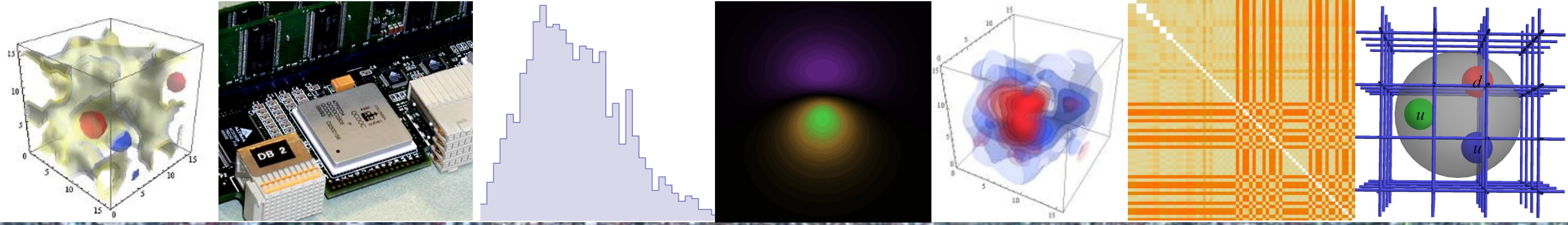


Nucleon Tensor Charges and Their Implications

Huey-Wen Lin

Outline

- Consumer's Guide to Lattice Nucleon Calculations
- Isovector Tensor Charges
  - Impacts on transversity distribution
  - BSM interactions in beta decay
- Flavor-Dependent Tensor Charges
  - nEDM applications

Lattice 101

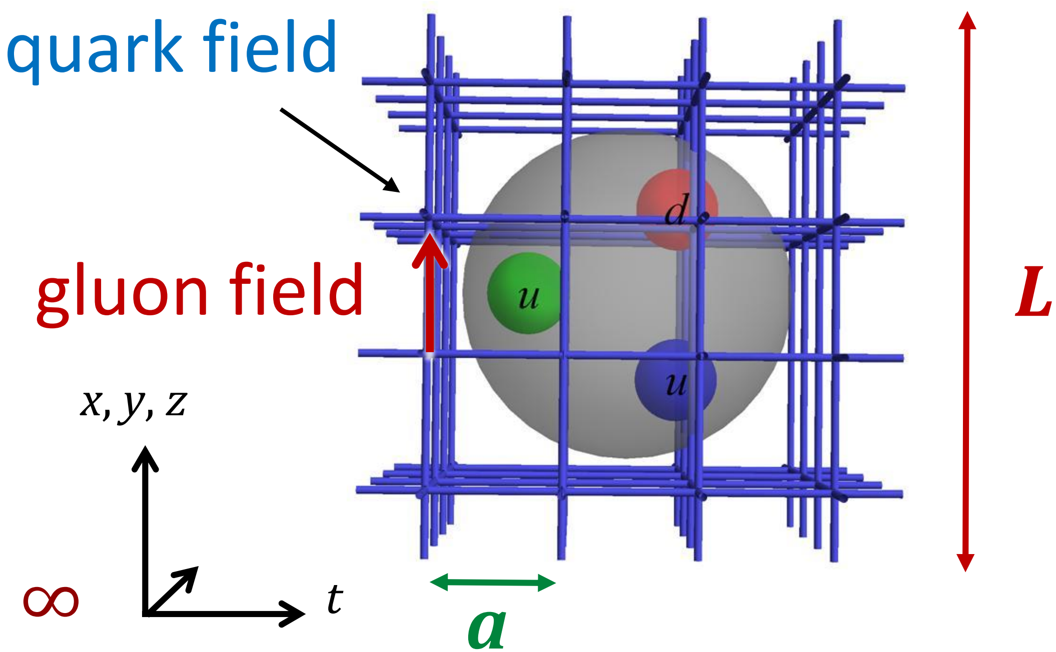
§ Lattice QCD is an ideal theoretical tool for investigating the strong-coupling regime of quantum field theories

§ Physical observables are calculated from the path integral

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

in **Euclidean** space

- Quark mass parameter (described by m_π)
- Impose a UV cutoff
  discretize spacetime
- Impose an infrared cutoff
  finite volume



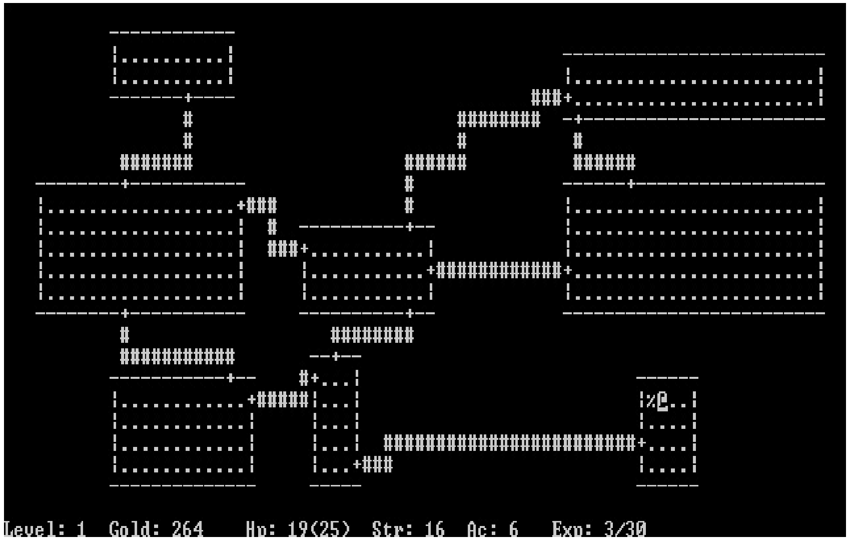
§ Recover physical limit

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

Are We There Yet?

- Lattice gauge theory was proposed in the 1970s by Wilson
  - Why haven't we solved QCD yet?
- Progress is limited by computational resources

1980s



Today

- Greatly assisted by advances in algorithms
  - Physical pion-mass ensembles are not uncommon!

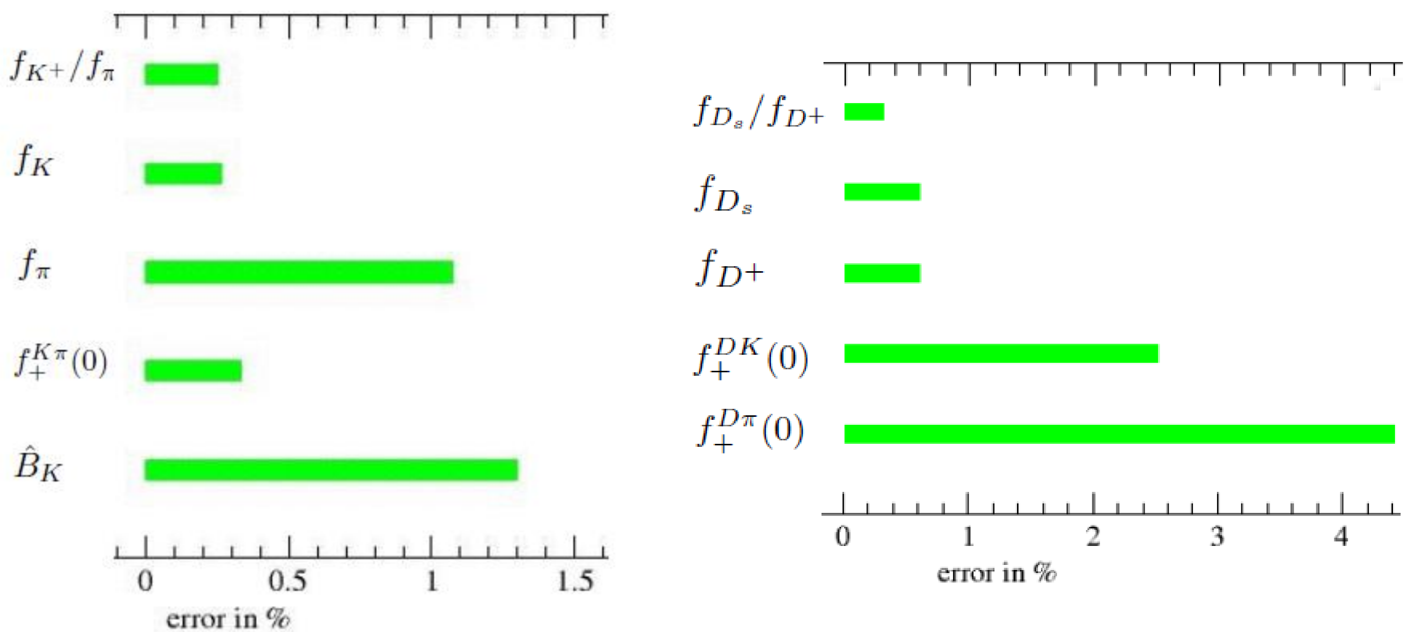
Successful Examples

§ Lattice flavor physics provides precise inputs from the SM

A. El-Khadra, Sep. 2015, INT workshop "QCD for New Physics at the Precision Frontier"

- Very precise results in many meson systems

errors (in %) (preliminary) FLAG-3 averages



§ We are beginning to do precision calculations in nucleons

The Trouble with Nucleons

Nucleons are more complicated than mesons because…

- Noise issue
  - Signal diminishes at large t_E relative to noise
  - Get worse when quark mass decreases
- Excited-state contamination
  - Nearby excited state: Roper(1440)
- Hard to extrapolate in pion mass
  - Δ resonance nearby; multiple expansions, poor convergence…
  - Less an issue in the physical pion-mass era
- Requires larger volume and higher statistics
  - Ensembles are not always generated with nucleons in mind
  - **High-statistics**: large measurement and long trajectory

The Trouble with Nucleons

Nucleons are more complicated than mesons because…

§ Noise iss

- Signal d
- Get wor

§ Excited-s

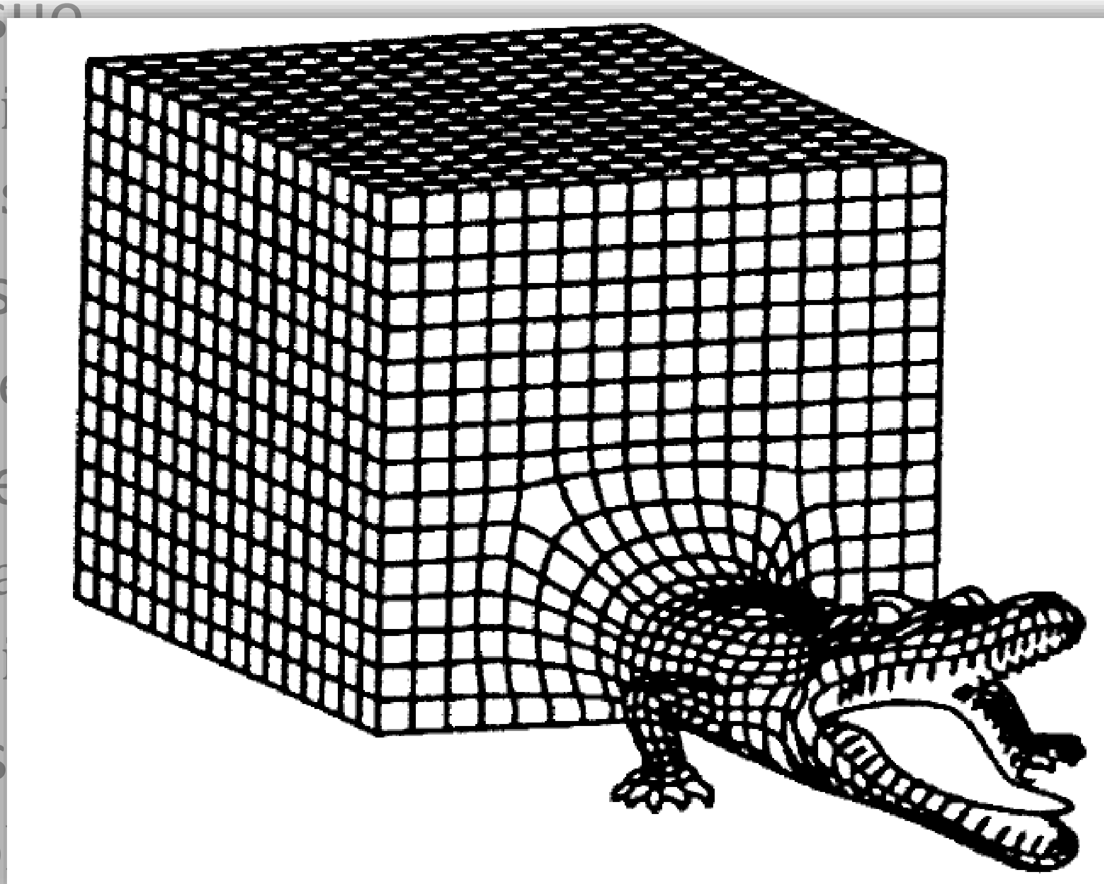
- Nearby

§ Hard to e

- Δ resona … onvergence…
- Less an

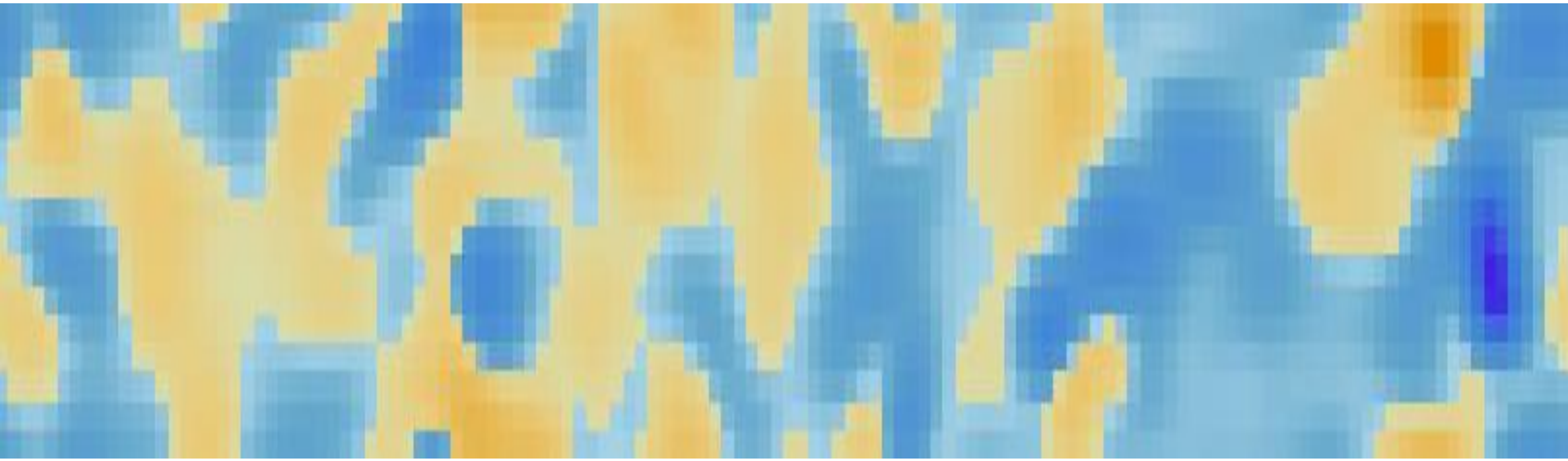
§ Requires

- Ensemb … ns in mind
- **High-s** … tory



PROCEED WITH CAUTION

Nucleon Matrix Elements

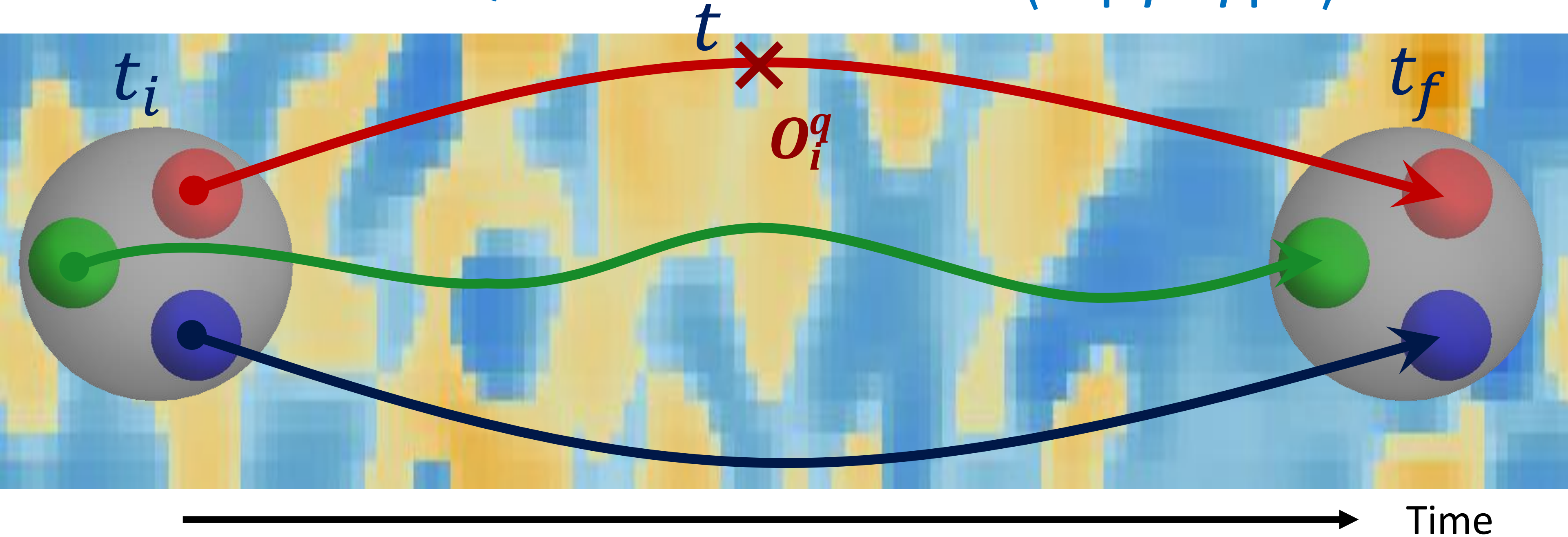


§ Pick a QCD vacuum

- Gauge/fermion actions, flavour (2, 2+1, 2+1+1), m_π, a, L, ...

Nucleon Matrix Elements

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

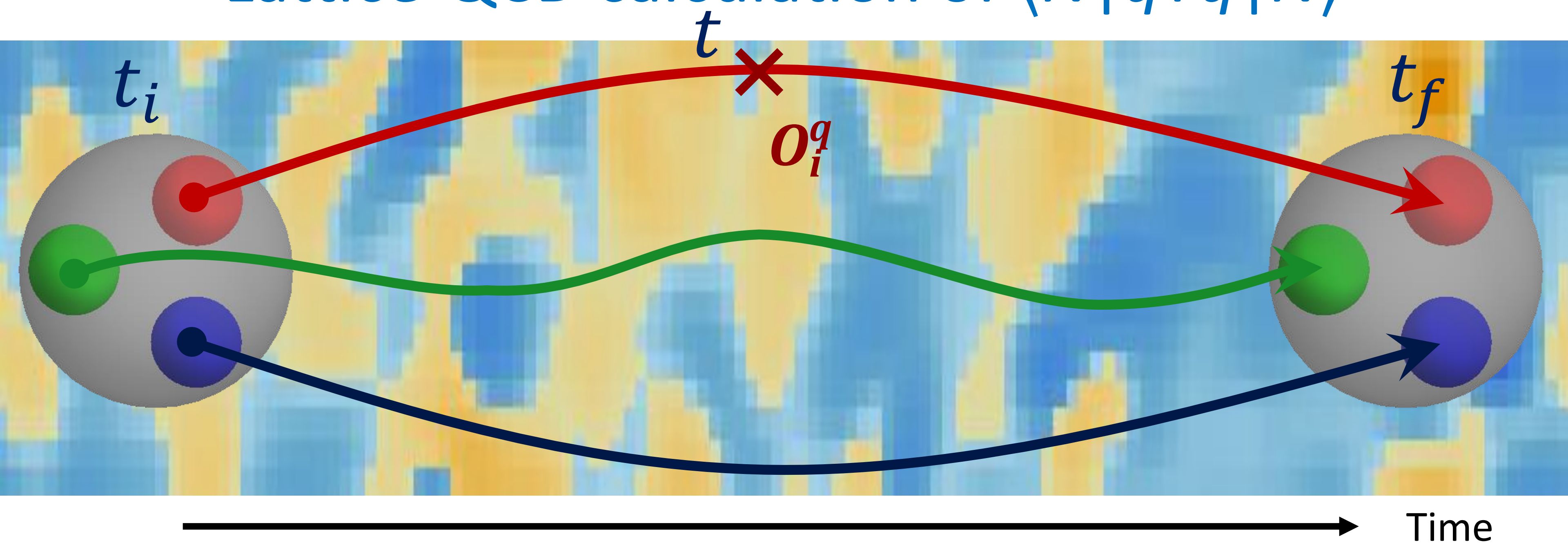


§ Construct correlators (hadronic observables)

- Requires "quark propagator"
  Invert Dirac-operator matrix (rank $O(10^{12})$)

Nucleon Matrix Elements

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



§ Analysis (extract couplings)

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

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

Analysis

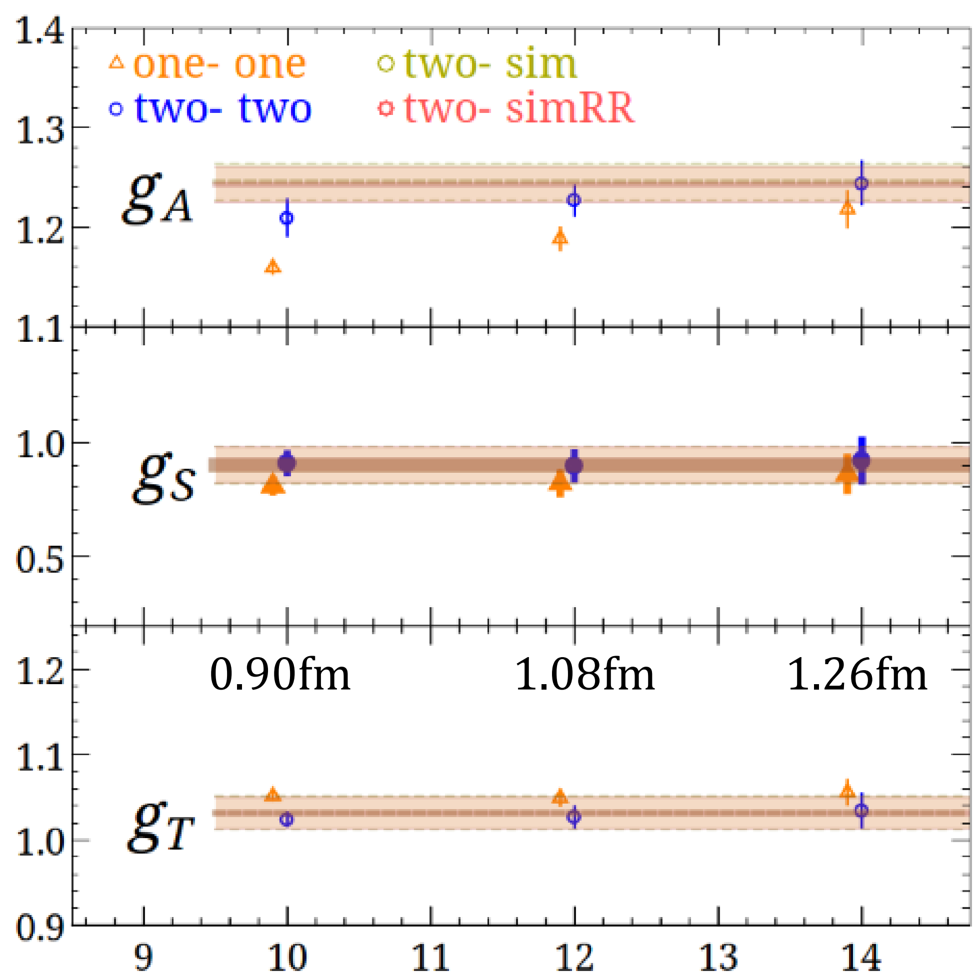
§ An example from PNDME

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

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

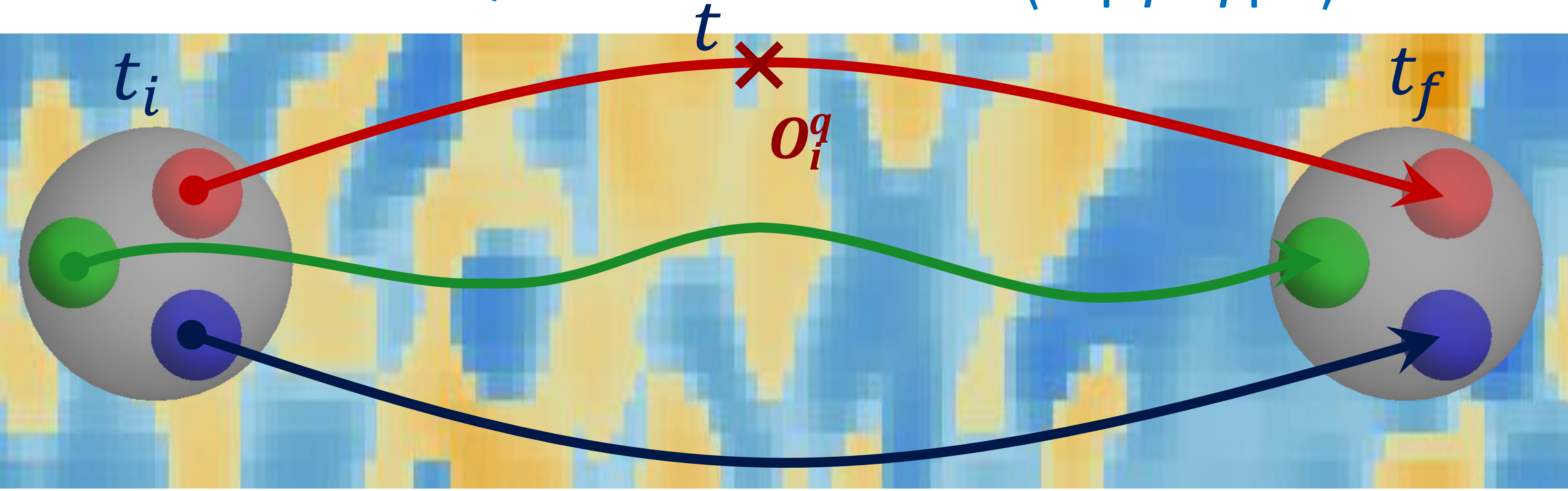
- Much stronger effect at finer lattice spacing!
- Needs to be studied case by case

$a = 0.09$ fm, 310-MeV pion



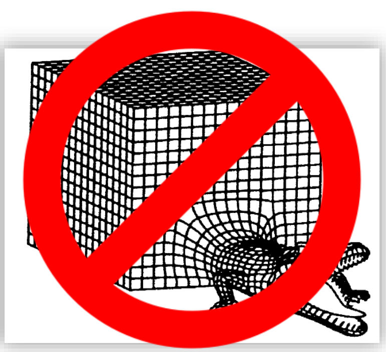
Nucleon Matrix Elements

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



§ Systematic Uncertainty (nonzero *a*, finite *L*, etc.)

- Contamination from excited states
- Nonperturbative renormalization
  e.g. RI/SMOM scheme in $\overline{\text{MS}}$ at 2 GeV
- Extrapolation to the continuum limit
  $(m_\pi \to m_\pi^{\text{phys}}, L \to \infty, a \to 0)$



Isovector Tensor Charge

PNDME

Precision Neutron-Decay Matrix Elements (2010-)

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

Tanmoy Bhattacharya

Rajan Gupta

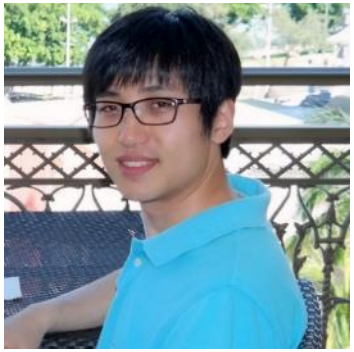
HWL

+ Vincenzo Cirigliano

Saul Cohen

Anosh Joseph

Yong-Chull Jang



Boram Yoon

Precision Nucleon Couplings

- Much effort has been devoted to controlling systematics
- A state-of-the art calculation (PNDME): **2016**

a (fm)	V	$M_\pi L$	M_π (MeV)	t_{sep}	# Meas.
0.12	$24^3 \times 64$	4.55	310	8,10,12	64.8k
0.12	$24^3 \times 64$	3.29	220	8,10,12	24k
0.12	$32^3 \times 64$	4.38	220	8,10,12	7.6k
0.12	$40^3 \times 64$	5.49	220	8,10,12,14	64.6k
0.09	$32^3 \times 96$	4.51	310	10,12,14	7.0k
0.09	$48^3 \times 96$	4.79	220	10,12,14	7.1k
0.09	$64^3 \times 96$	3.90	130	10,12,14	56.5k
0.06	$48^3 \times 144$	4.52	310	16,20,22,24	64.0k
0.06	$64^3 \times 144$	4.41	220	16,20,22,24	41.6k
We thank MILC collaboration for sharing their 2+1+1 HISQ lattices					

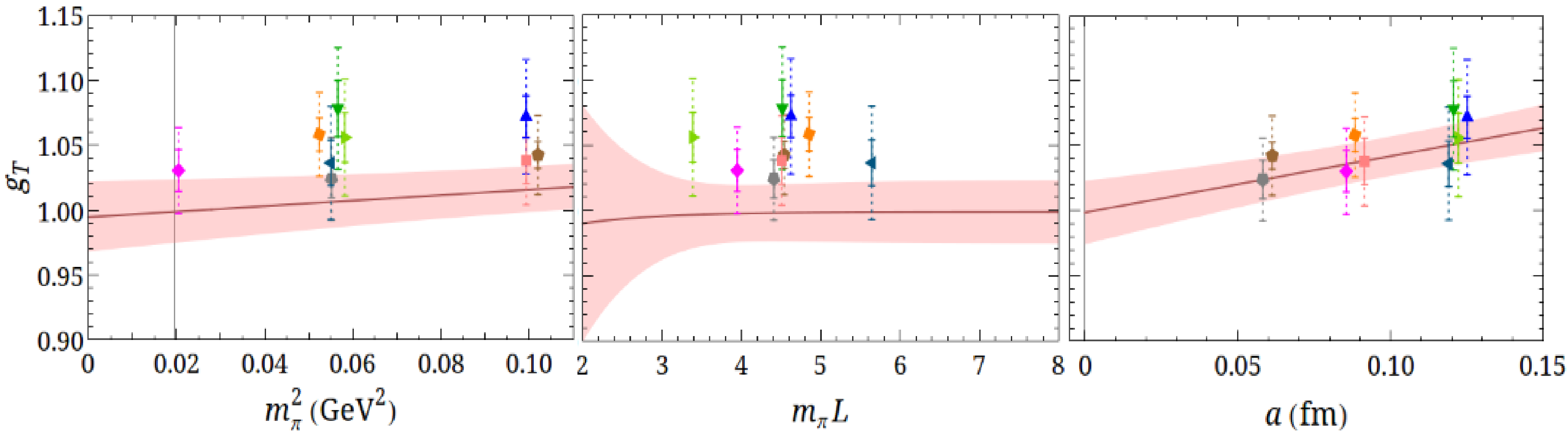
Precision Nucleon Couplings

§ A state-of-the art calculation (PNDME)

- Extrapolate to the **continuum** limit ($m_\pi \to m_\pi^{\rm phys}$, $L \to \infty$, $a \to 0$)

PNDME, 1606.07049

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



2016: First extrapolation to the physical limit of a nucleon matrix element!

Precision Nucleon Couplings

§ **2018**: 4 lattice spacings, 2 physical pion mass, $M_\pi \leq 320$ MeV

a (fm)	V	$M_\pi L$	M_π (MeV)	t_{sep}	# Meas.
0.15	**$16^3 \times 48$**	**3.93**	**310**	5,6,7,8,9	122.7K
0.12	$24^3 \times 64$	4.55	310	8,10,12	64.8k
0.12	$24^3 \times 64$	3.29	220	8,10,12	60.5K
0.12	$32^3 \times 64$	4.38	220	8,10,12	47.6K
0.12	$40^3 \times 64$	5.49	220	8,10,12,14	128.6K
0.09	$32^3 \times 96$	4.51	310	10,12,14	114.9K
0.09	$48^3 \times 96$	4.79	220	10,12,14	123.4K
0.09	$64^3 \times 96$	3.90	130	8,10,12,14,16	165.1K
0.06	$48^3 \times 144$	4.52	310	18,20,22,24	64.0K
0.06	$64^3 \times 144$	4.41	220	18,20,22,24	41.6K
0.06	**$96^3 \times 192$**	**3.80**	**130**	16,18,20,22	43.2K

Precision Nucleon Couplings

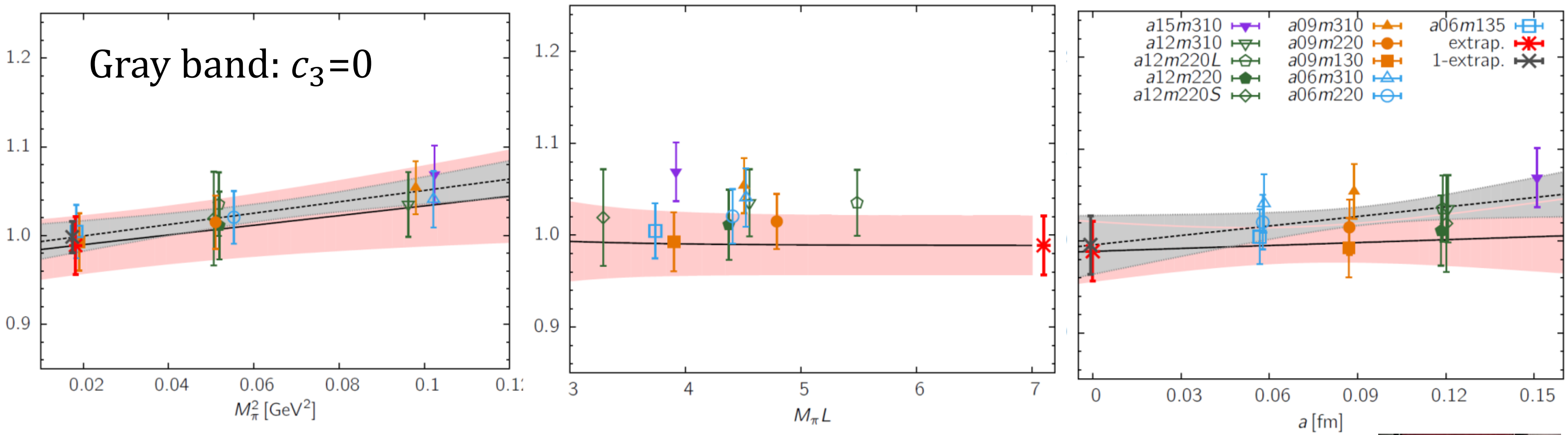
§ Much effort has been devoted to controlling systematics

§ A state-of-the art calculation (PNDME)

PNDME, 1806. 09006

- Extrapolate to the physical limit (varying ansatz)

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



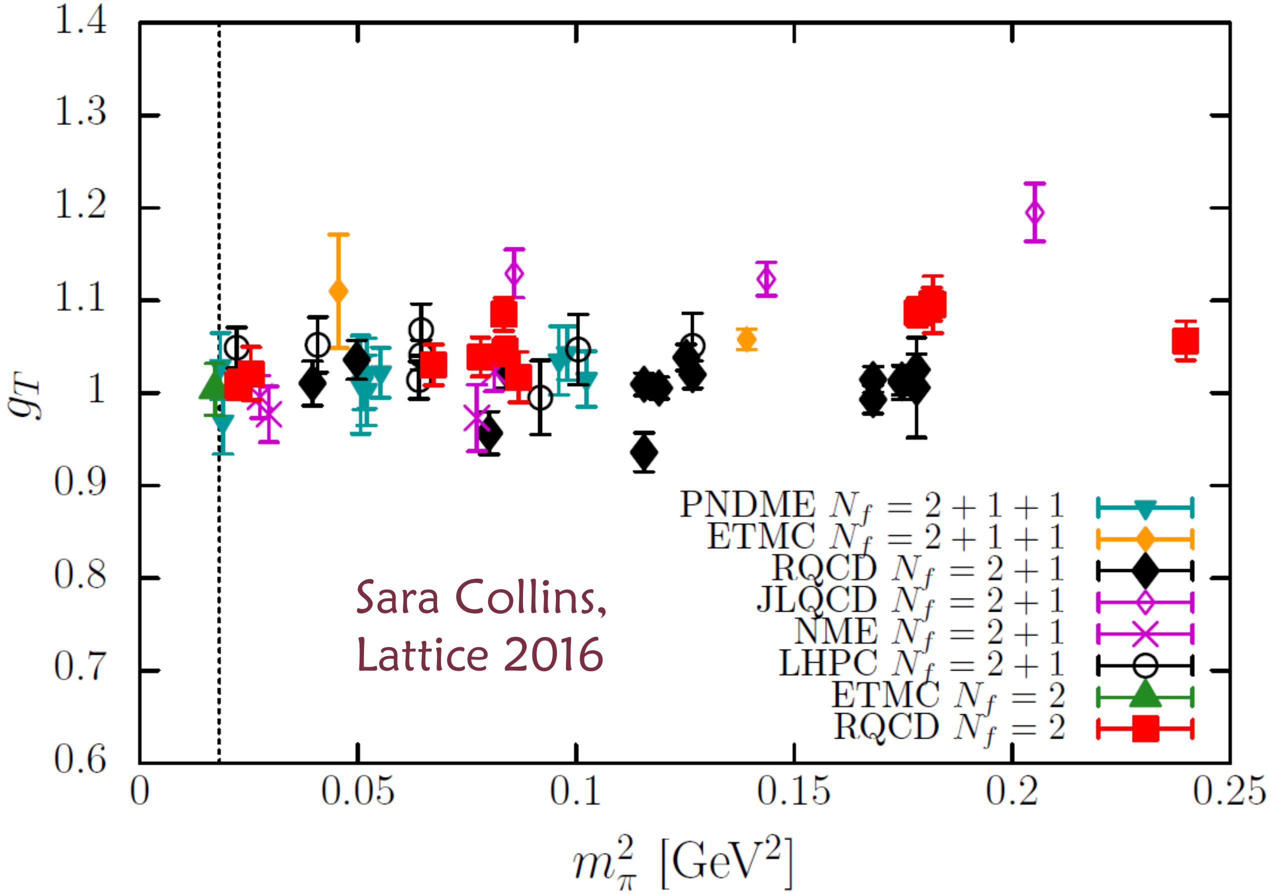
2018: Still the only collaboration that has a full continuum-extrapolated g_T

Yong-Chull Jang

Precision Nucleon Couplings

§ Usually more than one LQCD calculation

- For example, tensor charge
- Lattice results should agree in the continuum limit



Jeremy Green,
Lattice 2018

Precision Nucleon Couplings

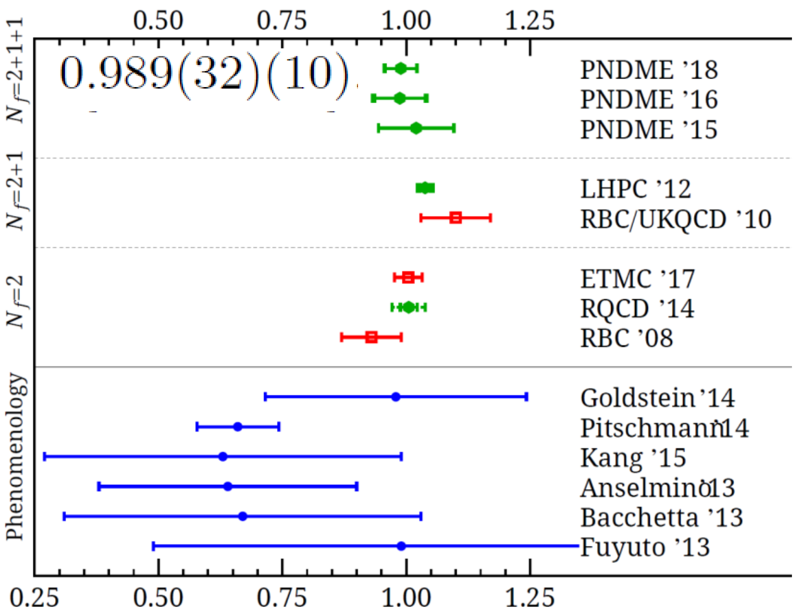
FLAG rating system

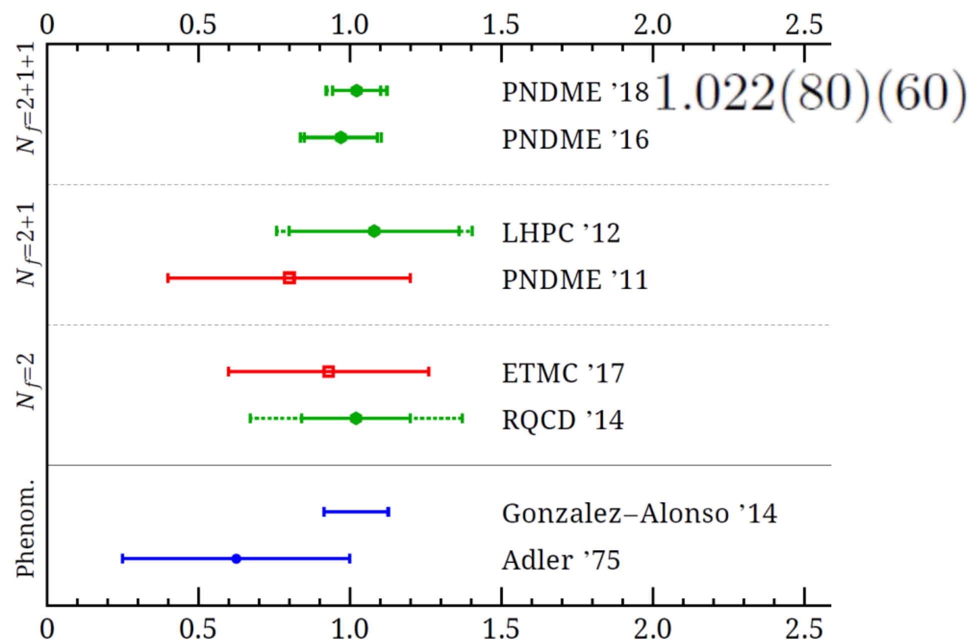
PNDME, 1506.06411; 1606.07049

New: excited-state rating

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]

PNDME, 1806.09006





Precision Nucleon Couplings

FLAG rating system PNDME, 1506.06411; 1606.07049

New: ex

FLAG nucleon matrix elements

Sara Collins, Trento workshop of
Mapping PDF and DA

Nucleon matrix element working group:

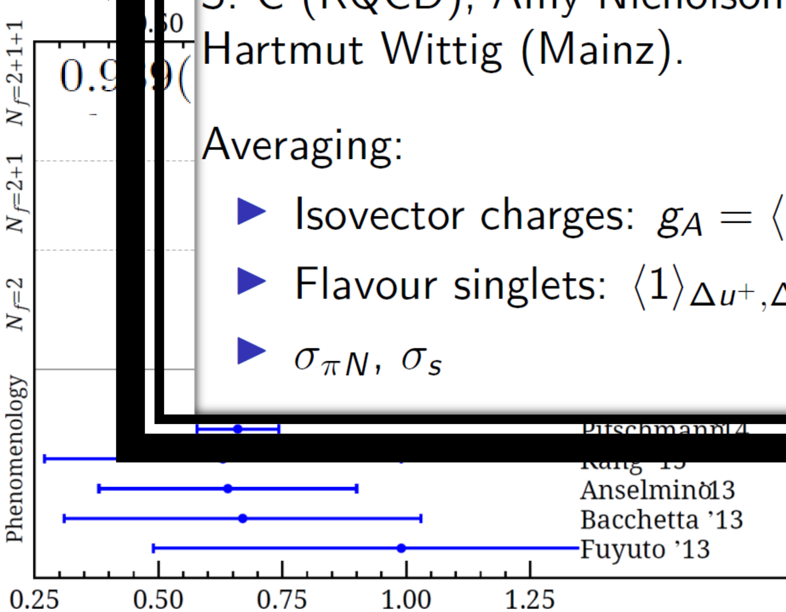
S. C (RQCD), Amy Nicholson (CalLat), Rajan Gupta (PNDME), Hartmut Wittig (Mainz).

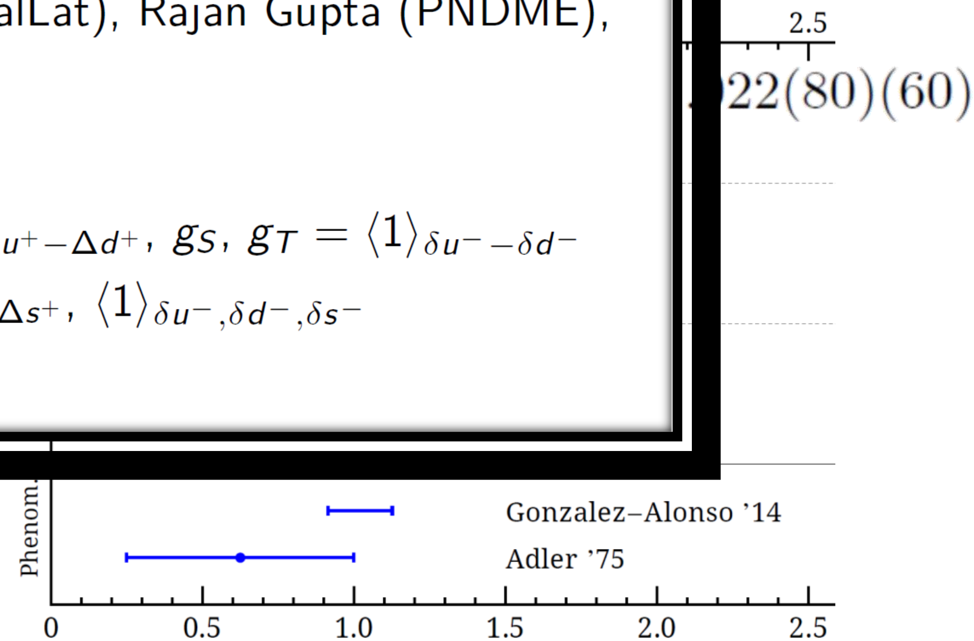
Averaging:

- Isovector charges: $g_A = \langle 1 \rangle_{\Delta u^+ - \Delta d^+}$, g_S, $g_T = \langle 1 \rangle_{\delta u^- - \delta d^-}$
- Flavour singlets: $\langle 1 \rangle_{\Delta u^+, \Delta d^+, \Delta s^+}$, $\langle 1 \rangle_{\delta u^-, \delta d^-, \delta s^-}$
- $\sigma_{\pi N}$, σ_s

Collab		
PNDME 15		020(76)[a]
ETM 13		1(3)[b]
LHPC		037(20)[c]
RBC/ KQ		0(7)[d]
RQCD 14		005(17)(29))[e]
ETM 13		14(46)[f]
RBC		3(6)[g]

PNDME, 80

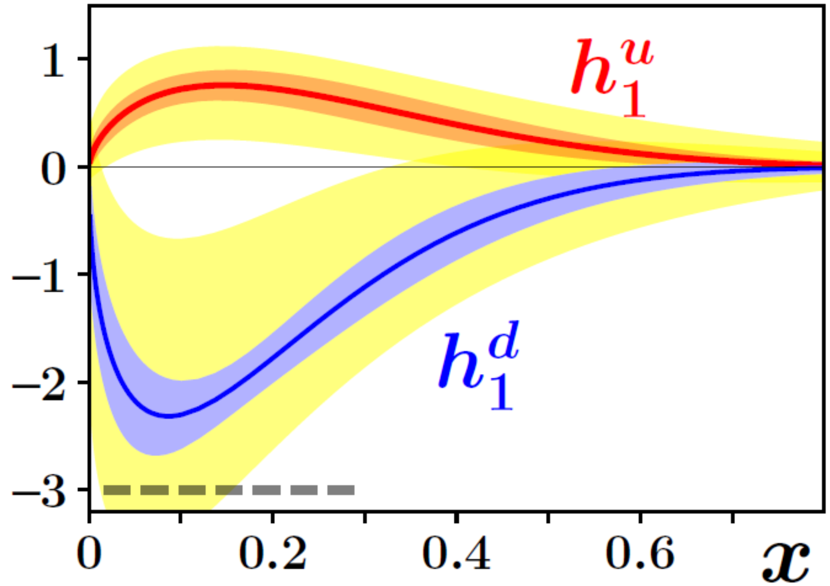


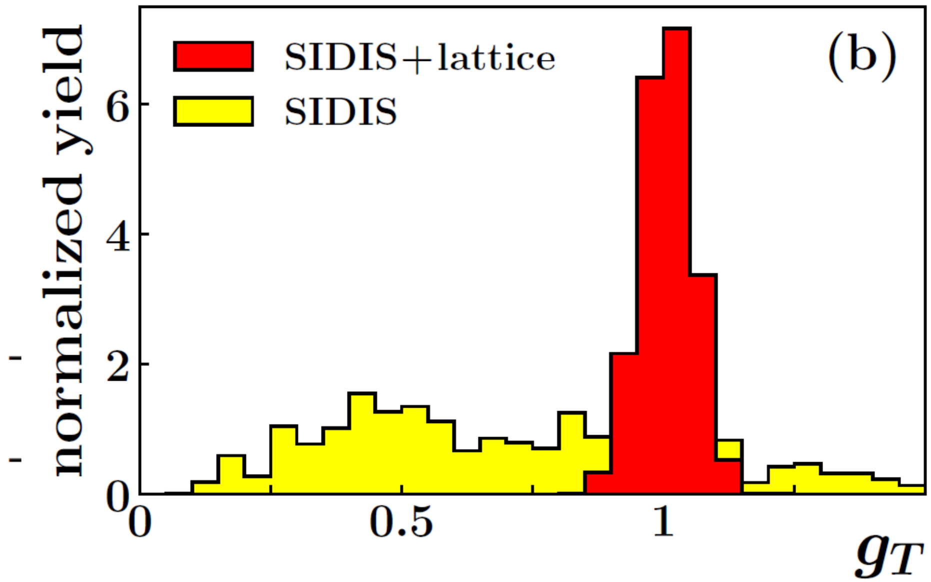


From Charges to PDFs

§ Improved transversity distribution with LQCD g_T

- Global analysis with 12 extrapolation forms: $g_T = 1.006(58)$
- Use to constrain the global analysis fits to SIDIS $\pi^{\pm}$ production data from proton and deuteron targets





Lin, Melnitchouk, Prokudin, Sato, 1710.09858, Phys. Rev. Lett. 120, 152502 (2018)

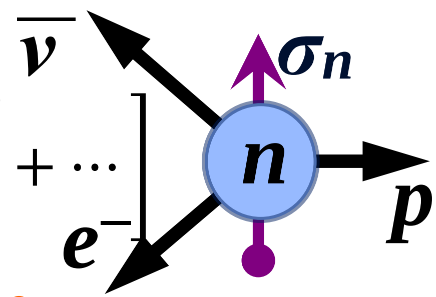
New Interactions

§ 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
- Parameters sensitive to new physics

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



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

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

$$\{b, B\}_{\text{BSM}} = f_O(\varepsilon_{S,T}\, g_{S,T})$$

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

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

New Interactions

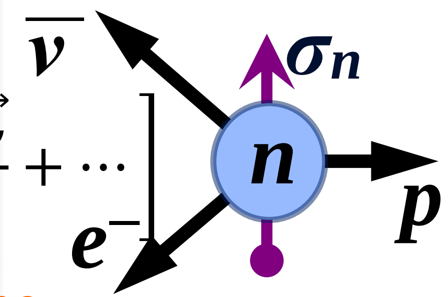
§ Neutron beta decay could be related to new interactions:

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

- ε_S and ε_T are related to the masses of the new TeV-scale particles
- Paramete

$d\Gamma \propto F(E_e)$ ... $+\cdots$

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} to 10^{-4}



Fierz inter

Deviations f

leading-ord

he

arameter

$\{b,B\}_{\text{BSM}} = f(\varepsilon_{S,T}\, g_{S,T})$

Precision LQCD input

(m_π≈140 MeV, a→0)

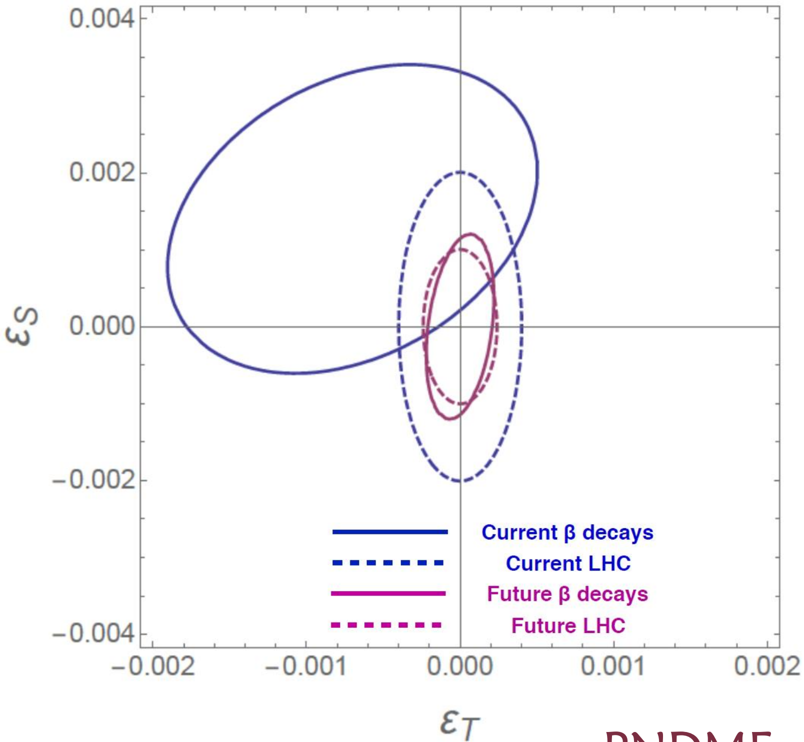
$$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$$

Beta Decays & BSM

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

Low-Energy Expt → $O_{\text{BSM}} = f_O(\varepsilon_{S,T}\, g_{S,T})$ ← Precision LQCD input ($m_\pi \to 140$ MeV, $a \to 0$)

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



Upcoming precision low-energy experiments

LANL/ ORNL UCN neutron decay exp't

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

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

CENPA: $^6\text{He}(b_{\text{GT}})$ at 10^{-3}

Also see talk by A. Garcia, E. Mereghetti

Plots by Vincenzo Cirigliano

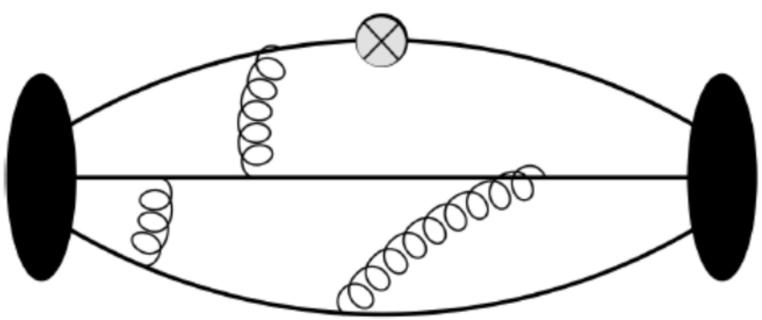
PNDME, PRD85 054512 (2012); 1306.5435; 1606.07049; 1806.09006

Flavor-Dependent Tensor Charges

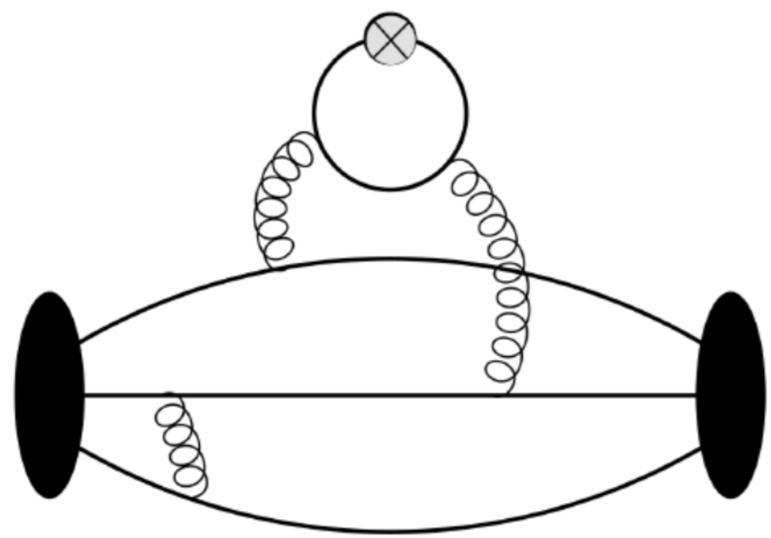
Flavor-Dependent Quark Spin

§ New type of diagram is needed: “disconnected”

- Historically, notoriously noisy to calculate on the lattice
- Recent developments offer new methods and increasing computational resources
  - Truncated solver, hopping-parameter expansion, hierarchical probing, …

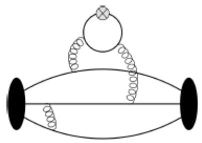


Connected



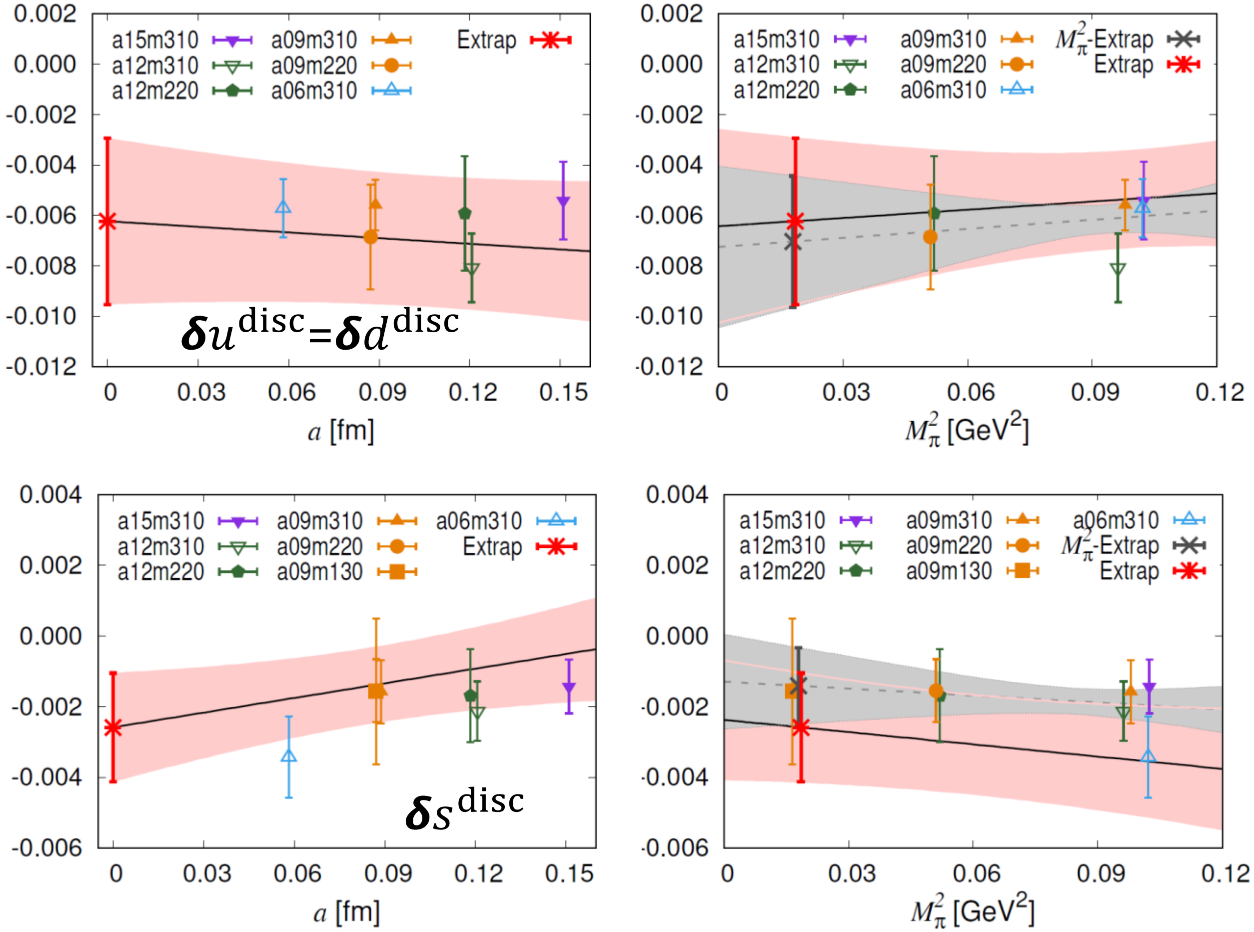
Disconnected

§ Up and down quark "disconnected" contribution



PNDME, 1806.09006, 1808.07597

$$\boldsymbol{\delta}\, q^{\text{disc}} = c_1 + c_2 m_\pi^2 + c_3 a + c_4 e^{-m_\pi L}$$



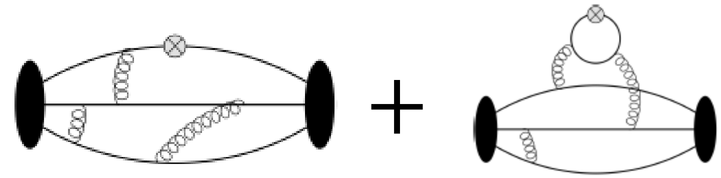
First time in LQCD

Mild dependence on a and pion mass!

Yong-Chull Jang

Quark Contribution

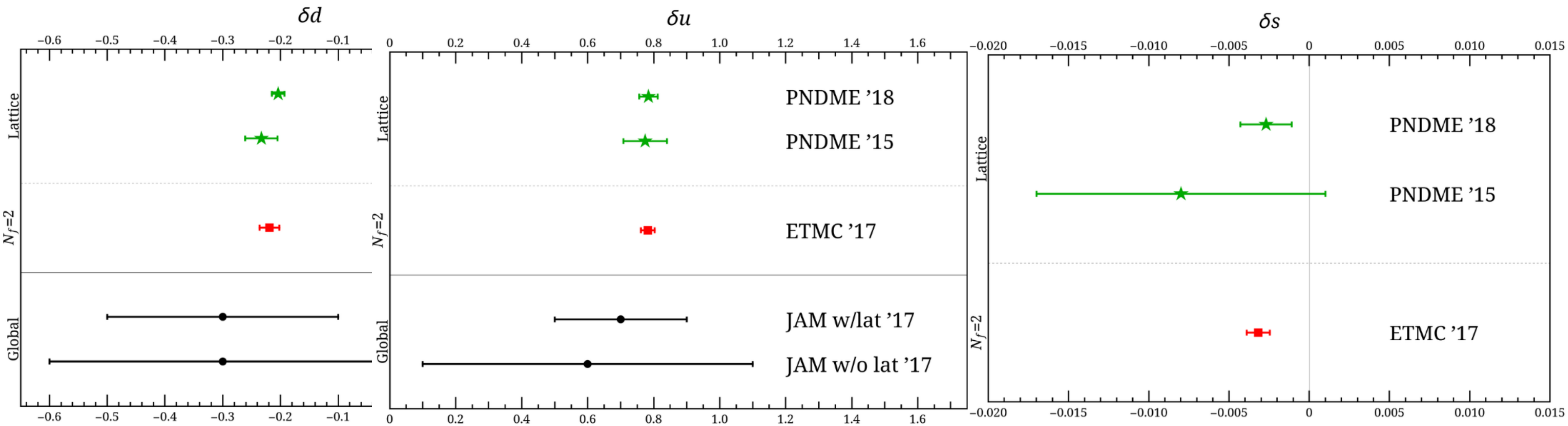
§ Sum up both contributions



	g_T^u	g_T^d	g_T^s
Connected	0.790(27)	−0.198(10)	
Disconnected	−0.0064(33)	−0.0064(33)	−0.0027(16)
PDNME'18 (Sum)	0.784(28)	−0.204(11)	−0.0027(16)
ETMC'17 [14]	0.782(21)	−0.219(17)	−0.00319(72)
PNDME'15 [5]	0.774(66)	−0.233(28)	0.008(9)

Calculation from one lattice ensemble only
No cont. extrapolation errors

PNDME, 1806.09006, 1808.07597



Proton tensor charges from a Poincaré-covariant Faddeev equation

Qing-Wu Wang,[1] Si-Xue Qin,[2,*] Craig D. Roberts,[3] and Sebastian M. Schmidt[4]

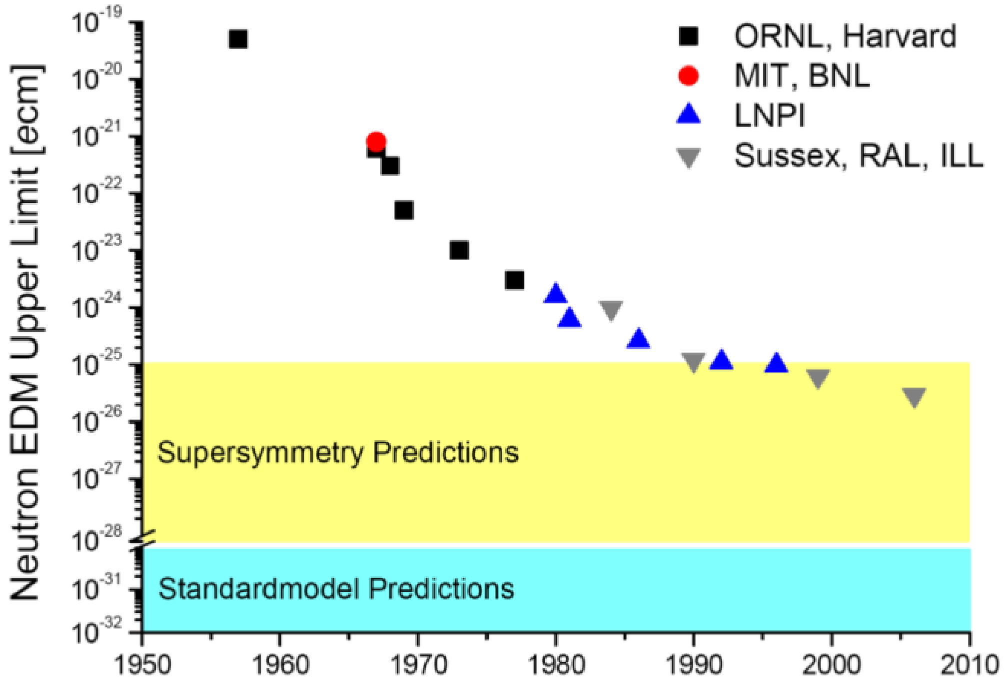
1806.01287

$$\delta_T u = 0.912^{(42)}_{(47)}, \quad \delta_T d = -0.218^{(4)}_{(5)}$$

Electric Dipole Moment

§ Why do we care?

- 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



nEDM

- Lattice community are working on various contributions
- Lagrangian $L = L_{\text{QCD}}^{CP\text{ Even}} + L_{\Theta} + L_{\text{quark}}^{\text{dim}-5} + L_{\text{chromo}-\text{quark}}^{\text{dim}-5} + \cdots$

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

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

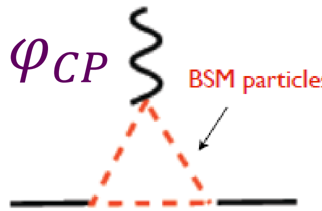
RBC, J/E, CP-PACS(2005), CP-PACS(2006, 2010), QCDSF(2011), …

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

Electric Dipole Moment

§ 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: $\langle N|\bar{q}\sigma_{\mu\nu}q|N\rangle$, $q \in \{u, d, s\}$

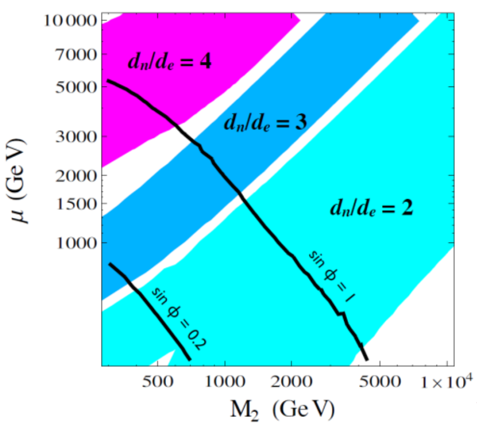
§ Extrapolate to the continuum limit PNDME, 1808.07597

$$g_T^u = 0.784(28),\ g_T^d = -0.204(11),\ g_T^s = 0.0027(16)$$

§ Implications for new physics?

- Take <u>split SUSY</u> for example

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



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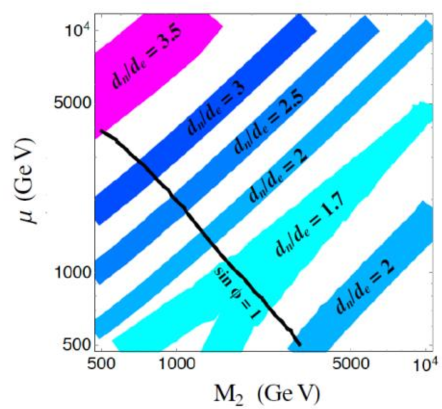

1808.07597

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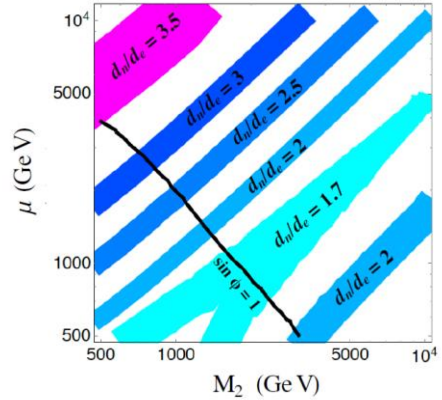
§ Implications for new physics? Wells, 2003; Arkani-Hamed and Dimopoulos, 2004; Giudice and Romanino, 2004

- Take split SUSY for example
- Using our lattice inputs, we can derive an upper limit for the neutron EDM in split SUSY PNDME, 1808.07597

$$|d_n| < 3 \times 10^{-28} e\cdot\text{cm}$$

using $|d_e| < 8.7 \times 10^{-29} e\cdot\text{cm}$ with 90% confidence
ACME Coll., Science Vol. 343 no. 6168 pp. 269-272 (2014)



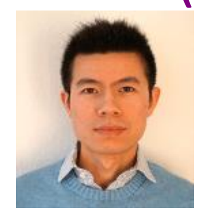
Summary

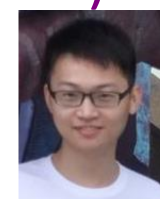
§ Exciting era using LQCD to study nucleon structure

- Well-studied systematics → precision nucleon structures
- Address neglected disconnected contributions
  obtaining flavor-dependent quantities
- BSM applications with fundamental symmetry community and PDFs

§ Overcoming longstanding obstacle to full *x*-distribution (LP^3)

- Progress made in first lattice pion PDF (1804.01483) &
  meson distribution amplitudes (1702.0008,1712.10025)
- More systematics study planned in the near future


J. Zhang


R. Zhang

§ Stay tuned for many more exciting results from LQCD

Titan
@ORNL
IC@LANL

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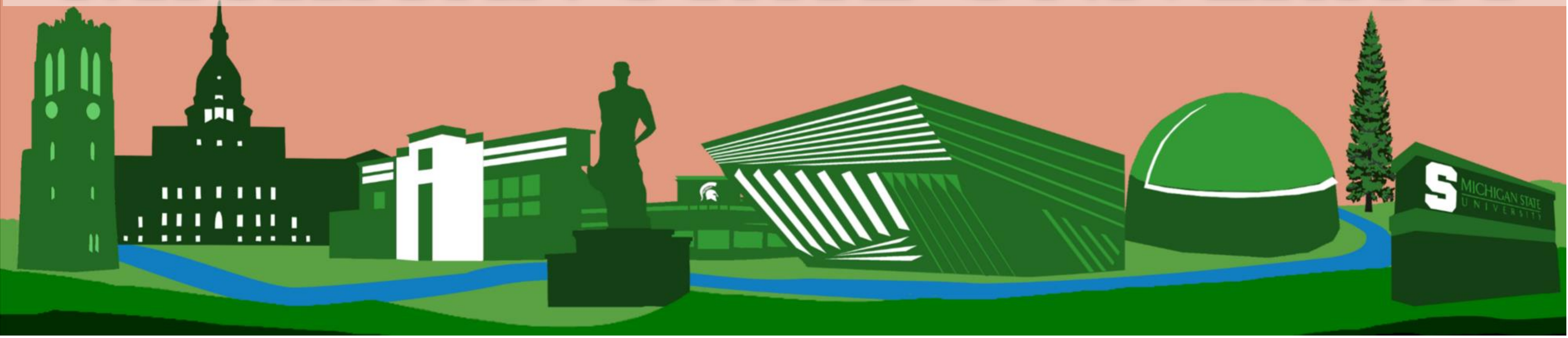
36TH International Symposium on Lattice field Theory

Michigan State University



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https://web.pa.msu.edu/conf/Lattice2018/