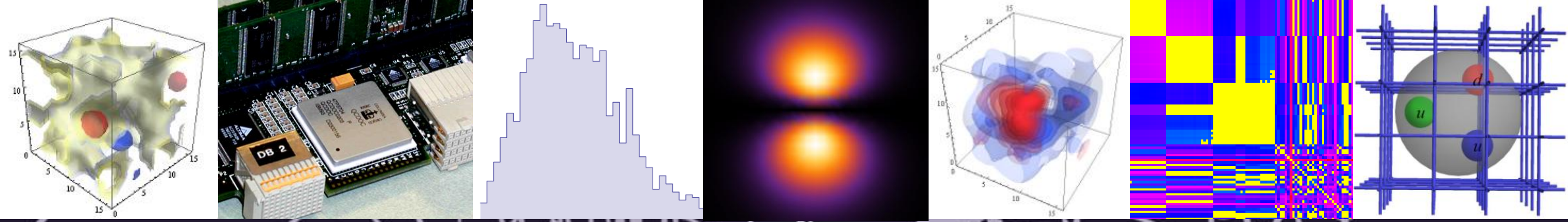


Beyond the Standard Model with Precision Nucleon Matrix Elements on the Lattice

Huey-Wen Lin
University of Washington

UNIVERSITY OF WASHINGTON

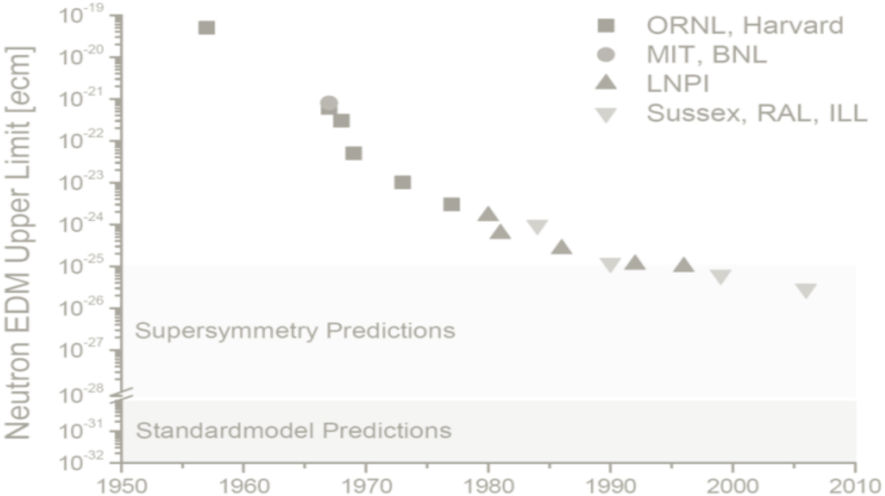
A Tale of Two Scales

- § LHC strikes out onto the high-energy frontier (7 TeV)
  - Direct measurement of Higgs and BSM particles
- § Many experiments refine low-energy measurements
  - Discern small discrepancies from the Standard Model
    - Muon $g-2$, Q_{weak}, CKM matrix
  - Probe small signals that are suppressed in the SM
    - $0\nu\beta\beta$, nEDM, dark matter, non-$V-A$ interactions in β decay…

Nucleons and BSM

Many opportunities to probe BSM with nucleons

- § Dark matter scattering
  - Certain candidates (e.g. SuSy neutralinos) exchange Higgs
  - Cross section around 1 zeptobarn (in the CMSSM)
- § Electric dipole moment
  - CP-violating effect
  - Extremely small in SM: $\approx 10^{-30}$ e-cm



- § Neutron beta decay
  - Non-V–A (e.g. scalar and tensor) interactions
  - To probe the existence of new particles (mediating new forces) with masses in the multi-TeV range

The Strange Proton

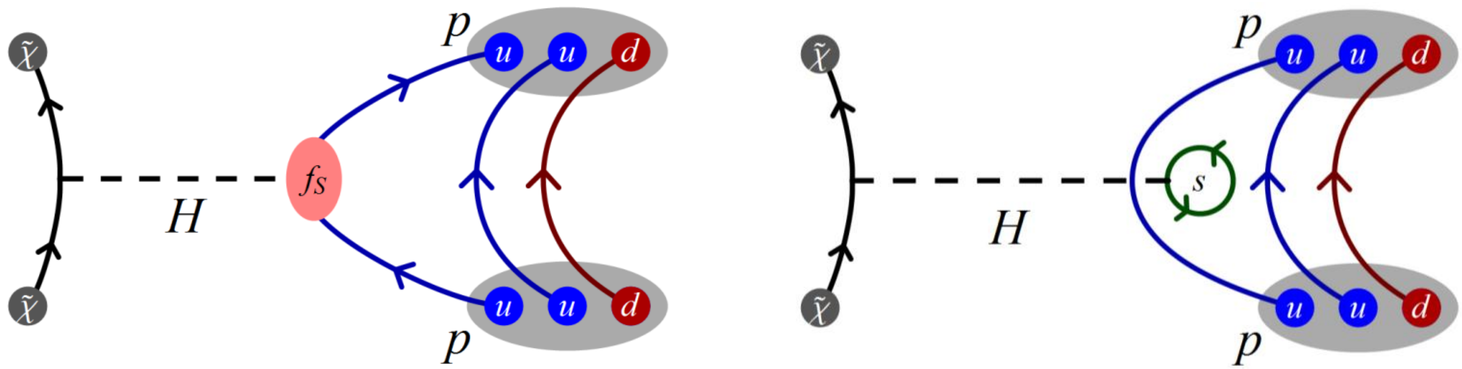
§ Strange contribution to proton scalar density/spin

- Strange contribution has larger uncertainty

§ Neutralino dark matter search

$$\sigma_s = m_s \langle N \,|\, \bar{s}\, s \,|\, N \rangle$$

- Spin-Independent (SI) cross-section
- Interactions with nucleon mediated by Higgs exchange



§ Lepton Flavor Violation

- $\mu \to e\gamma$ and $\mu X \to e X$ probe different combinations of operators
- Certain operators in SuSy models mediated by Higgs exchange require this input

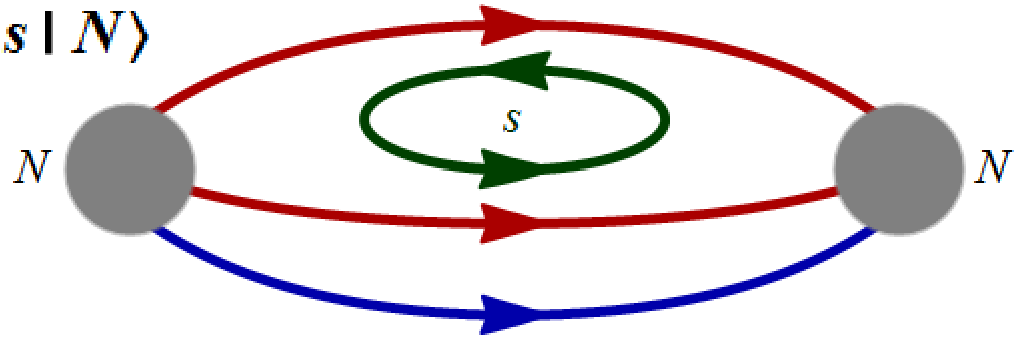
V. Cirigliano et al., Phys. Rev. D80, 013002 (2009)

Strangeness on the Lattice

§ Direct: Compute the "disconnected" loop

- Various techniques developed to improve the signal
  (BU , χQCD, Engelhardt, JLQCD, QCDSF 2f, …)

$\langle N \,|\, \bar{s}\, s \,|\, N \rangle$

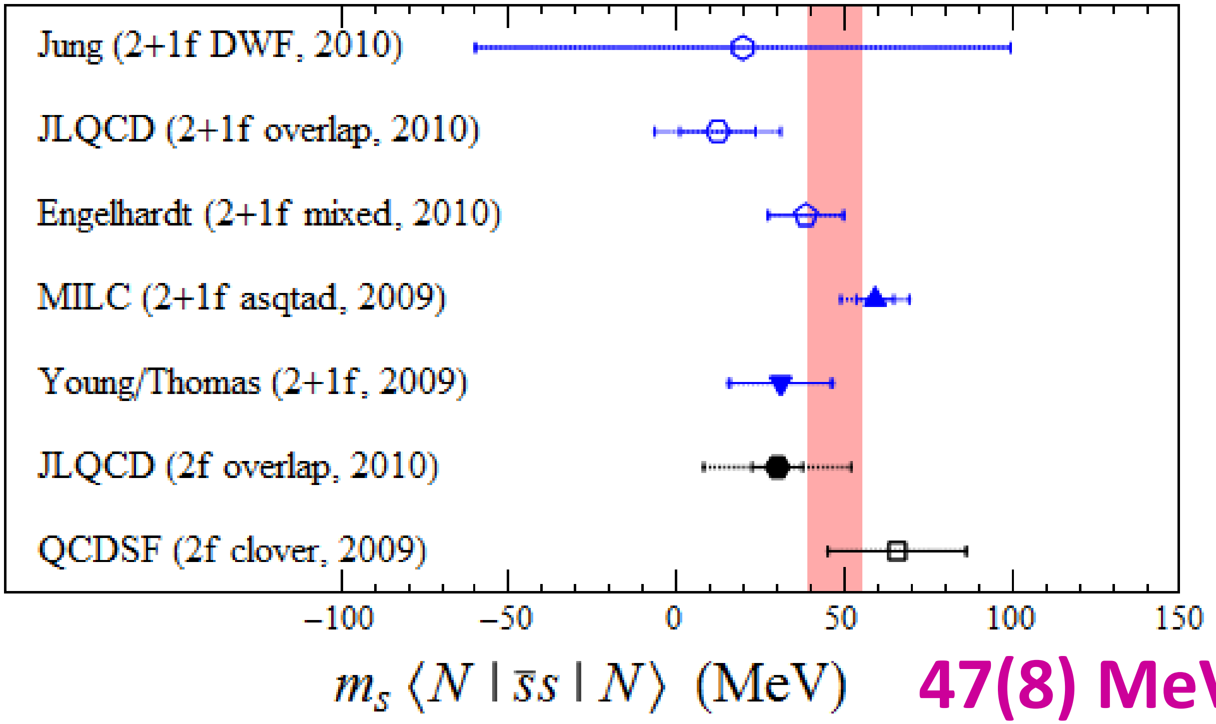


§ Indirect: Use the Feynman-Hellman Theorem

- Take numerical derivative $d\,M_N/d\,m_s$ either by
  direct SU(3) fitting to baryon masses
  (Young/Thomas, QCDSF 2+1f, BMW, …)
  or reweighting strange part of action
  (Jung, MILC, …)

Strangeness on the Lattice

- § Direct: Compute the disconnected loop
- § Indirect: Use the Feynman-Hellman Theorem
- § Global fit to current dynamical lattice data
  - Weighted by lattice spacing, lightest m_π, dynamical strange, etc…



47(8) MeV

Strangeness on the Lattice

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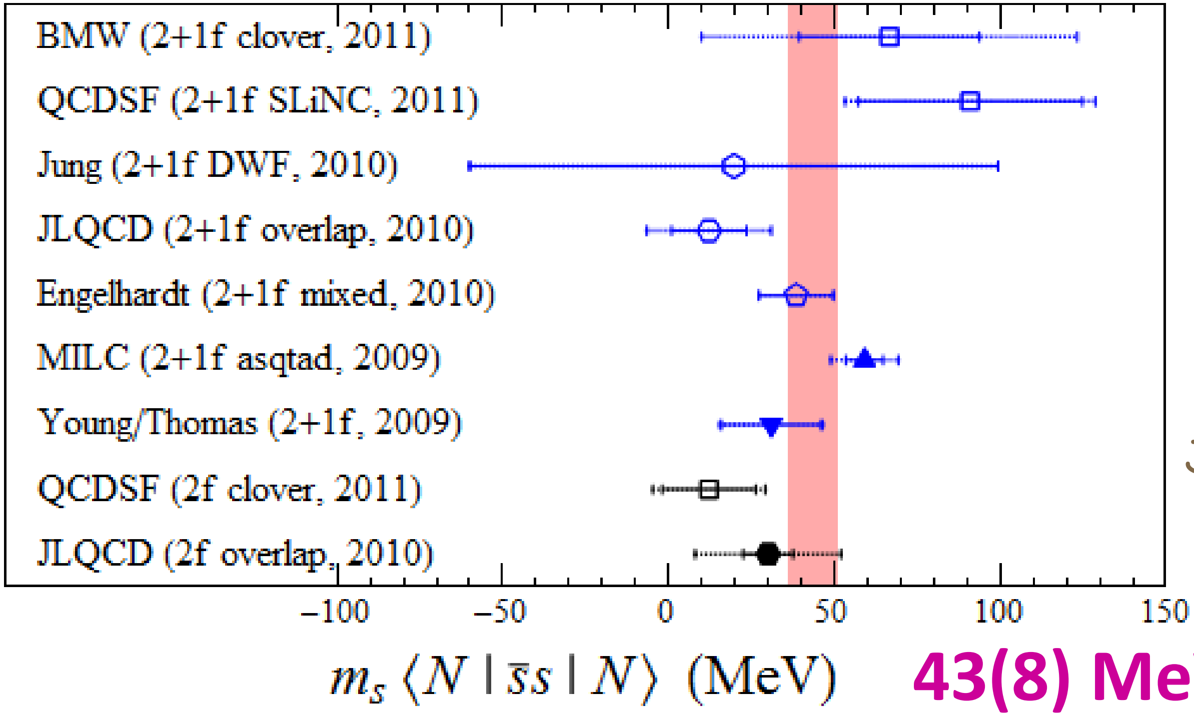

43(8) MeV

Applications to CMSSM

J. Giedt et al, Phys.Rev.Lett.103, 201802 (2009)

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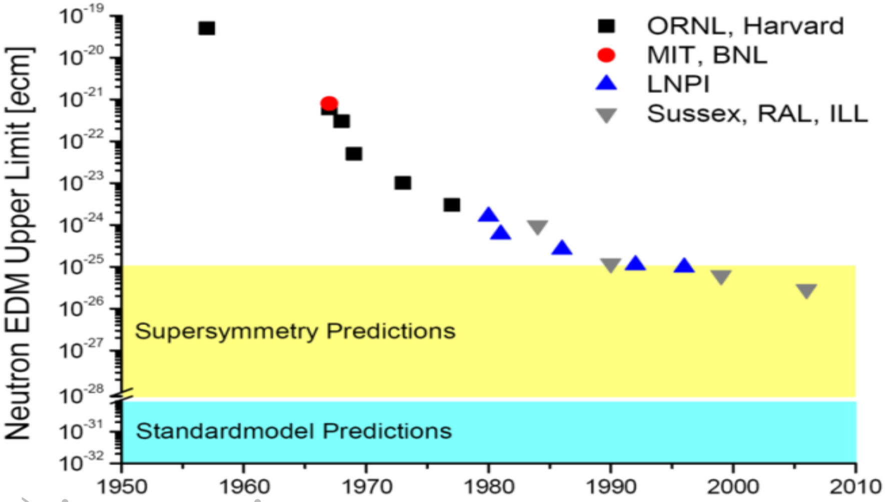

§ Neutron beta decay

- Non-V–A (e.g. scalar and tensor) interactions
- To probe the existence of new particles (mediating new forces) with masses in the multi-TeV range

nEDM from LQCD

Add CP-odd θ-term $i\frac{\theta}{32\pi^2}\int d^4x\,\frac{1}{4}\epsilon_{\mu\nu\alpha\beta}G_{\alpha\beta}(x)G_{\mu\nu}(x)$ to L_{QCD}

§ Direct: nucleon EM form factor $eF_3(0)/2M_N$

RBC, J/E, CP-PACS(2005), …

$$\langle p', s'|J_\mu|p, s\rangle = \bar{u}(\vec{p}', s')\,\mathcal{J}_\mu\,u(\vec{p}, s)$$

$$\mathcal{J}_\mu = \gamma_\mu F_1^\theta(q^2) - i\sigma_{\mu\nu}q_\nu\frac{F_2^\theta(q^2)}{2m_N^\theta} + \left[i(\gamma_\mu\,q^2 - \gamma q\,q_\mu)\,\gamma_5\,F_A^\theta(q^2) - \sigma_{\mu\nu}q_\nu\,\gamma_5\frac{F_3^\theta(q^2)}{2m_N^\theta}\right]$$

§ Indirect:

- Energy shift in nucleon mass with external $\vec{E}$

  $m^\theta_{\vec{s}}(\vec{E}) - m^\theta_{-\vec{s}}(\vec{E}) = 2d_N(\theta)\vec{S}\cdot\vec{E} + O((\vec{E})^3)$ CP-PACS (2006, 2010), …
- Calculate $\tan[2\alpha(\theta)]\,F_2(0)$ QCDSF (2011), …

where $\alpha(\theta)$ is $u(\vec{p}, s) \to u_\theta(\vec{p}, s) = e^{i\alpha(\theta)\gamma_5}\,u(\vec{p}, s)$

nEDM from LQCD

Add CP-odd θ-term $i\frac{\theta}{32\pi^2}\int d^4x \frac{1}{4}\epsilon_{\mu\nu\alpha\beta}G_{\alpha\beta}(x)G_{\mu\nu}(x)$ to L_{QCD}

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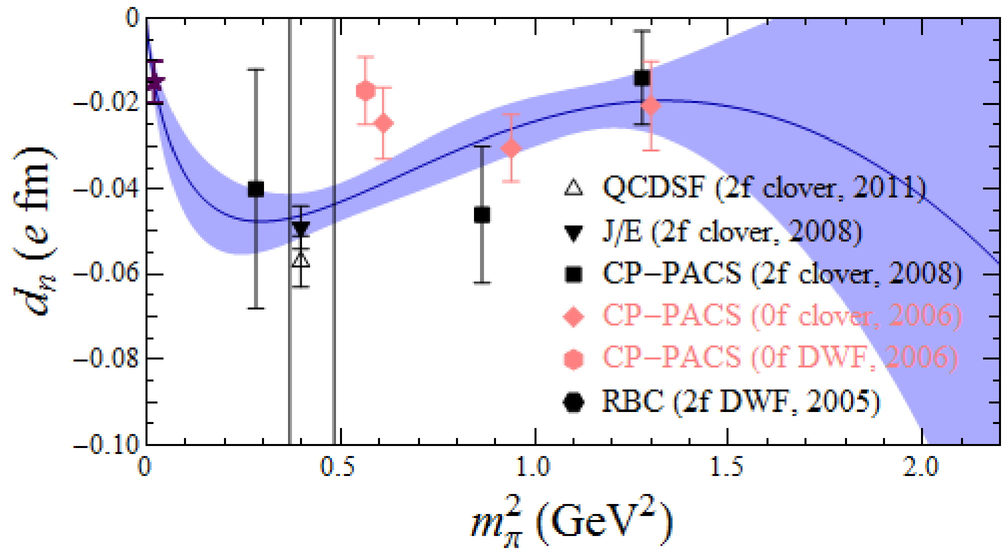
- Indirect:
  - Energy shift in nucleon mass with external $\vec{E}$ CP-PACS(2006, 2010), …
  - Calculate $\tan[2\alpha(\theta)]\,F_2(0)$ QCDSF(2011), …



Chiral extrapolation using K. Ottnad et al, 2010

−0.015(5) θ e·fm

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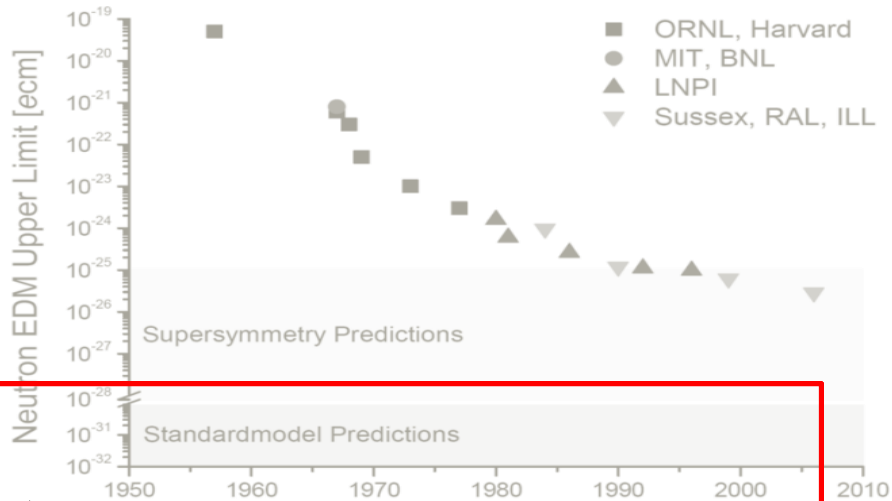


- § Neutron beta decay
  - Non-V–A (e.g. scalar and tensor) interactions
  - To probe the existence of new particles (mediating new forces) with masses in the multi-TeV range

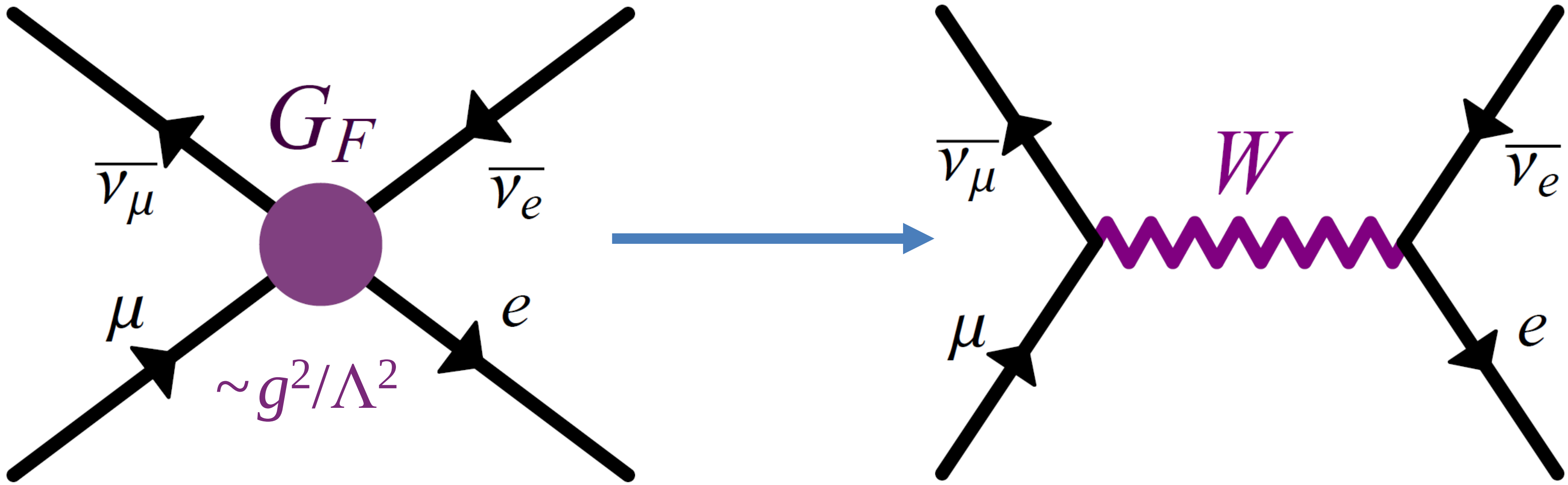
Fermi Theory of Beta Decay

§ Four-fermion interaction explained beta decay before electroweak theory was proposed

- New operators in effective low-energy theories

§ Electroweak theory adds 3 vector bosons

- *W* and *Z* bosons directly detected later at CERN

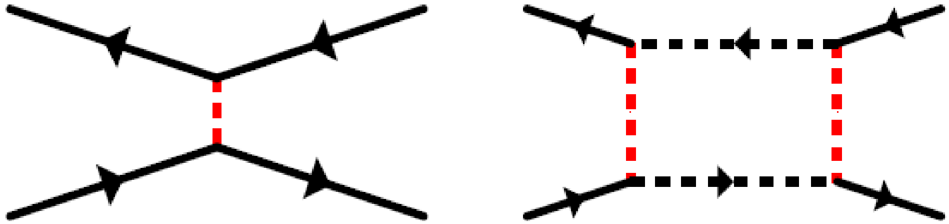


$$\Lambda \approx m_W \approx 80 \text{ GeV}, m_Z \approx 90 \text{ GeV}$$

What You See/How You Look

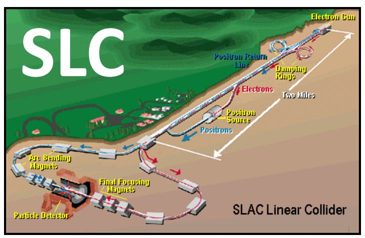
E

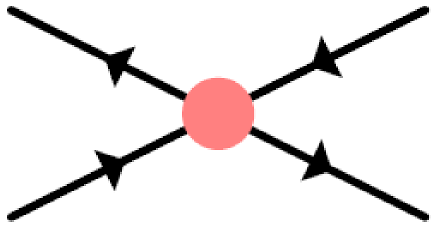
$\Lambda_{\text{BSM}} \approx \text{TeV}$



$$L_{\text{SM}} + L_{\text{BSM}}$$

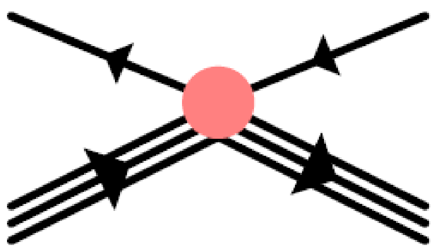
$M_{W,Z}$





$$L_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \hat{O}_i$$

$\Lambda_{\text{QCD}} \approx \text{GeV}$



$$g_S = \langle n | \overline{u} d | p \rangle$$

$$g_T = \langle n | \overline{u} \sigma_{\mu\nu} d | p \rangle$$

BSM Interactions

§ Neutron beta decay could be related to new interactions: the scalar and tensor

$$H_{\mathrm{eff}} = G_F \left(J_{V-A}^{\mathrm{lept}} \times J_{V-A}^{\mathrm{quark}} + \sum_i \varepsilon_i^{\mathrm{BSM}} \hat{O}_i^{\mathrm{lept}} \times \hat{O}_i^{\mathrm{quark}} \right)$$

$$\hat{O}_S = \overline{u}d \times \overline{e}(1-\gamma_5)\nu_e \quad \rightarrow \quad g_S = \langle n|\overline{u}d|p\rangle$$

$$\hat{O}_T = \overline{u}\sigma_{\mu\nu}d \times \overline{e}\sigma^{\mu\nu}(1-\gamma_5)\nu_e \quad \rightarrow \quad g_T = \langle n|\overline{u}\sigma_{\mu\nu}d|p\rangle$$

- ε_S and ε_T are related to the masses of the new TeV-scale particles
- … but the unknown coupling constants $g_{S,T}$ are needed

§ Given precision $g_{S,T}$ and O_{BSM}, predict new-physics scales

Exp't → $O_{BSM} = f_o(\varepsilon_{S,T}\, g_{S,T})$ ← Precision LQCD input ($m_\pi \approx 140$ MeV, $a \rightarrow 0$)

$$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$$

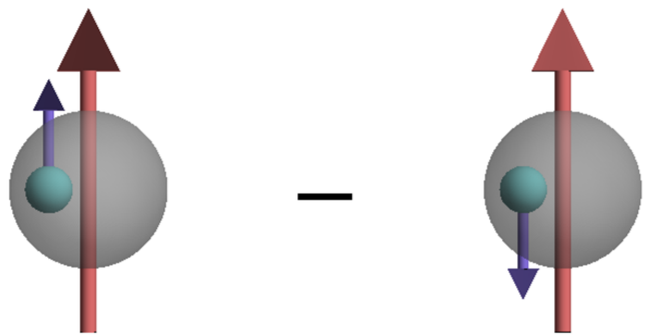
g_T 101

§ Tensor charge: the zeroth moment of the transversity

$g_T = \delta u - \delta d$

- Experimentally, probed through SIDIS (HERMES and COMPASS)

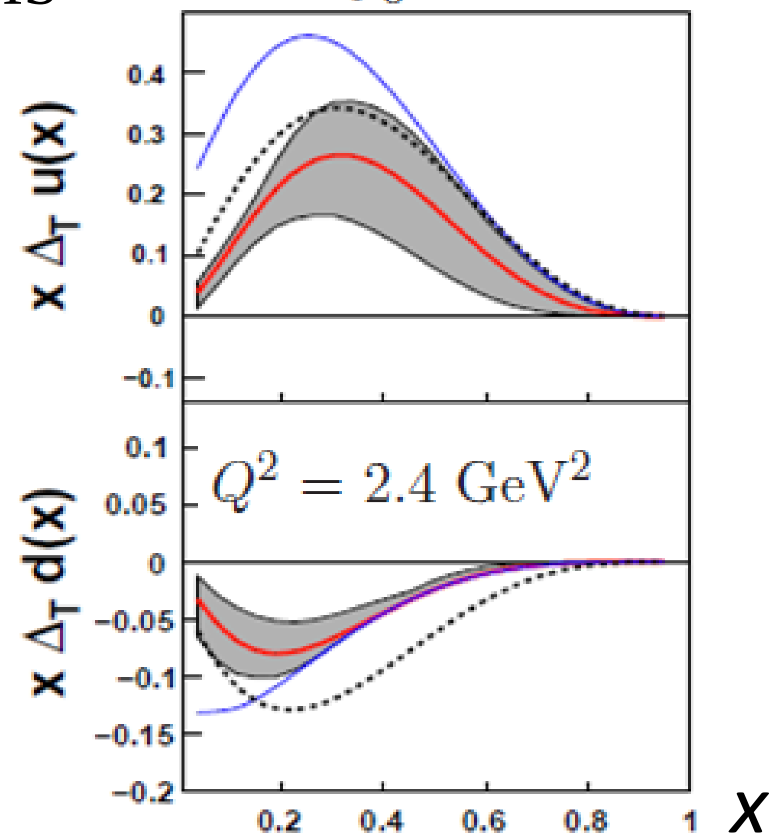
M. Anselmino et al., Phys. Rev. D75, 054032 (2007)



- Model-dependent extractions
- Combined with other experiments

$$g_T(Q^2=0.8\ \mathrm{GeV}^2) = 0.77^{+0.18}_{-0.24}$$

$$\delta q := \int_0^1 dx\, \Delta_T q$$



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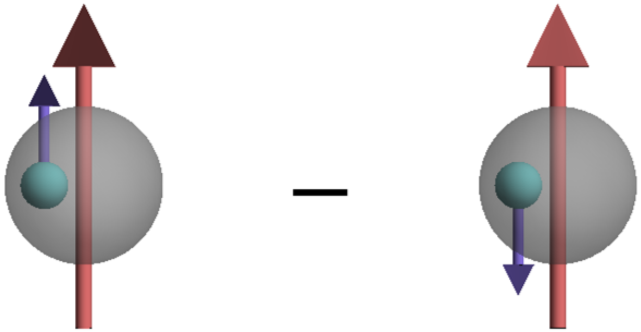
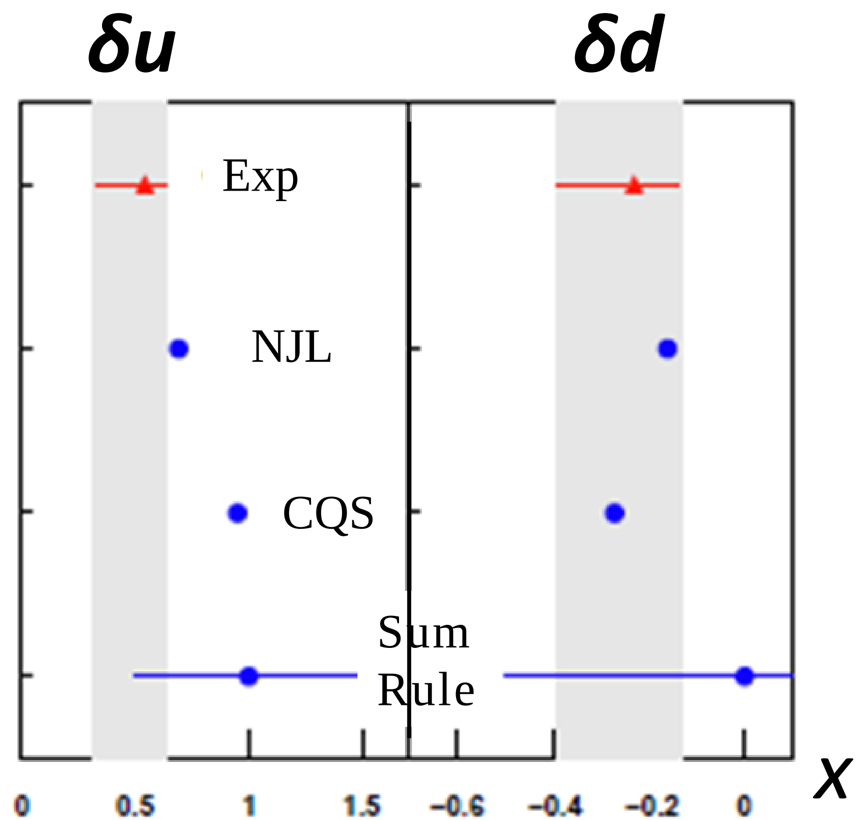




- Comparisons with other theoretical model estimates

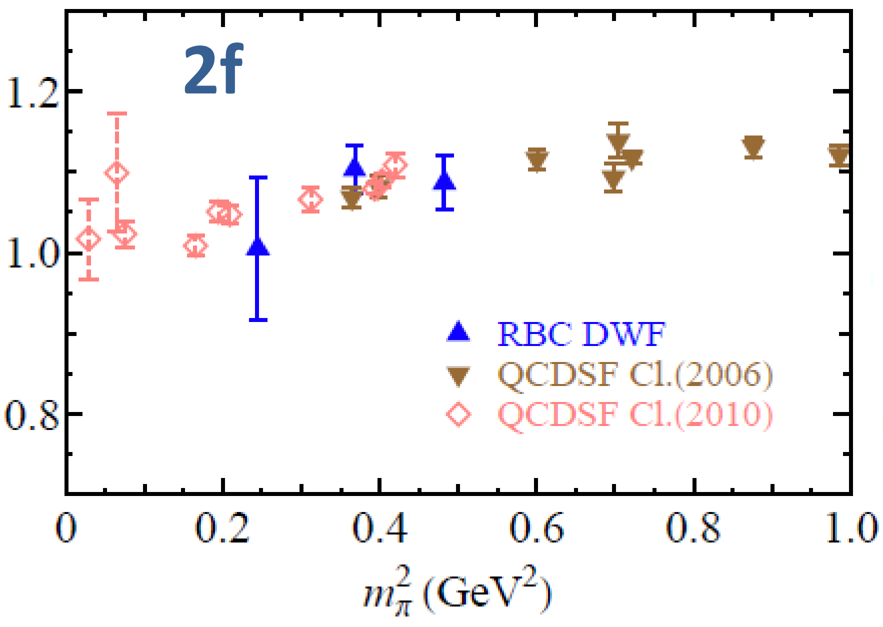
I. Cloet et al., Phys. Lett. B659, 214 (2008); M. Wakamatsu, Phys. Lett. B653, 398 (2007); H.-x. He et al., Phys. Rev. D52, 2960 (1995)

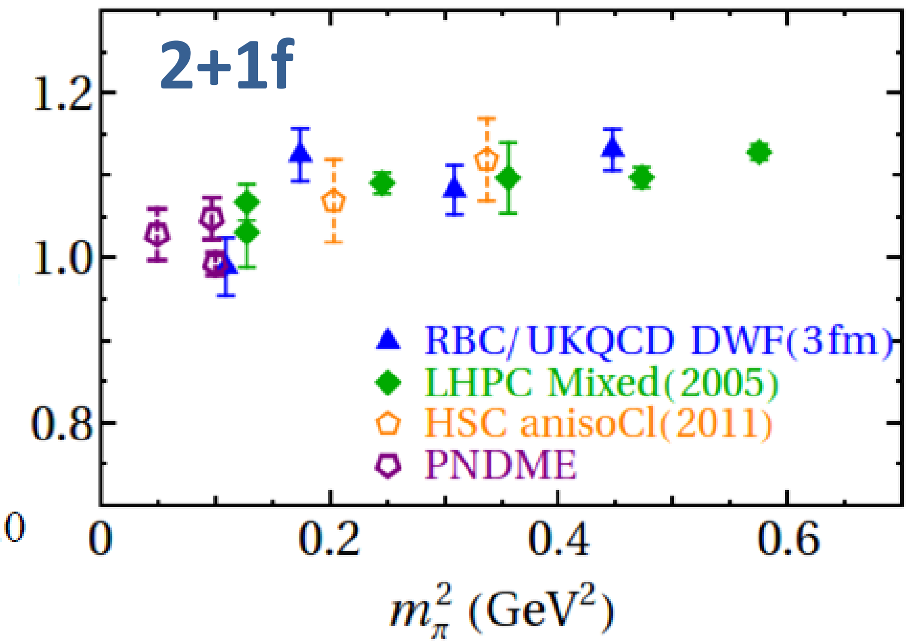
g_T on the Lattice

- Tensor charge: the zeroth moment of the transversity

$$g_T = \delta u - \delta d = \langle N | T_{\mu\nu} | N \rangle$$

- A few published dynamical results





HWL et al., Phys. Rev. D78, 014505 (2008) and RBC/UKQCD arXiv:1003.3387[hep-lat]; LHPC, arXiv:1001.3620[hep-lat]; S. Collins et al., arXiv:1101.2326[hep-lat].

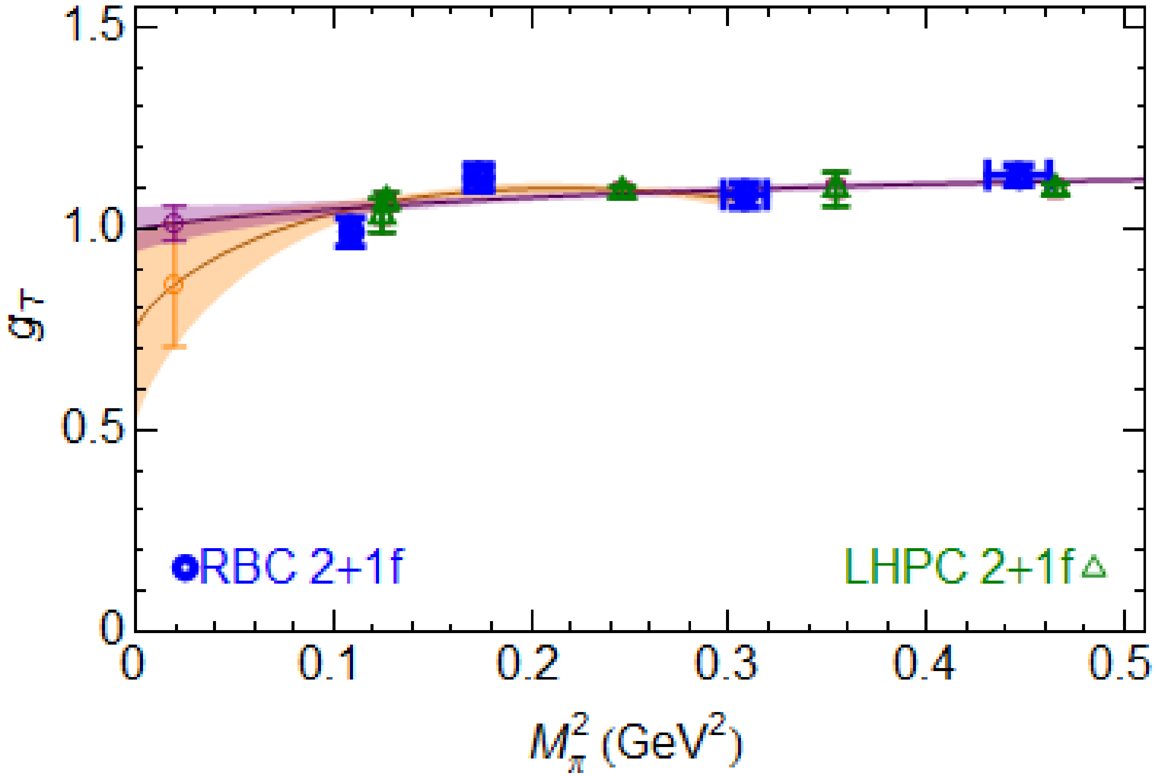
g_T on the Lattice

§ Global fit to 2+1f g_T

- With/without pion-mass cut

§ Including PNDME numbers

- $a = 0.12$ fm, 220- and 310-MeV; $a = 0.09$ fm, 310-MeV pion



$$C\left[1-\frac{3g_A^2+1}{(4\pi f_\pi)^2}m_\pi^2\log\left(\frac{m_\pi^2}{\mu^2}\right)\right]+e\frac{m_\pi^2}{(4\pi f_\pi)^2}$$

W. Detmold et al., Phys.Rev.D66:054501 (2002)

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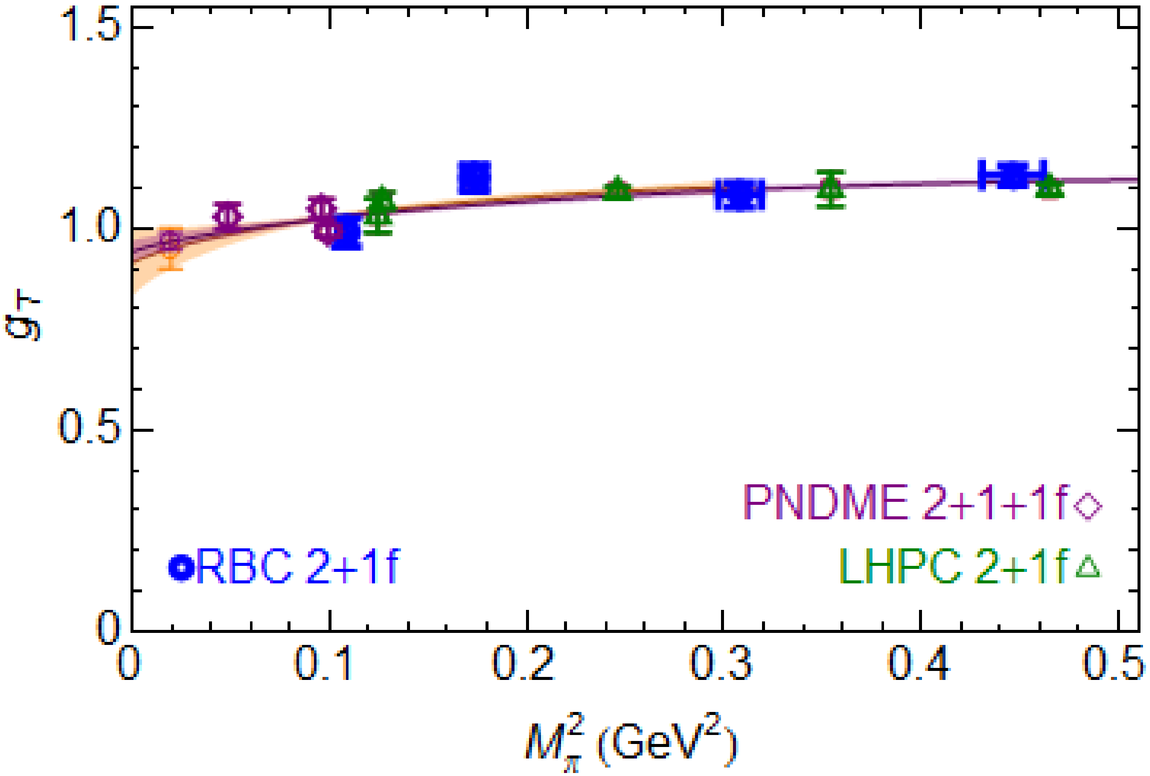

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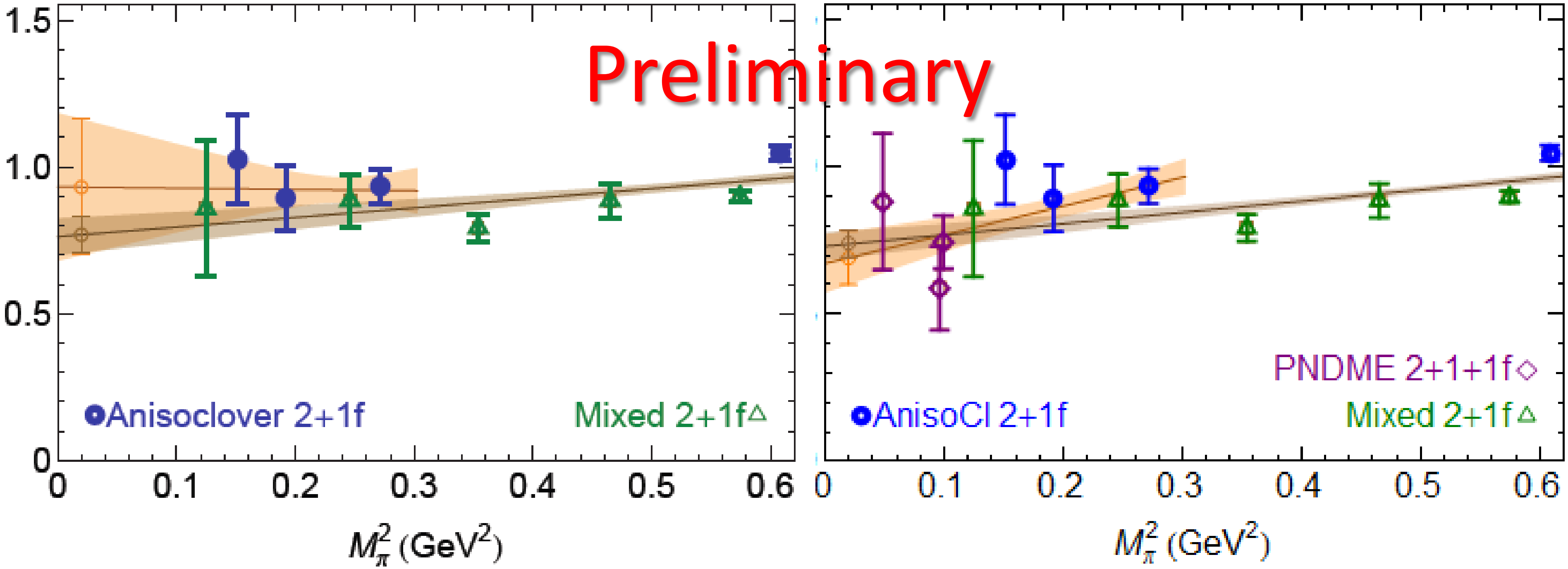
W. Detmold et al., Phys.Rev.D66:054501 (2002)

g_S on the Lattice

- Scalar charge: $\langle n|\bar{u}d|p\rangle$
- Earlier theoretical estimate (with various models):

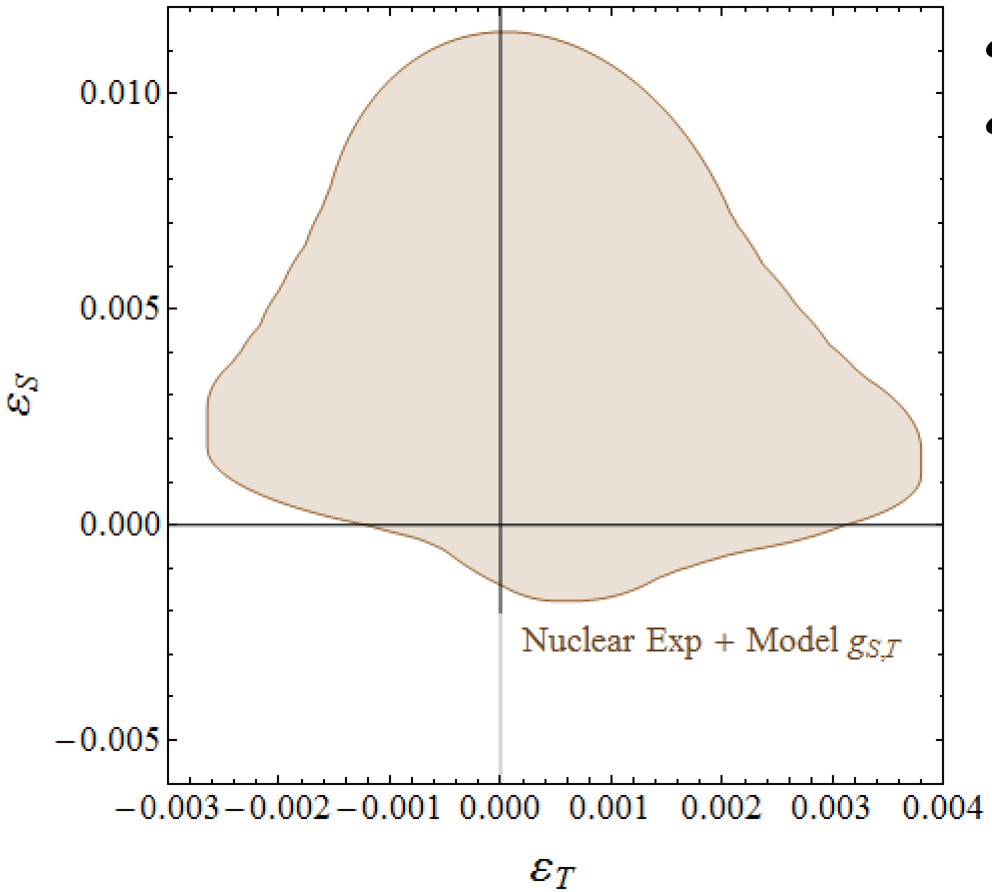
$$1 \gtrsim g_S \gtrsim 0.25$$

- First g_S calculation from LQCD



Combined with Experiments

§ Using our lattice input for the tensor and scalar charges is a key ingredient in precision measurement



- $0^+ \longrightarrow 0^+$ transitions
- Nuclear beta decays
  - β asym in Gamow-Teller ^{60}Co
  - polarization ratio between Fermi and GT in ^{114}In
  - positron polarization in polarized ^{107}In
  - β-ν correlation parameter a

$$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$$

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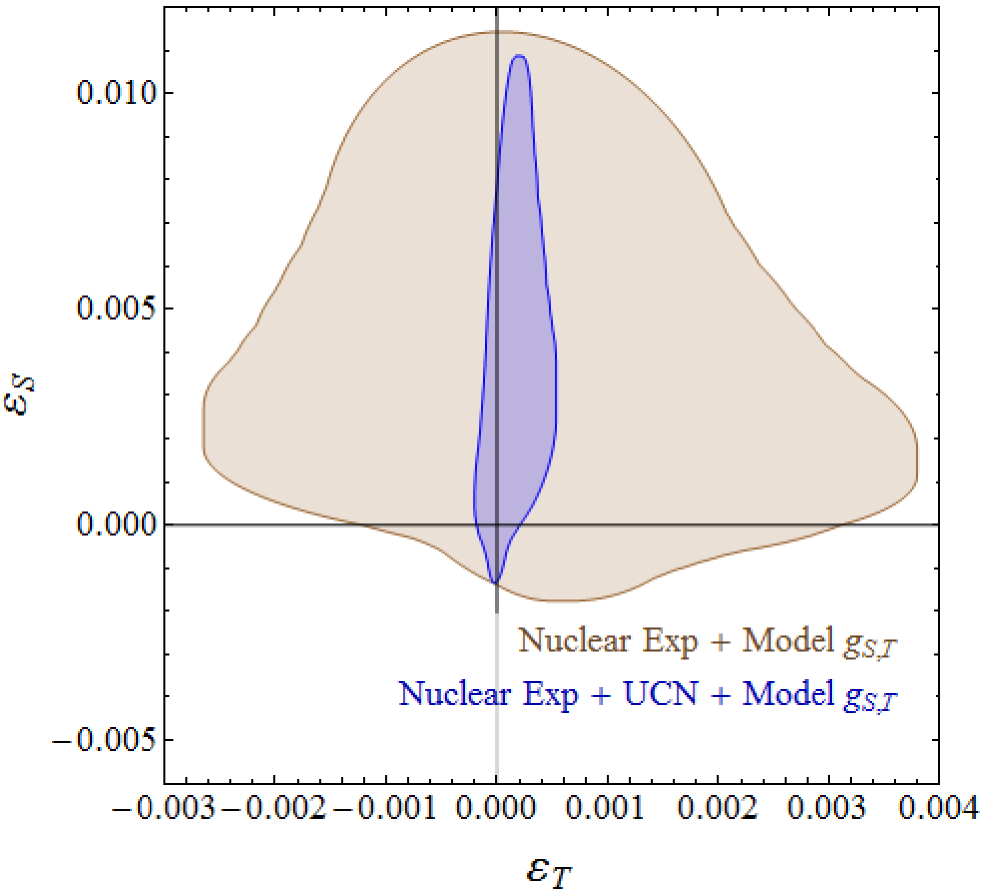

LANL UCN neutron decay exp't

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

Expect by 2013:

$$|B_1 - b|_{\mathrm{BSM}} < 10^{-3}$$
$$|b|_{\mathrm{BSM}} < 10^{-3}$$

Similar proposal at ORNL by 2015

$$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$$

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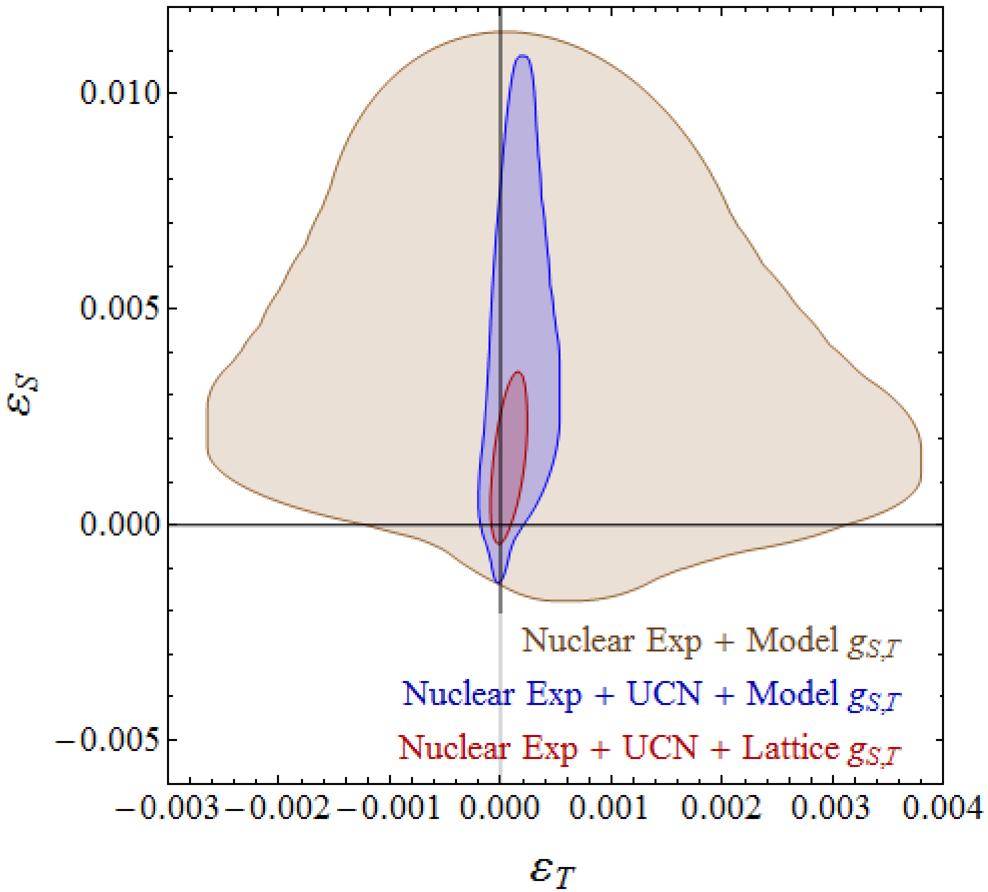

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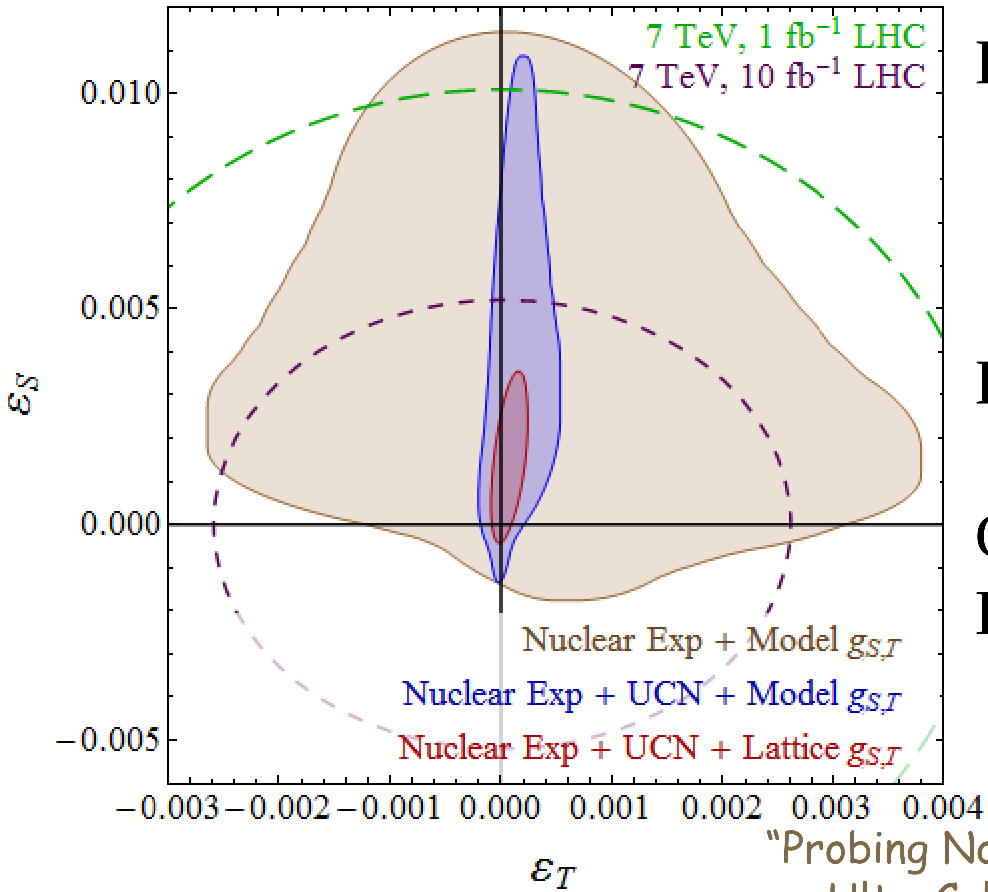
High-Energy Constraints

§ Constraints from high-energy experiments?

LHC current bounds and near-term expectation



Estimated though effective L

$$\mathcal{L} = -\frac{\eta_S}{\Lambda_S^2} V_{ud} (\overline{u}d)(\overline{e}P_L\nu_e) - \frac{\eta_T}{\Lambda_T^2} V_{ud} (\overline{u}\sigma^{\mu\nu} P_L d)(\overline{e}\sigma_{\mu\nu} P_L \nu_e)$$

Looking at high transverse mass in $e\,\nu + X$ channel

Compare with W background

Estimated 90% C.L. constraints on

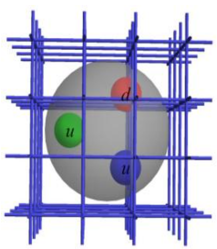
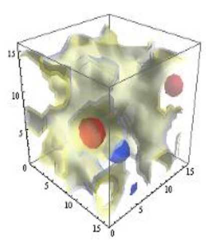
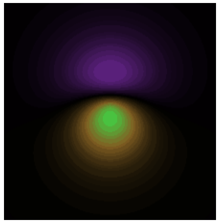
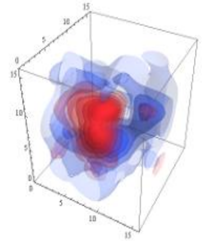
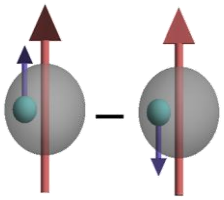
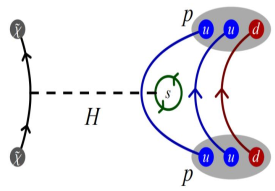
$$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$$

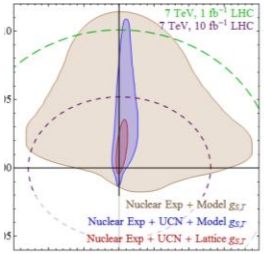
"Probing Novel Scalar and Tensor Interactions from UltraCold Neutrons to LHC", arXiv (soon)

Summary

The name of the game is precision

- § The precision frontier enables us to probe BSM physics
  - Opportunities combining both high- (TeV) and low- (GeV) energy
- § Exciting era using LQCD for precision inputs from SM
  - Increasing computational resources and improved algorithms
  - Enables exploration of used-to-be-impossible calculations



- § Necessary in cases when experiment is limited (e.g. g_S)

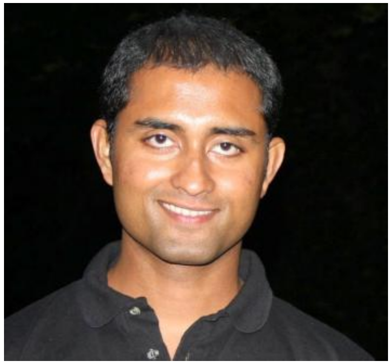
PNDME Collaboration

Precision Neutron-Decay Matrix Elements (2010–)

Tanmoy Bhattacharya

Saul Cohen

Rajan Gupta



Anosh Joseph

HWL

http://www.phys.washington.edu/users/hwlin/pndme/index.xhtml