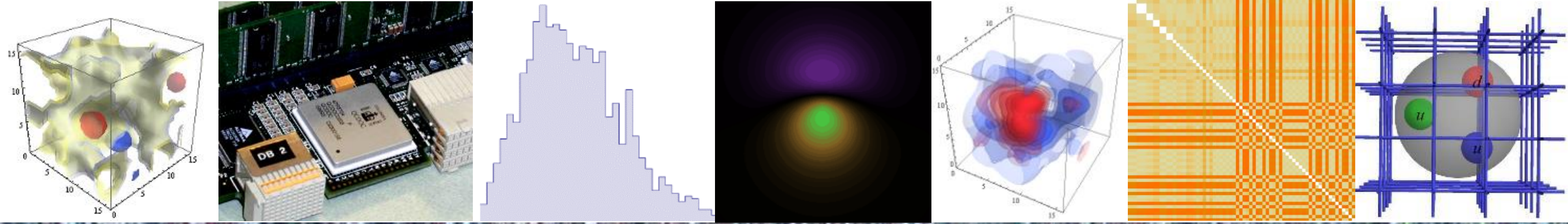


LATTICE QCD FOR NEW PHYSICS & DARK MATTER

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
  - Parton distribution functions for SM background
- Many experiments refine low-energy measurements
  - Discern small discrepancies from the Standard Model

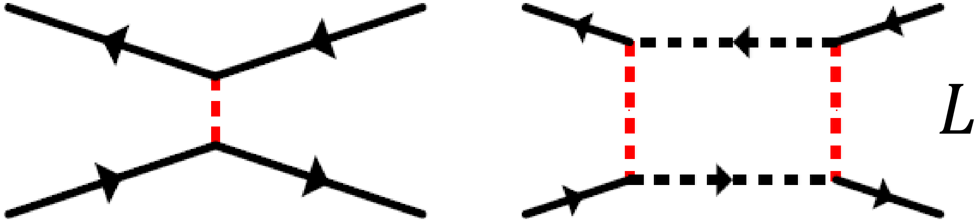
    Muon g−2, Q_{weak}, CKM matrix…
  - Probe small signals that are suppressed in the SM

    dark matter, nEDM, $0\nu\beta\beta$, **neutron β decay**…

New Physics in TeV Scale

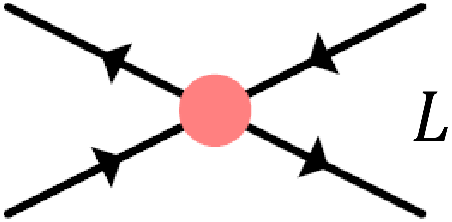
E

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



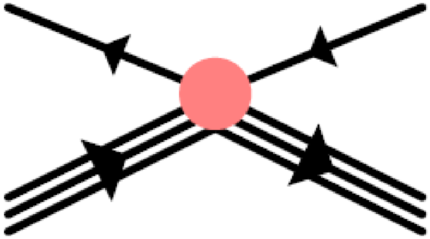
$$L_{\text{SM}} + L_{\text{BSM}}$$

$M_{W,Z}$



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

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



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

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

Also see talk by Emanuele Mereghetti

Outline

- Lattice Nucleon Structure 101
  - All about systematics
- Precision nucleon inputs for applications in
  - New interactions in beta decay
  - Dark matter searches
  - Neutrino physics
  - nEDM

Lattice 101

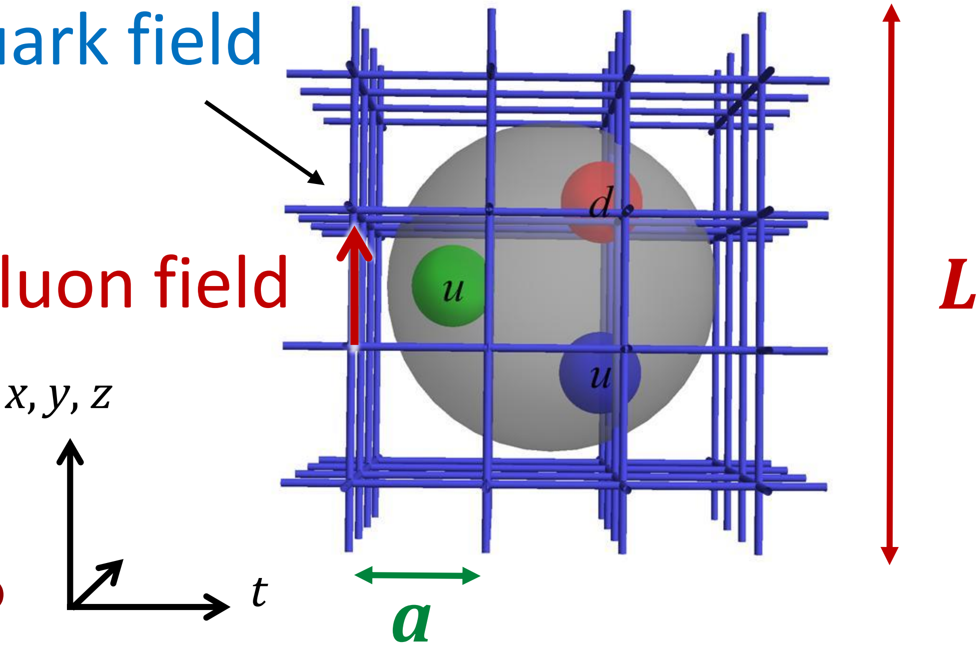
- Lattice QCD is an ideal theoretical tool for investigating the strong-coupling regime of quantum field theories
- Physical observables are calculated from the path integral

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

in **Euclidean** space

Also see talk by Andreas Kronfeld

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



quark field

gluon field

- Recover physical limit

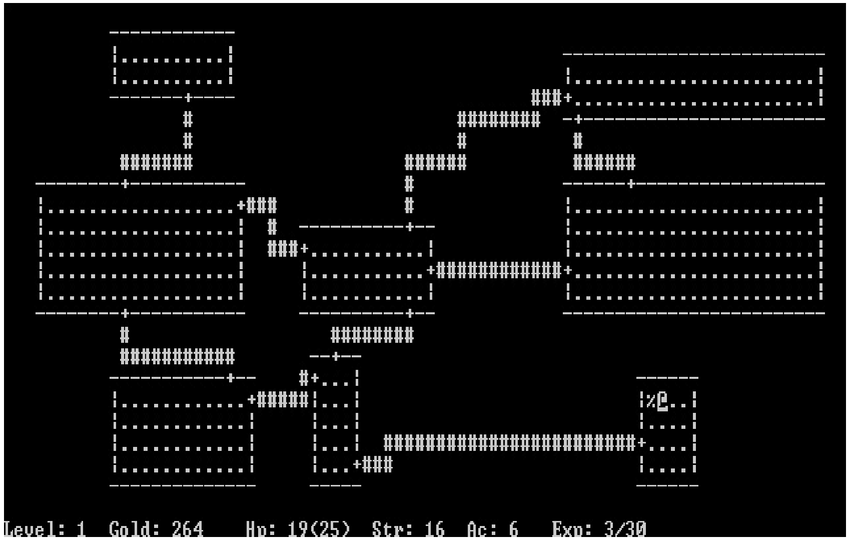
$$m_\pi \rightarrow m_\pi^{\text{phys}},\ a \rightarrow 0,\ L \rightarrow \infty$$

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



```
Level: 1  Gold: 264   Hp: 19(25)  Str: 16  Ac: 6   Exp: 3/30
```

Today

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

Successful Examples

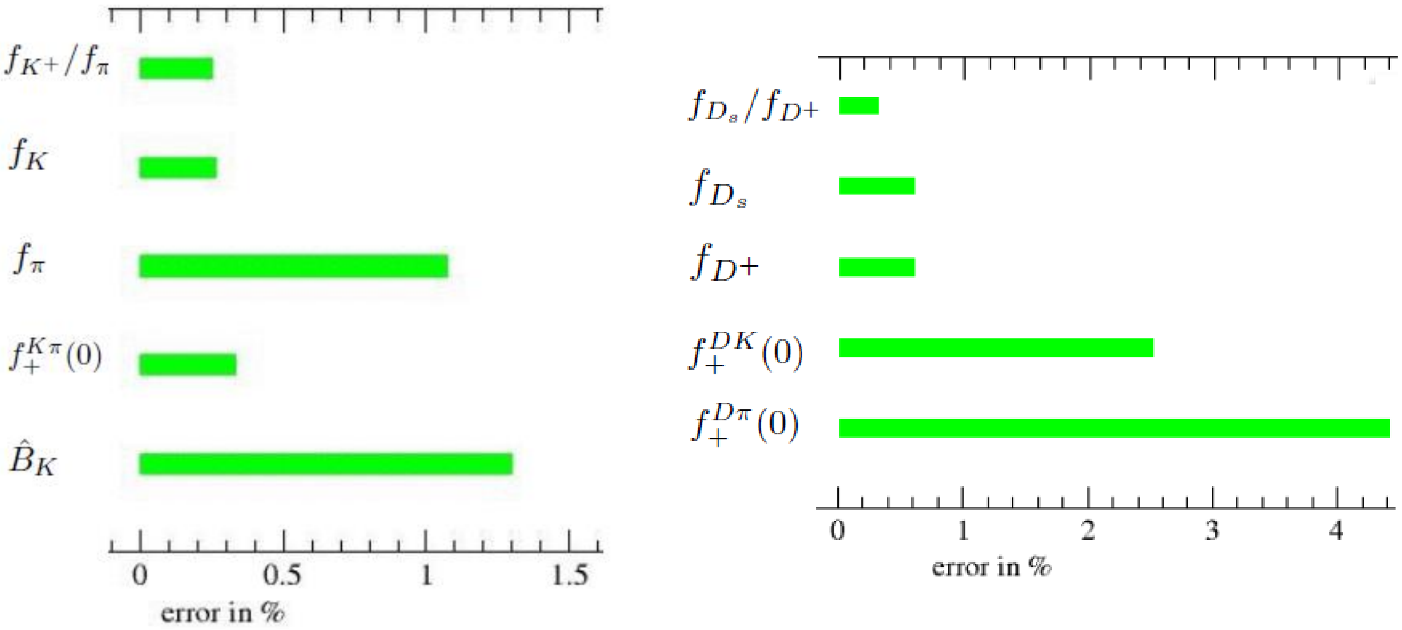
- Lattice flavor physics provides precise inputs from the SM

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

- Very precise results in many meson systems

Also see talk by Andreas Kronfeld

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



- We are beginning to do precision calculations in nucleons

The Trouble with Nucleons

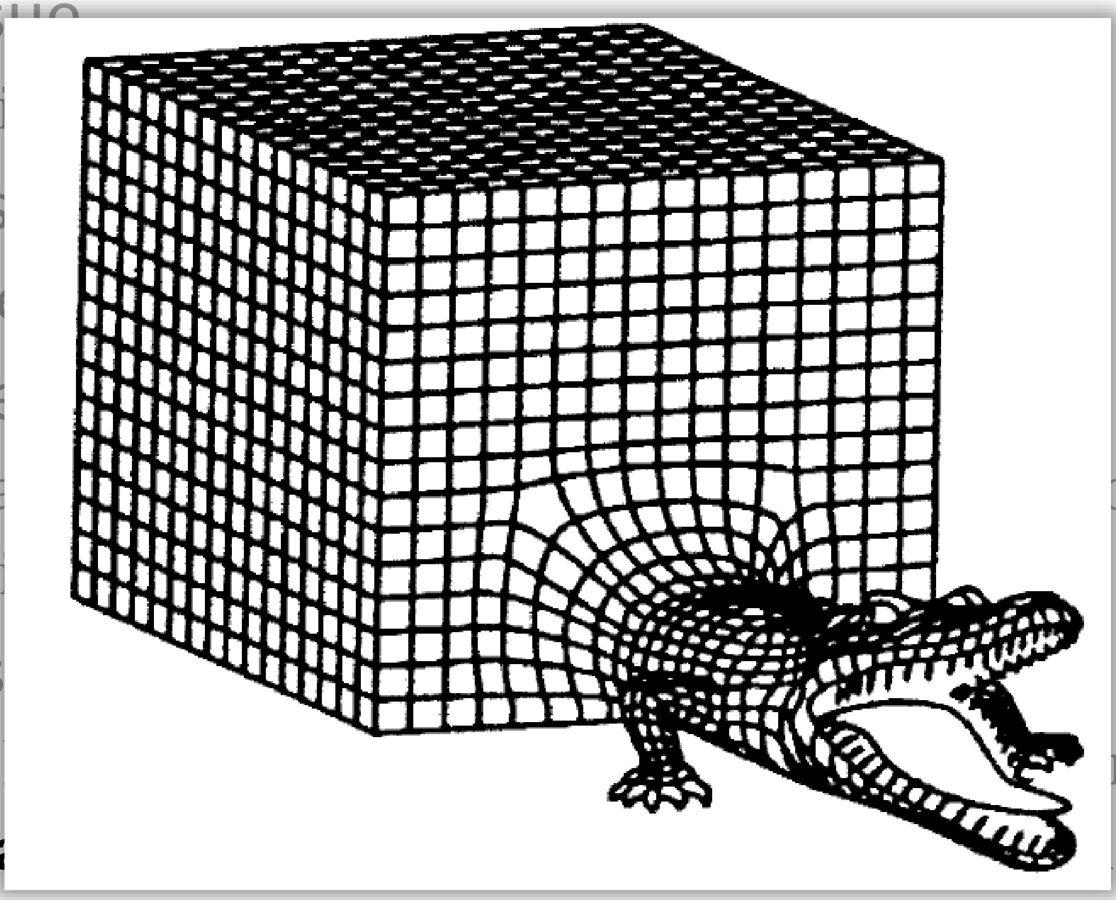
Nucleons are more complicated than mesons because…

- 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

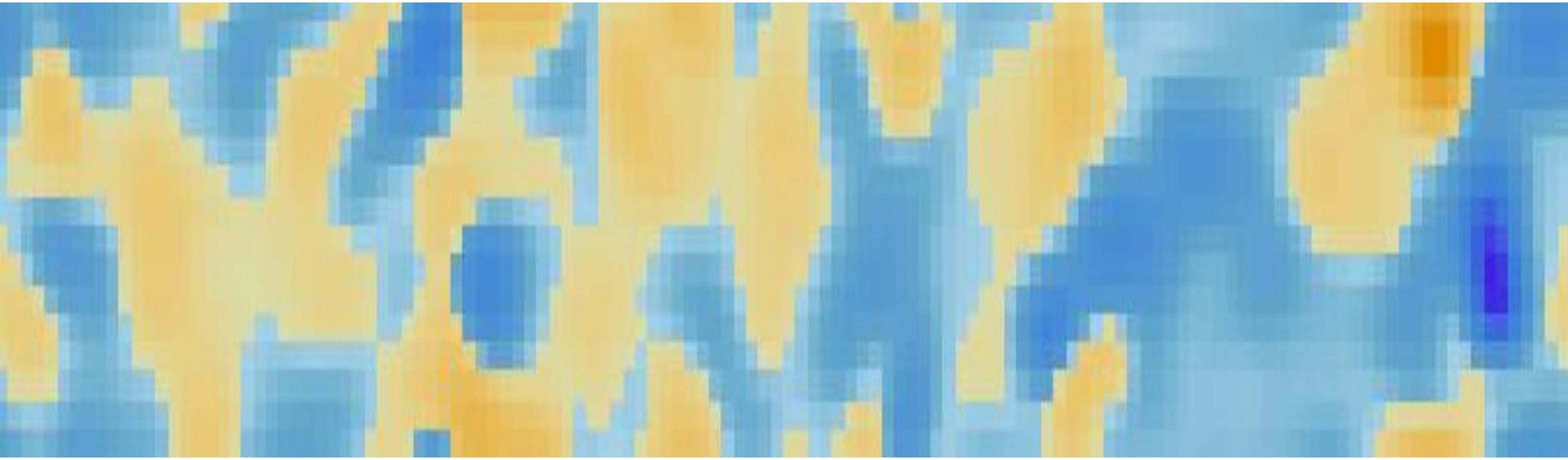
Nucleons are more complicated than mesons because…

- Noise iss
  - Signal di
- Excited-s
  - Nearby
- Hard to e
  - Δ resona onvergence…
  - Less an
- Requires
  - Ensemb ns in mind
  - **High-st** ples



PROCEED WITH CAUTION

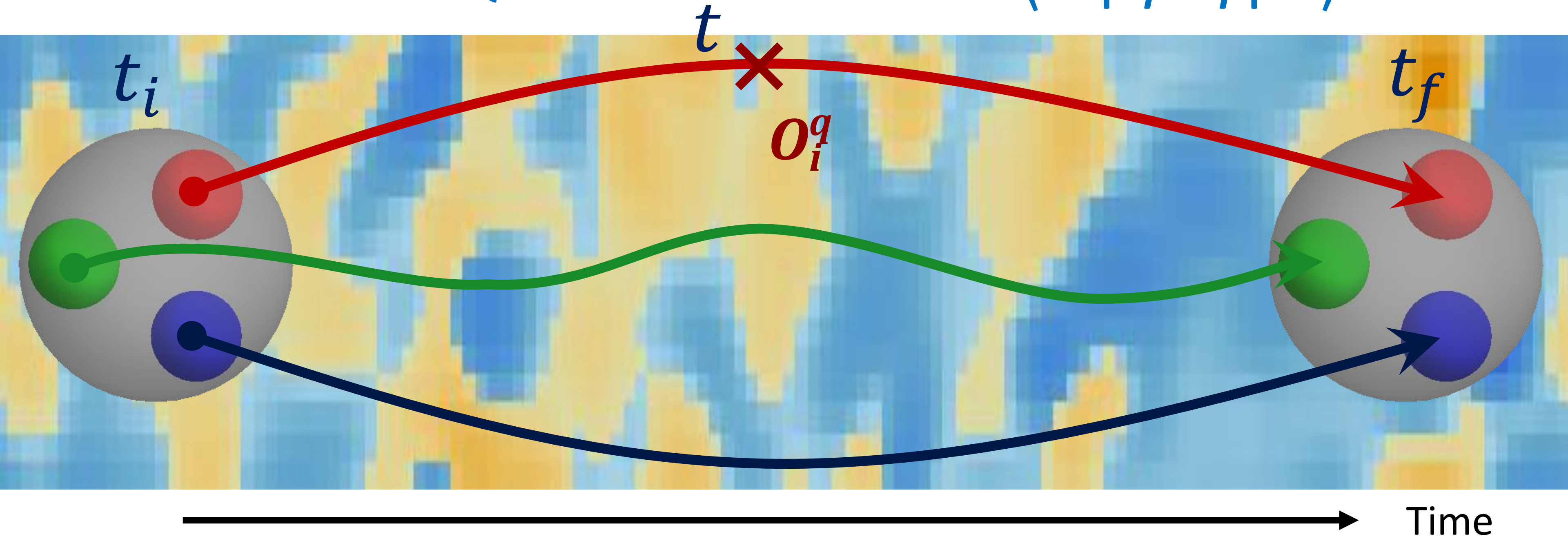
Nucleon Matrix Elements



- 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 $\langle N|\bar{q}\Gamma q|N\rangle$



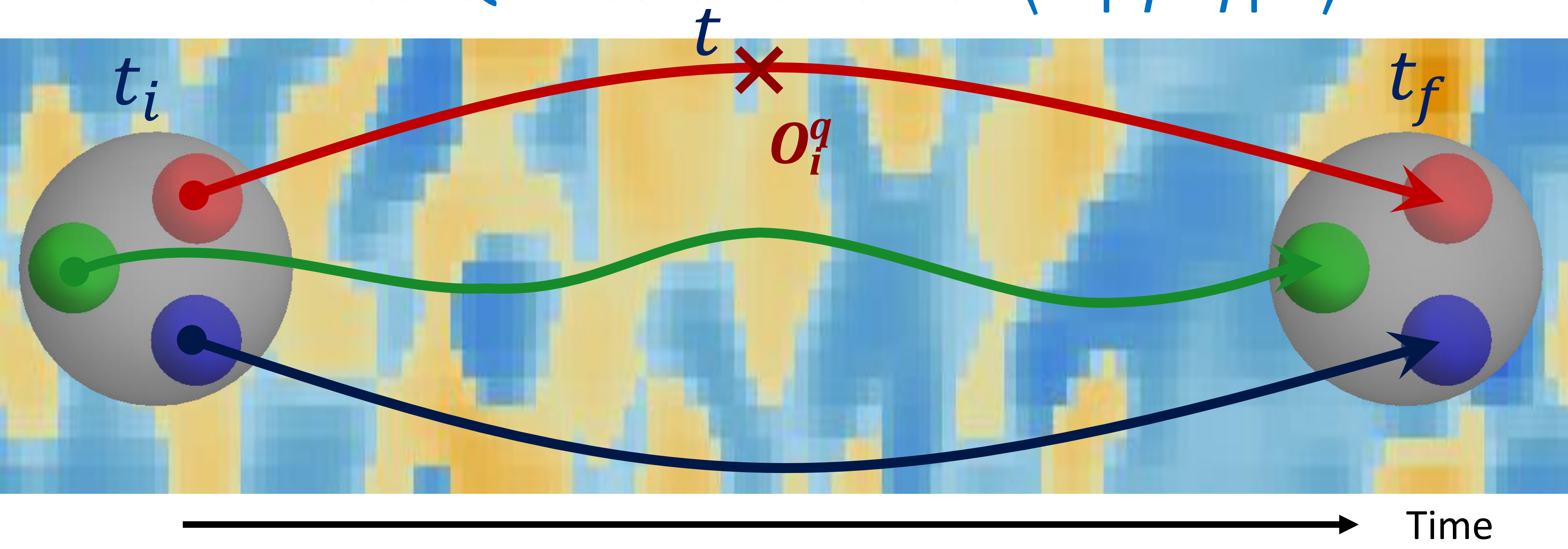
§ Construct correlators (hadronic observables)

- Requires “quark propagator”

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

Nucleon Matrix Elements

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



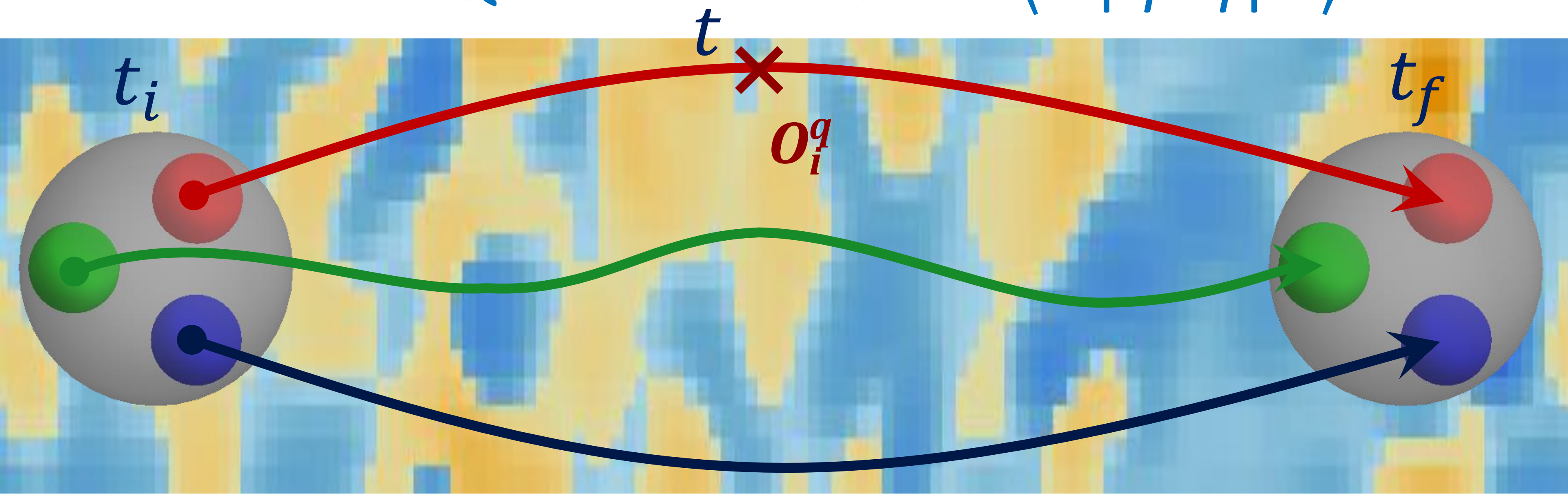
§ Analysis (extract couplings)

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

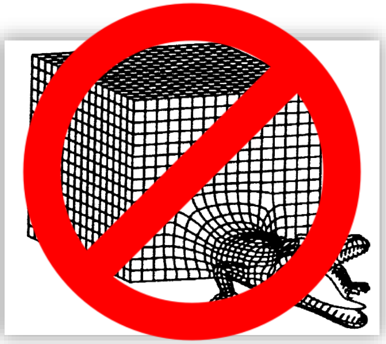
$$C^{\mathrm{2pt}}(t_f,t_i) = |\mathcal{A}_0|^2 e^{-M_0(t_f-t_i)} + |\mathcal{A}_1|^2 e^{-M_1(t_f-t_i)} + \ldots$$

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



PNDME

Precision Neutron-Decay Matrix Elements (2010-)

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

Tanmoy Bhattacharya

Rajan Gupta

HWL

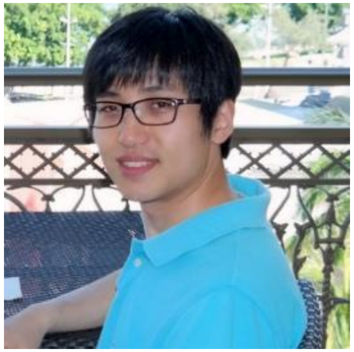
+

Vincenzo Cirigliano

Saul Cohen

Anosh Joseph

Yong-Chull Jang



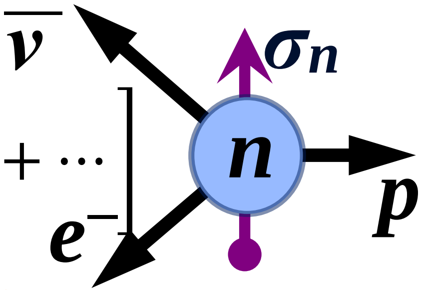
Boram Yoon

New Interactions

§ Neutron beta decay could be related to new interactions:

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

- ε_S and ε_T are related to the masses of the new TeV-scale particles
- Parameters sensitive to new physics



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

Fierz interference term:

Deviations from the leading-order e^- spectrum

Energy-dependent part of the

neutrino asymmetry parameter

with neutron spin

$$\boxed{\{b,B\}_{\mathrm{BSM}} = f_0(\varepsilon_{S,T}\,g_{S,T})}$$

Precision LQCD input

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

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

Also see talks by Alejandro Garcia, Emanuele Mereghett

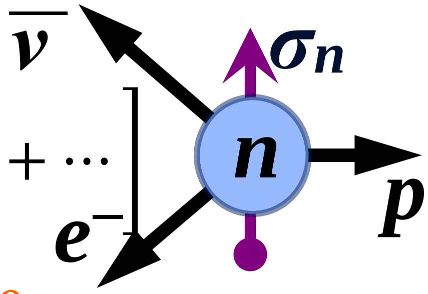
New Interactions

§ Neutron beta decay could be related to new interactions:

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

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

$$d\Gamma \propto F(E_e) \Big[\quad \vec{\nu} + \cdots \Big]$$



Fierz inter

Deviations f

leading-ord

he

arameter

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}

$$\{b,B\}_{\text{BSM}} = f_0(\varepsilon_{S,T}\, g_{S,T})$$

Precision LQCD input

(m_π≈140 MeV, a→0)

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

Also see talks by Alejandro Garcia, Emanuele Mereghetti

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

- **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

Systematic Control

- Much effort has been devoted to controlling systematics
- A state-of-the art calculation (PNDME) $a = 0.12$ fm, 310-MeV pion

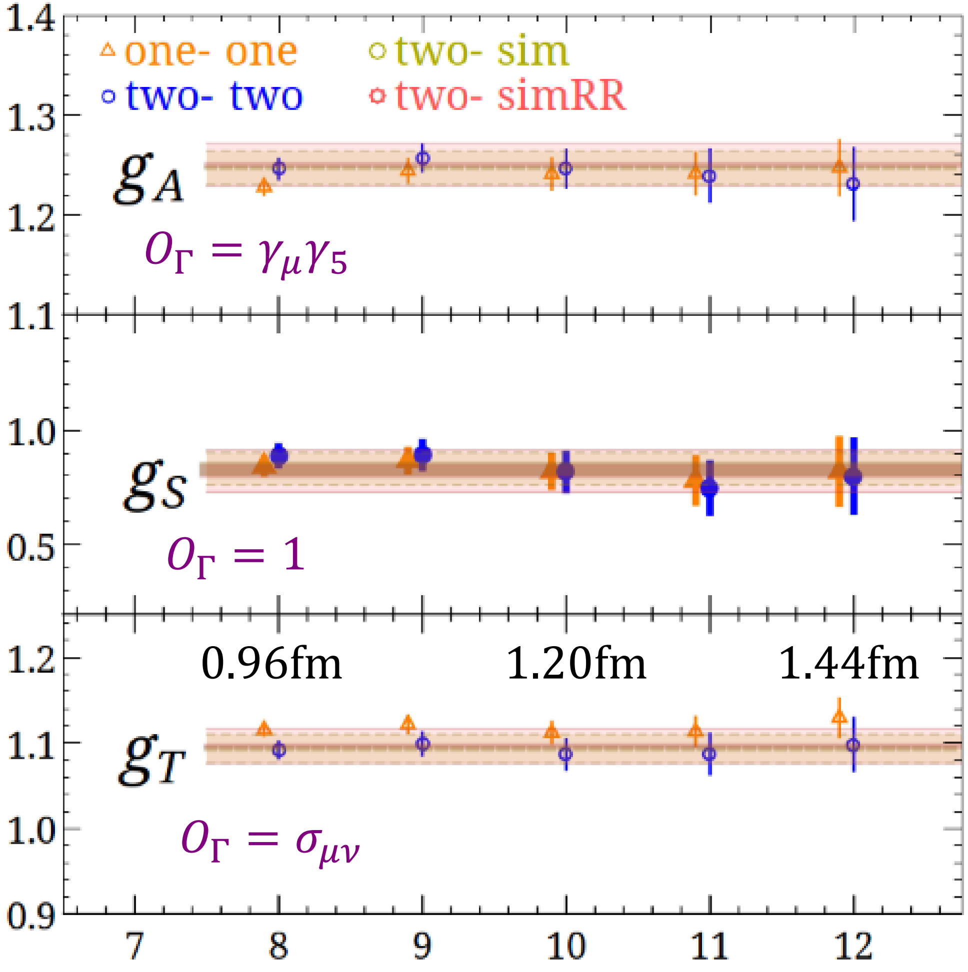
- Move the **excited-state systematic** into the statistical error

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

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

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

$$+|\mathcal{A}_1|^2\langle 1|\mathcal{O}_\Gamma|1\rangle e \quad t_i)$$



- No obvious contamination between 0.96 and 1.44 fm separation

Systematic Control

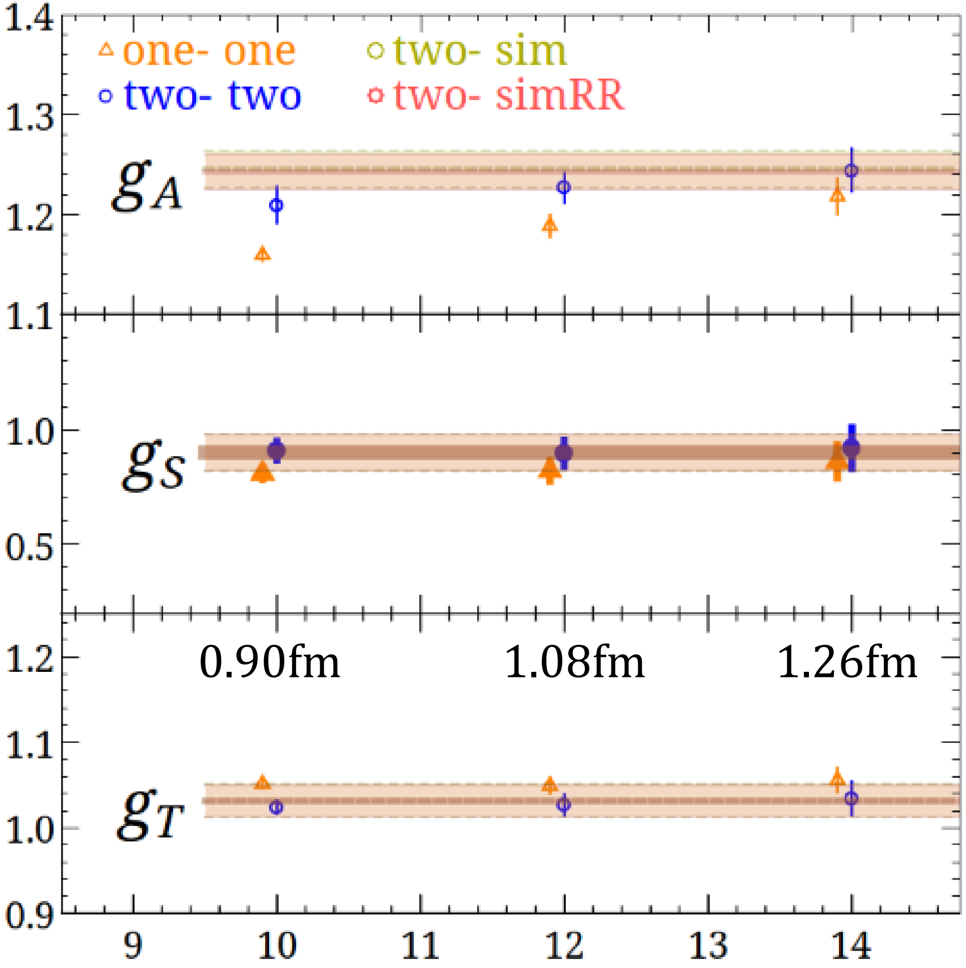
- § Much effort has been devoted to controlling systematics
- § A state-of-the art calculation (PNDME) a = **0.09 fm**, 310-MeV pion

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

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

$$\boxed{\begin{array}{l} +\mathcal{A}_0\mathcal{A}_1^*\langle 0| \quad 1\rangle e^{-M_0(t-t_i)}e^{-M_1(t_f-t)} \\ +\mathcal{A}_0^*\mathcal{A}_1\langle 1|\mathcal{O}_\Gamma|0\rangle e \quad (t-t_i)e^{-M_0(t_f-t)} \\ \qquad +|\mathcal{A}_1|^2\langle 1|\mathcal{O}_\Gamma|1\rangle e \quad t_i) \end{array}}$$

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



Systematic Control

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

Statistical effect

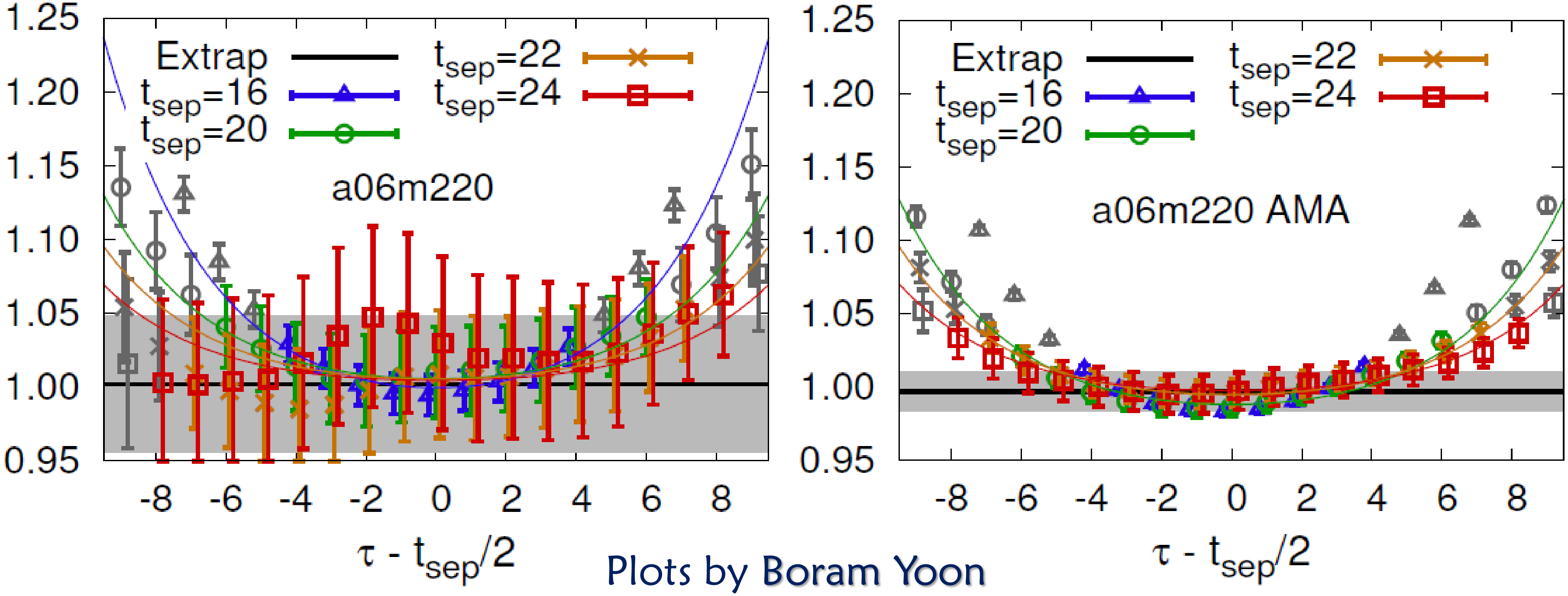
$a = 0.06$ fm, 220-MeV pion

PNDME, 1606.07049

g_T^{bare}

2.6k

41.6k



Plots by **Boram Yoon**

Systematic Control

- § Much effort has been devoted to controlling systematics
- § A state-of-the art calculation (PNDME)
  - Statistical effect

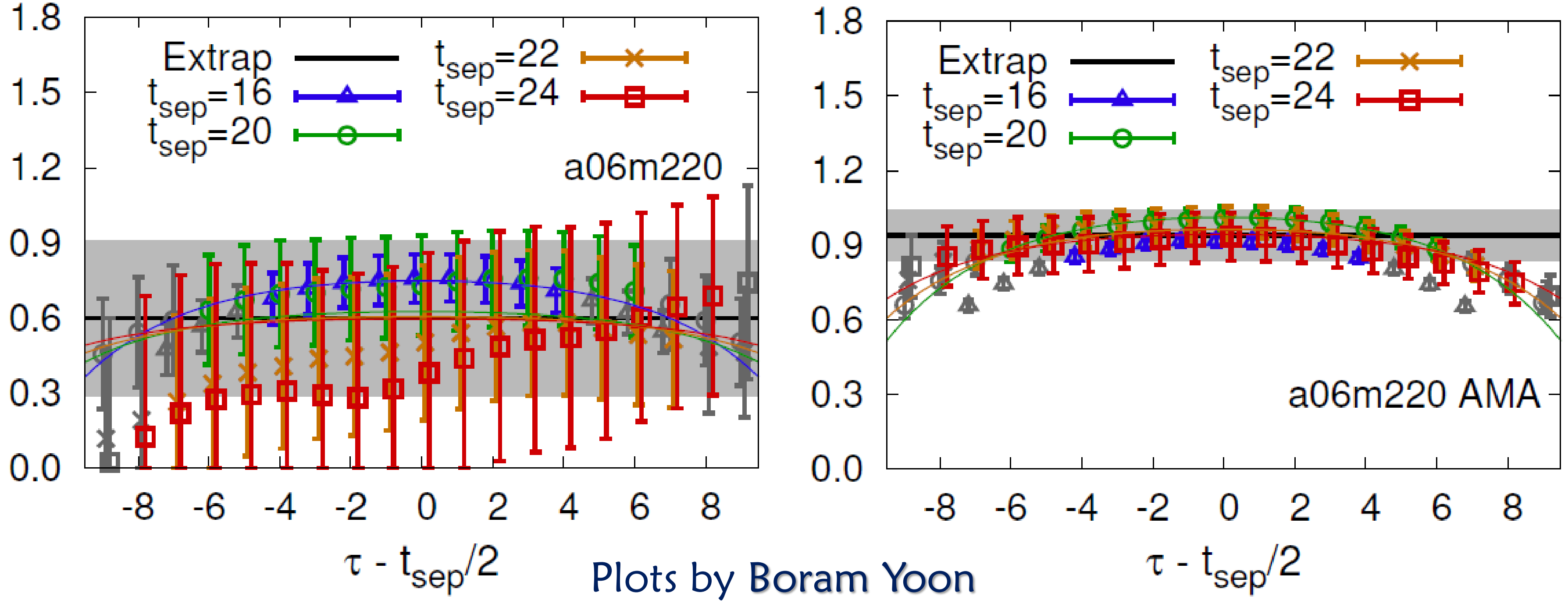
$a = 0.06$ fm, 220-MeV pion

PNDME, 1606.07049

g_S^{bare}

2.6k

41.6k



Plots by **Boram Yoon**

Systematic Control

- Much effort has been devoted to controlling systematics
- A state-of-the art calculation (PNDME)
  - **Statistical effect** (worst case)

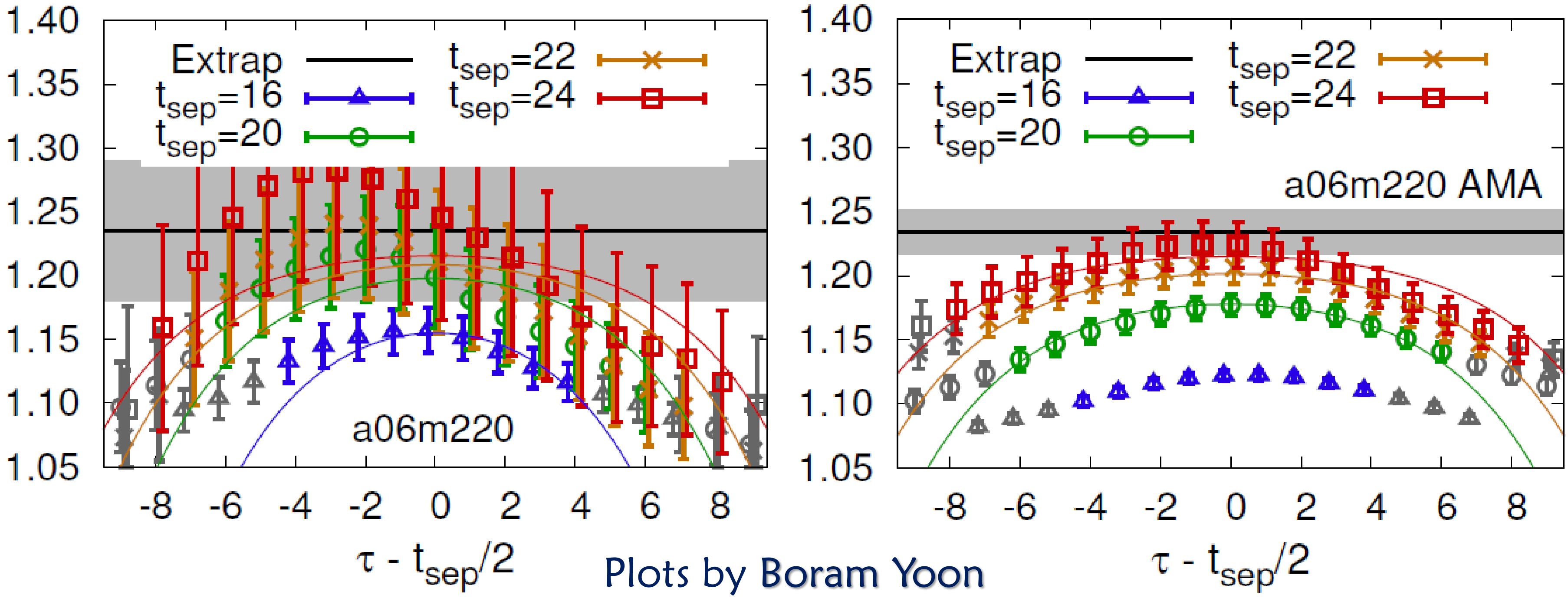
$a = 0.06$ fm, 220-MeV pion

PNDME, 1606.07049

g_A^{bare}

2.6k

41.6k



Plots by **Boram Yoon**

Systematic Control

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

➢ Robustness of the 2-state fit

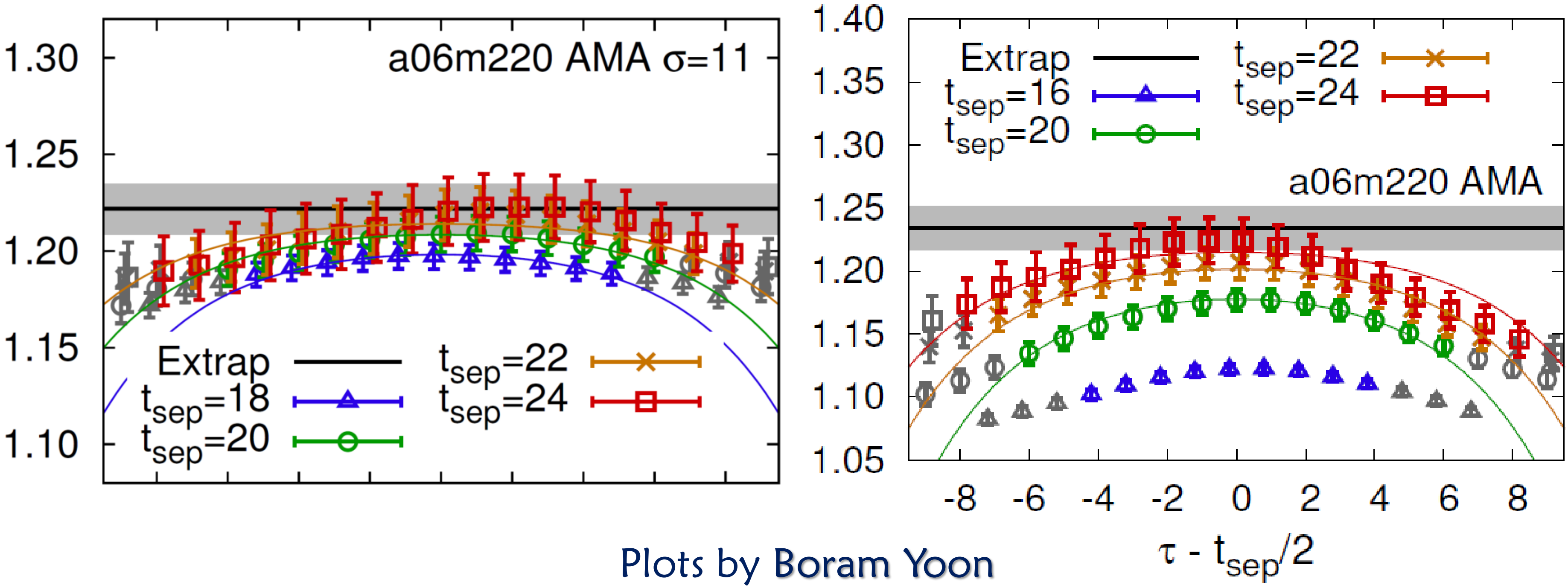
$a = 0.06$ fm, 220-MeV pion

PNDME, 1606.07049

41.6k

g_A^{bare}

41.6k



Plots by **Boram Yoon**

Systematic Control

- Much effort has been devoted to controlling systematics

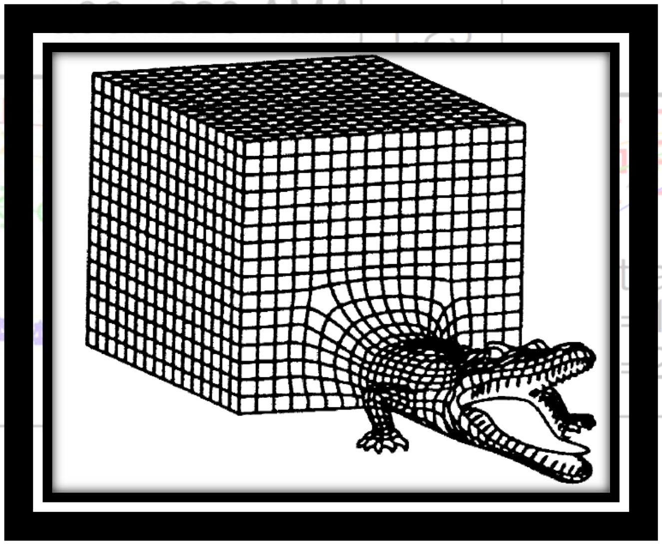
My Two Cents

- g_A is *not* a gold-plated quantity

  Early impressions that g_A would be easy underestimated systematics

- You can still trust lattice g_A

  ...from groups who do due diligence for *every* ensemble and carefully study systematics



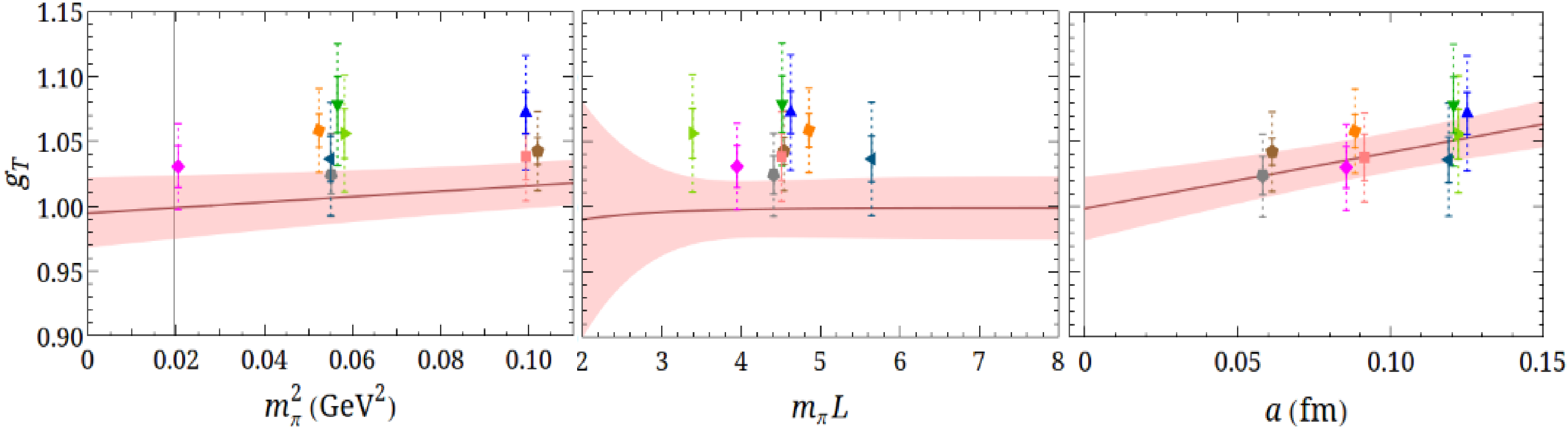
Precision Nucleon Couplings

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

PNDME, 1606.07049

- Extrapolate to the physical limit

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



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

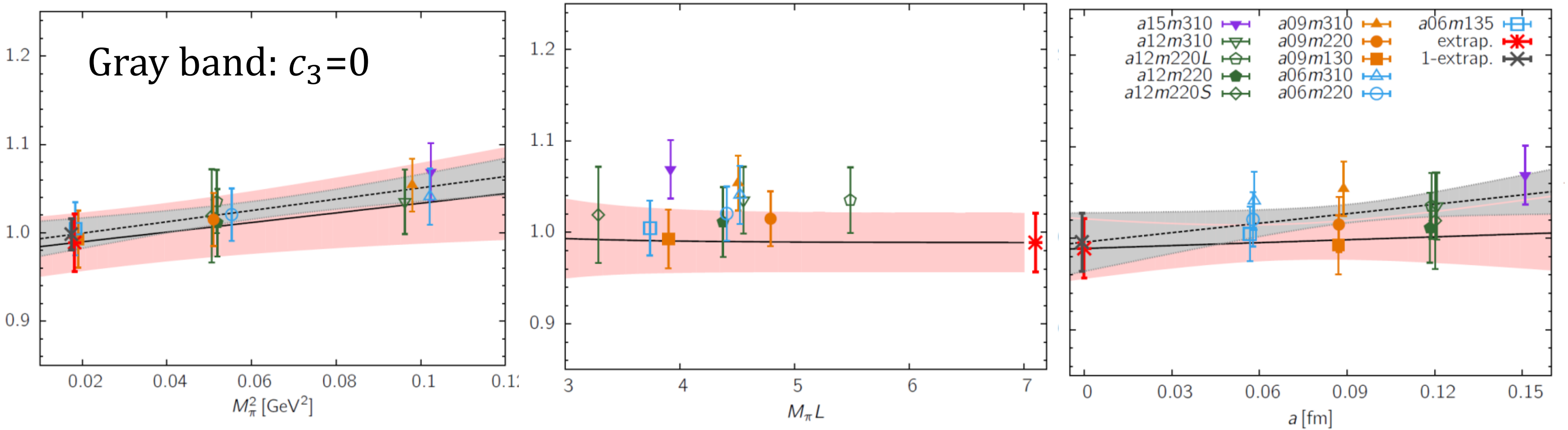
Precision Nucleon Couplings

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

PNDME, 1806. 09006

☙ Extrapolate to the physical limit

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



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

Yong-Chull Jang

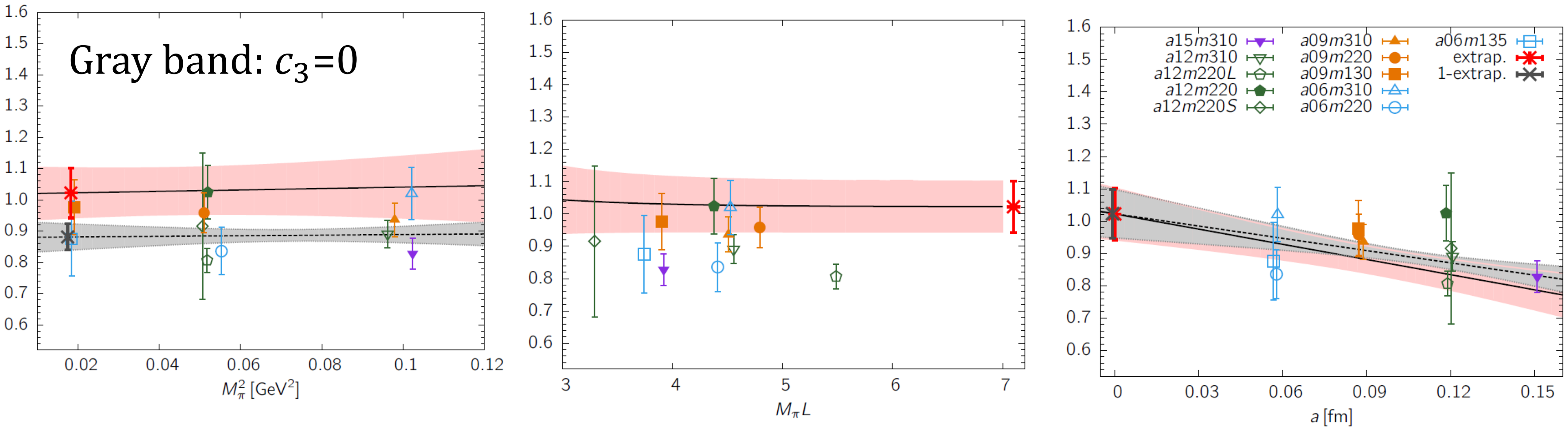
Precision Nucleon Couplings

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

PNDME, 1806. 09006

- Extrapolate to the physical limit

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



2018: Still the only collaboration has the full continuum extrapolated g_S

Yong-Chull Jang

Precision Nucleon Couplings

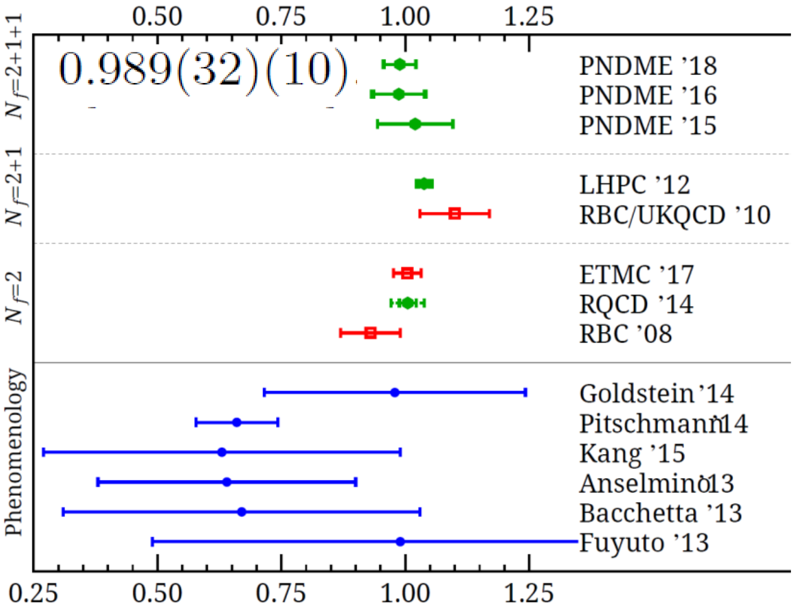
FLAG rating system

PNDME, 1506.06411; 1606.07049

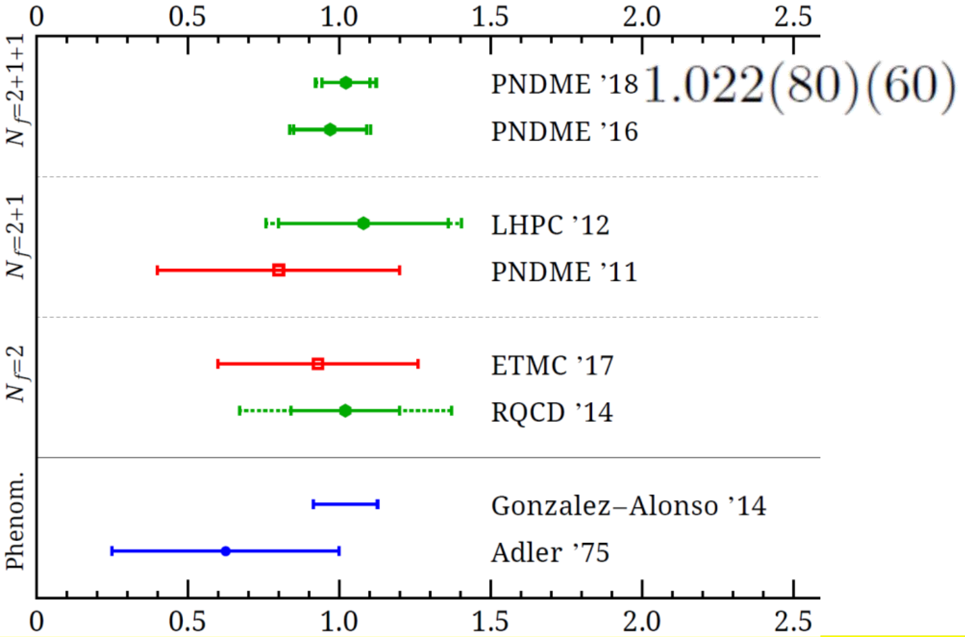
New: excited-state rating

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



$0.989(32)(10)$



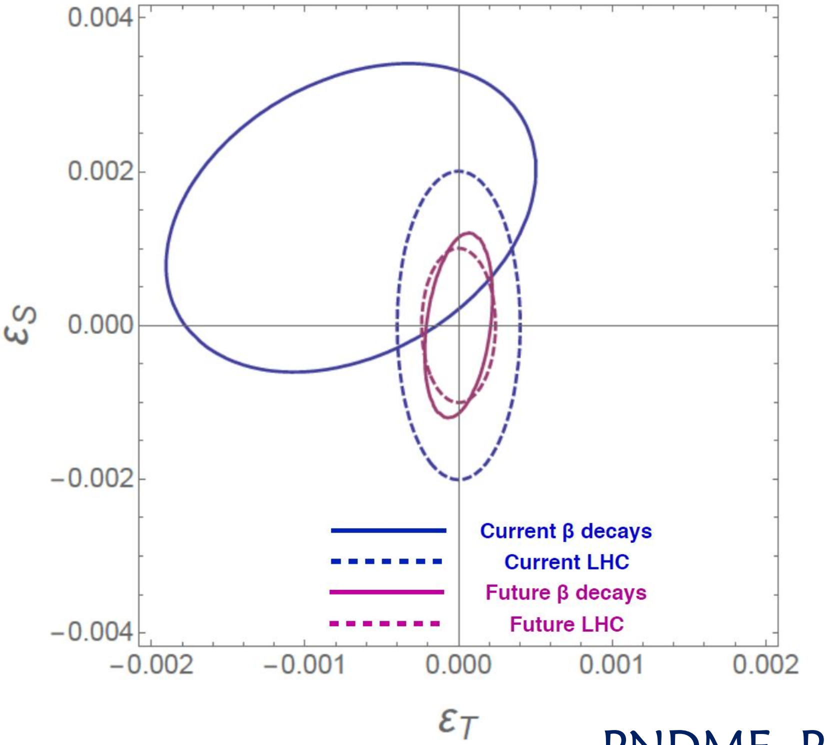
$1.022(80)(60)$

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

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



Plots by Vincenzo Cirigliano

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}He(b_{GT}) at 10^{-3}

Also see talk by A. Garcia, E. Mereghetti

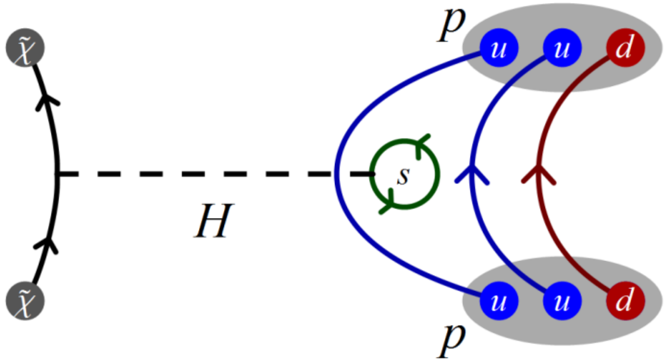
PNDME, PRD85 054512 (2012); 1306.5435; 1606.07049; 1806.09006

WIMPs as Dark Matter

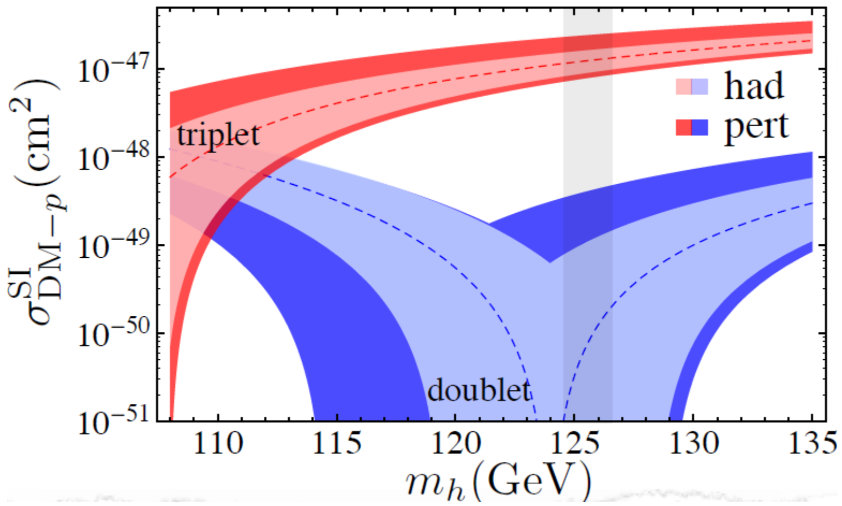
WIMPs for Dark Matter

§ WIMPs dark-matter (DM) searches

- Certain candidates (e.g. SuSy neutralinos) exchange Higgs
- Spin-Independent (SI) or Spin-Dependent (SD) cross-section
- Interactions with nucleon mediated by Higgs exchange



[Hill & Solon, PRL112, 211602 (2014)]



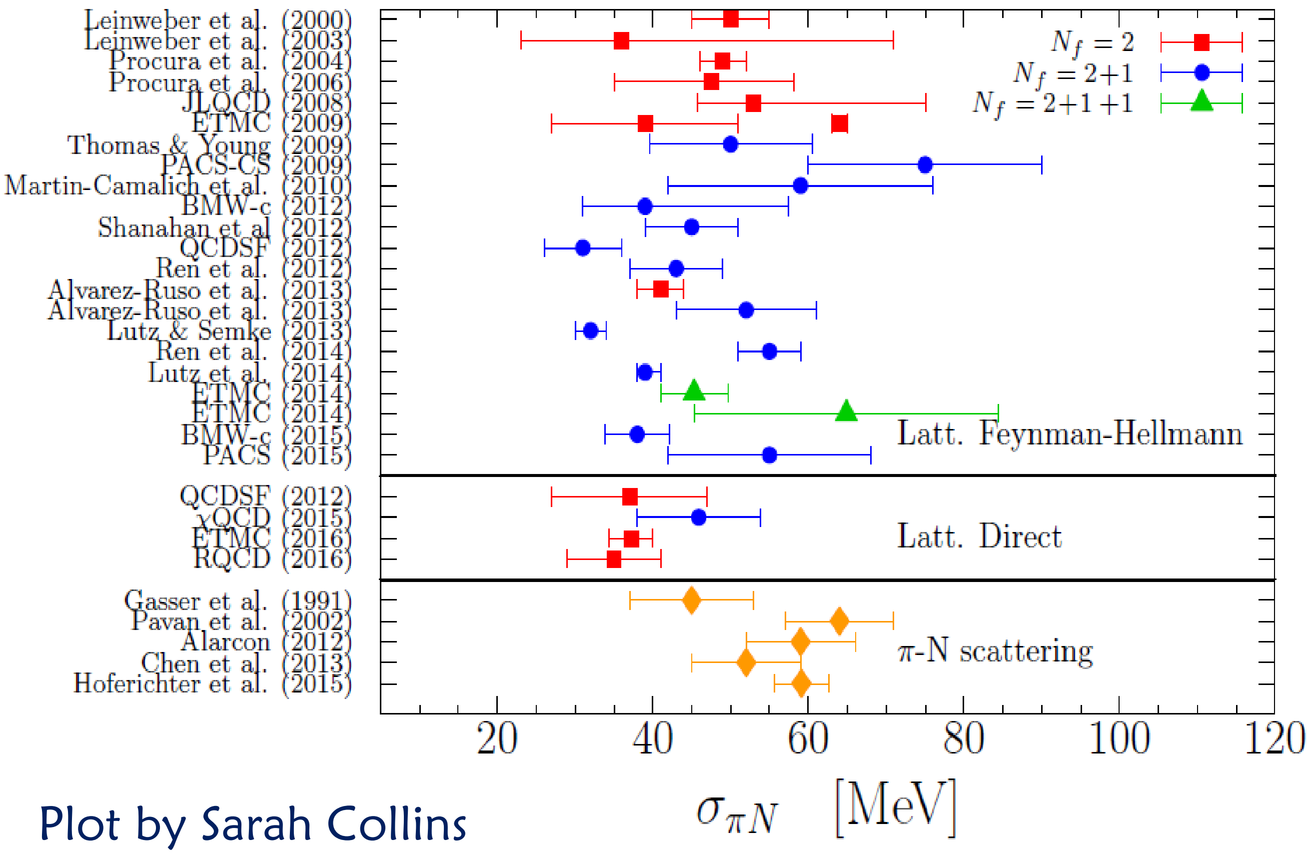
§ Errors on DM cross-section are dominated QCD

§ Wanted from lattice QCD

- Nucleon (nuclear) sigma terms, strangeness
- Quark spin contribution

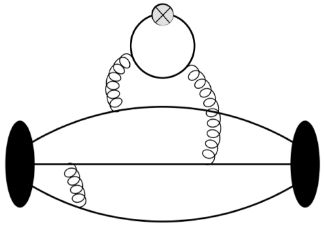
Input to SI Cross Section

§ Tensions in nucleon sigma $\sigma_{\pi N}$ determination



$$\sigma_{\pi N} = m_\pi^2 \frac{\partial m_N}{\partial m_\pi^2}$$

$$\langle N | u\bar{u} + d\bar{d} | N \rangle$$

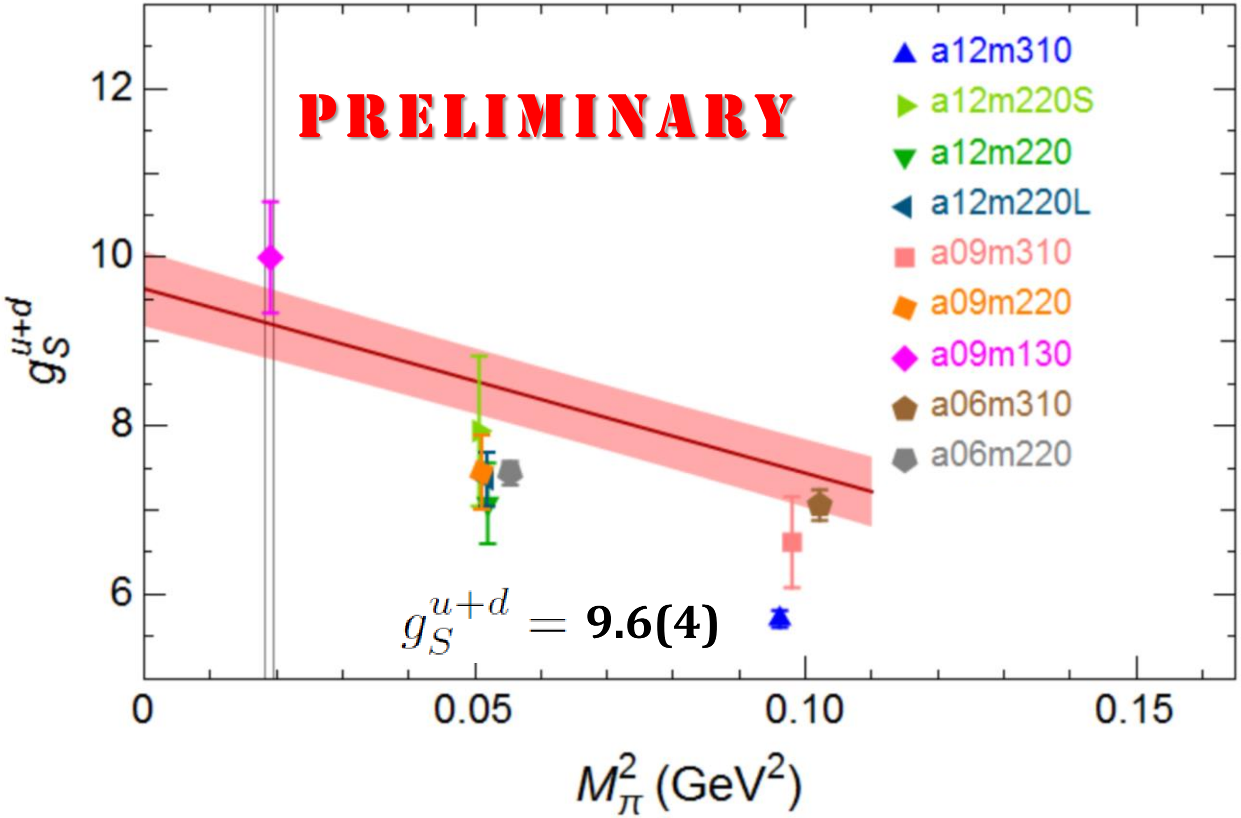


Plot by Sarah Collins
@Lattice 2016

Input to SI Cross Section

- We first calculate the matrix element of $\langle N|u\bar{u} + d\bar{d}|N\rangle$
  - Require the disconnected contribution

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



9.3(1.8) RQCD
~9.5(6) ETMC
1603.00827,1703.08788

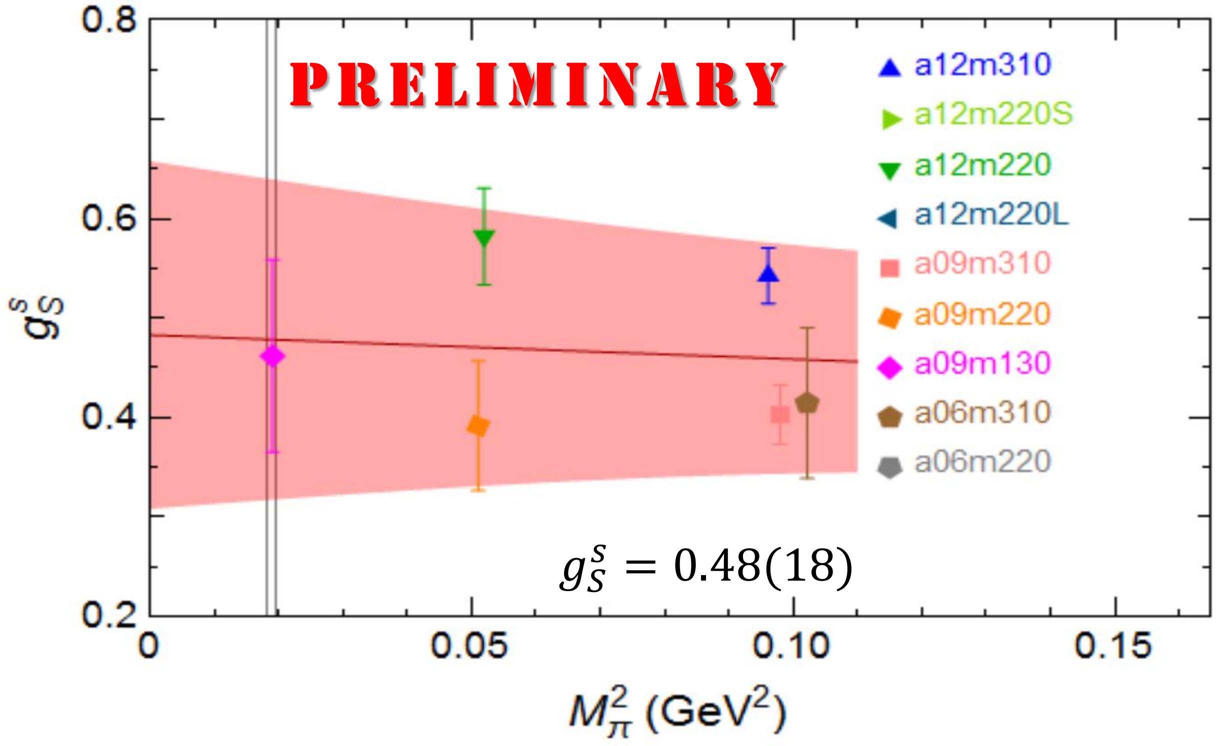
Convert to sigma term using FLAG 2+1+1f m_{ud}, we have 35.5(2.2) MeV

Input to SI Cross Section

§ $\langle N|s\bar{s}|N\rangle$

- Purely disconnected contribution

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

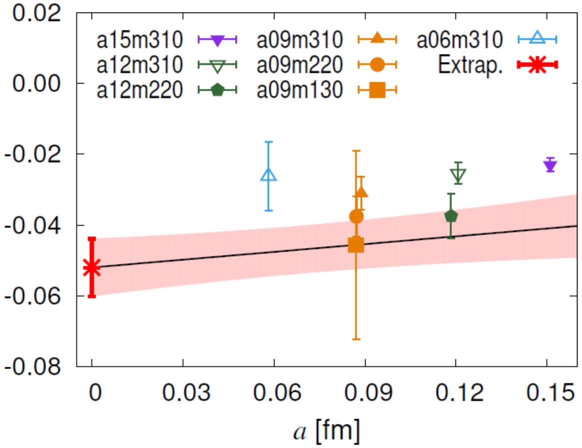


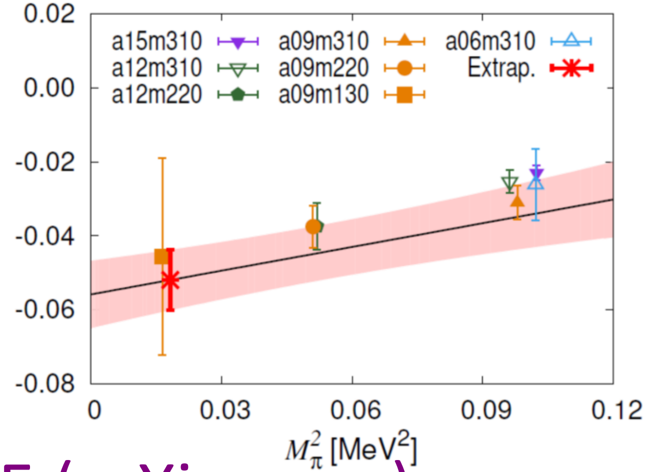
0.42(13) χQCD
(preliminary)

0.35(15) RQCD
0.33(9) ETMC
1603.00827,1703.08788

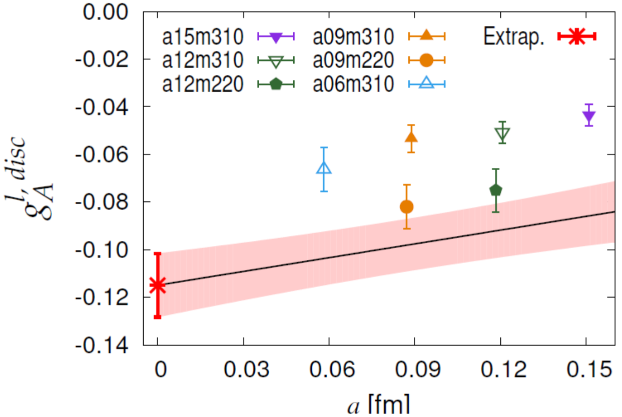
Input to SD Process

§ Strange is the most poorly known quark spin

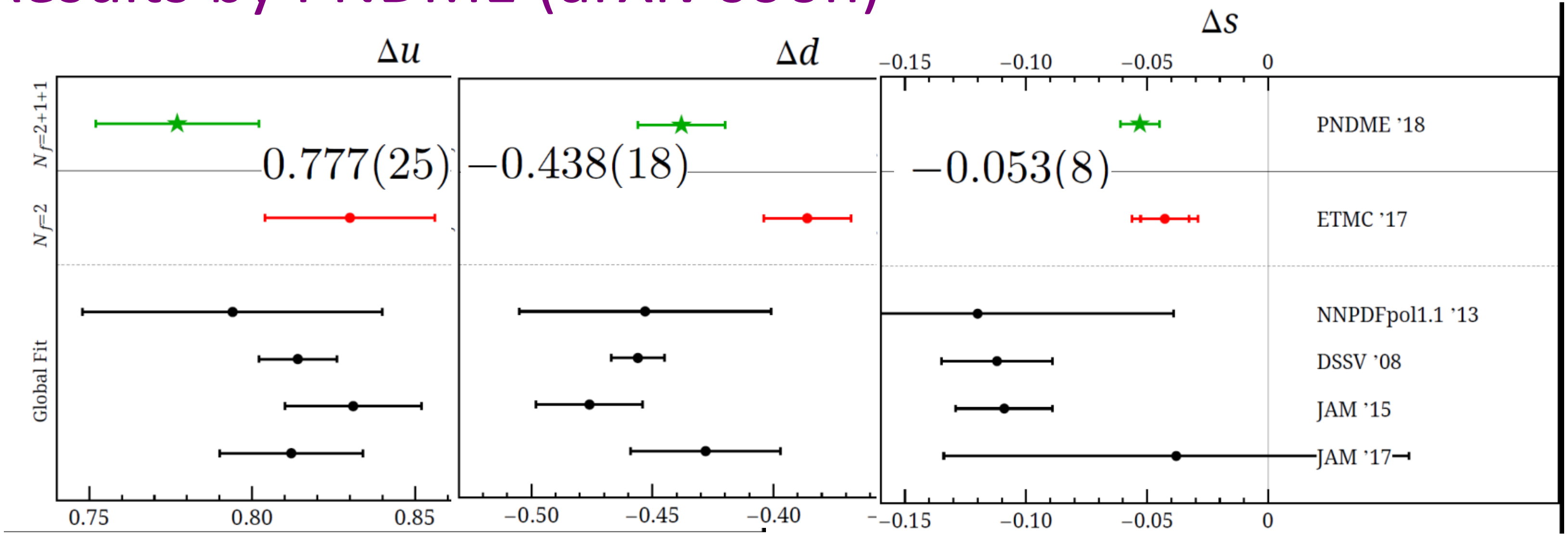




Strong a dependence!



§ Results by PNDME (arXiv soon)



$0.777(25)$ $-0.438(18)$ $-0.053(8)$

Neutrino Physics Application

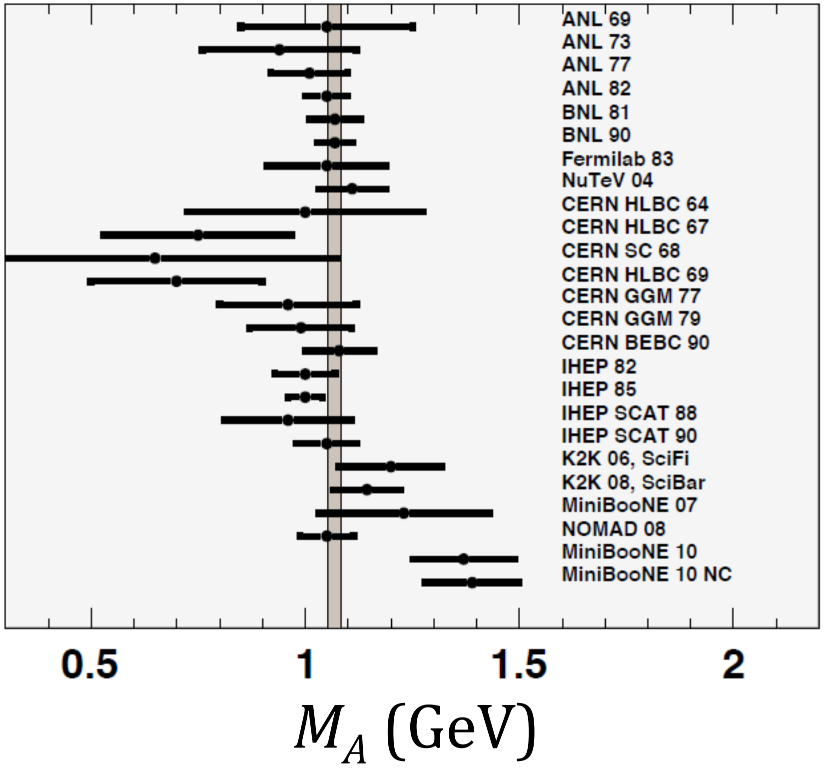
Nucleon axial form factors

For more complete review on LQCD contributions to neutrino physics, please see talk by Phiala Shanahan

Axial Form Factors

- Controversial axial form factor determinations from ν data
  - Inconsistent determination of M_A (difficult or uncontrollable experimental systematics)

Hills, et al



- Lattice can provide SM inputs for event Monte Carlo

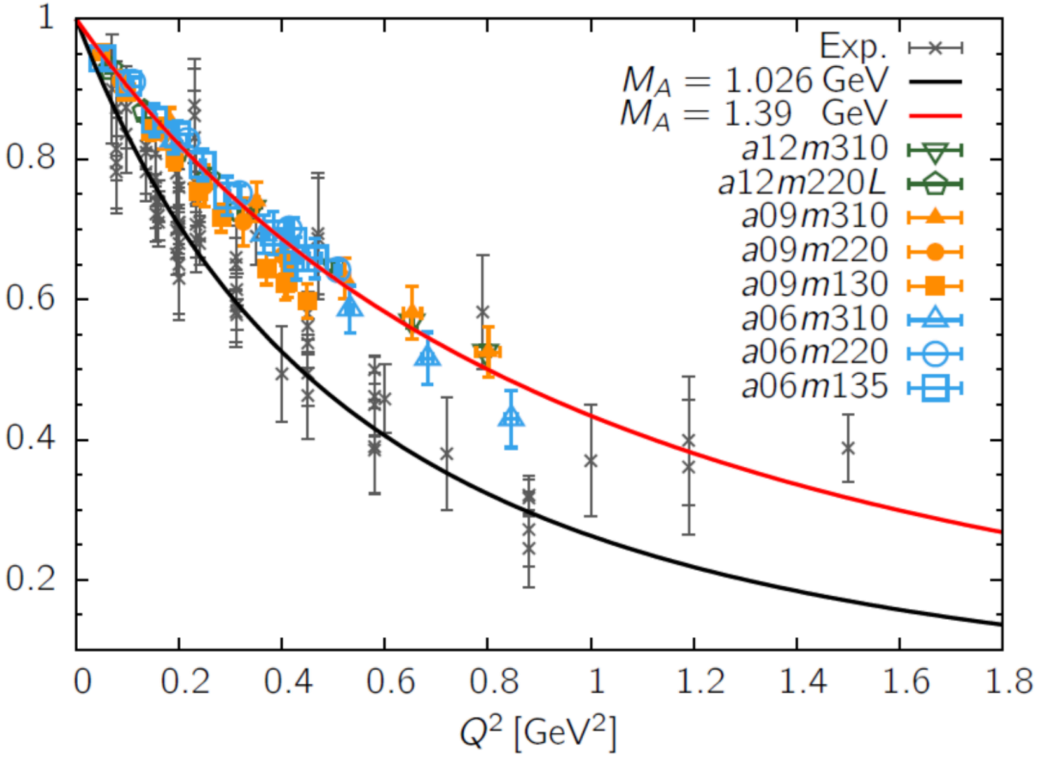
Axial Form Factors

§ Nucleon isovector axial form factor

PNDME, 1705.06834

$$\left\langle N(\vec{p}_f) \left| A_\mu \left(\vec{Q}\right) \right| N(\vec{p}_i) \right\rangle = \bar{u}(\vec{p}_f) \left[\boldsymbol{G_A(Q^2)} \gamma_\mu + q_\mu \frac{\tilde{G}_P(Q^2)}{2M_N} \right] \gamma_5 u(\vec{p}_i)$$

$\boldsymbol{G_A(Q^2)/g_A}$



Fits done using z-expansion (and dipole)

	Eq. (23)			Eq. (23) with $c_4 = 0$		
	$\langle r_A^2 \rangle$	r_A	M_A	$\langle r_A^2 \rangle$	r_A	M_A
dipole	0.24(3)	0.49(3)	1.41(08)	0.23(2)	0.48(2)	1.42(06)
z^{2+4}	0.19(4)	0.44(5)	1.56(18)	0.17(3)	0.42(4)	1.65(16)
z^{3+4}	0.24(7)	0.49(7)	1.39(19)	0.18(5)	0.43(6)	1.60(23)

$$c_1 + c_2 a + c_3 M_\pi^2 + c_4 M_\pi^2 e^{-M_\pi L} . \quad (23)$$

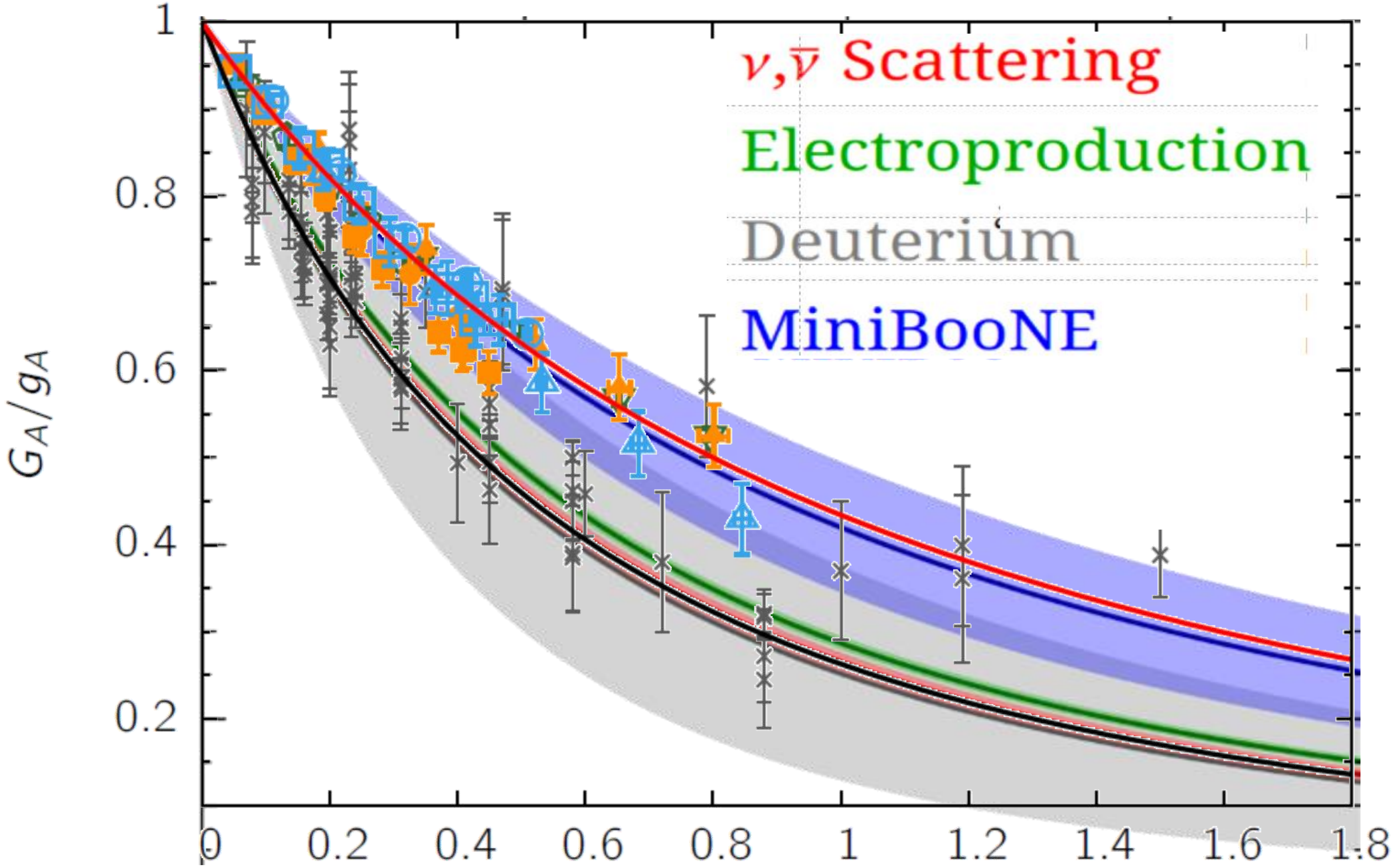
Plot by Yong-Chull Jang

Axial Form Factors

§ Nucleon isovector axial form factor

PNDME, 1705.06834

- $\left\langle N(\vec{p}_f)\left|A_\mu\left(\vec{Q}\right)\right|N(\vec{p}_i)\right\rangle = \bar{u}(\vec{p}_f)\left[G_A(Q^2)\gamma_\mu + q_\mu \frac{\tilde{G}_P(Q^2)}{2M_N}\right]\gamma_5 u(\vec{p}_i)$

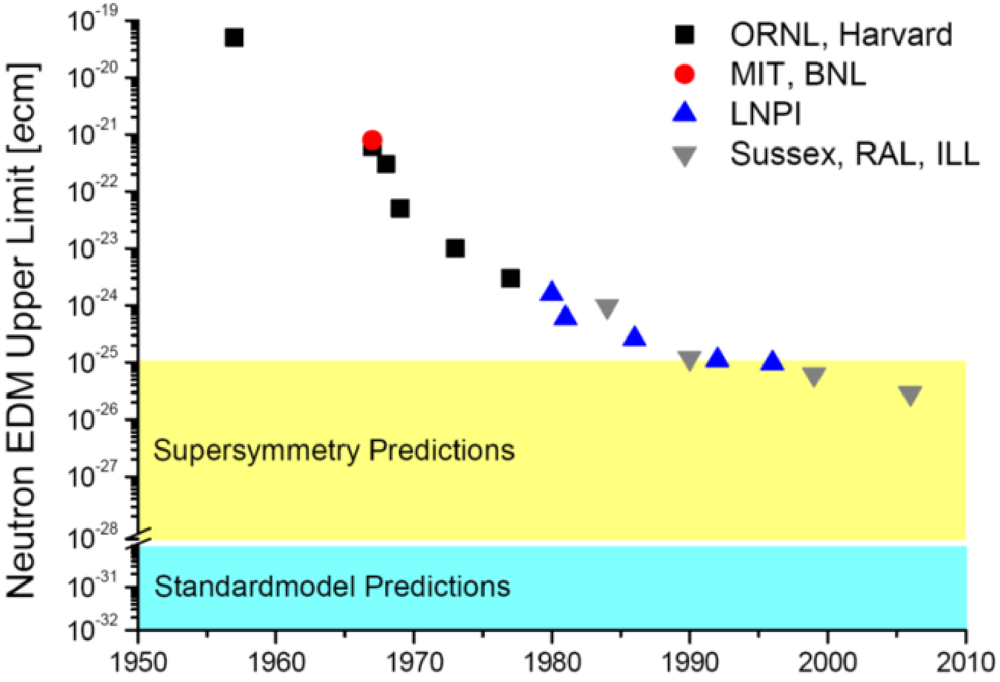


nEDM

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

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

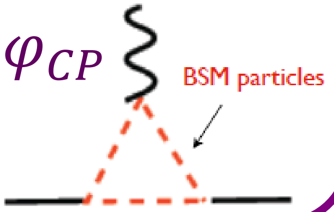
CP-even QCD vacuum
with θ-term expansion; noisy
RBC, J/E, CP-PACS(2005),
CP-PACS(2006, 2010), QCDSF(2011), …

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

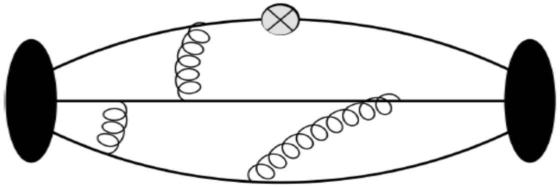
- Quark EDM (d_q) in nucleon comes from

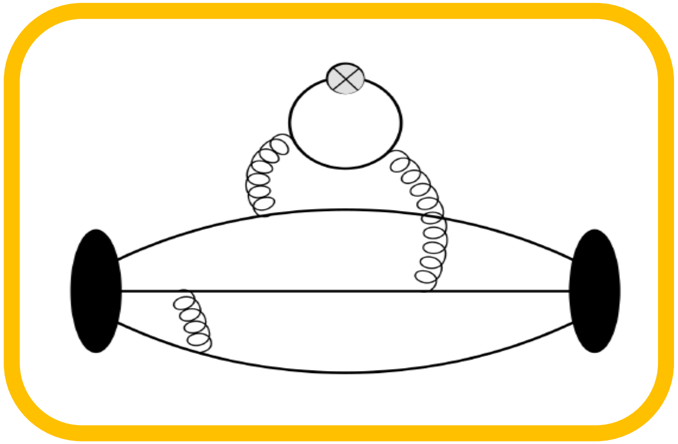
$$d_N = d_u g_T^{(n,u)} + d_d g_T^{(n,d)} + d_s g_T^{(n,s)}$$

  - 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, …

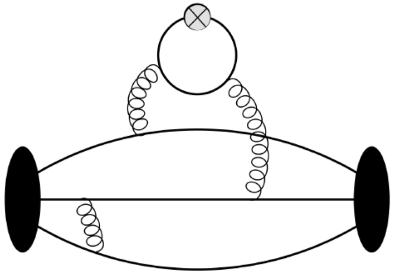




Electric Dipole Moment

- Quark EDM (d_q) in nucleon comes from

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

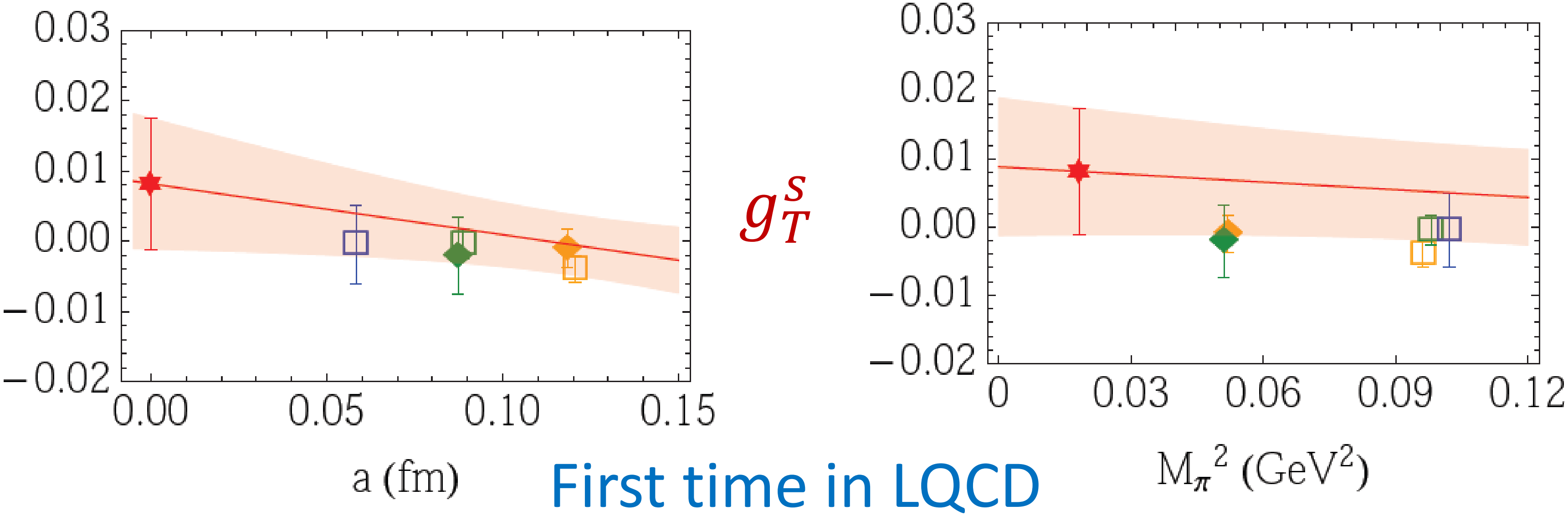


- Hadronic contribution: $\langle N | \bar{q} \sigma_{\mu\nu} q | N \rangle$, $q \in \{u, d, s\}$

- Need “disconnected” diagram contributions
- Extrapolate to the continuum limit

PNDME, 1506.04196; 1506.06411

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

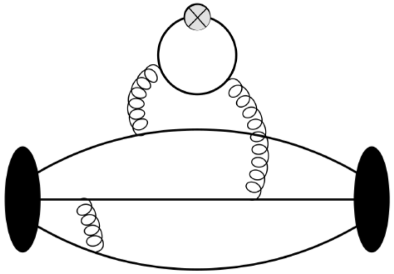


First time in LQCD

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

§ Need "disconnected" diagram contributions

§ Extrapolate to the continuum limit PNDME, 1506.04196; 1506.06411

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

§ Implications for new physics?

§ Take split SUSY for example

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

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

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

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

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

Summary

- Exciting era using LQCD to study SM nucleon inputs
  - Well-studied systematics → precision inputs
  - More nucleon matrix elements with physical pion masses
- Precision low-E experiments to probe BSM physics
  - Combined effort from experiment and theory sides
  - More work devoted to the intensity frontier, e.g. nEDM
- Overcoming longstanding obstacles
  - Address neglected disconnected contributions (e.g. g_T^S)
  - Bjorken-x dependence of parton distribution functions
- Stay tuned for many more exciting results from LQCD

TeV
↑
GeV

Titan @ORNL
IC@LANL

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

The work of HL is sponsored by NSF CAREER Award under grant PHY 1653405

36TH INTERNATIONAL SYMPOSIUM ON LATTICE FIELD THEORY

MICHIGAN STATE UNIVERSITY

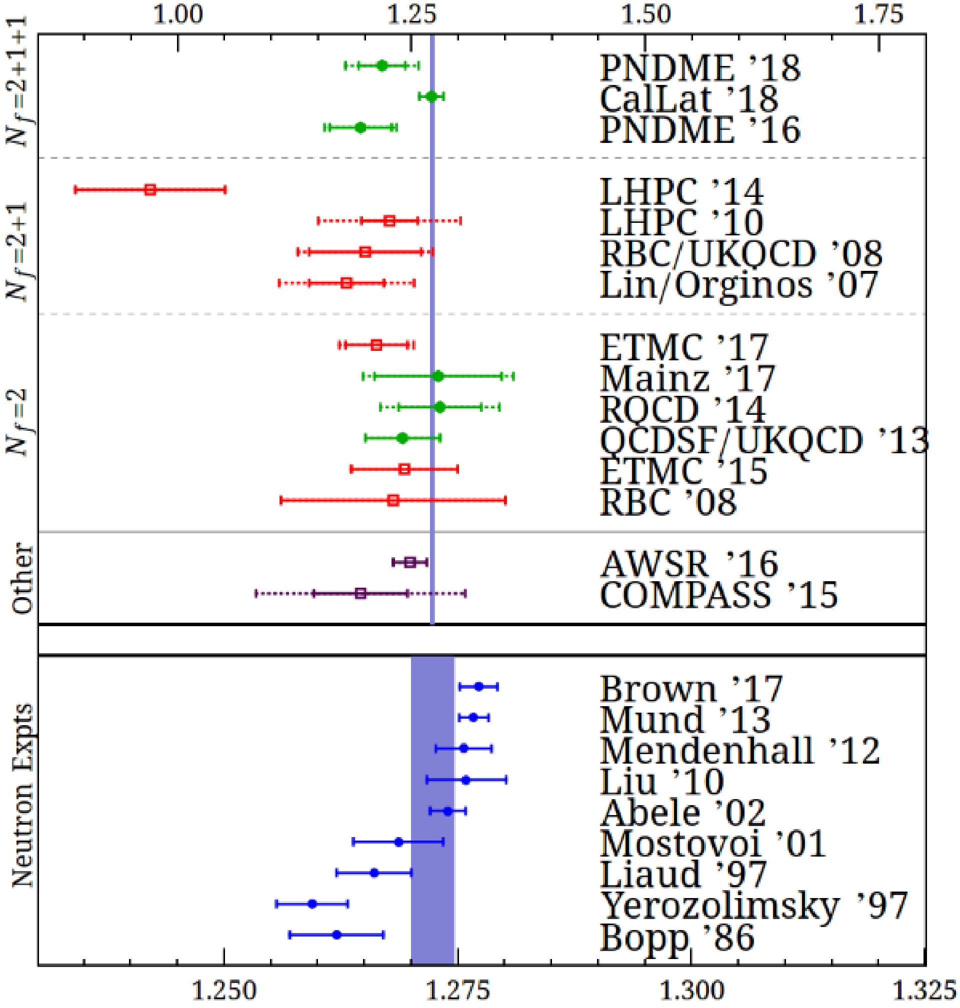
MICHIGAN STATE
UNIVERSITY

http://www.pa.msu.edu/conf/Lattice2018/

Backup Slides

Nucleon Axial Charge

§ Summary



§ Implications?

- 2σ might go away with greater statistics

Lattice 2016 Prelim.

- RBC* 2+1f 1.15(4)
- PACS* 2+1f 1.8(4)

§ New physics?

- $\lambda = g_A / g_V f_{NP}$

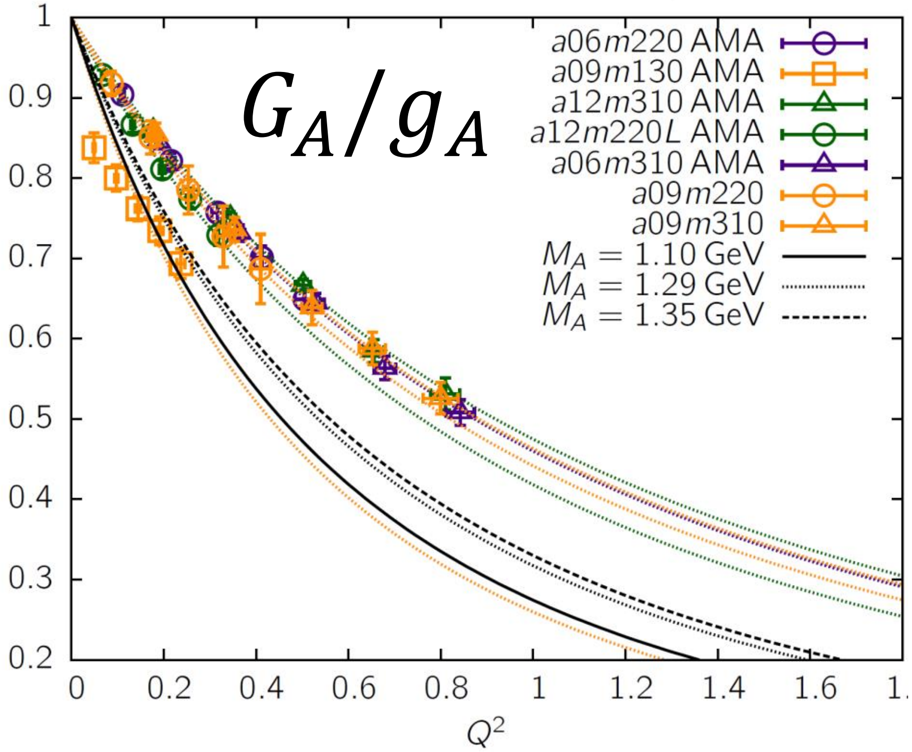
$$A_0 = \frac{-2(\lambda^2 - |\lambda|)}{1 + 3\lambda^2}$$

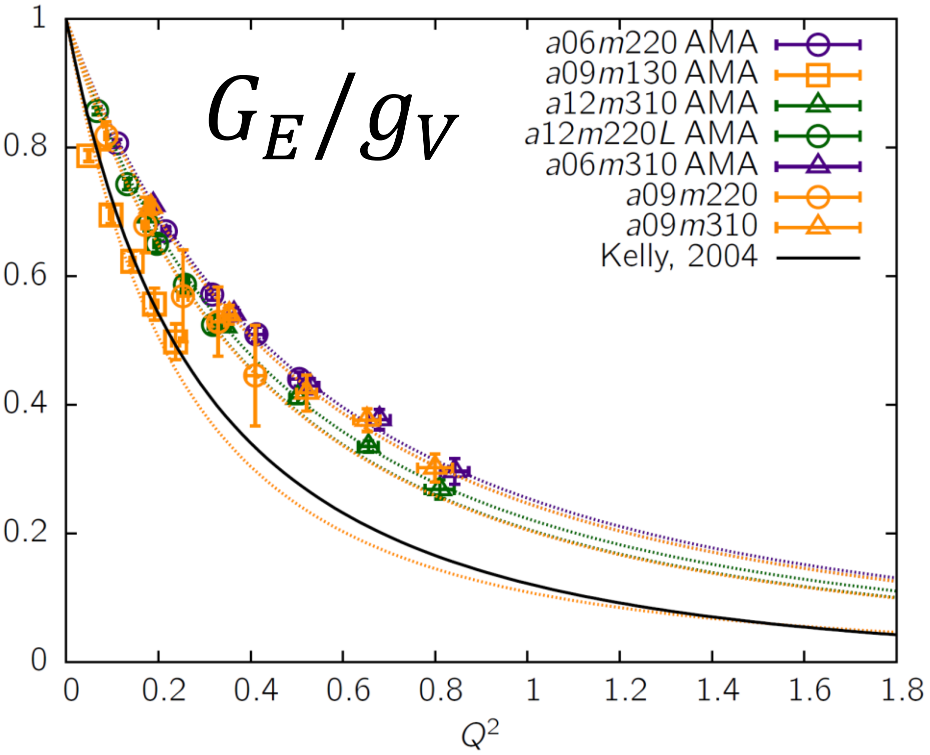
§ Stay tuned…

Others Results

§ Isovector form factors

Plots by **Yong-Chull Jang**





§ Flavor-dependent couplings, 1ST moments on PDFs, …

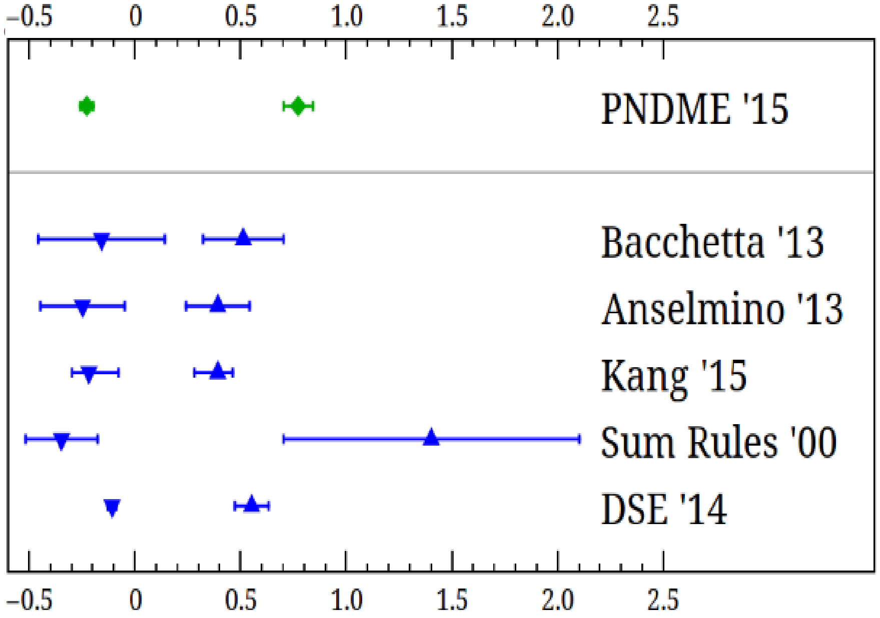
- qEDM by Cirigliano (this afternoon)

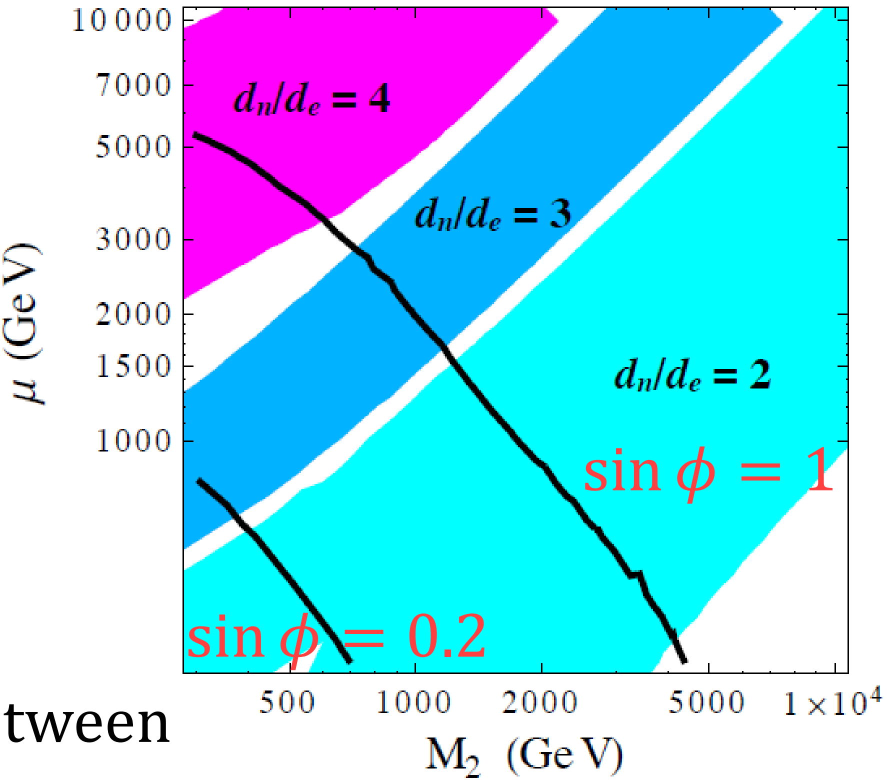
Quark EDM

§ Extrapolate to the physical limit

PNDME, 1506.04196; 1506.06411

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

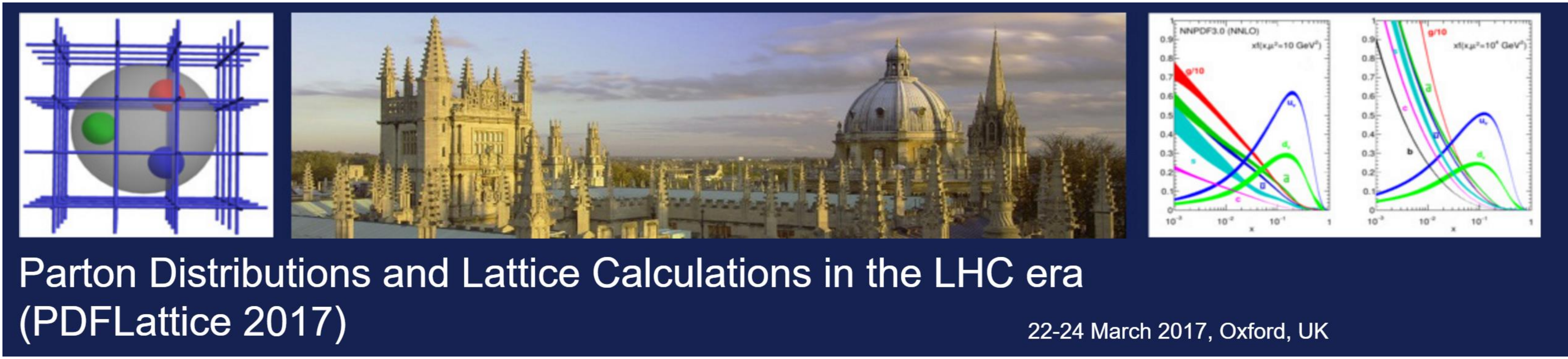




Observation of a neutron EDM between the current limit and $4 \times 10^{-28} e \cdot \mathrm{cm}$ would falsify the split-SUSY scenario with gaugino mass unification

Future Prospects

- A first joint workshop with global-fitting community to address key LQCD inputs
  - http://www.physics.ox.ac.uk/confs/PDFlattice2017



Parton Distributions and Lattice Calculations in the LHC era (PDFLattice 2017)

22-24 March 2017, Oxford, UK

"The goal of this workshop is to ***bring together the global PDF analysis and lattice-QCD communities*** *to explore ways to improve current PDF determinations. In particular, we plan to* ***set precision goals for lattice-QCD*** *calculations so that these calculations, together with experimental input, can achieve more reliable determinations of PDFs. In addition we will discuss what impact such improved determinations of PDFs will have on future new-physics searches."*