Effective Field Theories for BSM searches at low- and high-energy

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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

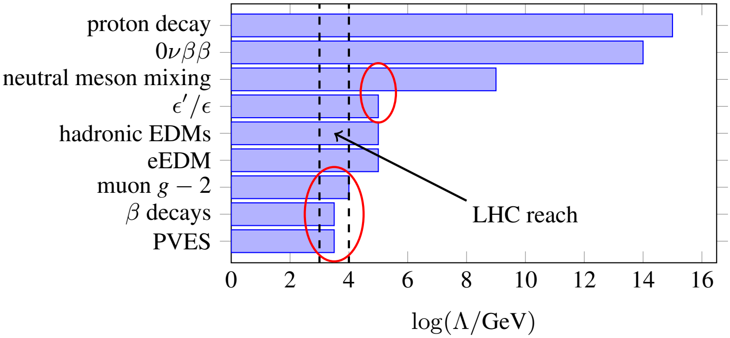
Finding new physics: the precision frontier

Majorana demonstrator

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

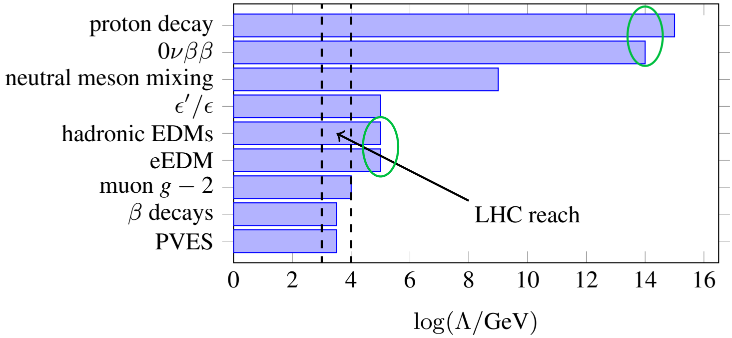
- electric dipole moments
- kaon physics
- rare B decays, $b \to s\gamma$
- muon and electron $g - 2$
- neutrinoless double β decay
- lepton flavor violation ($\mu \to e(\gamma)$)

Finding new physics: the precision frontier



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

Finding new physics: the precision frontier

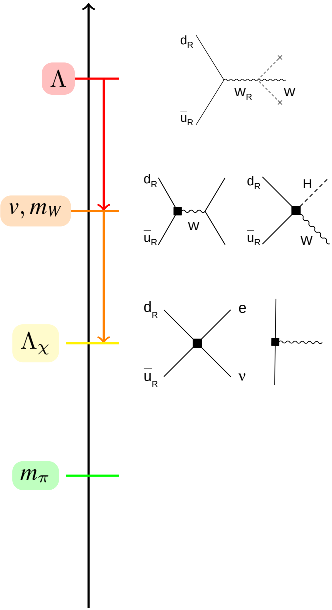


1. observables w. SM background
   need precise SM background to claim discovery

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 high- and low-energy probes



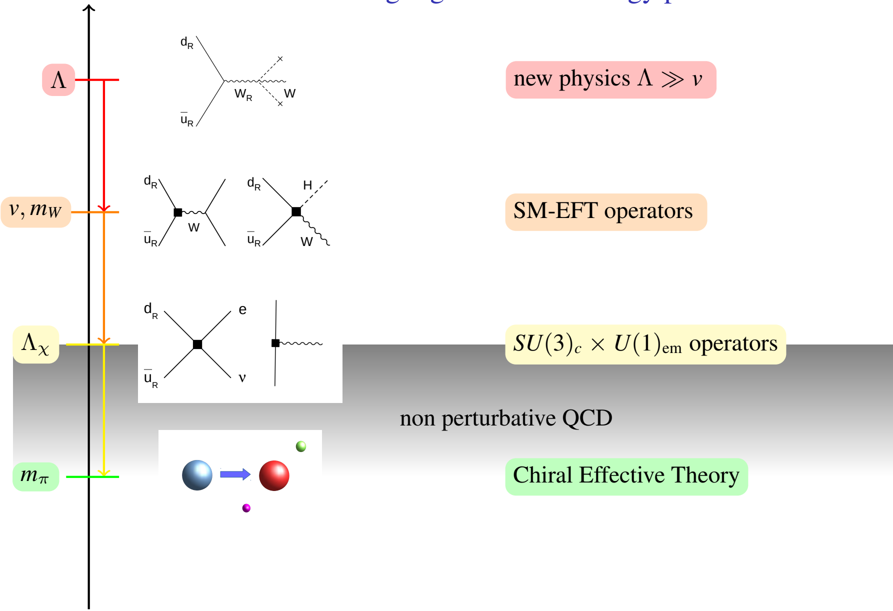
new physics $\Lambda \gg v$

SM-EFT operators

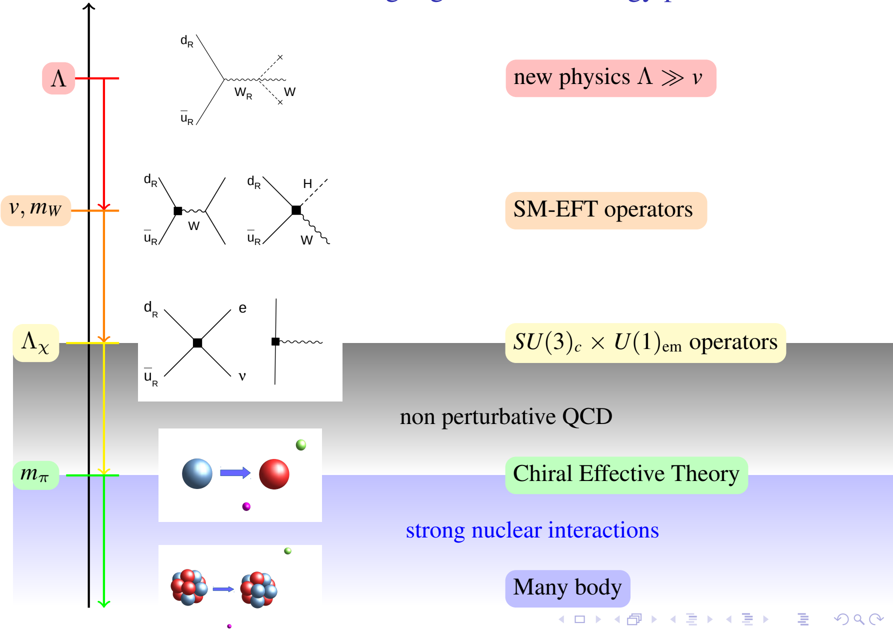
$SU(3)_c \times U(1)_{\rm em}$ operators

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

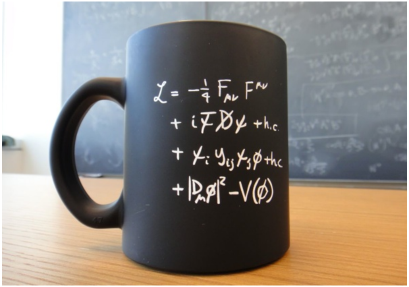
Connecting high- and low-energy probes



Connecting high- and low-energy probes



Effective Field Theories: the Standard Model

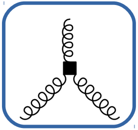


All possible operators:

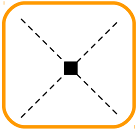
- written in terms of SM fields (and maybe some light ν_R)
- with local $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance
- organized in a power counting based on canonical dimension

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_{i,\,5}}{\Lambda} \mathcal{O}_{5\,i} + \sum \frac{c_{i,\,6}}{\Lambda^2} \mathcal{O}_{6\,i} + \sum \frac{c_{i,\,7}}{\Lambda^3} \mathcal{O}_{7\,i} + \dots$$

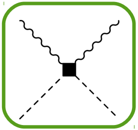
The Standard Model as an EFT



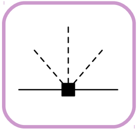
three/four bosons



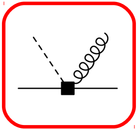
h self-coupling



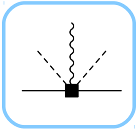
scalar-gauge



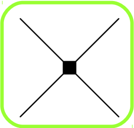
Yukawa



dipole



vector/axial currents



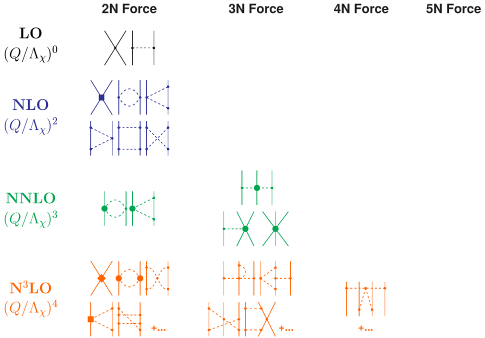
four-fermion

- **many** dimension 6, $\propto 1/\Lambda^2$

  Buchmuller & Wyler ‘86, Weinberg ‘89, de Rujula *et al.* ‘91, Grzadkowski *et al.* ‘10 . . .
- model independent description of BSM physics
- robust framework to analyze LHC data

see K. Mimasu, R. Boughezal, W. Altmannshofer

Effective Field Theories: Chiral EFT



from D. R. Entem and R. Machleidt, '17

see also:

P. Reinert, H. Krebs, E. Epelbaum, '18

M. Piarulli *et al*, '16

M. Piarulli *et al*, '14

A. Nogga, R. Timmermans, B. van Kolck, '05

D. Kaplan, M. Savage, M. Wise, '96

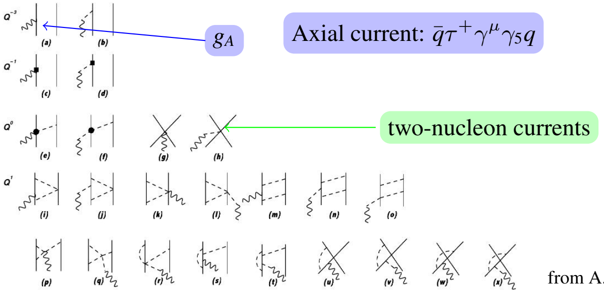
see talks by C. Drischler, H. Hergert, M. Piarulli

Exploit QCD symmetries & scale separation in hadronic/nuclear physics

$$Q \sim m_\pi \ll \Lambda_\chi = 4\pi F_\pi \sim 1 \text{ GeV}$$

- expand *NN* potential and external currents in Q/Λ_χ
- fit LECs to data in 2- and 3-nucleon systems & calculate everything else
- small expansion parameter allow for uncertainty estimation

External currents in chiral EFT



from A. Baroni *et al*, '16

- formalism can be applied to operators that mediate BSM interactions
- external currents consistent w. nuclear potential

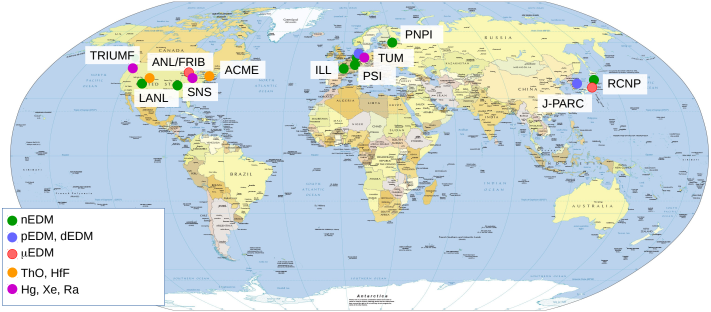
  e.g. vector, axial, scalar, pseudoscalar, tensor
- and symmetry-breaking potentials

  e.g. neutrino potential in $0\nu\beta\beta$, P- and T-violating potentials
- Lattice QCD needed for LECs!

see M. Wagman

Electric dipole moments and BSM CP violation

Electric dipole moments



- probe BSM CP-violation, needed for baryogenesis
- large worldwide experimental program

$$d_e < 1.0 \cdot 10^{-16}\, e\text{ fm} \qquad d_n < 1.8 \cdot 10^{-13}\, e\text{ fm}$$
$$d_{^{225}\text{Ra}} < 1.2 \cdot 10^{-10}\, e\text{ fm} \qquad d_{^{199}\text{Hg}} < 6.2 \cdot 10^{-17}\, e\text{ fm}$$

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

- orders of magnitude improvements in next generation G. Bison, R. Garcia Ruiz, Y. Sato, A. Tewsley-Booth, W. Schreyer, F. Piegsa, J. Chen, R. Mammei, A. Aleksandrova, J. Singh

CP violation in the SM(EFT)

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}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$	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

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

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

CP violation in the SM(EFT)

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	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	[illegible]	[illegible]	[illegible]
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	[illegible]	[illegible]	[illegible]	[illegible]
$X^2\varphi^2$		[illegible]		[illegible]	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	[illegible]	[illegible]	[illegible]
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	[illegible]	[illegible]	[illegible]
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	[illegible]	[illegible]	[illegible]
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	[illegible]	[illegible]	[illegible]
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	[illegible]	[illegible]	[illegible]
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu}B^{\mu\nu}$	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}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
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$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
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[illegible]	[illegible]	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
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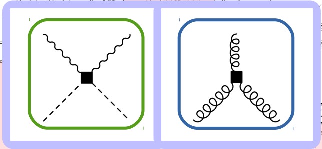
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

[illegible]		B-violating	
[illegible]	[illegible]	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$
Q_{quqd}	[illegible]	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q^j_p T^A u_r)\varepsilon_{jk}(\bar q^k_s T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$Q_{lequ}^{(1)}$	$(\bar l^j_p e_r)\varepsilon_{jk}(\bar q^k_s u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q^k_s\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$



Grzadkowski *et al.* ‘10

- two CPV sources in SM

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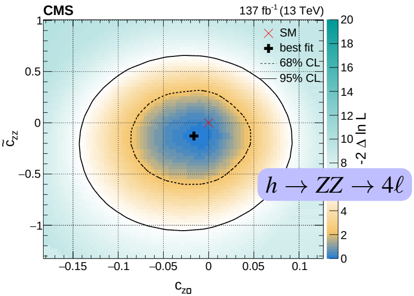
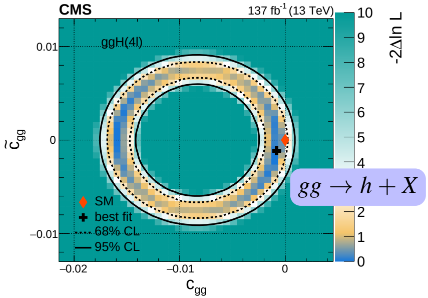
- 53 (1350) CP-even, 23 (1149) CP-odd dimension-6 operators ($\mathcal{O}(v^2/\Lambda^2)$)
- focus on bosonic operators

arise in “universal theories”, evade flavor bounds

Collider constraints on CPV operators





CMS 2104.12152

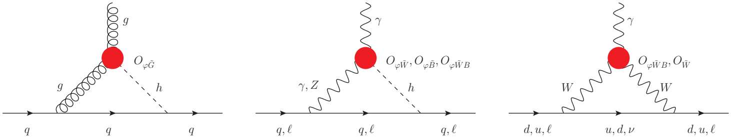
- used to be an afterthought, more and more SMEFT analyses coming up

ATLAS: 1905.04242, 2202.11382, ...
CMS: 1907.03729, 2110.11231, 2104.12152, ...

- most studies involve heavy SM particles (Higgs, WW, WZ, single t, $\bar{t}t$)
- CPV-sensitive observables via angular correlations
- $\Lambda \lesssim 1 - 2$ TeV, larger sensitivity for loop-dominated processes

See A. Gritsan et al, 2104.12152, 2109.13363 for HL-LHC study and A. McDougall

Matching & running to low energy



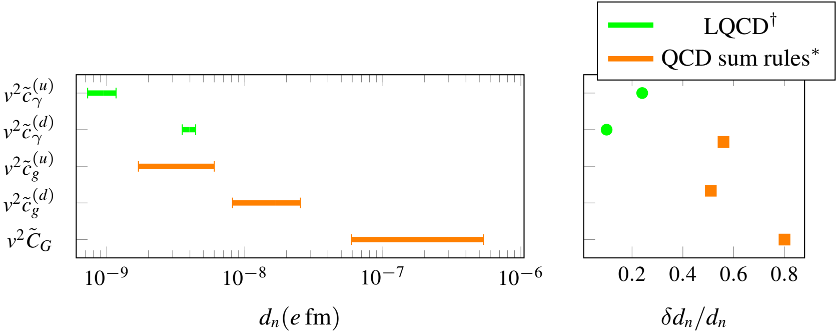
- $C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{W}B}$, $C_{\varphi\tilde{B}}$ and $C_{\tilde{W}}$ $\Longrightarrow$ lepton & quark EDM @ 1 EW loop
- gluonic operators $\Longrightarrow$ qCEDM and gCEDM @ $\mathcal{O}(\alpha_s)$

10^{-2} – 10^{-3} suppression

- flavor observables suppressed by same CKM/mass factors as in SM
- hadronic matrix elements?

$\tilde{c}_{\gamma}^{(q)} \langle N\gamma|\bar{q}\sigma^{\mu\nu} q\tilde{F}_{\mu\nu}|N\rangle$ $\tilde{c}_{g}^{(q)} \langle N\gamma|\bar{q}\sigma^{\mu\nu}\tilde{G}_{\mu\nu} q|N\rangle$ $C_{\tilde{G}}\langle N\gamma|G^{\mu\rho}G^{\nu}_{\rho}\tilde{G}_{\mu\nu}|N\rangle$

From quarks to hadrons. Nucleon EDM matrix elements



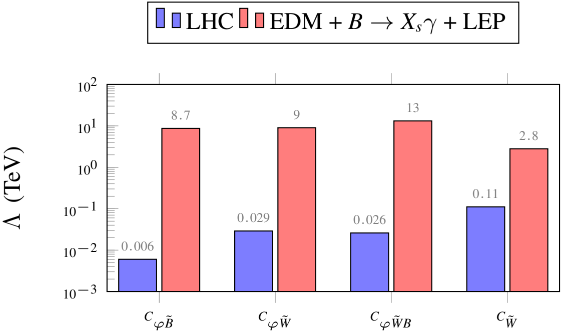
† FLAG ‘21   * Pospelov and Ritz, ‘05, Haisch and Hala, ‘19

- small error on the eEDM and ThO precession frequency

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

- tensor charges control qEDMs, very well calculated in Lattice QCD
- large (uncontrolled) errors on purely hadronic operators

Constraints on weak gauge-Higgs operators

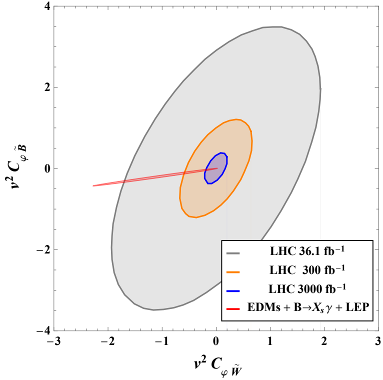


$$C_X = \frac{1}{(4\pi\Lambda)^2}$$

V. Cirigliano, A. Crivellin, W. Dekens, J. de Vries, M. Hoferichter, EM, '19

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

Constraints on weak gauge-Higgs operators



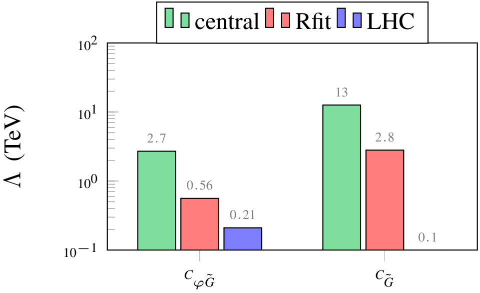
marginalized over $C_{\tilde{W}}$, $C_{\varphi \tilde{W} B}$

LHC projections of Bernlochner *et al*, '18

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

strong correlations to avoid EDMs

Constraints on gluonic operators



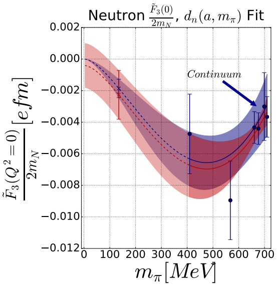
"central":
no theory errors

"Rfit":
vary ME in allowed th. ranges

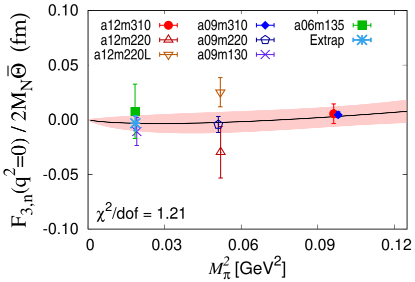
- depend strongly on treatment of hadronic uncertainties
- limits on $C_{\varphi\tilde{G}}$, $C_{\tilde{G}}$ weakened by factor ~ 20
- very close to collider constraints

need improved LQCD & nuclear theory calculations

Lattice QCD calculations of EDMs



J. Dragos, T. Luu, A. Shindler, *et al* '19



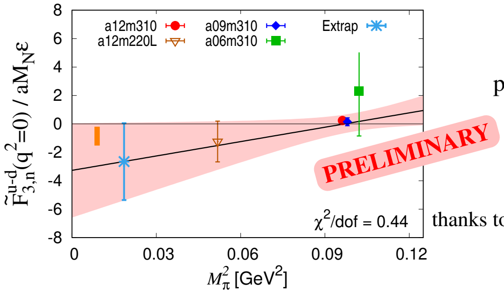
T. Bhattacharya, *et al*, '21

- EDM from QCD $\bar{\theta}$ term extremely challenging

  vanishing signal at small m_π, large excited state contamination, ...
- published results compatible with zero
- approaching $d_n \sim 10^{-3}\,\bar{\theta}\,e\,\mathrm{fm}$, size of "chiral log"

Crewther, Di Vecchia, Veneziano and Witten, '79

EDMs from dimension-6 operators



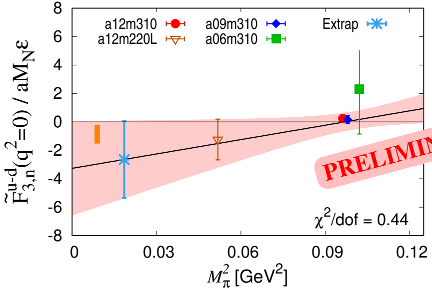
$\bar{q}\tau_3\sigma\tilde{G}q$

power div. subtracted

thanks to T. Bhattacharya and B. Yoon

- preliminary results for qCEDM and gCEDM
- complicated by power divergences on the lattice
- error still a factor of 5 larger than QCD sum rule estimate

EDMs from dimension-6 operators



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- preliminary results for qCEDM and gCEDM
- complicated by power divergences on the lattice
- error still a factor of 5 larger than QCD sum rule estimate

- sustained effort in LQCD community
- EFT/LQCD collaboration for renormalization and excited state subtraction

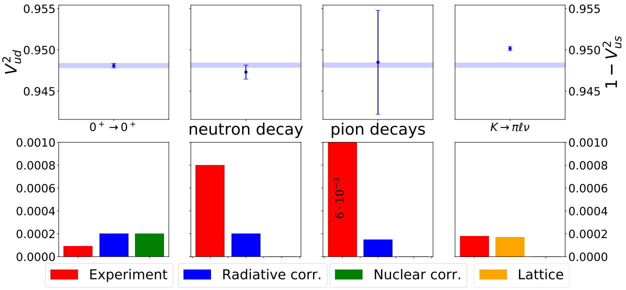
more results coming soon!

see A. Shindler and T. Bhattacharya, J. Kim, K. F. Liu, A. Shindler at Lattice 2022

BSM in charged-current interactions.
The Cabibbo anomaly and more

see R. Pattie, EW β decay session

CKM unitarity and the Cabibbo anomaly



adapted from Towner and Hardy, '18

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

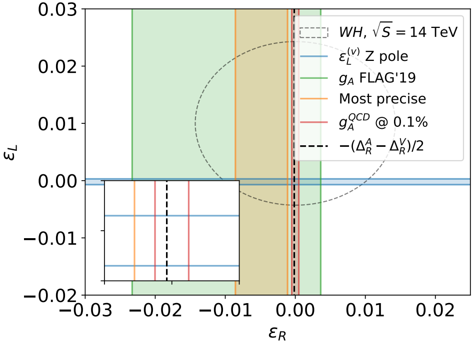
  C. Y. Seng, M. Gorchtein, H. Patel, M. Ramsey-Musolf, '18; A. Czarnecki, W. Marciano, A. Sirlin, '19; J. C. Hardy and I. S. Towner, '20

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

  A. Bazavov, *et al*, FLAB and MILC, '18; FLAG21

$$\Delta = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = (1.5 \pm 0.7) \cdot 10^{-3}$$

β decays probes of BSM physics: g_A



$$\epsilon_R V_{ud} \bar{u}_R \gamma^\mu d_R W_\mu$$

from L. Hayen, '21

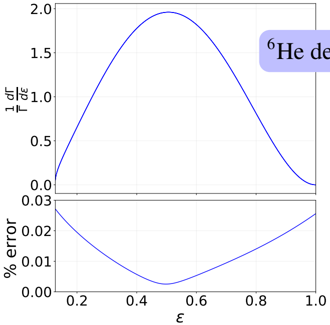
- nucleon axial coupling g_A sensitive to right-handed currents

$$\frac{g_A}{g_V} = g_A^{\text{LQCD}} \left(1 + \frac{1}{2} \left(\Delta_R^A - \Delta_R^V \right) - 2(\epsilon_R)_{ud} \right),$$

- **if** EM corrections $\Delta_R^A - \Delta_R^V$ under control **and** $g_A^{\text{LQCD}} \lesssim 1\%$

$\Longrightarrow$ outperform collider probes of RH currents
& sensitive to RH current explanations of Cabibbo anomaly

β decays probes of BSM physics: β spectra



^{6}He decay

$$\frac{d\Gamma}{d\varepsilon} = \frac{G_F^2 W_0^5 V_{ud}^2}{2\pi^3}\sqrt{1-\frac{m_e^2}{E_e^2}}\,\varepsilon^2(1-\varepsilon)^2\,\frac{4\pi}{3}\,|L_1^{(0)}|^2$$

$$\times\left(1-8\frac{m_e}{E_e}\frac{g_T\epsilon_T}{g_A}+\mathcal{O}\left(\frac{\mathcal{Q}}{m_N},\frac{\mathcal{Q}^2}{m_\pi^2},\alpha_{\rm em}\right)\right)$$

$$\mathcal{Q}\sim 4\text{ MeV}$$

- spectral shape determined by phase space and small recoil/EM corrections
- next generation of experiments aims at 10^{-3}-10^{-4} uncertainties
- probe of chiral-breaking charged-currents at $\Lambda \sim 10$ TeV

is theory controlled at the same level?

^{6}He-CRES

W. Byron[1], W. DeGraw[1], M. Fertl[2], A. Garcia[1], B. Graner[1], H. Harrington[1], L. Hayen[3], X. Huyan[4] , D. McClain[5], D. Melconian[5], P. Mueller[6], N. Oblath[4], R.G.H. Robertson[1], G. Rybka[1], G. Savard[6], D. Stancil[3], D.W. Storm[1], H.E. Swanson[1], R.J. Taylor[3], B.A. VanDevender[4], F. Wietfeldt[7], A. Young[3]

Cyclotron **R**adiation **E**mission **S**pectroscopy

Beta in magnetic field produces cyclotron radiation

$$f = \frac{|e|c^2}{2\pi}\frac{B}{E}$$

He6-CRES phases

Phase I: proof of principle

- Observe ^{83}Kr lines
- Understand RF issues and spectra
- Study power distribution
- Show detection of cycl. radiation from ^{6}He

done

Recently demonstrated:

- 5 keV- 5 MeV capability of detection
- measurements of $\beta^{\pm}$ from ^{6}He and ^{19}Ne

Phase II: first measurement ($b < 10^{-3}$)

- ^{6}He and ^{19}Ne measurements.
- Develop ^{14}O source.

Starting

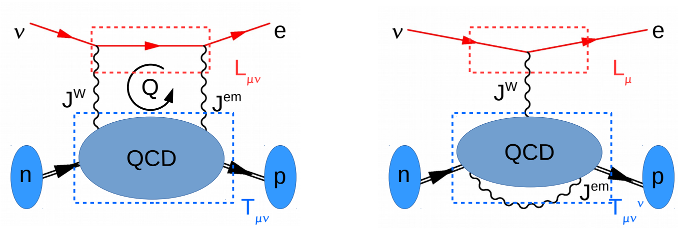
Phase III: ultimate measurement ($b < 10^{-4}$)

- ^{14}O measurements.
- ion-trap for no limitation from geometric effect.

See talk at CIPANP by Heather Harrington

see H. Harrington thanks to A. Garcia

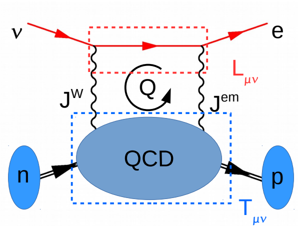
Radiative corrections to nucleon decay

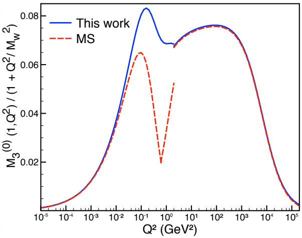


$$|V_{ud}|^2_{\text{neutron}} = \frac{5024.7\,\text{s}}{\tau_n(1+3g_A^2)(1+\delta_R(E_0)+\Delta_R^V)}, \qquad \Delta_R^V = \frac{\alpha}{2\pi}\left(4\ln\frac{m_Z}{m_p}+\Delta_{\text{np}}\right)$$

- $\delta_R(E_0)$ (universal soft photon emission) and ptb. log dominate EM corrections
- Δ_{np} is nonperturbative and small, but dominates the error
- for Fermi decays, Δ_{np} proportional to the $W-\gamma$ box

Radiative corrections to nucleon decay





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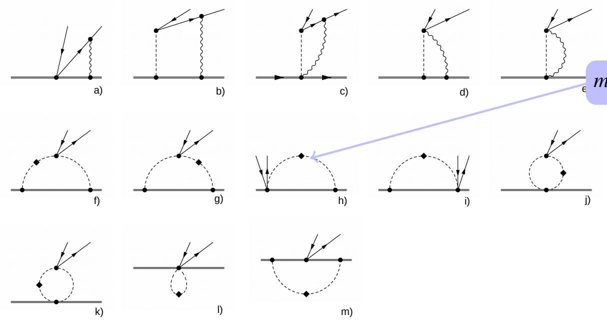
- $\delta_R(E_0)$ (universal soft photon emission) and ptb. log dominate EM corrections
- Δ_{np} is nonperturbative and small, but dominates the error
- for Fermi decays, Δ_{np} proportional to the $W-\gamma$ box
- new dispersive analysis

$$\Delta_R^V = 0.02361(38) \rightarrow 0.02467(22)$$

C. Y. Seng, M. Gorchtein, M. Ramsey-Musolf, '18; + H. Patel, '18.

Pion-induced electromagnetic corrections to g_A



$$m^2_{\pi^+} - m^2_{\pi^0} = 2Z_\pi F^2_\pi e^2$$

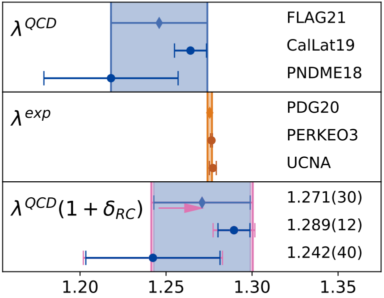
- very small EM corrections to g_A/g_V in standard methods

$$\Delta^A_R - \Delta^V_R = 0.60(5) \cdot 10^{-3}$$

L. Hayen, '21; C. Y. Seng, M. Gorchtein, '21

- chiral EFT analysis reveals overlooked pion-mediated corrections

Pion-induced electromagnetic corrections to g_A



$$g_A = g_A^{\mathrm{QCD}} \left(1 + \frac{\alpha}{2\pi} \sum \Delta_{\mathrm{em}}^{(n)}\right)$$

V. Cirigliano, J. de Vries, L. Hayen, EM, A. Walker-Loud, '22

see L. Hayen's talk

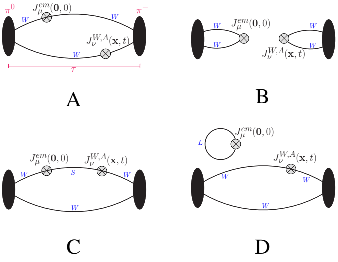
- no corrections to the vector current
- sizable correction to g_A

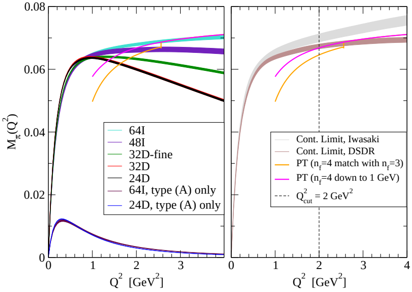
$$\frac{\alpha}{2\pi}\left(\Delta_{\mathrm{em}}^{(0)} + \Delta_{\mathrm{em}}^{(1)}\right) = 1.9\% + \frac{\alpha}{2\pi}\hat{C}_A$$

- shift improves agreement between LQCD and data, but need to predict $\hat{C}_A$!
- construct QCD representation of $\hat{C}_V$ and $\hat{C}_A$ (for lattice/models)?

in progress with **O. Tomalak** and V. Cirigliano

$W-\gamma$ box in Lattice QCD



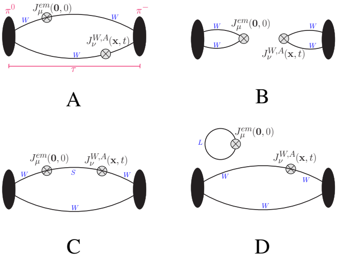


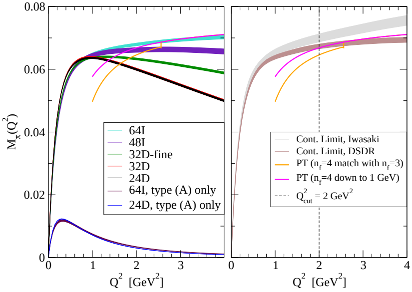
thanks to B. Yoon

X. Feng, *et al*, '20; C. Y. Seng, *et al*, '20

- first calculations for $\pi^0 \to \pi^- e\nu$ & $K \to \pi\ell\nu$
- good agreement between LQCD & dispersive approach

$W-\gamma$ box in Lattice QCD





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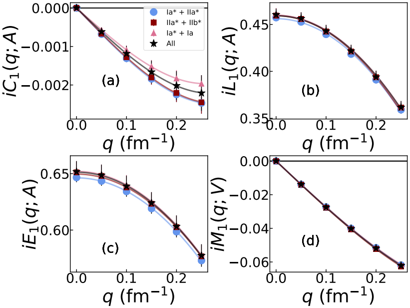
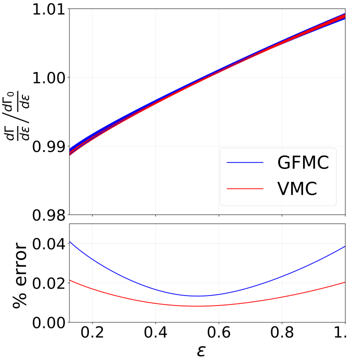
X. Feng, *et al*, '20; C. Y. Seng, *et al*, '20

- first calculations for $\pi^0 \to \pi^- e\nu$ & $K \to \pi\ell\nu$
- good agreement between LQCD & dispersive approach
- calculations for neutron decay in progress:

1. signal to noise? excited state contamination?
2. beyond the $W-\gamma$ box for GT decays?

^{6}He β spectrum in chiral EFT

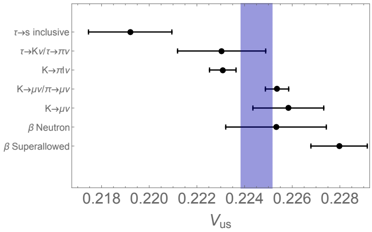




G. B. King, **A. Baroni**, *et al*, ‘22; A. Glick-Magid, D. Gazit (*et al*), ‘21, ‘22

- SM uncertainties validated by 2 *ab initio* calculations
- estimate theory error by varying EFT cut-off, *NN* energy range input for three-body force & QMC method
- total error on normalized spectrum well below 10^{-3}

Fitting the Cabibbo anomaly in LEFT



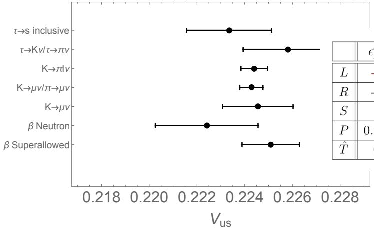
V. Cirigliano, D. Diaz-Calderon, A. Falkowski, M. Gonzalez-Alonso, A. Rodriguez-Sanchez, '21

- most general charged-current Lagrangian at low-energy

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

- can be fit by new left- or right-handed charged-currents
- scalar, pseudoscalar and tensor currents do not improve the fits

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

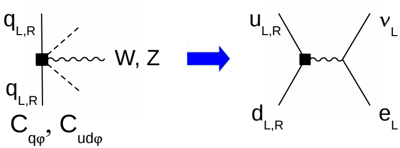
- most general charged-current Lagrangian at low-energy

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

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

- can be fit by new left- or right-handed charged-currents
- scalar, pseudoscalar and tensor currents do not improve the fits

Charged currents in the SMEFT



- ϵ are defined in a low-energy theory w/o $SU(2)_L \times U(1)_Y$ invariance

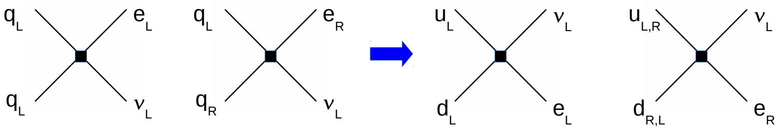
  to make contact with high-energy pheno, match to SMEFT !

1. "vertex corrections": correlated corrections to W and Z couplings

   affect Higgs and electroweak precision data

$$\epsilon_L = v^2 \left(C_{\varphi\ell}^{(3)} + C_{\varphi q}^{(3)} \right) \qquad \epsilon_R = \frac{1}{2} v^2 C_{\varphi ud}$$

Charged currents in the SMEFT



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to make contact with high-energy pheno, match to SMEFT !

1. "vertex corrections": correlated corrections to W and Z couplings

   affect Higgs and electroweak precision data

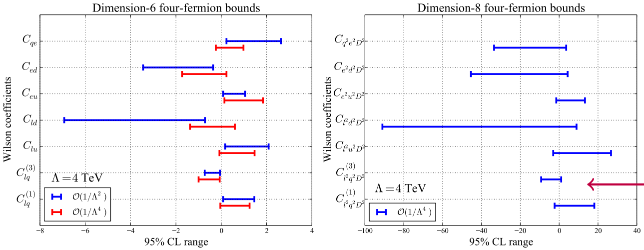
2. 5-fermion operators (2 purely left-handed, 3 scalar/tensor)

   corrections to high-invariant mass Drell-Yan

$$\epsilon_L = v^2\left(C^{(3)}_{\varphi\ell} + C^{(3)}_{\varphi q}\right) - v^2 C^{(3)}_{\ell q} - v^2 C^{(3)}_{\ell\ell}, \qquad \epsilon_R = \frac{1}{2} v^2 C_{\varphi ud}$$

$$\epsilon_P = \frac{v^2}{2}\left(C_{ledq} - C^{(1)}_{lequ}\right), \qquad \epsilon_S = \frac{v^2}{2}\left(C_{ledq} - C^{(1)}_{lequ}\right), \qquad \epsilon_T = -\frac{v^2}{2} C^{(3)}_{lequ}$$

Dimension-8 contributions to Drell-Yan



$D^\nu(\bar{q}\gamma^\mu q)D_\nu(\bar{\ell}\gamma_\mu \ell)$

charged currents

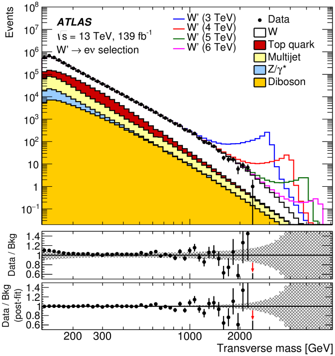
R. Boughezal, F. Petriello, EM, '21

- 4-fermion operators affect the high m_T, $m_{\ell\ell}$ tails in charged/neutral current DY
- need dim-8 contribution for consistent analysis
- high-energy data sensitive to classes of dim-8 ops at 2-4 TeV scale
- with 8 TeV data

$(\epsilon_L)_{4f} \in [0, 3.4] \cdot 10^{-3} \quad 95\% CL$ $\qquad (\epsilon_L)_{4f}|_{\rm CKM} \in [-8.9, -5.4] \cdot 10^{-4}$

disfavoring 4-fermion interpretation of V_{ud}/V_{us} anomaly

V_{ud}/V_{us} vs colliders. 13 TeV data



more data and higher masses!

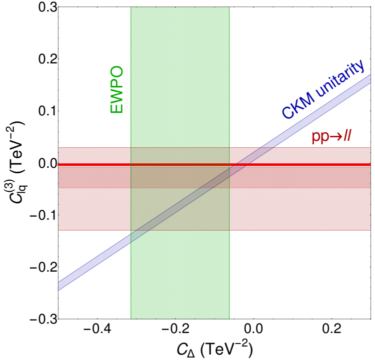
- in a single coupling analysis

$$(\epsilon_L)_{4f} \in [0, 2.5] \cdot 10^{-4} \quad 95\% CL \qquad\qquad (\epsilon_L)_{4f}|_{\rm CKM} \in [-8.9, -5.4] \cdot 10^{-4}$$

- bound is stable against including dim-8 corrections

V. Cirigliano, W. Dekens, J. de Vries, EM, T. Tong, *in preparation*

Electroweak precision observables and the *W* anomaly



$$C_\Delta = 2\left(C_{q\varphi}^{(3)} - C_{\ell\varphi}^{(3)} + \hat{C}_{\ell\ell}\right)$$

LHC 13 TeV

V. Cirigliano, W. Dekens, J. de Vries, EM, T. Tong, '22

- *L*-handed vertex corrections contribute to EW precision observables (EWPO)
- in MFV, tension between EWPO, W mass, DY and V_{ud}/V_{us} anomaly

right-handed currents most viable explanation?

Conclusion

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

How robust are collider constraints?

- extend to higher order in couplings, v/Λ expansions
- dedicated high-invariant-mass SMEFT studies @ATLAS, CMS?

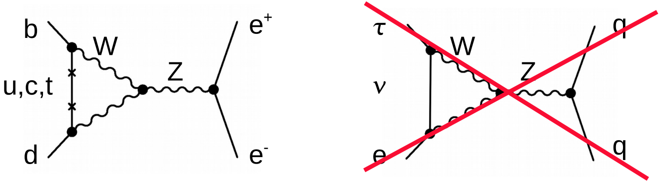
How well do we control hadronic/nuclear theory?

- 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

Backup

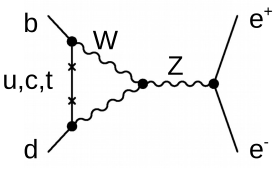
Lepton-flavor-violation and the Electron-Ion-Collider

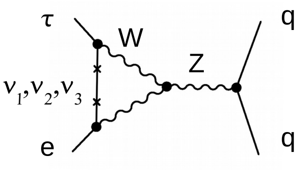
Charged lepton flavor violation



- 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



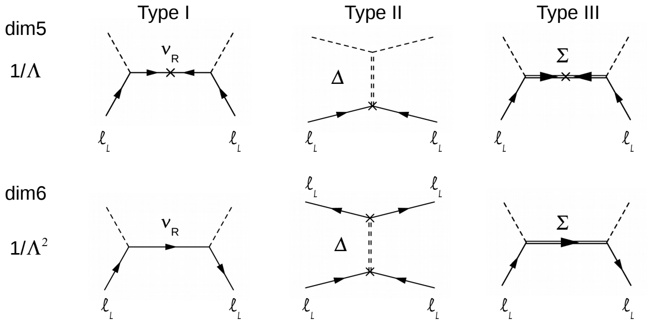


- mismatch between quark weak and mass eigenstates
  $\Longrightarrow$ quark family number is not conserved
  visible in several rare $\Delta F = 1$ and $\Delta F = 2$ processes
- in minimal SM with massless neutrinos, no such mismatch
  $\Longrightarrow$ lepton family (LF) is exactly conserved
- but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

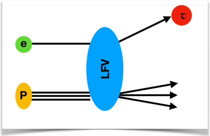


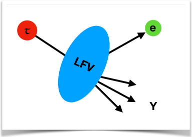
- ... however, models that explain m_ν usually introduce new CLFV at tree or loop level

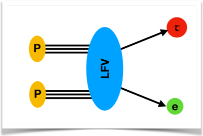
e.g. type I, II and III see-saw
A. Abada, C. Biggio, F. Bonnet, M. B. Gavela, T. Hambye, '08

- 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

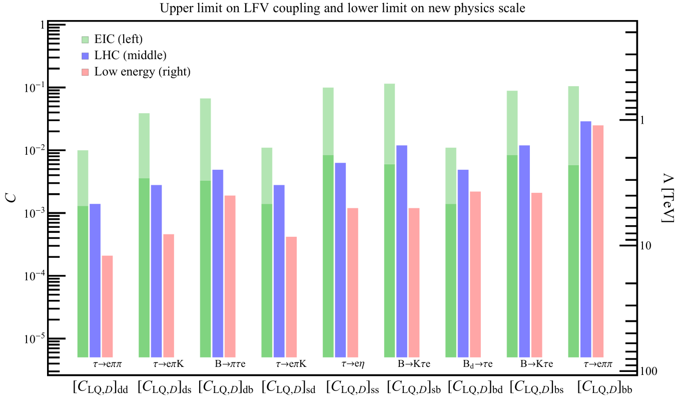
$$\tau \to e\gamma,\, \tau \to e\pi\pi,\, \tau \to eK\pi,\, B \to \pi\tau e,\, \ldots$$

- *pp* collisions

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

- & the upcoming EIC

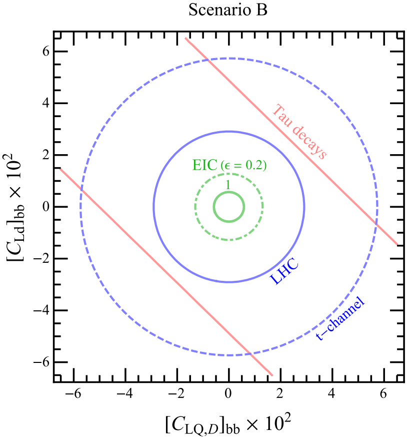
High-energy vs low-energy: four-fermion



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
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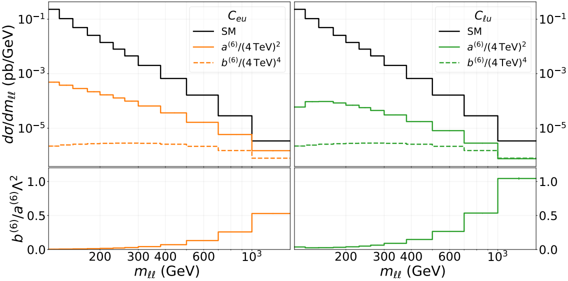
V_{ud}/V_{us} vs colliders in the SMEFT



$$\frac{d\sigma}{dm_{\ell\ell}} = \frac{d\sigma_{\rm SM}}{dm_{\ell\ell}} + \frac{a_i^{(6)}(m_{\ell\ell})}{\Lambda^2} C_i^{(6)} + \frac{b_{ij}^{(6)}(m_{\ell\ell})}{\Lambda^4} C_i^{(6)} C_j^{(6)},$$

- 4-fermion operators affect the high m_T, $m_{\ell\ell}$ tails in charged/neutral current DY
- for operators that interfere with SM,
  quadratic contributions as important as interference, even for converging EFT
- scalar, tensor only constrained via quadratic term

need dimension 8 operators!