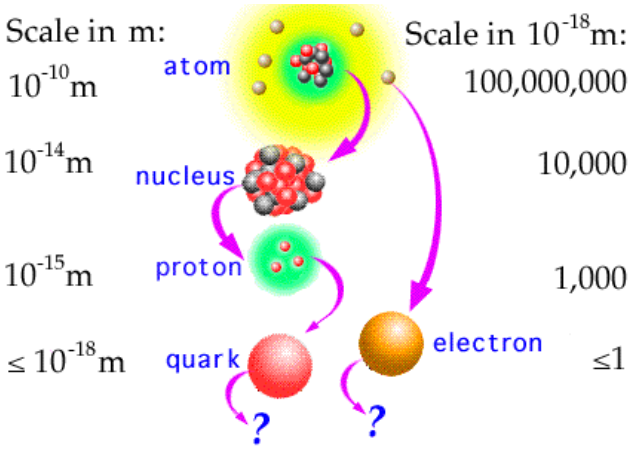
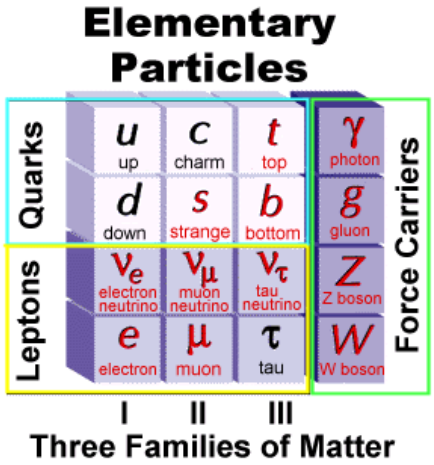
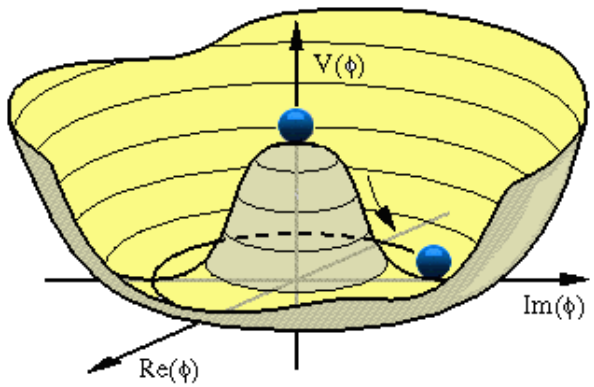
Probing BSM physics via precision measurements of nucleon structure

Rajan Gupta
Laboratory Fellow
Theoretical Division
Los Alamos National Laboratory, USA







LA-UR 16-29009

SNU, 24 May 2017

Work done in collaboration with

PNDME collaboration
(Clover-on-HISQ)

- Tanmoy Bhattacharya
- Vincenzo Cirigliano
- Huey-Wen Lin
- Boram Yoon
- Yong-Chull Jang

Bhattacharya et al, PRD85 (2012) 054512
Bhattacharya et al, PRD89 (2014) 094502
Bhattacharya et al, PRD92 (2015) 114026
Bhattacharya et al, PRL 115 (2015) 212002
Bhattacharya et al, PRD92 (2015) 094511
Bhattacharya et al, PRD94 (2016) 054508
Gupta et al, arXiv:1705:06834

NME collaboration
(Clover-on-Clover)

- Tanmoy Bhattacharya
- Vincenzo Cirigliano
- Jeremy Green
- Yong-Chull Jang
- Bálint Joó
- Huey-Wen Lin
- Kostas Orginos
- David Richards
- Sergey Syritsyn
- Frank Winter
- Boram Yoon

Yoon et al., PRD D93 (2016) 114506
Yoon el al., PRD D95 (2017) 074508

Acknowledgement: Computing Resources

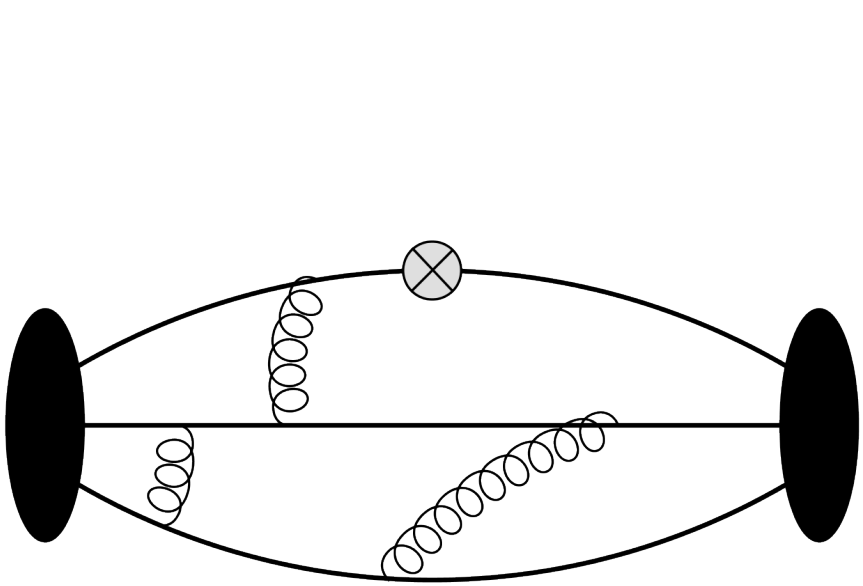
- Clover-on-Clover: Oak Ridge Leadership Computing Facility at the Oak Ridge National Laboratory, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.
- Institutional Computing at Los Alamos National Laboratory.
- The USQCD Collaboration, funded by the Office of Science, U.S. DOE

- Clover-on-HISQ
- The National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. DOE under Contract No. DE-AC02-05CH11231
- The USQCD Collaboration, funded by the Office of Science, U.S. DOE
- The Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant number ACI-1053575
- Institutional Computing at Los Alamos National Laboratory.

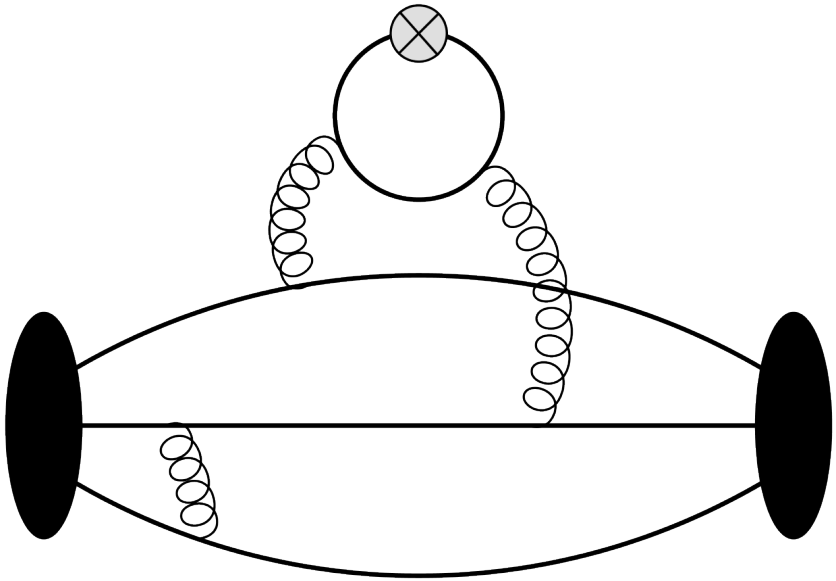
Outline

- Physics Motivation
  - Nucleon structure
  - Probing BSM physics in low-energy experiments
  - Novel CP violation & Neutron EDM (Baryogenesis)
- Matrix elements within nucleon states
  - Status of control over systematic errors
- Results:
  - g_A, g_S, g_T
  - Electric, magnetic, axial form factors
  - Quark EDM
  - Quark Chromo EDM

If we can extract the matrix elements of quark bilinear operators within the nucleon state by calculating the "connected" and "disconnected" correlation functions with high precision, we can address a number of physics questions.



Connected

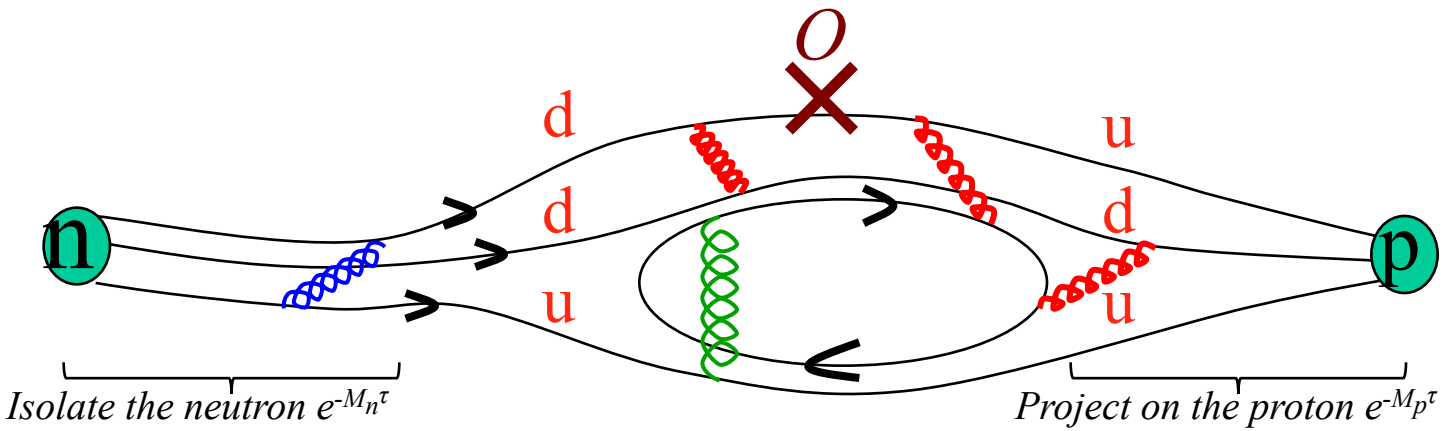


Disconnected

A number of matrix elements within nucleon states become accessible

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

Calculating matrix elements using Lattice QCD

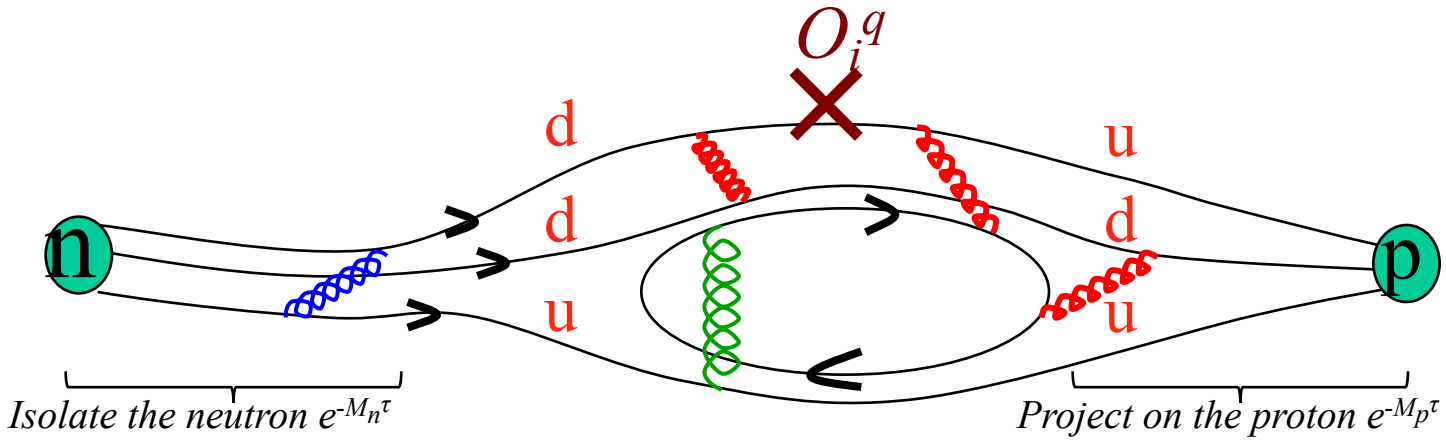


$$\left\langle \Omega \left| \hat{N}(t,p')\hat{O}(\tau,p'-p)\hat{N}(0,p) \right| \Omega \right\rangle =$$

$$\sum_{i,j} \left\langle \Omega \left| \hat{N}(p') \right| N_j \right\rangle e^{-\int dt\, H} \left\langle N_j \left| \hat{O}(\tau,p'-p) \right| N_i \right\rangle e^{-\int dt\, H} \left\langle N_i \left| \hat{N}(p) \right| \Omega \right\rangle =$$

$$\sum_{i,j} \left\langle \Omega \left| \hat{N}(p') \right| N_j \right\rangle e^{-E_j(t-\tau)} \left\langle N_j \left| \hat{O}(\tau,p'-p) \right| N_i \right\rangle e^{-E_i\tau} \left\langle N_i \left| \hat{N}(p) \right| \Omega \right\rangle$$

Achieving <10% uncertainty in nuclear charges $\langle p|\bar{u}\,\Gamma d|n\rangle$



- **Reached <10% uncertainty in nuclear charges. It required:**
  - High Statistics: O(1,000,000) measurements
  - Demonstrating control over all Systematic Errors:
    - Non-perturbative renormalization of bilinear operators (RI_{smom} scheme)
    - Contamination from excited states
    - Finite volume effects
    - Chiral extrapolation to physical m_u and m_d (simulate at physical point)
    - Extrapolation to the continuum limit (lattice spacing $a \rightarrow 0$)

Simplest quantities to calculate are the isovector charges

g_A, g_S, g_T

g_A, g_S, g_T: What is known

- Experiment: Neutron decay
  - $g_A = 1.276(2)$

- CVC + Lattice QCD

Gonzalez-Alonso & Camalich
Phy. Rev. Lett. 112 (2014) 042501

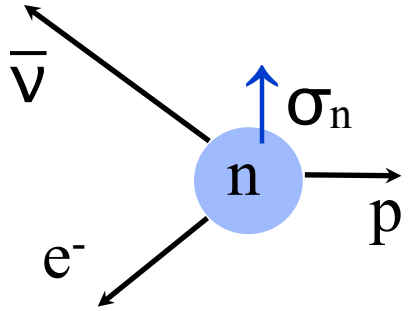
$$\frac{g_S}{g_V} = \frac{(M_N - M_P)^{QCD}}{(m_d - m_u)^{QCD}} = 1.02(8)(7)$$

$$\left[g_S^{PNDME} = 0.97(12)\right] \odot \left[(m_d\text{-}m_u)^{FLAG} = 2.67(35)\ \text{MeV}\right]$$

$$(M_N\text{-}M_P)^{QCD} = 2.59(49)\ \text{MeV}$$

[Ultra]Cold Neutron Decay: Parameters sensitive to new physics

Neutron decay can be parameterized as



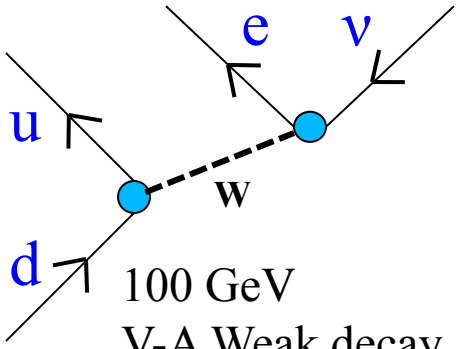
$$d\Gamma \propto F(E_e)\left[1 + b\frac{m_e}{E_e} + \left(B_0 + B_1\frac{m_e}{E_e}\right)\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + \cdots\right]$$

b: Deviations from the leading order electron spectrum: Fierz interference term

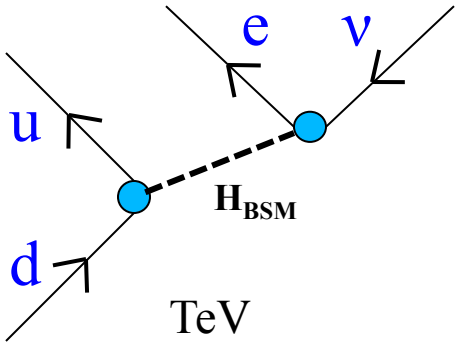
B_1: Energy dependent part of correlation of antineutrino momentum with the neutron spin

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

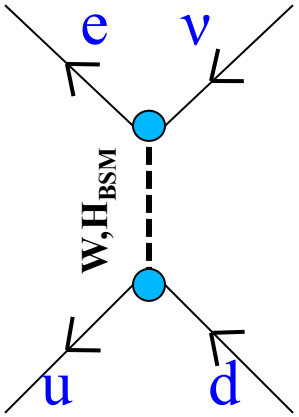
Many BSM possibilities for novel Scalar & Tensor interactions: Higgs-like, leptoquark, loop effects, …



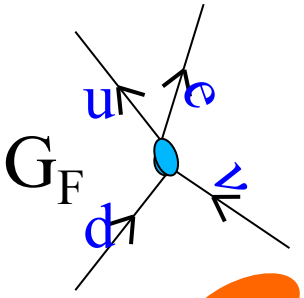
100 GeV
V-A Weak decay
e_L with a ν_L

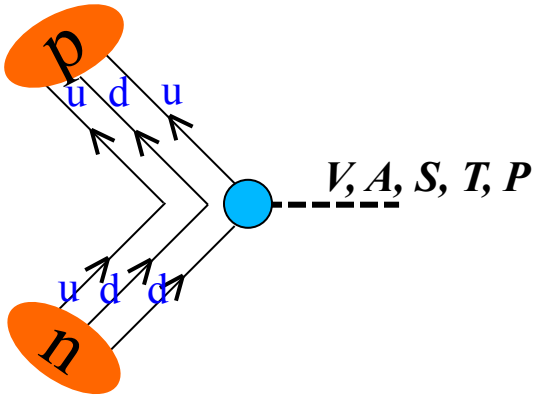


TeV
Novel S,T Interactions
e_R with a ν_L



LHC





Neutron
Decay

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

Relating b, B_1 to $g_{S,T}$ & BSM couplings $\varepsilon_{S,T}$

$$H_{eff} \supset G_F \left[\varepsilon_S \overline{u}d \; \overline{e}(1-\gamma_5)\nu_e + \varepsilon_T \overline{u}\sigma_{\mu\nu}d \; \overline{e}\sigma^{\mu\nu}(1-\gamma_5)\nu_e \right]$$

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

Lattice QCD

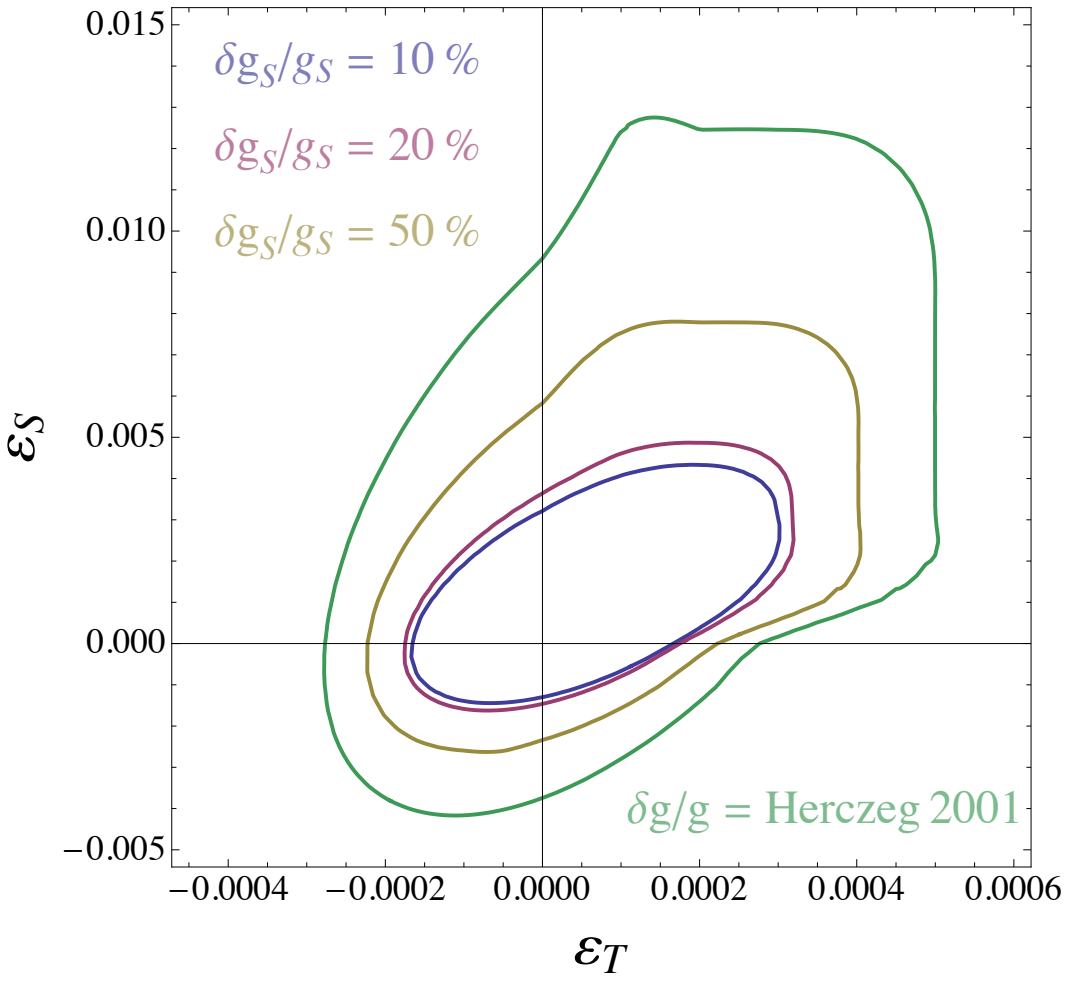
Linear order relations from $n \rightarrow p\, e\, \bar{\nu}$ decay

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

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

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

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



Experimental input

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

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

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

Impact limited by precision of ME from Lattice QCD

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

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

Goal: 10% accuracy in g_S and g_T

Challenges to obtaining high precision results for matrix elements within nucleon states

- **High Statistics: O(1,000,000) measurements**
- **Demonstrating control over all Systematic Errors:**
  - Non-perturbative renormalization of bilinear operators (RI_{smom} scheme)
  - Contamination from excited states
  - ➢ Finite volume effects
  - ➢ Chiral extrapolation to physical m_u and m_d (simulate at physical point)
  - ➢ Extrapolation to the continuum limit (lattice spacing $a \rightarrow 0$)

Perform simulations on ensembles with multiple values of

- ➢ Lattice size $M_\pi L \rightarrow \infty$
- ➢ Light quark masses $\rightarrow$ physical m_u and m_d
- ➢ Lattice spacing $a \rightarrow 0$

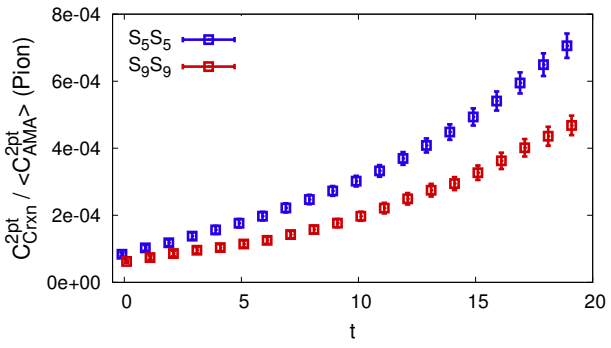
Toolkit

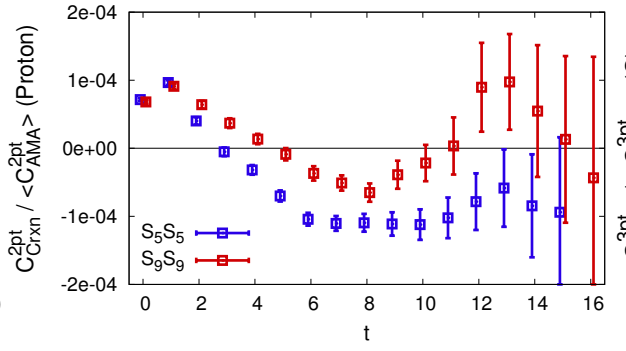
- Multigrid Dirac invertor → propagator $S_F = D^{-1}\eta$
- Truncated solver method with bias correction (AMA)
- Coherent source sequential propagator
- Deflation + hierarchical probing
- 3-5 values of t_{sep} with smeared sources
- 2-state (3-state fit) to multiple values of t_{sep}
- Non-perturbative methods for renormalization constants
- Combined extrapolation in a, M_π, $M_\pi L$
- Variation of results with extrapolation Ansatz

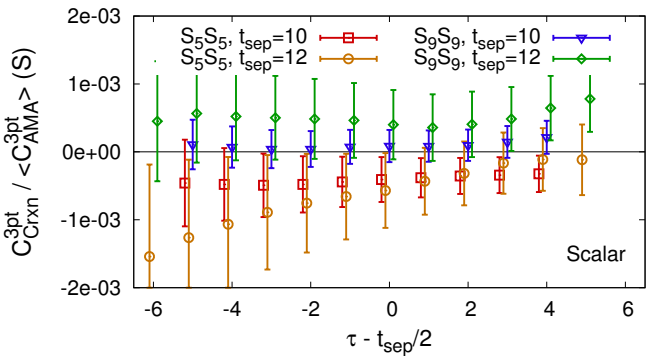
Truncated solver + bias correction (AMA)

$$C^{AMA} = \frac{1}{N_{LP}} \sum_{i=1}^{N_{LP}} C_{LP}(x_i^{LP}) + \frac{1}{N_{HP}} \sum_{i=1}^{N_{HP}} \{C_{HP}(x_i^{HP}) - C_{LP}(x_i^{HP})\}$$

- Use multigrid inverter with
  - $r_{LP} = 10^{-3}$
  - $r_{HP} = 10^{-7} - 10^{-10}$
  - $N_{LP} = 64-160$, $N_{HP} = 3\text{-}5$ per configuration
- The bias term is negligible (~1% of the error)
- The AMA error is <15% larger than LP







2+1+1 flavor HISQ lattices from MILC

M_s tuned to its physical value using M_{ss}

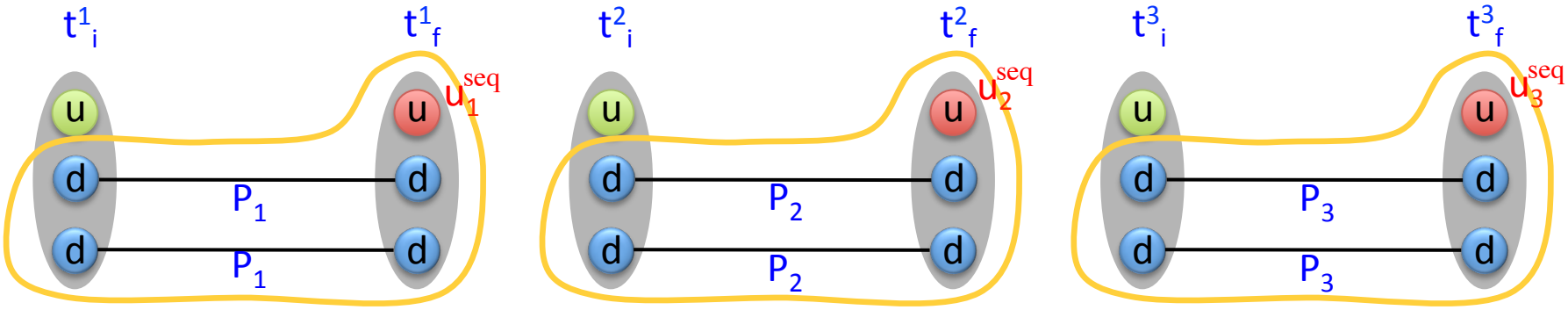
a (fm)	m_l/m_s	Volume	$M_\pi L$	M_π (MeV)	# Configs	$\bar{HP}$	AMA
0.12 □	0.2	$24^3 \times 64$	4.55	310	1013	8,104	64,832
0.12 △	0.1	$24^3 \times 64$	3.29	225	1000	24,000	
0.12 ◆	0.1	$32^3 \times 64$	4.38	228	958	7,664	
0.12 ▽	0.1	40^3 x 64	5.49	228	1010	8,080	68,680
0.09 □	0.2	$32^3 \times 96$	4.51	313	881	7,048	
0.09 ◆	0.1	$48^3 \times 96$	4.79	226	890	7,120	
0.09 ○	0.037	$64^3 \times 96$	3.90	138	883	7,064	84,768
0.06 □	0.2	$48^3 \times 144$	4.52	320	1000	8,000	64,000
0.06 ◆	0.1	$64^3 \times 144$	4.41	235	650	2,600	41,600
0.06 ○	0.037	$96^3 \times 192$	3.7	135	322	1,610	51,520

2+1 flavor Clover lattices (Jlab/W&M)

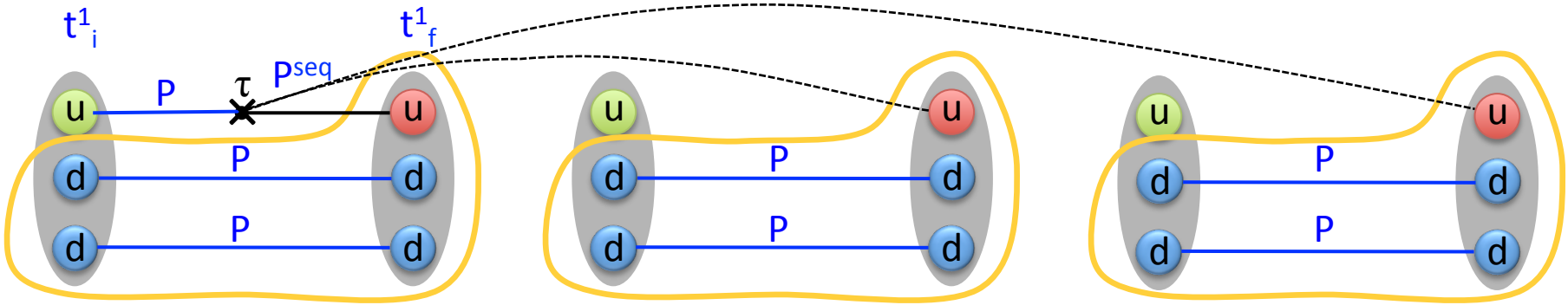
M_s tuned to its physical value using $(2M_{K^+}^2 - M_{\pi^0}^2)/M_{\Omega^-}^2$

a fm	M_π MeV	Lattice Volume	M_π L	t_{sep}	Smearing σ	# of Configs	HP Src.	LP Src
0.114	316	$32^3 \times 96$	5.85	8,10,12,14	5	1000	4000	128,480
0.081	312	$32^3 \times 64$	4.11	10,12,14,16,18	5	1005	3,015	96,480
0.081	312	$32^3 \times 64$	4.11	8,10,12,14,16	7	1005	3,015	96,480
0.081	312	$32^3 \times 64$	4.11	10,12,14,16,18	9	1005	3,015	96,480
0.081	312	$32^3 \times 64$	4.11	12	V357, V579	443	0,1329	42,528
0.079	192	$48^3 \times 96$	3.7	8,10,12,14,16	7	629	2,516	80,512
0.079	198	$64^3 \times 128$	5.08	8,10,12,14,16	7	467	2,335	74,720

Coherent Source Sequential Propagator



3 measurements being done in a single computer job



Bias = 0 after gauge integral: Increase in Variance ???

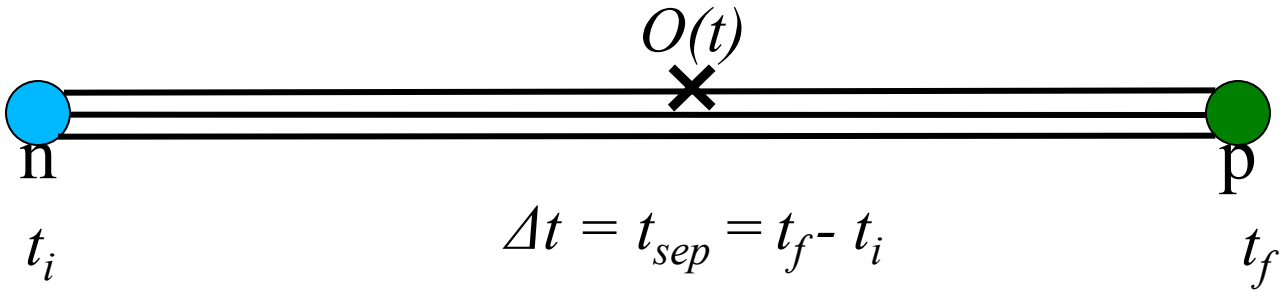
Controlling excited-state contamination: n-state fit

$$\Gamma^2(t) = |A_0|^2 e^{-M_0 t} + |A_1|^2 e^{-M_1 t} + |A_2|^2 e^{-M_2 t} + |A_3|^2 e^{-M_3 t} + \ldots.$$

$$\Gamma^3(t, \Delta t) = |A_0|^2 \langle 0|O|0\rangle e^{-M_0 \Delta t} + |A_1|^2 \langle 1|O|1\rangle e^{-M_1 \Delta t} +$$
$$A_0 A_1^* \langle 0|O|1\rangle e^{-M_0 \Delta t} e^{-\Delta M(\Delta t - t)} + A_0^* A_1 \langle 1|O|0\rangle e^{-\Delta M t} e^{-M_0 \Delta t} + \ldots$$

M_0, M_1, … masses of the ground & excited states

A_0, A_1, … corresponding amplitudes



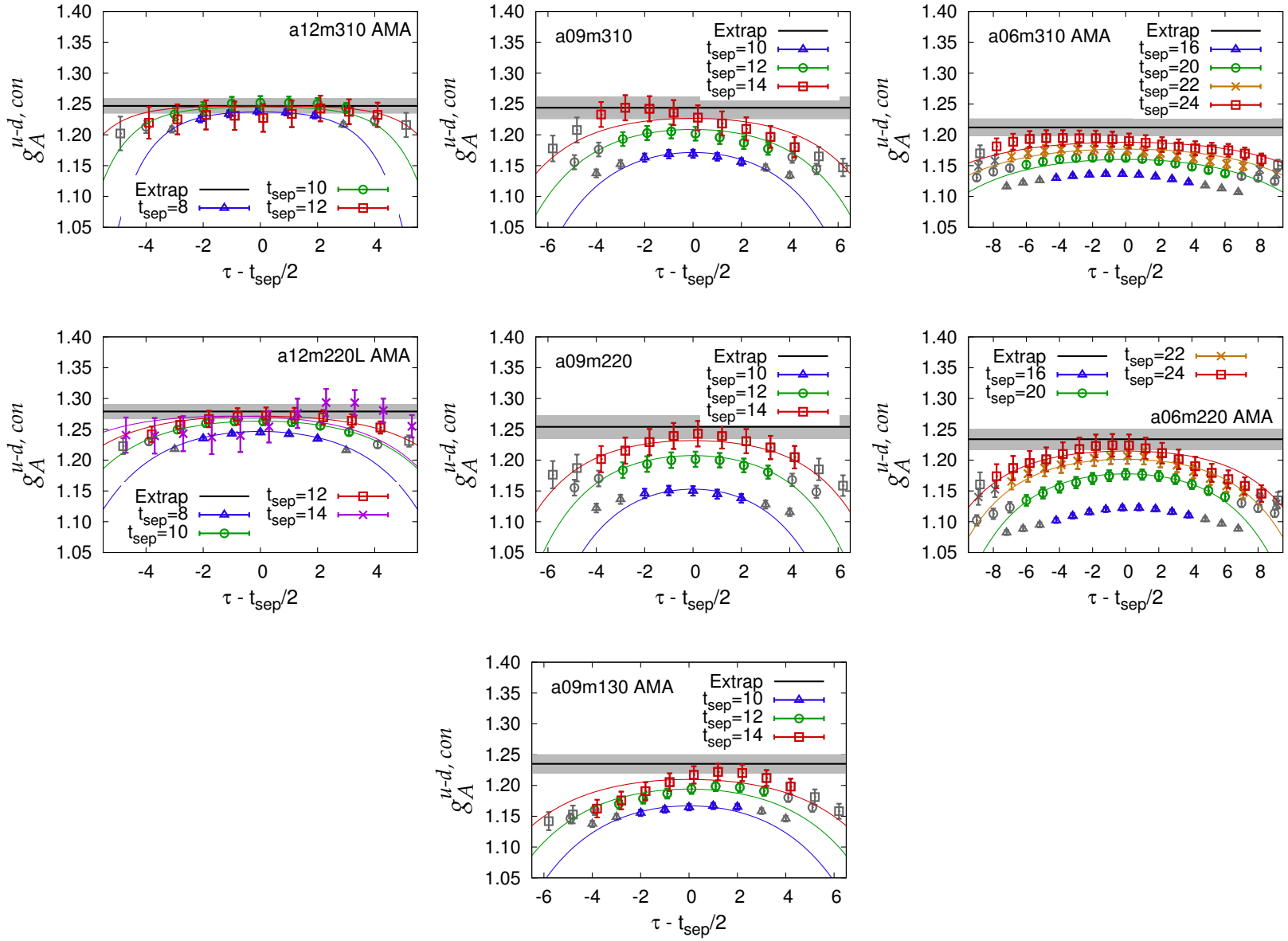
Make a simultaneous fit to data at multiple $\Delta t = t_{sep} = t_f - t_i$

Controlling excited-state contamination

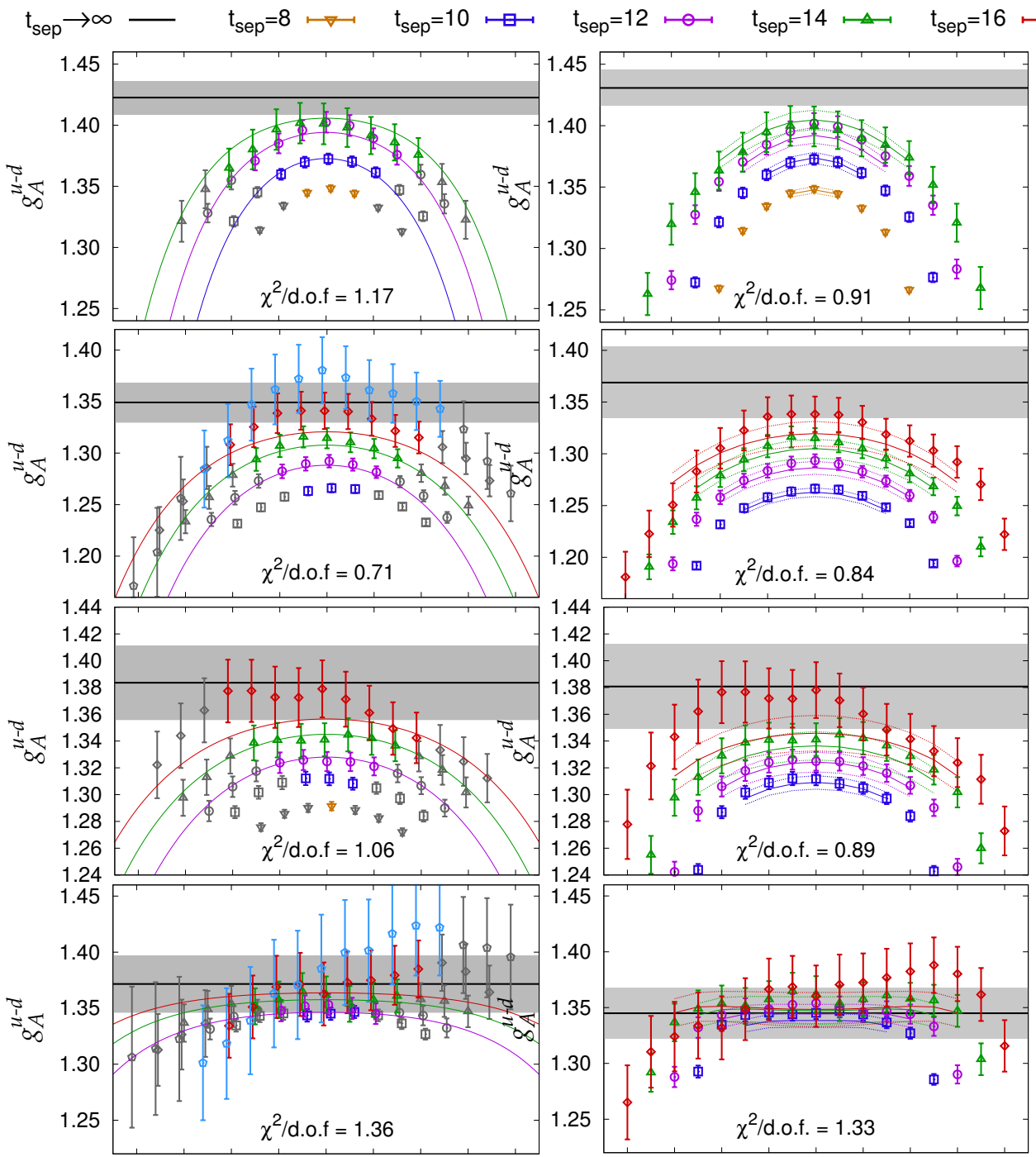
- Reduce A_n/A_0 in an n-state fit
  - Tune source smearing size σ
  - Tune the interpolating operator
  - Variational method
- Generate data at multiple values of t_{sep}
- 2- versus 3-state fits to data at multiple values of t_{sep}

Yoon et al, PRD D93 (2016) 114506
Yoon el al, PRD D95 (2017) 074508

g_A: Excited State Contamination



Data and fits on 7 clover-on-HISQ ensembles: Bhattacharya et al, PRD94 (2016) 054508



Clover on Clover ESC

Yoon et al., PRD D93 (2016) 114506

Analyzing lattice data $\Omega(a, M_\pi, M_\pi L)$:
Extrapolations in a, M_π^2, $M_\pi L$

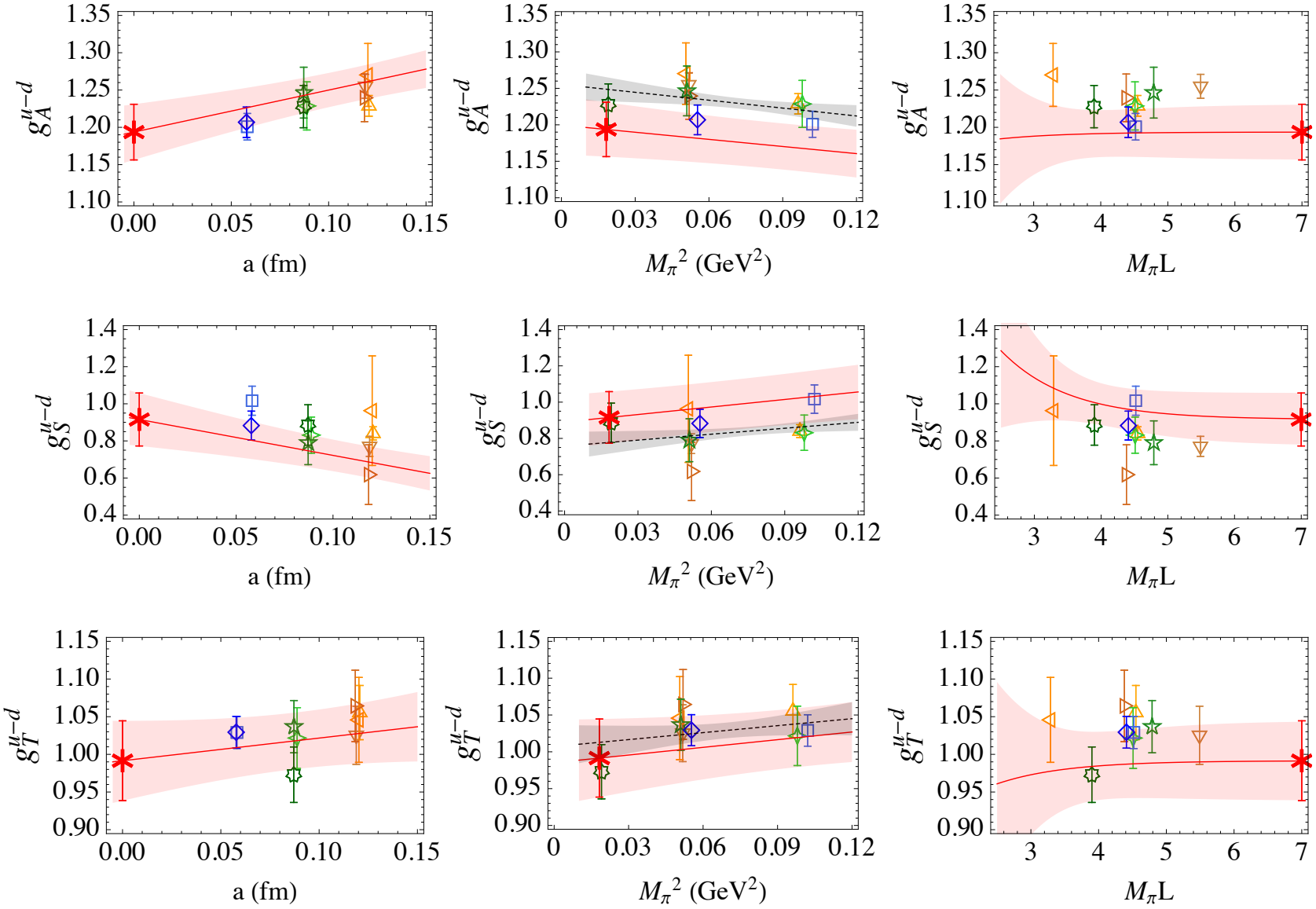
We use lowest order corrections when fitting lattice data w.r.t.

- Lattice spacing: a
- Dependence on light quark mass: $m_q \sim M_\pi^2$
- Finite volume: $M_\pi L$

$$g_{A,T}(a, M_\pi, L) = g + A\, a + B\, M_\pi^2 + C\, M_\pi^2 e^{-M_\pi L} + \ldots$$

$$g_S(a, M_\pi, L) = g + A\, a + B\, M_\pi + C\, M_\pi e^{-M_\pi L} + \ldots$$

Simultaneous extrapolation in a, M_π^2, $M_\pi L$



9 clover-on-HISQ ensembles: Bhattacharya et al, PRD94 (2016) 054508

Results on isovector charges of the proton (clover-on-HISQ)

(Bhattacharya et al, PRD94 (2016) 054508)

Isovector charges

*** $g_T = 0.987(51)$

** $g_A = 1.195(33)$

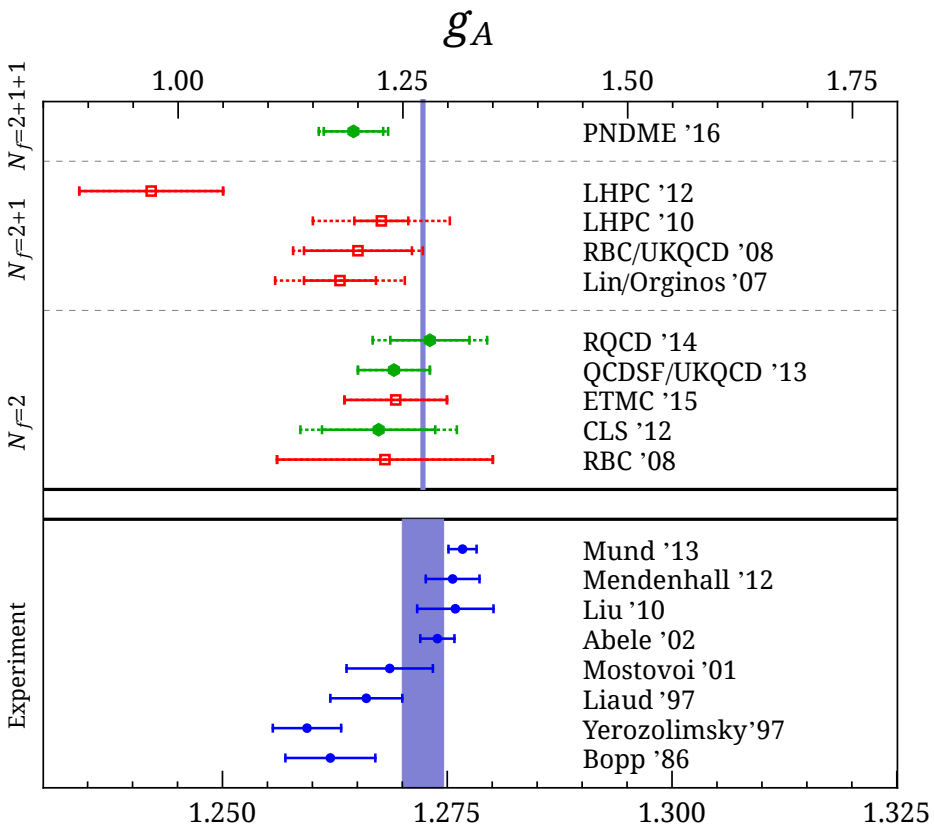
** $g_S = 0.97(12)$

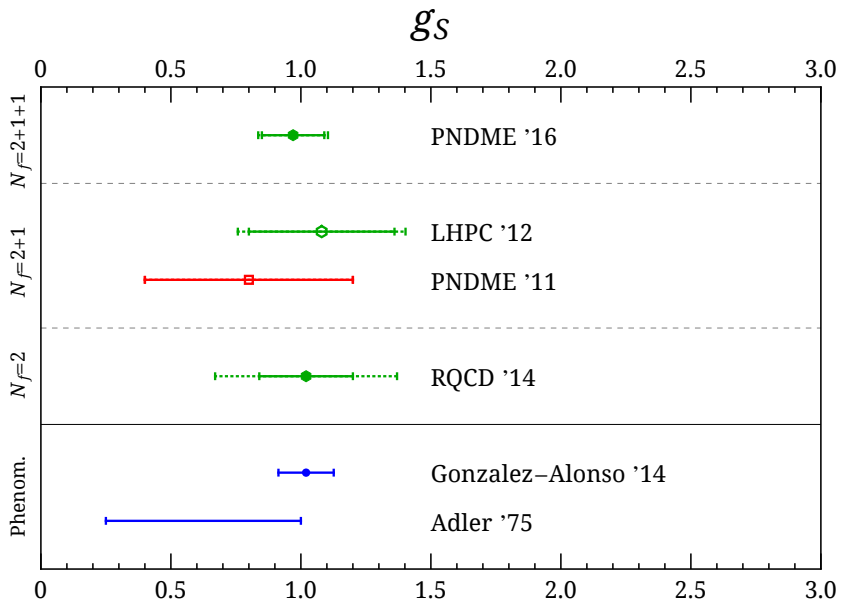
Flavor diagonal charges

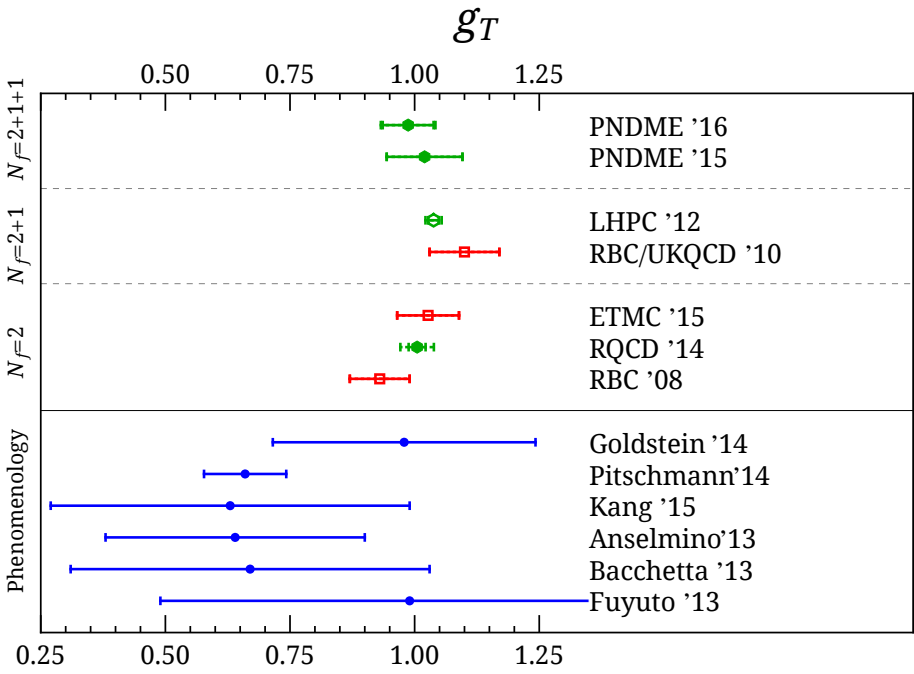
$g_T^u = 0.792(42)$

$g_T^d = -0.194(14)$

Status: g_A, g_S, g_T

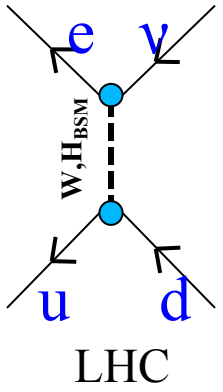


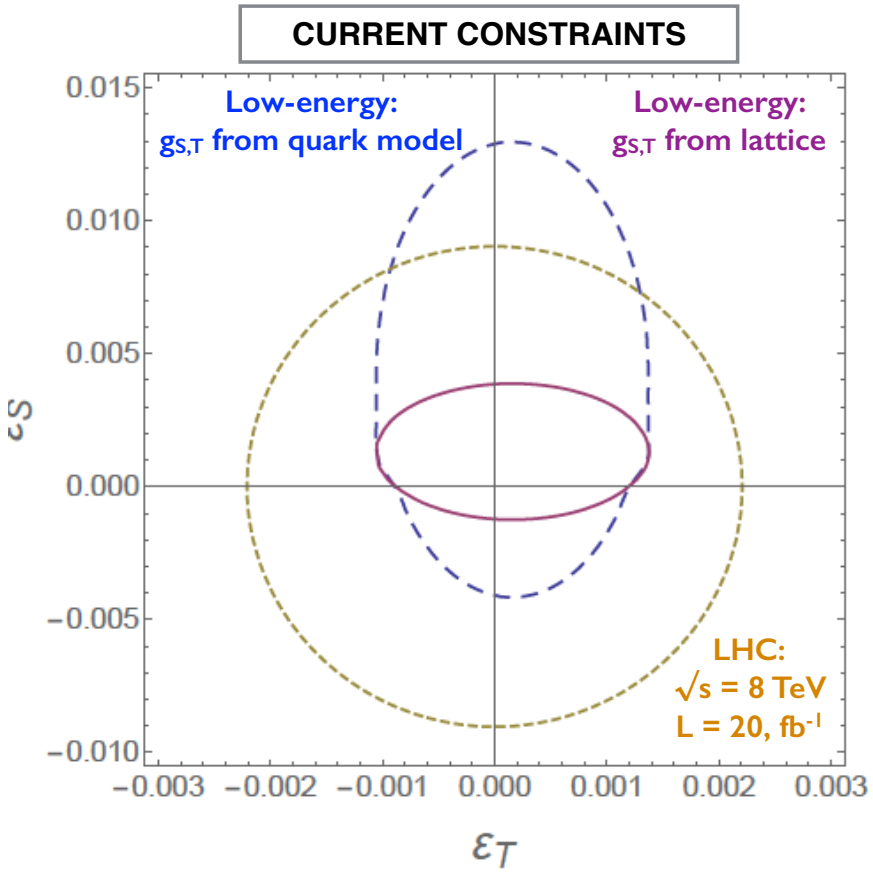


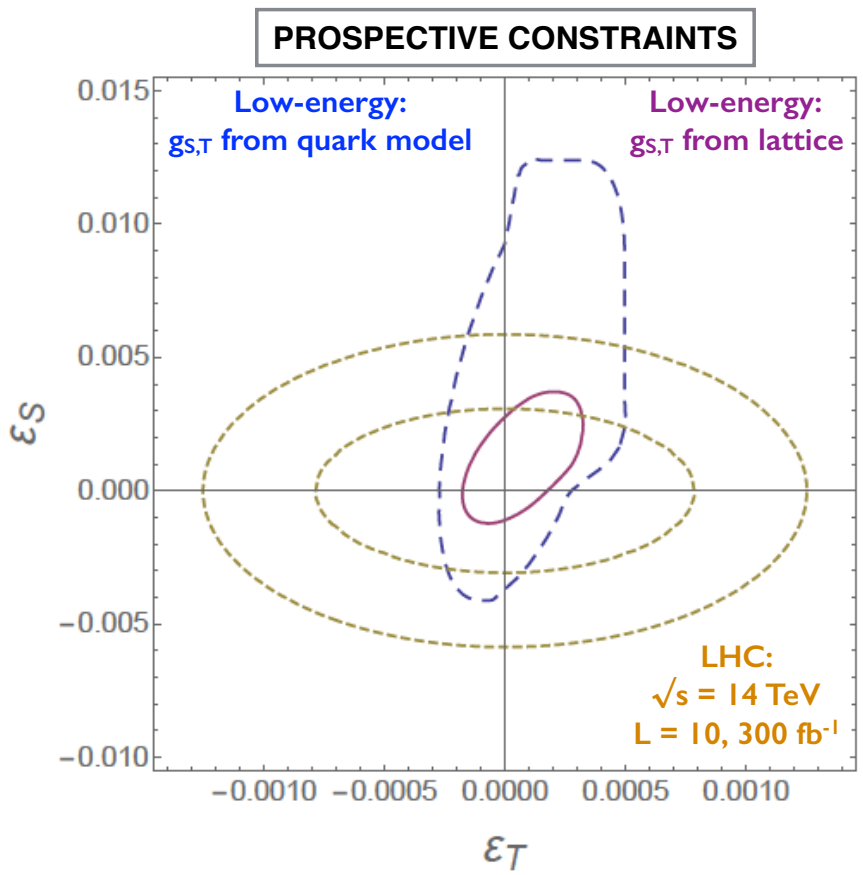


Constraints on $[\varepsilon_S, \varepsilon_T]$: β-decay versus LHC

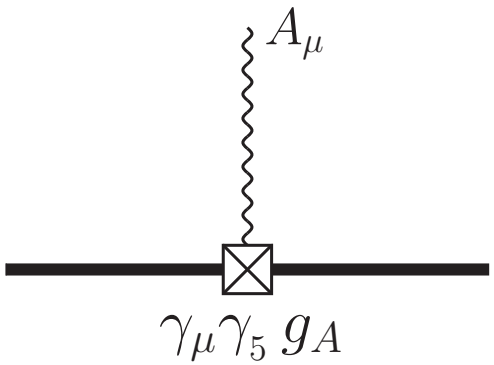
- LHC: (u+d → e+ν) look for events with an electron and missing energy at high transverse mass
- low-energy experiments + lattice with $\delta g_S/g_S \sim 10\%$

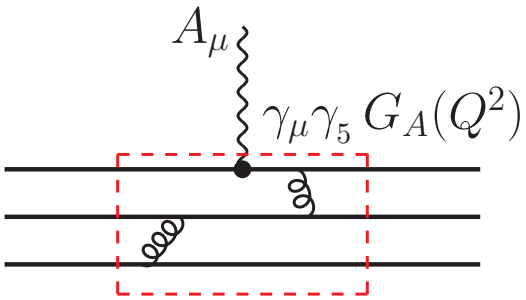


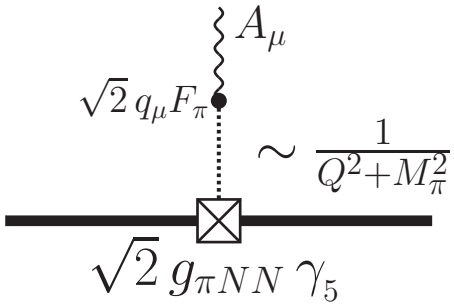




E, M, & Axial-vector form factors







E, M, & Axial-vector form factors

Vector Matrix Elements → Dirac (F_1) and Pauli (F_2) form factors

$$\left\langle N(p_f)\left|V^{\mu}(q)\right|N(p_i)\right\rangle = \bar{u}(p_f)\left[\gamma^{\mu}F_1(q^2) + \sigma^{\mu\nu}q_{\nu}\frac{F_2(q^2)}{2M}\right]u(p_i)$$

Define Sachs Electric (G_E) and Magnetic (G_M) form factors

$$G_E(q^2) = F_1(q^2) - \frac{q^2}{4M^2}F_2(q^2), \qquad G_M(q^2) = F_1(q^2) + F_2(q^2)$$

Axial-vector Matrix Elements → Axial (G_A) and Pseudoscalar (G_P)

$$\left\langle N(p_f)\left|A^{\mu}(q)\right|N(p_i)\right\rangle = \bar{u}(p_f)\left[\gamma^{\mu}G_A(q^2) + q_{\mu}\frac{\tilde{G}_P(q^2)}{2M}\right]\gamma_5 u(p_i)$$

Charge Radii

Electric, Magnetic, Axial Charge Radii from G_E, G_M, G_A

$$\left\langle r_i^2 \right\rangle = -\frac{6}{dq^2}\left[\frac{\hat{G}_i(q^2)}{\hat{G}_i(0)}\right]_{q^2=0}$$

Where

$$\hat{G}_{E,M} = \frac{G_{E,M}}{g_V}, \qquad \hat{G}_{A,P} = \frac{G_{A,P}}{g_A}, \qquad \hat{G}_M(0) = \mu = 1+\kappa$$

The dipole ansatz for G_E, G_M, G_A; pion-pole dominance for $\tilde{G}_P$

$$\hat{G}_i(q^2) = \frac{\hat{G}_i(0)}{\left(1+\frac{q^2}{M_i^2}\right)^2} \quad \rightarrow \quad \left\langle r_i^2 \right\rangle = \frac{12}{M_i^2}; \quad \hat{G}_P(q^2) = \hat{G}_A(q^2)\left[\frac{4m_\pi^2}{q^2+m_\pi^2}\right]$$

fit ansatz

A model independent approach is the z-expansion:

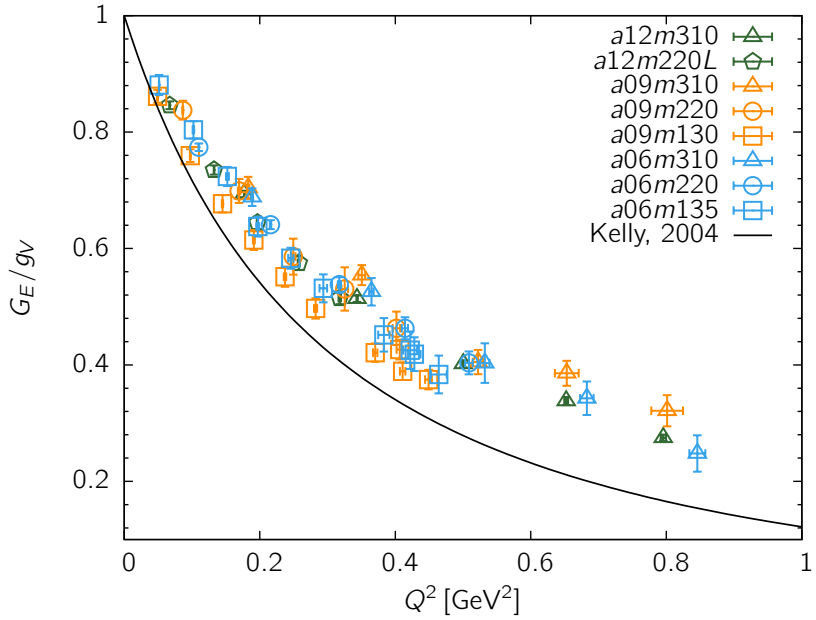
$$\hat{G}(Q^2) = \sum_{k=0}^{\infty} a_k z(Q^2)^k \qquad \text{with} \qquad z = \frac{\sqrt{t_{\text{cut}} + Q^2} - \sqrt{t_{\text{cut}} + Q_0^2}}{\sqrt{t_{\text{cut}} + Q^2} + \sqrt{t_{\text{cut}} + Q_0^2}}$$

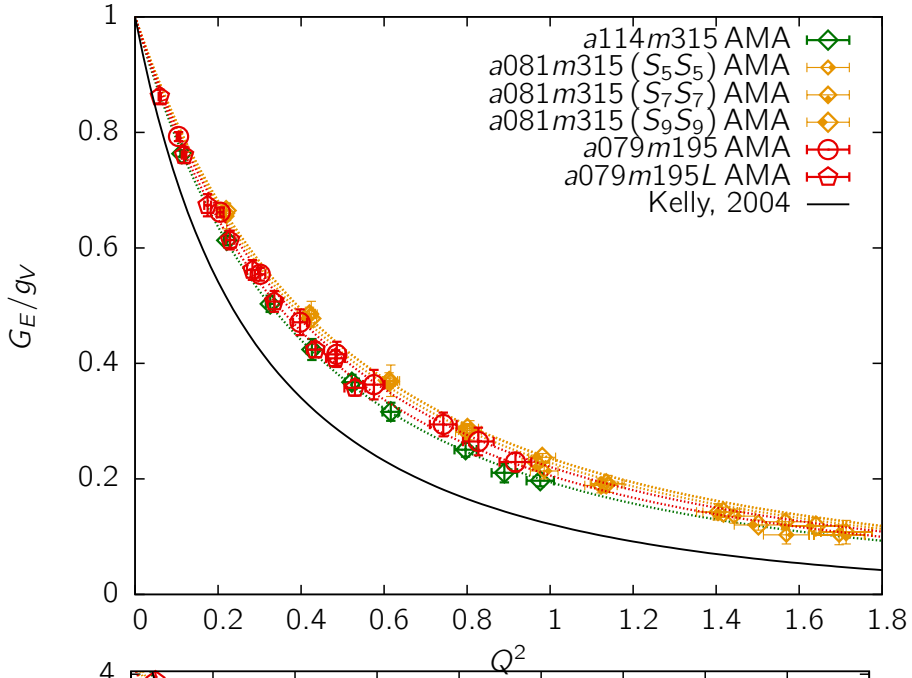
with $t_{\text{cut}} = 4m_\pi^2$ for $G_{E,M}$ and $t_{\text{cut}} = 9m_\pi^2$ for G_A. We choose $Q_0 = 0$

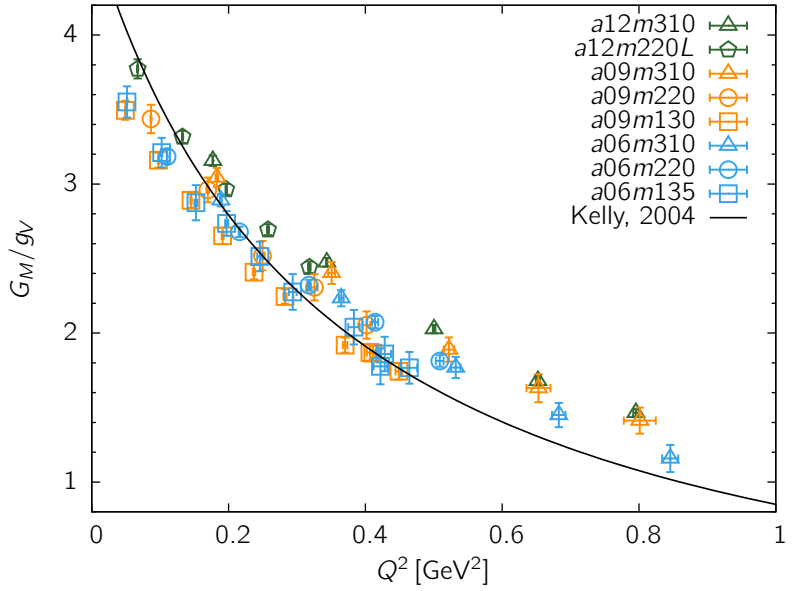
Kelly parameterization of the experimental data for G_E, G_M

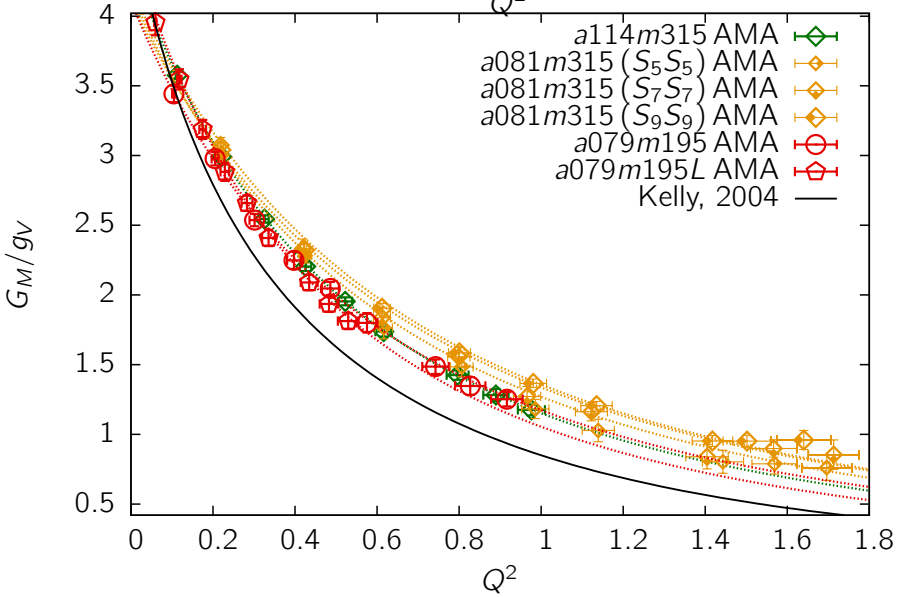
$$\hat{G}_X(Q^2) = \frac{\hat{G}(0) \sum_{k=0}^{n} a_k \tau^k}{\left\{1 + \sum_{k=1}^{n+2} b_k \tau^k\right\}}, \quad \hat{G}_Y(Q^2) = \frac{A\tau}{1 + B\tau} \frac{1}{\left(1 + Q^2/0.71\text{GeV}^2\right)^2}$$

where $\tau = Q^2/4\mathcal{M}^2$. The parameters $\mathcal{M}$, $G(0)$, a_k, b_k, A, and B are determined from fit to the data.



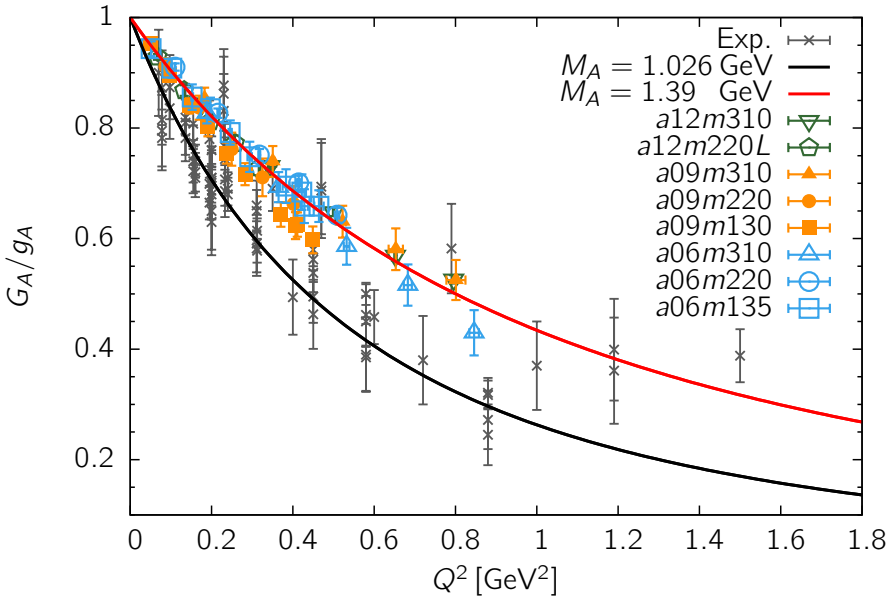


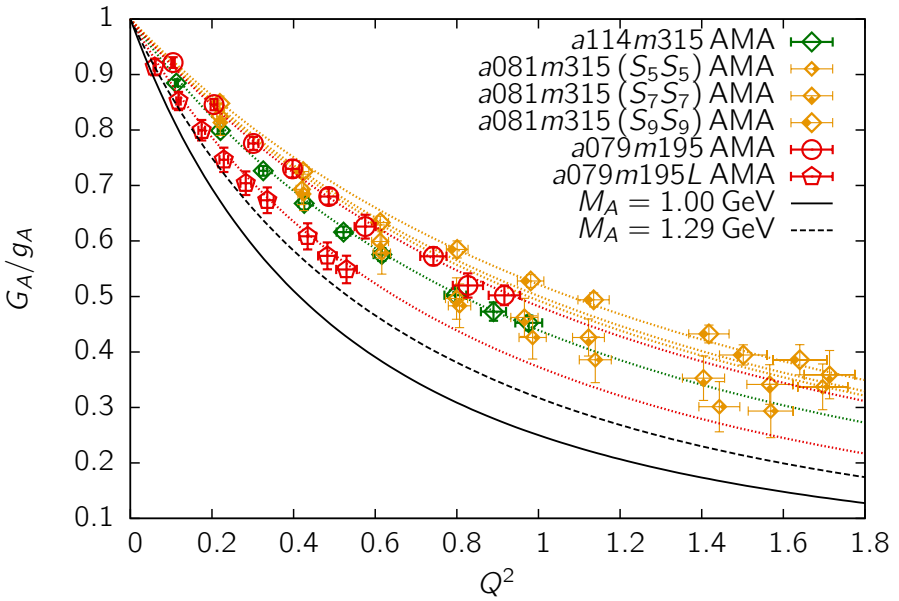


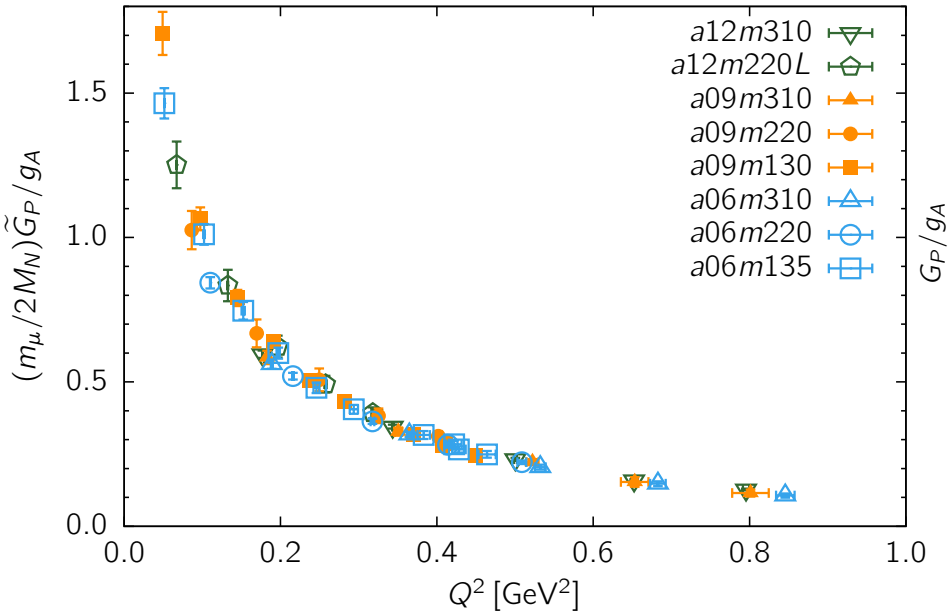


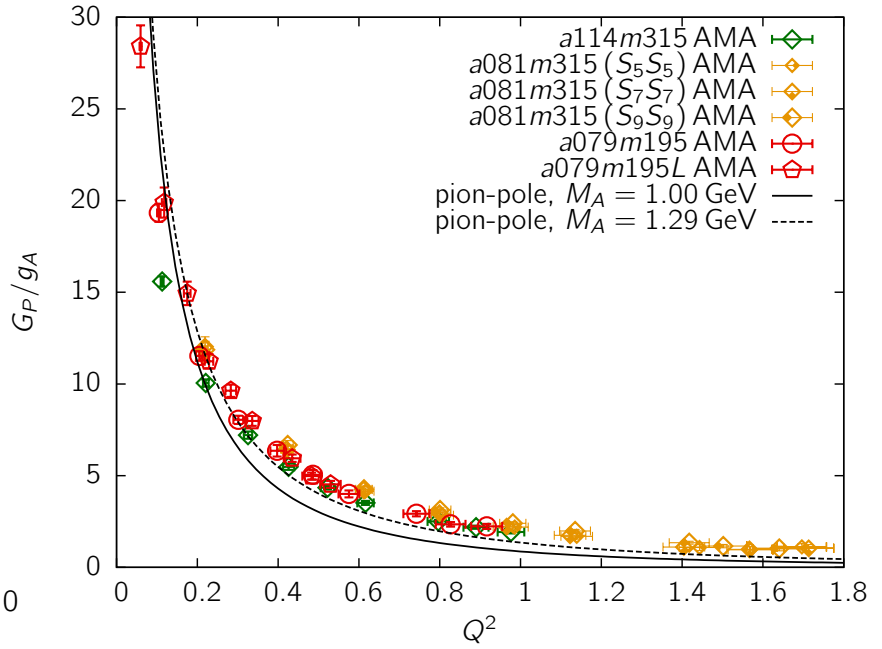
Data and Fits: clover-on-HISQ

Data and Fits: clover-on-clover









Data and Fits: clover-on-HISQ

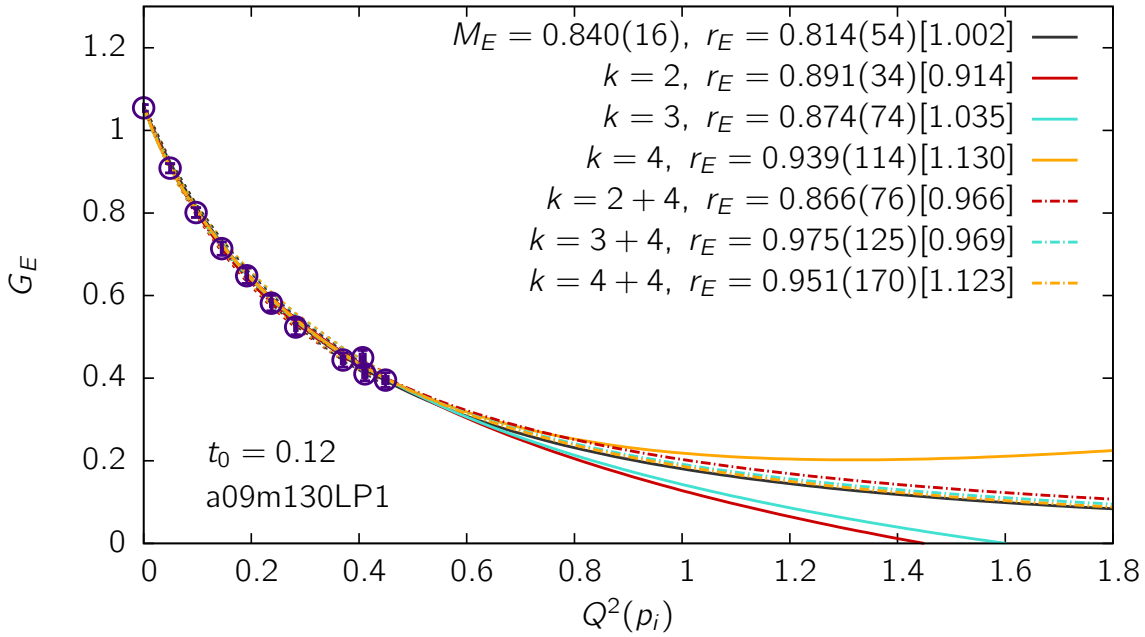
Data and Fits: clover-on-clover

Experimental Results

$r_E = 0.875(6)$ fm	Electron scattering
$r_E = 0.8409(4)$ fm	Muonic hydrogen
$r_M = 0.86(3)$ fm	
$r_A = 0.80(17)$ fm	ν scattering
$r_A = 0.74(12)$ fm	Electroproduction
$r_A = 0.68(16)$ fm	Deuterium target
$\mu_P = 2.7928$	
$\mu_N = -1.9130$	

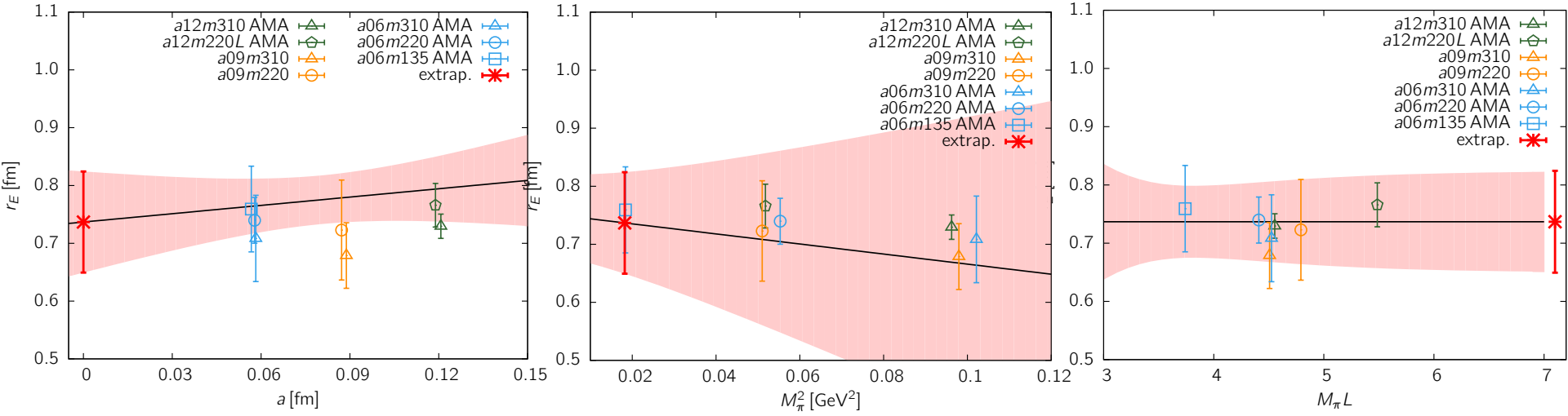
Electric Charge Radius $<r_E>$fm (clover-on-HISQ)

Dipole	a=0.12fm	a=0.09fm	a=0.06fm
310 MeV	0.729(21)	0.679(57)	0.708(75)
220 MeV	0.766(38)	0.723(86)	0.739(37)
135 MeV		0.814(54)	0.754(76)



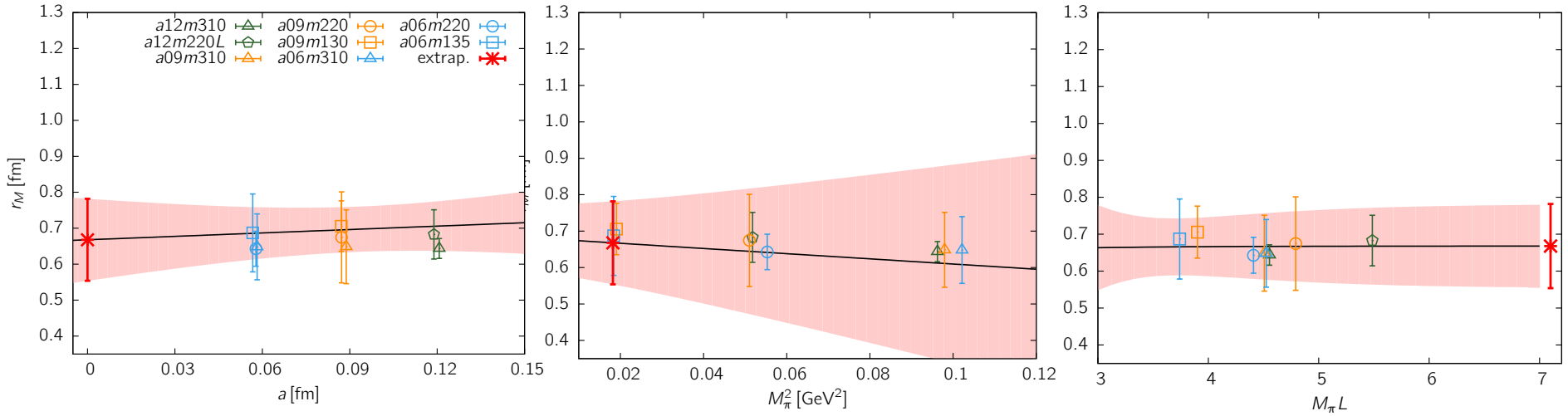
Electric Charge Radius $<r_E>$fm (clover-on-HISQ)

dipole	**0.74(9)**
Z^{2+4}	0.78(5)
Z^{3+4}	0.96(9)
Expt.	0.84-0.88

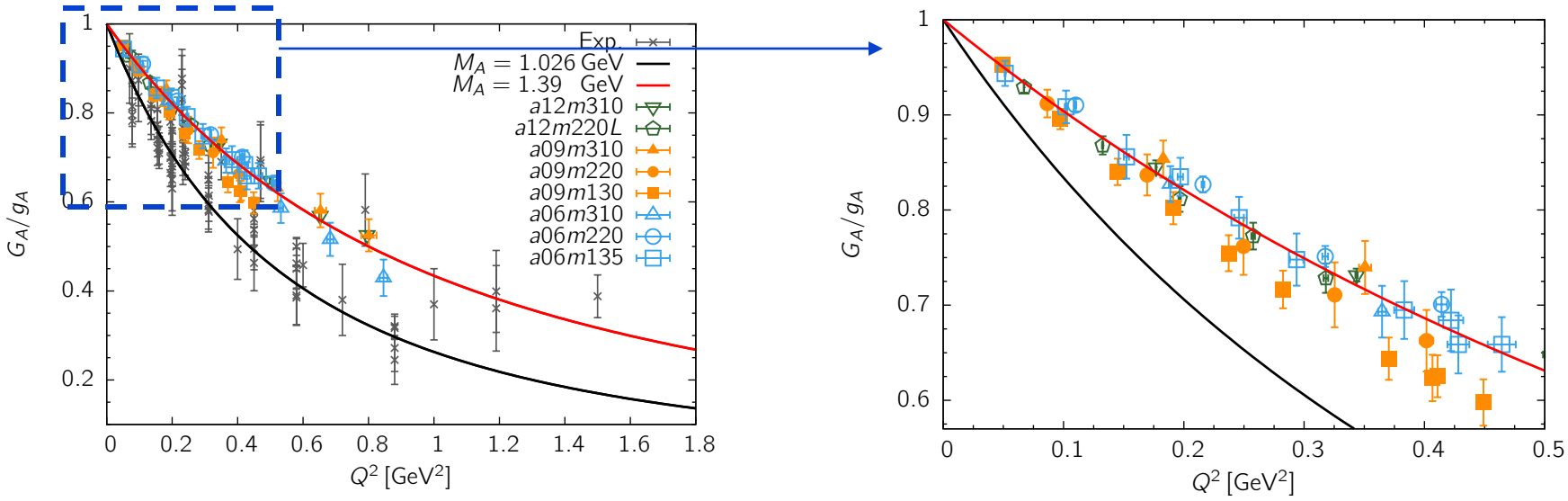


Magnetic Charge Radius $\langle r_M \rangle$fm (clover-on-HISQ)

dipole	**0.67(11)**
Z^2	0.72(5)
Z^{2+4}	0.54(14)
Expt.	0.86(3)



Axial Charge Radius $\langle r_E \rangle$ (clover-on-HISQ)



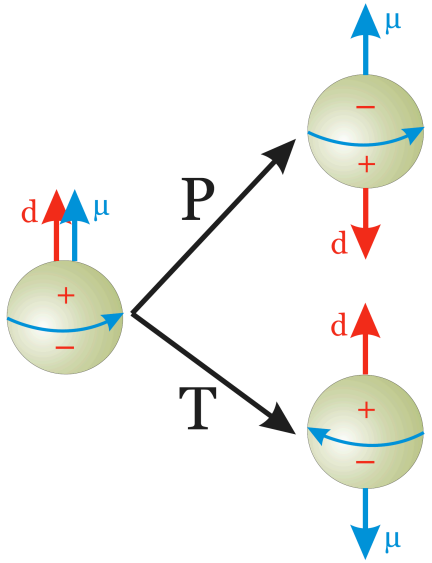
Experimental data from:
Bernard, Elouadrhiri, and Meissner, J. Phys. G28, R1 (2002), arXiv:hep-ph/0107088

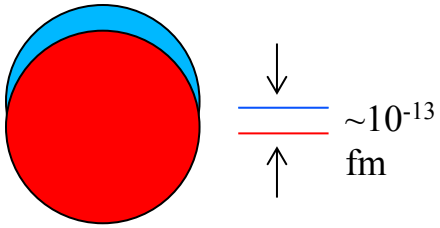
Gupta et al, arXiv:1705:06834

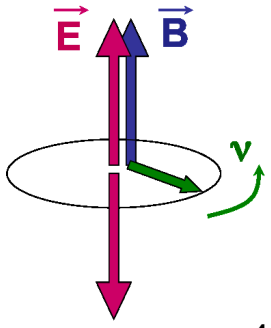
	$\langle r_A \rangle$ fm	M_A GeV
dipole	0.49(10)	1.39
Z^{2+4}	0.44(5)	1.52
Z^{3+4}	0.50(7)	1.37
Expt.+Pheno	0.68-0.80	1.026

Neutron Electric Dipole Moment

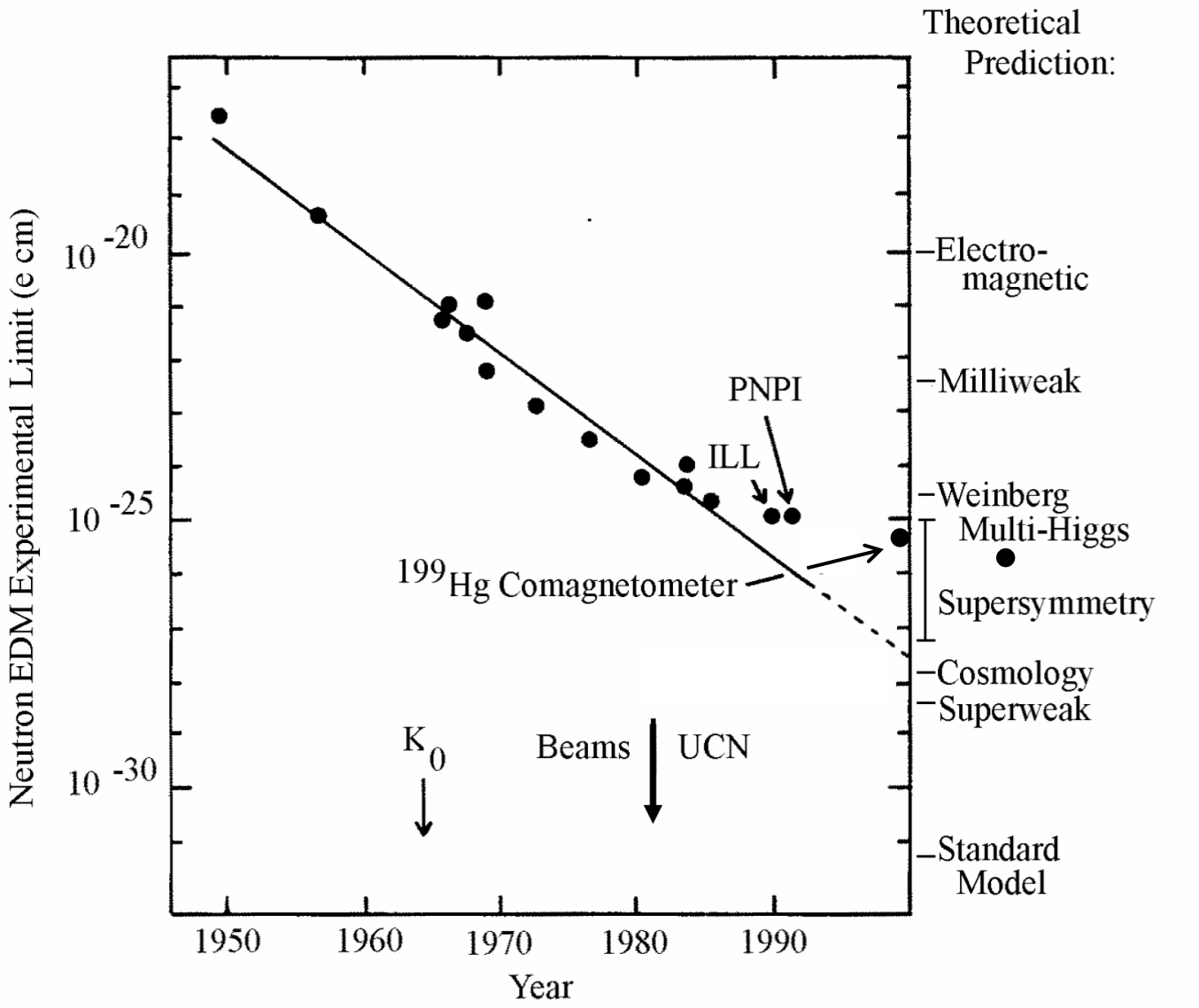
- Quark EDM: contribution of quark EDM to the NEDM
- Quark Chromo EDM: CPV contribution due to the interaction of quarks with the color electric field





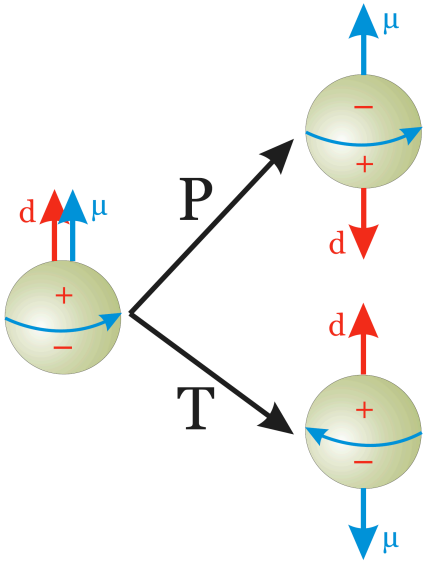


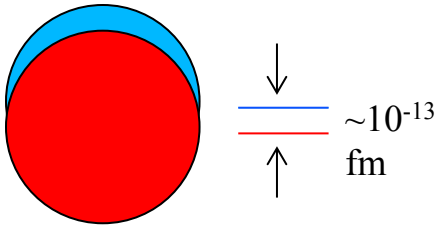
Evolution of EDM Experiments

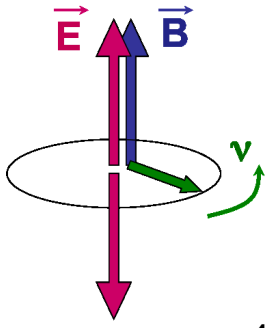


Neutron Electric Dipole Moment

- New (larger) CP violation needed to explain weak scale Baryogenesis
- All CPV (T-violating) interactions contribute to the nEDM
- nEDM provides stringent constraints on BSM theories
- Need precise values of matrix elements of CP violating effective operators to convert bounds on nEDM into bounds on BSM parameters.
- Next gen experiments will reduce the bound $d_n < 2.9 \times 10^{-26}$ e cm **<u>to</u>** $\approx 10^{-28}$ e cm







Baryogenesis

- Matter-antimatter asymmetry of the universe
  - The observed universe has $6.1_{-0.2}^{+0.3} \times 10^{-10}$ baryons for every black body photon rather than 10^{-20}
- Sakharov's three necessary conditions:
  - Baryon number violation
  - Evolution out of equilibrium
  - T-Violation (CP violation)
- Need CPV much larger than in the SM
  - CKM phase gives $d_n \sim 10^{-32}$ *e cm*
  - Θ determined from d_n *(=0 with Pecchi-Quinn)*

Novel CP violation

- Standard Model
  - CKM matrix of flavor mixing
    - $d_n \sim 10^{-32}$ e cm
  - Θ-term (Strong CP violation)
    - Zero if Pecchi-Quinn
    - Suppressed at high T
- Most BSM theories have new sources of CP violation
- Effective field theory: a model-independent tower of operators made of SM fields & ordered by dimension
- We are calculating matrix elements of leading operators
  - Quark EDM (contribution of each quark EDM to nEDM)
  - Quark chromo EDM (CPV contribution of each quark flavor's interaction with the color electric field)
  - Weinberg 3 gluon operator
  - 4 fermi operators

CP violating operators

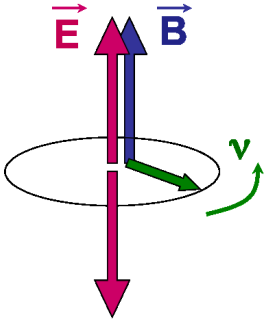
- Dimension 3 and 4:
  - CP violating mass $\psi\bar{\gamma}_5\psi$
  - Topological charge $G_{\mu\nu}\tilde{G}^{\mu\nu}$.
- Suppressed by v_{EW}/M^2 : BSM
  - Electric Dipole Moment $\bar{\psi}\sigma_{\mu\nu}\tilde{F}^{\mu\nu}\psi$.
  - Chromo Dipole Moment $\bar{\psi}\sigma_{\mu\nu}\tilde{G}^{\mu\nu}\psi$.

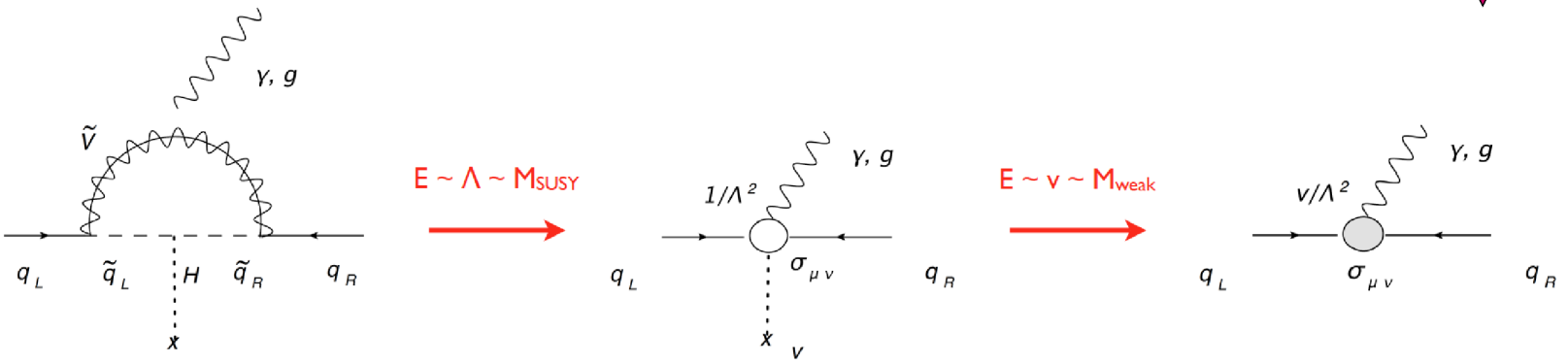
BSM:Suppressed by v/M^2

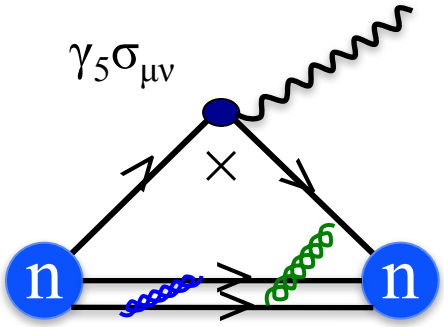
- Weinberg operator (Gluon chromo-electric moment):
  - $G_{\mu\nu}\, G_{\lambda\nu}\, \tilde{G}_{\mu\lambda}$
- There are 3 four-fermi operators.

BSM:Suppressed by $1/M^2$

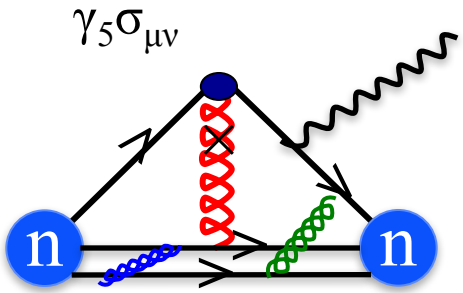
Novel CP violation: operators in EFT







γ attaches to the vertex



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

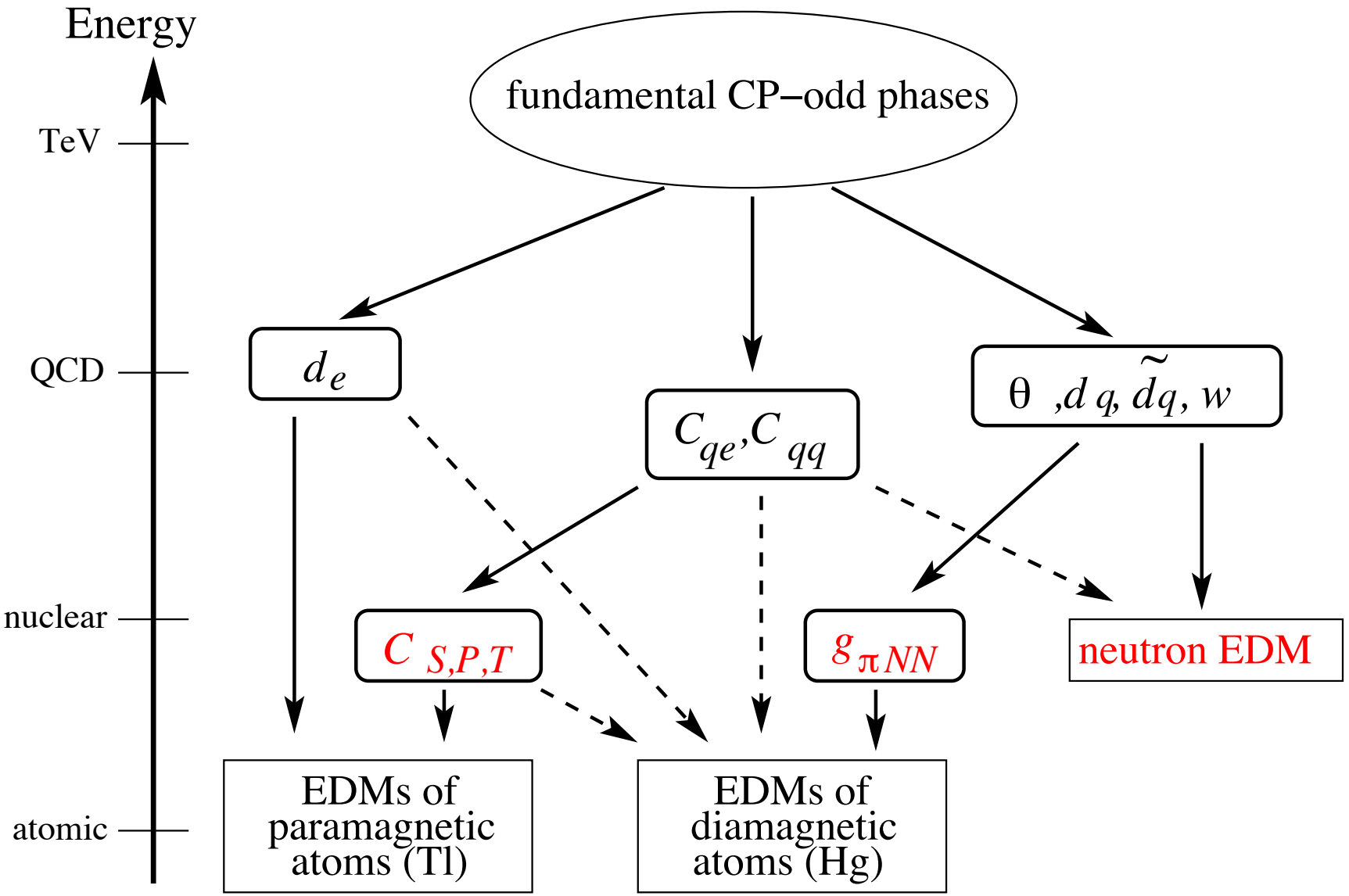
Quark-EDM

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

Chromo-EDM

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

BSM → Couplings in EFT → EDM



Pospelov and Ritz, *Ann. Phys.* **318** (2005) 119

QCD + novel CPV Interactions

The low-energy effective Lagrangian is

$$L_{CPV} = L_{QCD} + i\Theta G_{\mu\nu}\tilde{G}^{\mu\nu} + i\sum_q d_q^{\gamma}\bar{q}\sigma^{\mu\nu}\tilde{F}_{\mu\nu}q + i\sum_q d_q^{G}\bar{q}\sigma^{\mu\nu}\tilde{G}_{\mu\nu}q + \cdots$$

The electromagnetic current, given by $\delta L/\delta A\mu$, becomes

$$j_F^{\mu} = j_{EM}^{\mu} + j_{CPV}^{\mu} = e\sum_q \bar{q}\gamma^{\mu}q + i\varepsilon^{\alpha\beta\mu\nu}p_{\nu}\sum_q d_q^{\gamma}\bar{q}\sigma^{\alpha\beta}q + \cdots$$

Need to calculate 3-point functions

$$\langle\Omega|N(t,p')j_F^{\mu}(\tau,p'-p)N(0,p)|\Omega\rangle =$$

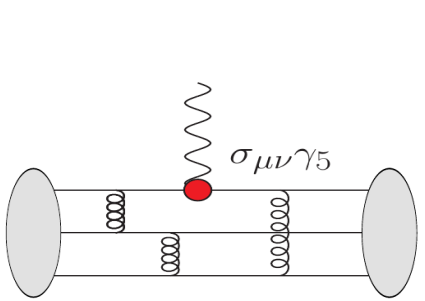
$$\langle\Omega|N(p')|N_j\rangle e^{-\int dt\, H_F}\langle N_j|j_F^{\mu}(\tau,p'-p)|N_i\rangle e^{-\int dt\, H_F}\langle N_i|N(p)|\Omega\rangle \approx$$

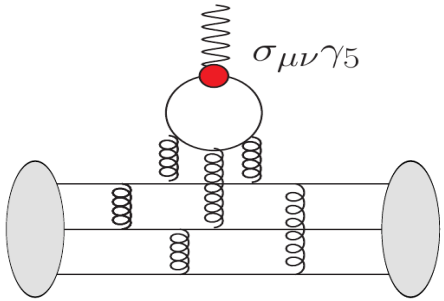
$$\langle\Omega|N(p')|N_j\rangle e^{-\int dt\, H}(1-H_{CPV})\langle N_j|j_{EM}^{\mu}+j_{CPV}^{\mu}|N_i\rangle(1-H_{CPV})e^{-\int dt\, H}\langle N_i|N(p)|\Omega\rangle$$

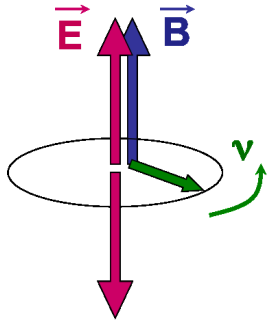
$$\approx\langle\Omega|N(p')|N_j\rangle e^{-\int dt\, H}\langle N_j|j_{EM}^{\mu}+j_{CPV}^{\mu}+j_{EM}^{\mu}H_{CPV}+\ldots|N_i\rangle e^{-\int dt\, H}\langle N_i|N(p)|\Omega\rangle$$

Constraining BSM using nEDM

quark EDM



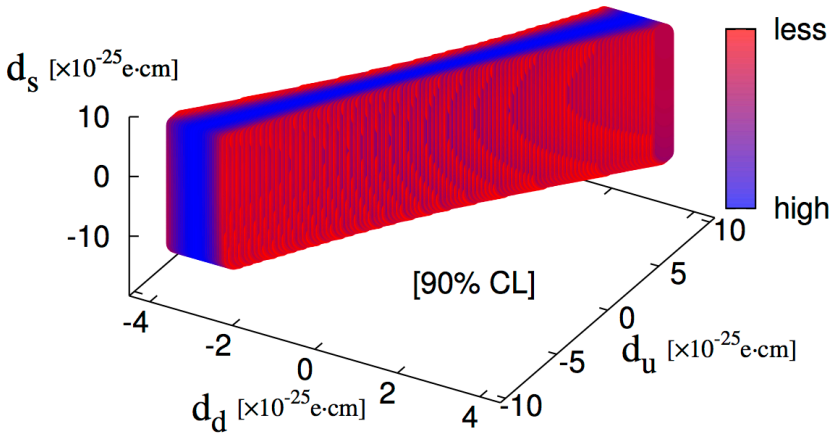




Assuming only quark EDM contribute to nEDM, then

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

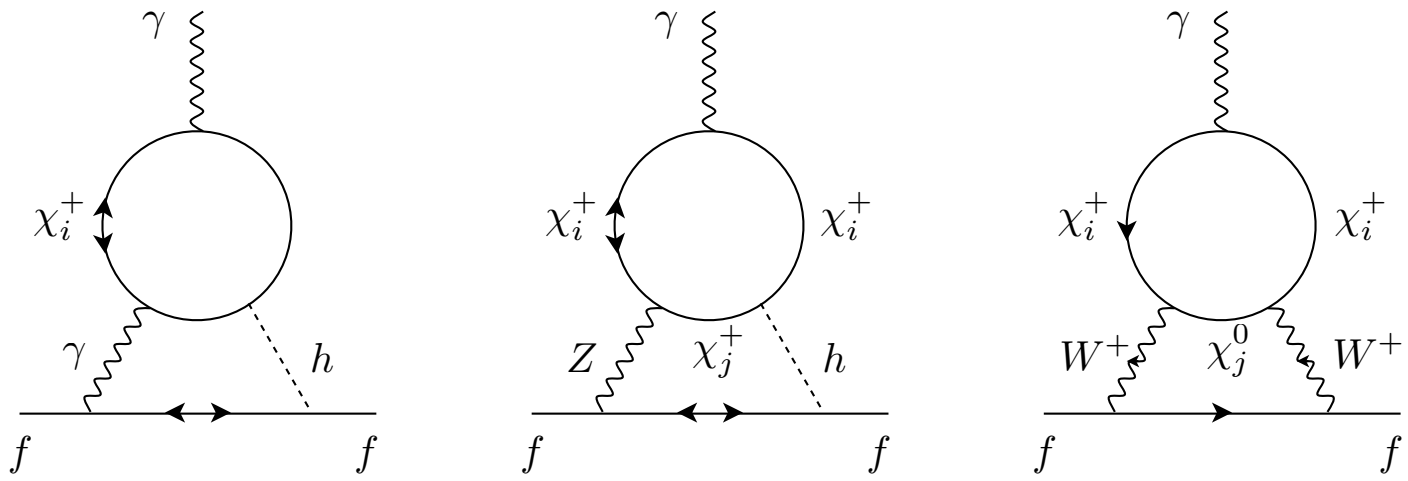
	New in 2016
$g_T^u = -0.232(28)$	-0.192(12)
$g_T^d = 0.774(68)$	0.800(38)
$g_T^s = 0.008(9)$	



Bhattacharya et al, PRL 115 (2015) 212002
Bhattacharya et al, PRD92 (2015) 094511
Bhattacharya et al, PRD94 (2016) 054508

Split Supersymmetry

- All scalars but one Higgs doublet are much heavier than Λ_{EW}
- Has gauge coupling unification, dark matter candidate
- Avoids flavor and CP constraints mediated by 1-loop terms with scalars
- Fermion EDMs arise at 2-loops: phases in gaugino-Higgsino sector communicated to SM fermions through *γh, Zh, WW* exchanges
- chromoEDM, Weinberg, …, operators do not arise at 2-loop

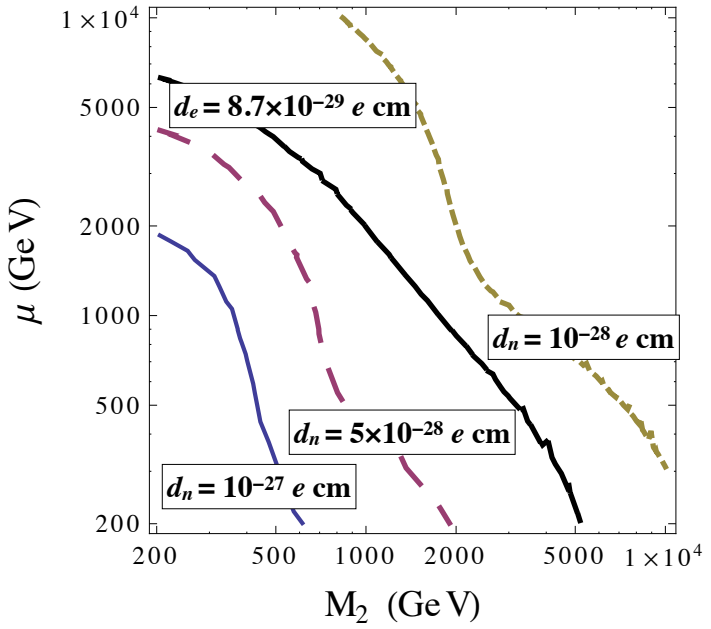


Our analysis followed the work of Giudice & Romanino, PL B634 (2006) 307

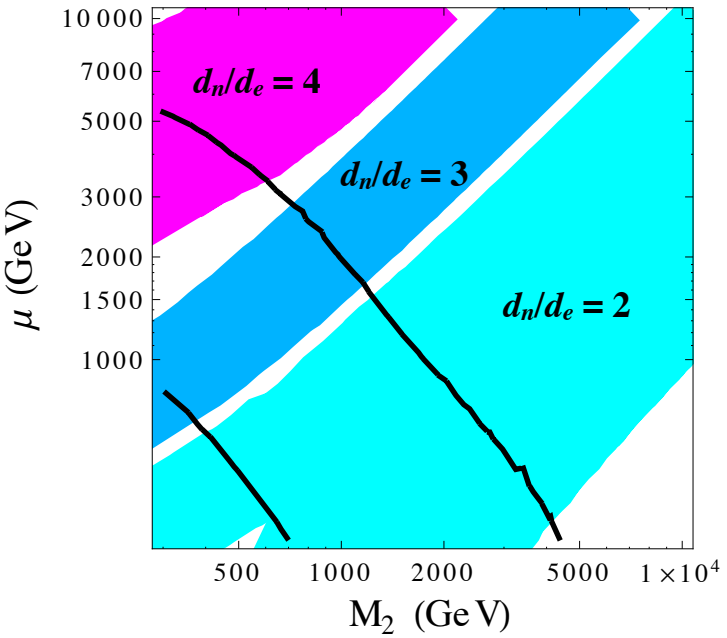
Constraint on Split Supersymmetry

- The correlation between d_n and d_e provides a constraint on Split SUSY.
- Using our estimates of $g_T(u,d,s)$ and $d_e = 8.7 \times 10^{-29}$ e cm gives a stringent upper bound:

$$d_n < 4 \times 10^{-28} \text{ e cm}$$



Contours of d_n , d_e versus gaugino (M_2) and Higgsino (μ) mass parameters setting tanβ=1 and sinϕ=1



Correlation between d_n , d_e in split SUSY. Bands are for different d_n/d_e (ϕ independent) and solid lines are for $d_e = 8.7 \times 10^{-29}$ e cm & sinϕ=0.2 and 1

Bhattacharya et al, PRL 115 (2015) 212002

Conclusions and Future

- Controlled excited state contamination to < 2%
- Renormalization Factors–Z: Parameterize and Control O(4) breaking to < 2%:
- Higher Statistics: 9 ensembles; O(10000) configurations; O(100) measurements → g_A (1-2%), g_S (8%), g_T (2%)
- Improve the calculation of flavor-diagonal operators:
  - qEDM– high precision *s,c* quark EDM g_T^s, g_T^c
- quark chromo EDM operator:
  - Signal in connected diagrams
  - Start calculations of disconnected diagram
  - Non-perturbation calculations of renormalization and mixing