Probing TeV physics using neutron decays and nEDM

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- Taku Izubuchi, Amarjit Soni, Shigemi Ohta, Christoph Lehner and Sergey Syritsyn (RBC, BNL)

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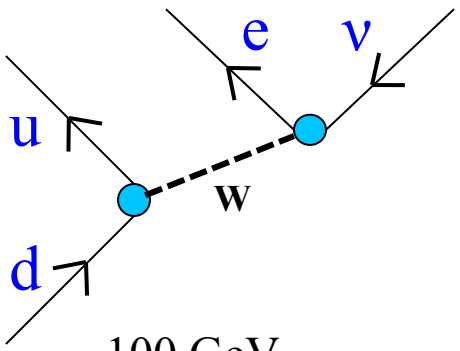
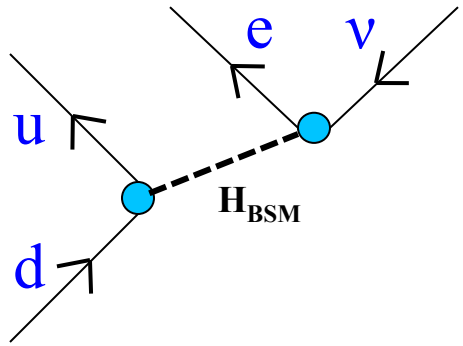
Probing New Interactions: $M_{BSM} >> M_W >> 1$ GeV

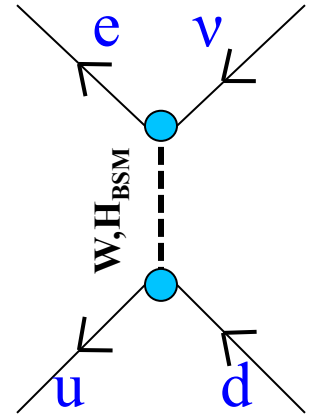
Many BSM possibilities for Scalar & Tensor: Higgs-like, leptoquark, loop effects, …



100 GeV
V-A Weak decay
e_L with a ν_L

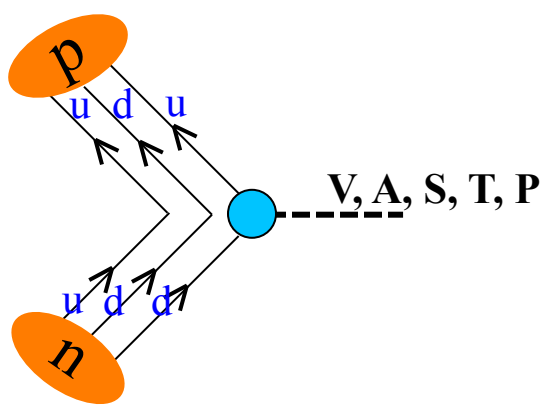


TeV
Novel S,T Interactions
e_R with a ν_L



LHC

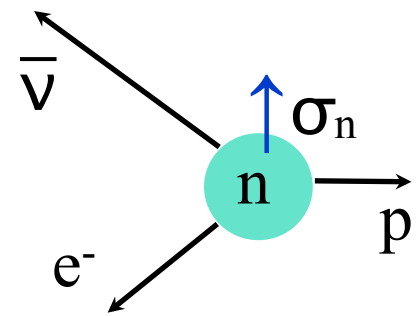
Neutron Decay



Effective Theory @ ~2 GeV
V-A (g_A, g_V) Weak interactions
S, T (g_S, g_T) New Interactions

[Ultra] Cold Neutron Decay: Parameters sensitive to new physics

Neutron decay can be parameterized as



$$d\Gamma \propto F(E_e)\left[1 + b\frac{m_e}{E_e} + \left(B_0 + B_1\frac{m_e}{E_e}\right)\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + \cdots\right]$$

b: Deviations from the leading order electron spectrum: Fierz interference term

B_1: Energy dependent part of antineutrino correlation with neutron spin

Relating b and B_1 to ME & BSM couplings

$$H_{eff} \supset G_F\left[\varepsilon_S \boxed{\bar{u}d} \times \bar{e}(1-\gamma_5)\nu_e + \varepsilon_T \boxed{\bar{u}\sigma_{\mu\nu}d} \times \bar{e}\sigma^{\mu\nu}(1-\gamma_5)\nu_e\right]$$

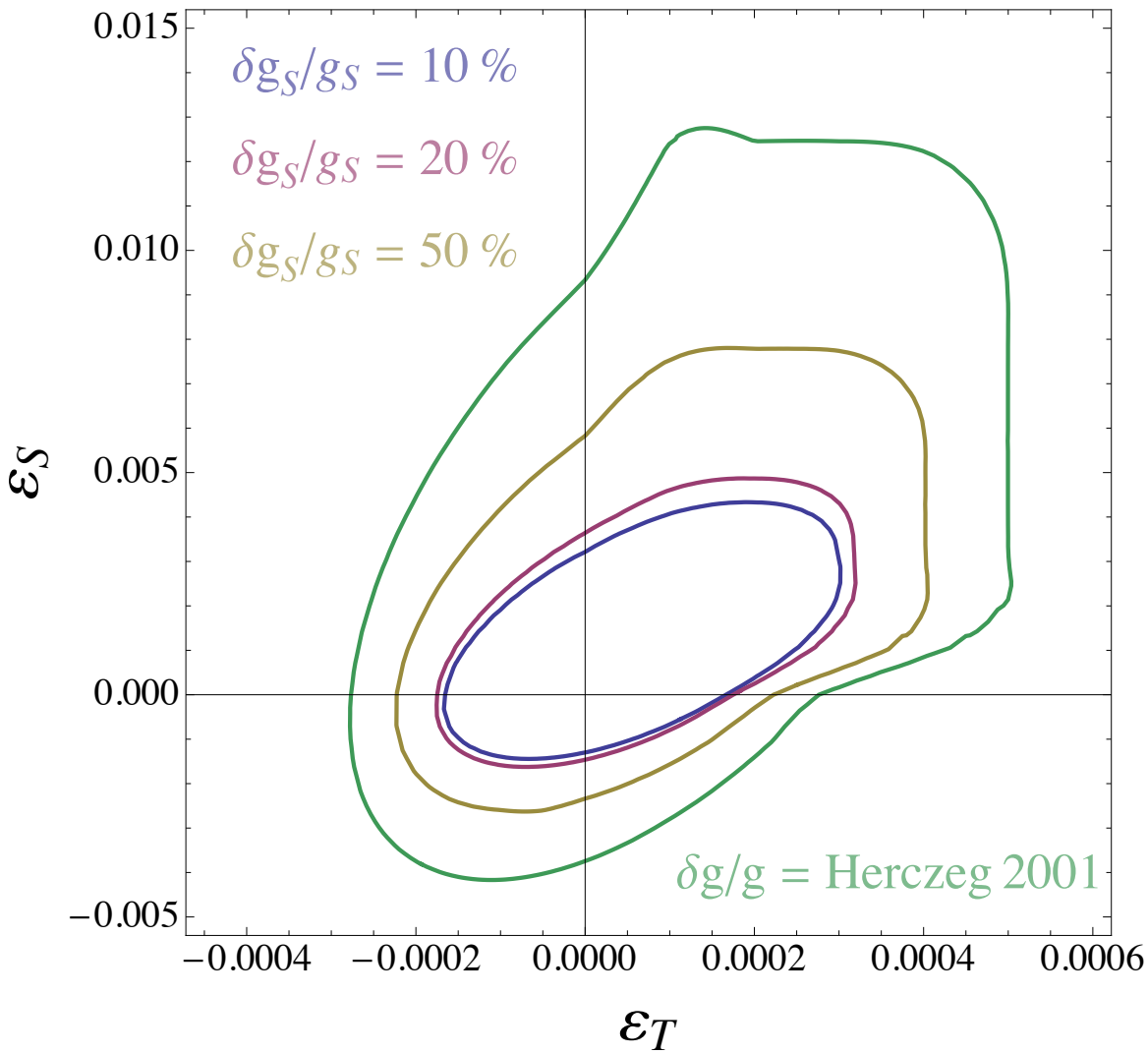
$$g_S \sim \langle p|\bar{u}d|n\rangle \qquad g_T \sim \langle p|\bar{u}\sigma_{\mu\nu}d|n\rangle$$

Linear order relations from $n \to p\, e\, \bar{\nu}$ decay

$$b^{BSM} \approx 0.34 g_S\varepsilon_S - 5.22 g_T\varepsilon_T$$

$$b_\nu^{BSM} \equiv B_1^{BSM} = E_e \frac{\partial B^{BSM}(E_e)}{\partial m_e} \approx 0.44 g_S\varepsilon_S - 4.85 g_T\varepsilon_T$$

Target Precision for g_S, g_T: 10-20%



Expt. input

$|B_1\text{-}b| < 10^{-3}$
$|b| < 10^{-3}$
$b_{0+} = 2.2\ (4.3) * 10^{-3}$

Allowed region in [ε_S , ε_T] (90% contours)

Clover on 2+1+1 flavor HISQ lattices: ~1000 configs

- m_s set to its physical value using $M_{\bar{s}s}$

a(fm)	m_l/m_s	Lattice Volume	M_π L	M_π (MeV)	Configs. X sources
0.12	0.2	$24^3 \times 64$	4.54	305	1013 x 8
0.12	0.1	$24^3 \times 64$	3.22	217	1000 x 12
0.12	0.1	$32^3 \times 64$	4.3	217	958 x 8
0.12	0.1	$40^3 \times 64$	5.36	217	1010 x 8
0.09	0.2	$32^3 \times 96$	4.5	313	881 x 8
0.09	0.1	$48^3 \times 96$	4.71	220	890 x 8
0.09	0.035	$64^3 \times 96$	3.66	130	883 x 4
0.06	0.2	$48^3 \times 144$	4.51	320	865 x 4
0.06	0.1	$64^3 \times 144$	4.25	229	200 x 4

Observations and Lessons Learned

- Exceptional configurations: Clover-on-HISQ with HYP smearing:
  -- Exist on the a=0.12fm lattices with M_π=130MeV
  -- None found for a=0.09 and 0.06 lattices

- Statistics: $\sigma(g_S) \sim 5\ \sigma(g_A)$ [or $5\ \sigma(g_T)$]
  Need O(15000) independent measurement (Configs $\times$ Sources)

- Excited state contamination is significant
  Need multiple T_{sep} with $T_{sep} > 1.2$fm
  $T_{sep} > 1.2$fm and fits including at least one excited state

- Renormalization (RI-sMOM): Smearing introduces artifacts.
  Need a prescription with a well-defined continuum limit

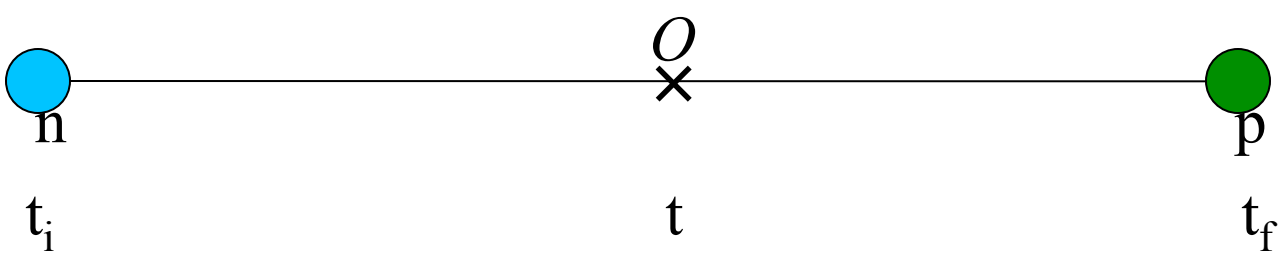
Reducing excited state contamination

Simultaneous fit to all $\Delta t = t_{sep} = t_f - t_i$

Assuming 1 excited state, the 3-point function is given by

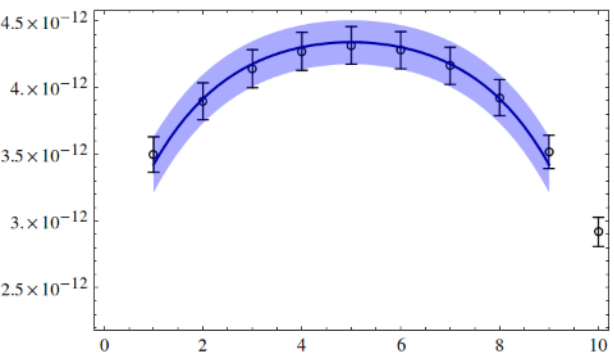
$$\Gamma^3(t_f, t, t_i) = |A_0|^2 \langle 0|O|0\rangle e^{-M_0 \Delta t} + |A_1|^2 \langle 1|O|1\rangle e^{-M_1 \Delta t} +$$
$$A_0 A_1^* \langle 0|O|1\rangle e^{-M_0 \Delta t} e^{-M_1(\Delta t - t)} + A_0^* A_1 \langle 1|O|0\rangle e^{-M_1 \Delta t} e^{-M_0(\Delta t - t)}$$

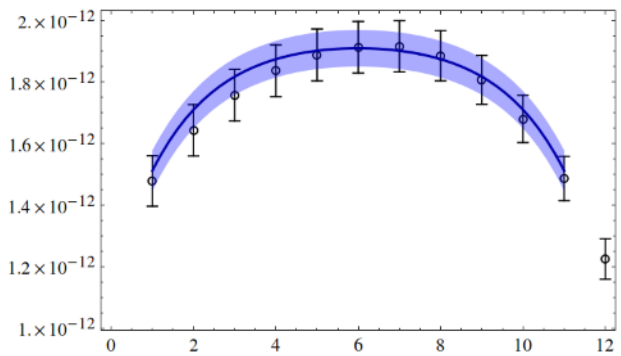
Where M_0 and M_1 are the masses of the ground & excited state and A_0 and A_1 are the corresponding amplitudes.

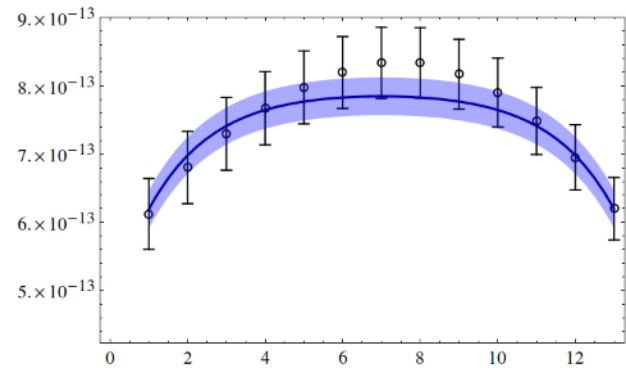


Simultaneous fit to all t_{sep}

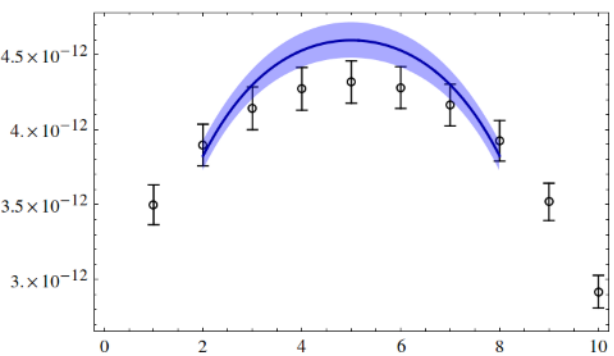
Data for g_S on the M_π=220 MeV ensemble at a=0.09fm



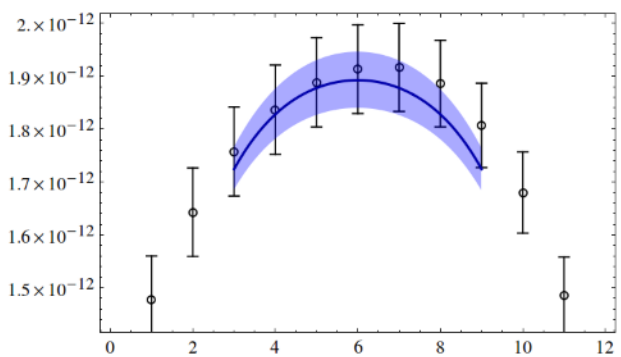




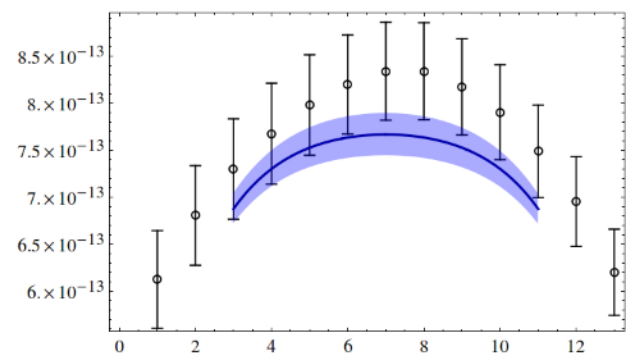
Excluding the $\langle 1|O|1\rangle$ Term



t_{sep}=10



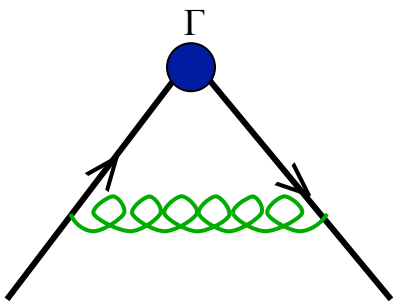
t_{sep}=12

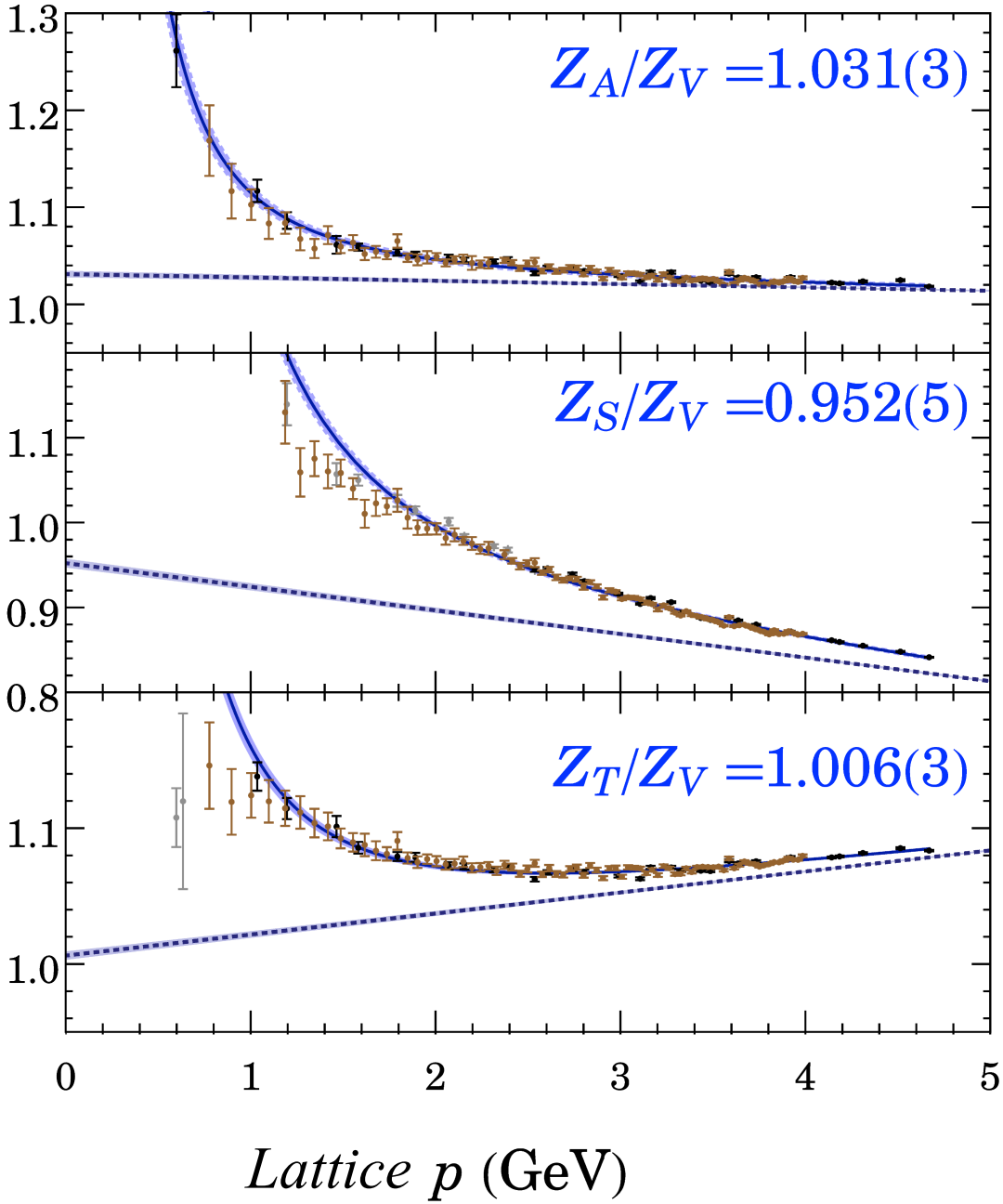


t_{sep}=14

Renormalization of bilinear operators

- Non-perturbative renormalization Z_Γ using the RI-sMOM scheme
  - Need quark propagator in momentum space
- Assumption: there exists a window
  - $\Lambda_{QCD} << p << \pi/a$
- HYP Smearing introduces artifacts
  - Gluon momentum above $\sim 1/a$ are an average
  - A window may no longer exist on coarse lattices
- No detectable dependence of Z's on m_q





$$\frac{Z_{A,S,T}}{Z_V}\left(\overline{MS}, 2\,GeV\right)$$

Fit data to: A/p + Z + Cp
in the range {1<p<4 GeV}
Or
Choose Z at p^2 = 5GeV^2
& errors from {4<p^2<6GeV^2}

Renormalized Charges

$$\frac{Z_{A,S,T}}{Z_V} \times \frac{g_{A,S,T}}{g_V}$$

Use Ward identity $Z_V g_V = 1$

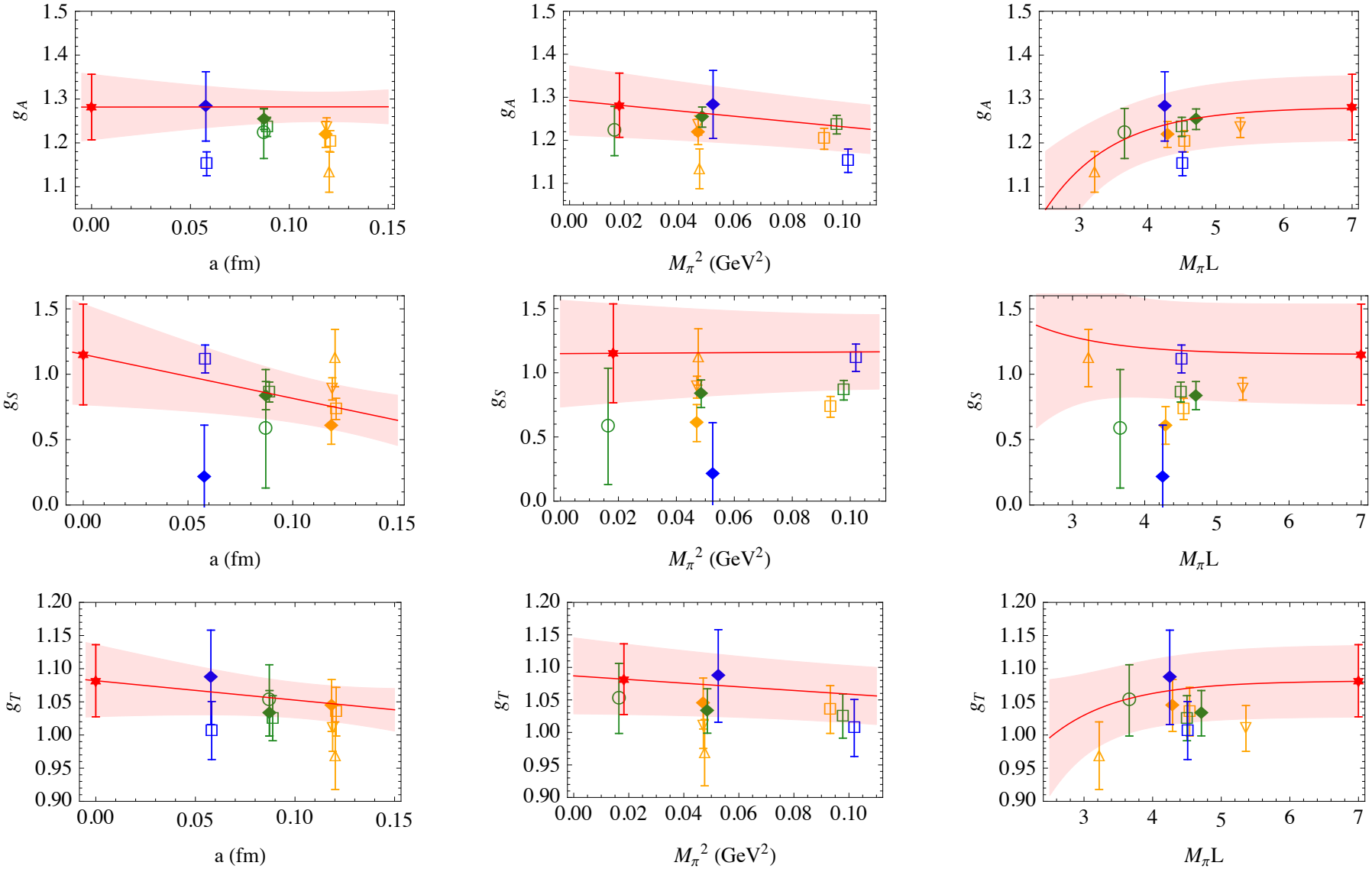
Extrapolations in a, M_π^2, L

$$g(a, M_\pi, L) = g + A\,a + B\,M_\pi^2 + C\,e^{-M_\pi L} + \ldots$$

We use the lowest order corrections when fitting 9 points

- Lattice spacing a
- Dependence on quark mass $m_q \sim M_\pi^2$
- Finite volume

★: Preliminary Results at the physical point



Orange: a=0.12; Green: a=0.09; Blue: a=0.06fm

□=310; ◆=220; ○=130 MeV

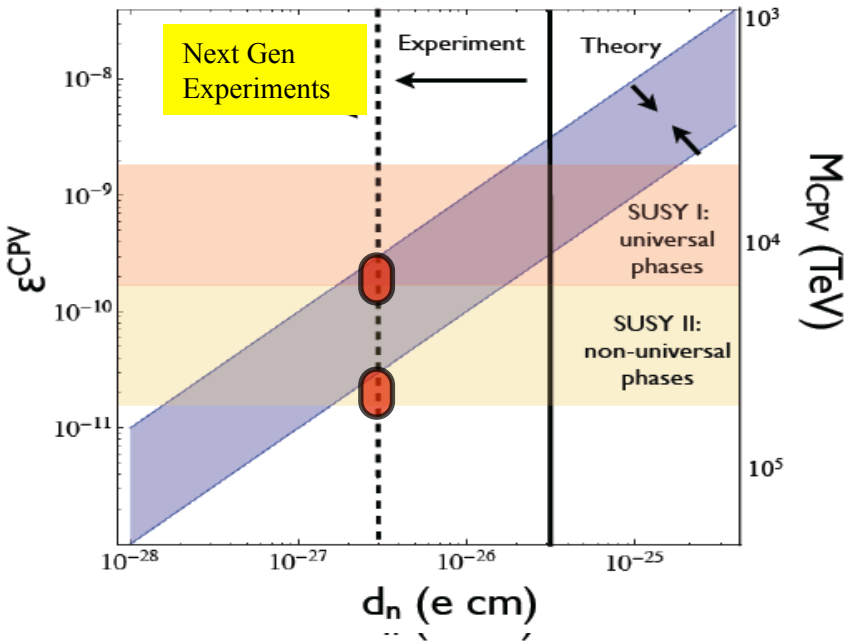
Towards Physical Estimates

- g_T: 1.08(5) [preliminary]
  - Estimate of Z_T is reliable
  - Small dependence on a, M_π^2, $M_\pi L$
- g_A:
  - Estimate of Z_A is reliable
  - $\exp\{-M_\pi L\}$ is the largest effect → Expt. result
- g_S:
  - Statistical errors are large
  - Z_S is not well-determined
  - Extrapolations in a, M_π^2, $M_\pi L$ are not stable

CP Violation, Baryogenesis, nEDM

CP Violation, Baryogenesis, nEDM

- CPV in SM is too small to explain Baryogenesis
- BSM theories have new sources of larger CPV that can explain baryogenesis
- These novel CPV may also give rise to larger nEDM (d_n ~10^{-27} e-cm)
- Next generation nEDM will push limit from (d_n ~3×10^{-26} e-cm) to (d_n ~10^{-28} e-cm)
- Low energy effective theory at ~2 GeV: Two leading dimension-5 CPV operators
- To use experimental value of d_n to constrain BSM, need high precision ME

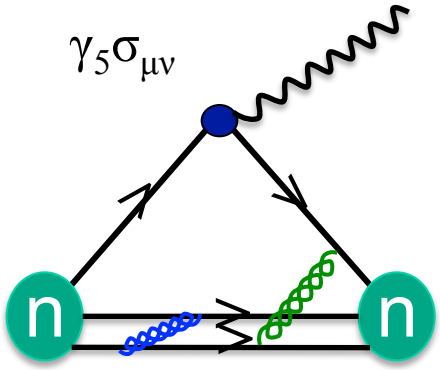


EXAMPLE: 10^{-27} e-cm sensitivity in nEDM experiments requires O(1) accuracy in ME to constrain BSM

Current uncertainty in ME is O(10)
[Engels, Ramsey-Musolf, Kolck, Prog. Part. Nucl. Phys., 71]

ME of novel CP violating operators: nEDM

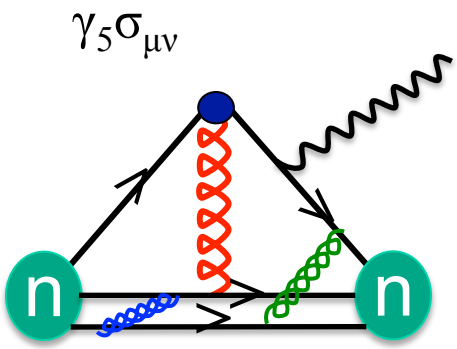
Quark-EDM



γ attaches to the vertex

$$\bar{q}\,\sigma_{\mu\nu}\gamma_5\,q\,F^{\mu\nu}$$

Chromo-EDM



- 4-pt function as γ can attach to any quark line
- Gluon free end can attach to any quark line

$$\bar{q}\,\sigma_{\mu\nu}\gamma_5\,q\,\lambda^a G_a^{\mu\nu}$$

- Formulation of the problem
- Operator mixing and renormalization
- Signal in disconnected diagrams
- Formulating lattice calculation of chromo EDM, a 4-point function

Mixing between D-5 CP violating operators in MS schemes

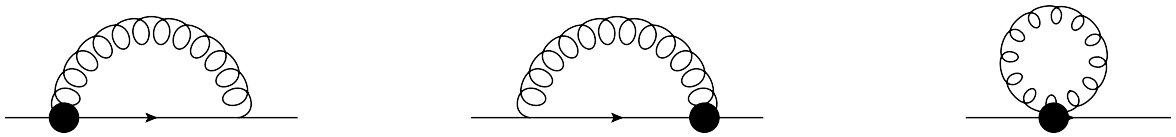
	E	C	P_{EE}	$\partial \cdot A_E$	A_G	$\partial^2 P$	mP_E	$m\partial \cdot A$	$m^2 P$	mG
E	$\cdot$	0	0	0	0	0	0	0	0	0
C	$\cdot$	$\cdot$	$\cdot$	$\cdot$	$\cdot$	$\cdot$	$\cdot$	$\cdot$	$\cdot$	$\cdot$
P_{EE}	0	0	$\cdot$	$\cdot$	$\cdot$	0	$\cdot$	0	0	0
$\partial \cdot A_E$	0	0	0	$\cdot$	0	$\cdot$	0	$\cdot$	0	0
A_G	0	0	$\cdot$	$\cdot$	$\cdot$	0	$\cdot$	0	0	0
$\partial^2 P$	0	0	0	0	0	$\cdot$	0	0	0	0
mP_E	0	0	0	0	0	0	$\cdot$	0	0	0
$m\partial \cdot A$	0	0	0	0	0	0	0	$\cdot$	0	0
$m^2 P$	0	0	0	0	0	0	0	0	$\cdot$	0
mG	0	0	0	0	0	0	0	$\cdot$	0	$\cdot$

The operators are defined as

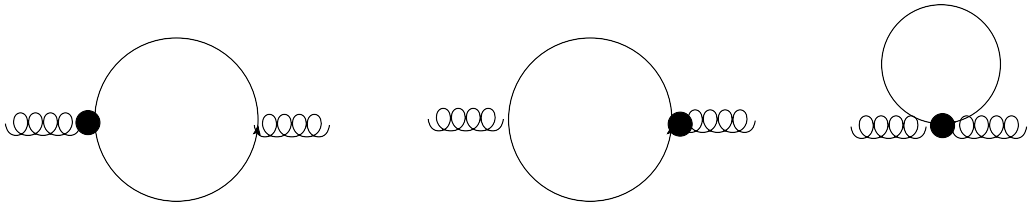
$$
\begin{aligned}
E \quad e &\equiv \bar{\psi}\sigma \cdot \tilde{F}\psi, \\
C \quad g &\equiv \bar{\psi}\sigma \cdot \tilde{G}\psi, \\
P_{EE} &\equiv \bar{\psi}(i\not{D} - m)\gamma_5(i\not{D} - m)\psi, \\
A_E^\mu &\equiv \bar{\psi}\gamma_\mu\psi + h.c., \\
A_G &\equiv i\bar{\psi}(i\not{D} + m)\,\not{\partial}\,\psi + h.c., \\
P &\equiv \bar{\psi}\gamma_5\psi, \\
P_E &\equiv \bar{\psi}(i\not{D} + m)\gamma_5\psi + h.c., \\
A^\mu &\equiv \partial_\mu\bar{\psi}\gamma^\mu\gamma_5\psi, \\
G &= G_{\mu\nu}\tilde{G}^{\mu\nu}
\end{aligned}
$$

- Entries marked 0 are prohibited by the structure of the operators.
- Only *E, C, P, and G* contribute to physical (`on-shell') matrix elements at zero momentum
- Rest need to be evaluated to connect the minimal subtraction scheme to a regularization independent off-shell scheme like RI-sMOM.

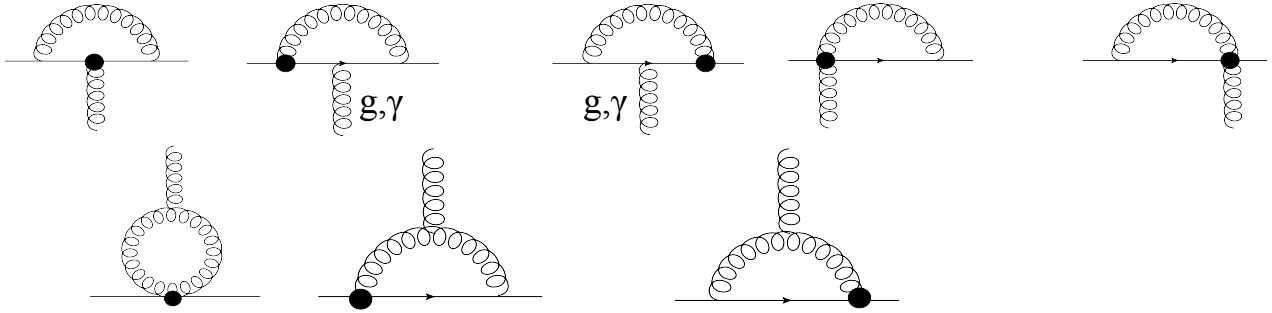
Feynman diagrams for CEDM



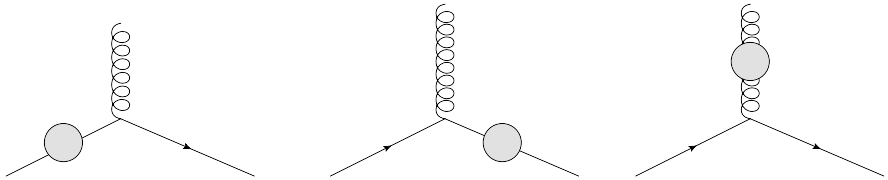
Diagrams contributing to the quark 2-pt function



Diagrams contributing to the gluon 2-pt function



IPI diagrams contributing to the quark 3-pt function



Non IPI diagrams contributing to the quark 3-pt function

Summary

- Calculation of g_A, g_S, g_T on track
  - Need higher statistics to get g_S with 10%
  - Need further finite volume study especially for g_A
  - $g_T = 1.08(5)$ [preliminary]
- QEDM calculations are on track
  - DWF on DWF [See talk by Michael Abramczyk]
  - Disconnected diagrams [See talk by Boram Yoon]
- CEDM calculation is hard
  - Mixing and renormalization: perturbative calculations are nearing completion
  - We are formulating the lattice calculation of the ME

Acknowledgements

- Computing resources from
  - USQCD
  - XSEDE
  - LANL
- 2+1+1 HISQ lattices generated by the MILC collaboration
- Computer code uses CHROMA library
- Supported by DOE and LANL-LDRD