(82)	0.035(70)	x	2(18)	28(10)	-55(27)

$> 3\sigma$

V. Cirigliano, D. Diaz-Calderon, A. Falkowski, M. Gonzalez-Alonso, A. Rodriguez-Sanchez, '21

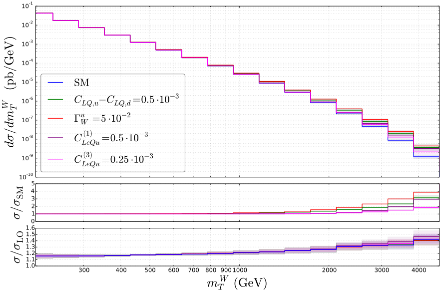
- most general charged-current Lagrangian at low-energy

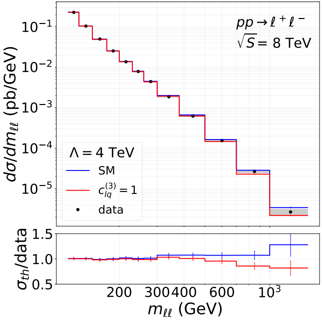
$$\begin{aligned}\mathcal{L}_{\text{LEFT}} &= -\frac{4G_F}{\sqrt{2}} V_{ud_j} \times \Bigg\{ \bar{\ell}_L \gamma_\mu \nu_L \Big[\Big(1 + \epsilon_L^{\ell j}\Big) \bar{u}_L \gamma^\mu d_{Lj} + \epsilon_R^{\ell j} \, \bar{u}_R \gamma^\mu d_{Rj} \Big] \\ &+ \frac{1}{2} \epsilon_S^{\ell j} \; \bar{\ell}_R \nu_L \, \bar{u} d_j - \frac{1}{2} \epsilon_P^{\ell j} \; \bar{\ell}_R \nu_L \, \bar{u} \gamma_5 d_j + \epsilon_T^{\ell j} \; \bar{\ell}_R \sigma_{\mu\nu} \nu_L \, \bar{u}_R \sigma^{\mu\nu} d_{Lj} \Bigg\} + \text{h.c.}\end{aligned}$$

- can be fit by new left- or right-handed charged-currents

$$\Lambda \sim 3.5 - 7 \text{ TeV}$$

Collider constraints in the SMEFT





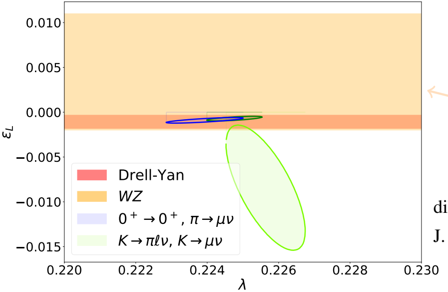
- at EW scale, vertex corrections & four-fermion operators

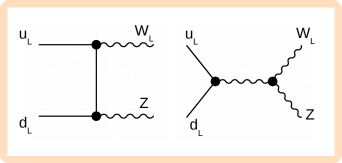
$$\epsilon_L=\frac{v^2}{\Lambda^2}\left(c^{(3)}_{q\varphi}+c^{(3)}_{\ell q}\right),\qquad \epsilon_R=\frac{v^2}{\Lambda^2}c_{ud\varphi}$$

- high-invariant mass Drell-Yan put strong constraints on four-fermion operators
- need full analysis of charged- and neutral-current Drell-Yan at dim-8

R. Boughezal, F. Petriello, EM, ‘21

Collider constraints in the SMEFT





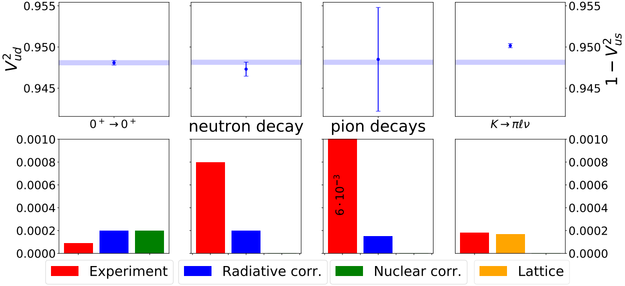
diboson analysis from

J. Ethier, R. Gomez-Ambrosio, G. Magni, J. Rojo, ‘21

- W vertex corrections probed by Z-pole, WZ, WH production

  corrections to WZ & WH with different energy dependence from the SM
- analyses of VV and VBS in tension with kaon anomaly
- HL-LHC can probe full param. space for Cabibbo anomaly

Theory/experimental input for CKM unitarity tests



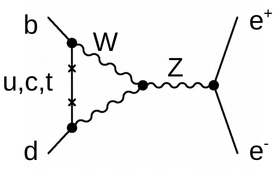
1. validate nuclear corrections to $0^+ \to 0^+$ with *ab initio* chiral EFT methods
2. evaluate radiative corrections to $n \to pe\nu$ in Lattice QCD
3. reduce exp. error on neutron lifetime, β asymmetry, β-ν correlation

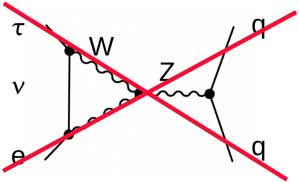
$$\delta\tau_n = 0.1\,\mathrm{s}, \qquad \delta A/A = 0.1\%, \qquad \delta a/a = 0.1\%$$

in reach of UCNτ+, PERC, UCNA+, Nab

Lepton-flavor-violation and the Electron-Ion-Collider

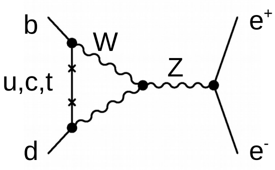
Charged lepton flavor violation

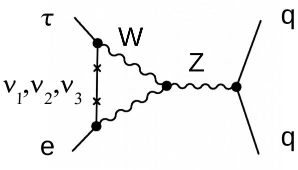




- mismatch between quark weak and mass eigenstates
  $\Longrightarrow$ quark family number is not conserved
  visible in several rare $\Delta F = 1$ and $\Delta F = 2$ processes
- in minimal SM with massless neutrinos, no such mismatch
  $\Longrightarrow$ lepton family (LF) is exactly conserved

Charged lepton flavor violation



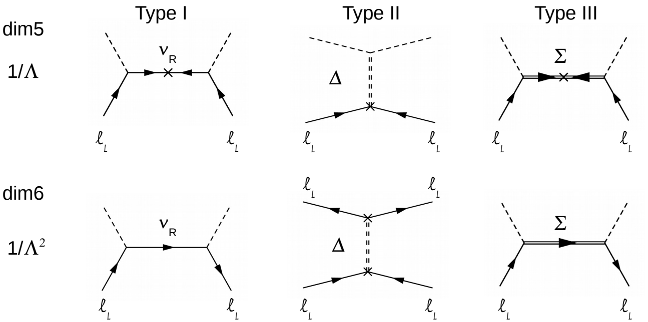


- mismatch between quark weak and mass eigenstates
  $\Longrightarrow$ quark family number is not conserved
  visible in several rare $\Delta F = 1$ and $\Delta F = 2$ processes
- in minimal SM with massless neutrinos, no such mismatch
  $\Longrightarrow$ lepton family (LF) is exactly conserved
- but neutrino have masses! oscillation exps. imply LF broken in neutrino sector
- …still charged LFV highly suppressed by GIM mechanism

$$\mathrm{BR} \sim \left(\frac{m_\nu}{m_W}\right)^4 \sim 10^{-44}$$

S. Petcov, ‘77; W. Marciano and A. Sanda, ‘77

Charged lepton flavor violation

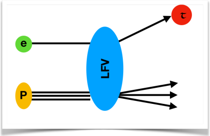


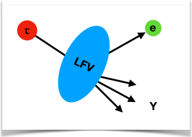
- . . . however, models that explain m_ν usually introduce new CLFV at tree or loop level

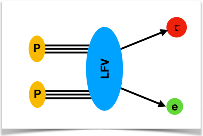
e.g. type I, II and III see-saw
A. Abada, C. Biggio, F. Bonnet, M. B. Gavela, T. Hambye, ‘08

- CLFV experiments crucial to falsify TeV origin of m_ν

CLFV at low- and high-energy







- $\mu \to e$ transitions well constrained at low-energy
- study $\tau \to e$ transitions in τ and meson decays

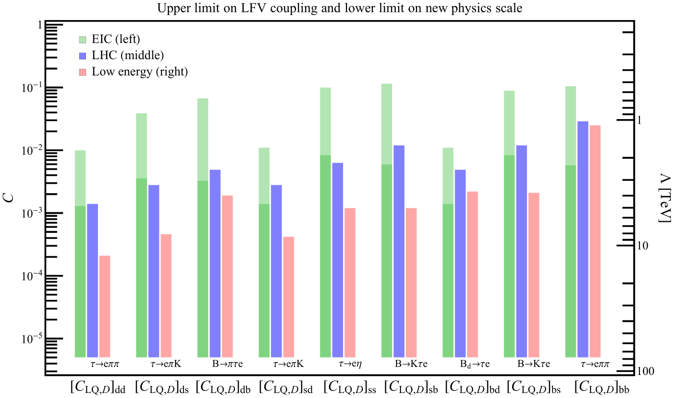
$$\tau \to e\gamma,\, \tau \to e\pi\pi,\, \tau \to eK\pi,\, B \to \pi\tau e,\, \ldots$$

- pp collisions

$$pp \to e\tau,\, h \to \tau e,\, t \to q\tau e\, \ldots$$

- & the upcoming EIC

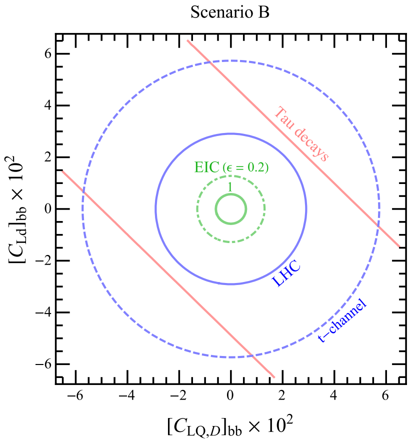
High-energy vs low-energy: four-fermion



EIC with $\sqrt{S} \sim 100$ GeV, $\mathcal{L} = 100$ fb^{-1}

- competitive on heavy flavor and flavor-changing channels
- complementary to Belle II and LHC

High-energy vs low-energy: four-fermion



EIC with $\sqrt{S} \sim 100$ GeV, $\mathcal{L} = 100\ \mathrm{fb}^{-1}$

- competitive on heavy flavor and flavor-changing channels
- complementary to Belle II and LHC

Conclusion

- exploit the complementarity of high- and low-energy to probe BSM physics
- EFTs powerful tools to connect different frontiers

How robust are collider constraints?

- extend to higher order in couplings, v/Λ expansions

How well do we control hadronic/nuclear theory?

- nucleon matrix elements with one/two weak currents in Lattice QCD
- two-nucleon matrix elements in Lattice QCD
- extend *ab initio* methods to medium mass and heavy nuclei