Exploring Novel Physics at the TeV Scale through Lattice QCD Simulations of the Nucleon

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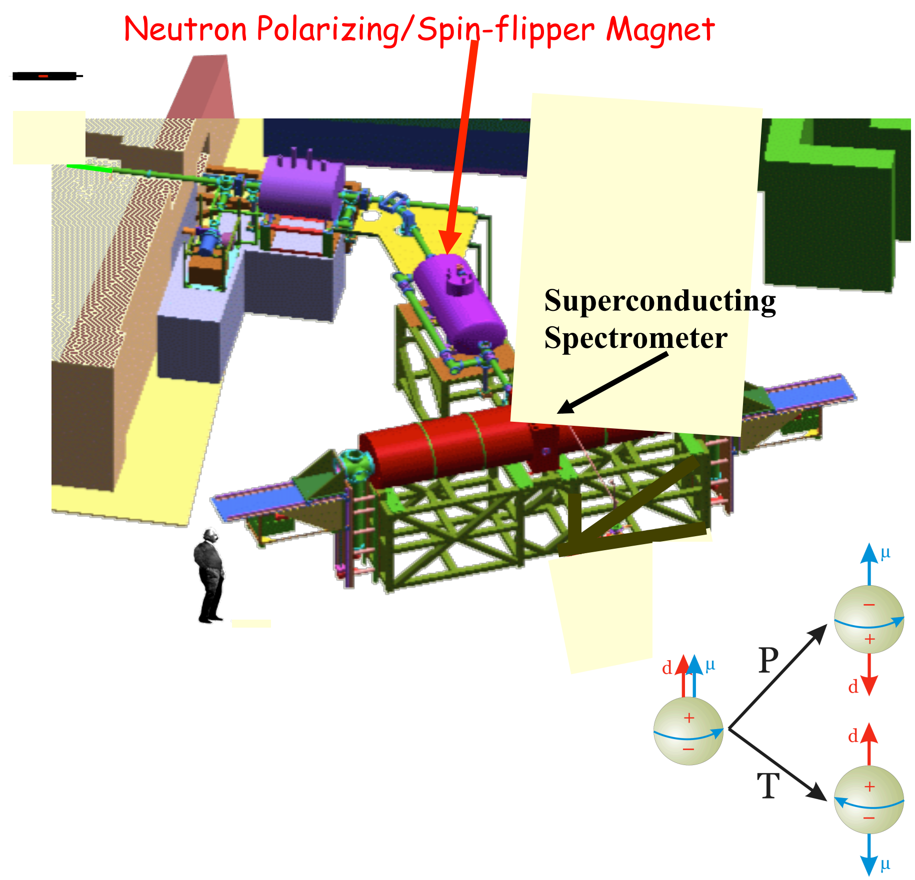


LAUR-12-20208

Outline

- Probing novel scalar and tensor interactions at the TeV scale in neutron β-decay
- Lattice QCD calculations of the matrix elements
- Novel CP violation and Neutron EDM

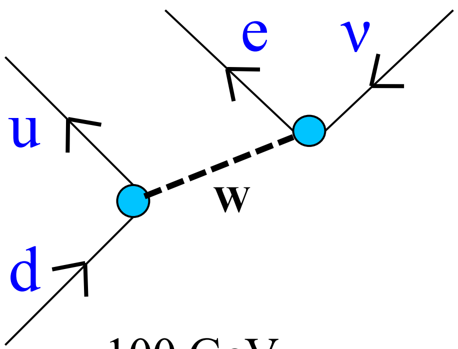
Work done in collaboration with:

- T. Bhattacharya, V. Cirigliano, M. Graesser, A. Joseph, B. Yoon (LANL)
- Saul Cohen (Google), Huey-Wen Lin (Berkeley)

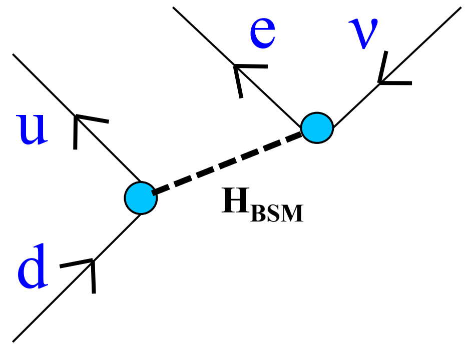
Novel Scalar and Tensor Interactions

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

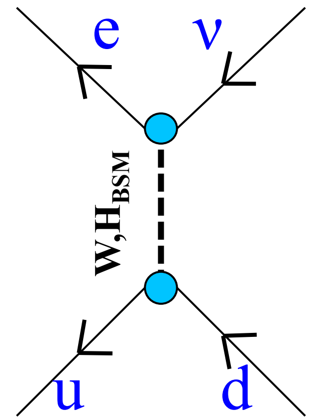
Many BSM possibilities for novel Scalar & Tensor interactions: Higgs-like, leptoquark, loop effects, …



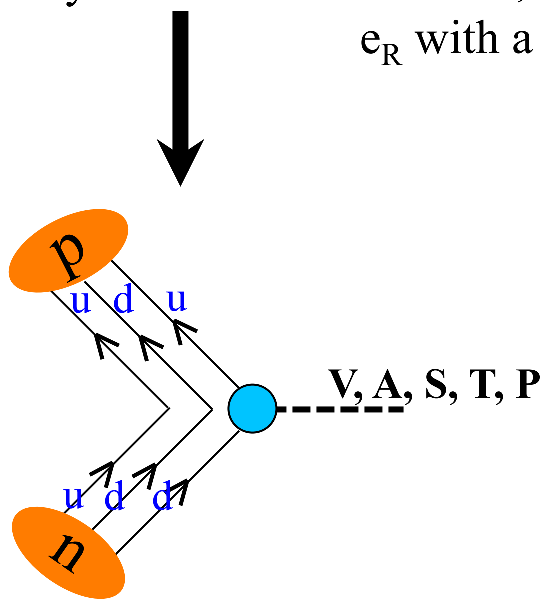
100 GeV
V-A Weak decay
e_L with a ν_L



TeV
Novel S,T Interactions
e_R with a ν_L



LHC



Neutron
Decay

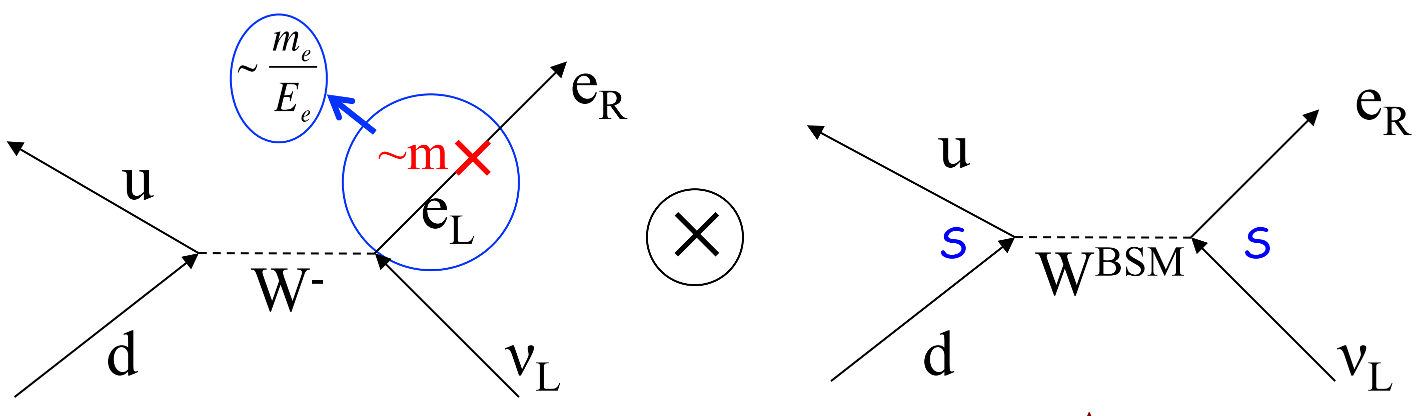
Effective Theory @ ~2 GeV
V-A (g_A, g_V) Weak interactions
S, T (g_S, g_T) New Interactions

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

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

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

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

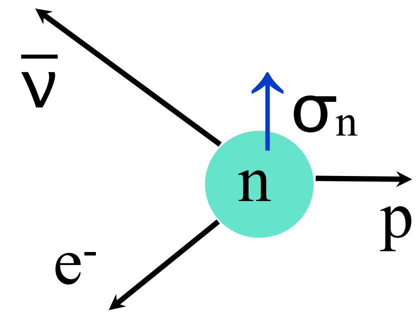


A_{SM} $\otimes$ A_{BSM}

[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

Physics Case $n \rightarrow pe\bar{\nu}$: (BSM/SM) ~ O(1)

- Couplings $\varepsilon_{P,S,T}$ $\sim (v/\Lambda_{BSM})^2 \sim 10^{-3}$
- SM contribution($\sim 10^{-3}$) and known to ($\sim 10^{-5}$): contribution is controlled by 2 small parameters $(M_n - M_p)/M_n$ and α/π
- Radiative corrections: $\alpha/\pi \sim 10^{-3}$
- Isospin-breaking: $(M_N - M_P)/M_N \sim q/M_N \sim 10^{-3}$
- Recoil corrections: $q/M_N \sim 10^{-3}$
- UCN: smaller Doppler broadening of *e* spectrum
- 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 extensions

Relating *b* and *B₁* to BSM couplings

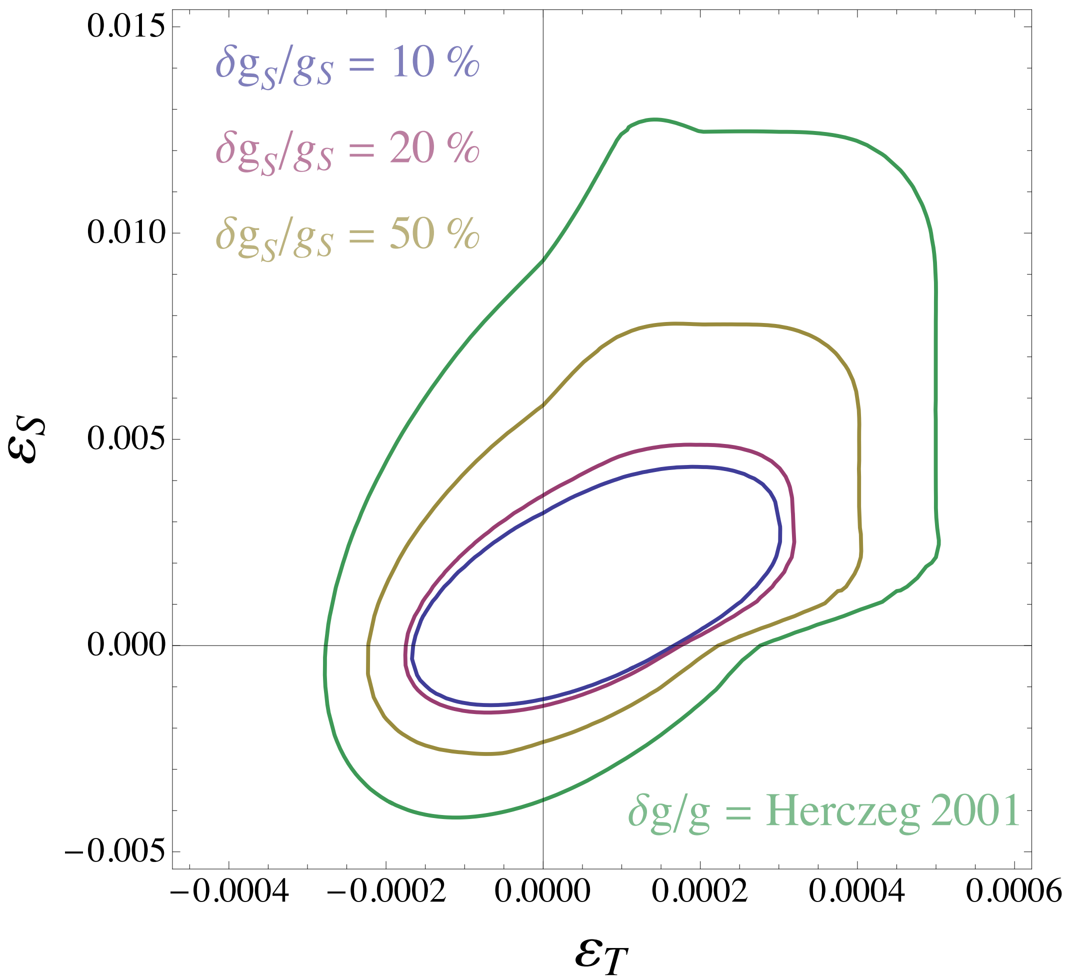
Linear order relations: n → p e ν decay

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

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

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

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



Expt. input

$|B_1 - b| < 10^{-3}$

$|b| < 10^{-3}$

$b_{0+} = 2.6\ (4.3) * 10^{-3}$

Impact limited by precision of ME from Lattice QCD

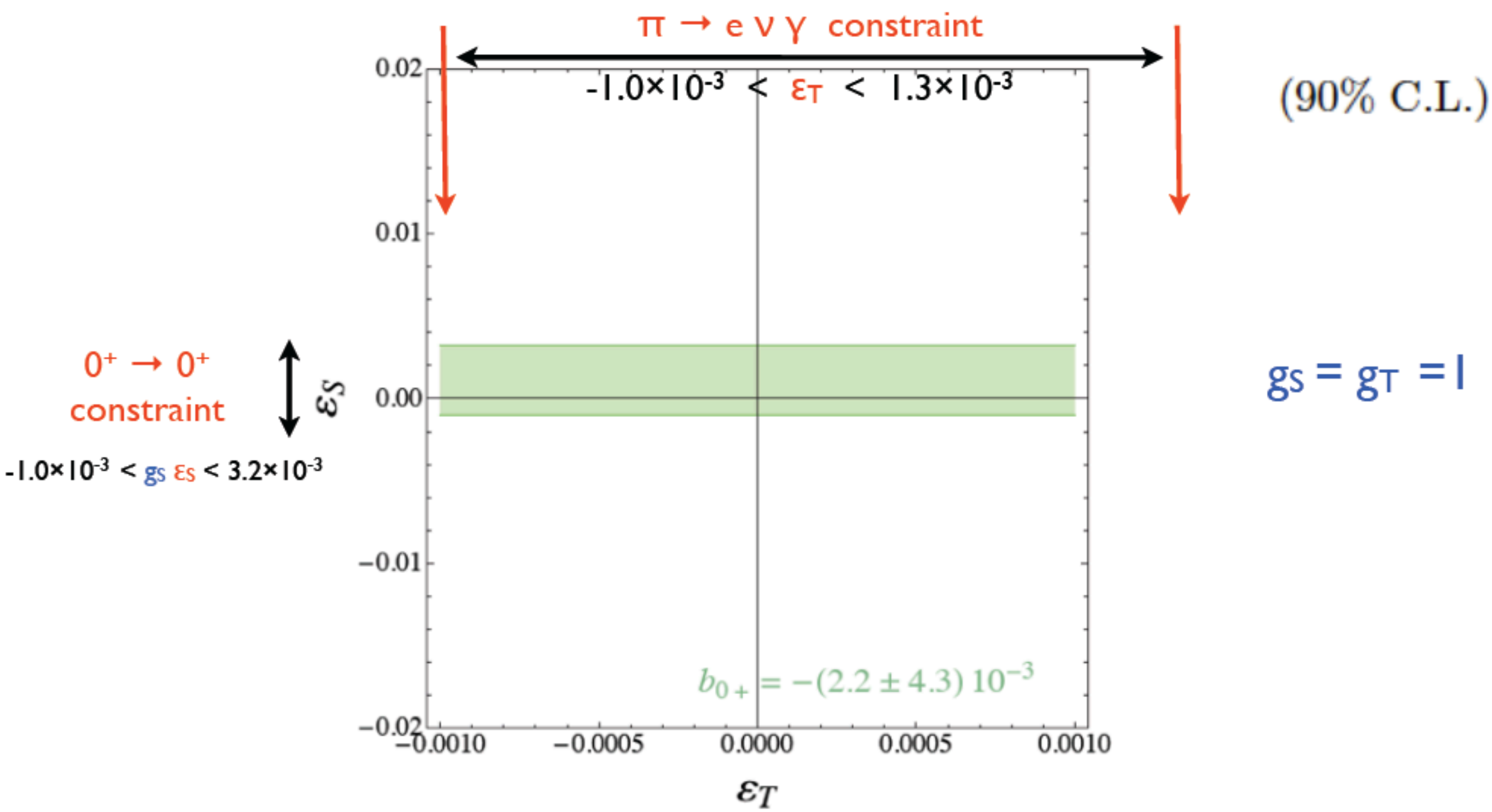
$$g_S \sim \langle p | \bar{u} d | n \rangle$$

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

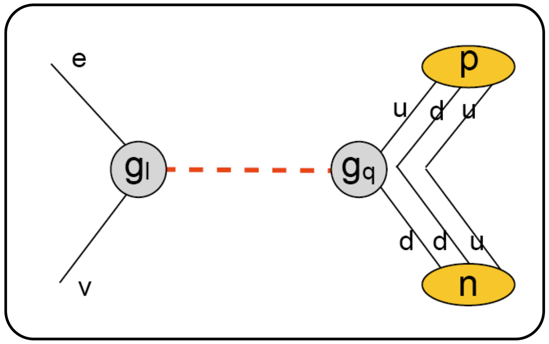
Goal: 10% accuracy in g_S and g_T

Other low energy constraints

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



Precision Calculations of g_S, g_T using Lattice QCD

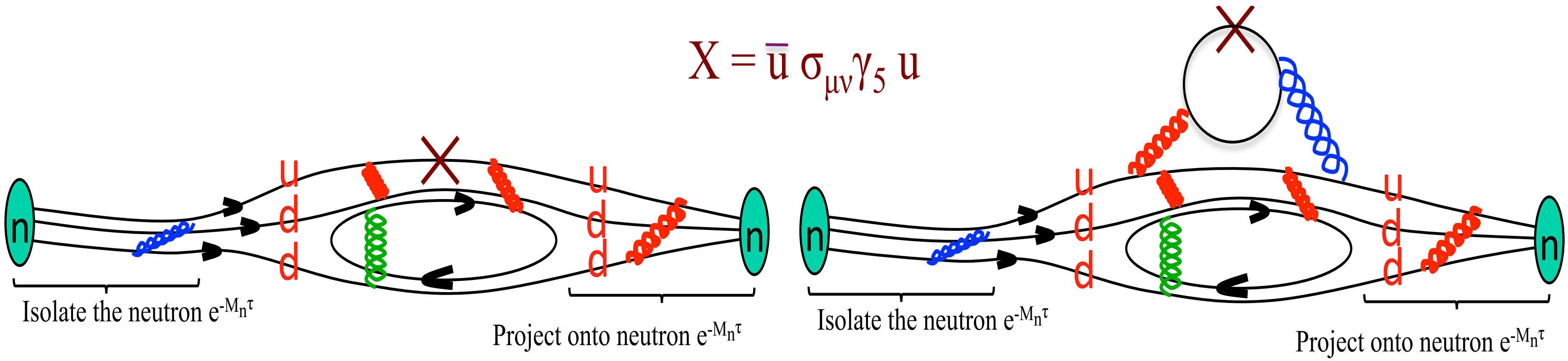


Precision Neutron Decay Matrix Elements Collaboration (PNDME)
T. Bhattacharya, S. Cohen, R. Gupta, A. Joseph, H-W Lin, B. Yoon

- PRD 85 (2012) 054512
- PRD 89 (2014) 094502
- In Preparation
  - Iso-vector and Iso-scalar Tensor Charges of the Nucleon from Lattice QCD
  - Why Lattice QCD underestimates g_A
  - Electric and Magnetic Form-factors from lattice QCD
  - Axial Form-factors from lattice QCD

What we calculate using LQCD

$X = \bar{u}\, \sigma_{\mu\nu}\gamma_5\, u$

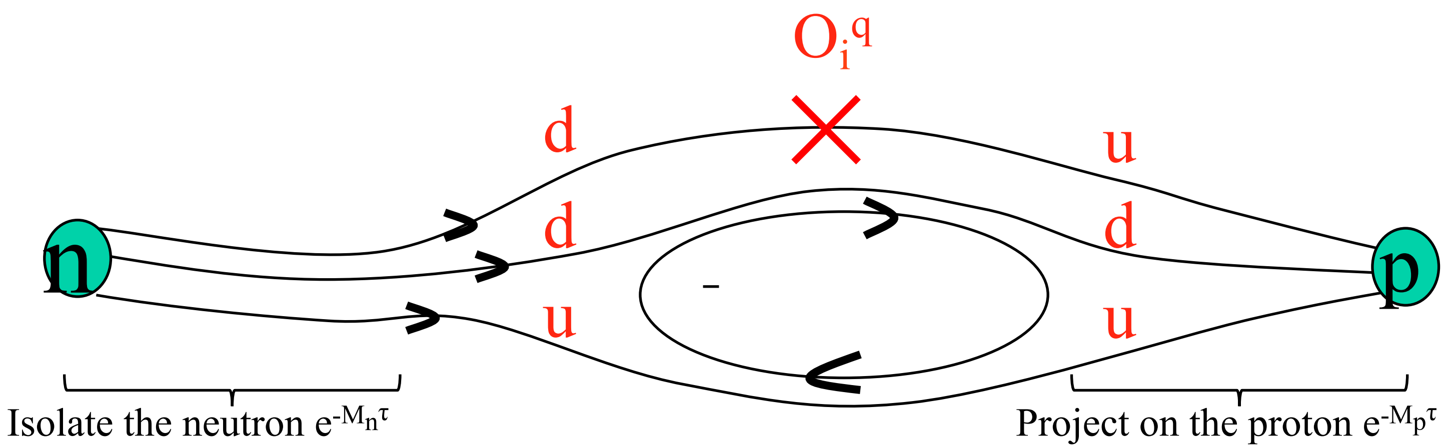


Connected 3-point function ***Disconnected 3-point function***

<u>Building Blocks: Monte Carlo integration of QCD path integral</u>

- Generate importance sampled background gauge configurations using a (2+1+1) flavor action
- Calculate Feynman quark propagators on these configurations
- Construct the correlation functions
- Average correlation functions over gauge configurations

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



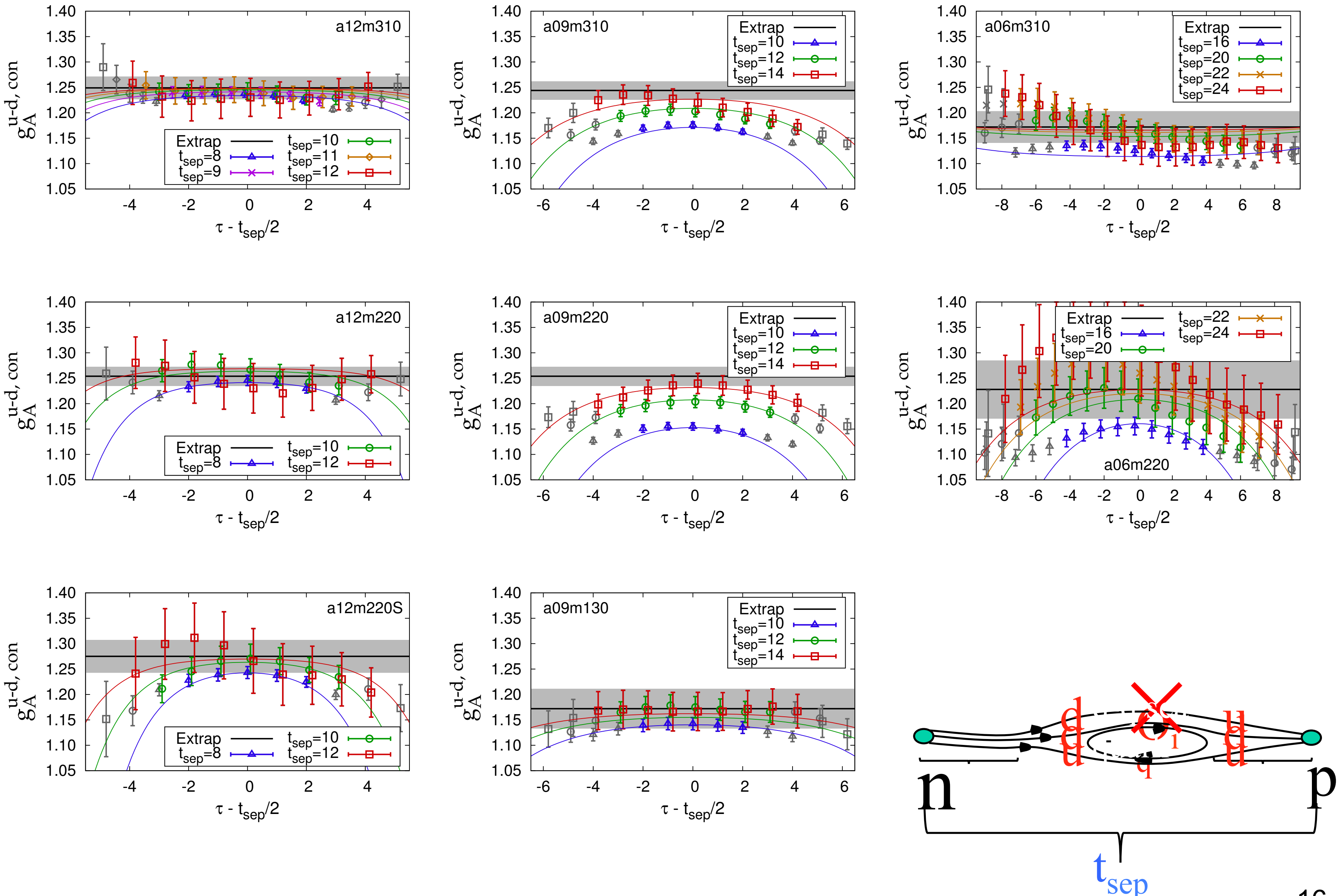
- **Achieving 10% uncertainty is a realistic goal but requires:**
  - High Statistics:
  - Controlling all Systematic Errors:
    - Contamination from excited states
    - Non-perturbative renormalization of bilinears using the RI_{smom} scheme
    - ➢ Finite volume effects
    - ➢ Chiral Extrapolations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

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	$M_\pi L$	M_π (MeV)	Measurements
0.12	0.2	$24^3 \times 64$	4.54	310	8104
0.12	0.1	$32^3 \times 64$	4.29	227	7664
0.09	0.2	$32^3 \times 96$	4.5	313	7048
0.09	0.1	$48^3 \times 96$	4.73	226	7120
0.09	0.037	$64^3 \times 96$	3.66	138	7064
0.06	0.2	$48^3 \times 144$	4.53	320	8000
0.06	0.1	$64^3 \times 144$	4.28	235	2600

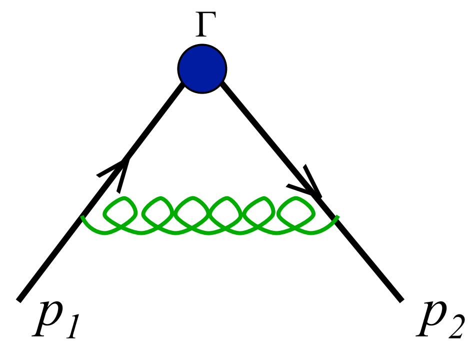
Excited state contamination



Renormalization of bilinear operators

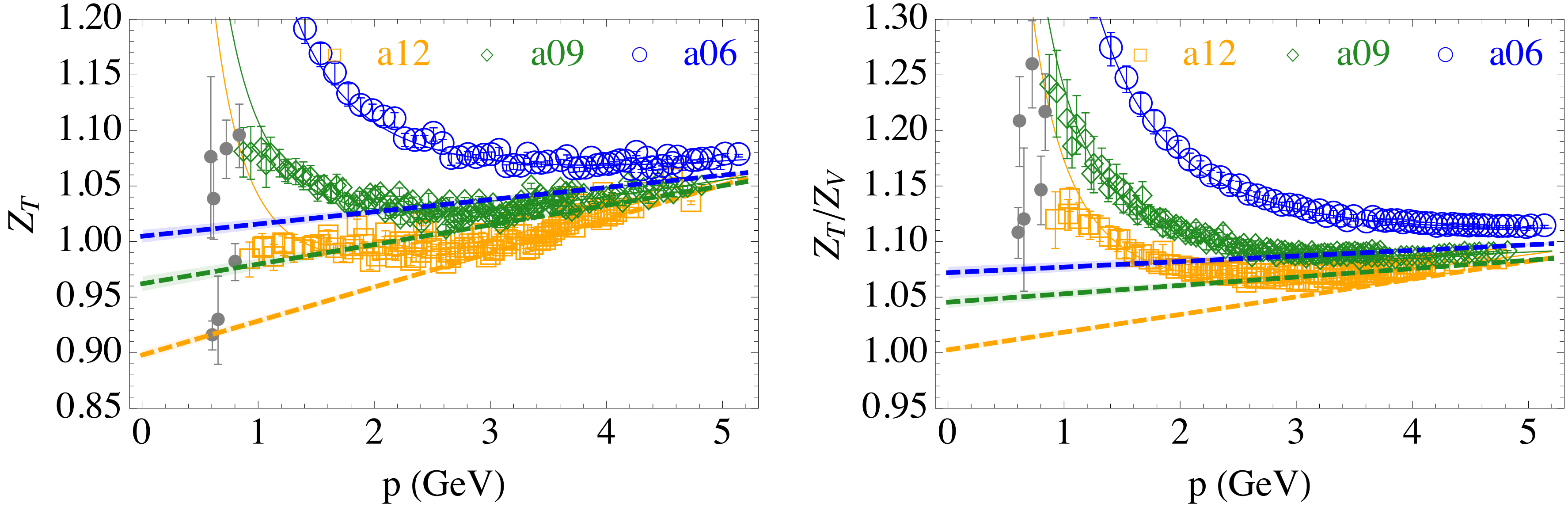
- Non-perturbative renormalization factors Z_Γ using the RI-sMOM scheme ($p_1^2 = p_2^2 = q^2$)
  - Need quark propagator in momentum space
- Basic Assumption: there exists a window

  $$\Lambda_{QCD} << p << \pi/a$$



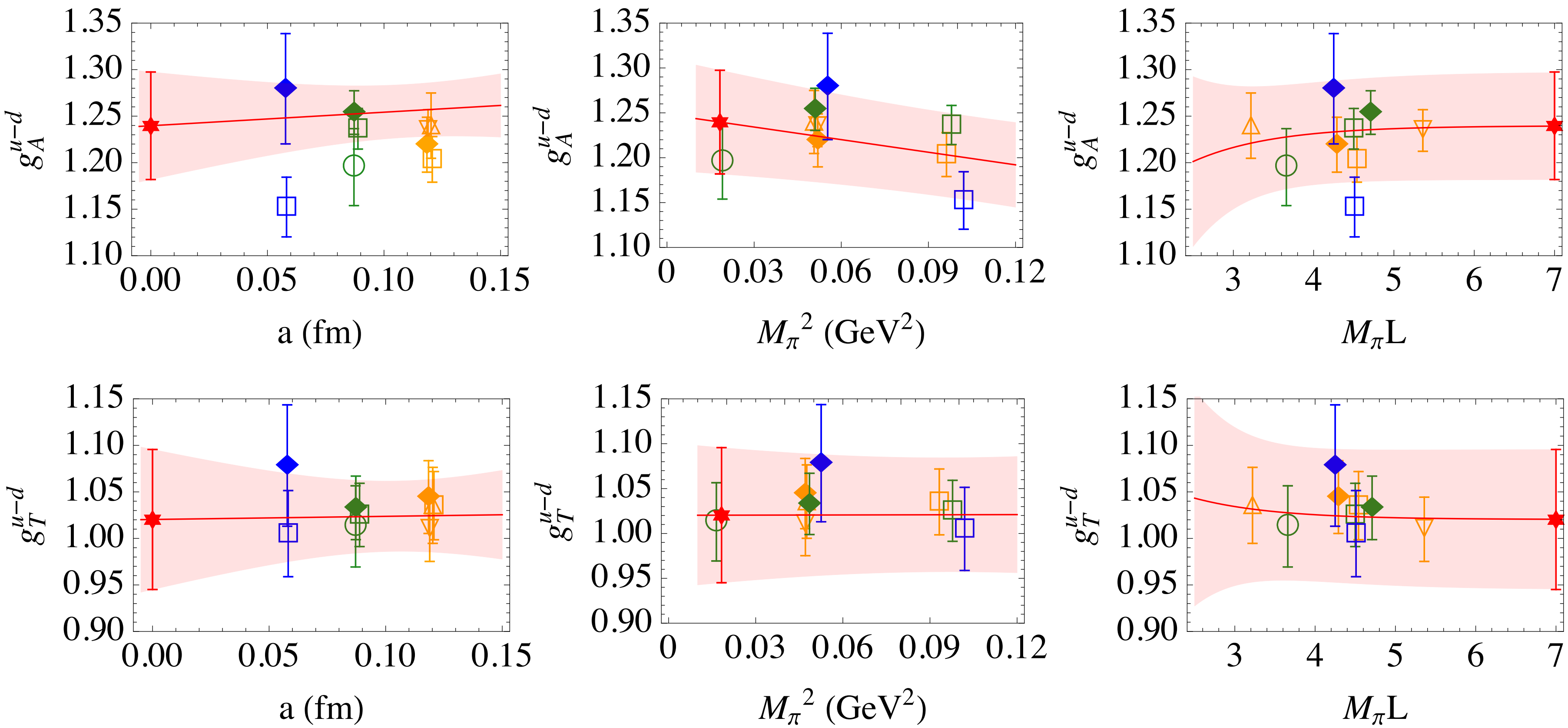
- HYP Smearing introduces artifacts
  - Gluon momentum above (~$1/a$) are averaged out
  - $\Lambda_{QCD} << p << \pi/a$ window may not exist on coarse lattices
- Matching to MS: 1-loop matching and 2-loop running

Renormalization: RI-sMOM



- No detectable dependence of *Z'*s on m_q
- Ratios (Z_Γ/Z_V) have smoother behavior
- Current error estimates have ~4% uncertainty

Simultaneous extrapolation in quark mass, lattice spacing and volume



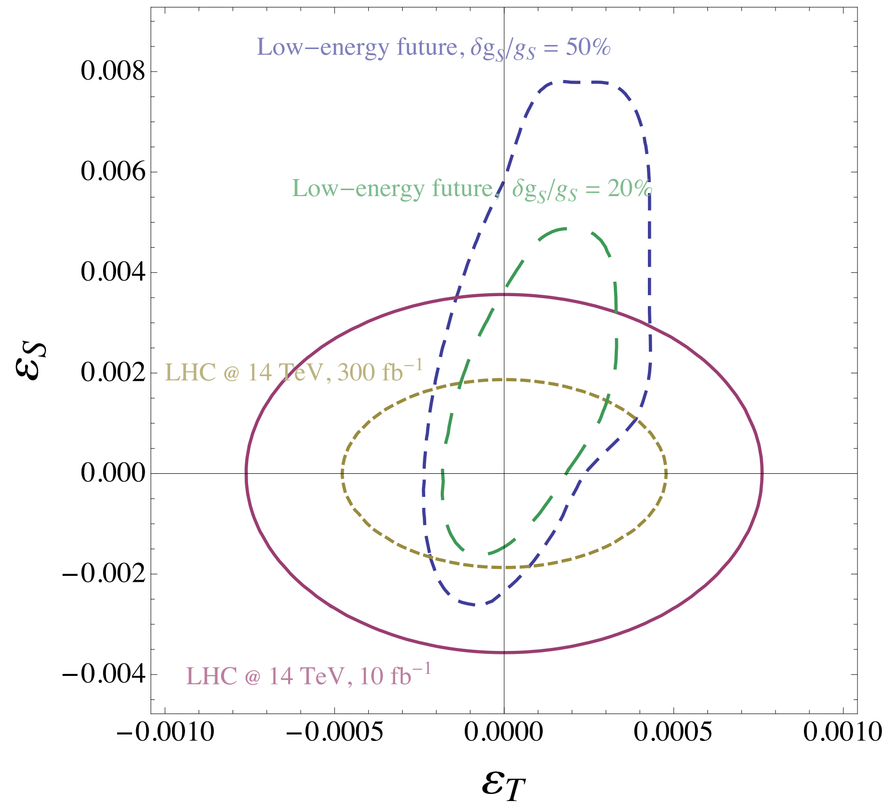
Status

- $g_A = 1.24(6)$
- $g_S = 1.13(25)$
- $g_T = 1.020(75)$

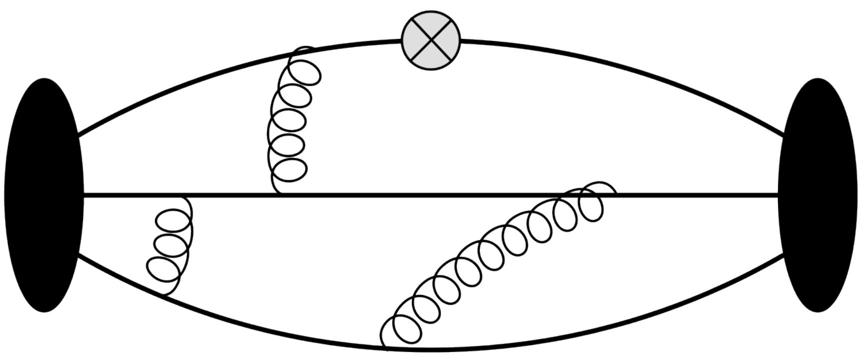
Need to reduce errors in g_S by a factor of 2

β-decay versus LHC constraints

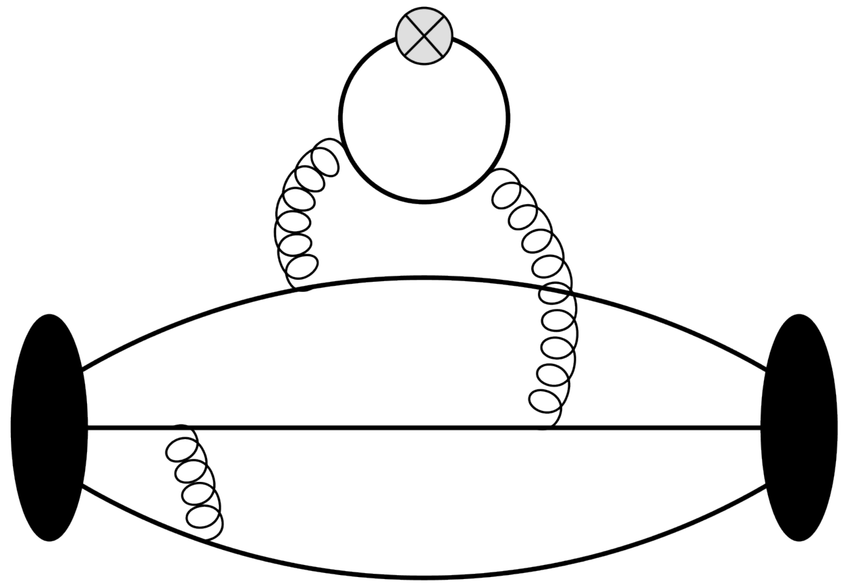
- LHC @ 14 TeV and 300 fb^{-1}, will provide comparable constraints to low-energy ones with $\delta g_S/g_S$ ~20%



Types of diagrams



Connected



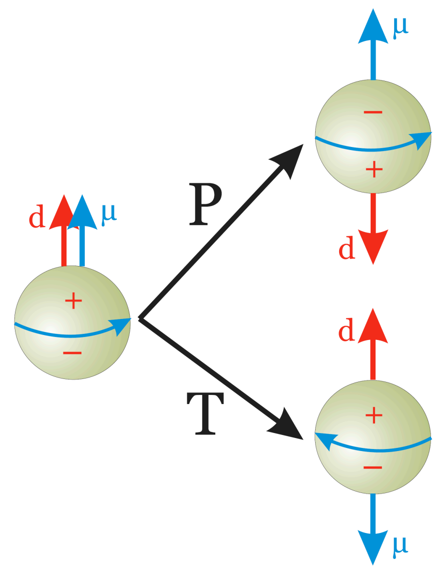
Disconnected

A number of matrix elements are being calculated

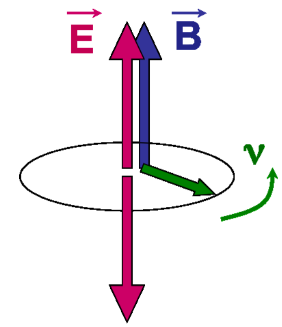
- Iso-vector charges g_A, g_S, g_T $\langle p|\bar{u}\Gamma d|n\rangle$
- Axial vector form factors $\langle p(q)|\bar{u}\gamma_\mu\gamma_5 d(q)|n(0)\rangle$
- Vector form factors $\langle p(q)|\bar{u}\gamma_\mu d(q)|n(0)\rangle$
- Flavor diagonal matrix elements $\langle p|\bar{q}q|p\rangle$
- Quark EDM and quark chromo EDM
- Generalized Parton Distribution Functions

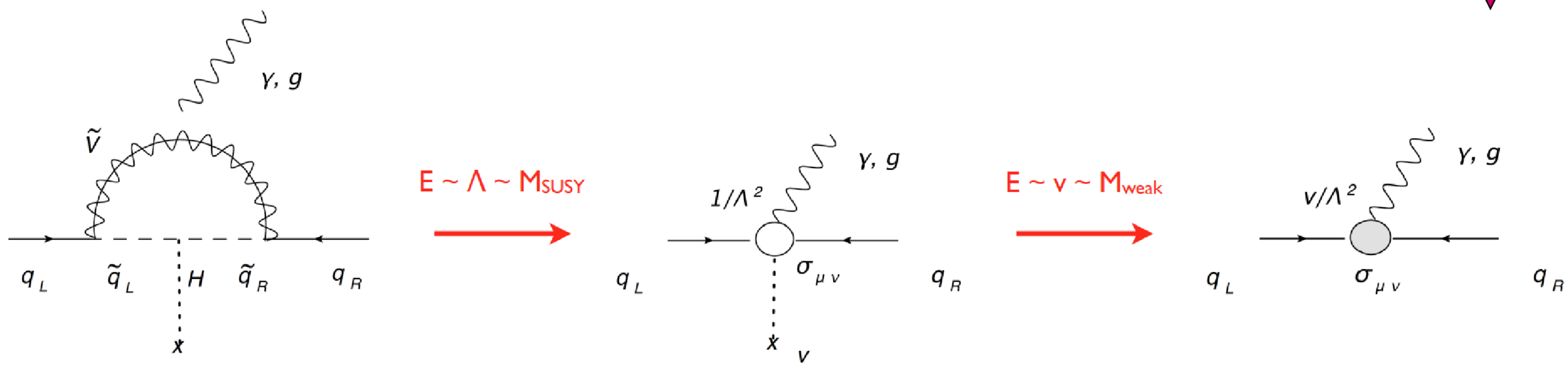
Neutron Electric Dipole Moment

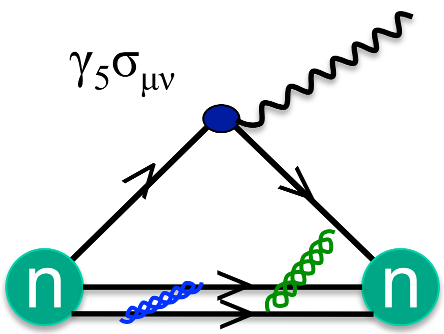
- nEDM is a very sensitive probe of CP violation from BSM theories
- New CP violation needed to explain Baryogenesis
- Need precise values of matrix elements of new CP violating effective operators to convert bounds on nEDM into bounds on BSM theories.



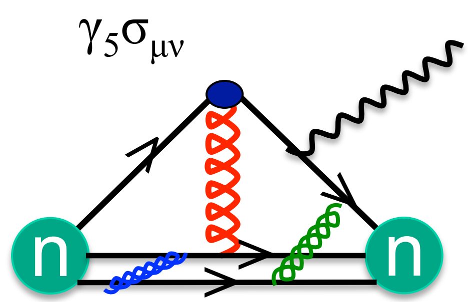
Effective operators: novel CP violation







γ attaches to the vertex



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

Quark-EDM

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

Chromo-EDM

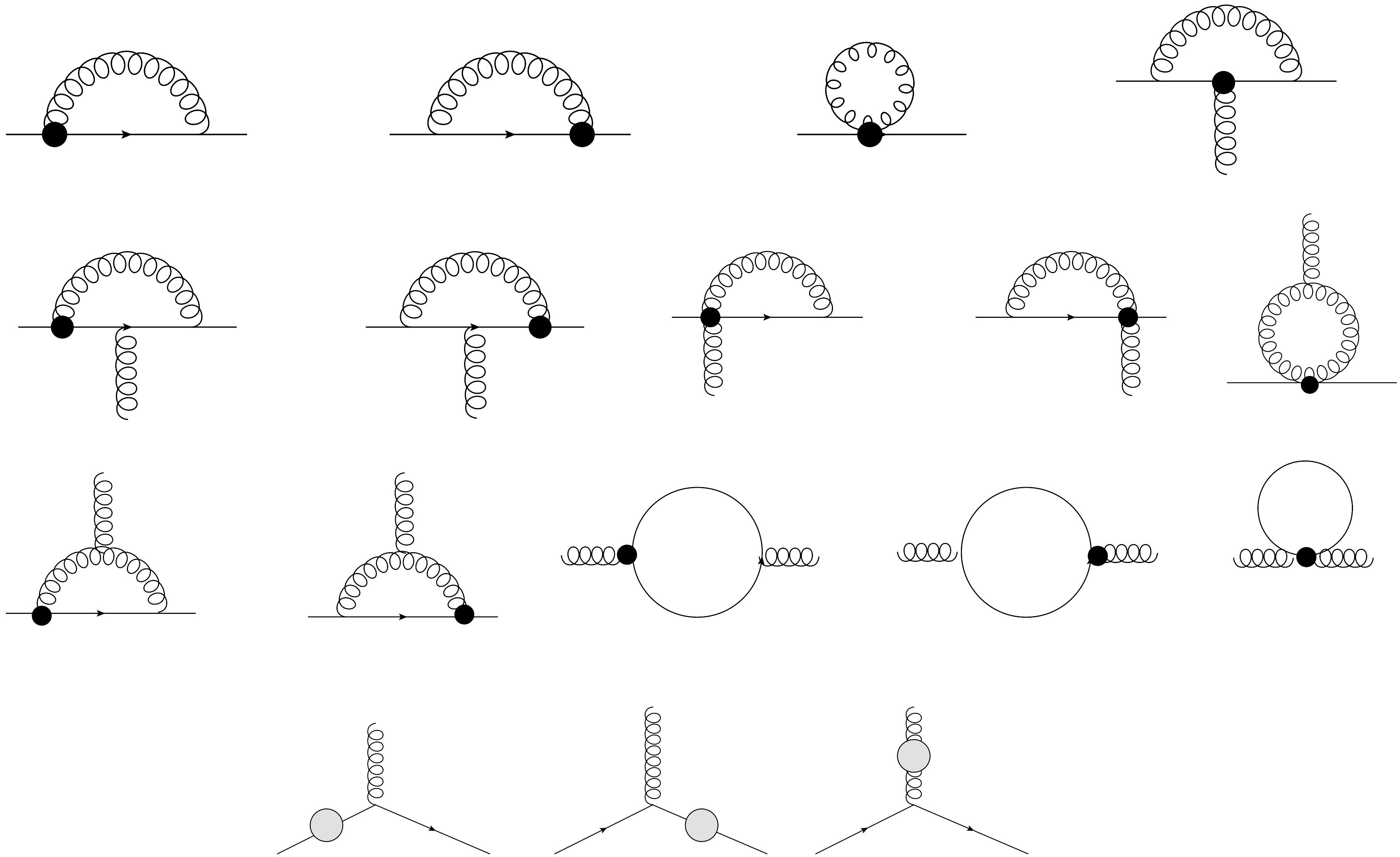
$$\bar{q}\,\sigma_{\mu\nu}\gamma_5\,q\;\lambda^a G_a^{\mu\nu}$$

Quark Chromoelectric Operator: Mixing

	C	$\partial^2 P$	E	$mF\tilde{F}$	$mG\tilde{G}$	$m\partial \cdot A$	$m^2 P$	P_{EE}	$\partial \cdot A_E$	A_∂	$A_{A(\gamma)}$
C	Z_C	X	X	X	X	X	X	X	X	X	X
$\partial^2 P$	0	Z_P	0	0	0	0	0	0	0	0	0
E	0	0	Z_T	0	0	0	0	0	0	0	0
$mF\tilde{F}$	0	0	0	$Z_m^{-1} Z_{F\tilde{F}}$	0	0	0	0	0	0	0
$m\,G\tilde{G}$	0	0	0	0	$Z_m^{-1} Z_{G\tilde{G}}$	X	0	0	0	0	0
$m\,\partial \cdot A$	0	0	0	0	0	$Z_m^{-1} Z_{\partial A}$	0	0	0	0	0
$m^2 P$	0	0	0	0	0	0	Z_m^{-1}	0	0	0	0
P_{EE}	0	0	0	0	0	0	0	X	X	X	0
$\partial \cdot A_E$	0	0	0	0	0	0	0	0	X	0	0
A_∂	0	0	0	0	0	0	0	X	X	X	0
$\partial \cdot A_E$	0	0	0	0	0	0	0	0	X	0	0
A_∂	0	0	0	0	0	0	0	X	X	X	0
$A_{A(\gamma)}$	0	0	0	0	0	0	0	0	0	0	X

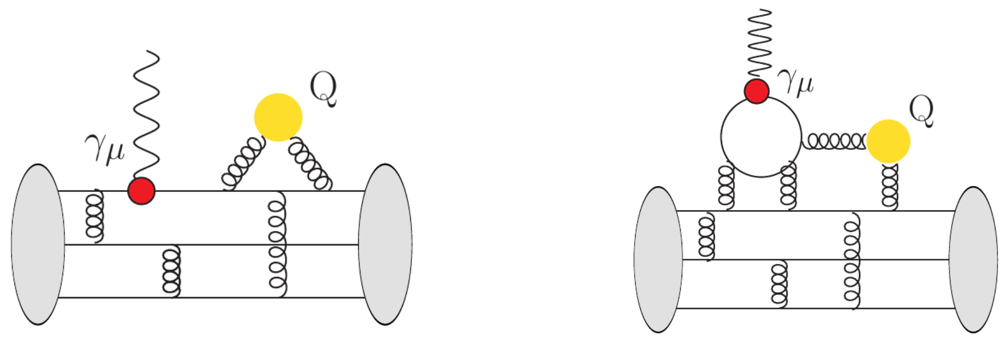
Bhattacharya et al., arXiv:1502.07325 [hep-ph]

Renormalization and Mixing

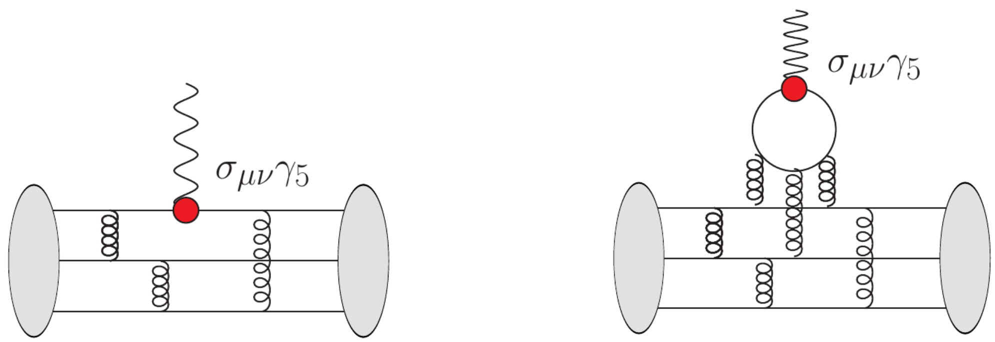


Diagrams to be calculated: Lattice

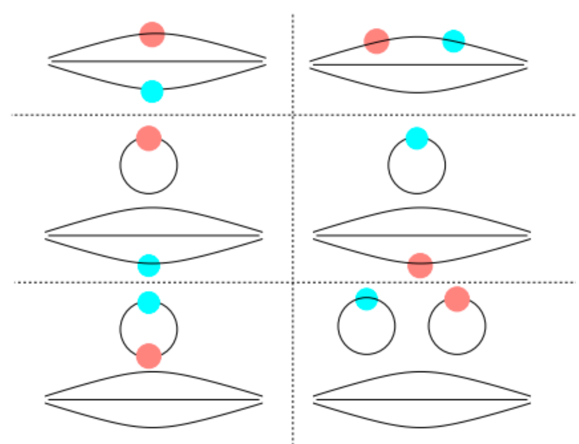
Θ-term



quark EDM

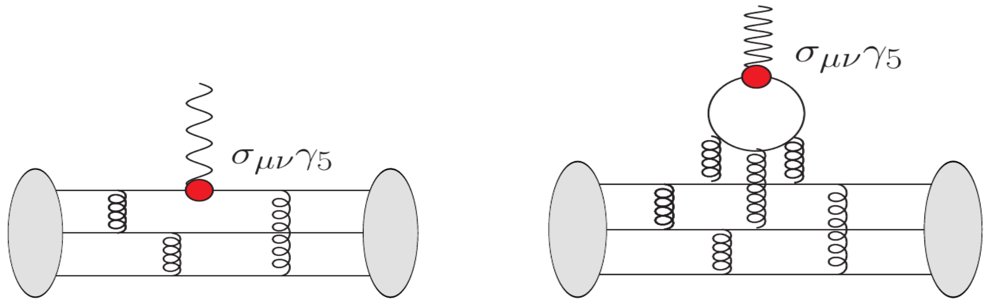


quark Chromo EDM
(4-pt function)



Constraining BSM using nEDM

quark EDM



Assuming only quark EDM contribute to nEDM, then

$$d_n = d_u^\gamma g_T^u + d_d^\gamma g_T^d + d_s^\gamma g_T^s$$

$g_T^u = -0.232(28)$

$g_T^d = 0.774(68)$

$g_T^s = 0.008(9)$