Exploring TeV scale physics in decays of [ultra]cold neutrons and from nEDM

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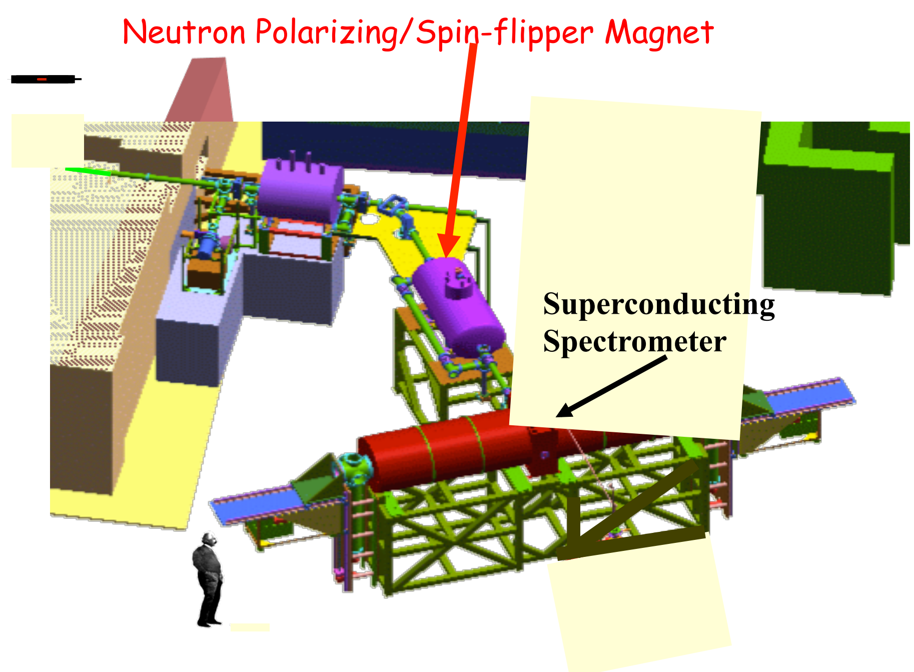


Theory and Experimental effort at LANL

LAUR-12-20208

Theory and Lattice QCD Collaboration (PNDME)

PRD85:5 (2012) 054512 arXiv:1110.6448
arXiv:1306.5435

- Tanmoy Bhattacharya (LANL)
- Vincenzo Cirigliano (LANL)
- Saul Cohen (U of Washington)
- Alberto Filipuzzi (Valencia, Spain)
- Martin Gonzalez-Alonso (Madison, Wisconsin)
- Michael Graesser (LANL)
- Rajan Gupta (LANL)
- Anosh Joseph (LANL/Zuethen)
- Huey-Wen Lin (U of Washington)
- Boram Yoon (LANL)

Experimental Colleagues

P-25 (LANL Team)

- M. Makela,
- P. McGaughey
- C. Morris
- A. Saunders
- S. Wilburn
- S. Sjue
- J. Wang

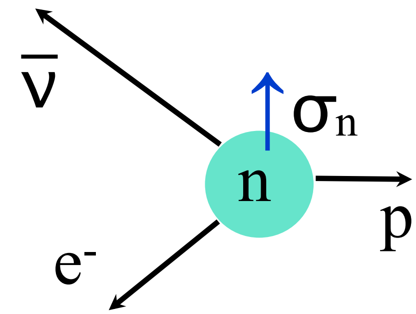
External Collaborators

- B. Filippone (Caltech)
  - K. Hickerson
- A. Young (NCSU)
  - B. Zeck
- B. Plaster (UK)
- R.B. Vogelaar (VT)

Ultra Cold Neutron Decay:

Parameters sensitive to new physics

Neutron decay can be parameterized as



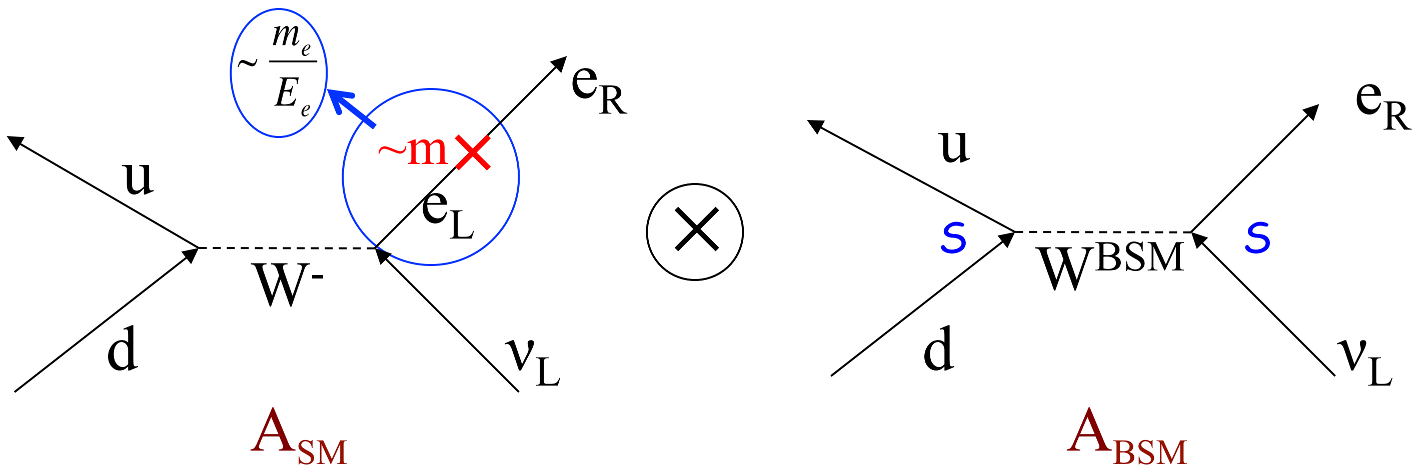
$$d\Gamma \propto F(E_e)\left[1 + b\frac{m_e}{E_e} + \left(B_0 + B_1\frac{m_e}{E_e}\right)\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + \cdots\right]$$

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

B_1: Energy dependent part of antineutrino correlation with neutron spin

Novel S and T interactions at TeV scale
→ Effective Theory at ~ 1 GeV

At leading order, contributions from BSM physics arise due to interference of A_{SM} and A_{BSM} and contribute to b and B_1 only through ε_S and ε_T



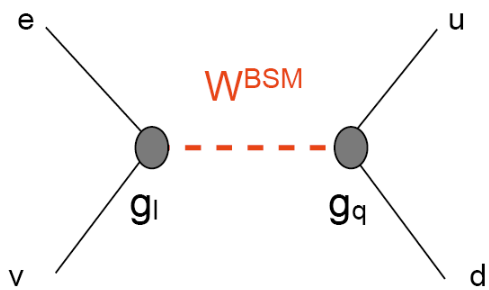
$$H_{\rm eff} = G_F \left[J^{\rm lept}_{V-A} \times J^{\rm quark}_{V-A} + \sum_{n=1,10} \epsilon_n^{\rm BSM} \hat{O}_n \right]$$

$\epsilon_S \; \bar{u} d \times \bar{e}(1-\gamma_5)\nu_e$

$\epsilon_T \; \bar{u}\sigma_{\mu\nu} d \times \bar{e}\sigma^{\mu\nu}(1-\gamma_5)\nu_e$

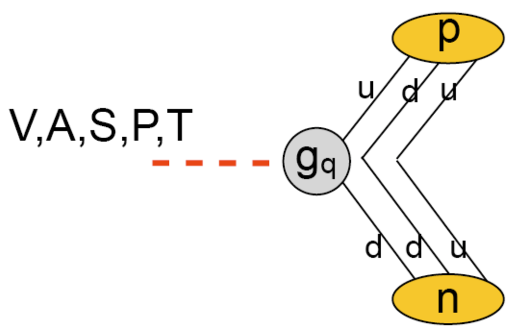
Bridging the scales: $M_{BSM} >> M_W$

- TeV scale:



Analyze models with new interactions (supersymmetry, extra dimensions, ...)
[Cirigliano, Gonzalez-Alonso, Graesser]

- GeV scale:



Calculate matrix elements (Lattice QCD, Chiral Perturbation Theory)
[Bhattacharya, Cirigliano, Cohen, Gonzalez-Alonso, Gupta, Joseph, Lin]

↓

Probe BSM physics in precision neutron decay &
relate to other measurements and collider (LHC) searches

Physics Case: (BSM/SM) ~ O(1)

- Couplings $\varepsilon_{P,S,T}$ $\quad \sim (v/\Lambda_{BSM})^2 \sim 10^{-3}$
- Recoil corrections: $\quad q/M_N \sim 10^{-3}$
- Radiative corrections: $\quad \alpha_{em}/\pi \sim 10^{-3}$
- Isospin-breaking: $\quad (M_N-M_P)/M_N \sim q/M_N \sim 10^{-3}$
- UCN: small Doppler broadening of *e* spectrum
- SM contribution is $O(10^{-3})$ and known to $(\sim 10^{-5})$: It is controlled by 2 small parameters $(M_n-M_p)/M_n$ and α_{em}/π
- Unique: scalar and tensor BSM interactions involve helicity-flip (m_e/E_e suppression) and are hard to detect in high energy experiments

Physics program

- *In order to bound ε_S and ε_T and quantify significance of the results, we are pursuing an integrated experimental and theoretical program*

$$b = f_b\,(\varepsilon_{S,T}\;\; g_{S,T})$$
$$B_1 = f_B\,(\varepsilon_{S,T}\;\; g_{S,T})$$

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

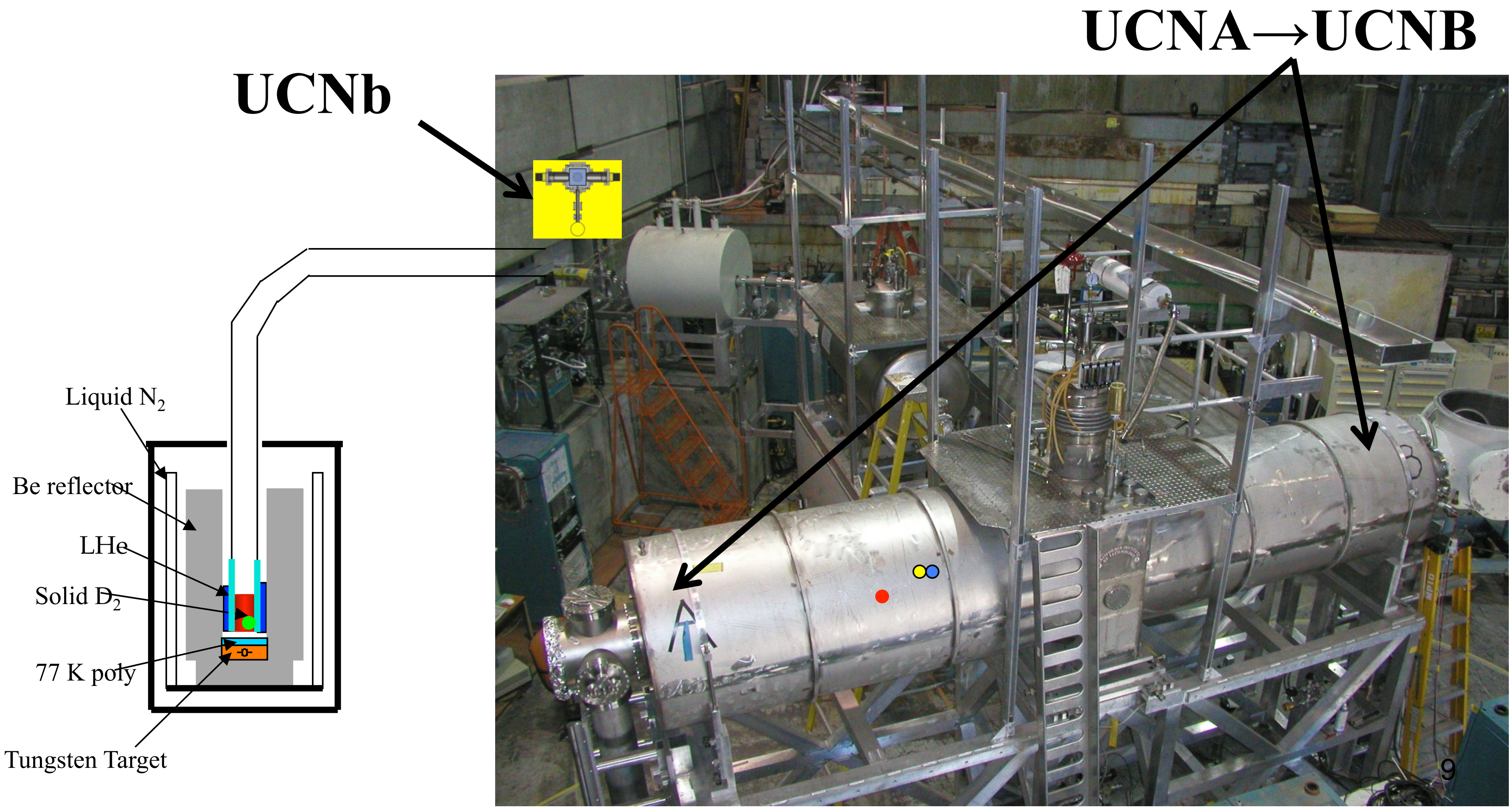
Measure these quantities with UCNs

Calculate these hadronic matrix elements using Lattice QCD

Analyze bounds on ε_S and ε_T from multiple measurements (including LHC signals). Examine BSM candidates

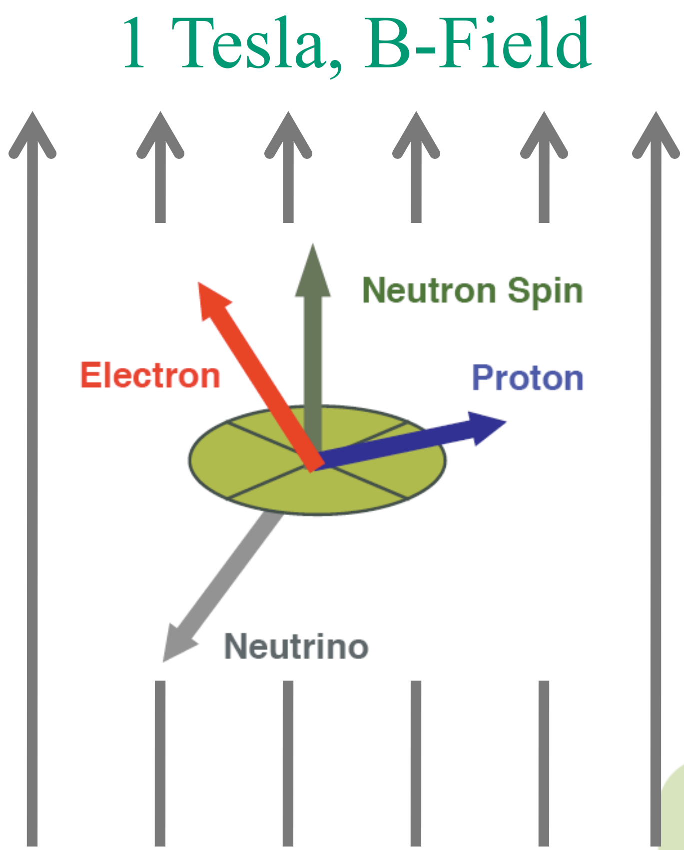
UCNA->UCNB, UCNb

Current facility DOE and NSF funded



The "UCNB" concept

[W.S. Wilburn et al., submitted to Rev. Mex. Fis.]



<u>Basic Idea</u>: Detect e-p coincidences

e: "start" (prompt)

p: "slow" (~ μs - ms)

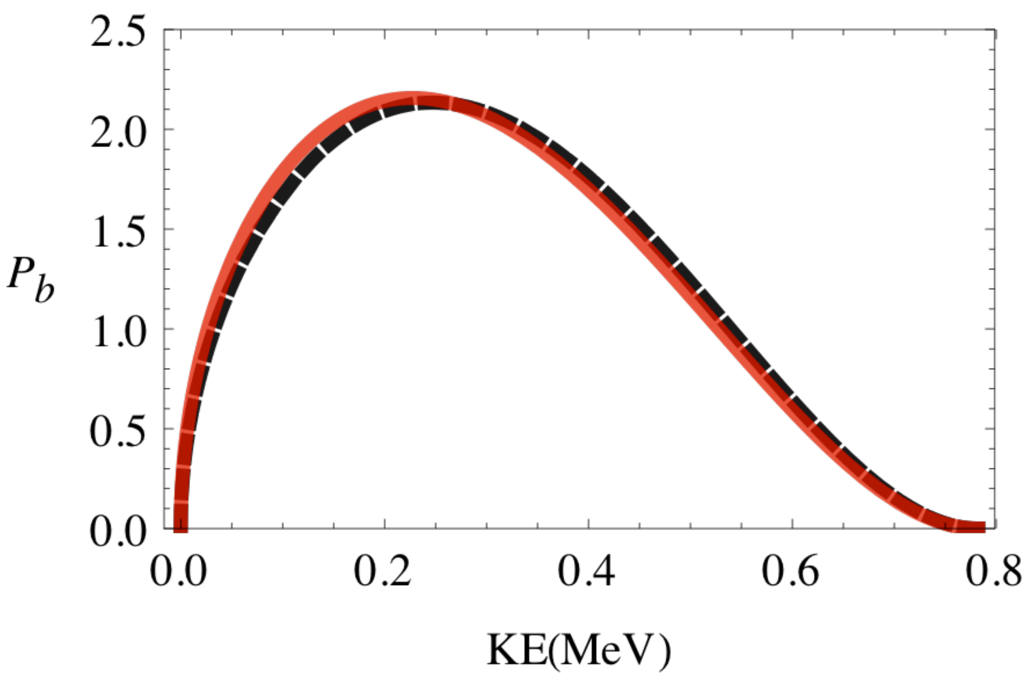
First-Pass Goal: 0.1% on B

<u>UCNB Observables</u>

- Neutron Polarization
- Electron and Proton Directions
- Electron Energy

UCNb – Precision measurement of electron spectrum

Measuring a small m_e/E_e modification of the electrons energy spectrum



- This experiment requires very high signal to noise ratio.
- Mount detector close to the UCN source for highest density.
- A combination of shield and low backgrounds is necessary.

Relating *b* and *B*$_1$ to BSM couplings

Linear order relations from n → p e ν decay

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

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

Phenomenology: Constraining ε_S and ε_T

- Constraints on ε_S and ε_T from UCN experiments combined with improved g_S and g_T will be more stringent than existing probes ($0^+ \to 0^+$; $\pi \to e\nu\gamma$).

- Collider experiments competitive with $\sqrt{s}$=14 TeV & 50–100 fb^{-1}

- Measurements at 10^{-3} to 10^{-4} will probe multi-TeV scale and place stringent constraints on scalar and tensor BSM interactions

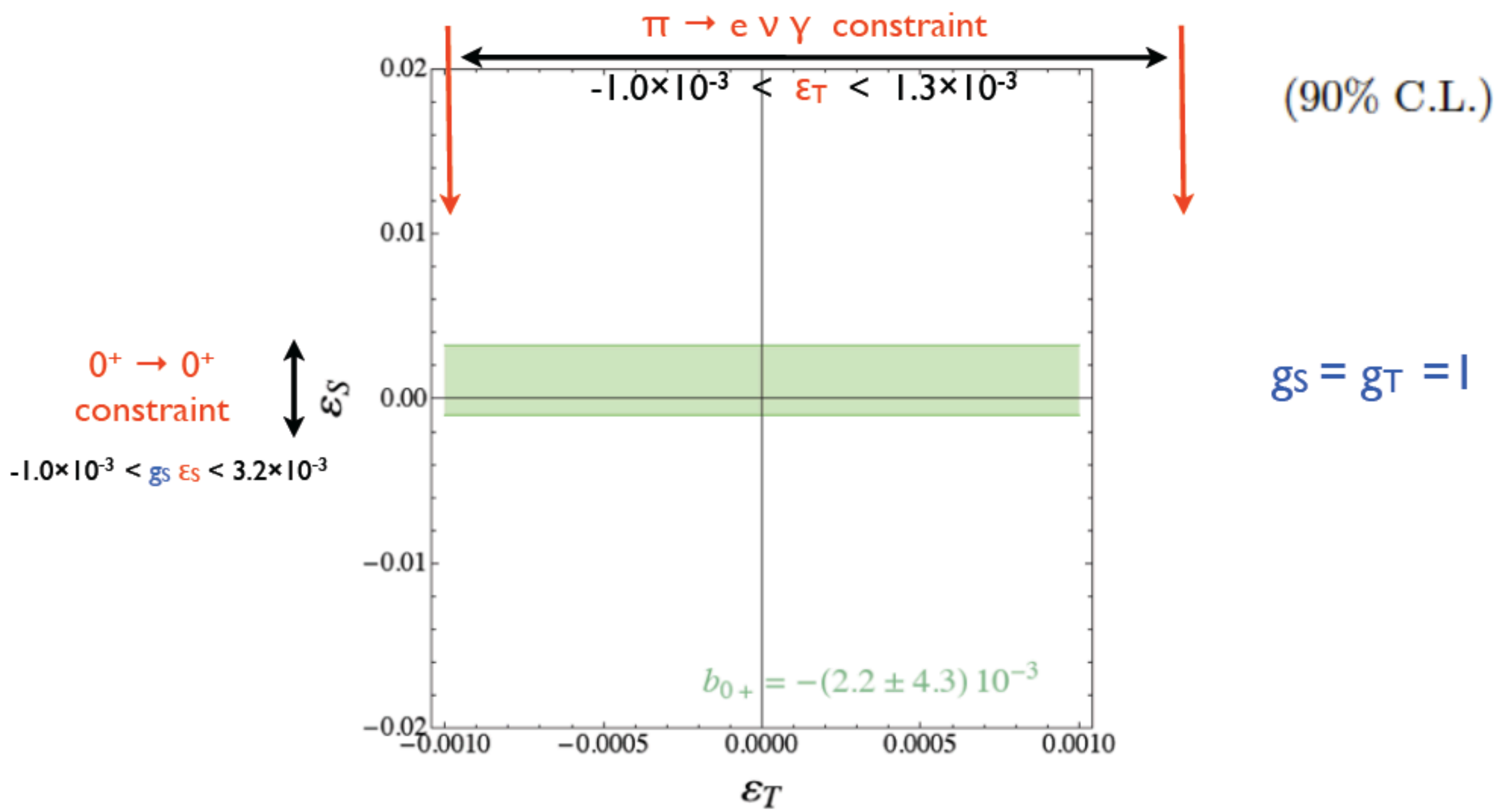
- Bounds:

    - $G_F * \varepsilon_{S,T} = (1/\Lambda_{S,T})^2$
    - $\varepsilon_{S,T} = v^2/\Lambda^2_{S,T} \sim 10^{-3}$

$$\boxed{\Lambda_{S,T} \sim 5 \text{ TeV}}$$

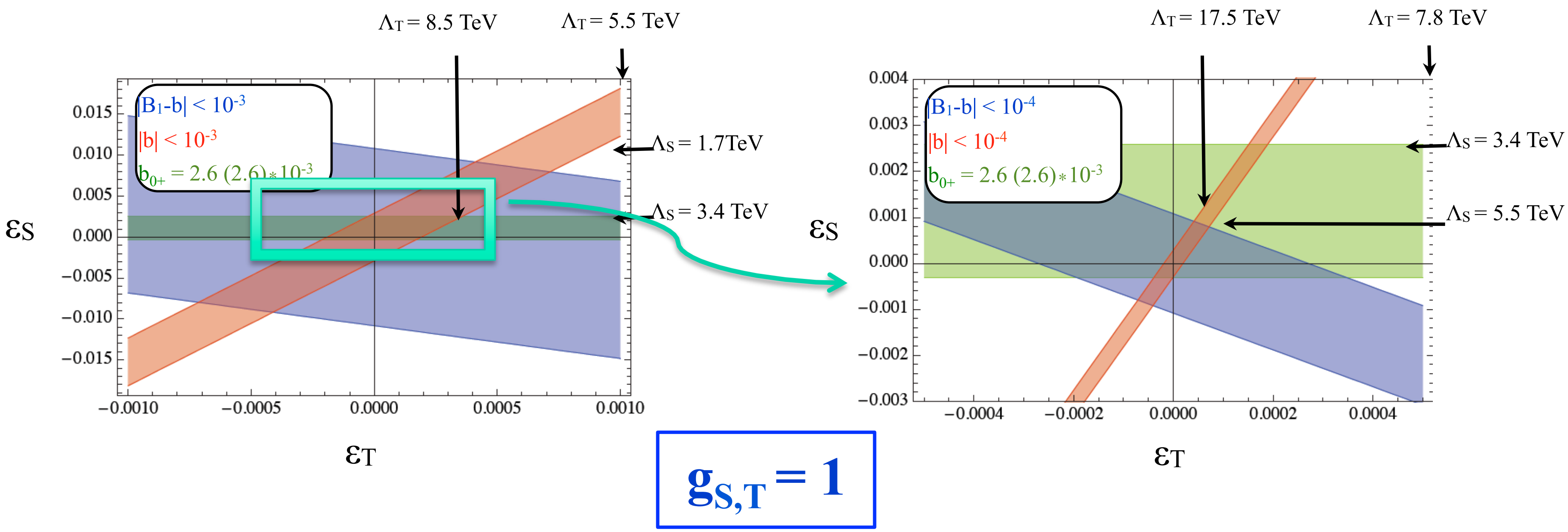
Low energy constraints

- Current: $0^+ \to 0^+$ and $\pi \to e\,\nu\,\gamma$

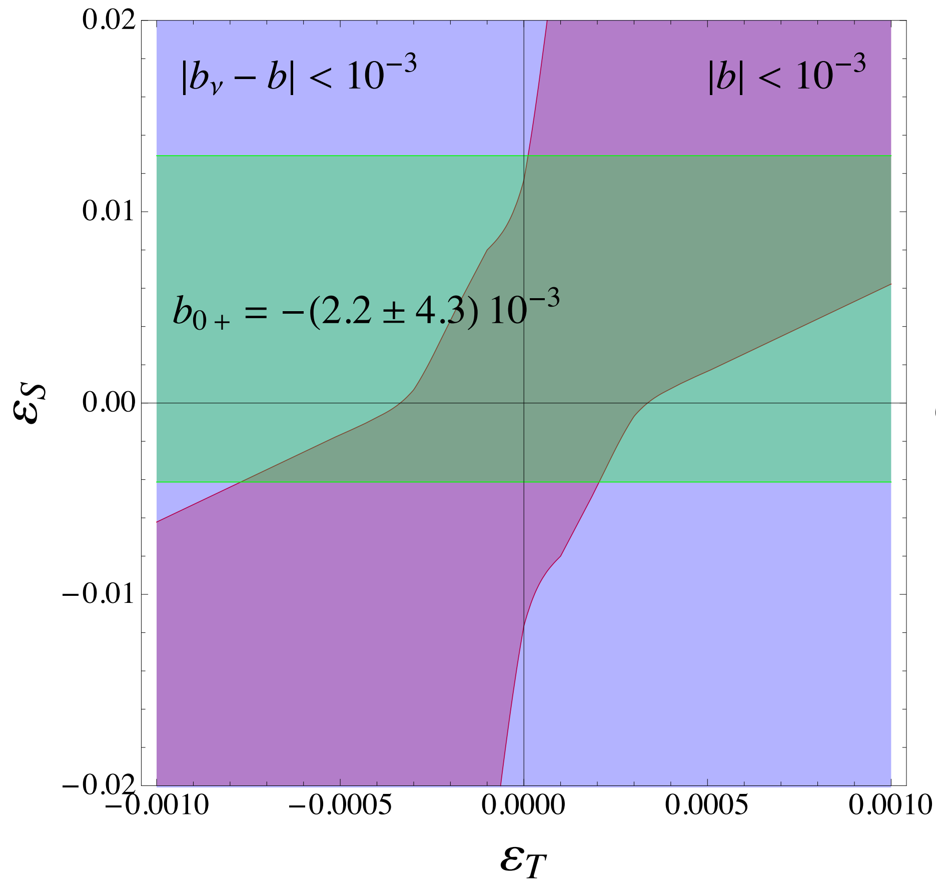


Phenomenology $n \to p\, e\, \nu$: Deriving Bounds

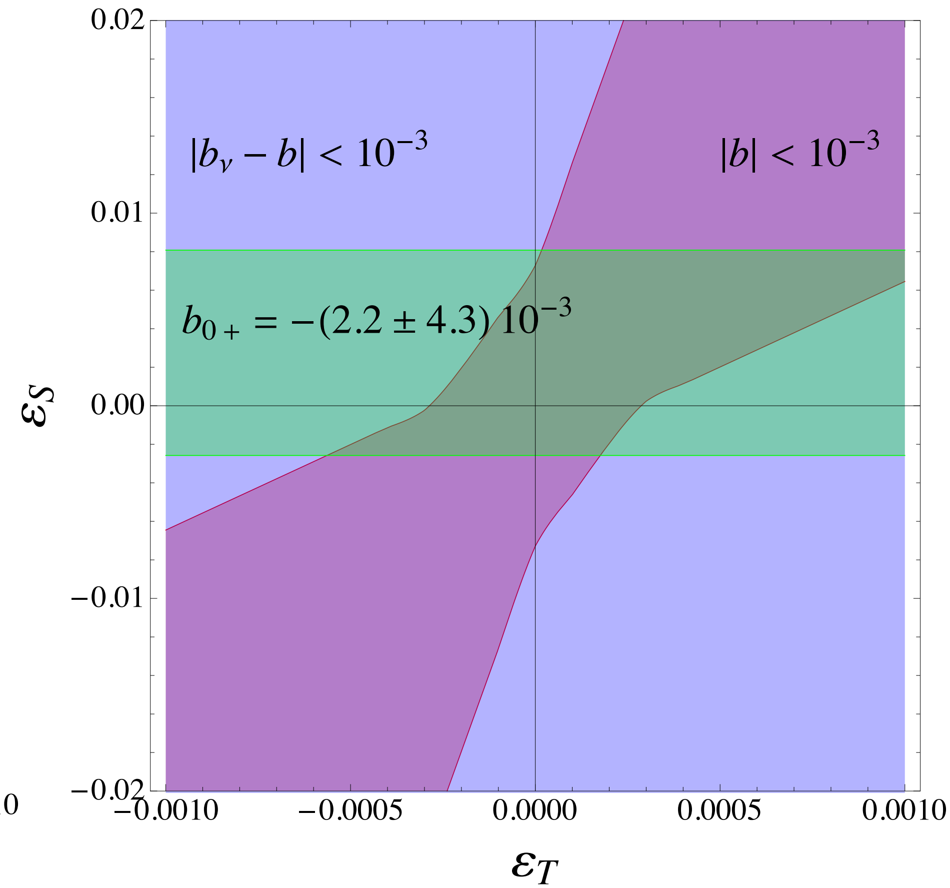
- Bounds: $G_F{*}\varepsilon_{S,T} = (1/\Lambda_{S,T})^2$ $\varepsilon_{S,T} = v^2/\Lambda^2_{S,T} \sim 10^{-3}$ implies $\Lambda_{S,T} \sim 5$ TeV



Constrain allowed region in ε_S and ε_T by improving estimates of g_S and g_T



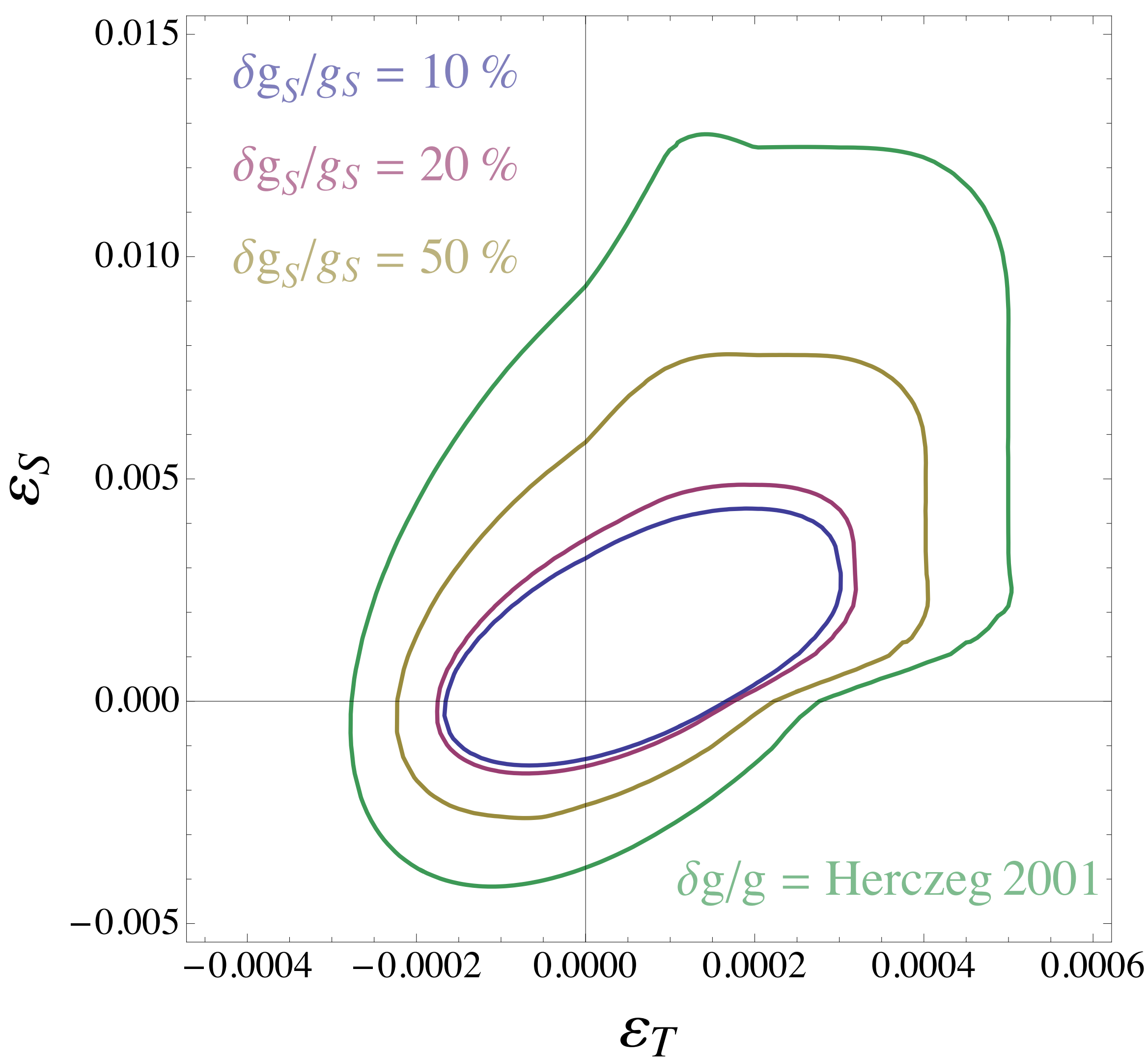
Herczeg–2001
$0.25 < g_S < 1.0$
$0.6 \quad < g_T < 2.3$



Lattice–2011
$g_S = 0.8(4)$
$g_T = 1.05(35)$

Impact of reducing errors in g_S and g_T from 50→10%

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



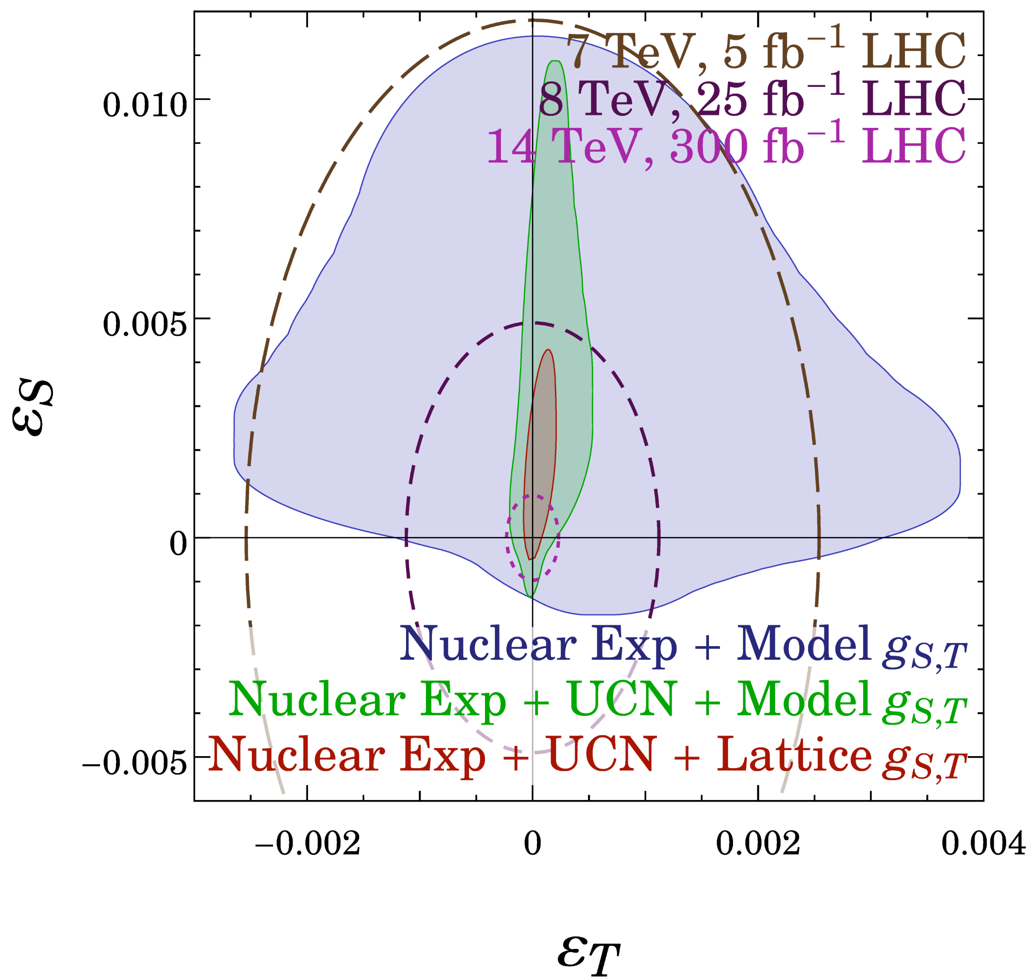
Expt. input

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

Limited by precision of ME

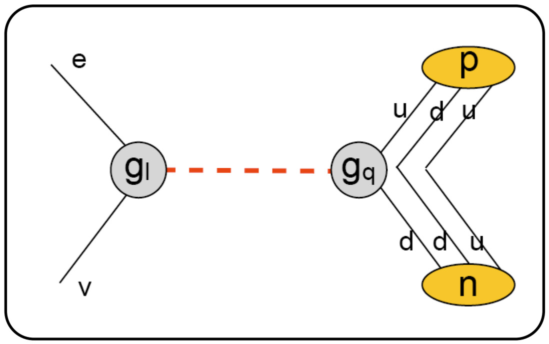
$g_S \sim \langle p|\bar{u}d|n\rangle$
$g_T \sim \langle p|\bar{u}\sigma_{\mu\nu}d|n\rangle$

β-decay versus LHC constraints



LHC @ 14TeV and 300fb^{-1}, will provide comparable constraints to low-energy ones with $\delta g_S/g_S$ ~20%

Precision calculations of g_S, g_T using Lattice QCD



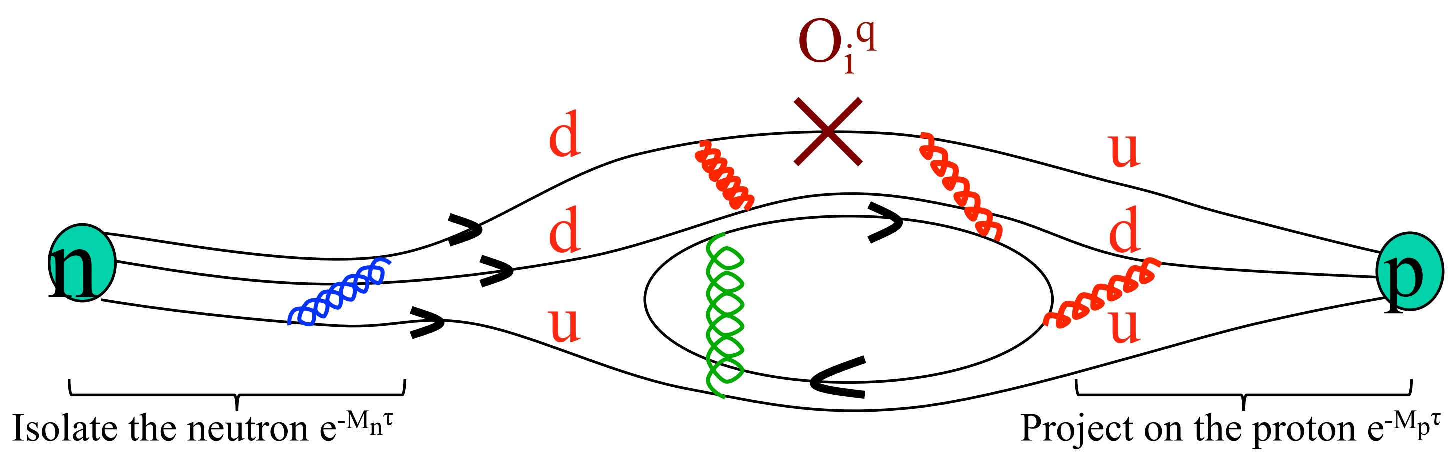
$$g_S \sim \langle p | \bar{u} d | n \rangle$$

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

Goal: 10-20% accuracy

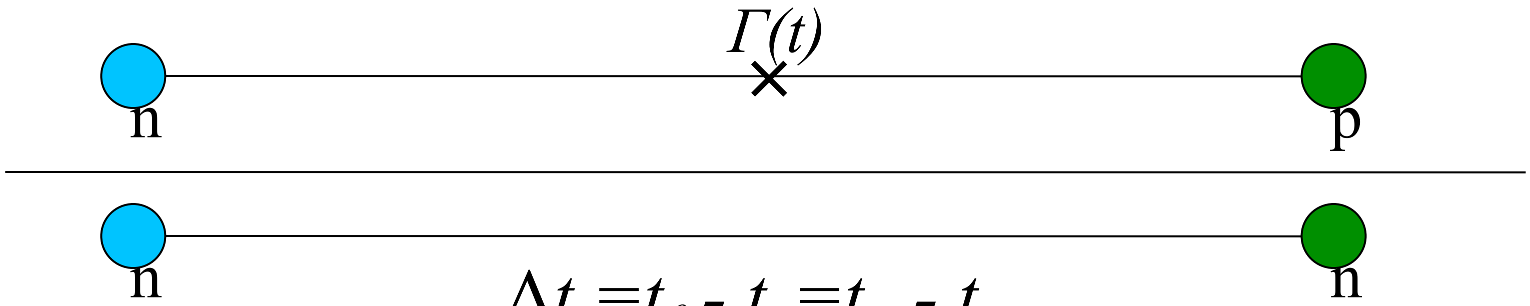
T. Bhattacharya, S. Cohen, R. Gupta, H-W Lin, A. Joseph, B. Yoon

Lattice QCD calculation of $\langle p|\bar{u}\,\Gamma d|n\rangle$



- **Achieving 10-20% uncertainty is a realistic goal but requires:**
  - High Statistics: computer resources from USQCD, XSEDE, LANL
  - Controlling all Systematic Errors:
    - Finite volume effects
    - Contamination from excited states
    - Chiral Extrapolations to physical *u* and *d* quark masses
    - Extrapolation to the continuum limit (lattice spacing $a \to 0$)
    - Non-perturbative renormalization of bilinears using the RI_{smom} scheme

Signal in the ratio $\frac{g_\Gamma}{Z_\Gamma} = \frac{\langle p | \bar{u} \Gamma d | n \rangle}{\langle p | n \rangle}$



$$\Delta t = t_f - t_i = t_p - t_n$$

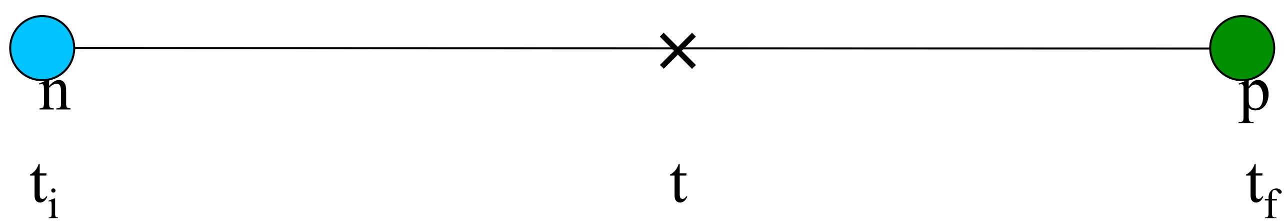
- Statistical signal
  - Improve overlap with ground state of *(p,n)* operators
- Plateau (result independent of Δt *and t*)
  - Otherwise need to eliminate excited state contribution
- Non-perturbative calculation of renormalization Z_Γ

Reducing excited state contamination
Simultaneous fit to all $\Delta t = t_f - t_i$

Assuming 1 excited state, the 3-point function behaves as

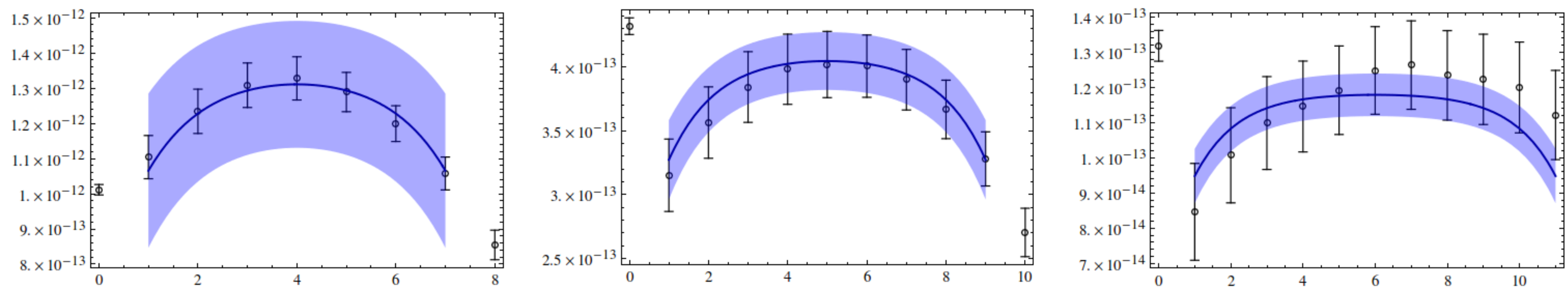
$$\Gamma^3(t_f, t, t_i) = |A_0|^2 \langle 0|O|0\rangle e^{-M_0 \Delta t} + |A_1|^2 \langle 1|O|1\rangle e^{-M_1 \Delta t} +$$
$$A_0 A_1^* \langle 0|O|1\rangle e^{-M_0 \Delta t} e^{-M_1(\Delta t - t)} + A_0^* A_1 \langle 1|O|0\rangle e^{-M_1 \Delta t} e^{-M_0(\Delta t - t)}$$

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

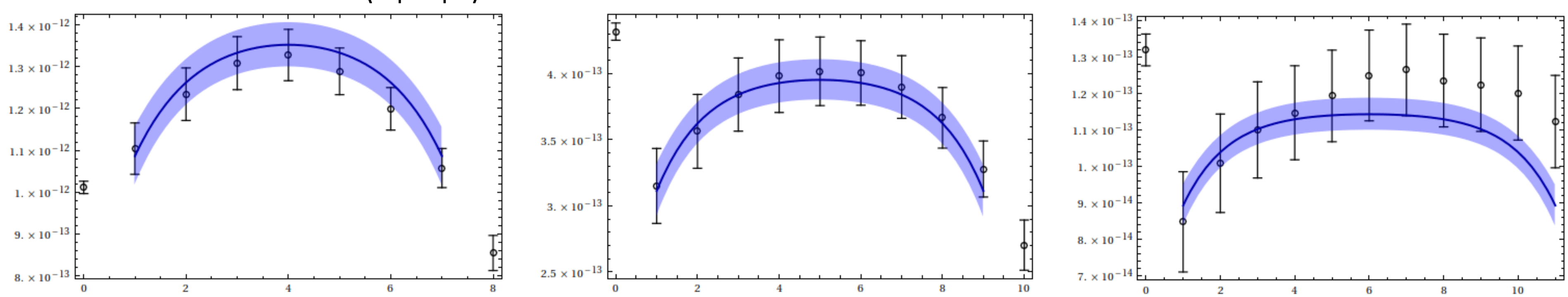


Simultaneous fit to all Δt

Data for g_S on the M_π=220 MeV ensemble at a=0.12fm



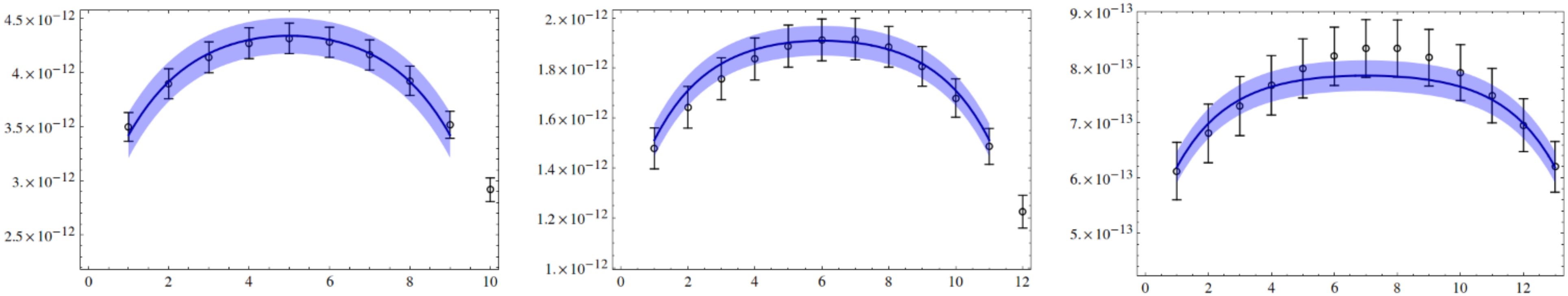
Excluding $\langle 1|O|1\rangle$ Term



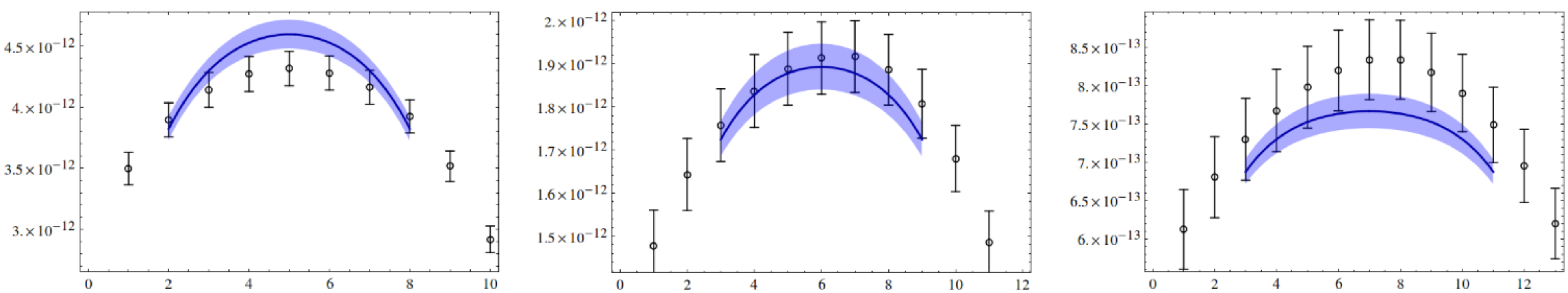
Δt=8 Δt=10 Δt=12

Simultaneous fit to all Δt

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



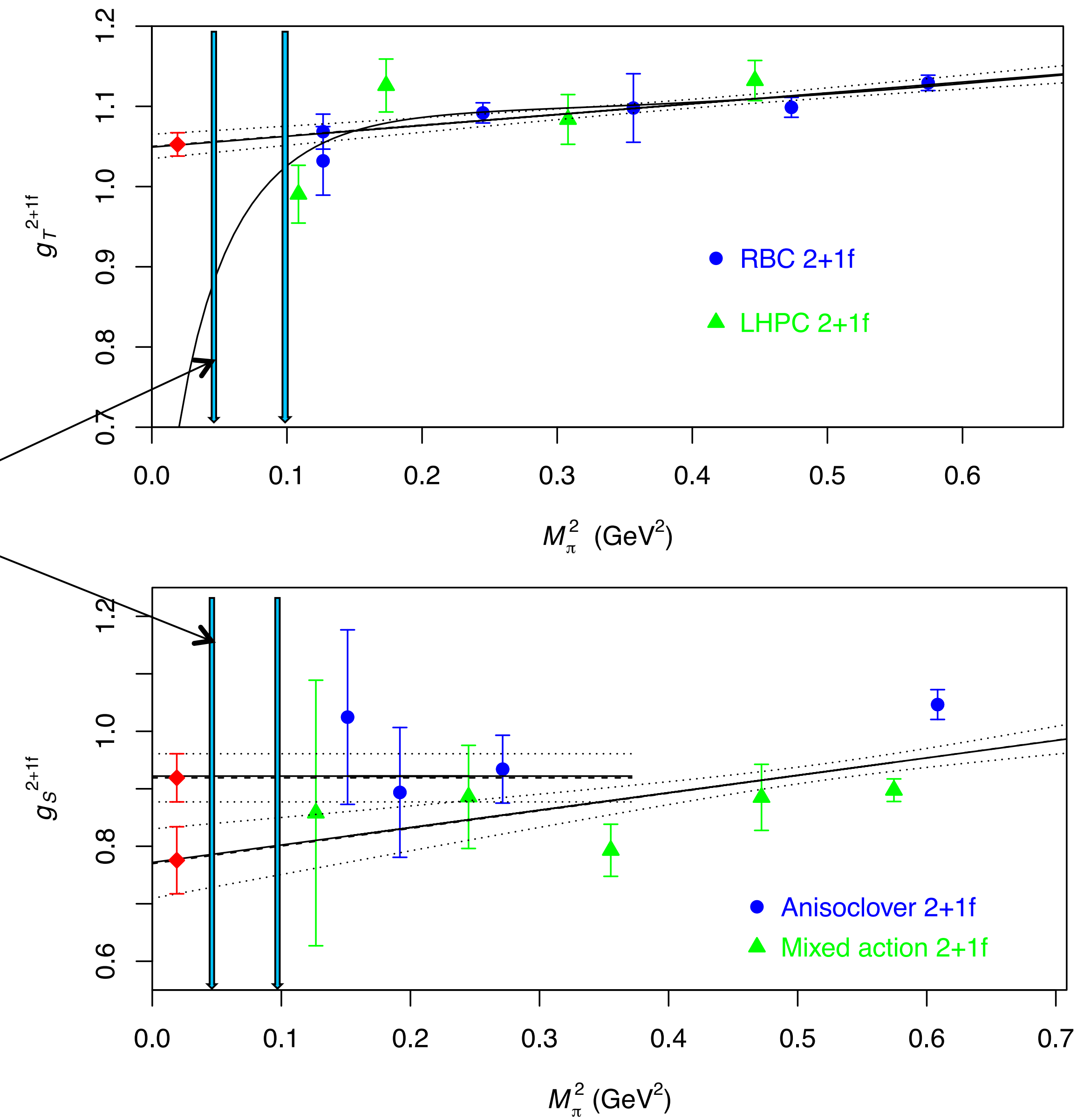
Excluding $\langle 1|O|1\rangle$ Term



Δt=10 Δt=12 Δt=14

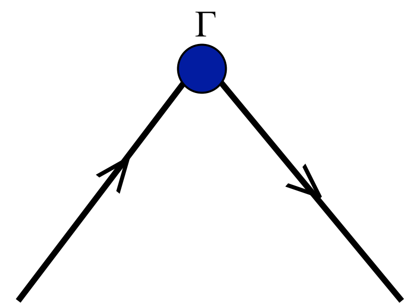
Simulations at physical quarks masses will remove uncertainty in the chiral extrapolation

Ongoing simulations



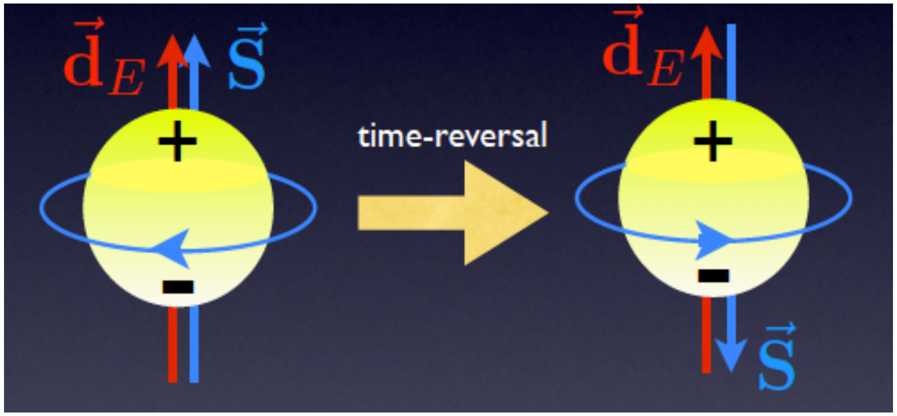
Renormalization of bilinear operators

- Non-perturbative renormalization Z_Γ using the RI-sMOM scheme
  - Need quark propagator in momentum space



- First calculations
  - 101 lattices at a=0.12fm M_π=310
  - 60 lattices at a=0.12fm M_π=220

nEDM is an excellent probe of Novel CP Violation

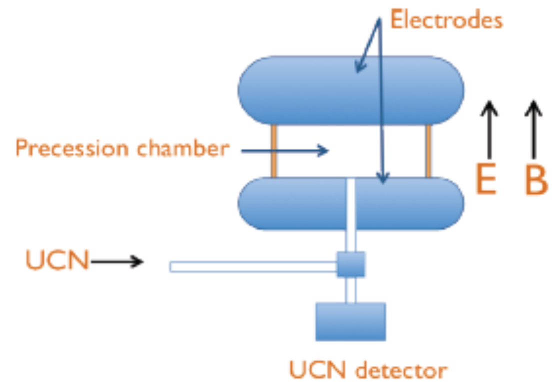


T. Bhattacharya, V. Cirigliano, R. Gupta

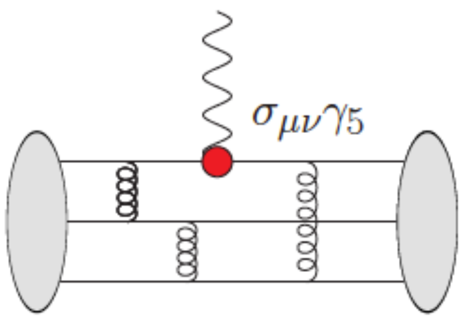
Project Goals

Probe new sources of T (CP) violation with the neutron Electric Dipole Moment (nEDM) to unprecedented levels, through synergy of

- Experiment: develop new experiment with10-fold sensitivity improvement ($\delta d_n = 3\times10^{-26}$ e-cm $\rightarrow \delta d_n = 3\times10^{-27}$ e-cm) taking advantage of unique Ultra Cold Neutron (UCN) source at LANL

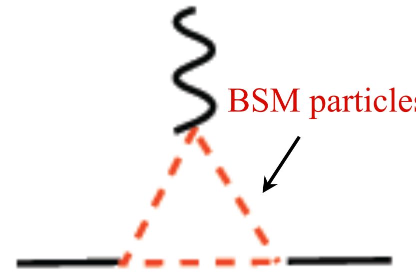


- Theory: set up robust framework to connect nEDM measurements to physics beyond the Standard Model, based on effective theory and first-principles non-perturbative calculation of matrix elements using lattice QCD



Exciting and timely science

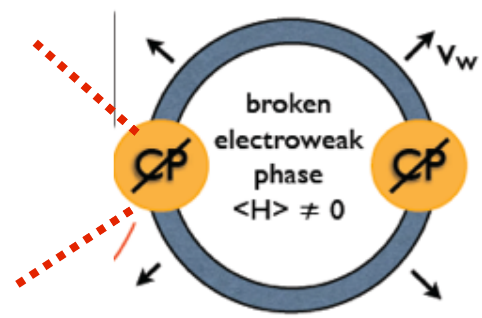
- EDMs probe high scale BSM physics
  - EDMs are sensitive (through virtual quantum mechanical effects) to particles with $M_{BSM} > 1$ TeV



- EDMs probe new sources of CP violation, a key ingredient of baryogenesis mechanisms

Sakharov '67

- B (baryon number) violation ← SM at T≠0
- C and CP violation ← EDMs
- Departure from equilibrium ← LHC (EWSB)



CP violation in the standard model

- Strong CP violation
  - Θ-term in the action
- Complex Phase in the quark mixing matrix
  - K_0 - K_0 mixing
  - B decays
- Current limits

$d_n < 2.9 \times 10^{-26}$ *e-cm* puts an upper bound on $\Theta < 10^{-10}$

These sources of CPV are too small to explain baryogenesis

CP violation in BSM ($\Lambda_{\mathrm{BSM}} \sim$ TeV)

- Don't know the theory of nature at this scale
- Most extensions of SM have new sources of CPV
- Use model independent effective theory framework
- Classify CPV operators in powers of $1/\Lambda_{\mathrm{BSM}}$
- 2 operators at lowest order

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

$\boxed{\text{Quark EDM}}$ $\qquad$ $\boxed{\text{Chromo EDM}}$

Effective theory at low energy

- At low energy, all BSM physics is described by local operators, with values of the coefficients determining the specific model

$$\boxed{\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{1}{M_i^2} O_i^{(6)} + \ldots}$$

$$M_i = M_{\rm BSM}/\sqrt{g_i^{\rm BSM}}$$

- In this framework, nEDM is given by linear combination of new physics couplings times matrix elements of quark-gluon level operators in the neutron state ($c_i^{QCD} \sim \langle n|\, O_i\, |n\rangle$)

$$\boxed{d_n = \sum_i c_i^{QCD}\, \epsilon_i^{CPV}}$$

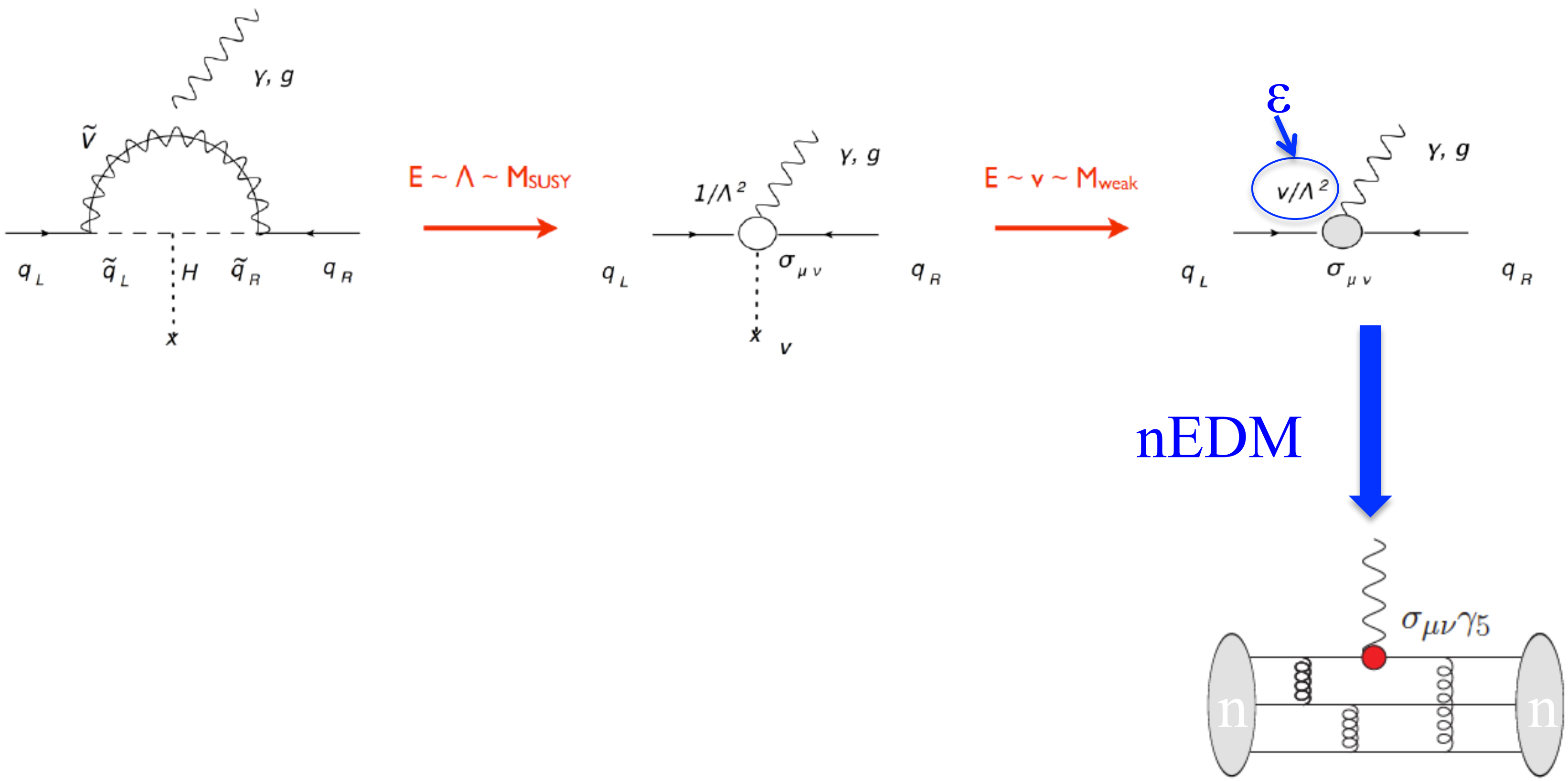
$$\varepsilon_i^{CPV} = (v_{EW}/M_{i,CPV})^2$$

Experiment

Theory

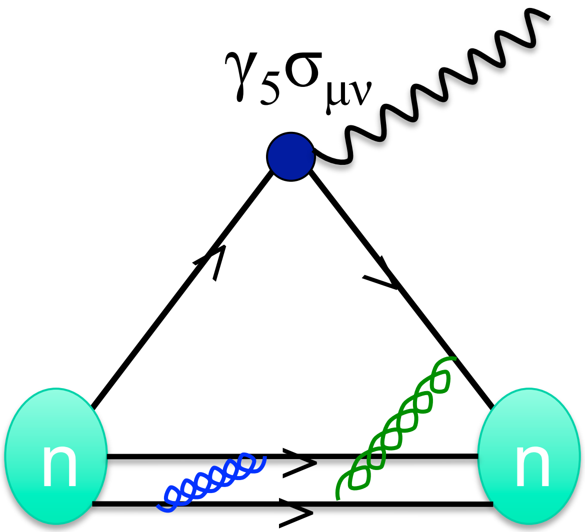
New Physics

How BSM feeds into neutron physics TeV $\rightarrow$ M_{weak} $\rightarrow$ GeV



Large QCD corrections:
ME evaluated using
Lattice QCD

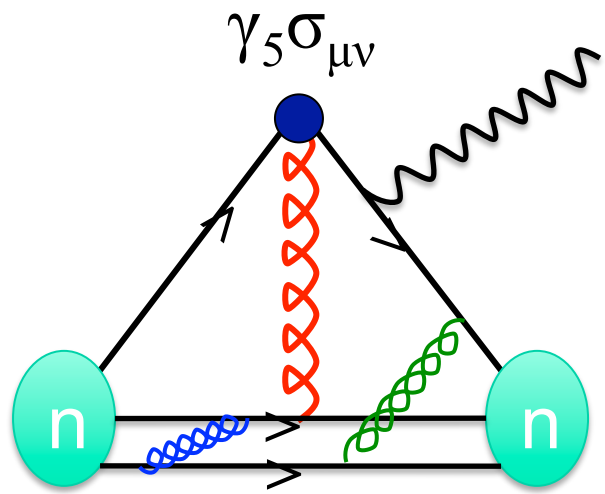
Feynman Diagrams



γ attaches to the vertex

Quark-EDM

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



- 4-pt function as γ can attach to any quark
- Gluon can attach to any of the quark lines

Chromo-EDM

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

Need experiment and theory to constrain BSM

$$d_n = \Sigma_i \ \varepsilon_i \times \langle O \rangle_i$$

Measurement

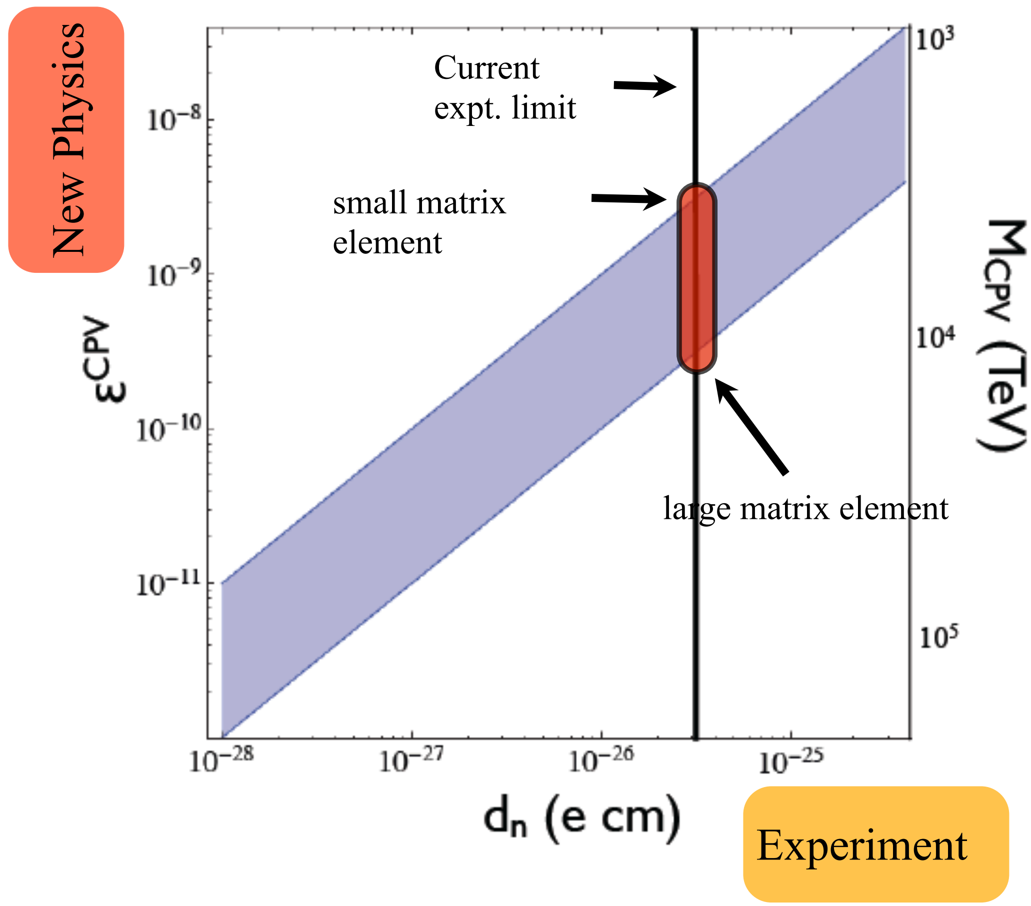
Couplings (strengths of the CPV operators)

Matrix elements of CP violating operators within a neutron state

Need experiment and theory

$$d_n = c^{QCD}\,\epsilon^{CPV}$$

- Goal: probe ε^{CPV}
- Ideal world: diagonal band is a sharp line
- Real world: O(10) theory uncertainty in c^{QCD} associated with leading BSM operators**
- Corresponding dilution in in the extraction of ε^{CPV}, for a given expt. result

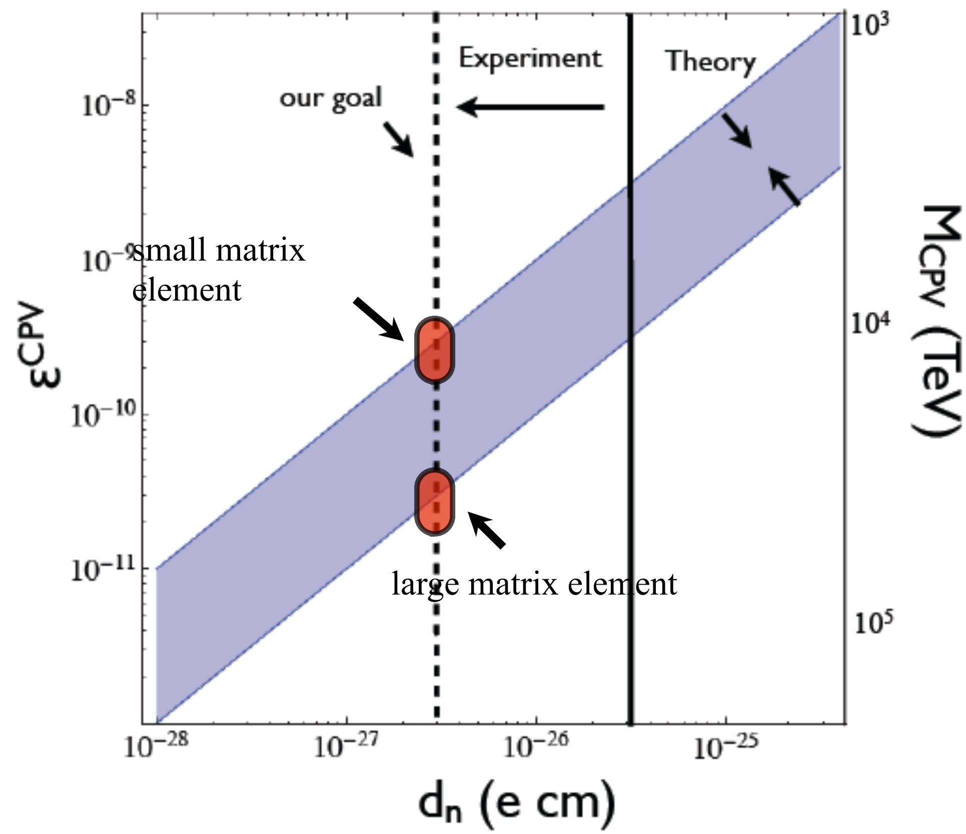


** Engel, Ramsey-Musolf, van Kolck, arXiv:1303.2371

Need experiment and theory

$$d_n = c^{QCD} \epsilon^{CPV}$$

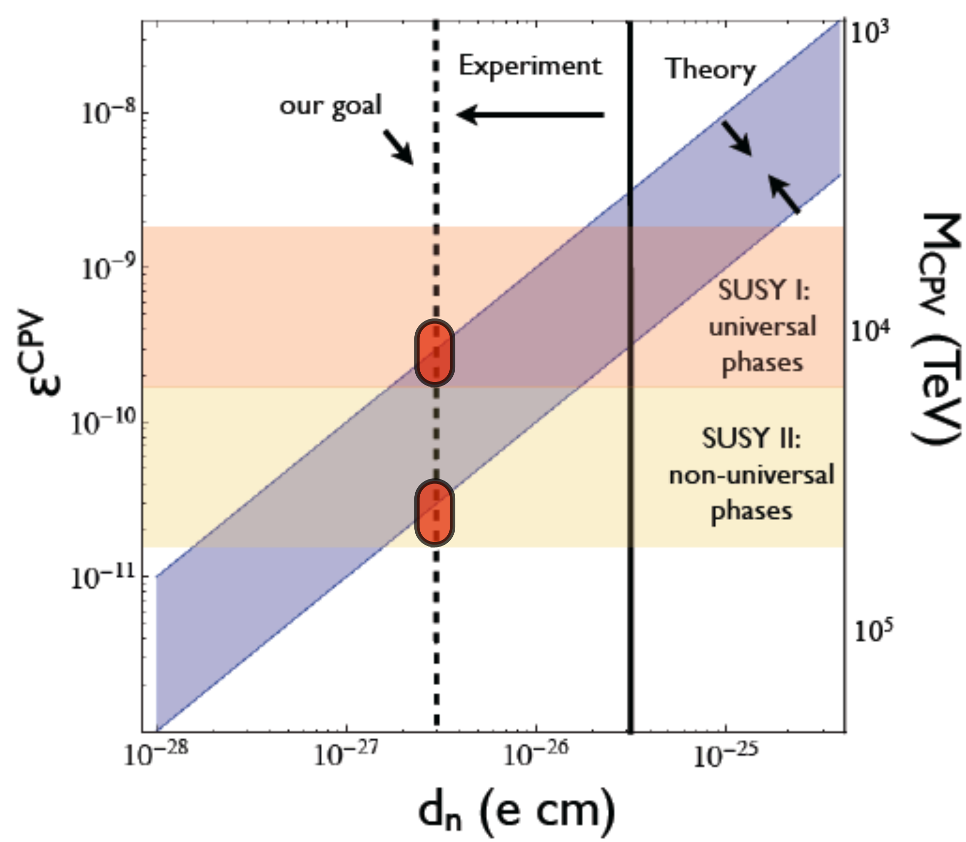
- Goal: probe ε^{CPV}
- Combined effort will:
- improve sensitivity to ε^{CPV} by up to two orders of magnitude



Need experiment and theory

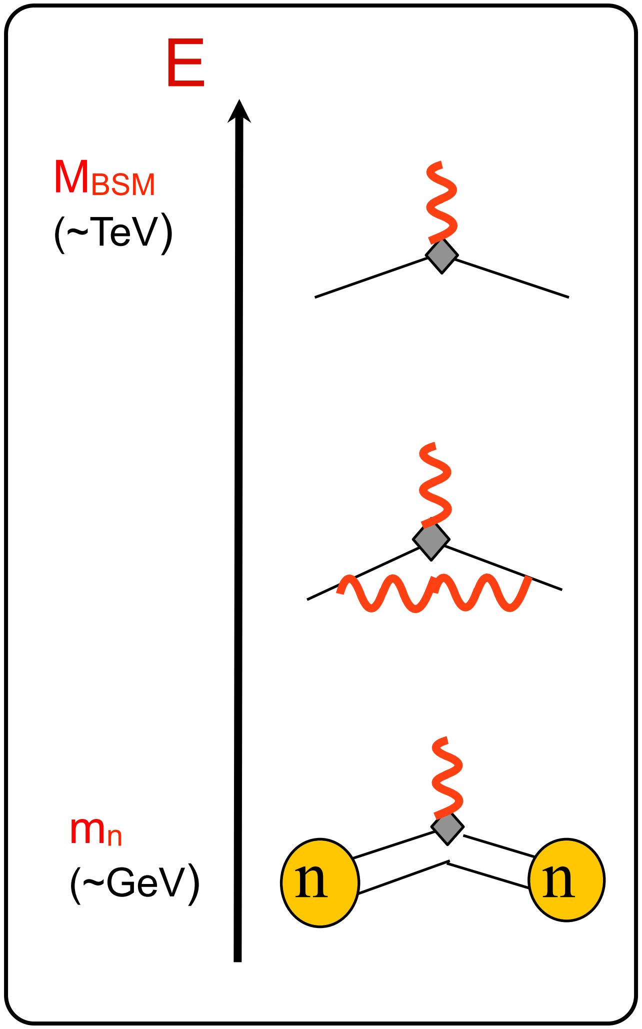
- Goal: probe ε^{CPV}
- Combined effort will:
- improve sensitivity to ε^{CPV} by up to two orders of magnitude
  - enable quantitative tests of weak scale baryogenesis scenarios

$$\boxed{d_n \;=\; c^{QCD}\,\epsilon^{CPV}}$$



Theory program overview

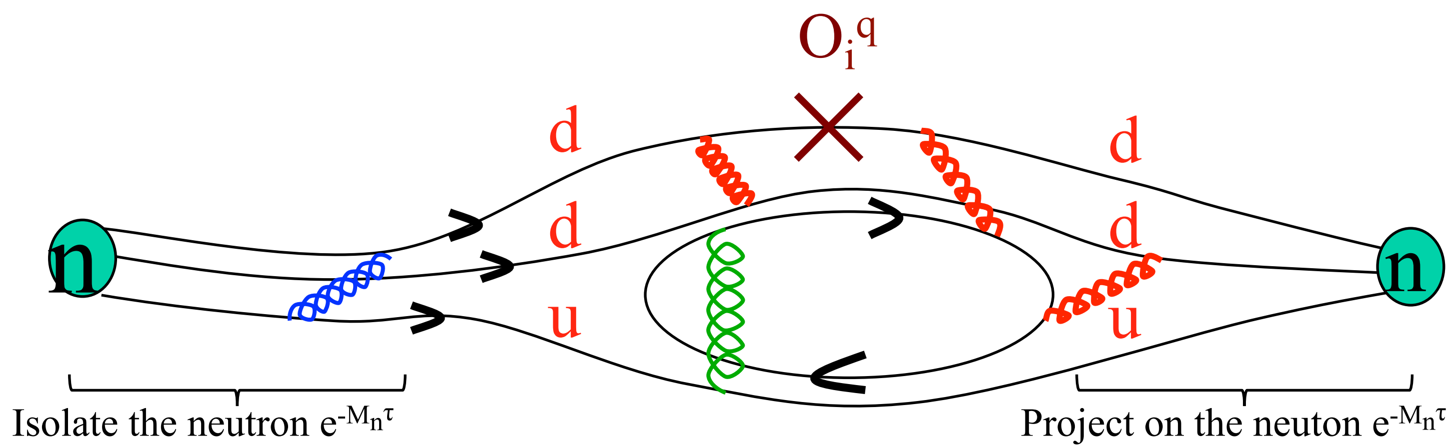
- Calculate connection between TeV and GeV scale couplings (perturbative)
  - BSM defined at the TeV scale (M_{BSM})
  - Measurement at the GeV scale (m_n)
- Compute matrix elements of quark-gluon CPV operators in the neutron
  - Focus on quark EDM and chromo-EDM operators (leading in most models)
  - First calculation within lattice QCD



Using Lattice QCD to calculate Matrix Elements

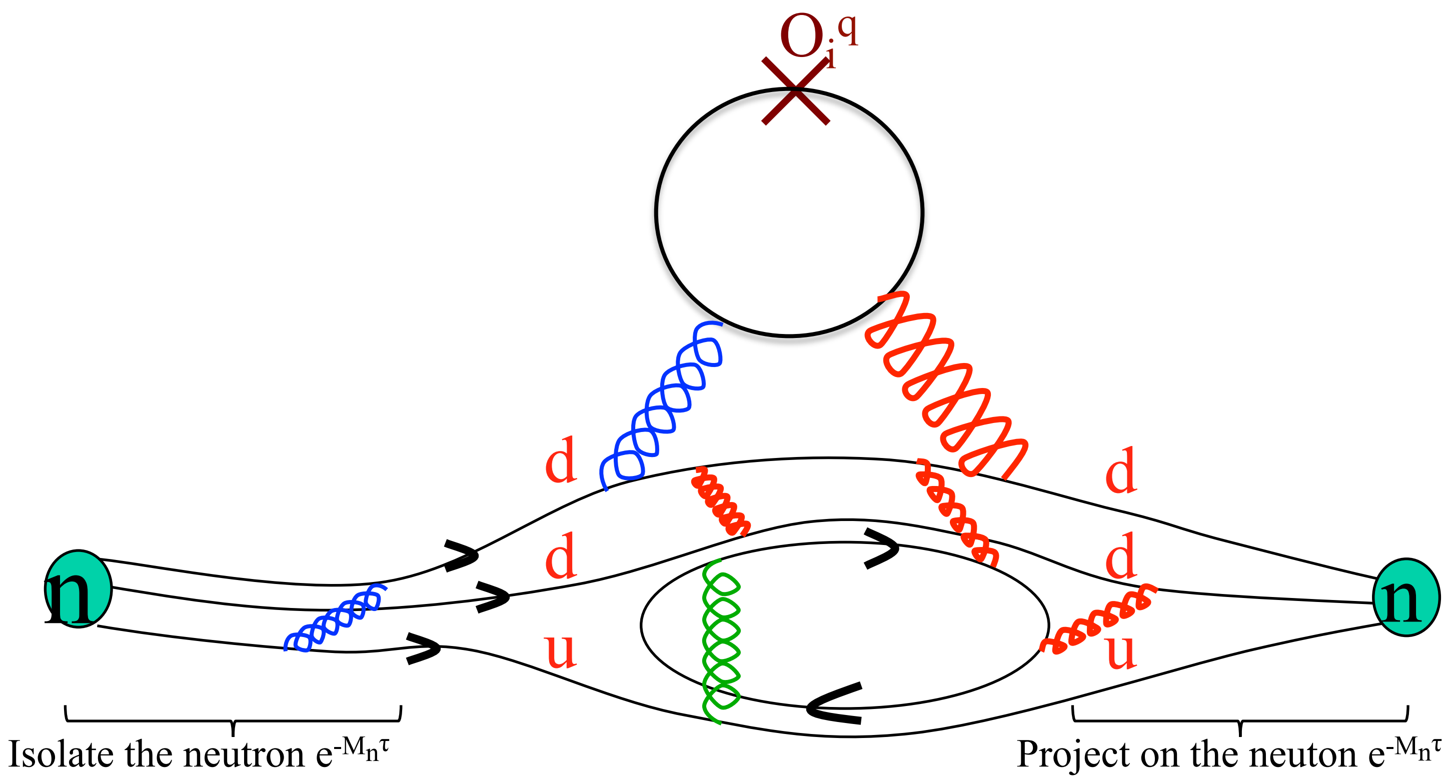
- RBC
  - M. Abramczyk, T. Blum, T. Izubuchi, C. Lehner, S. Ohta, E. Shintani, A. Soni,
- LANL
  - T. Bhattacharya, V. Cirigliano, R. Gupta, B. Yoon
  - Experimental: T. Ito, M. Cooper, M. Makela, et al.

Lattice QCD calculation of $\langle n|\bar{q}\,\Gamma q|n\rangle$



- **First calculations demonstrating and quantifying signal/noise require:**
  - High Statistics: computer resources from USQCD, XSEDE, LANL
  - Controlling all Systematic Errors:
    - Finite volume effects
    - Contamination from excited states
    - Chiral Extrapolations to physical *u* and *d* quark masses
    - Extrapolation to the continuum limit (lattice spacing $a \rightarrow 0$)
    - Non-perturbative renormalization of bilinears using the RI_{smom} scheme

Disconnected diagrams



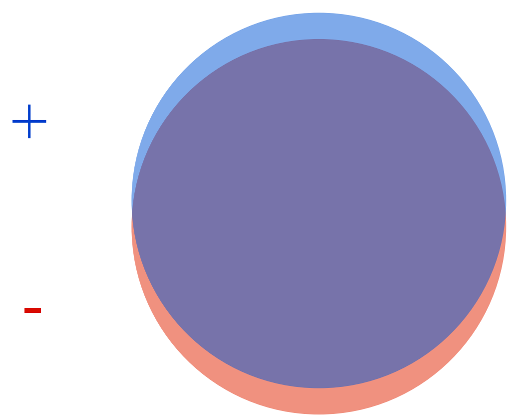
We know how to calculate disconnected diagrams. The challenge is to improve the signal to noise ratio for the specific matrix elements needed for nEDM

Operator Mixing and Renormalization

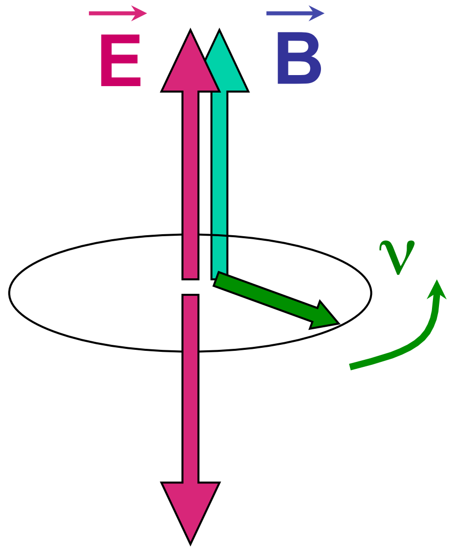
- At the TeV scale, the theory will, in principle prescribe the CPV operators and their couplings
- Under change of scale, these operators mix due to interactions of quarks and gluons (QCD)
- At the GeV scale, every TeV operator becomes a linear combination of all operators it can mix with. This mixing can be calculated in QCD perturbation theory
- The renormalization of the lattice operators is also calculated non-perturbatively

A tiny effect can have a huge impact

- Amazing (and difficult) precision experiment
- A neutron EDM of 3×10^{-27} e-cm amounts to a separation of positive and negative charges by 10^{-14} of the neutron radius !!



nEDM measurement principle

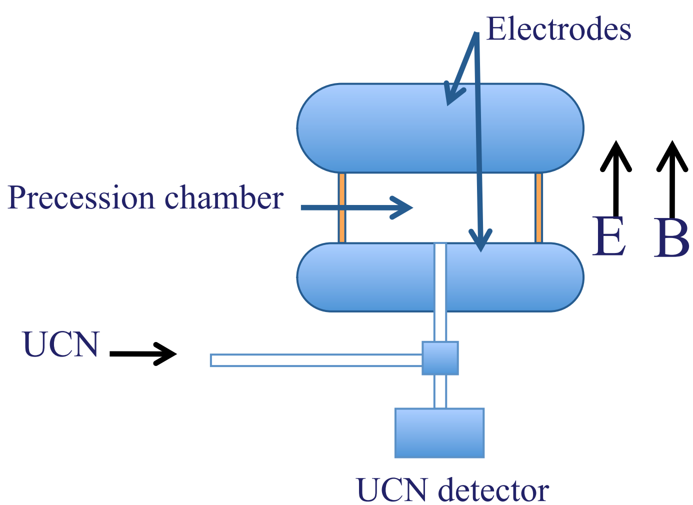


$$\nu = \left(2\mu_n B \pm 2d_n E\right)/h$$

$$\Delta\nu = 4d_n E/h$$

$$\delta d_n = h\frac{\delta\Delta\nu}{4E}$$

For B ~ 10 mG, ν = 30 Hz.
For E = 10 kV/cm and $d_n = 3\times10^{-27}$ e-cm, Δν=0.03 μHz. → comagnetometer essential



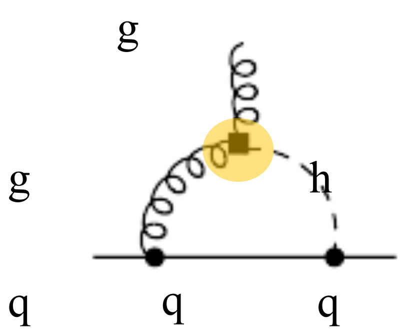
Statistical uncertainly of each measurement is given by

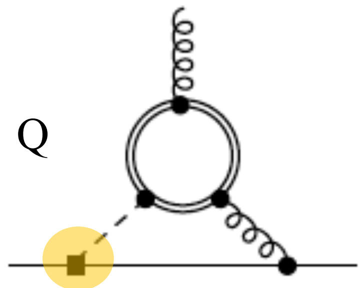
$$\delta d_n = \frac{\hbar}{2\alpha E T\sqrt{\rho_{UCN} V}}$$

For Sussex-ILL experiment
- E=10 kV/cm — significant improvement difficult
- T = 130 s — significant improvement difficult
- ρ_{UCN} ~ 1 UCN/cc — 100 UCN/cc goal at LANL
- V = 20 liters —significant improvement difficult

nEDM and non-standard Higgs couplings

- Exciting byproduct of the “coupling evolution” analysis: use nEDM to probe/constrain non-standard couplings of the Higgs boson





Non-standard CPV Higgs couplings to gluons and quarks induce a neutron EDM

- Phase 1: Standard Model Higgs (one doublet)
- Phase 2: extended Higgs sector (2 Higgs Doublet Models)

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