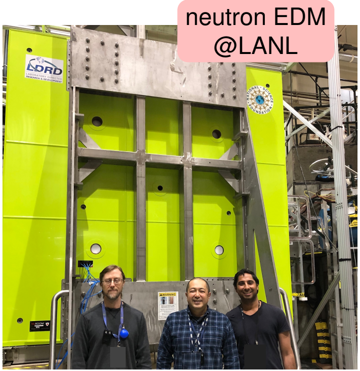
The synergy between low- and high-energy experiments and the role of the EIC.

E. Mereghetti

CFNS Workshop: New Opportunities for Beyond-the-Standard Model Searches at the EIC

Finding BSM: energy vs. precision frontier



- SM is (likely) a low-energy EFT of a more complete theory

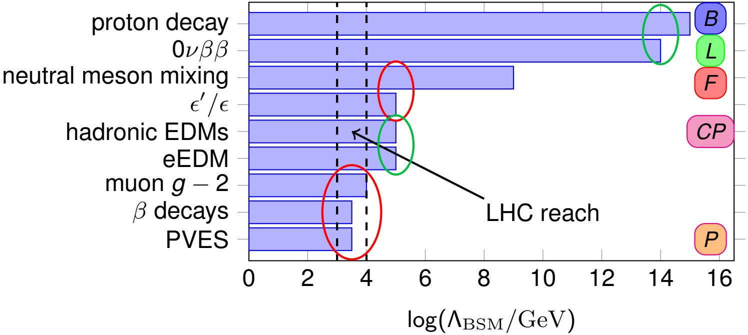
  matter-antimatter asymmetry, origin and nature of neutrino masses, dark matter . . .

1. LHC to directly create new particles at 1-10 TeV
2. search for tiny indirect effects in low-energy precision experiments

   $0\nu\beta\beta$, EDMs, $\mu \to e$ conversion, muon and electron $g-2$, . . . , EIC?

Finding BSM: energy vs. precision

$$O = (Q/\Lambda_{\rm BSM})^n$$



a. observables w/o (w. negligible) SM background: violation of SM symmetries, doors to new sectors?

- “naive” scale much larger than the TeV

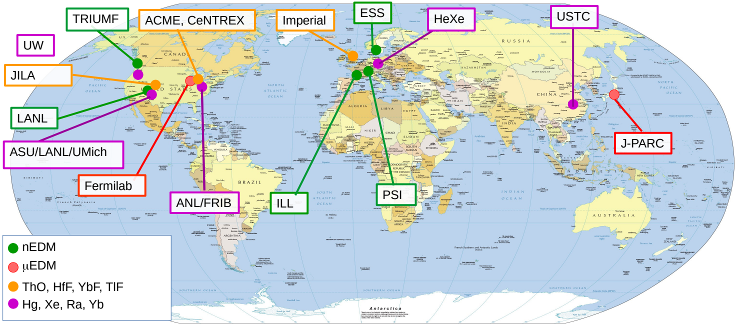
does the naive picture hold up?
what’s the role of the theory uncertainties?

b. observables w. SM background: need strong experiment/theory synergy to claim BSM discovery

- $\lesssim 0.5 \cdot 10^{-3}$ experimental/theory uncertainties needed to probe $>$ 10 TeV scale

CP violation

The EDM landscape



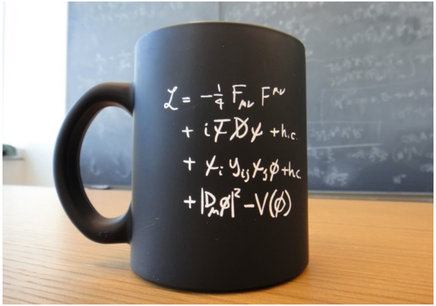
a. neutron EDM: $d_n < 1.8 \cdot 10^{-26}$ e cm (nEDM PSI) $\Longrightarrow 10^{-27}$-10^{-28} e cm

b. atomic EDMs: $d_{^{199}\mathrm{Hg}} < 6.2 \cdot 10^{-30}\, e\,\mathrm{cm}$, $d_{^{129}\mathrm{Xe}} < 4.2 \cdot 10^{-27}\, e\,\mathrm{cm}$, $d_{^{225}\mathrm{Ra}} < 2.2 \cdot 10^{-22}\, e\,\mathrm{cm}$,

c. Molecular EDMs: $d_e < 4.1 \cdot 10^{-30}\, e\,\mathrm{cm}$ (HfF exp.)

- great progress in the last 10 years, best limit on the eEDM
- searches in systems with Schiff or magnetic quadrupole moments under development

CP violation in the SM(EFT)



- two CPV sources in SM

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

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar R$	
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}	$(\bar l_p \gamma_\mu l_r$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

$\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$

Grzadkowski *et al.* ‘10

- two CPV sources in SM

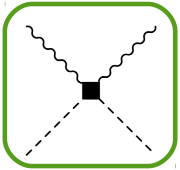
$$\mathcal{L}^{(4)}_{\rm CPV} = -\theta \frac{g_s^2}{64\pi^2}\varepsilon^{\alpha\beta\mu\nu} G_{\mu\nu} G_{\alpha\beta} + \bar u_L^i \left[V_{\rm CKM}\right]_{ij} \gamma^\mu d_L^j W_\mu$$

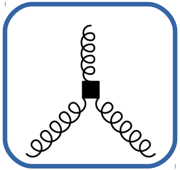
- 53 (1350) CP-even, 23 (1149) CP-odd dimension-6 operators ($\mathcal{O}(v^2/\Lambda^2)$)

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

- number flavor-diagonal CPV operators still limited
  6 Higgs-gauge, 9 Yukawas, 24 dipoles, 9 right-handed currents, . . . , 4 fermion

Higgs-gauge operators





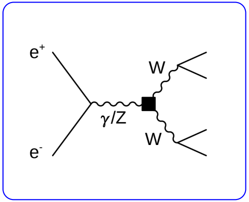
$$\mathcal{L} = -g^2 C_{\varphi\tilde{W}}\, \varphi^\dagger\varphi\, \tilde{W}^i_{\mu\nu} W_i^{\mu\nu} - g'^2 C_{\varphi\tilde{B}}\, \varphi^\dagger\varphi\, \tilde{B}_{\mu\nu} B^{\mu\nu} - gg' C_{\varphi\tilde{W}B}\, \varphi^\dagger\tau^i\varphi\, \tilde{W}^i_{\mu\nu} B^{\mu\nu}$$
$$- g_s^2 C_{\varphi\tilde{G}}\, \varphi^\dagger\varphi G^a_{\mu\nu}\tilde{G}_a^{\mu\nu} + \frac{C_{\tilde{G}}}{3}\, g_s f_{abc} \tilde{G}^a_{\mu\nu} G_b^{\nu\rho} G_\rho^{c\,\mu} + \frac{C_{\tilde{W}}}{3}\, g\varepsilon_{ijk} \tilde{W}^i_{\mu\nu} W_j^{\nu\rho} W_\rho^{k\,\mu}\,,$$

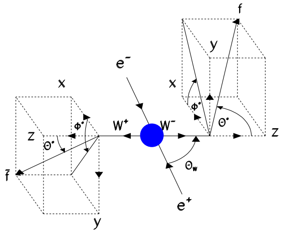
- CP-odd partners of operators contributing to EWPO
- motivated by “universal theories”: BSM couple to SM only via gauge/Yukawa currents

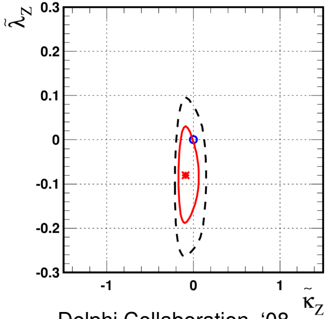
R. Barbieri, A. Pomarol, R. Rattazzi, A. Strumia, ‘04

- $C_{\varphi\tilde{W}B}$, $C_{\tilde{W}}$: anomalous $WW\gamma$ and WWZ couplings
- $C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{B}}$, $C_{\varphi\tilde{W}B}$, $C_{\varphi\tilde{G}}$: Higgs production and decay
- $C_{\tilde{G}}$: three gluon couplings

CPV Higgs-gauge operators. LEP







Delphi Collaboration, '08

- W polarization measurements at LEP2 constrain anomalous $WW\gamma$ and WWZ couplings

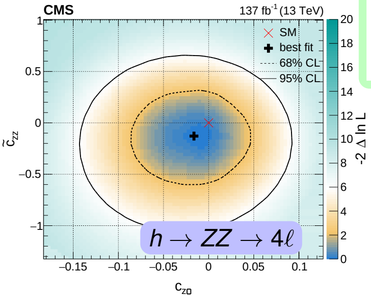
$$\tilde{\kappa}_Z = -0.12^{+0.06}_{-0.04} \qquad \tilde{\lambda}_Z = -0.09^{+0.07}_{-0.07}$$

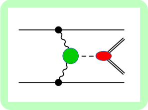
- can be mapped onto $\varphi^\dagger\varphi\tilde{W}B$ and $WW\tilde{W}$ SMEFT operators

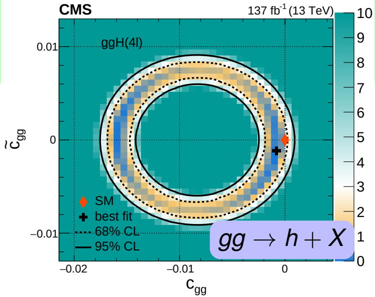
$$v^2 C_{\varphi\tilde{W}B} = -0.93^{+0.47}_{-0.31}, \qquad v^2 C_{\tilde{W}} = 0.42 \pm 0.33$$

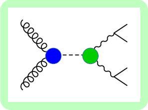
$\Lambda \sim 250 - 350$ GeV, sensitive to EW scale physics

CPV Higgs-gauge operators. LHC









CMS 2104.12152

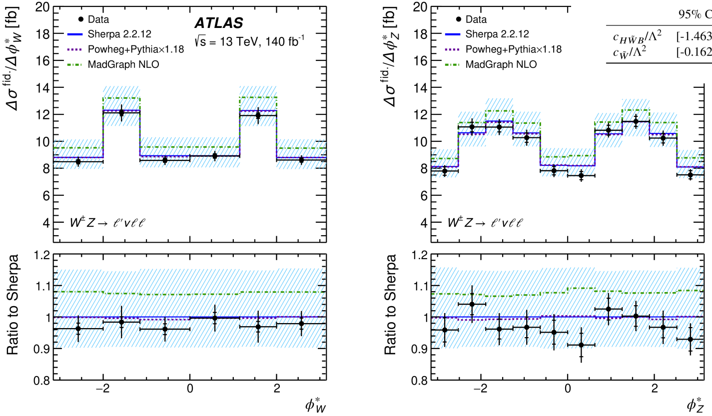
- more and more SMEFT analyses of CPV at LHC coming out

ATLAS: 1905.04242, 2202.11382, 2208.02338, ...
CMS: 1907.03729, 2110.11231, 2104.12152, ...

- Higgs-gauge couplings probed in *WW*, *WZ*, Higgs production and decay
- 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 and 2205.07715

CPV Higgs-gauge operators. LHC



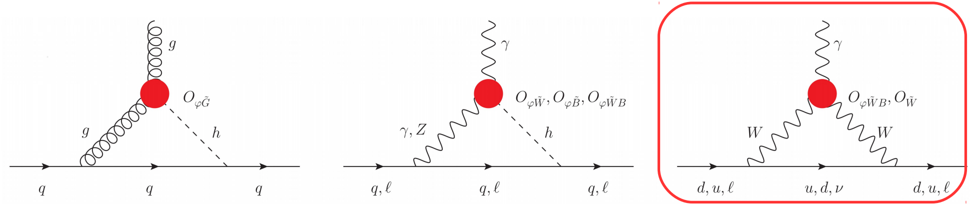
	Expected [TeV $^{-2}$]		Observed [TeV $^{-2}$]	
	95% CL (lin.)	95% CL (lin.+quad.)	95% CL (lin.)	95% CL (lin.+quad.)
$c_{H\tilde{W}B}/\Lambda^2$	[-1.463, 1.456]	[-1.458, 1.459]	[-1.625, 1.332]	[-1.505, 1.263]
$c_{\tilde{W}}/\Lambda^2$	[-0.162, 0.162]	[-0.127, 0.128]	[-0.186, 0.139]	[-0.109, 0.093]

ATLAS arXiv:2507.03500

- *WZ* production, sensitive to CP-odd operators via angular correlations
- bounds stable under inclusion of quadratic effects (real sensitivity to CP-violation)
- converting to our conventions

$$-0.16 < v^2 C_{\varphi\tilde{W}B} < 0.19 \qquad -0.05 < v^2 C_{\tilde{W}} < 0.04$$

EDM constraints on Higgs-gauge operators



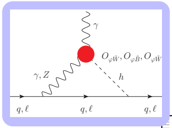
- Higgs-gauge operators run into dipoles at one-loop, typical suppression 10^{-2} - 10^{-3}
- e.g. $C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{W}B}$, $C_{\varphi\tilde{B}}$ and $C_{\tilde{W}}$ $\Longrightarrow$ lepton & quark EDM @ 1 EW loop

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

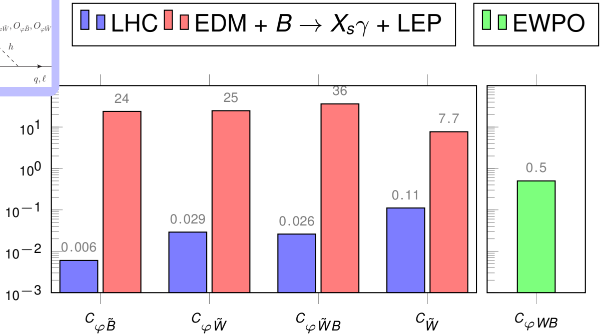
- gluonic operators $\Longrightarrow$ qCEDM and gCEDM @ $\mathcal{O}(\alpha_s)$
- matching & running links different low-energy observables.
  e.g. $C_{\varphi\tilde{W}B}$ and $C_{\tilde{W}}$ match on flavor-changing dipoles

correlations with $B \to X_s\gamma$, $K_L \to \pi^0 e^+ e^-$

Constraints on weak Higgs-gauge operators



$C = (4\pi\Lambda)^{-2}$



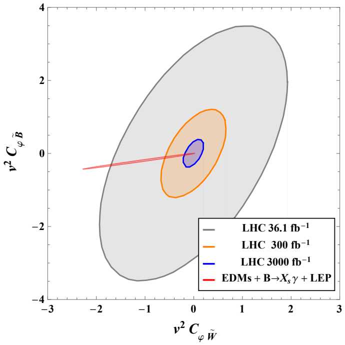
V. Cirigliano, A. Crivellin, W. Dekens, J. de Vries, M. Hoferichter, EM, ‘19

- eEDM dominates single coupling analysis (since then 2× improvement)

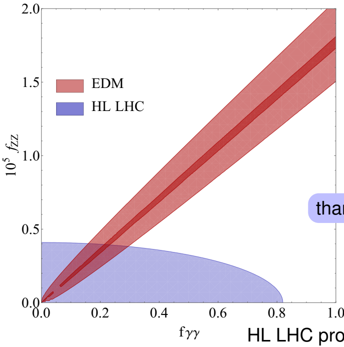
$$|v^2 C_{\varphi\tilde{B}}| < 5.1 \cdot 10^{-6}, \quad |v^2 C_{\varphi\tilde{W}}| < 4.7 \cdot 10^{-6}, \quad |v^2 C_{\varphi\tilde{W}B}| < 2.2 \cdot 10^{-6}, \quad |v^2 C_{\tilde{W}}| < 4.8 \cdot 10^{-5},$$

- couplings out of reach of LEP, LHC, EIC

Constraints on weak Higgs-gauge operators



LHC projections of Bernlochner *et al*, ‘18



thanks to W. Dekens

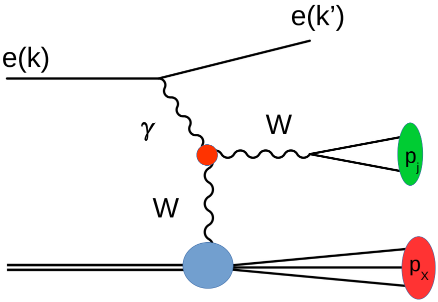
HL LHC projections from 2205.07715

- weak operators match and run into photon dipoles
- contribute to atomic EDMs via d_n, d_p $\Longrightarrow$ d_n, $d_{\rm Hg}$, $d_{\rm Xe}$ and $d_{\rm Ra}$ largely degenerate
- EDMs only constrain two directions in parameter space

need LEP, $B \to X_s\gamma$ or LHC to close free directions

- expect strong correlations to avoid EDMs

Higgs-gauge couplings at the EIC?

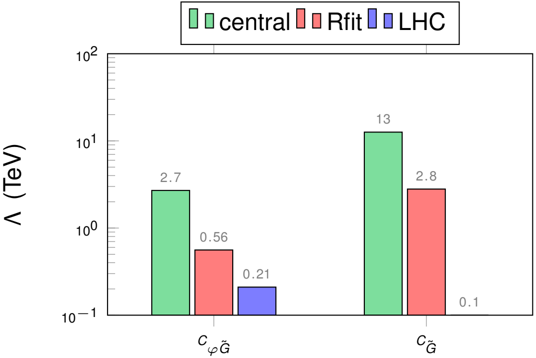


- can exploit beam (target) polarization to build naively T-odd quantities

$$\mathbf{S}_e \cdot (\mathbf{k}' \times \mathbf{p}_j), \qquad \mathbf{S}_p \cdot (\mathbf{k}' \times \mathbf{p}_j)$$

interesting channel to be studied?
enough cross section to be sensitive and compete with LHC?

Constraints on gluonic Higgs-gauge operators



"central": no theory errors

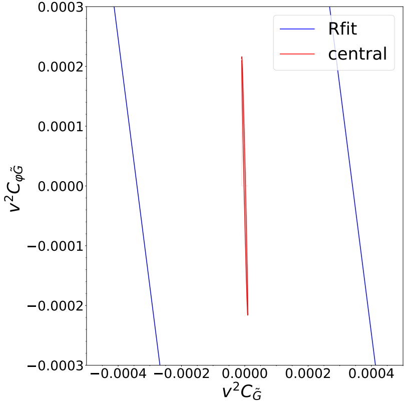
"Rfit": vary ME in allowed th. ranges

- match and run onto quark EDM, chromo-EDM and Weinberg operator

  constrained by d_n, d_{Hg}, d_{Xe}, d_{Ra}

- nucleon and nuclear matrix elements are poorly known
- limits depend strongly on how treat hadronic uncertainties
- once we account for theory errors, LHC limits from $gg \to h$ become competitive

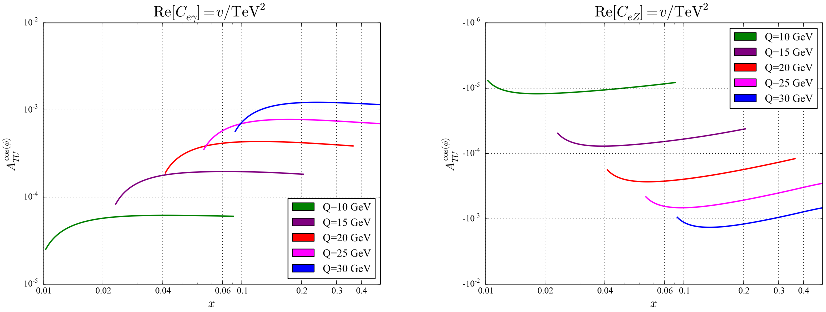
Constraints on gluonic Higgs-gauge operators



- hadronic and nuclear uncertainties severely weaken d_{Hg} constraint
- in a 2 couplings scenario, theory uncertainties lead to free directions
- couplings might be hard to study at EIC (jet substructure?)

can nucleon structure info from EIC help on the theory uncertainties?

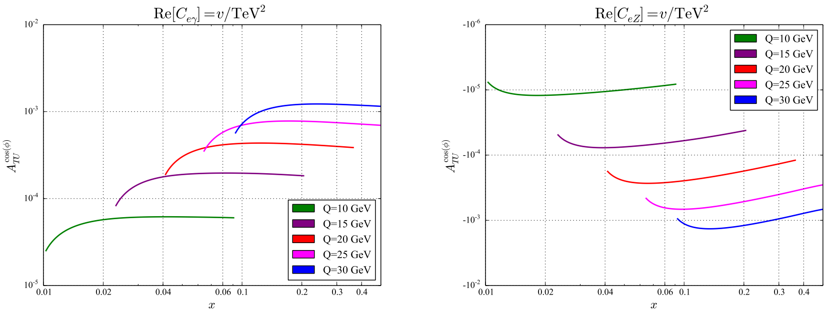
Dipoles at the EIC



- single-spin asymmetry (SSA) can probe SMEFT operators with different chiral structure from SM
  R. Boughezal, D. de Florian, F. Petriello, W. Vogelsang, '23
- transverse SSAs sensitive to CP-violation via $\varepsilon_{\mu\nu\rho\sigma} k^\mu k^{\nu\,\prime} P^\rho S_T^\sigma$
- SM contributions to the beam asymmetry suppressed by the lepton mass
- dipole contributions do not suffer from same suppression

$$\Delta A_{TU}(\phi) = \frac{g_Z}{2\pi\alpha}\frac{Q^3}{M_Z^3}\frac{y\sqrt{1-y}}{1-y+\frac{y^2}{2}}\frac{\sum_q Q_q f_q(x)\left[g_{aq}\mathrm{Re}[C_{eZ}e^{-i\phi}] - \mathrm{Re}[C_{e\gamma}e^{-i\phi}][g_{vq}g_{al}(1-2/y) - g_{aq}g_{vl}]/(s_W c_W)\right]}{\sum_q Q_q^2 f_q(x)}$$

Dipoles at the EIC



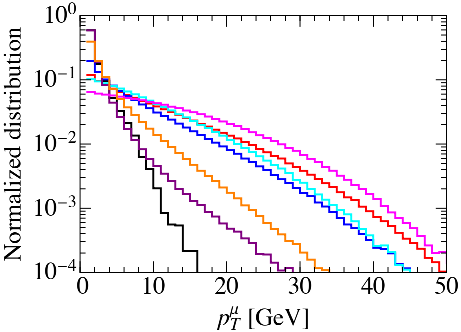
- for $\Lambda \sim 1$ TeV, measurable asymmetries can be produced.
- leverage y dependence to single out $C_{e\gamma}$ and C_{eZ}

orthogonal to eEDM, sensitive to one combination of $C_{e\gamma}$, C_{eZ}

- quark electric and magnetic dipole can be probed via target asymmetry
- other bilinears (Yukawa, RH currents) and semileptonic operators (scalar, tensor) suppressed

are there ways to probe remaining CP-odd SMEFT structures?

Lepton-flavor violating dipoles



$ep \to \tau X \to \mu \nu_\mu \nu_\tau X$

$\left[\Gamma^e_\gamma\right]_{\tau e}$

$\left[\Gamma^e_Z\right]_{\tau e}$

V. Cirigliano, *et al*, '21

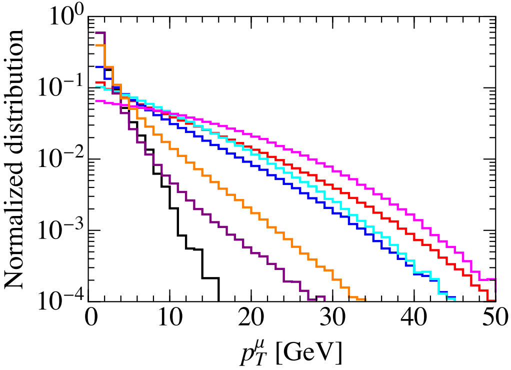
- similar analysis can be applied to lepton-flavor-violating dipoles $\bar{\tau}\sigma^{\mu\nu} e F_{\mu\nu}$ (see Kaori's talk)
- $\tau \to e\gamma$ strongly constrain one linear combination

$$\left|\Gamma^e_\gamma - 2 \cdot 10^{-2} \Gamma^e_Z\right| < 6.7 \cdot 10^{-6}$$

- EIC probes different linear combination

$$\hat{\sigma}^u_{RR(L)} = F_{\rm dip}(1-y)\left|\left[\Gamma^e_\gamma\right]_{\tau e} Q_u + \frac{z_{u_R}(z_{u_L})}{c_w^2 s_w^2} \frac{Q^2}{(Q^2+m_Z^2)} \left[\Gamma^e_Z\right]_{\tau e}\right|^2$$

Lepton-flavor violating dipoles



$ep \to \tau X \to \mu \nu_\mu \nu_\tau X$

$\left[\Gamma_\gamma^e\right]_{\tau e}$

$[\Gamma_Z^e]_{\tau e}$

V. Cirigliano, *et al*, '21

- similar analysis can be applied to lepton-flavor-violating dipoles $\bar{\tau}\sigma^{\mu\nu} e F_{\mu\nu}$ (see Kaori's talk)
- Z dipole has smaller cross section, but it is easier to suppress the background
- EIC can probe percent level couplings $\Longrightarrow \Lambda \sim 1$ TeV

$$\left|\Gamma_\gamma^e\right|_{\tau e}, \ \left|\Gamma_Z^e\right|_{\tau e} \lesssim 5.0 \cdot 10^{-2}$$

Summary 1.

- low-energy precision experiments naively dominate symmetry violation tests (B, L, LF, CP, . . .)

  naive BSM scale $\Lambda \gg 1 - 10$ TeV well beyond the TeV
- in a bottom-up approach, low-energy cannot constrain all directions in parameter space
- relatively easily to engineer scenarios in which LHC/EIC are competitive

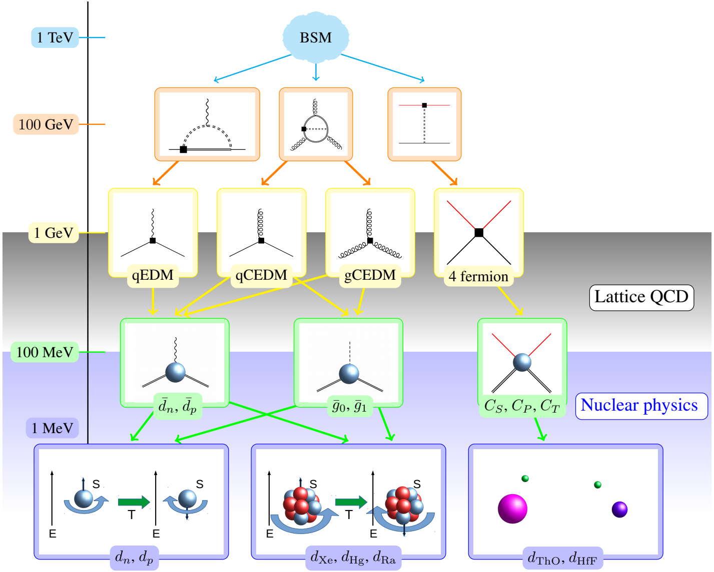
  multiple Higgs-gauge operators, γ and Z dipoles, . . .

- can we leverage polarization at the EIC to study T-odd observables?
  - transverse SSA in DIS ✓
  - asymmetries in W production or multi-jet final states?
- is it worth performing a more detailed comparison of EIC vs LHC vs low-energy sensitivities?

  e.g. R. Boughezal, F. Petriello, D. Wiegand, '20 in symmetry conserving or V. Cirigliano, *et al*, '21 for LFV cases
- can we search for SMEFT operators in parton evolution/jet substructure?

Theory uncertainties in low-energy experiments and the EIC

Low-energy EFT for flavor-diagonal CPV.



1149 CP-violating SMEFT operators

42 $\Delta F = 0$ LEFT operators with u, d, s and electrons

11 nucleon-level operators

Low-energy EFT for flavor-diagonal CPV: hadronic couplings

- in 1-nucleon sector, generate $N\pi$ and $N\gamma$ couplings

$$\mathcal{L}^N = \bar{N}\left(\bar{d}_n \frac{1-\tau_3}{2} + \bar{d}_p \frac{1+\tau_3}{2}\right)\boldsymbol{\sigma}\cdot\mathbf{E}N - \frac{\bar{g}_0}{2F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{2F_\pi}\pi_3\bar{N}N$$

- $\bar{d}_{n,p}$ contribute to neutron/proton EDMs
- $\bar{g}_{0,1}$ induce TV NN potentials $\Longleftrightarrow$ nuclear EDMs, MQMs and Schiff moments

dependence of $\bar{g}_{0,1}$, $\bar{d}_{n,p}$ on quark-level couplings very poorly determined!

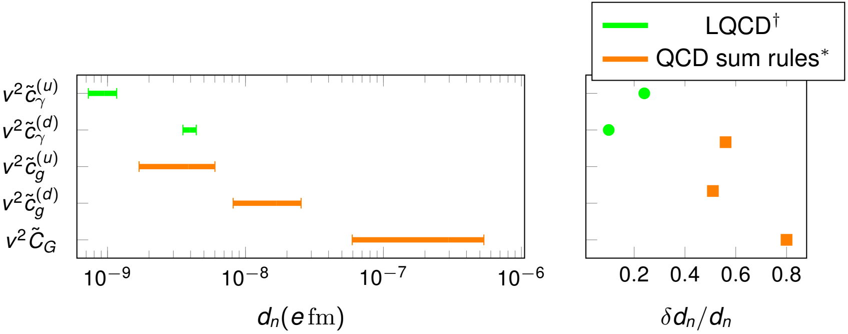
e.g. in the case of the quark chromo-EDM $\tilde{d}_{u,d}$

$$\bar{g}_0 = \left(\tilde{d}_u + \tilde{d}_d\right)[-0.5, 0.2]\ \text{GeV}^2, \qquad \bar{g}_1 = \left(\tilde{d}_u - \tilde{d}_d\right)[-2.2, -0.4]\ \text{GeV}^2.$$

QCD sum rule calculation by M. Pospelov, ‘02

large intervals, and model-dependent uncertainty

Nucleon EDM matrix elements



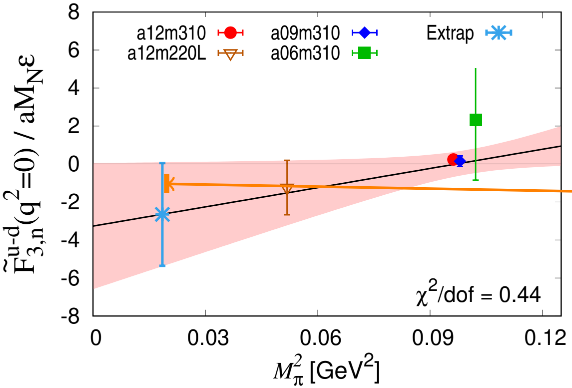
† FLAG '24

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

- same applies to the nucleon EDM
- qEDM contributions are mediated by nucleon tensor charges ✓

  related to 1st moment of transversity distribution h_1 C. Cocuzza *et al*, JAM coll, '23
- contributions from $\bar{\theta}$ term and hadronic operators has large and (uncontrolled) errors

Lattice QCD calculations of the nEDM



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

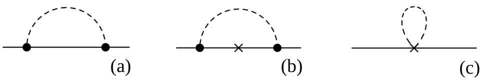
power div. subtracted

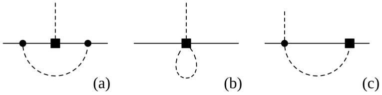
QCD sum rules

thanks to T. Bhattacharya and B. Yoon
T. Bhattacharya *et al*, ‘23

- EDM from QCD $\bar{\theta}$ term extremely challenging
- preliminary results for qCEDM and gCEDM
- statistical and systematic error still a factor of 5 larger than QCD sum rule estimate

Strategies for the determination of $\pi - N$ couplings





- chiral symmetry relates $\pi - N$ couplings induced by qCEDM to corrections to the baryon spectrum induced by qCMDM (generalized σ terms)

$$\bar{g}_0 = \tilde{d}_0 \left(\frac{d}{d\tilde{c}_3} + r \frac{d}{d(\bar{m}\varepsilon)} \right) \delta m_N + \delta m_{N,\mathrm{QCD}} \frac{1-\varepsilon^2}{2\varepsilon} \left(\bar{\theta} - \bar{\theta}_{\mathrm{ind}} \right) \;,$$

$$\bar{g}_1 = -2\tilde{d}_3 \left(\frac{d}{d\tilde{c}_0} - r \frac{d}{d\bar{m}} \right) \Delta m_N \;,$$

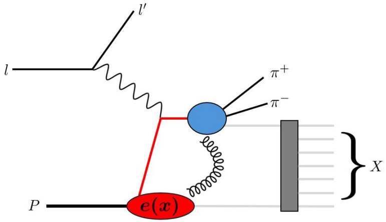
- relation is stable under loop corrections in chiral perturbation theory

J. de Vries, C. Y. Seng. EM, A. Walker-Loud, ‘16

- can be translated into matrix elements of a CP-even chromo-magnetic operator

$$\frac{d}{d\tilde{c}_0} \Delta m_N \Longrightarrow \langle N | g_s \bar{q} \sigma \cdot G q | N \rangle, \qquad \frac{d}{d\tilde{c}_3} \delta m_N \Longrightarrow \langle N | g_s \bar{q} \sigma \cdot G \tau_3 q | N \rangle$$

Extracting π-N couplings via twist-3 parton distributions



- chiral-odd twist-3 distributions can shed light on chiral-odd matrix nucleon matrix elements
- e.g. e^q contains info on nucleon sigma term

$$e^q(x) = \frac{1}{2m_N}\int \frac{d\lambda}{2\pi} e^{i\lambda x}\langle P|\bar{\psi}^q(0)[0,\lambda n]\psi^q(\lambda n)|P\rangle \,,$$

- third moment of e^q is related to the NME of a twist-3 chromo-magnetic operator

$$\mathcal{M}_n[e] \equiv \int_{-1}^{1} dx x^{n-1} e(x) \qquad \mathcal{M}_3[e^q_{\rm tw3}] = \frac{1}{4m_N(P^+)^2} \times \sum_{i=1}^{2}\langle P|\bar{\psi}^q(0) g_s \sigma^{+i} G^{+i}(0)\psi^q(0)|P\rangle$$

M. Burkardt and Y. Koike, ‘02

Extracting π-N couplings via twist-3 parton distributions

- C. Y Seng suggested the decomposition C. Y Seng, '18

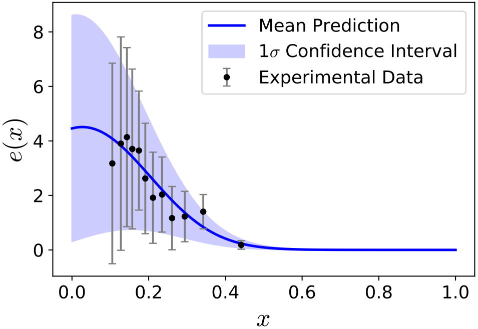
$$\langle P|\bar{\psi}^q(0) g_s G^{\alpha\mu}(0)\sigma_\alpha{}^\nu \psi^q(0)|P\rangle = A^q m_N \left(m_N^2 g^{\mu\nu} - P^\mu P^\nu\right) + B^q m_N P^\mu P^\nu ,$$
$$= \frac{1}{4} g^{\mu\nu} m_N^3 (3A^q + B^q) + m_N P^{\{\mu} P^{\nu\}} (B^q - A^q)$$

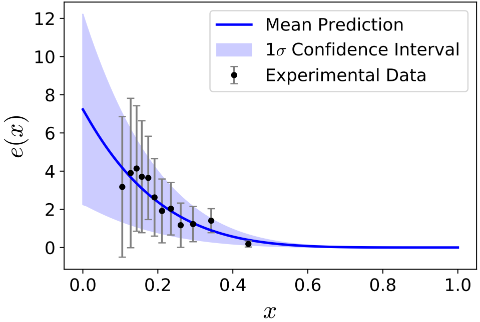
- leading to

$$\bar{g}_0 = \frac{1}{2}\left(\tilde{d}_u + \tilde{d}_d\right)\left(-\frac{1}{2} m_N^2 \left[3A^{u-d} + B^{u-d}\right] + \frac{r\sigma^3}{\bar{m}\varepsilon}\right),$$
$$\bar{g}_1 = -\left(\tilde{d}_u - \tilde{d}_d\right)\left(\frac{1}{4} m_N^2 \left[3A^{u+d} + B^{u+d}\right] - \frac{r\sigma^0}{\bar{m}}\right),$$
$$\mathcal{M}_3[e^q_{\mathrm{tw3}}] = \frac{A^q - B^q}{4}.$$

- in general, $\bar{g}_{0,1}$ and $\mathcal{M}_3$ depend on different linear combinations
- **if** $B^q \approx 0$, the 3rd moment of $e^q(x)$ determines $\bar{g}_{0,1}$

Extracting π-N couplings via twist-3 parton distributions

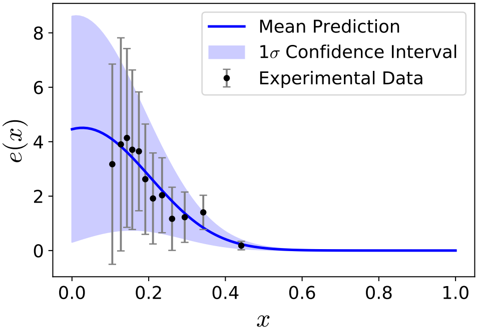


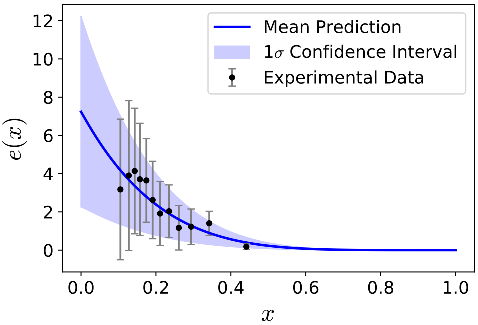


S. Bhattacharya, **K. Fuyuto**, EM, T. Richardson, '25

- $e(x)$ contributes to SSA in SIDIS with $\pi^+\pi^-$ production $\Longrightarrow$ analogous to h_1
- extraction is somewhat model dependent because of twist-3 fragmentation function at same order
- new extraction from CLAS + CLAS12 data A. Courtoy *et al*, '22

Extracting π-N couplings via twist-3 parton distributions





S. Bhattacharya, **K. Fuyuto**, EM, T. Richardson, '25

- use extraction from CLAS + CLAS12 data to get 3rd moment — A. Courtoy *et al*, '22
  - **Gaussian fit**:
  $$\mathcal{M}_3[e^u] + \mathcal{M}_3[e^d] = 0.2078 \pm 0.1356,$$
  - **Polynomial fit**:
  $$\mathcal{M}_3[e^u] + \mathcal{M}_3[e^d] = 0.2606 \pm 0.1750.$$
- compatible with model calculations of $\mathcal{M}_3$, and with C. Y. Seng's extraction

Extracting π-N couplings via twist-3 parton distributions

is $B^q \approx 0$?

- the non-relativistic argument does not apply

$$\langle N|\bar{q}\sigma^{0i}\bar{q}|N\rangle = \mathcal{O}\left(\frac{1}{m_N}\right) \not\to \langle N|\bar{q}\sigma^{0i}\bar{q}G_{0i}|N\rangle = \mathcal{O}\left(\frac{1}{m_N}\right)$$

- statement is not RGE invariant: $3A + B$ and $A - B$ have different RGE. In $\overline{\rm MS}$

$$\frac{d}{d\log\mu}(3A^q + B^q) = (10C_F - 4C_A)\frac{g_s^2}{(4\pi)^2}(3A^q + B^q)$$
$$\frac{d}{d\log\mu}(A^q - B^q) = -2\left(C_A + \frac{7}{3}C_F\right)\frac{g_s^2}{(4\pi)^2}(A^q - B^q)$$

- difference is even more pronounced in lattice schemes (gradient flow, RI-MOM)
- $\bar{q}\sigma^{\mu\nu}G_{\mu\nu}q$ has power-divergent mixing with $\bar{q}q$

$$[\bar{q}\sigma^{\mu\nu}G_{\mu\nu}q]\,(\tau) = \frac{\alpha_s C_F}{4\pi}\frac{6}{\tau}\,[\bar{q}q]_{\overline{\rm MS}} + \dots$$

- the symmetric and traceless part mixes only logarithmically

Extracting π-N couplings via twist-3 parton distributions

- large N_c arguments support the conclusion $A \sim B$

$$\left|A^{(u+d)}\right| \sim \left|B^{(u+d)}\right| \sim O(N_c)\,, \qquad \left|A^{(u-d)}\right| \sim \left|B^{(u-d)}\right| \sim O(N_c^0)\,,$$

- thus we restore the B^q contrib. and assume large N_c

$$\sigma_C^0 \approx m_N^2 \left(3\left(\mathcal{M}_3[e^u] + \mathcal{M}_3[e^d]\right) + B^u + B^d\right)\,,$$

$$\sigma_C^3 \approx -2m_N^2 \left(3\left(\mathcal{M}_3[e^u] - \mathcal{M}_3[e^d]\right) + B^u - B^d\right)\,.$$

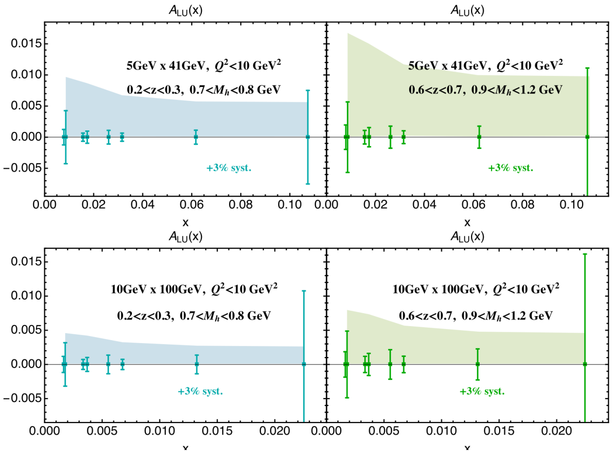
- putting everything together

$$\bar{g}_0 = \left(\tilde{d}_u + \tilde{d}_d\right) \times \begin{cases} +1.7 \\ -1.0 \end{cases} \mathrm{GeV}^2, \qquad \bar{g}_1 = -\left(\tilde{d}_u - \tilde{d}_d\right) \times \begin{cases} -1.5 \\ -9.6 \end{cases} \mathrm{GeV}^2,$$

most of the range determined by large N_c estimate of B^q

- larger errors than in QCD sum rules . . .
- started a collaboration with D. Pefkou (CalLat) to compute **both** $\mathcal{M}_3$ and $\langle N|\bar{q}\sigma \cdot g_s G q|N\rangle$ in LQCD

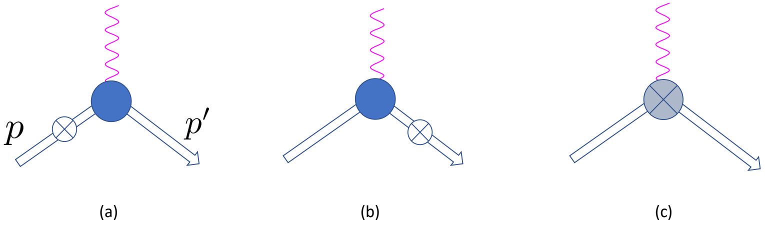
$e(x)$ at the EIC



EIC Yellow Report, '21

- $e(x)$ will be studied at the EIC, especially at small x
- LQCD calculations of $\mathcal{M}_3$ (and higher moments) can help reduce uncertainty bands
- & we can use EIC data to validate extraction of $\bar{g}_{0,1}$

EDMs and higher twists



Y. Hatta, '20

- other possible correlations between nucleon structure and nucleon EDM have been pointed out
  Y. Hatta, '20, Y. Hatta, '20
- for the chiral-even Weinberg operator,

$$d_n = \mu_n w \langle N|O_W|N\rangle + d_n|_{\mathrm{irr}}$$

- the nucleon matrix element O_W is bound by the twist-4 NME

$$\langle N|\bar{q} g_s G^{\mu\nu} \gamma_\mu q|N\rangle$$

map correlations for all dim-6 operators & study EIC sensitivity?

Conclusion

- we should explore all possible avenues to look for BSM physics
- EIC can play a direct role, complementary to LHC and low-energy searches

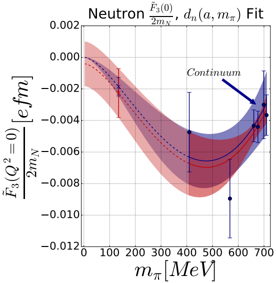
  see talks by Kaori and Sebastian for more examples

- and an indirect one, by improving knowledge of nucleon structure

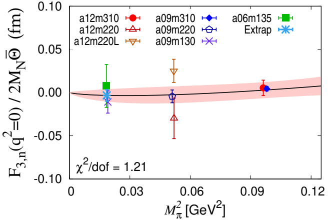
  more ways to exploit the interplay between hadron structure and matrix elements for BSM searches?

Backup

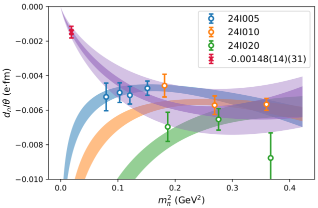
Lattice QCD calculations of nEDM.



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



T. Bhattacharya, *et al*, '21



J. Liang, *et al* (χQCD Coll.), '23

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

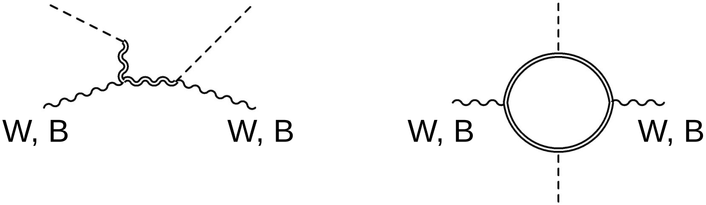
  vanishing signal at small m_π, large excited state contamination, ...

- published results compatible with zero at $\sim 2\sigma$
- approaching $d_n \sim 10^{-3}\,\bar{\theta}\,e\,\mathrm{fm}$, size of "chiral log"

  Crewther, Di Vecchia, Veneziano and Witten, '79

- need more work to control all systematics

Higgs-gauge operators



- induced at tree level in models with new vector bosons
- but more often at one loop

$>$ 2 families of vector-like fermions, vector-like fermions + scalars

J. de Blas, J. C. Criado, M. Pérez-Victoria, J. Santiago, '17 ; G. Guedes, P. Olgoso, J. Santiago, '23, G. Guedes, P. Olgoso '24

- correlated with CP-even corrections to EW propagators

Nuclear EDMs and Schiff moments

	A_{Schiff}	α_n	α_p	a_0 (e fm)	a_1 (e fm)	a_2 (e fm)
^{199}Hg	$-(2.1 \pm 0.5) \cdot 10^{-4}$	1.9 ± 0.1	0.20 ± 0.06	$0.13^{+0.5}_{-0.07}$	$0.25^{+0.89}_{-0.63}$	$0.09^{+0.17}_{-0.04}$
^{129}Xe	$-(0.33 \pm 0.05) \cdot 10^{-4}$	–	–	$0.10^{+0.53}_{-0.037}$	$0.076^{+0.55}_{-0.038}$	
^{225}Ra	$7.7 \cdot 10^{-4}$	–	–	2.5 ± 7.5	-65 ± 40	14 ± 6.5
d	1	0.9	0.9	0	-0.100	0
^{3}He	1	0.9	0	-0.027	-0.079	-0.060
^{3}H	1	0	0.9	0.027	-0.079	0.060

- nuclear physics adds another layer of uncertainty

$$d_{A_X} = A_{\text{Schiff}} \left(\alpha_n d_n + \alpha_p d_p + a_0 \frac{\bar{g}_0}{F_\pi} + a_1 \frac{\bar{g}_1}{F_\pi} + a_2 \frac{\bar{g}_2}{F_\pi} \right)$$

- for light ions, the nuclear theory input is under control (at the $\sim 10\%$ level)
- for diamagnetic atoms, Schiff moment calculations have large nuclear theory errors

Low-energy EFT for flavor-diagonal CPV

- dim-5 LEFT operators

$$\mathcal{L}^{(5)}_{\rm LEFT} = L_{e\gamma}\, \bar{e}_L \sigma^{\mu\nu} e_R\, F_{\mu\nu} + \sum_{q=u,d,s} L_{q\gamma}\, \bar{q}_L \sigma^{\mu\nu} q_R\, F_{\mu\nu} + \sum_{q=u,d,s} L_{qg}\, \bar{q}_L \sigma^{\mu\nu} t^a q_R\, G^a_{\mu\nu} + \text{h.c.},$$

- dim-6 LEFT operators

1. 3-gluon operator:

$$\mathcal{L}^{(6)}_{\rm LEFT} = L_{\tilde{G}} f^{abc} \tilde{G}^a_{\mu\nu} G^{b\,\nu\rho} G^{c\,\mu}_{\rho}$$

2. semi-leptonic:

$$\mathcal{L}^{(6)}_{\rm LEFT} = \sum_{q=u,d,s} L^{\rm SRL}_{eq} (\bar{e}_L e_R)(\bar{q}_R q_L) + L^{\rm SRR}_{eq} (\bar{e}_L e_R)(\bar{q}_L q_R) + L^{\rm TRR}_{eq} (\bar{e}_L \sigma^{\mu\nu} e_R)(\bar{q}_L \sigma_{\mu\nu} q_R) + \text{h.c.}$$

3. 4-fermion:

$$\mathcal{L}^{(6)}_{\rm LEFT} = L^{\rm V1LR}_{uddu} (\bar{u}_L \gamma^\mu d_L)(\bar{d}_R \gamma_\mu u_R) + L^{\rm S1RR}_{uu} (\bar{u}_L u_R)(\bar{u}_L u_R) + \ldots$$

- 24 operators, 6 of the *LL RR* type, 18 of the *LR LR* type

Low-energy EFT for flavor-diagonal CPV

- to calculate EDMs, need to matching to a nucleon-level theory
- "easy" in the leptonic/ semileptonic sector

$$\mathcal{L} = \frac{e}{2} m_\ell \tilde{c}_\ell \bar{\ell} \sigma^{\mu\nu} \gamma_5 \ell \, F_{\mu\nu} - \frac{G_F}{\sqrt{2}} \sum_{N=n,p} \left(C_P^{(N)} \bar{\ell}\ell \bar{N} i\gamma_5 N + C_S^{(N)} \bar{\ell} i\gamma_5 \ell \, \bar{N}N + C_T^{(N)} \bar{\ell}\sigma^{\mu\nu} \ell \, \bar{N} i\sigma_{\mu\nu}\gamma_5 N \right)$$

- the dependence of $\tilde{c}_\ell$, C_P, C_S, C_T on CPV at the EW scale is well understood
- e.g. semileptonic tensor operators (contributing to d_{Xe} and d_{Hg})

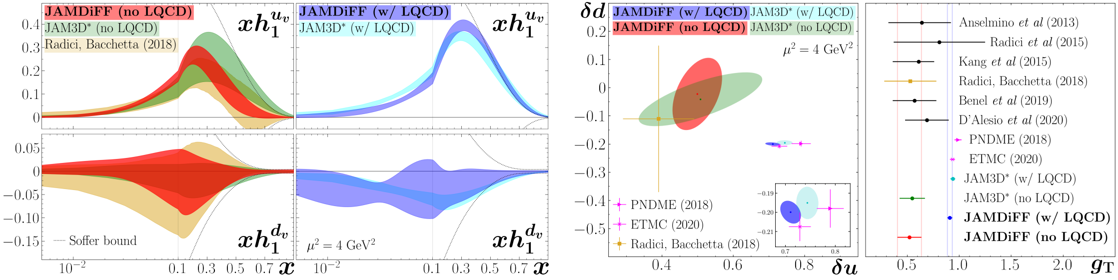
$$C_T^{(0)} = -\frac{v^2}{2} \left\{ \frac{g_T^u + g_T^d}{2} \left[\mathrm{Im} L_{eu}^{\mathrm{TRR}} + \mathrm{Im} L_{ed}^{\mathrm{TRR}} \right] + g_T^s \mathrm{Im} L_{ed}^{\mathrm{TRR}} \right\}$$

- L_{eq}^{TRR} are quark-level couplings at $\mu \approx 2$ GeV,
- non-perturbative input captured by nucleon tensor charges

$$g_T^u = 0.784(30), \qquad g_T^d = -0.204(14), \qquad g_T^s = -0.0027(16)$$

FLAG Lattice Averaging Group, '24

Tensor charges from PDFs



C. Cocuzza *et al*, JAM coll, '23

- tensor charges related to the first moment of the transversity distribution

$$g_T^{u-d} = \int_0^1 dx(h_1^u(x) - h_1^{\bar{u}}(x) - h_1^d(x) + h_1^{\bar{d}}(x))$$

- fits to data ($e^+e^- \to \pi\pi X$, SIDIS and $pp \to \pi\pi X$) alone prefers smaller tensor charges
- but data are in a small x range, including constraint on the first moment does not spoil χ^2

EIC data could reduce error by a factor of 10 EIC Yellow Report, '21