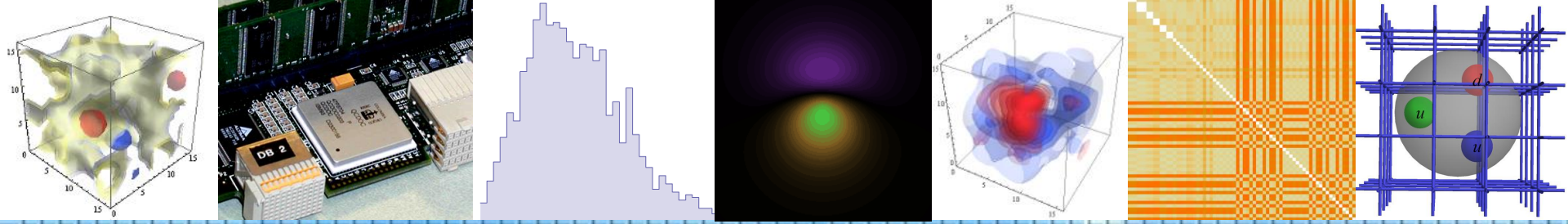


Probing New Physics Though Precision Nucleon Matrix Elements

Huey-Wen Lin

A Tale of Two Scales

§ LHC strikes out onto the high-energy frontier (13 TeV)

- Direct production of Higgs and BSM particles

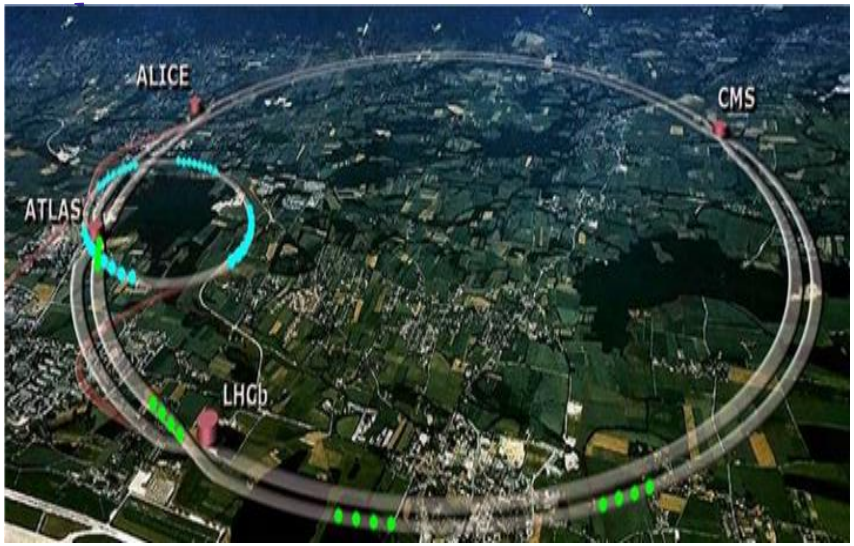
§ Many experiments refine low-energy measurements

- Discern small discrepancies from the Standard Model

  Muon $g-2$, Q_{weak}, CKM matrix…

- Probe small signals that are suppressed in the SM

  $0\nu\beta\beta$, dark matter, nEDM, non-$V-A$ interactions in β decay …



Nucleons and BSM

Many opportunities to probe BSM with nucleons

§ Parton distribution functions for SM background

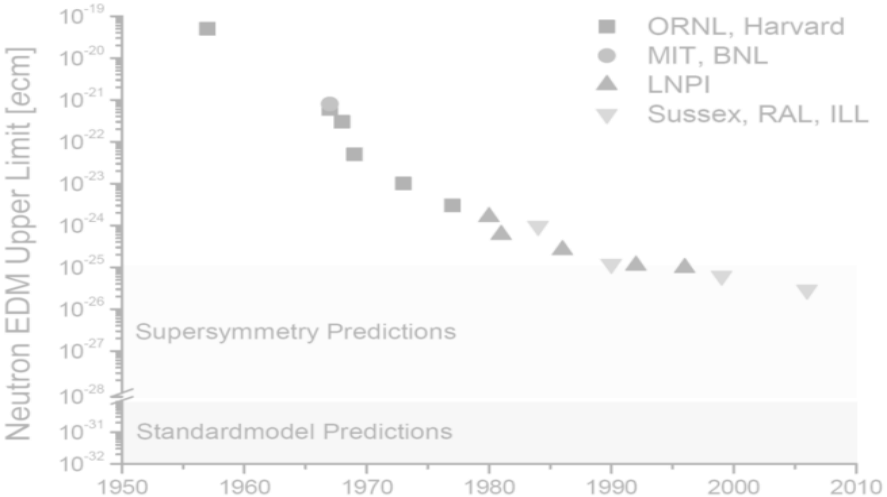
- Especially less known intrinsic strange/charm contribution

§ 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 interactions
- To probe the existence of new particles (mediating new forces) with masses in the multi-TeV range

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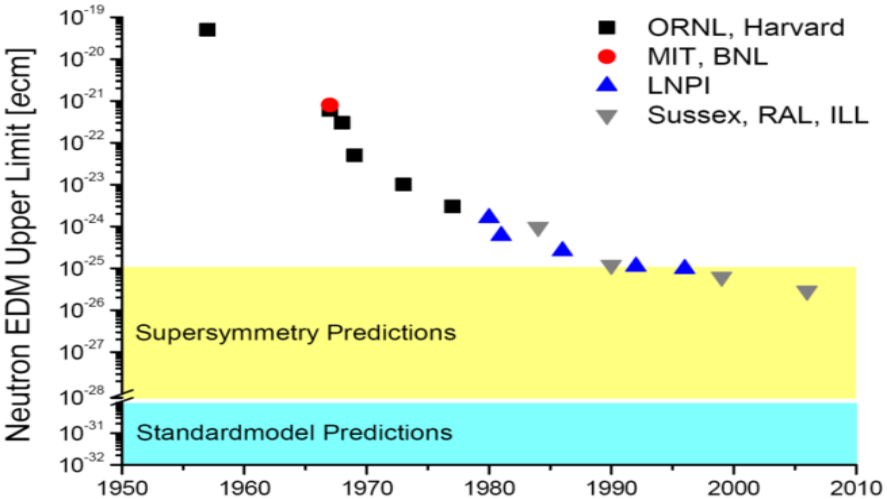

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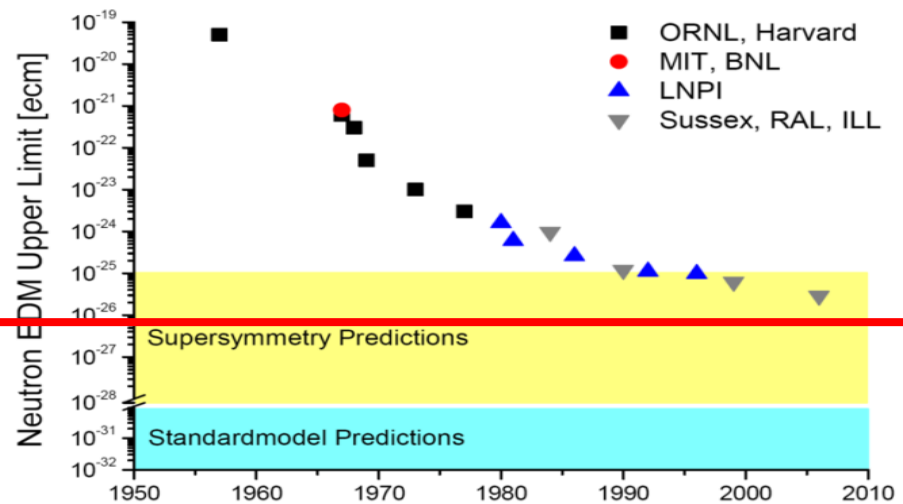

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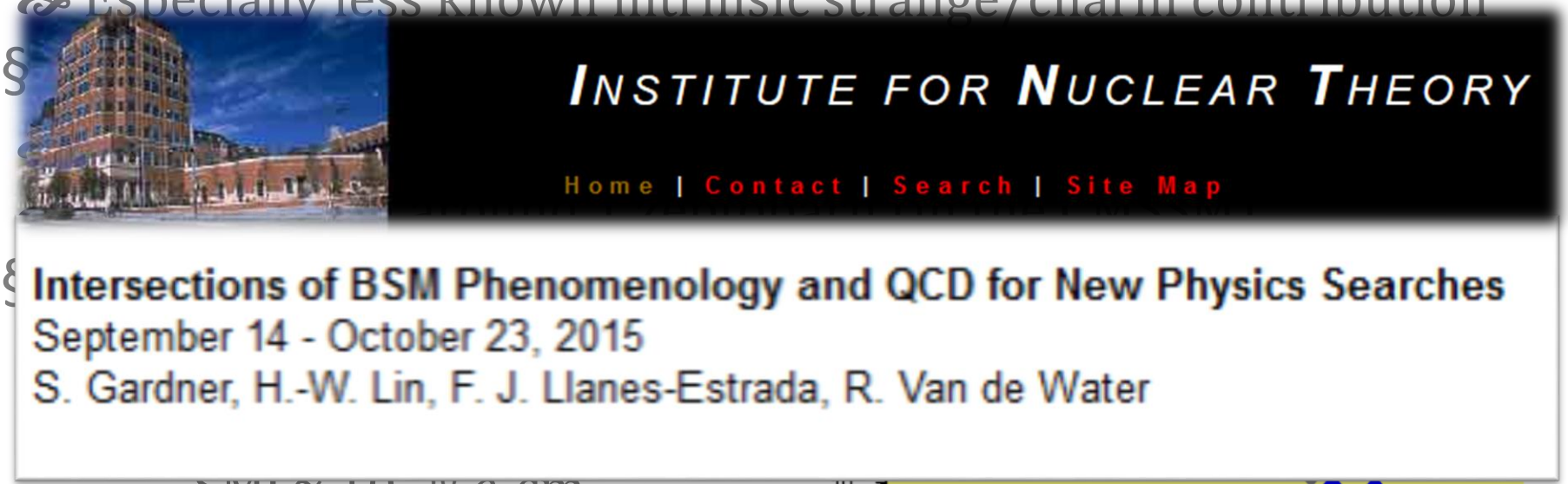
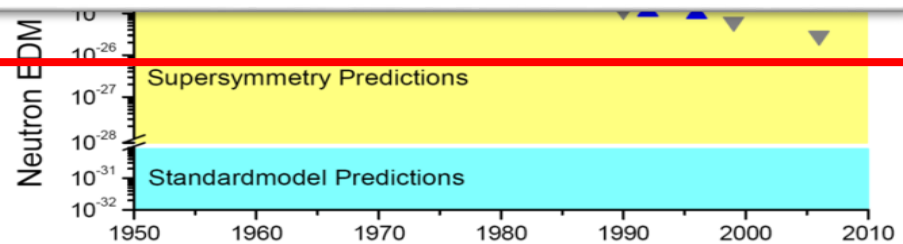


§

SM: $\approx 10^{-30}$ e-cm



§ Neutron beta decay

- Non-V–A interactions
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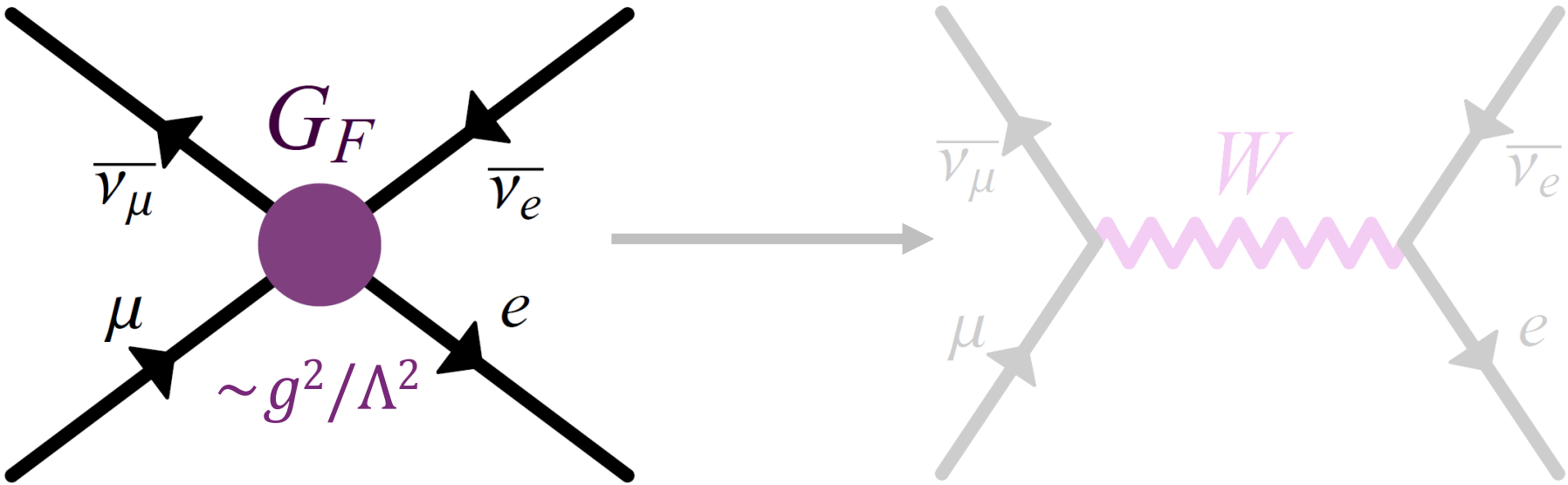
Fermi Theory of Beta Decay

§ 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



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

Fermi Theory of Beta Decay

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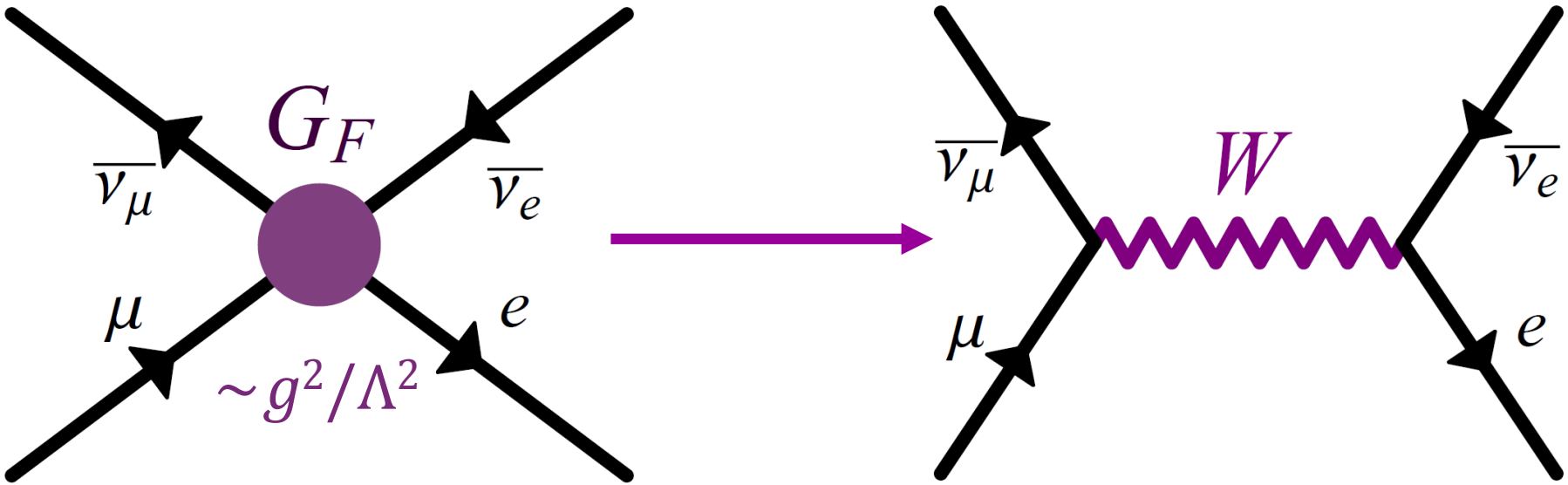
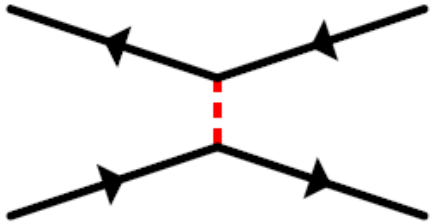


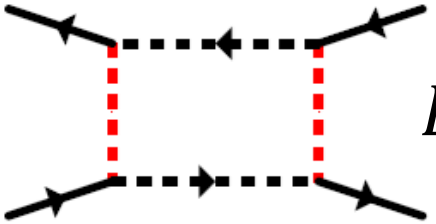
$$\Lambda \approx m_W \approx 80\ \text{GeV},\ m_Z \approx 90\ \text{GeV}$$

What You See/How You Look

E

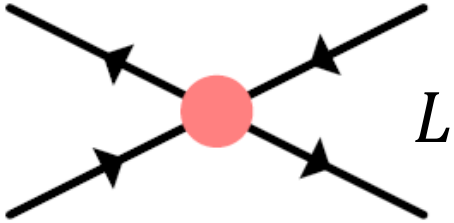
$\Lambda_{\rm BSM} \approx$ TeV





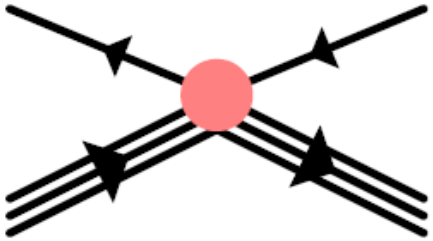
$L_{\rm SM} + L_{\rm BSM}$

$M_{W,Z}$



$$L_{\rm SM} + \sum_{i=S,T} \varepsilon_i^{\rm BSM} \hat{O}_i^{\rm BSM}$$

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



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

The Rest of the Talk…

§ Precision nucleon matrix elements

- Systematics, systematics, systematics…
- Concentration on g_T

§ Applications to New-Physics Searches

- Neutron beta decay
- Neutron electron dipole moment
- Spin-dependent dark-matter cross section

PNDME

Precision Neutron-Decay Matrix Elements

https://sites.google.com/site/pndmelqcd/

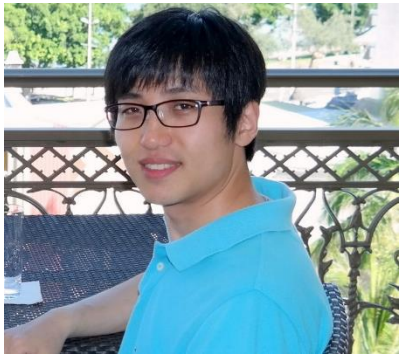
Tanmoy Bhattacharya

Rajan Gupta

HWL (PI)

Saul Cohen

Anosh Joseph



Boram Yoon

How Can LQCD Help?

§ Lattice QCD is an ideal theoretical tool for investigating strong-coupling regime of quantum field theories

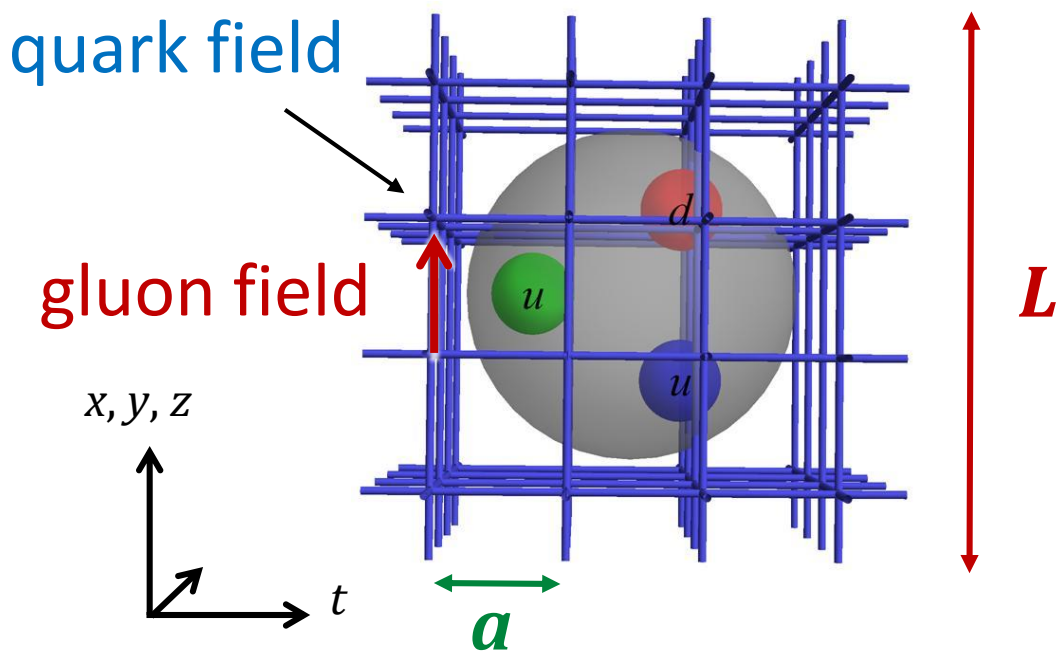
- Great for studying nonperturbative hadron structure

§ Physical observables are calculated from the path integral

$$\langle 0|O(\bar{\psi},\psi,A)|0\rangle = \frac{1}{Z}\int \mathcal{D}A\,\mathcal{D}\bar{\psi}\,\mathcal{D}\psi\; e^{iS(\bar{\psi},\psi,A)}\,O\,(\bar{\psi},\psi,A)$$

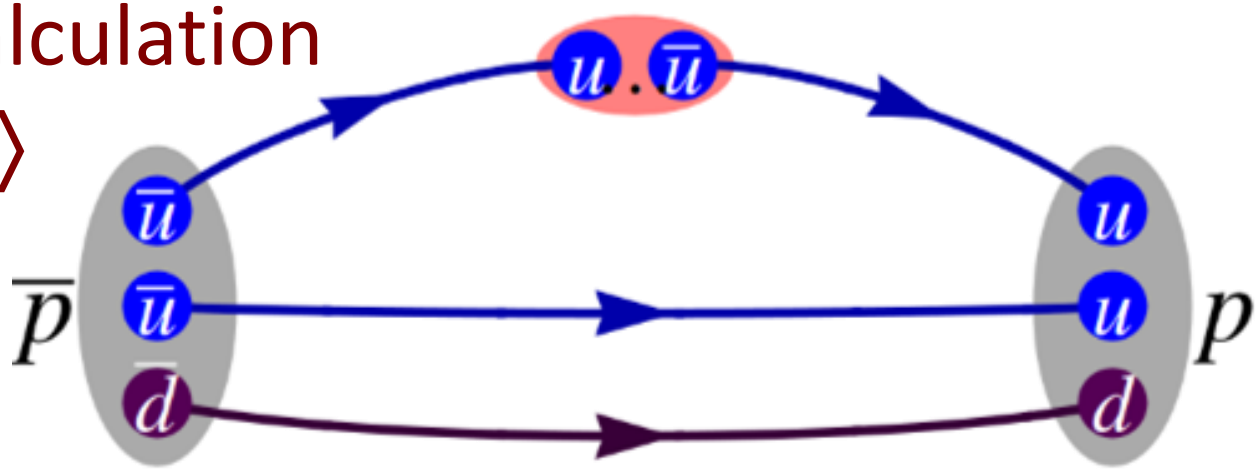
in Euclidian space

- Impose a UV cutoff
  discretize spacetime
- Impose an infrared cutoff
  finite volume



Nucleon Matrix Elements

Lattice-QCD calculation of $\langle p|\bar{u}\Gamma u|p\rangle$



§ High statistics

- Often requires multiple computational resources

§ Control all systematic error:

- Finite-volume effects
- Contamination from excited states
- Chiral extrapolations to physical u and d quark masses
- Extrapolation to the continuum limit (lattice spacing $a \to 0$)
- Nonperturbative renormalization (e.g. the RI/SMOM scheme)

The Trouble with Nucleons

Nucleons are more complicated than mesons because…

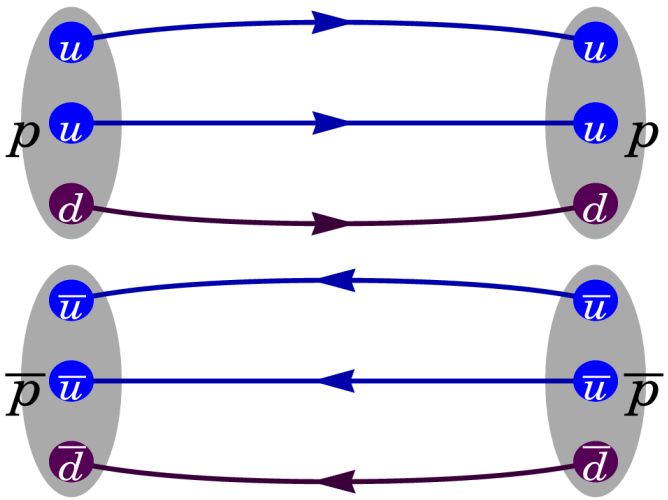
§ Noise issue (P. Lepage; D. Kaplan)

- Signal diminishes at large t_{sep} relative to noise

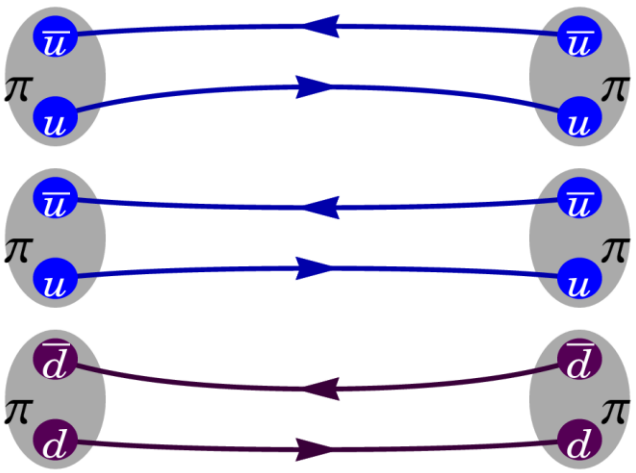
Correlator $C = \langle O \rangle = \langle qqq(t)\bar{q}\bar{q}\bar{q}(0) \rangle$

Variance (noise squared) of $C \propto \langle O^\dagger O \rangle - \langle O \rangle^2$

What you want:



What you get:



$S/N \sim e^{-M_N t}/e^{-2M_N t/2} \sim \text{const}$

$S/N \sim e^{-M_N t}/e^{-3M_\pi t/2} \sim e^{-(M_N - 3M_\pi/2)t}$

The Trouble with Nucleons

Nucleons are more complicated than mesons because…

§ Noise issue

- Signal diminishes at large t_{sep} relative to noise

§ Excited-state contamination

- Nearby excited state: Roper(1440)

§ Hard to extrapolate in pion mass

- Δ resonance nearby; multiple expansions, poor convergence…
- May not be an issue in the physical pion-mass era

§ Requires large volume and high statistics

- Ensembles are not always generated with nucleons in mind

The Trouble with Nucleons

Nucleons are more complicated than mesons because…

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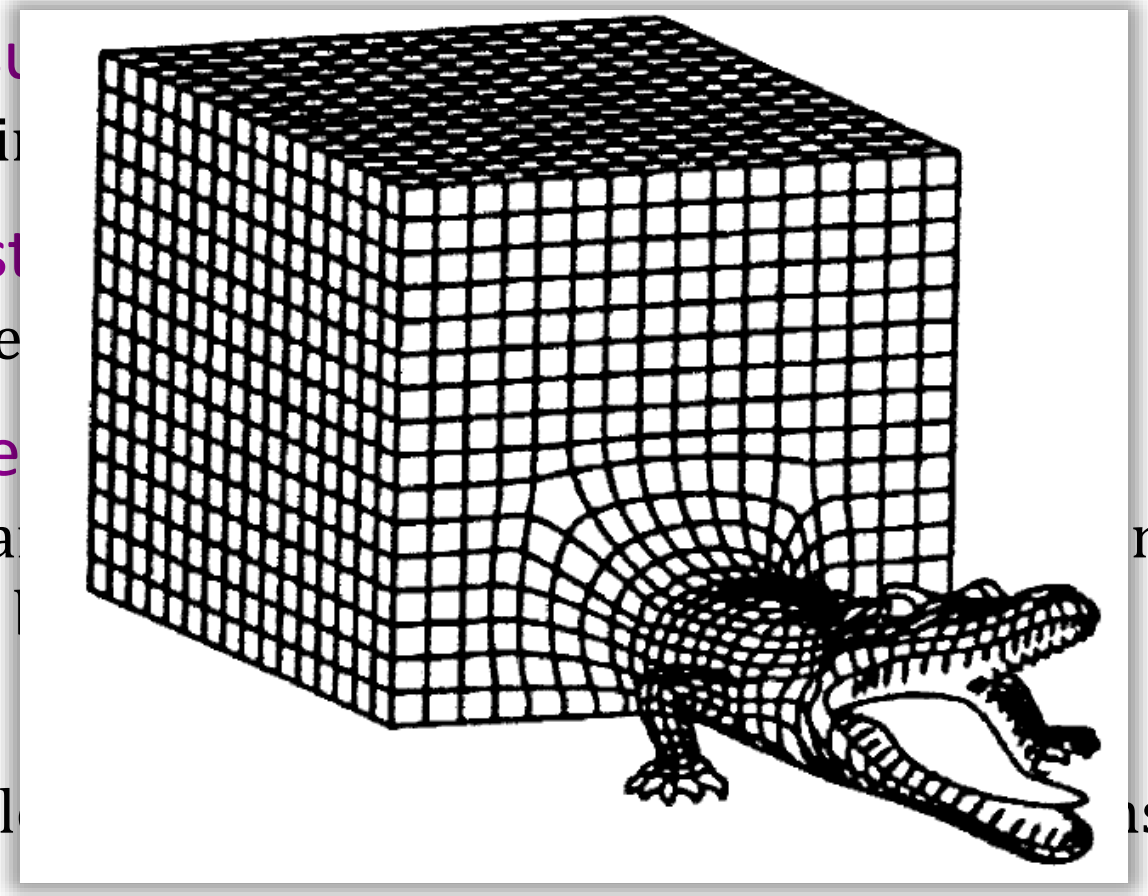
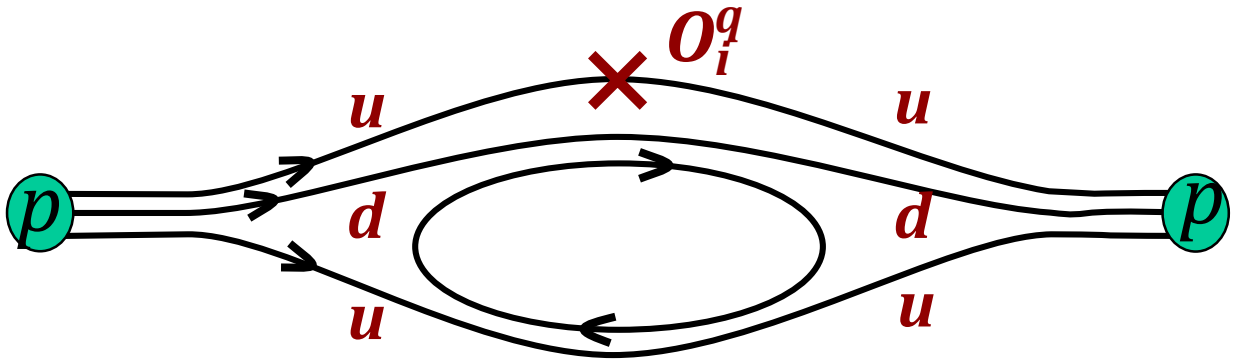


PROCEED WITH CAUTION

Nucleon Matrix Elements

Lattice-QCD calculation of $\langle N|\bar{q}\Gamma q|N\rangle$



§ Construct correlators (hadronic observables)

- Requires "quark propagator"

  Invert Dirac-operator matrix (rank $O(10^{12})$)

Nucleon Matrix Elements

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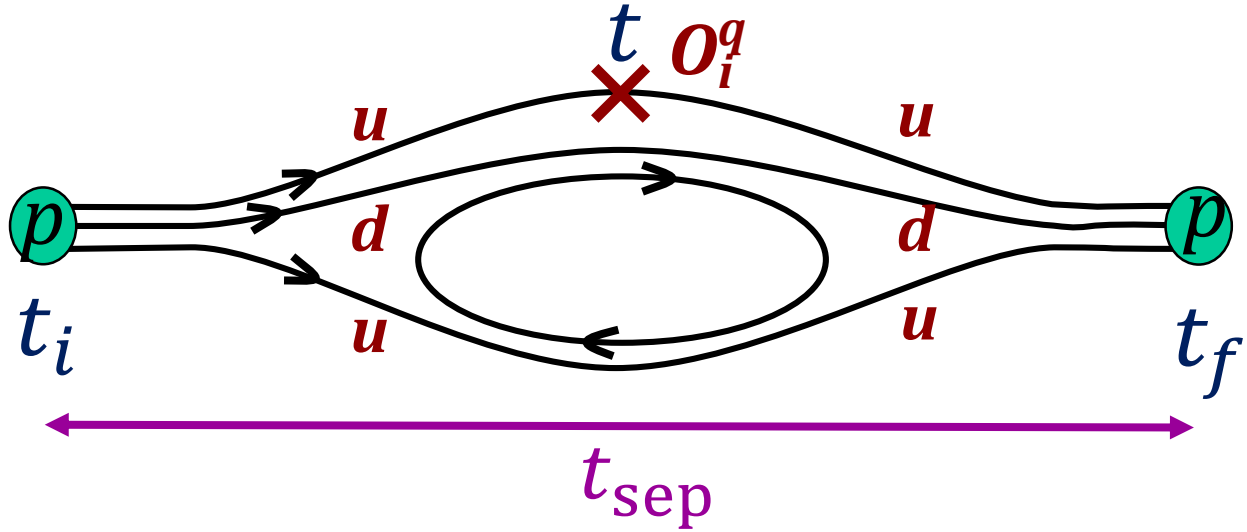


§ Analysis (extract couplings)

$$C^{2\rm pt}(t_f, t_i) = |\mathcal{A}_0|^2 e^{-M_0(t_f-t_i)} + |\mathcal{A}_1|^2 e^{-M_1(t_f-t_i)} + \ldots$$

$$C^{3\rm pt}(t_f, t, t_i) = |\mathcal{A}_0|^2 \langle 0|\mathcal{O}_\Gamma|0\rangle e^{-M_0(t_{\rm sep})}$$

Ratio method, one-one

$$+\mathcal{A}_0\mathcal{A}_1^*\langle 0|\mathcal{O}_\Gamma|1\rangle e^{-M_0(t-t_i)} e^{-M_1(t_f-t)}$$
$$+\mathcal{A}_0^*\mathcal{A}_1\langle 1|\mathcal{O}_\Gamma|0\rangle e^{-M_1(t-t_i)} e^{-M_0(t_f-t)}$$

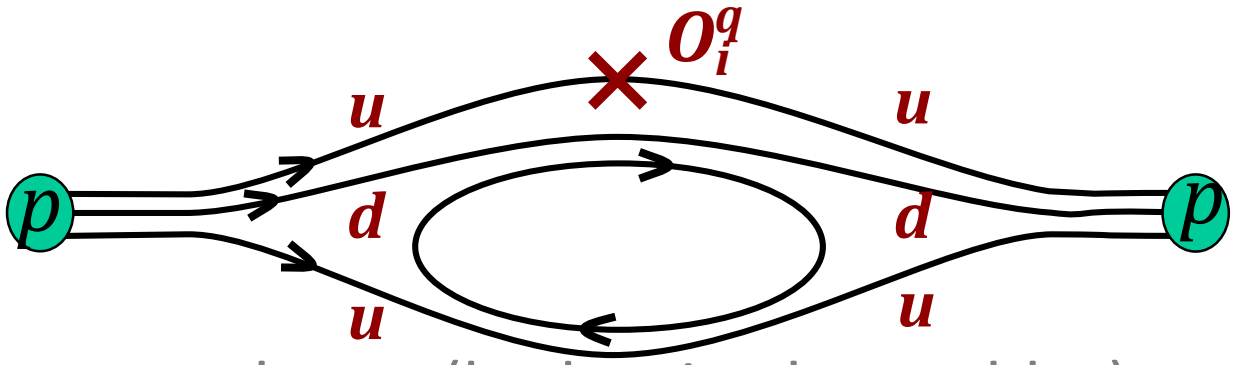
Summation, two-two, two-sim

$$+|\mathcal{A}_1|^2\langle 1|\mathcal{O}_\Gamma|1\rangle e^{-M_1(t_{\rm sep})}$$

two-simRR, variational method, …

Nucleon Matrix Elements

Lattice-QCD calculation of $\langle N|\bar{q}\Gamma q|N\rangle$



§ Construct correlators (hadronic observables)

- Invert Dirac-operator matrix (rank $O(10^{12})$)

§ Analysis (extract couplings)

§ Extrapolate to continuum limit

- Take $m_\pi \to m_\pi^{\text{phys}}$, $a \to 0$, $L \to \infty$

§ Control all systematic errors:

- Choice of extrapolation (e.g. Q^2 dependence for form factors), renormalization to 2 GeV $\overline{\text{MS}}$ scheme, etc.

Progress

§ Much effort has been devoted to controlling systematics

Characteristics

§ Lighter pion masses

- More measurements at the physical pion mass!

§ More intense systematics study

- Remove assumptions in the simulation (a, L, m_q)
- 10^4 measurements not uncommon

§ Investigate previously difficult calculations

- Such as disconnected diagrams, etc.

Progress

§ For example, PNDME's calculations

- Thanks to MILC for sharing their 2+1+1 HISQ lattices

a (fm)	V	$M_\pi L$	M_π (MeV)	t_{sep}	# Meas.
0.12	$24^3 \times 64$	4.55	310	8,9,10,11,12	8104
0.12	$24^3 \times 64$	3.29	220	8,10,12	24000
0.12	$32^3 \times 64$	4.38	220	8,10,12	7664
0.12	$40^3 \times 64$	5.49	220	10	8080
0.09	$32^3 \times 96$	4.51	310	10,12,14	7048
0.09	$48^3 \times 96$	4.79	220	10,12,14	7120
0.09	$64^3 \times 96$	3.90	130	10,12,14	7064
0.06	$48^3 \times 144$	4.52	310	16,20,22,24	8000
0.06	$64^3 \times 144$	4.41	220	16,20,22,24	2600
0.06	$96^3 \times 192$	3.80	130		0

Excited States

§ Much effort has been devoted to controlling systematics

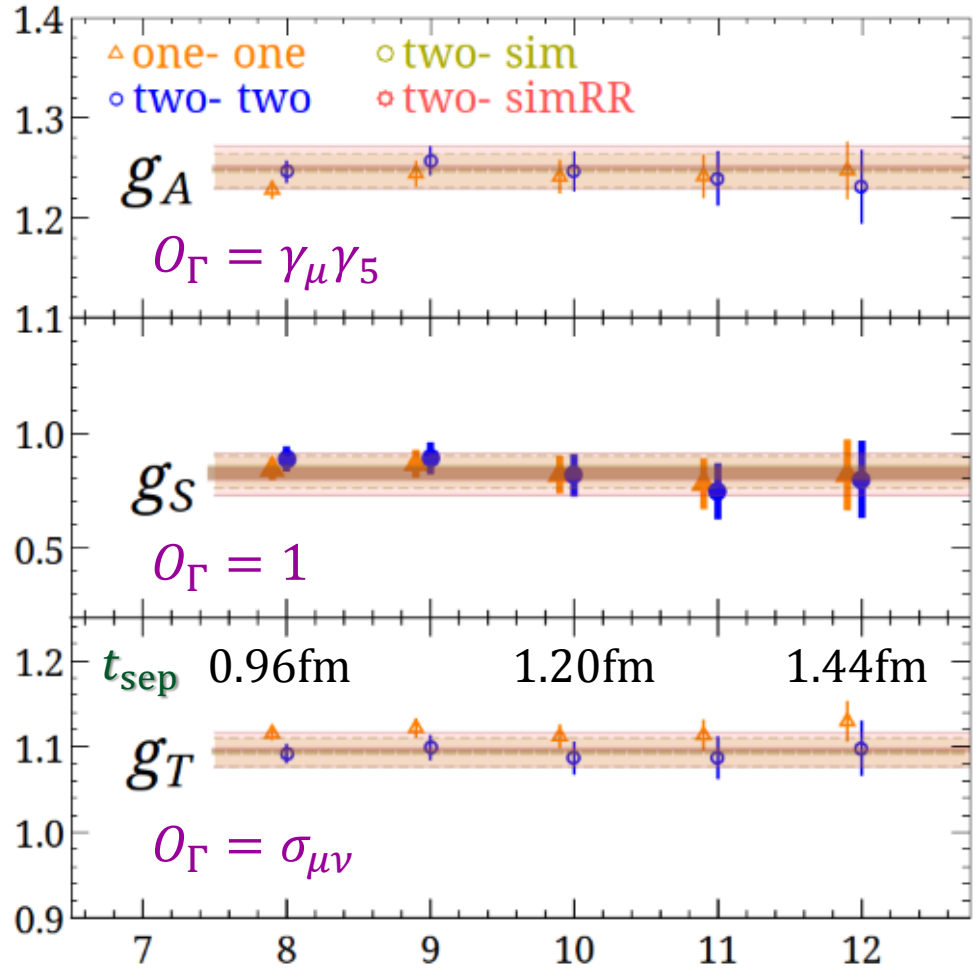
§ For example, PNDME's calculations

$a = 0.12$ fm, 310-MeV pion

- Move the **excited-state systematic** into the statistical error

$$C^{3\text{pt}}(t_f, t, t_i) = |\mathcal{A}_0|^2 \langle 0|\mathcal{O}_\Gamma|0\rangle e^{-M_0(t_{\text{sep}})}$$
$$+\mathcal{A}_0\mathcal{A}_1^* \langle 0|\mathcal{O}_\Gamma|1\rangle e^{-M_0(t-t_i)} e^{-M_1(t_f-t)}$$
$$+\mathcal{A}_0^*\mathcal{A}_1 \langle 1|\mathcal{O}_\Gamma|0\rangle e^{-M_1(t-t_i)} e^{-M_0(t_f-t)}$$
$$+|\mathcal{A}_1|^2 \langle 1|\mathcal{O}_\Gamma|1\rangle e^{-M_1(t_{sep})}$$

- No obvious contamination between 0.96 and 1.44 fm separation



Excited States

§ Much effort has been devoted to controlling systematics

§ For example, PNDME's calculations

$a = 0.09$ fm, 310-MeV pion

- Move the **excited-state systematic** into the statistical error

$$C^{3\text{pt}}(t_f, t, t_i) = |\mathcal{A}_0|^2 \langle 0|\mathcal{O}_\Gamma|0\rangle e^{-M_0(t_{\text{sep}})}$$
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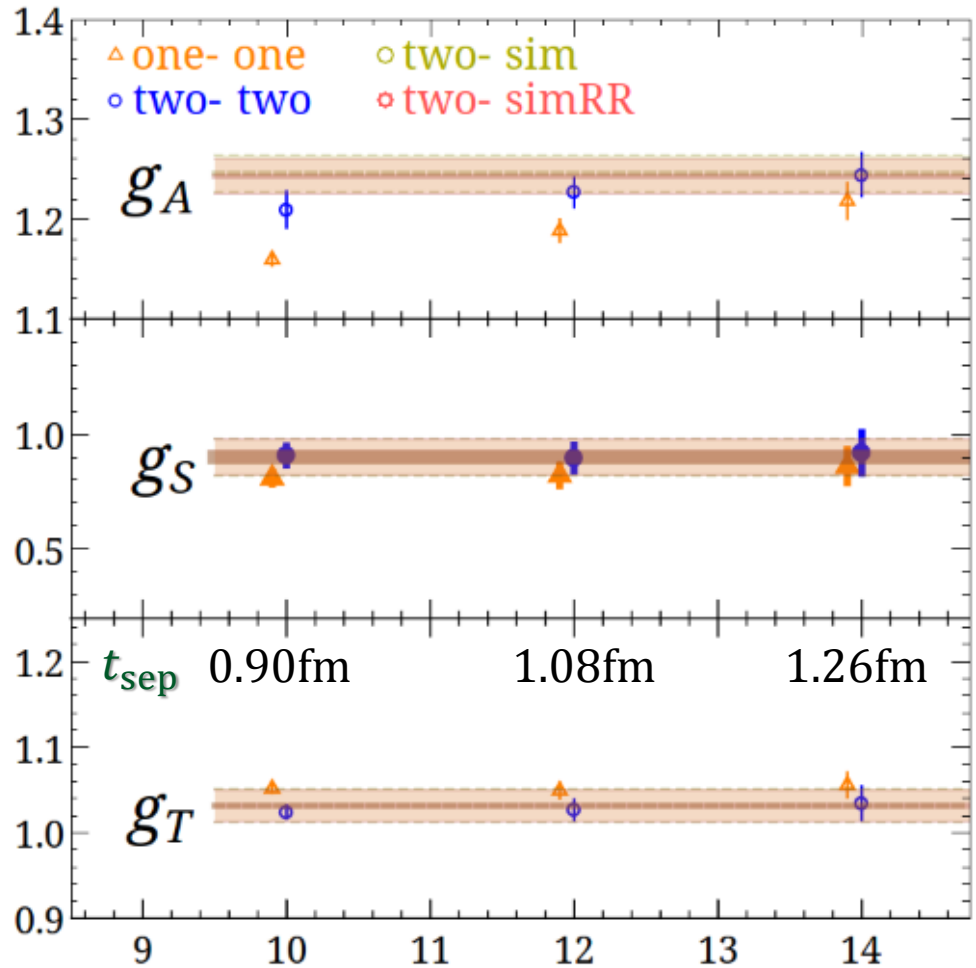
$$+|\mathcal{A}_1|^2 \langle 1|\mathcal{O}_\Gamma|1\rangle e^{-M_1(t_{sep})}$$

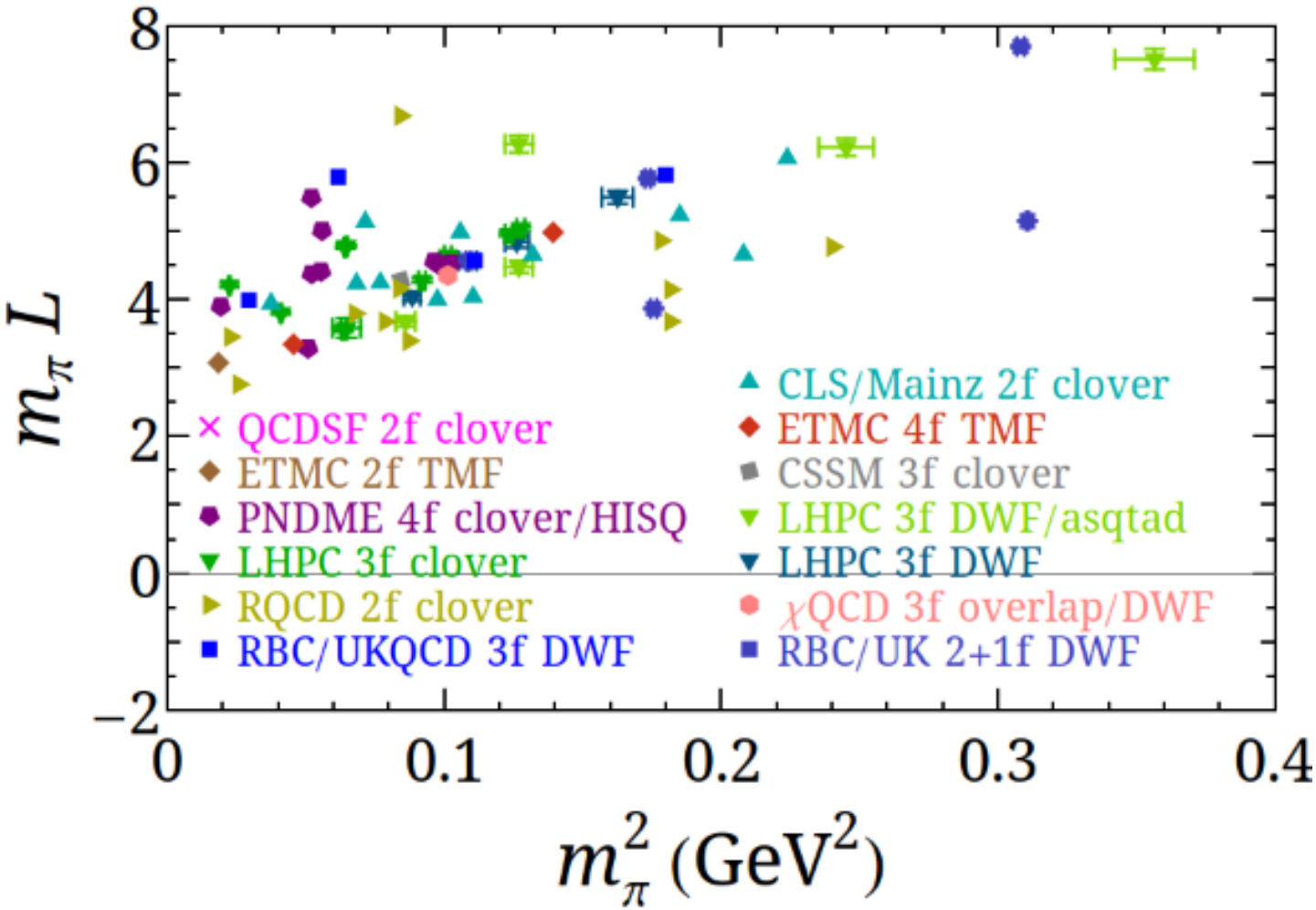
- Much stronger effect at finer lattice spacing!
- Needs to be studied case by case



LQCD NME

§ World players in LQCD nucleon structure

- Majority use $a < 0.1$ fm

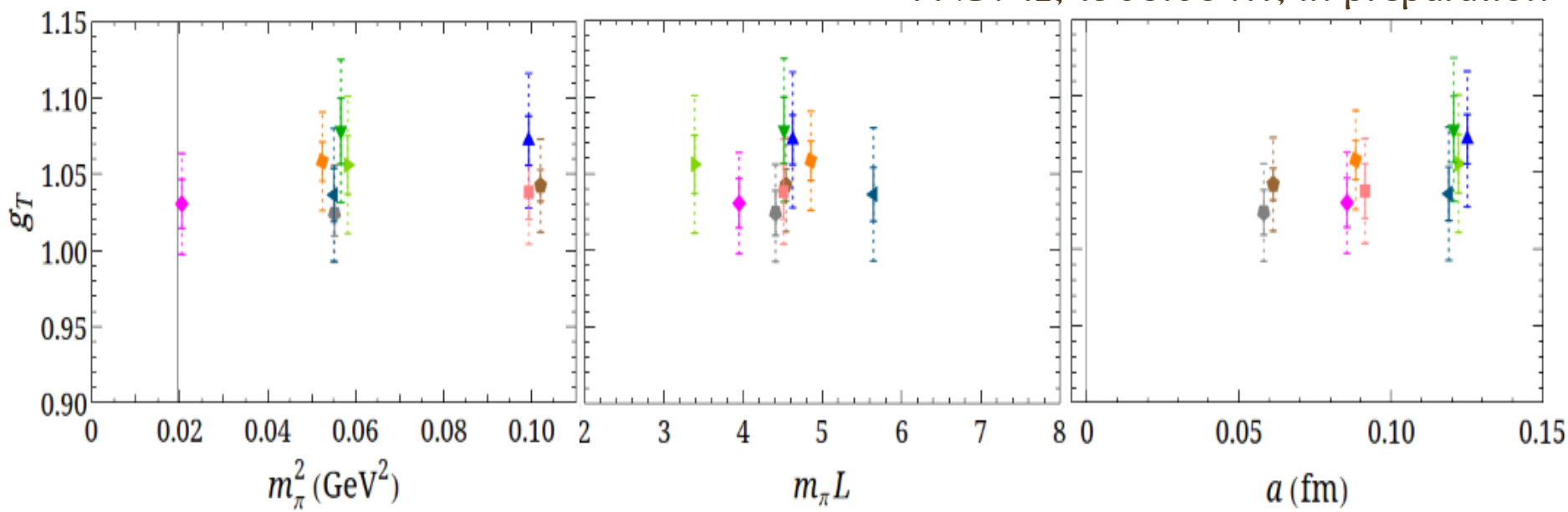


Tensor Charge

§ PNDME's g_T calculations

- Bare charges from 9 ensembles at percent level: 3 lattice spacings, volume study, $M_\pi \geq 130$ MeV
- Nonperturbative renormalization dominates overall error at 3–4% systematics
- Study the pion-mass, volume and lattice-spacing dependences

PNDME, 1506.06411; in preparation



Tensor Charge

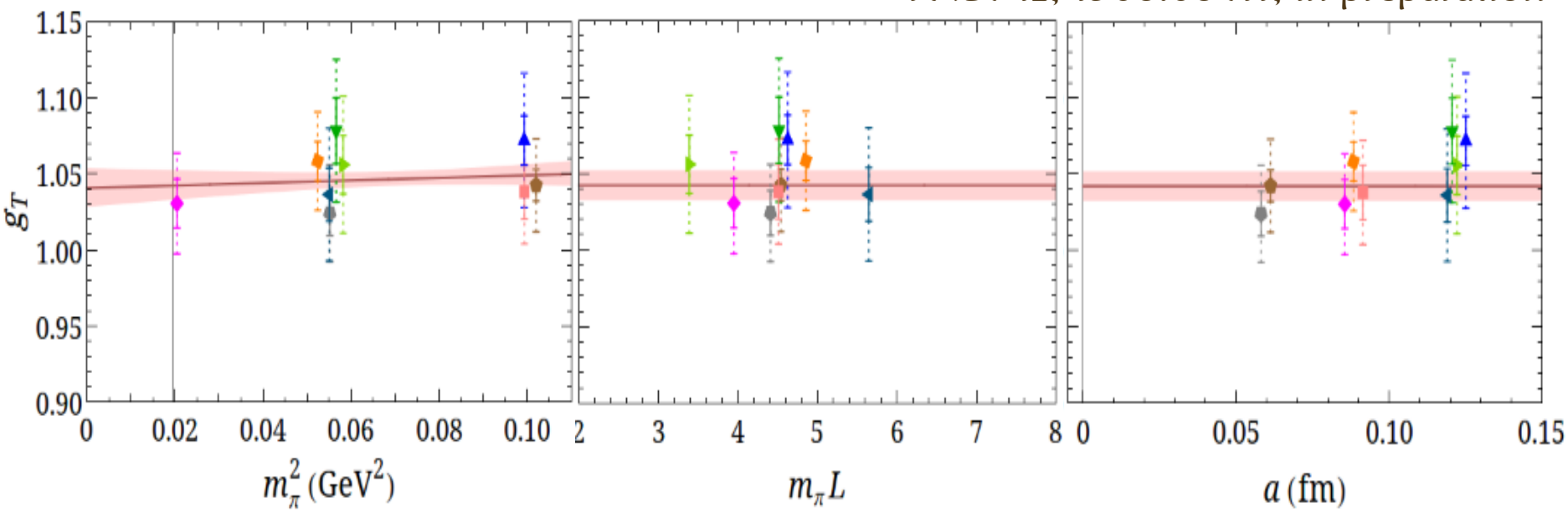
§ PNDME's g_T calculations

- Extrapolate to continuum limit

$$g_T(a, m_\pi, L) = c_1 + c_3 m_\pi^2 + c_2 a + c_4 e^{-m_\pi L}$$

$$\boldsymbol{g_T = 1.041(10)}$$

PNDME, 1506.06411; in preparation



Tensor Charge

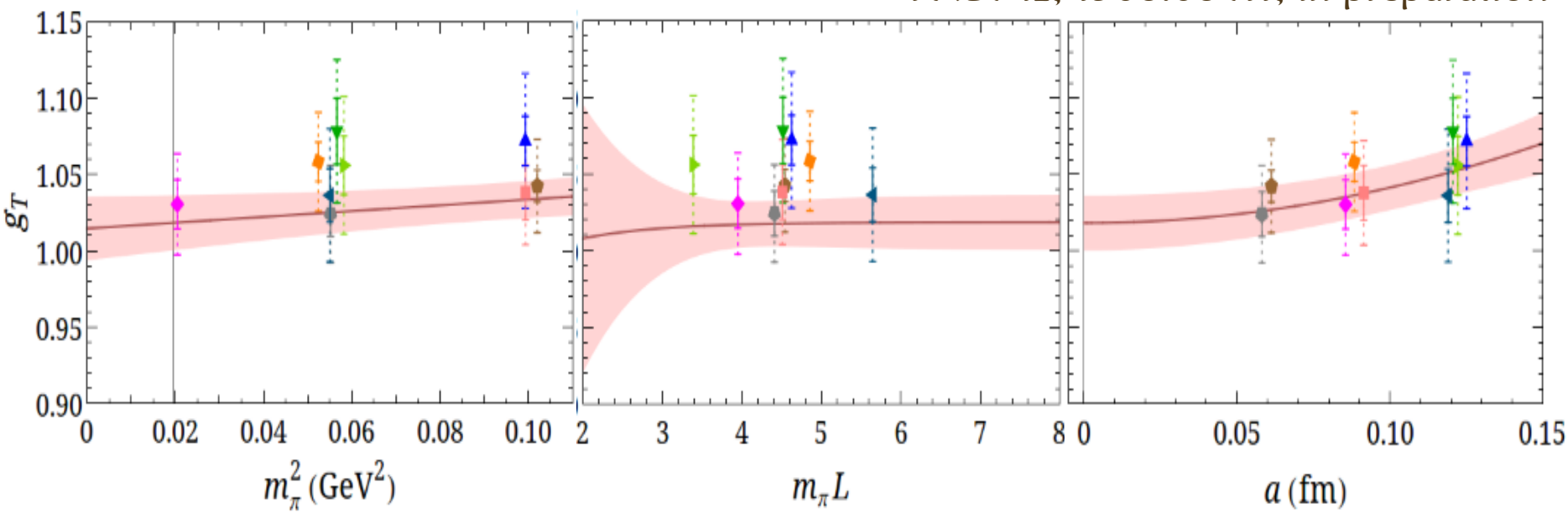
§ PNDME's g_T calculations

- Extrapolate to continuum limit (assume $O(a)$ is small)

$$g_T(a, m_\pi, L) = c_1 + c_3 m_\pi^2 + c_2 a^2 + c_4 e^{-m_\pi L}$$

$$\boldsymbol{g_T = 1.019(18)}$$

PNDME, 1506.06411; in preparation



Tensor Charge

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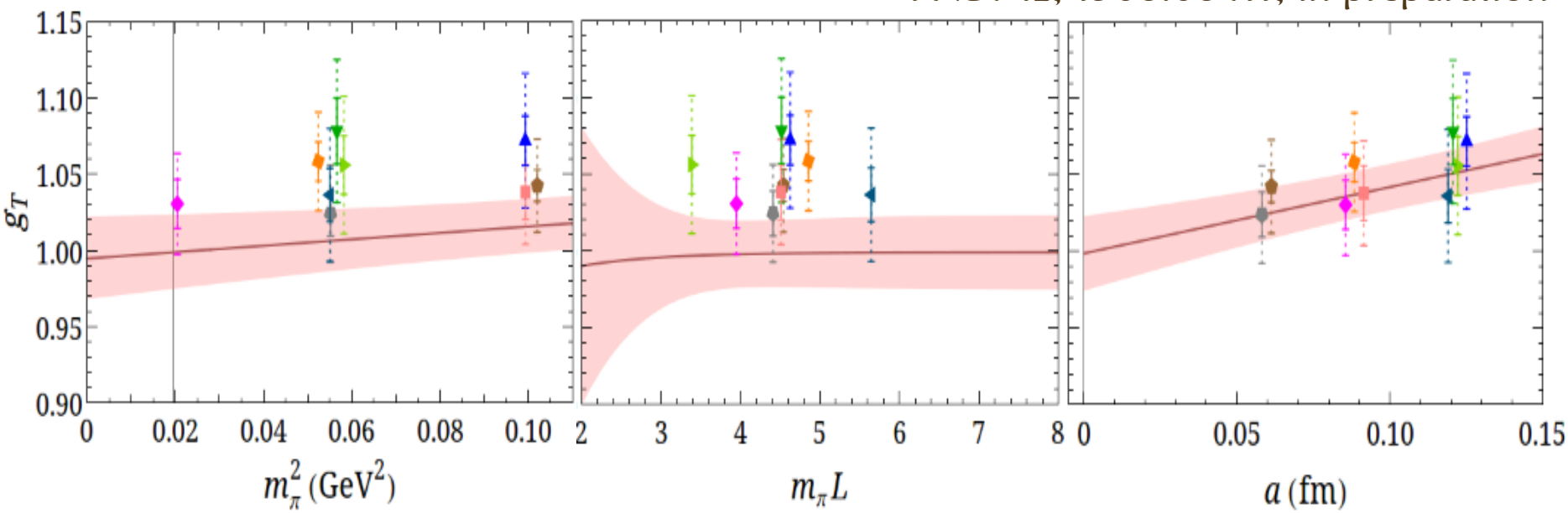
$$\boldsymbol{g_T = 0.999(23)}$$

PNDME, 1506.06411; in preparation



Tensor Charge

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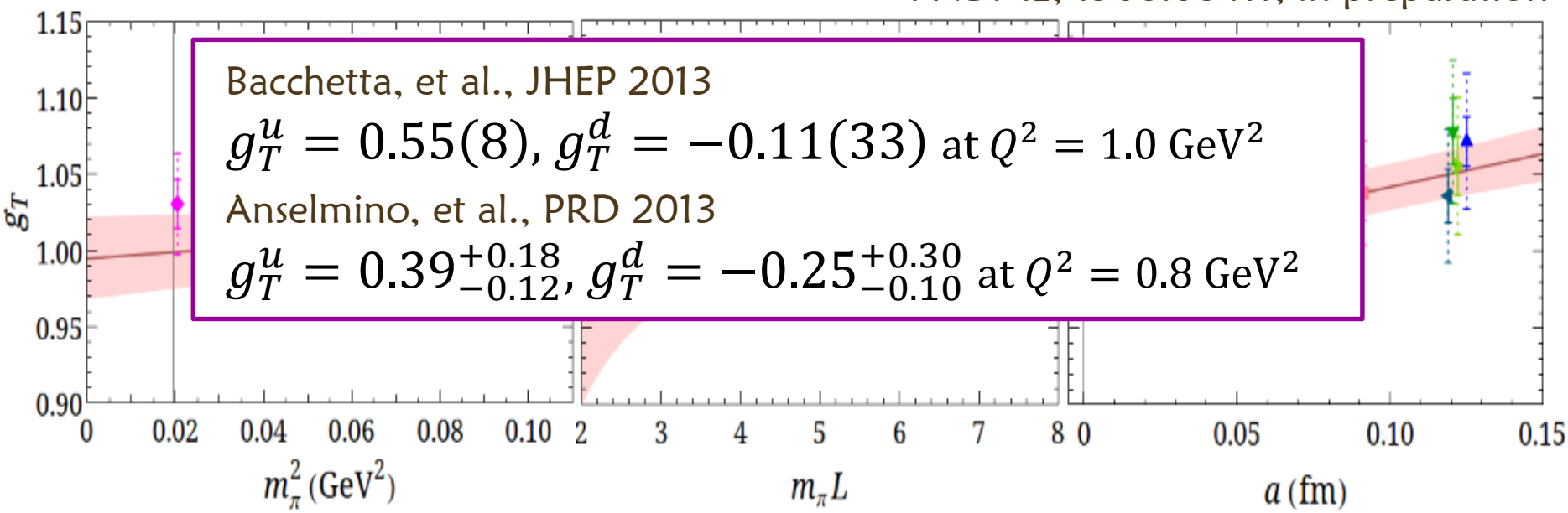
PNDME, 1506.06411; in preparation



Bacchetta, et al., JHEP 2013

$g_T^u = 0.55(8)$, $g_T^d = -0.11(33)$ at $Q^2 = 1.0\ \mathrm{GeV}^2$

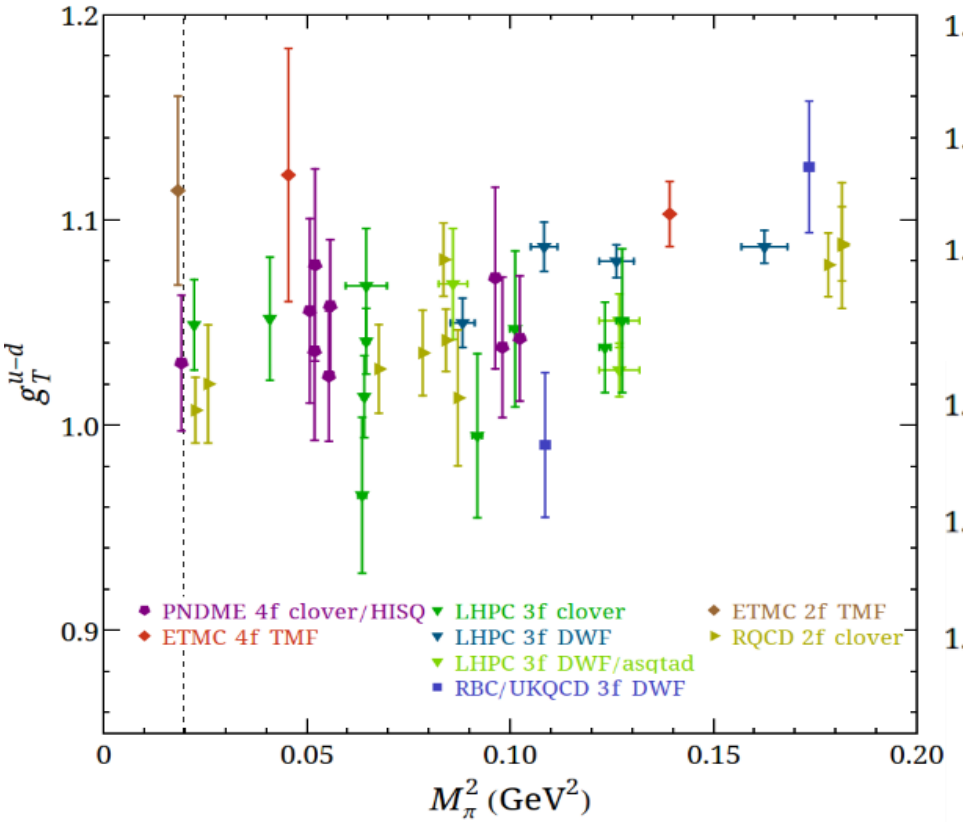
Anselmino, et al., PRD 2013

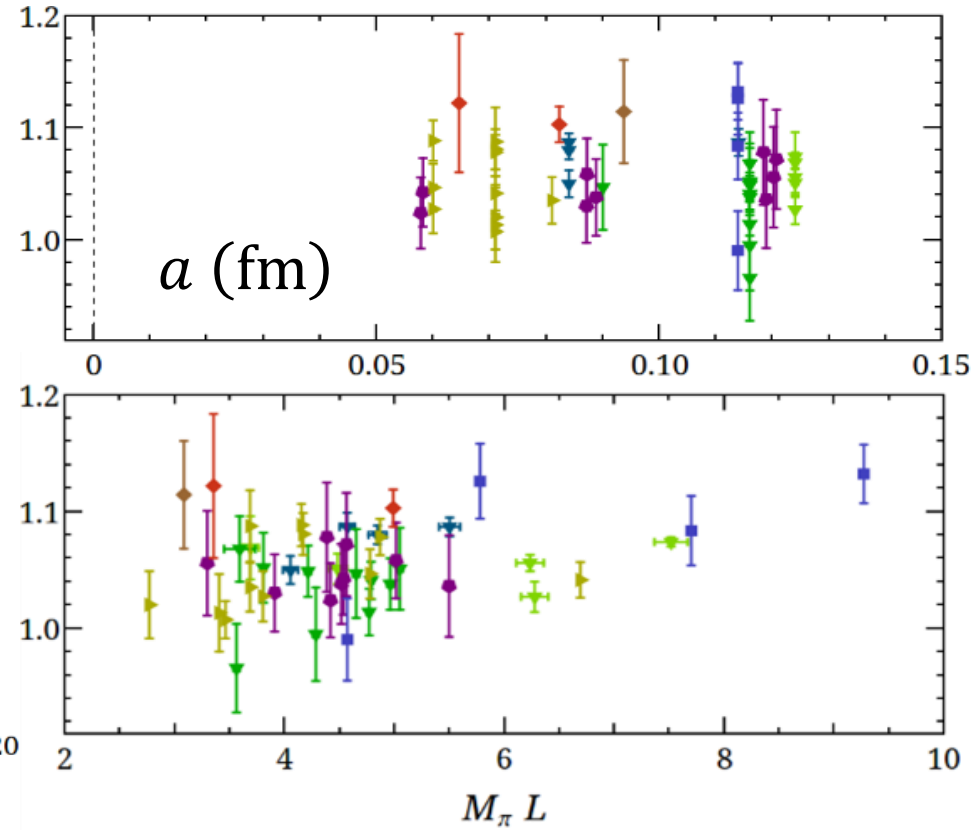
$g_T^u = 0.39^{+0.18}_{-0.12}$, $g_T^d = -0.25^{+0.30}_{-0.10}$ at $Q^2 = 0.8\ \mathrm{GeV}^2$

Tensor Charge

§ World lattice data

PNDME, 1506.06411; in preparation





Tensor Charge

PNDME, 1506.06411

Collaboration	Ref.	publication status	N_f	chiral extrapolation	continuum extrapolation	finite volume	excited state	renormalization	g_T
PNDME'15	This work	P	2+1+1	★	★	★	★	★	1.020(76)[a]
ETMC'13	[30]	C	2+1+1	■	○	○	■	★	1.11(3)[b]
LHPC'12	[28]	A	2+1	★	○	★	○	★	1.037(20)[c]
RBC/UKQCD'10	[29]	A	2+1	○	■	★	★	★	1.10(7) [d]
RQCD'14	[31]	P	2	★	★	★	○	★	1.005(17)(29))[e]
ETMC'13	[30]	C	2	★	■	○	■	○	1.114(46) [f]
RBC'08	[32]	P	2	■	■	★	■	★	0.93(6) [g]

[a] This estimate is obtained from a simultaneous fit versus a, M_π^2, and $e^{-M_\pi L}$ defined in Eq. (15) using data on nine clover-on-HISQ ensembles given in Table VII.

[b] The two estimates from $N_f = 2+1+1$ maximally twisted mass ensembles with $M_\pi = 213, 373$ MeV and $a = 0.064,\ 0.082$ fm, respectively, are consistent. The summation method with a single $t_{\rm sep} \sim 1$ fm was used for handling excited state contamination.

[c] The central value is from a three parameter chiral fit to data from three different lattice actions at different lattice spacings and with different volumes. Estimate does not include extrapolation in the lattice spacing a or in the finite volume controlled by $M_\pi L$ but dependence on these is found to be small.

[d] Result is based on simulations at one lattice spacing $1/a = 1.73$ GeV using domain wall fermions. The statistics for the ensembles corresponding to the four pion masses simulated, $M_\pi = 329,\ 416,\ 550,\ 668$ MeV, were 3728, 1424, 392, 424 measurements, respectively. The renormalization factor was calculated non-perturbatively.

[e] The result of this clover-on-clover study is obtained using a fit linear in M_π^2 keeping data with $M_\pi^2 < 0.1$ GeV^2 only. Data do not show significant dependence on lattice spacing or lattice volume. Excited state study is done on three of the eleven ensembles. Most of the data are with $t_{\rm sep} \sim 1$ fm. The second error is an estimate of the discretization errors assuming they are $O(a^2)$ since $O(a)$ improved operators with 1-loop estimates for the improvement coefficients are used. Preliminary estimates presented by the QCDSF collaboration [41] are superceded by this publication [42].

[f] Result from a single ensemble of maximally twisted mass fermions at $a = 0.094$ fm and $M_\pi = 135$ MeV. Used the ratio/summation method with a single $t_{\rm sep} \sim 1$ fm for handling excited state contamination.

[g] Results based on one lattice spacing $1/a = 1.7$ GeV with DBW2 domain wall action, three values of quark masses with $M_\pi = 493,\ 607,\ 695$ MeV, and $O(500)$ measurements. Used only one $t_{\rm sep} = 10$ (1.14 fm) except at the lighest mass where additional data with $t_{\rm sep} = 12$ was used only as a consistency check as it had large errors.

New Physics in Beta Decay

New Interactions

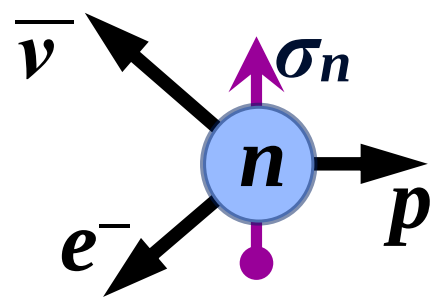
§ Neutron beta decay could be related to new interactions:

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

- 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
- Observable sensitive to new physics

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

$$d\Gamma \propto F(E_e) \left[1 + \boldsymbol{b} \frac{m_e}{E_e} + \left(B_0 + B_1 \frac{m_e}{E_e} \right) \frac{\overrightarrow{\sigma_n} \cdot \overrightarrow{p_\nu}}{E_\nu} + \cdots \right]$$



Fierz interference term: Deviations from the leading-order e^- spectrum

Energy dependent part of the **neutrino asymmetry parameter** with neutron spin

New Interactions

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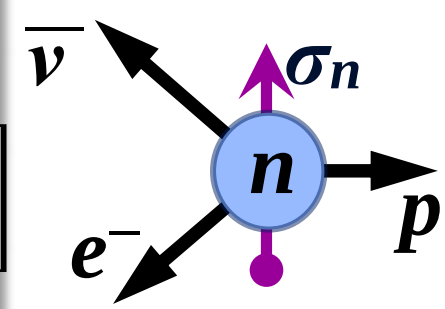
$$H_{\text{eff}} = G_F \left(J_{V-A}^{\text{lept}} \times J_{V-A}^{\text{quark}} + \sum_i \varepsilon_i^{\text{BSM}} \, \hat{O}_i^{\text{lept}} \times \hat{O}_i^{\text{quark}} \right)$$

- ε_S and ε_T [illegible] $\Lambda_{S,T}^{-2}$ the new [illegible]
- … but the [illegible] eeded
- Observal [illegible]

$d\Gamma \propto F$ [illegible]

Ongoing and Future Experiments	Expected Precision
UCNb & UCNB at LANL	10^{-3} to 10^{-4}
Nab at ORNL	10^{-3}
FRMII in Munich, …	
CENPA ^{6}He(b_{GT})	10^{-3}



Fierz interference term: Deviations from the leading-order e^- spectrum

Energy dependent part of the **neutrino asymmetry parameter** with neutron spin

Physics Program

Precision low-E experiments

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

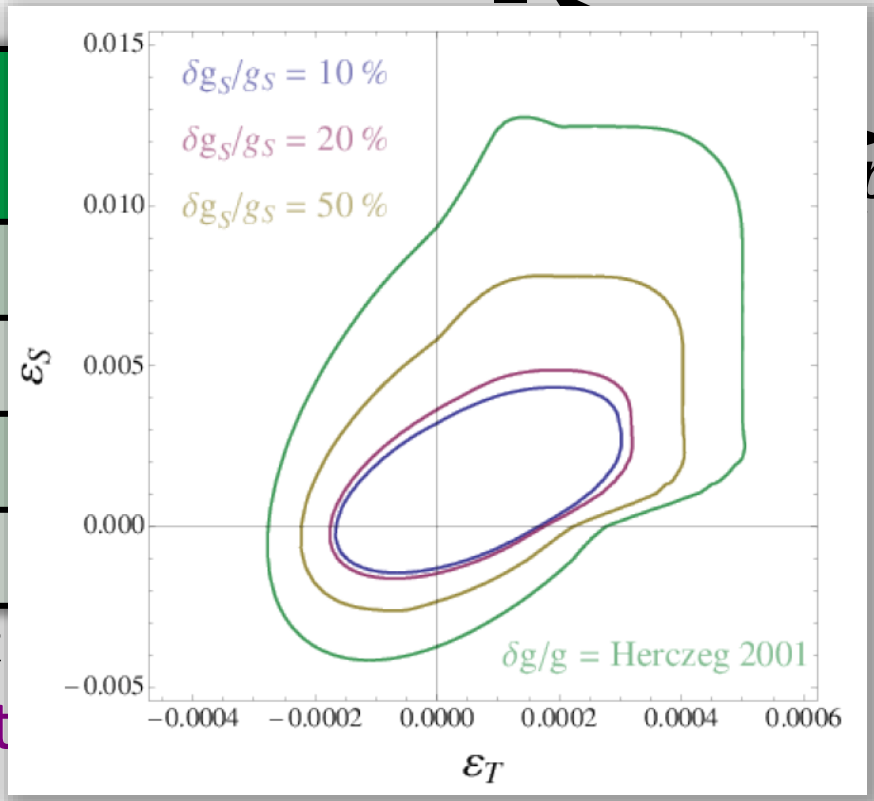
Precision LQCD input ($m_\pi \approx 140$ MeV, $a \to 0$)

§ Paramete

$d\Gamma \propto F($

Fierz inter

Ongoing and Future Experiments
UCNB at LANL
Nab at ORNL



What precision is needed to leverage a 10^{-3} experiment?

Only 10% total uncertainty

Scalar Charges

§ Scalar charge $\langle n|\bar{u}d|p\rangle$

- Experimentally not known
- Prior model estimate: $1 \leq g_S \leq 0.25$

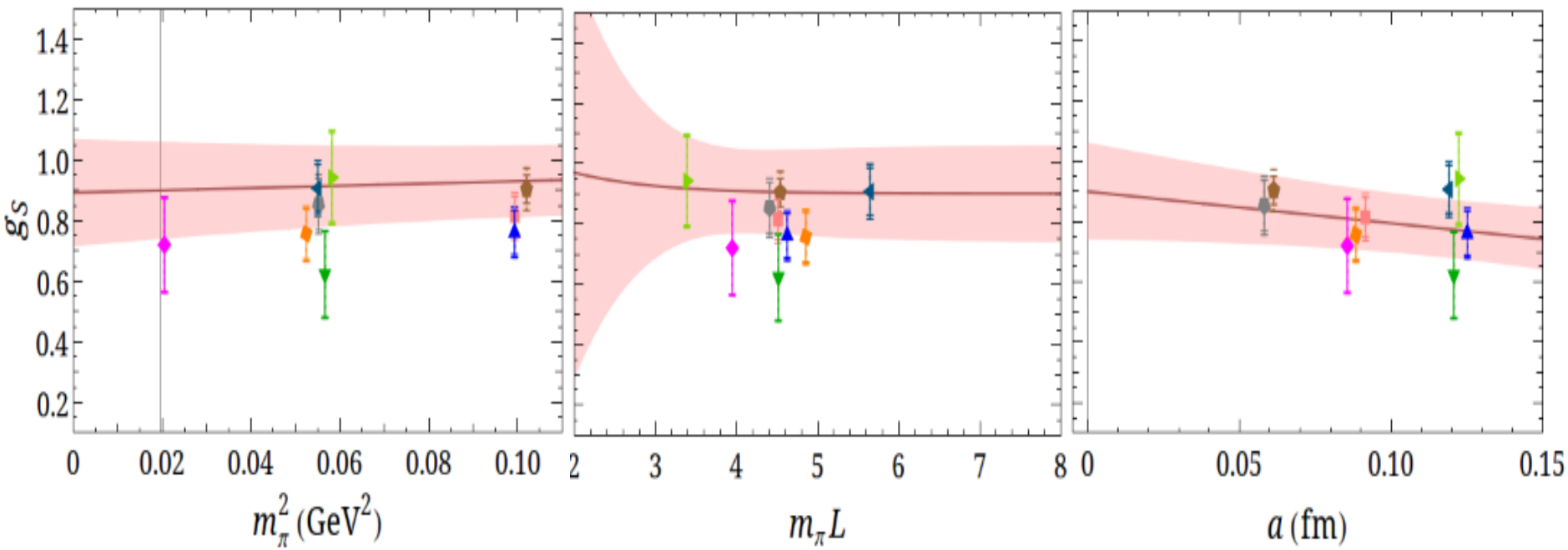
Herczeg, Prog. Part. Nucl. Phys. 46, 413 (2001)

§ PNDME's g_S calculations

- Extrapolate to continuum limit

$g_S = 0.89(16)$

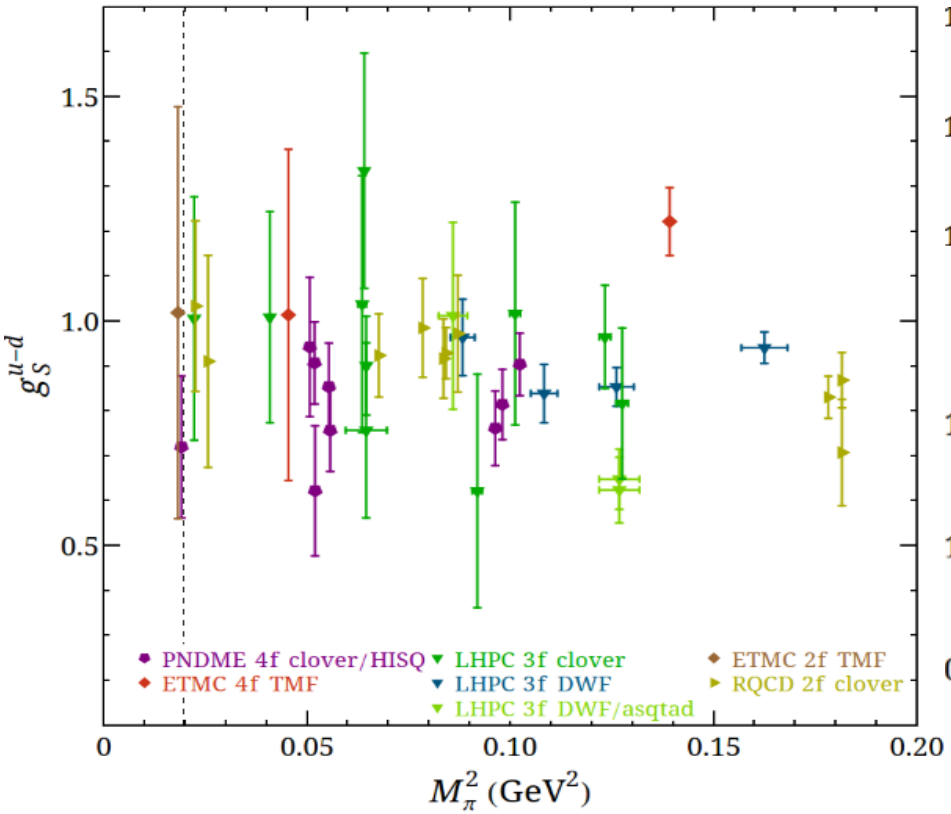
$$g_S(a, m_\pi, L) = c_1 + c_2 a + c_3 m_\pi^2 + c_4 e^{-m_\pi L}$$

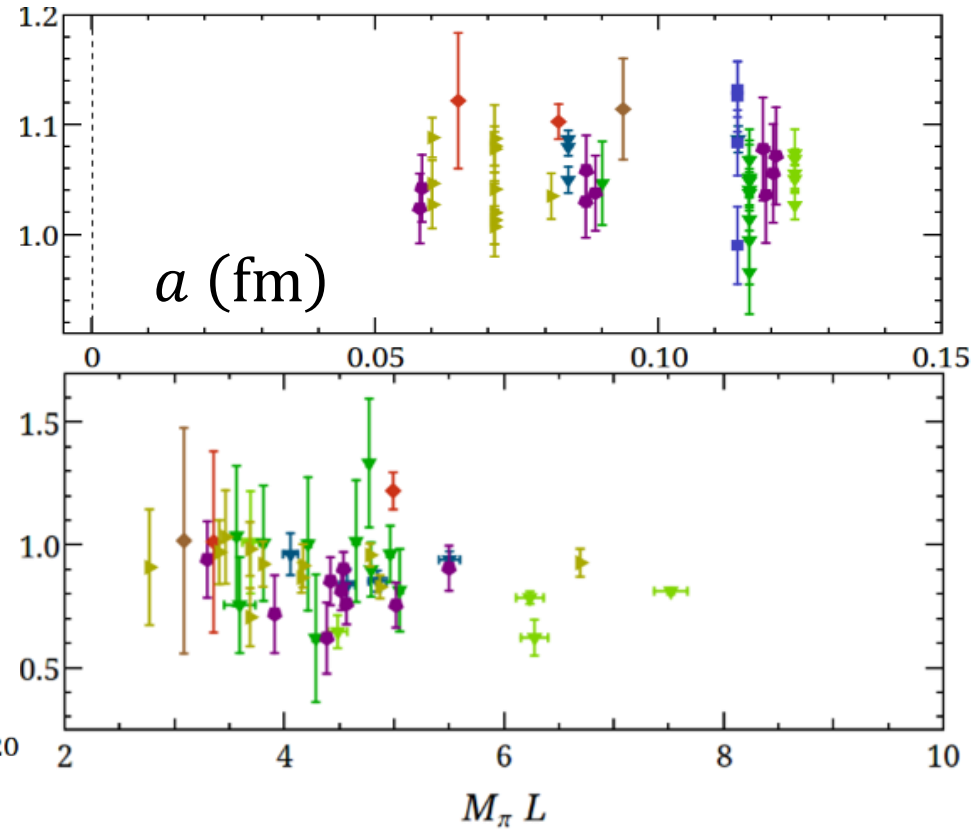


Scalar Charge

§ Scalar charge

- Hadronic inputs in nucleon(nuclear) beta decay BSM search
- Related CP-violating pion-nucleon coupling in nEDM EFT





Crucial Role of Lattice QCD

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

Nuclear Experiments

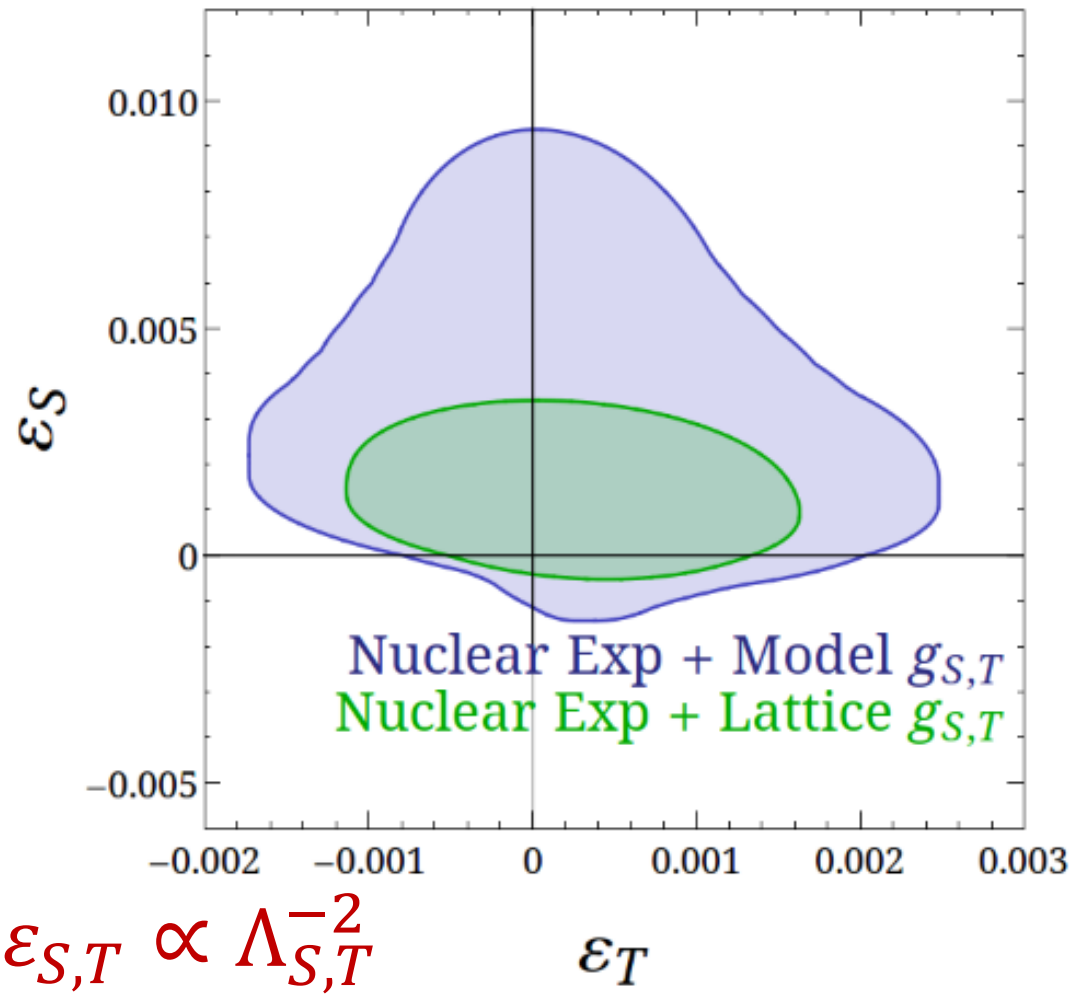
$0^+ \to 0^+$ transitions,

β asym in Gamow-Teller ^{60}Co, ...

$$O_{BSM} = f_O(\varepsilon_{S,T}\, g_{S,T})$$

Precision LQCD input

($m_\pi \to 140$ MeV, $a \to 0$)



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

PNDME, 1306.5435; in preparation

Future Beta Decays Leverage

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

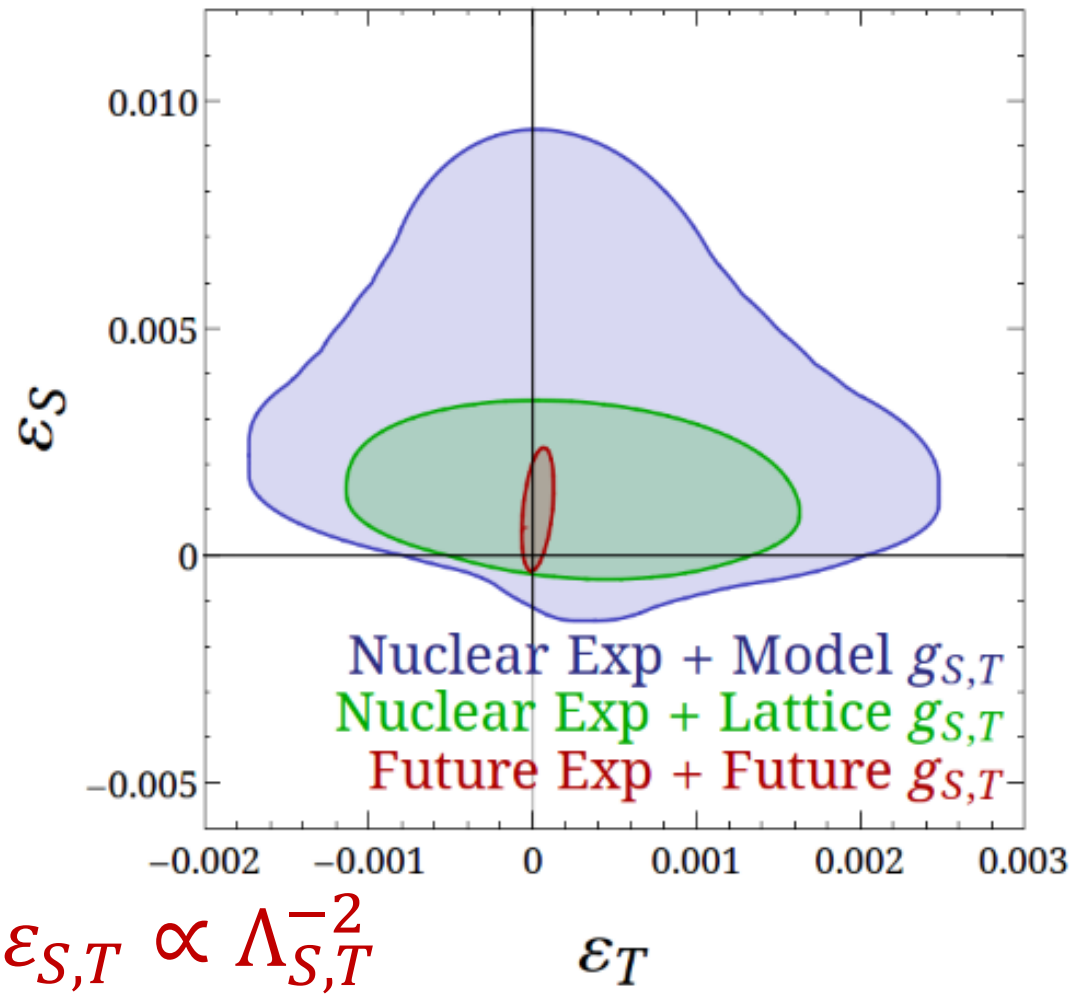
Nuclear Experiments + Future UCN

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

$$O_{\mathrm{BSM}} = f_O(\varepsilon_{S,T}\, g_{S,T})$$

Precision LQCD input

($m_\pi \to 140$ MeV, $a \to 0$)



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

PNDME, 1306.5435; in preparation

High-Energy Constraints

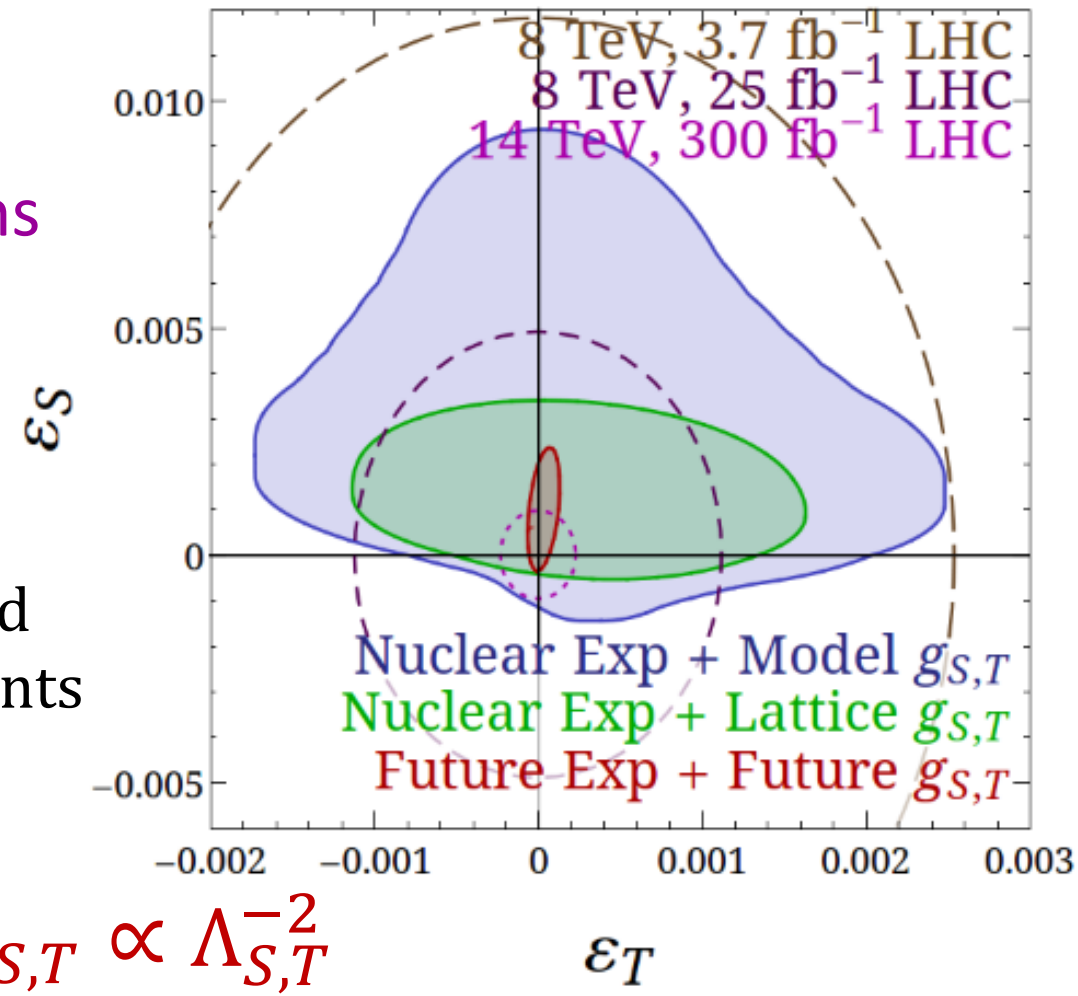
§ Are high-energy constraints competitive?

LHC current bounds, near-term and long-term expectations

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

Compare with W background

Estimated 90% C.L. constraints



PNDME, PRD85 054512 (2012); 1306.5435; in preparation

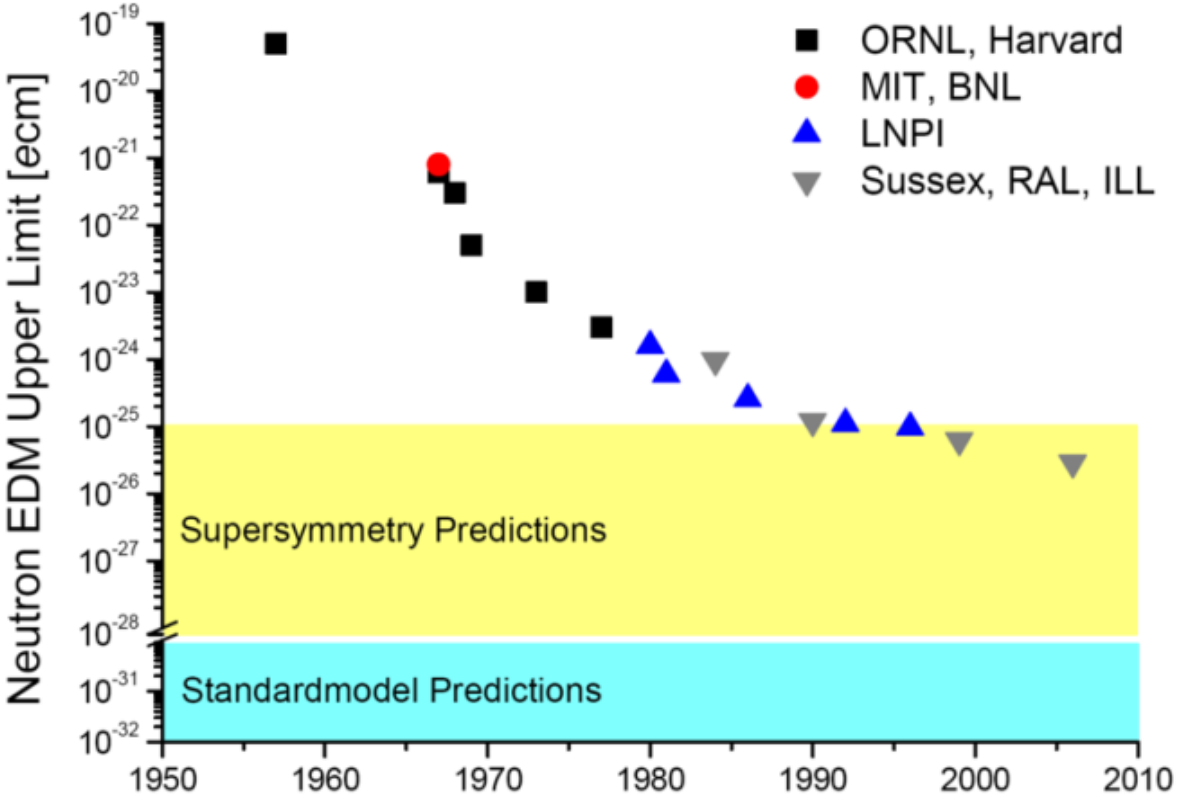
$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$

Neutron Electric Dipole Moment

$n\mathcal{EDM}$

§ Electric dipole moment is interesting because

- CP-violating effect ⇒ Key ingredient for baryogenesis
  ⇒ Why matter exists
- Extremely small in SM: ≈ 10^{-31} e-cm (expect to probe 10^{-28} soon)
- Good candidate to constrain BSM models



$n\mathcal{EDM}$

§ Lattice community are working on various contributions

§ Lagrangian $L = L_{\mathrm{QCD}}^{CP\ \mathrm{Even}} + L_{\Theta} + L_{\mathrm{quark}}^{\mathrm{dim-5}} + L_{\mathrm{chromo-quark}}^{\mathrm{dim-5}} + \cdots$

$$i\Theta \frac{g^2}{16\pi^2} \int d^4x\, G^{\mu\nu} \tilde{G}_{\mu\nu}$$

CP-even QCD vacuum with θ-term expansion; noisy

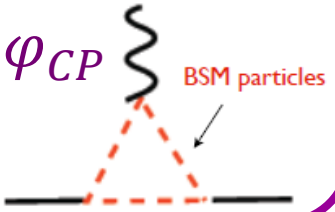
RBC, J/E, CP-PACS(2005), CP-PACS(2006, 2010), QCDSF(2011), …

CP-odd QCD vacuum 1502.02295 with dynamical quarks by QCDSF

−0.0038(2)(9) θ e·fm

Induced by a variety of BSM scenarios

$d_i \propto \frac{m_i}{\Lambda^2} \sin \varphi_{CP}$



$\bar{q}\sigma_{\mu\nu}\gamma_5 \lambda^A G^{\mu\nu A} q + \cdots$

A few works in progress

T. Bhattacharya et al, 1502.07325

$$-\frac{i}{2}\bar{q}\sigma_{\mu\nu}\gamma_5 q F^{\mu\nu}$$

This talk focuses on the quark EDM

Quark EDM

§ Quark EDM (d_q) in nucleon comes from

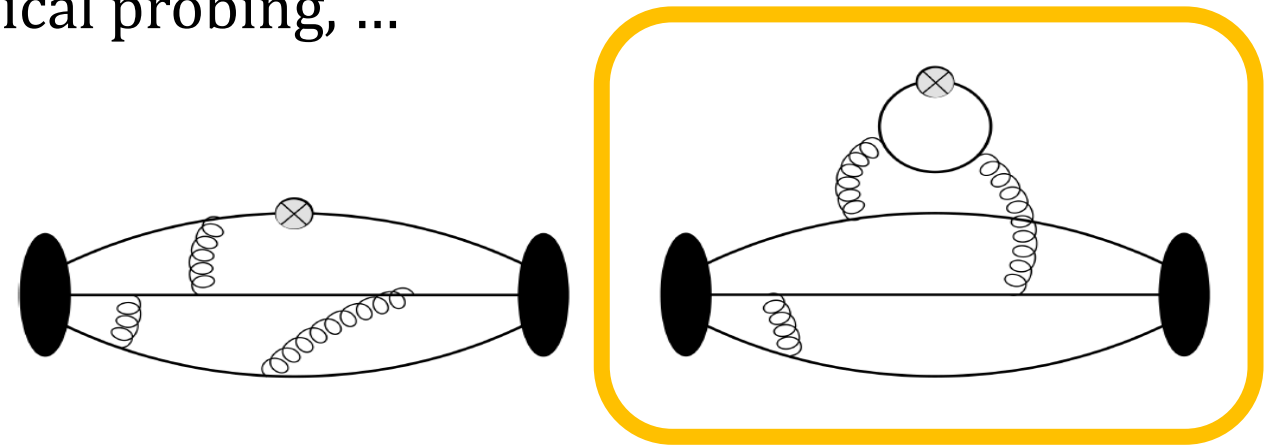
$$d_N = d_u g_T^{(n,u)} + d_d g_T^{(n,d)} + d_s g_T^{(n,s)}$$

- Hadronic contribution: $\langle N | \bar{q}\sigma_{\mu\nu} q | N \rangle$ ($q \in \{u, d, s\}$)

PNDME, 1506.04196; 1506.06411

§ Need "disconnected" diagram contributions

- Multiple ways to calculate this notorious contribution
- Truncated solver, hopping-parameter expansion, hierarchical probing, …



Quark EDM

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PNDME, 1506.04196; 1506.06411

§ Need "disconnected" diagram contributions

- Multiple ways to calculate this notorious contribution
- Truncated solver, hopping-parameter expansion, hierar

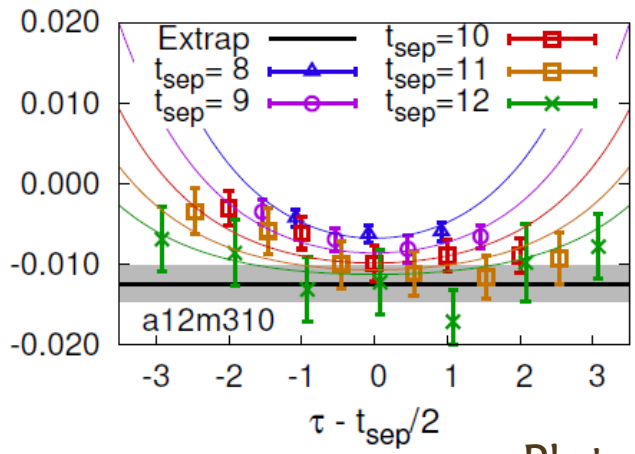
§ For lattice experts

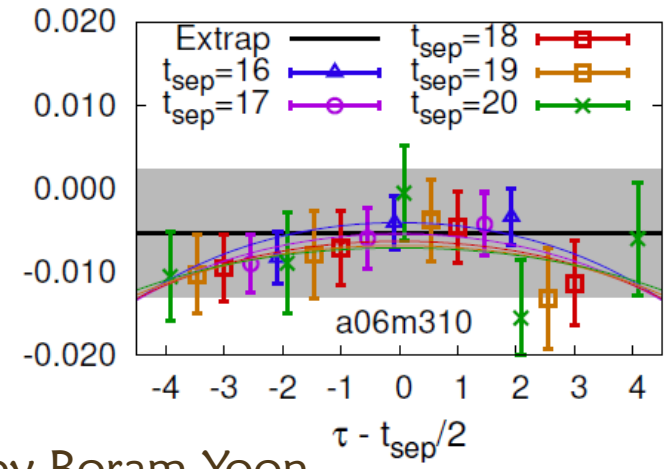
- We (PNDME) use a combined technique of stochastic source with truncated solver and hopping-parameter expansion

Quark EDM

§ Light disconnected contributions $g_T^{u,d\ \mathrm{disc}}$ small compared to $g_T^{u,d\ \mathrm{conn}}$

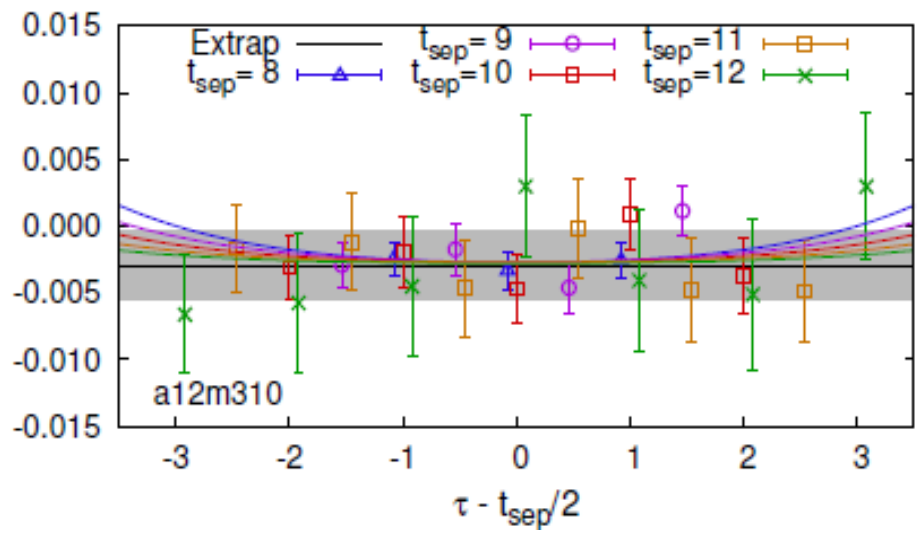
PNDME, 1506.04196; 1506.06411





Plots by Boram Yoon

§ Strange disconnected contributions are small too, but there is an m_s/m_l enhancement



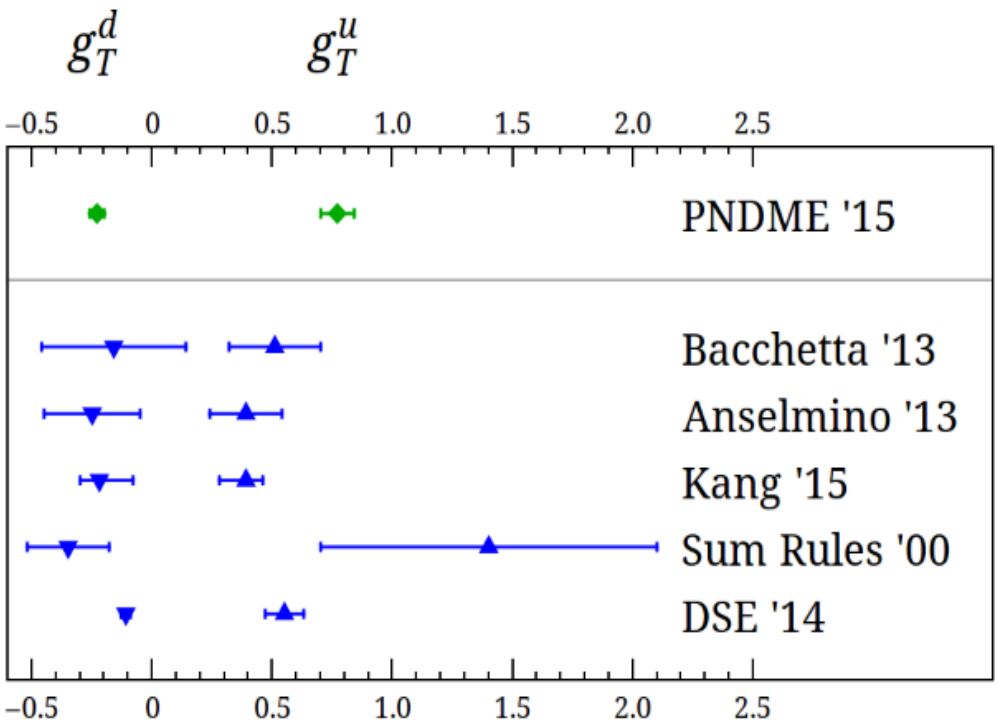
Quark EDM

§ Extrapolate to the physical limit

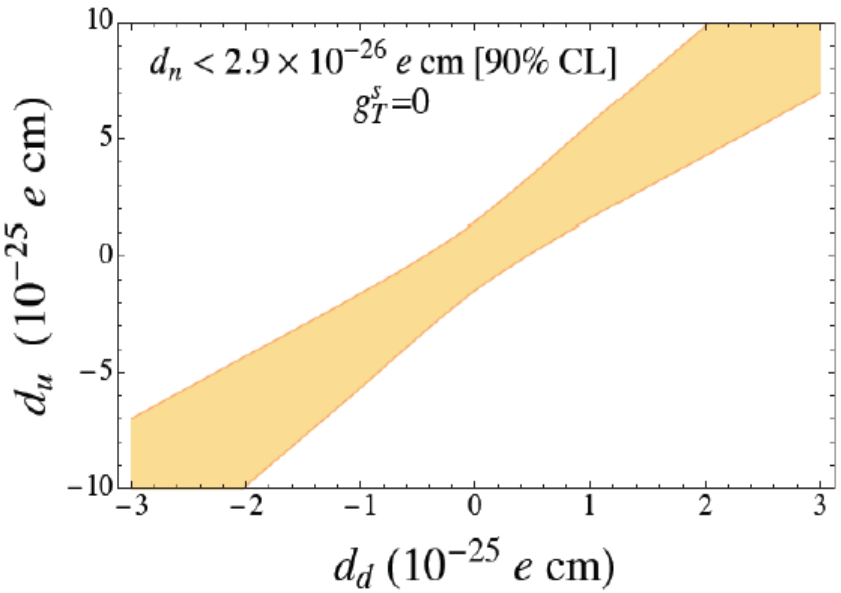
PNDME, 1506.04196; 1506.06411

$$g_T^u = 0.774(66),\ g_T^d = -0.233(28),\ g_T^s = 0.008(9)$$

§ Most reliable $g_T^{u,d}$



§ Combine with current limits to set bounds



Implications for New Physics

§ Example, split SUSY

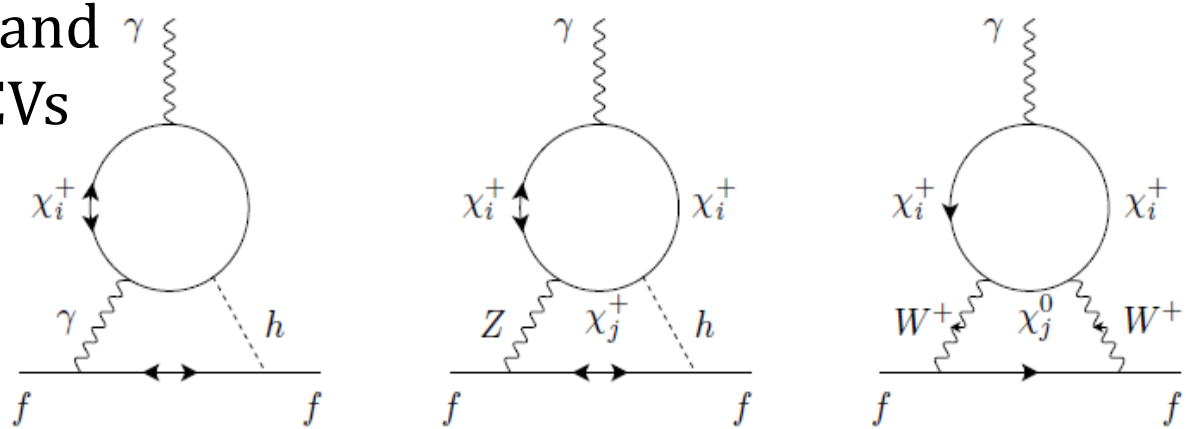
Wells, 2003;
Arkani-Hamed and Dimopoulos, 2004;
Giudice and Romanino, 2004

- All scalars heavy except for one Higgs doublet
- Useful features:
  gauge-coupling unification, dark-matter candidate, no "flavor/CP problem"

EDMs depend on:

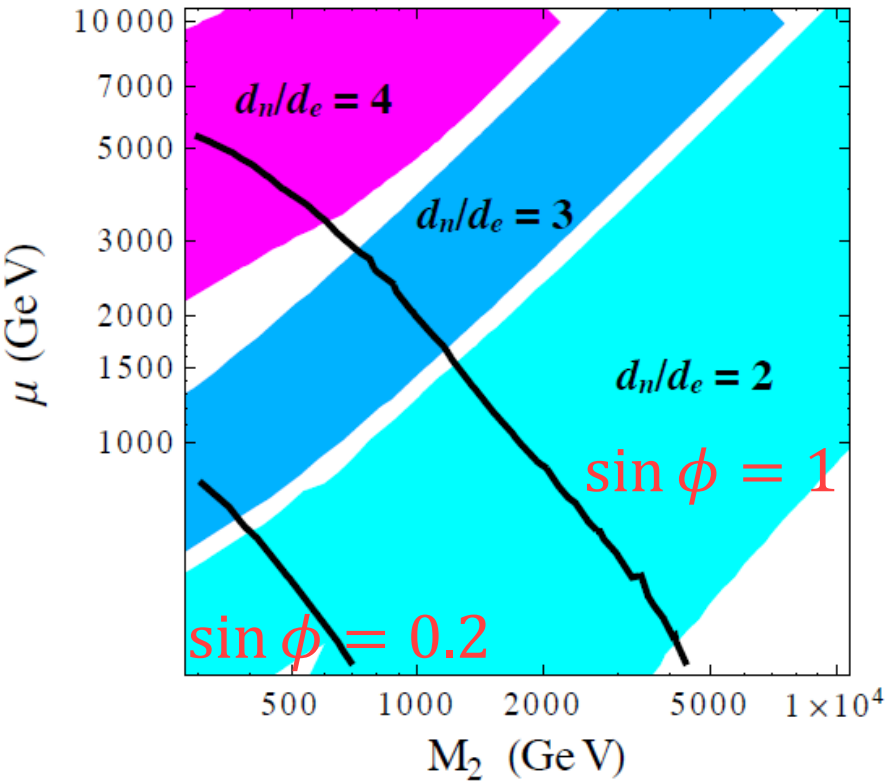
Giudice and Romanino, hep-lat/0510197

the gaugino (M_2) and Higgsino (μ) masses, their relative phase (ϕ) and the ratio of the Higgs VEVs



Implications for New Physics

§ Neutron and electron EDMs in split SUSY



ACME Coll., Science Vol. 343 no. 6168 pp. 269-272 (2014)

Take $|d_e| < 8.7 \times 10^{-29} e \cdot \mathrm{cm}$ with 90% confidence

Derive an upper limit for the neutron EDM in split SUSY

$$|d_n| < 4 \times 10^{-28} e \cdot \mathrm{cm}$$

PNDME, 1506.04196; 1506.06411

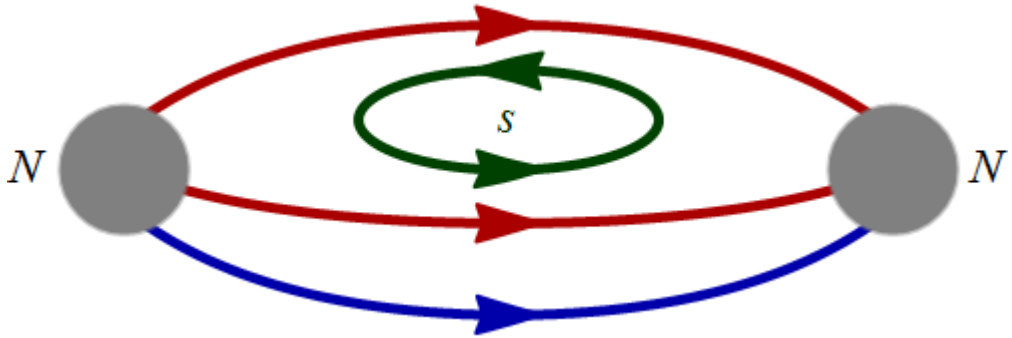
Observation of a neutron EDM between the current limit of $3 \times 10^{-26} e \cdot \mathrm{cm}$ and $4 \times 10^{-28} e \cdot \mathrm{cm}$ would falsify the split-SUSY scenario with gaugino mass unification

Inputs to Dark-Matter Cross Sections

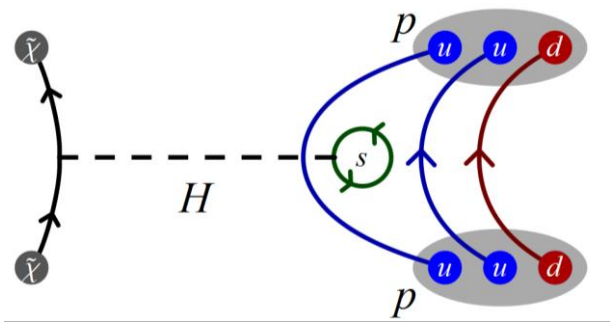
The Strange Proton

§ Strange contribution to proton scalar density/spin

- Neutralino dark matter search or flavor-violating processes
- Strange contribution has larger uncertainty



- Interactions with nucleon mediated by Higgs exchange

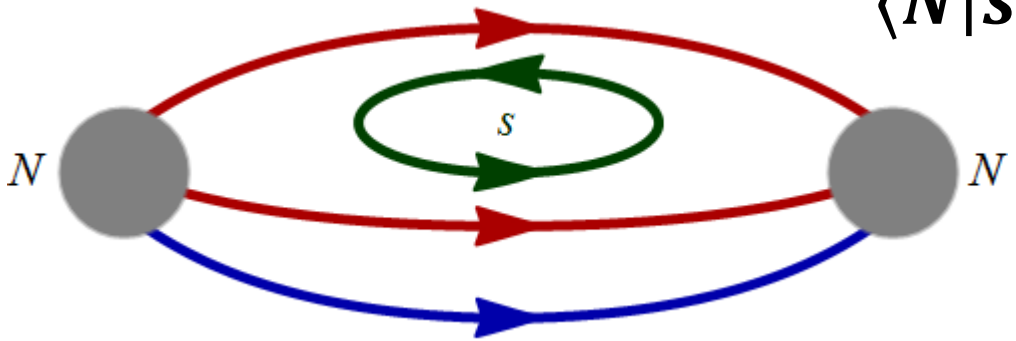


Strangeness on the Lattice

§ Direct: Compute the "disconnected" loop

- Various techniques developed to improve the signal
  JLQCD, QCDSF, BU, Engelhardt, …

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



§ Indirect: Use the Feynman-Hellman Theorem

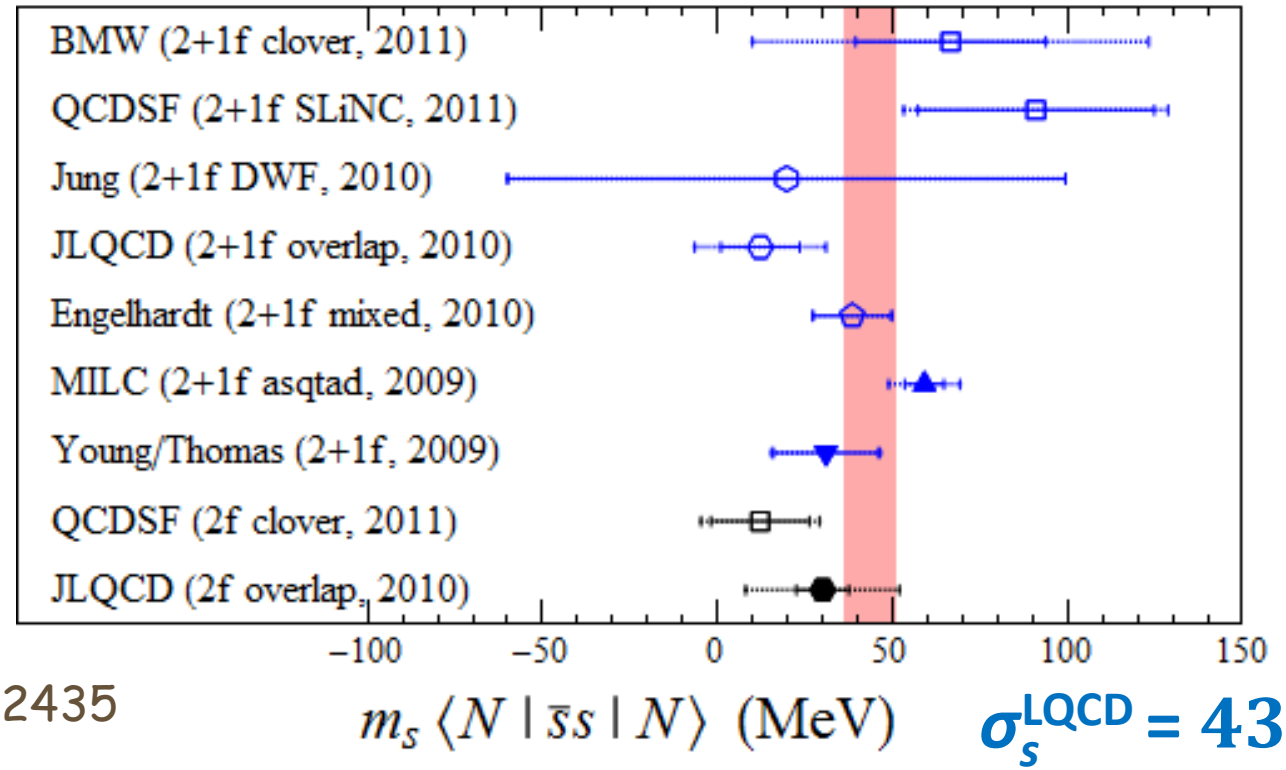
- Take numerical derivative dM_N/dm_s either by
  direct SU(3) fitting to baryon masses
  Young/Thomas 2009, …
  or reweighting strange part of action
  Jung 2010, MILC/Thomas 2009, …

The Strange Proton

§ Strange contribution to proton scalar density/spin

- Neutralino dark matter search or flavor-violating processes
- Strange contribution has larger uncertainty

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



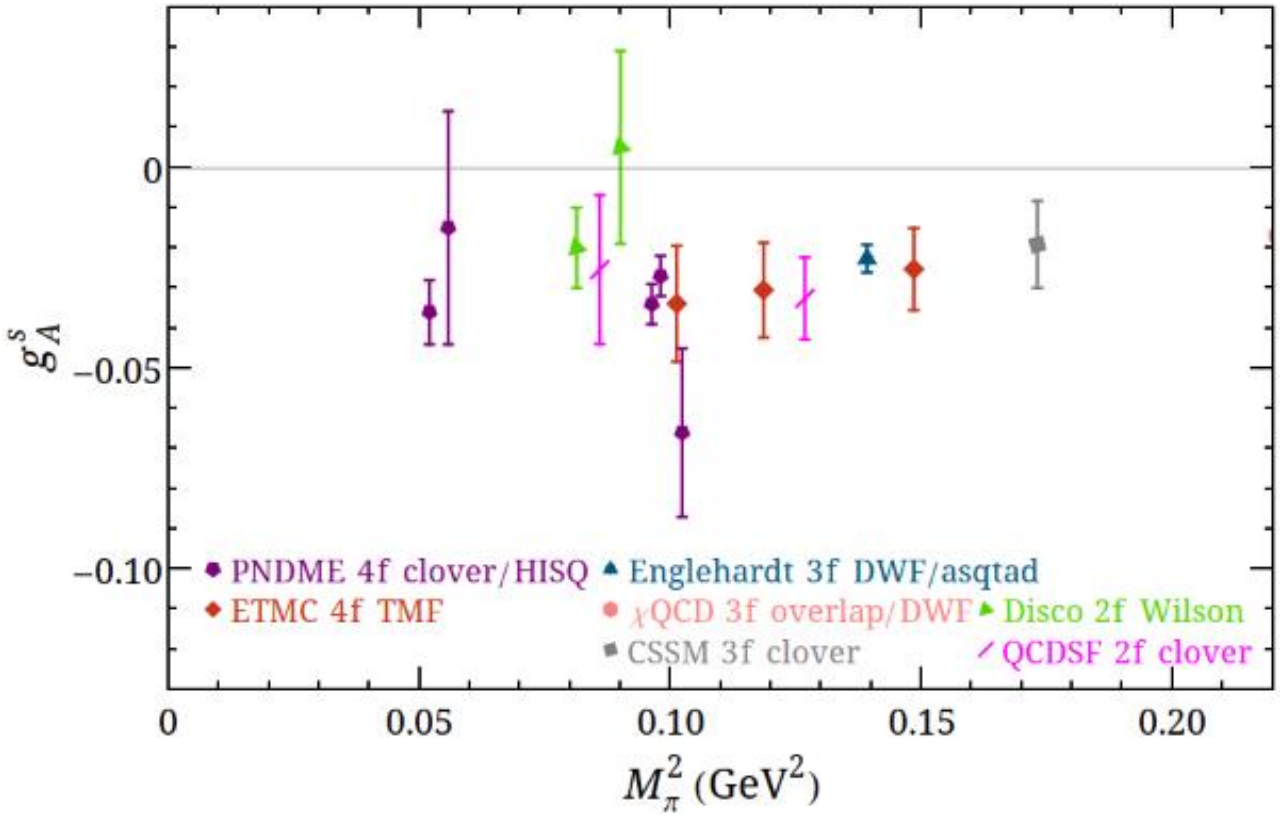
HWL, 1112.2435

$\sigma_s^{\mathrm{LQCD}} = 43(8)$ MeV

The Strange Proton

§ g_A^S still poorly known experimentally

- Good chance to have LQCD to improve the numbers



- Current LQCD data suggests about −0.04 contribution

Summary

TeV

GeV

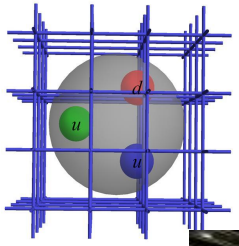
§ Exciting era using LQCD for precision SM nucleon inputs

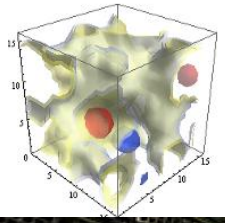
- Increased computational resources and improved algorithms
- Enable exploration of formerly impossible calculations

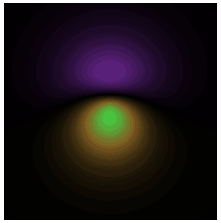
§ Precision frontier enables us to probe BSM physics

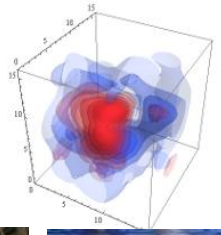
- Probes high-energy (TeV) physics at low energy (GeV)
- Combined effort from experiment and theory sides to set bounds on new-physics scenarios, constrain BSM models

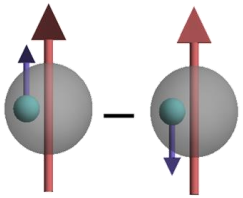
§ LQCD is necessary when experiment is less known (e.g. g_T, g_S^A) or impossible to measure (e.g. g_S)

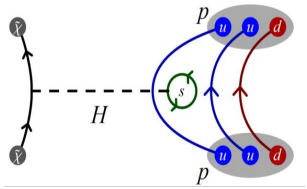


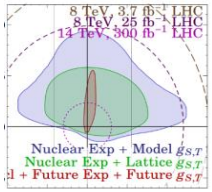










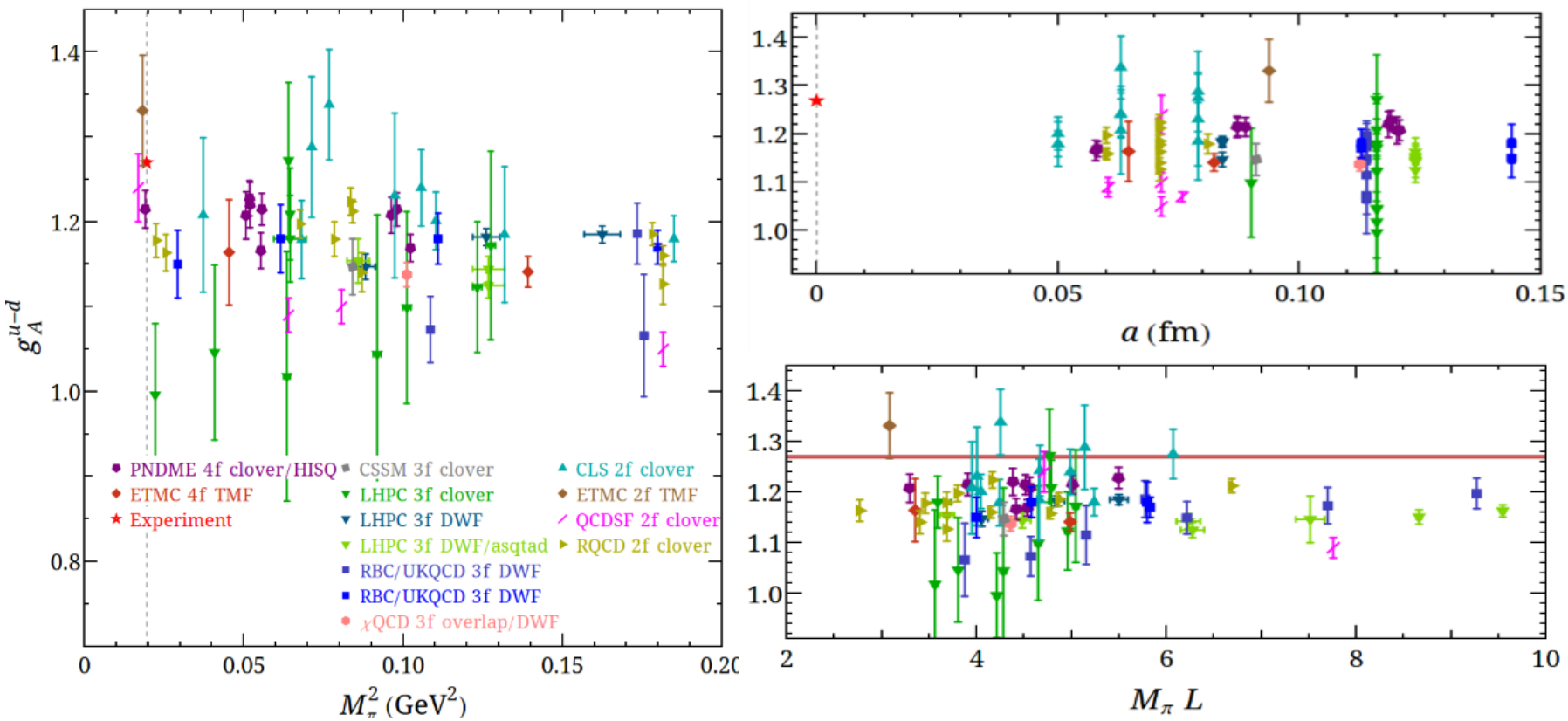


Backup Slides

Progress

§ Axial charge

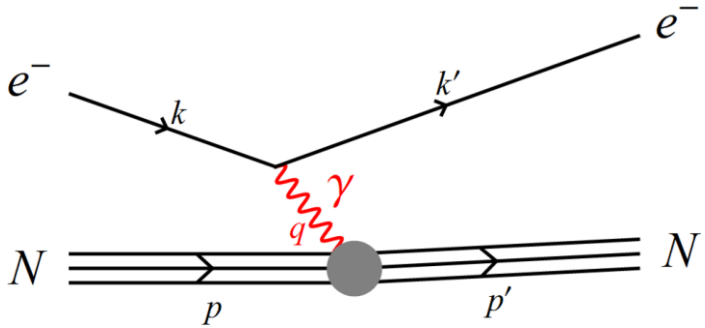
- Most well-known coupling with subpercent errors
- Important to the rate of *pp* fusion, *n*-lifetime, …
- Significant lattice systematics



Form Factors

§ Form factors

- Elastic scattering
- $F_1(Q^2), F_2(Q^2), G_A(Q^2), G_P(Q^2)$
- For example, octet baryons



$$\langle B|V_\mu|B\rangle(q) = \bar{u}_B(p')\left[\gamma_\mu F_1(q^2) + \sigma_{\mu\nu}q_\nu \frac{F_2(q^2)}{2M_B}\right]u_B(p)$$

Dirac Pauli

$$\langle B|A_\mu|B\rangle(q) = \bar{u}_B(p')\left[\gamma_\mu\gamma_5 G_A(q^2) + \gamma_5 q_\nu \frac{G_P(q^2)}{2M_B}\right]u_B(p)$$

Axial Induced Pseudoscalar

Sachs:

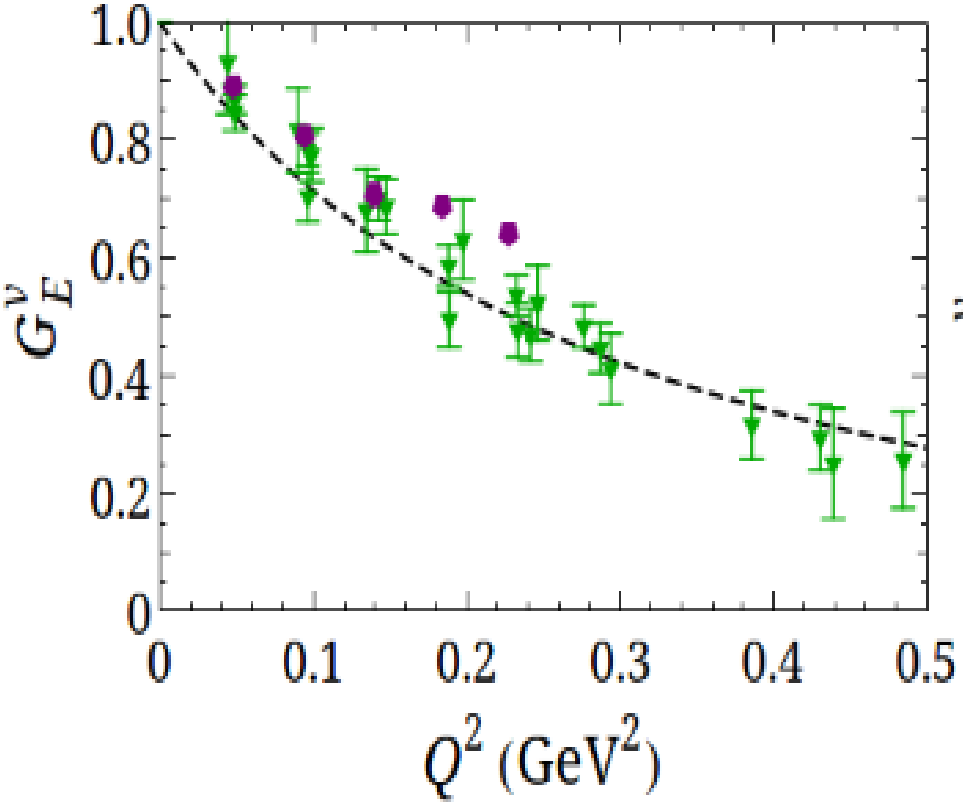
$$G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4M_B^2}F_2(Q^2),\ G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

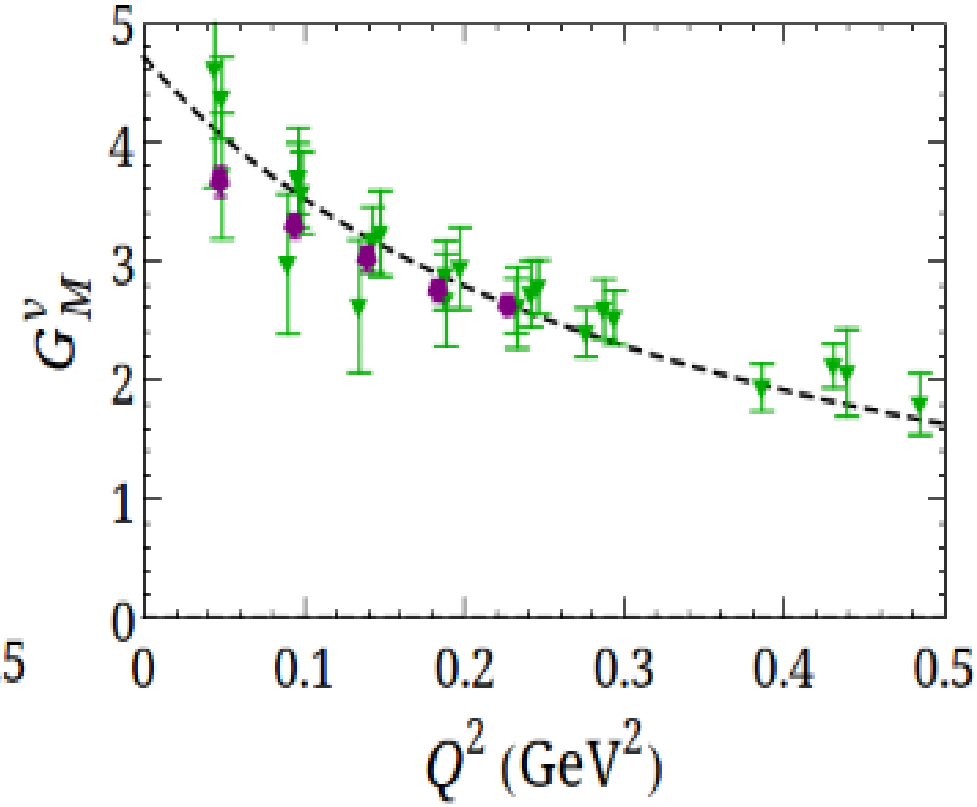
Electric Magnetic

Form Factors

§ EM form factors very close to physical pion mass

- Examples from PNDME (130 MeV) — PNDME, in preparation
  LHPC (149 MeV) — J. Green et al, 1404.4029

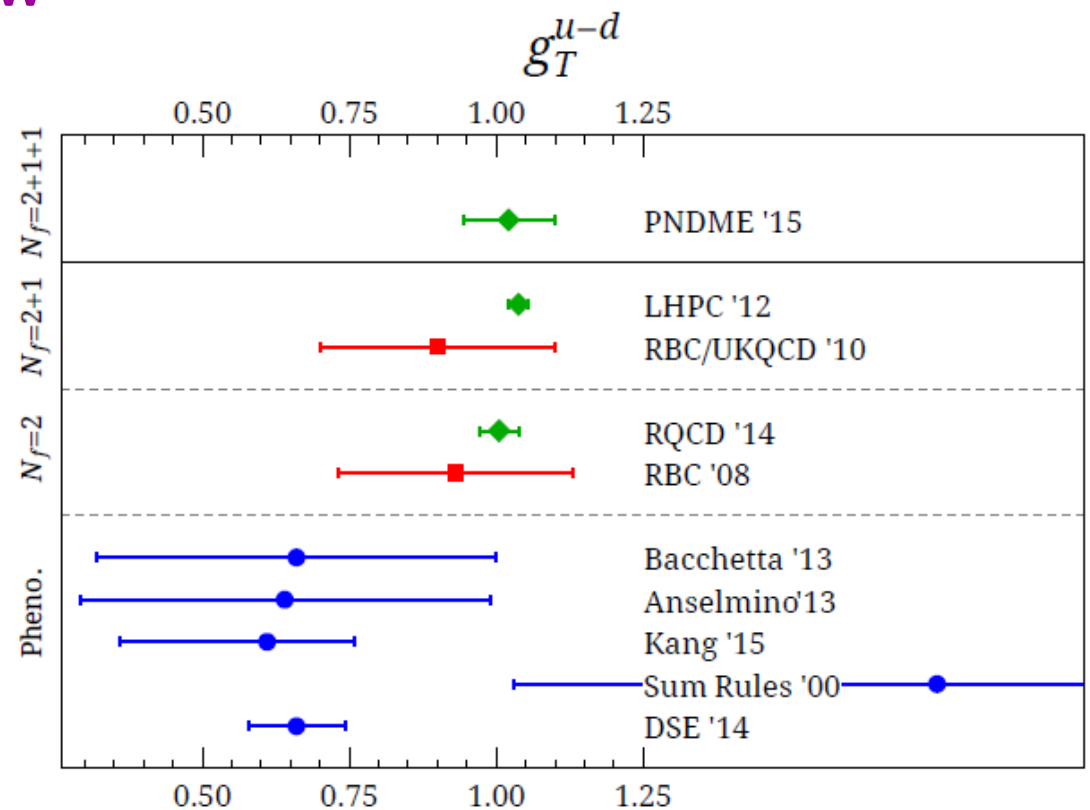




§ Expecting more precise results in the next couple years

Tensor Charge

§ Global view



- Experimentally, probed through SIDIS
  poor determination so far
- LHPC and RQCD did m_π^2 extrapolation only

nEDM

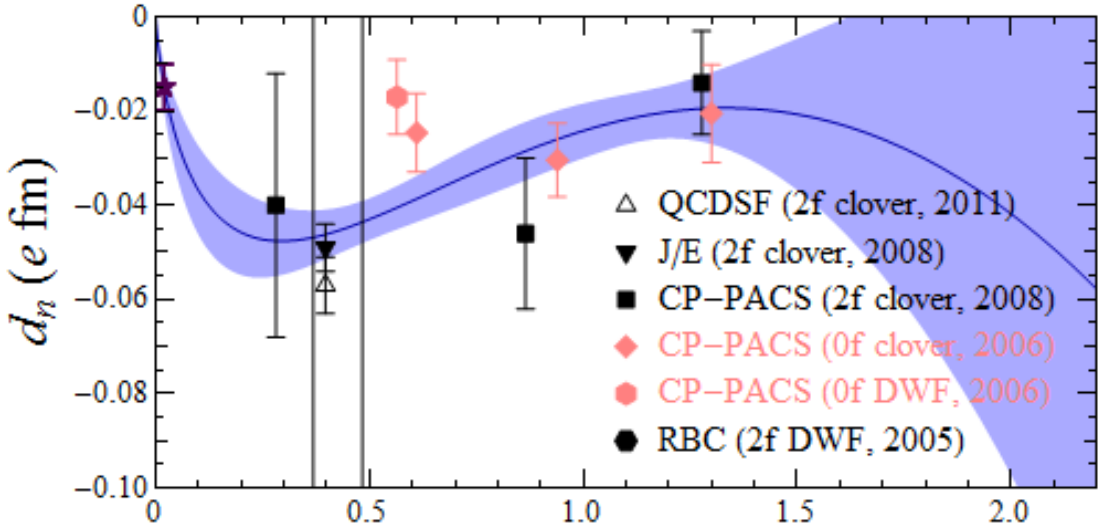
§ Lagrangian $L = L_{\mathrm{QCD}}^{CP\ \mathrm{Even}} + L_{\Theta} + \cdots$

$$i\Theta \frac{g^2}{16\pi^2} \int d^4x\, G^{\mu\nu} \tilde{G}_{\mu\nu}$$

§ Leading contribution

- Using CP-even QCD vacuum with θ-term expansion

  RBC, J/E, CP-PACS(2005), CP-PACS(2006, 2010), QCDSF(2011), …



Chiral extrapolation

K. Ottnad et al., 2010

$-0.015(5)\ \theta\ e{\cdot}\mathrm{fm}$

HWL, 1112.2435

§ Plenty of room for improvement

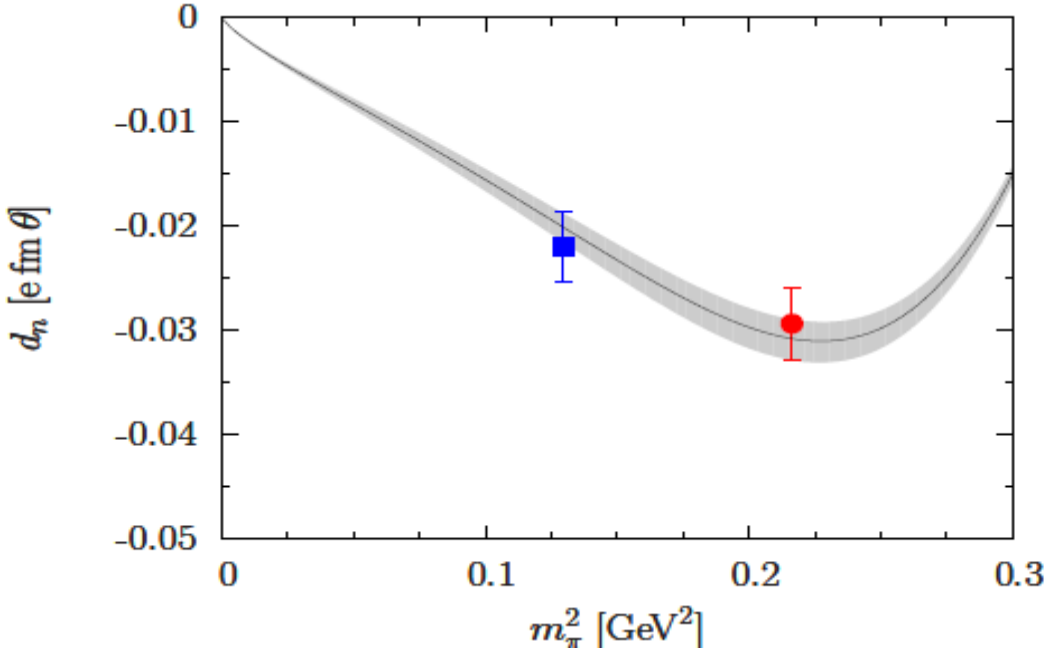
$n\mathcal{EDM}$

§ Lagrangian $L = L_{\mathrm{QCD}}^{CP\ \mathrm{Even}} + L_{\Theta} + \cdots$

$$i\Theta \frac{g^2}{16\pi^2} \int d^4x\, G^{\mu\nu} \tilde{G}_{\mu\nu}$$

§ Leading contribution

- CP-odd QCD vacuum in dynamical quarks by QCDSF
- Demonstrated concept with 3f clover at $M_\pi \approx 360$ and 465 MeV



$-0.0038(2)(9)\ \theta\ e{\cdot}\mathrm{fm}$

QCDSF 1502.02295

§ Stay-tuned for lighter pion mass results