Nucleon Charges, Form-factors and neutron EDM (PNDME Collaboration)

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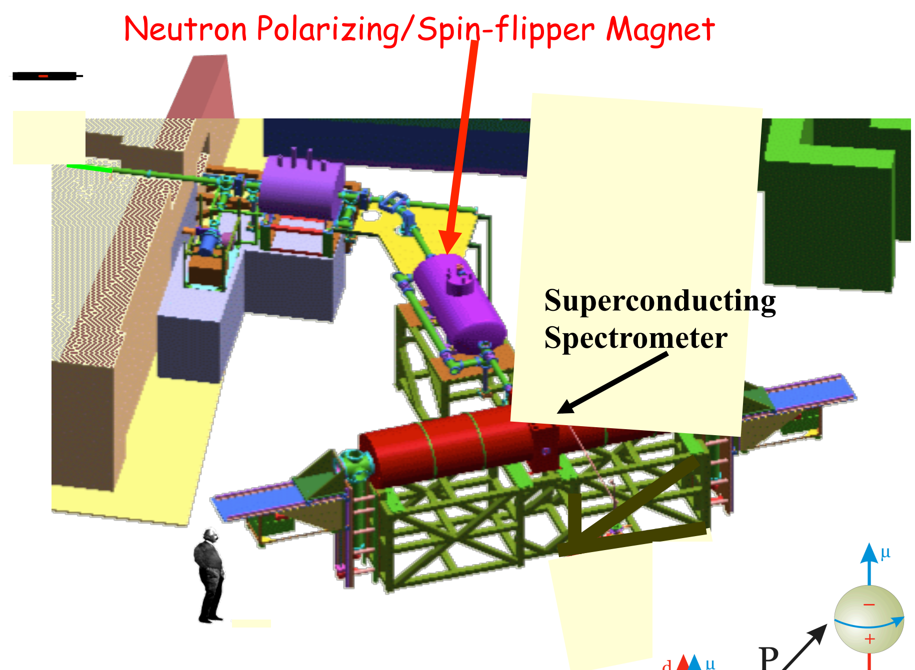
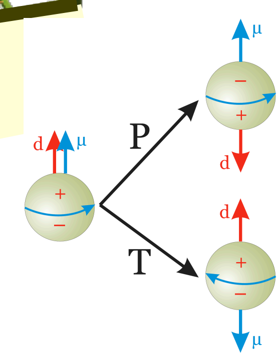




LAUR-15-23801

Outline

- Probing novel scalar and tensor interactions at the TeV scale in neutron β-decay
- Novel CP violation and Neutron EDM
- Lattice QCD calculations of Vector and Axial form-factors

PNDME Collaboration:

- T. Bhattacharya, V. Cirigliano, M. Graesser, A. Joseph, B. Yoon (LANL)
- Saul Cohen (Google), Huey-Wen Lin (Berkeley)

Highlights

- Results for g_T with control over all systematics. Status of g_A and g_A
- $g_T^{u,d,s}$: quark EDM contribution to Neutron EDM
- nEDM constraint on split SUSY
- Preliminary results for vector and axial-form-factors

Novel Scalar and Tensor Interactions

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

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

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

Lattice QCD

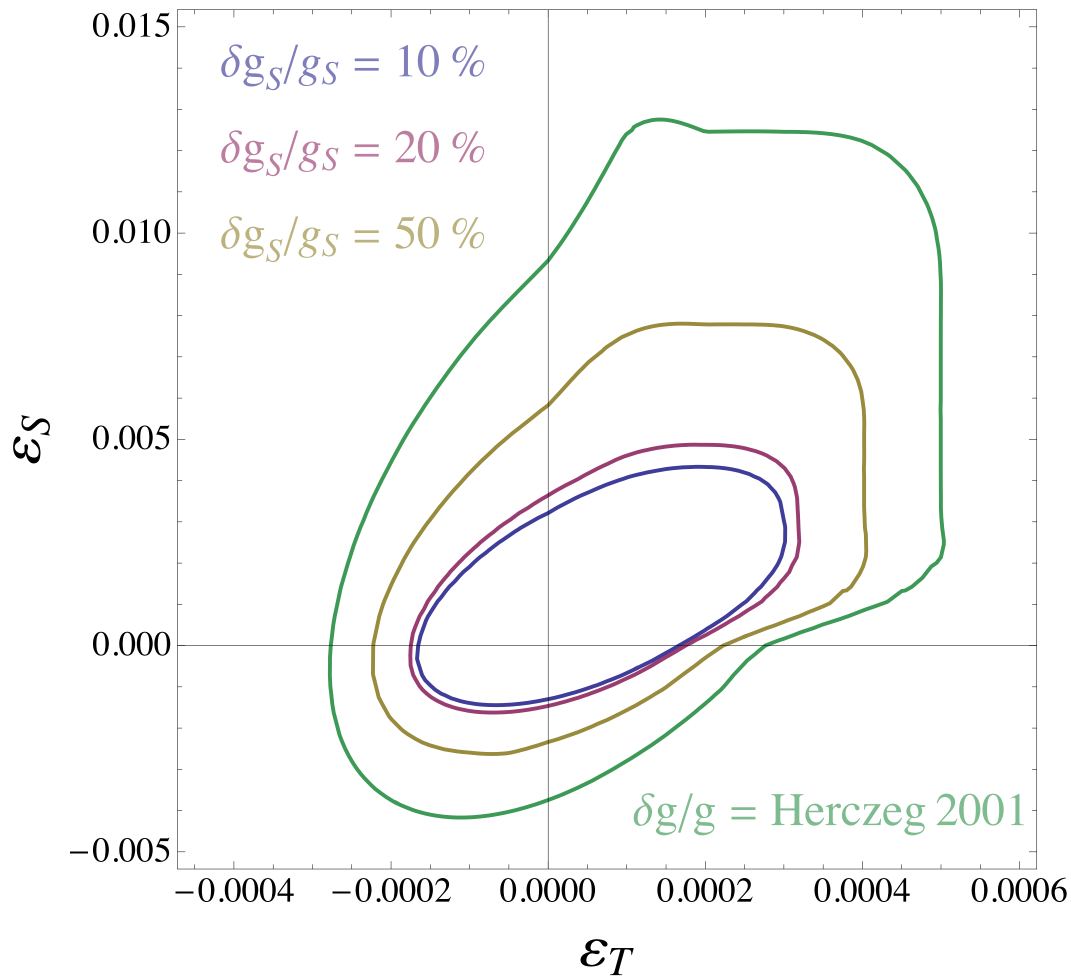
Linear order relations from $n \to p\, e\, \bar{\nu}$ decay

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

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

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

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



Expt. input

$|B_1 - b| < 10^{-3}$
$|b| < 10^{-3}$
$b_{0+} = 2.6\ (4.3) * 10^{-3}$

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

What we know

- Experiment
  - $g_A = 1.2701(25)$ (1.276(2)) Neutron decay
- Phenomenology: CVC

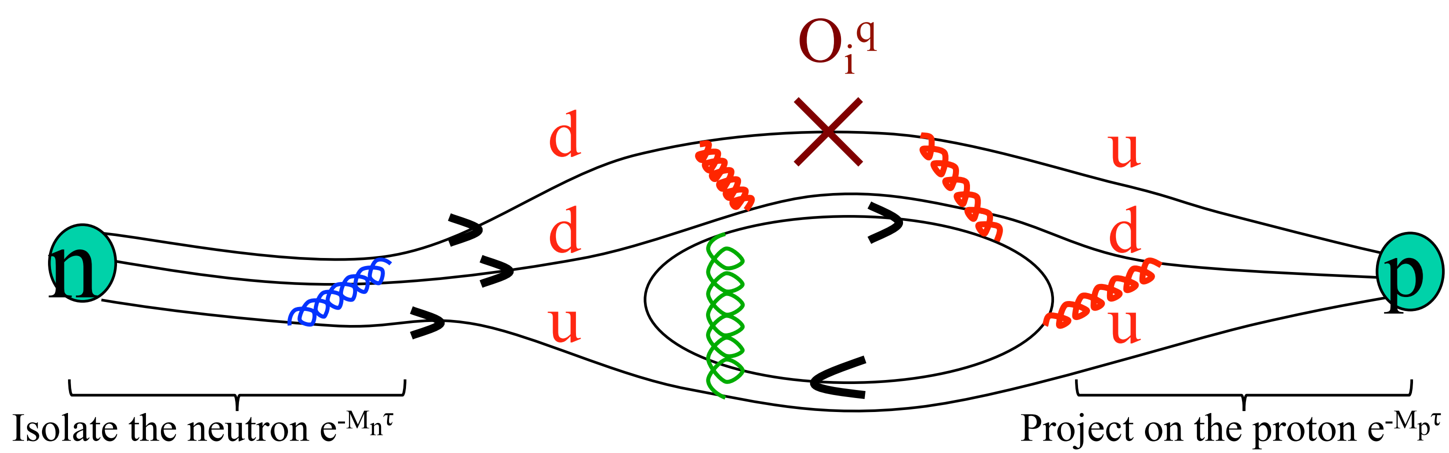
$$\frac{g_S}{g_V} = \frac{(M_N - M_P)^{QCD}}{(m_d - m_u)^{QCD}} = 1.02(8)(7)$$

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

Lattice QCD can provide precise estimates of nucleon structure

- Charges (g_A, g_S, g_T): iso-vector and flavor diagonal
- Vector and axial form factor
- Generalized Parton Distribution functions
- …

Precision Lattice QCD calculations: $\langle p|\bar{u}\,\Gamma d|n\rangle$



- **Reached <10% uncertainty in nuclear charges. It required:**
  - High Statistics (O(10,000) – O(35,000) 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 $a \rightarrow 0$)

2+1+1 flavor HISQ lattices: ~1000 configs

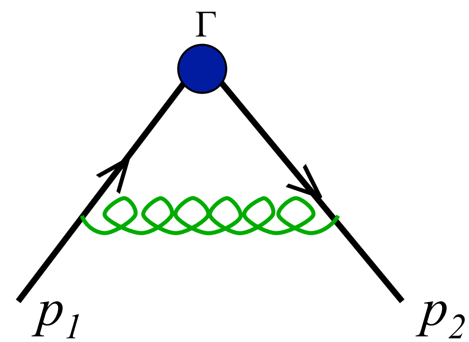
M_s "tuned" to its physical value using $M_{s\bar{s}}$

a(fm)	m_l/m_s	Lattice Volume	$M_\pi L$	M_π (MeV)	HP lat. x Src.	AMA (64LP + 4Corr)
0.12 □	0.2	$24^3 \times 64$	4.55	310	8,104	
0.12 △	0.1	$24^3 \times 64$	3.29	225	24,000	
0.12 ◆	0.1	$32^3 \times 64$	4.38	228	7,664	
0.12 ▽	0.1	40^3 x 64	5.49	228	8,080	running
0.09 □	0.2	$32^3 \times 96$	4.51	313	7,048	
0.09 ◆	0.1	$48^3 \times 96$	4.79	226	7,120	
0.09 ○	0.037	$64^3 \times 96$	3.90	138	7,064	33,408 (running)
0.06 □	0.2	$48^3 \times 144$	4.52	320	8,000	32,000 (running)
0.06 ◆	0.1	$64^3 \times 144$	4.41	235	2,600	26,400 (running)

Renormalization of bilinear operators

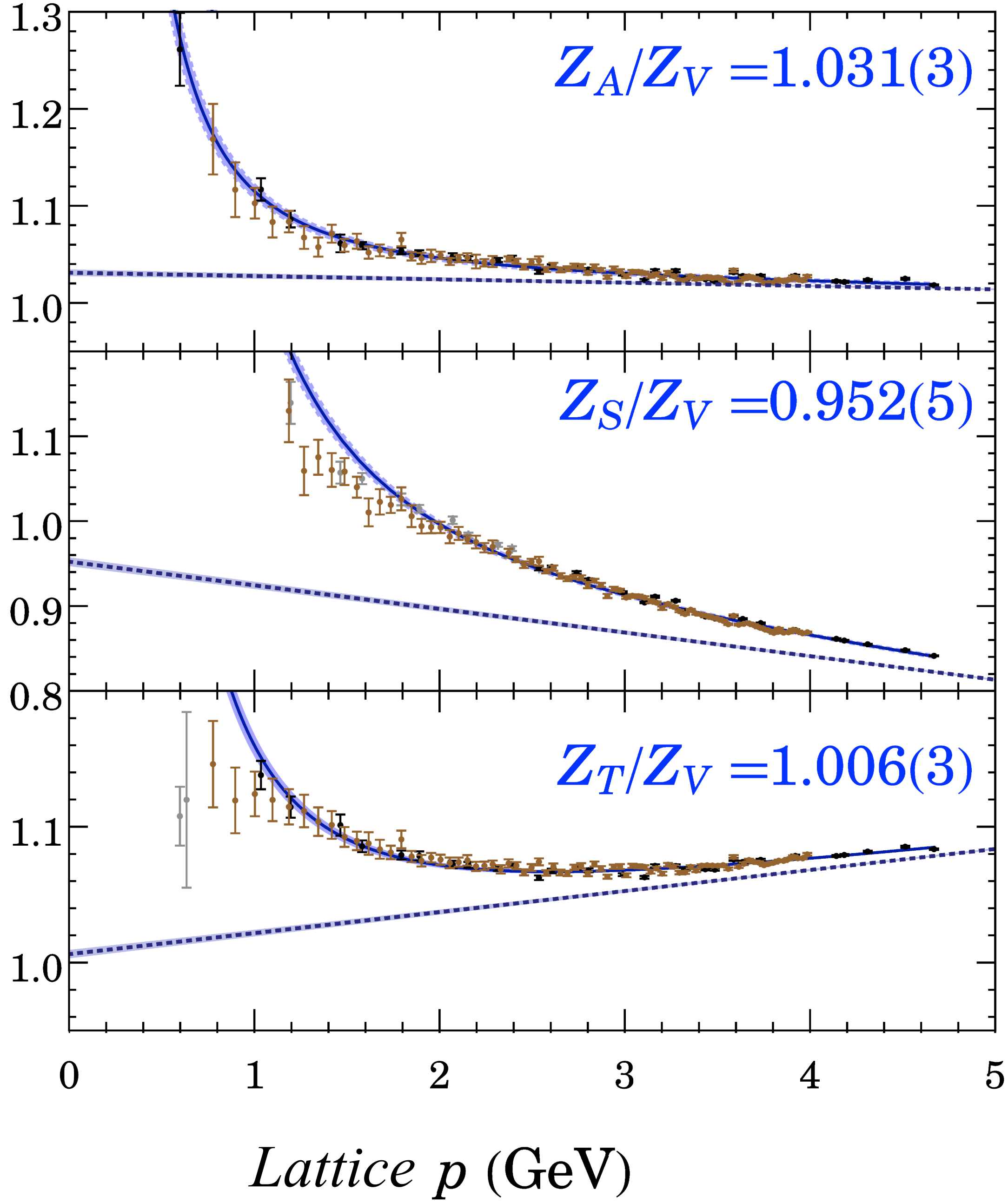
- Non-perturbative renormalization factors Z_Γ using the RI-sMOM scheme ($p_1^2 = p_2^2 = q^2$)
  - Need quark propagator in momentum space
- Basic Assumption: there exists a window

$$\Lambda_{QCD} << p << \pi/a$$



- HYP Smearing introduces artifacts
  - Gluon momentum above ($\sim 1/a$) are averaged out
  - $\Lambda_{QCD} << p << \pi/a$ window may not exist on coarse lattices
- Matching to MS: 1-loop matching and 2-loop running

$$\frac{Z_{A,S,T}}{Z_V}\left(\overline{MS}, 2\ GeV\right)$$



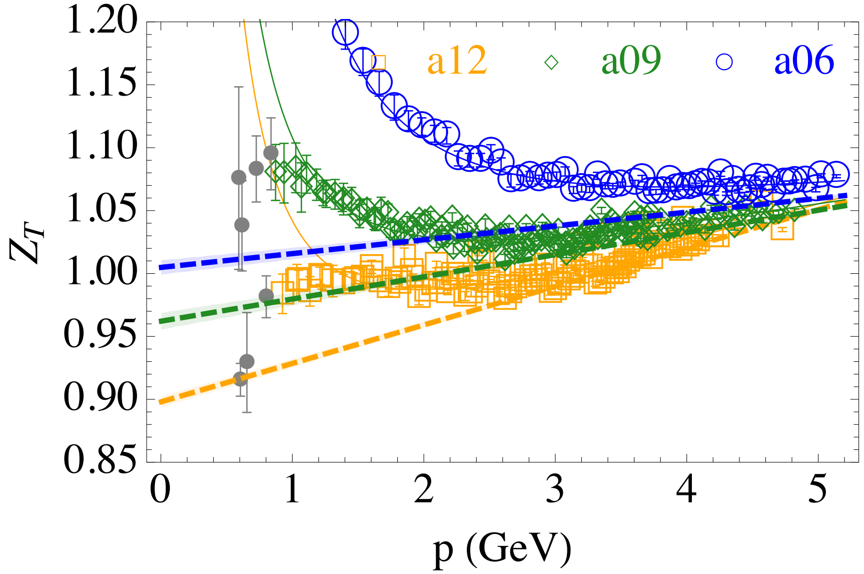
Fit data to: A/p + Z + Cp
in the range {1<p<4 GeV}
Or
Choose Z at p^2 = 5GeV^2
& errors from {4<p^2<6GeV^2}

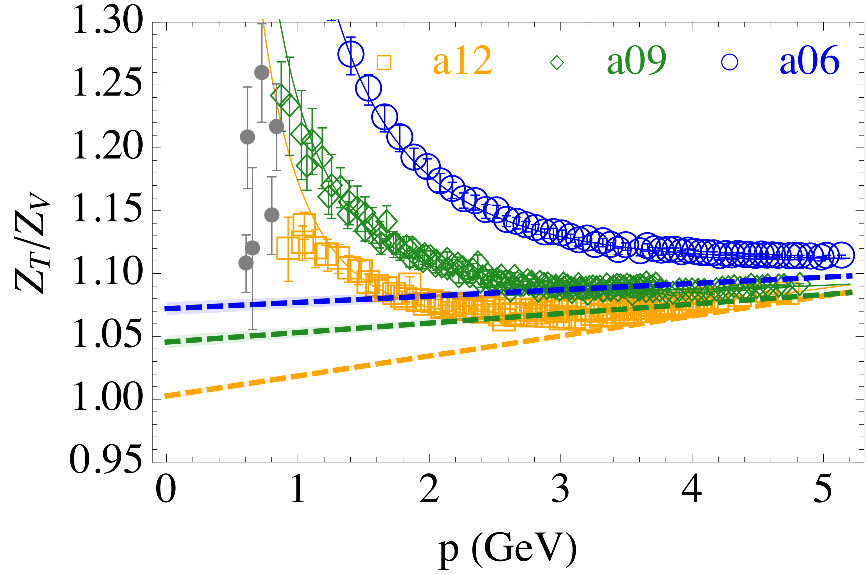
Renormalized Charges

$$\frac{Z_{A,S,T}}{Z_V} \times \frac{g_{A,S,T}}{g_V}$$

Ward identity: $Z_V g_V = 1$

Renormalization: RI-sMOM





- No detectable dependence of Z's on m_q
- Ratios (Z_T/Z_V) have smoother behavior
- Current errors: Z_A (1%), Z_T (4%), Z_S (6%)

Analyzing lattice data:

Extrapolations in a, M_π^2, L

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

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

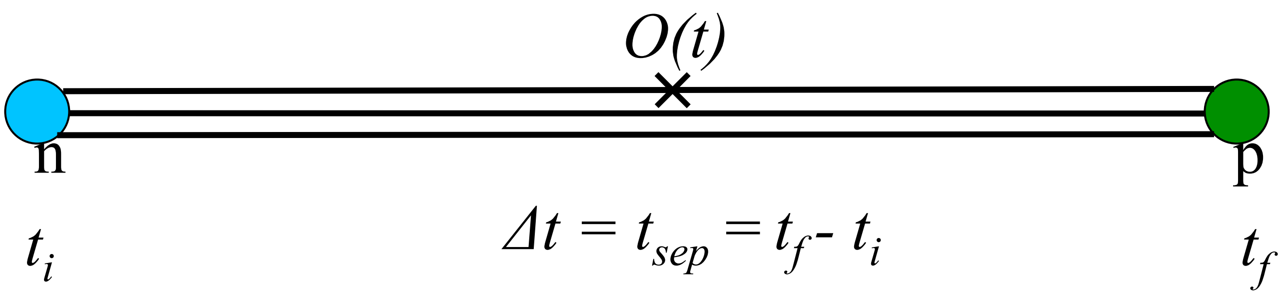
$$g(a, M_\pi, L) = g + A\, a + B\, M_\pi^2 + C\, e^{-M_\pi L} + \dots$$

Reducing excited state contamination: 3-pt fn.

Assuming 1 excited state, the 3-point function is given by

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

Where M_0 and M_1 are the masses of the ground & excited state and A_0 and A_1 are the corresponding amplitudes.



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

Rough estimates for g_T

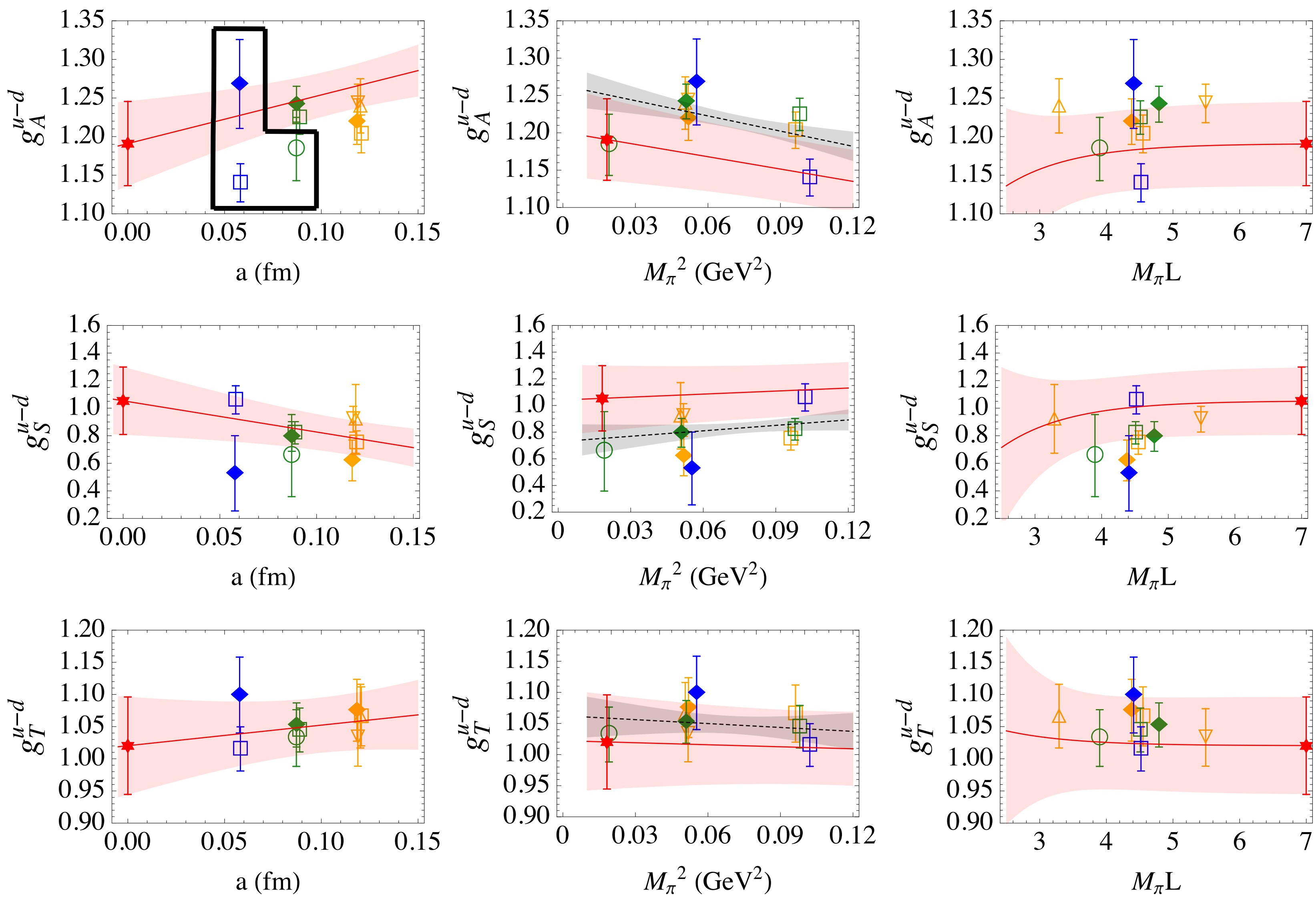
on the a=0.12, 0.09, 0.06 fm lattices

- $A_0 \sim A_1$
- Mass gaps (ΔM) are ~ 0.7, 0.45, 0.3
- $<1|O|1> \sim <0|O|0>$

  This term is ~1% for t_{sep} ~ 7, 10, 15
- $<0|O|1> \sim 0.16 <0|O|0>$

  This term is ~3% for t_{sep} ~ 7, 10, 16

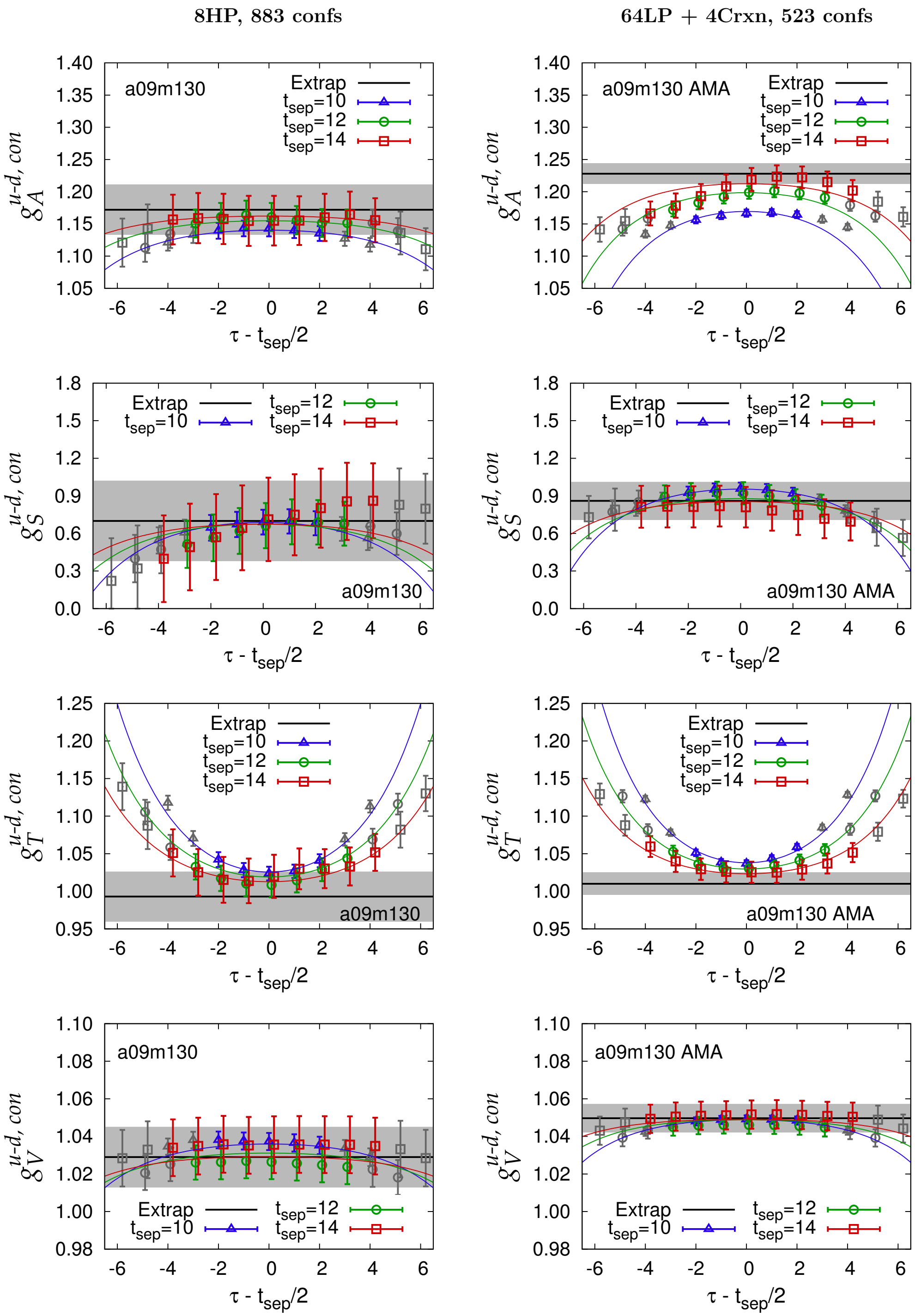
Simultaneous extrapolation in $a, M_\pi^2, M_\pi L$



O(8000) HP measurements

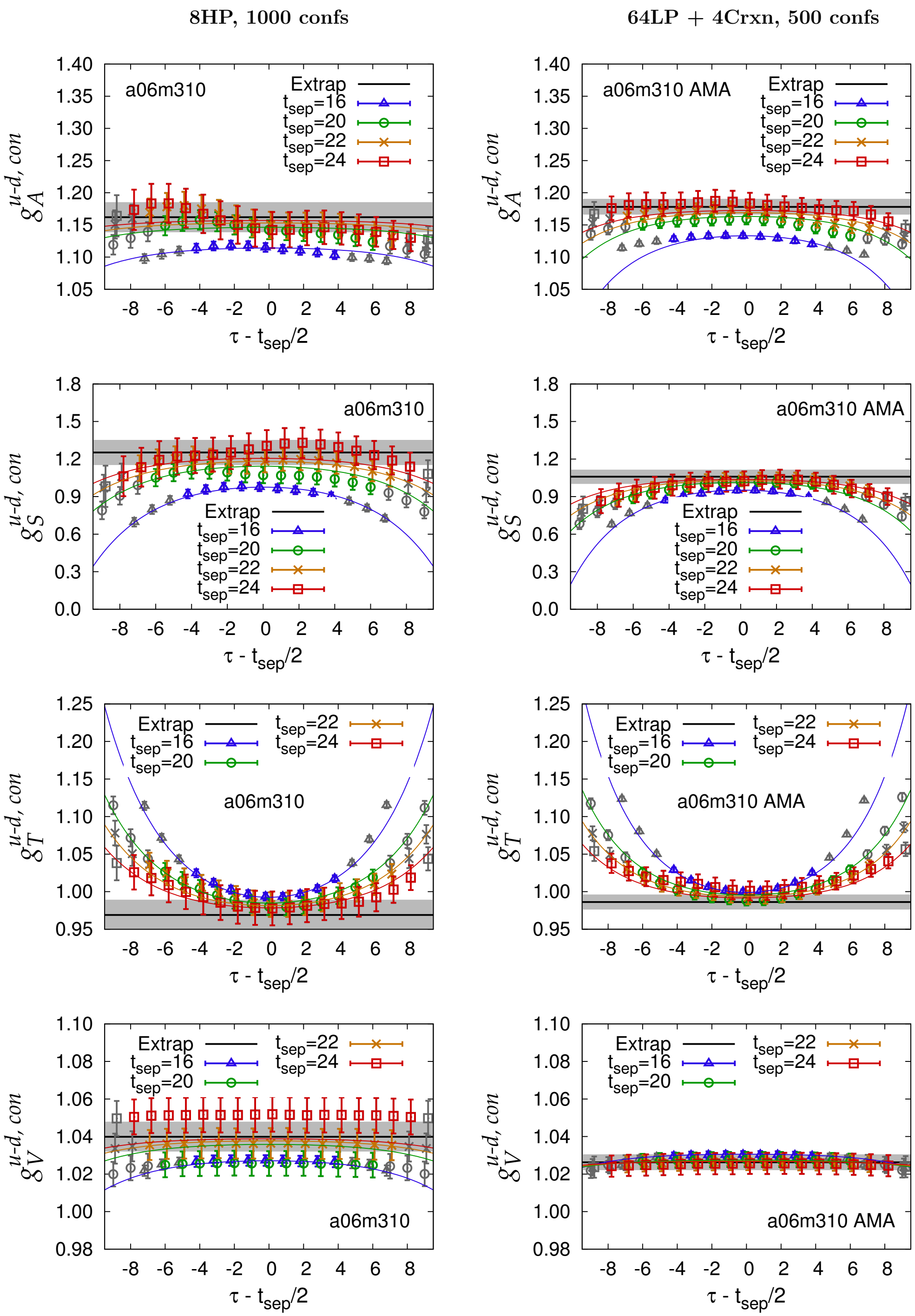
AMA analysis on 4 ensembles

- A low cost way to improve statistics
- 64 LP measurements and 4 (HP-LP) correction
- 4x – 16x higher statistics
- For 64 LP, choose random, well-separated locations for 16 source points on 4 time slices on each configuration. (Not sampling enough phase space with fixed source locations)



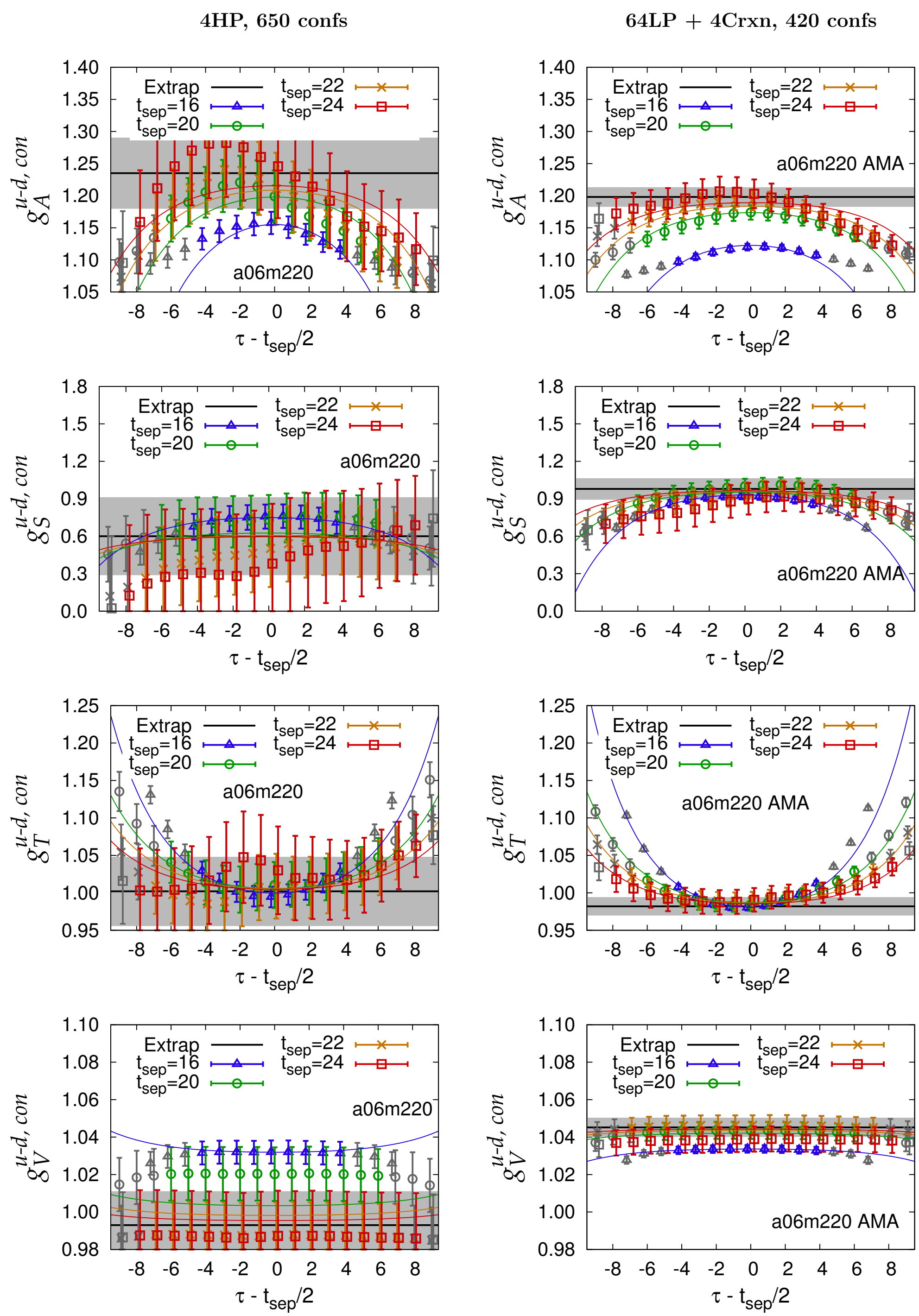
a = 0.09 fm

M_π = 138 MeV



a = 0.06 fm

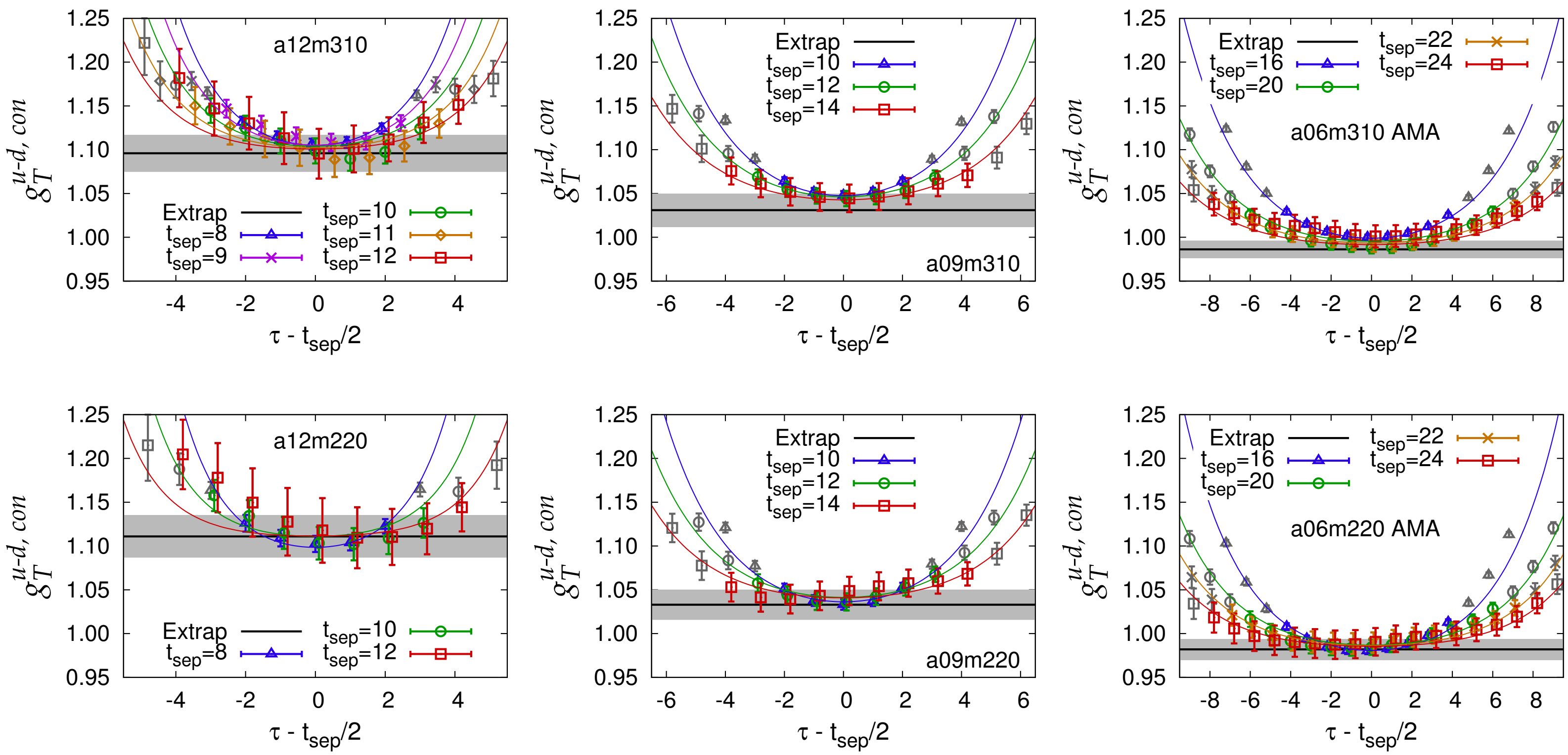
M_π = 320 MeV

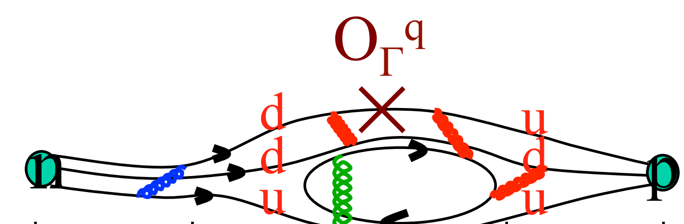


a $= 0.06$ fm

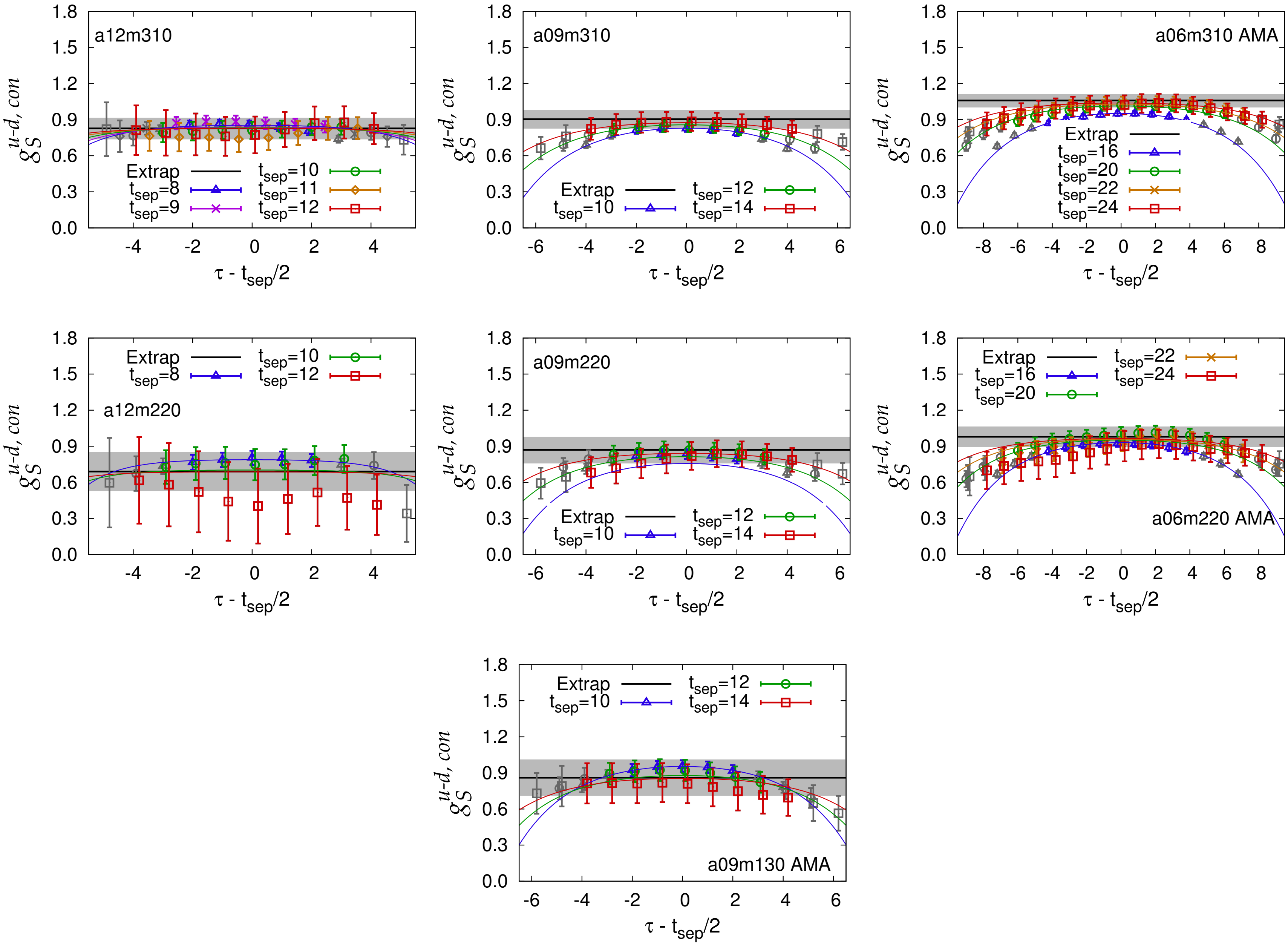
$M_\pi = 235$ MeV

g_T: Excited State Contamination

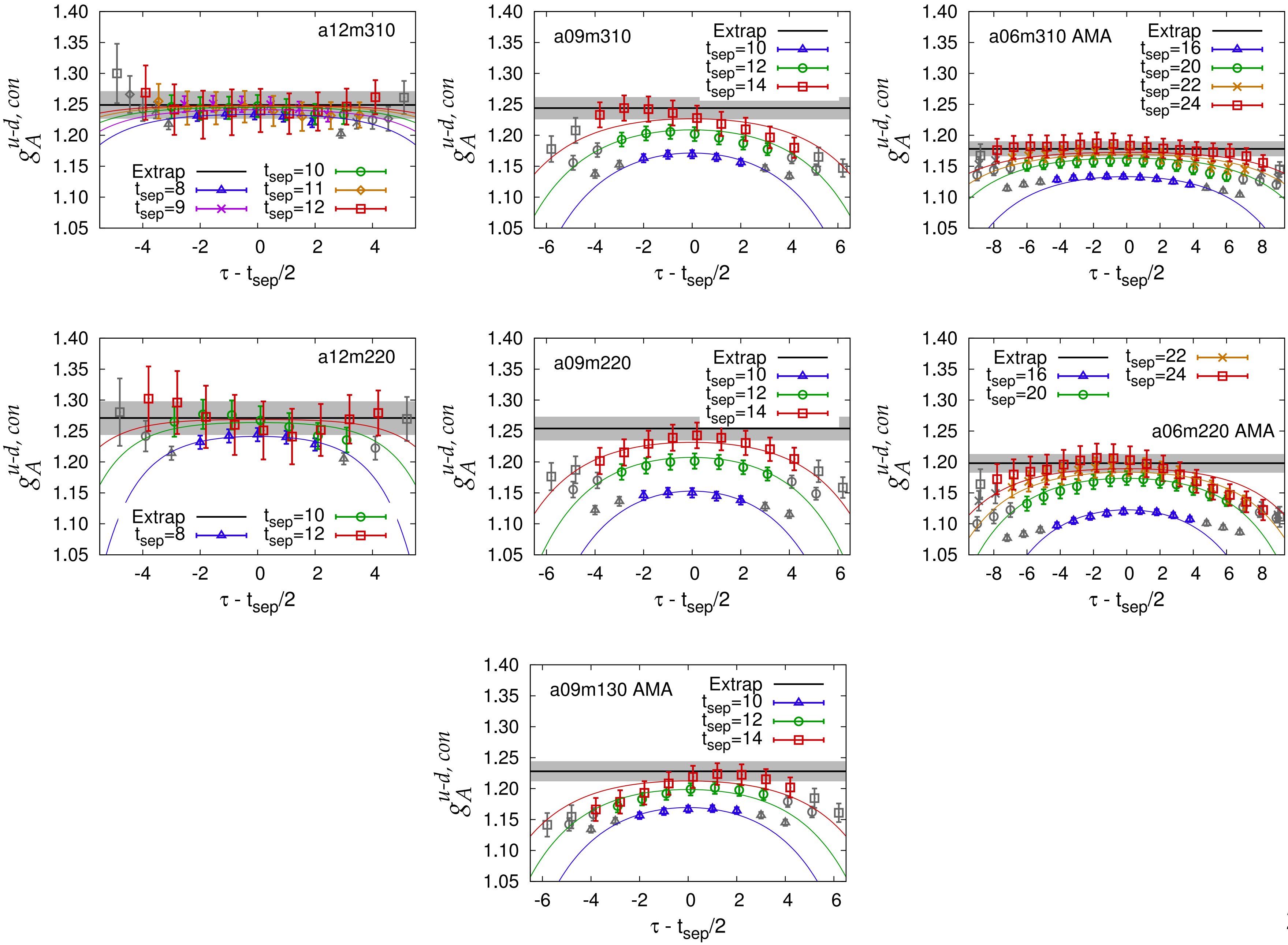




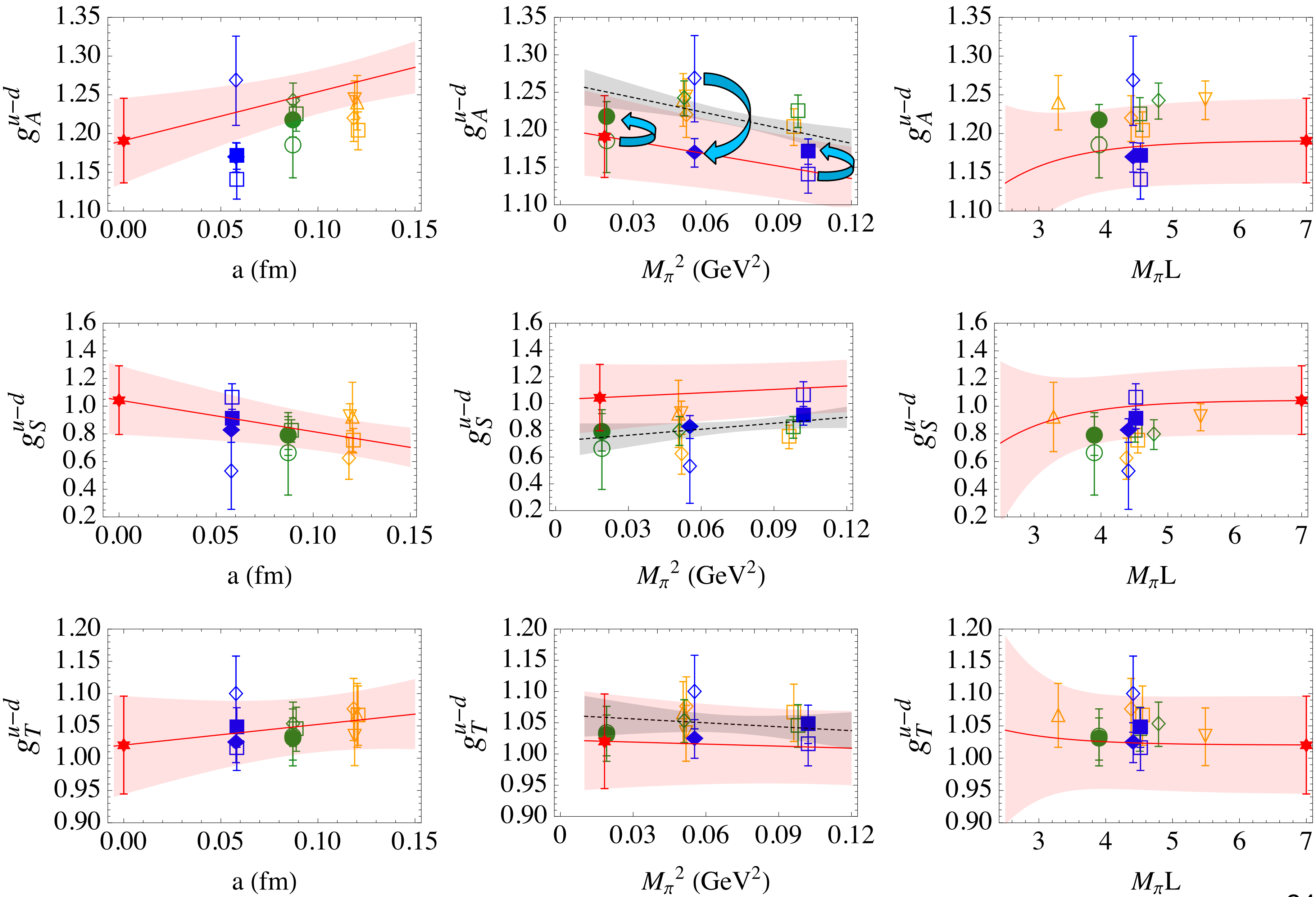
g_S: Excited State Contamination



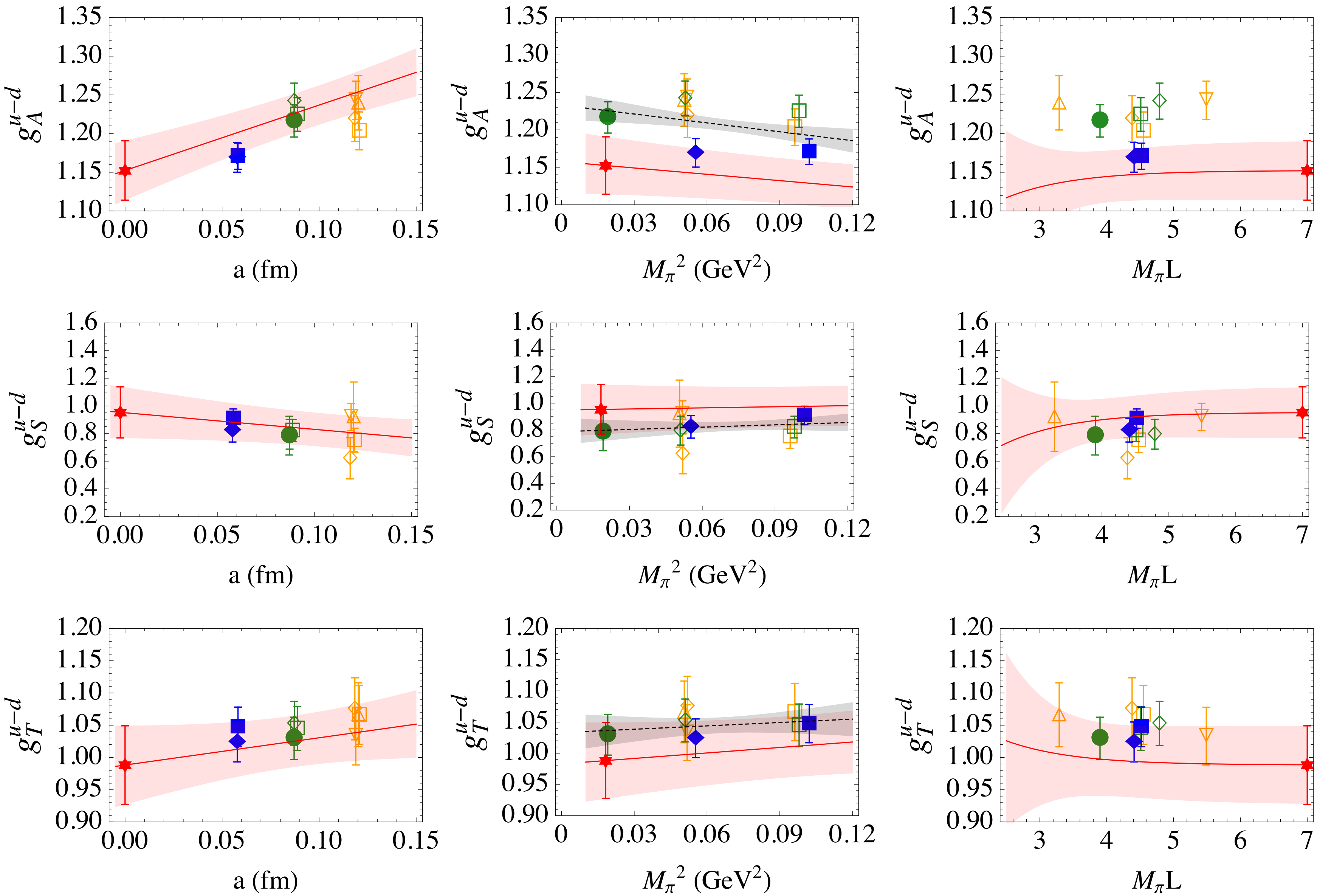
g_A: Excited State Contamination



AMA + HP data & HP extrapolation in $a, M_\pi^2, M_\pi L$



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



Status of results on iso-vector charges

All HP

- $g_A = 1.19(6)$
- $g_S = 1.04(25)$
- $g_T = 1.020(76)$

With AMA

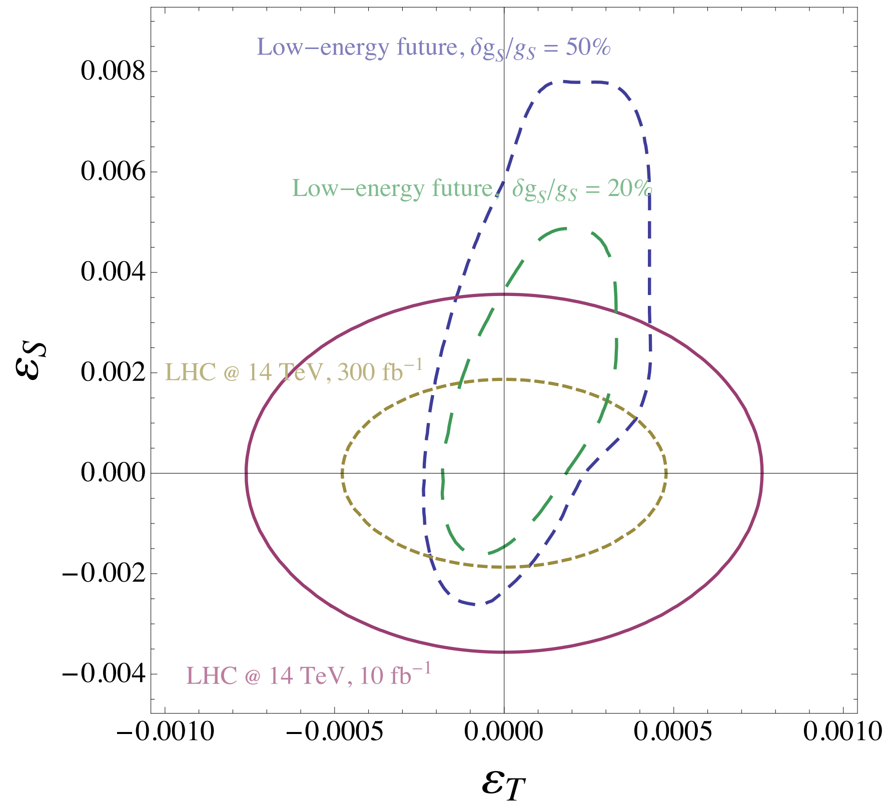
- $g_A = 1.15(4)$
- $g_S = 0.95(18)$
- $g_T = 0.99(6)$ [1.045(12)]

***** $g_T = 0.99(6)$**
**** $g_A = 1.15(4)$**
**** $g_S = 0.95(18)$**

β-decay versus LHC constraints

- LHC @ 14 TeV and 300 fb^{-1}: look for events with an electron and missing energy at high transverse mass

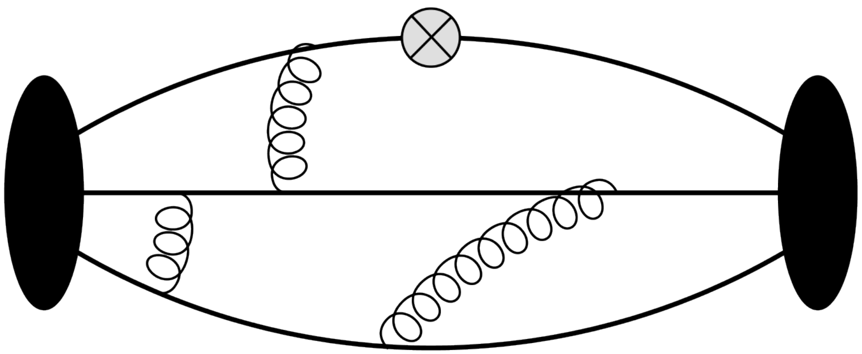
- Provides comparable constraints to low-energy ones with $\delta g_S/g_S$ ~20%



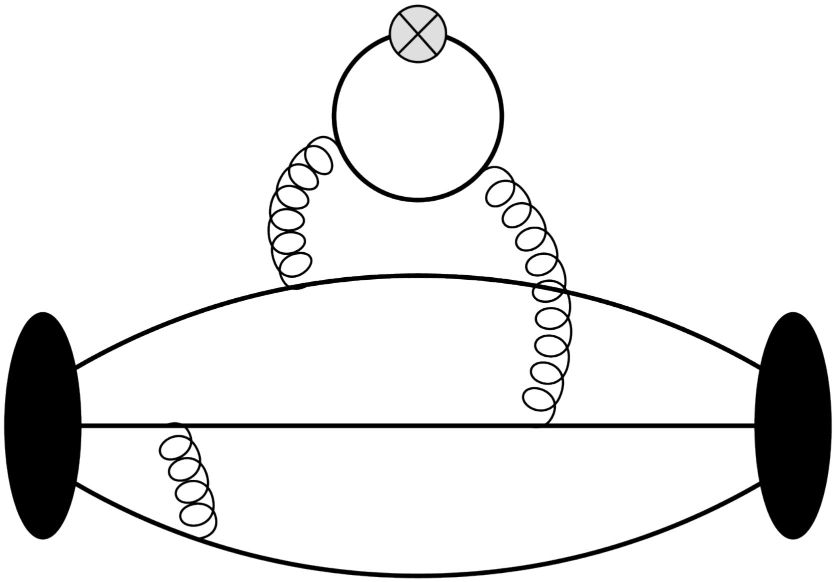
A number of matrix elements within nucleon states are being calculated

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

Need to evaluate both diagrams



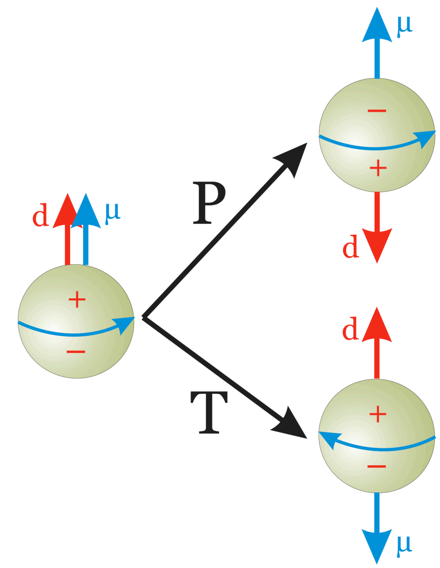
Connected

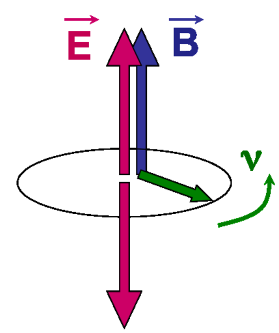


Disconnected

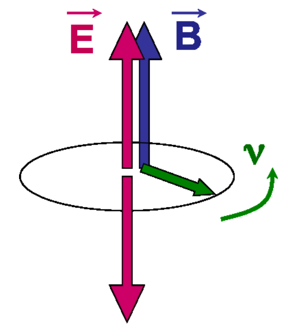
Neutron Electric Dipole Moment

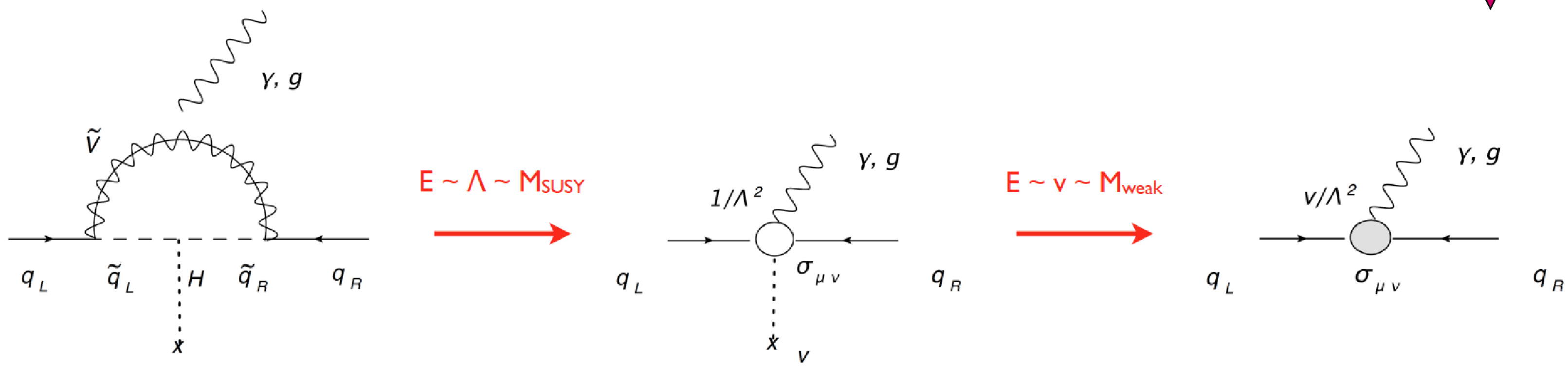
- nEDM is a very sensitive probe of CP violation from BSM
- New (larger) CP violation needed to explain Baryogenesis
- Need precise values of matrix elements of new CP violating effective operators to convert bounds on nEDM into bounds on BSM parameters.

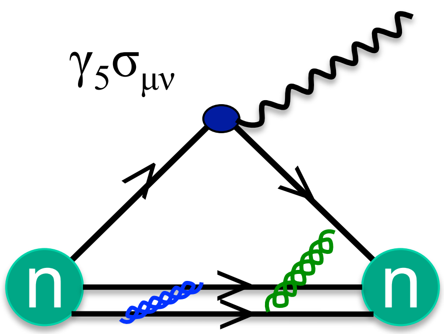




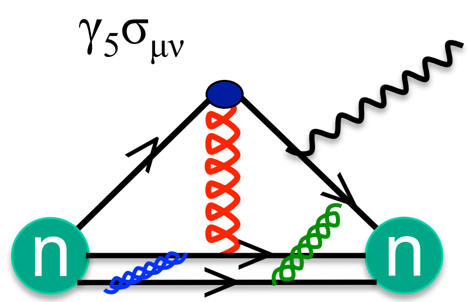
Effective operators: novel CP violation







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

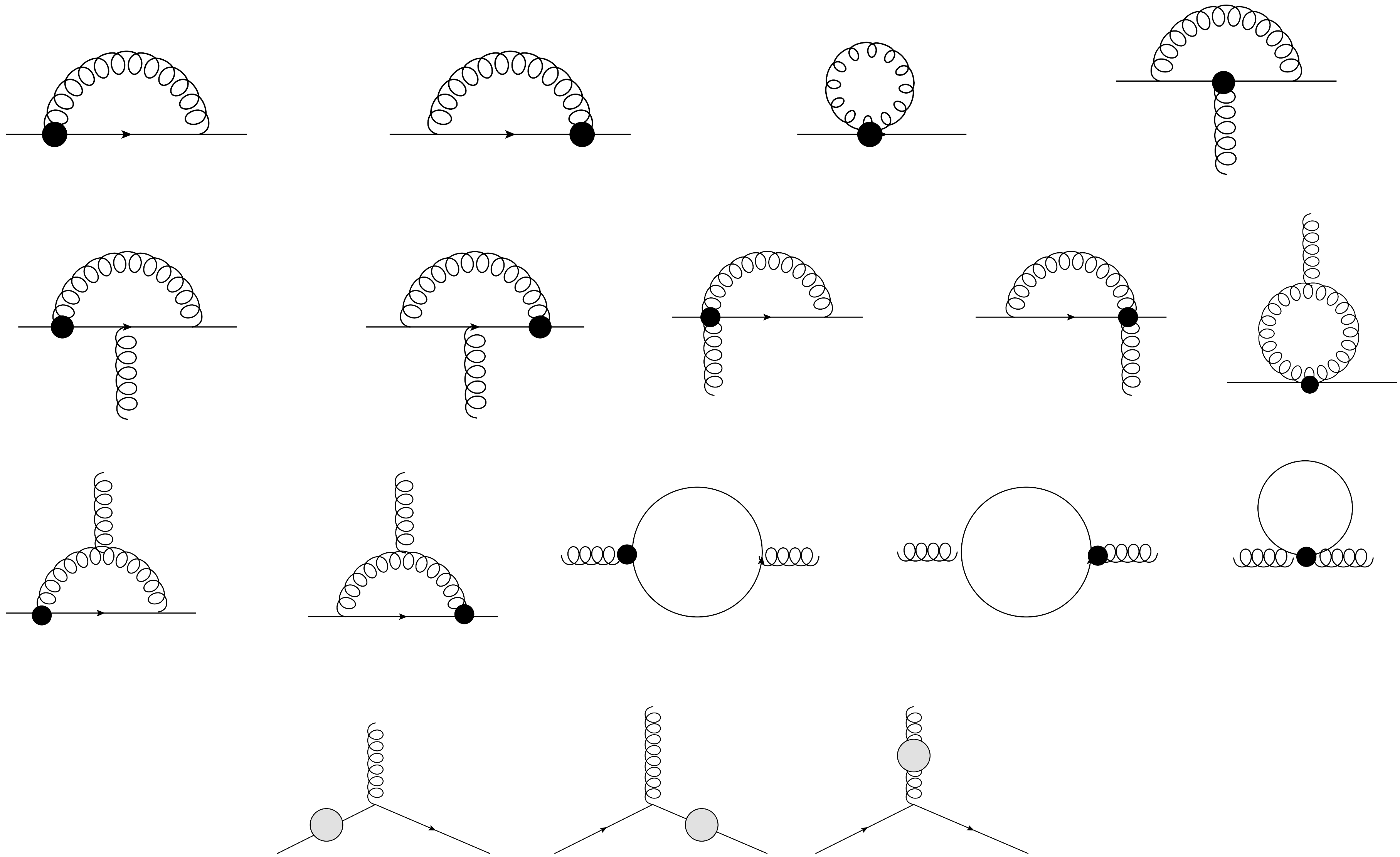
$$\bar{q}\,\sigma_{\mu\nu}\gamma_5\, q\; \lambda^a G_a^{\mu\nu}$$

Quark Chromoelectric Operator: Mixing

	C	$\partial^2 P$	E	$mF\tilde{F}$	$mG\tilde{G}$	$m\partial \cdot A$	$m^2 P$	P_{EE}	$\partial \cdot A_E$	A_∂	$A_{A(\gamma)}$
C	Z_C	X	X	X	X	X	X	X	X	X	X
$\partial^2 P$	0	Z_P	0	0	0	0	0	0	0	0	0
E	0	0	Z_T	0	0	0	0	0	0	0	0
$mF\tilde{F}$	0	0	0	$Z_m^{-1} Z_{F\tilde{F}}$	0	0	0	0	0	0	0
$m\, G\tilde{G}$	0	0	0	0	$Z_m^{-1} Z_{G\tilde{G}}$	X	0	0	0	0	0
$m\, \partial \cdot A$	0	0	0	0	0	$Z_m^{-1} Z_{\partial A}$	0	0	0	0	0
$m^2 P$	0	0	0	0	0	0	Z_m^{-1}	0	0	0	0
P_{EE}	0	0	0	0	0	0	0	X	X	X	0
$\partial \cdot A_E$	0	0	0	0	0	0	0	0	X	0	0
A_∂	0	0	0	0	0	0	0	X	X	X	0
$\partial \cdot A_E$	0	0	0	0	0	0	0	0	X	0	0
A_∂	0	0	0	0	0	0	0	X	X	X	0
$A_{A(\gamma)}$	0	0	0	0	0	0	0	0	0	0	X

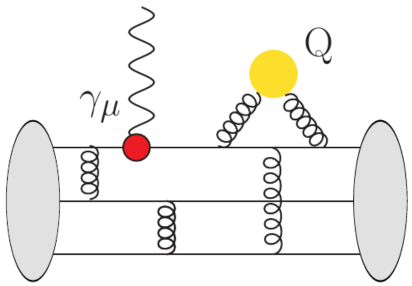
Bhattacharya et al., arXiv:1502.07325 [hep-ph]

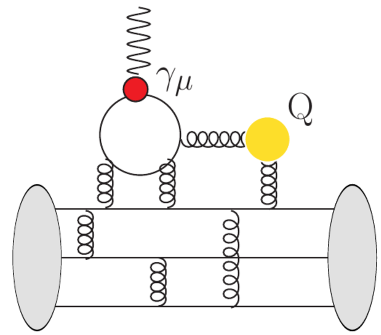
Renormalization and Mixing



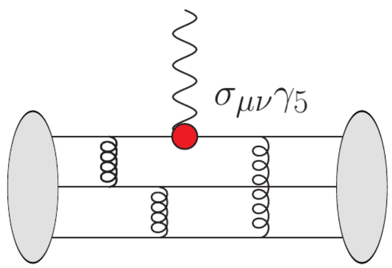
Diagrams to be calculated: Lattice QCD

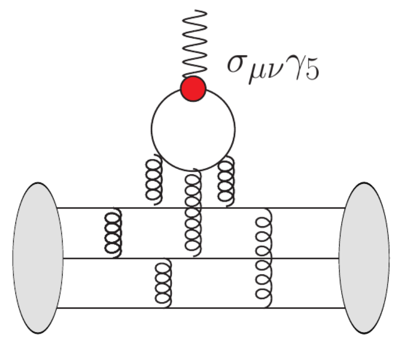
Θ-term



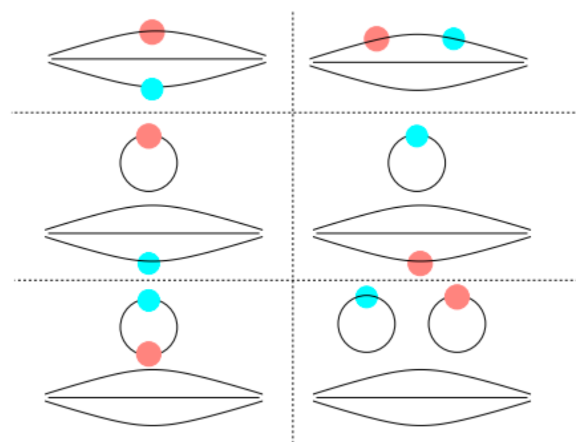


quark EDM

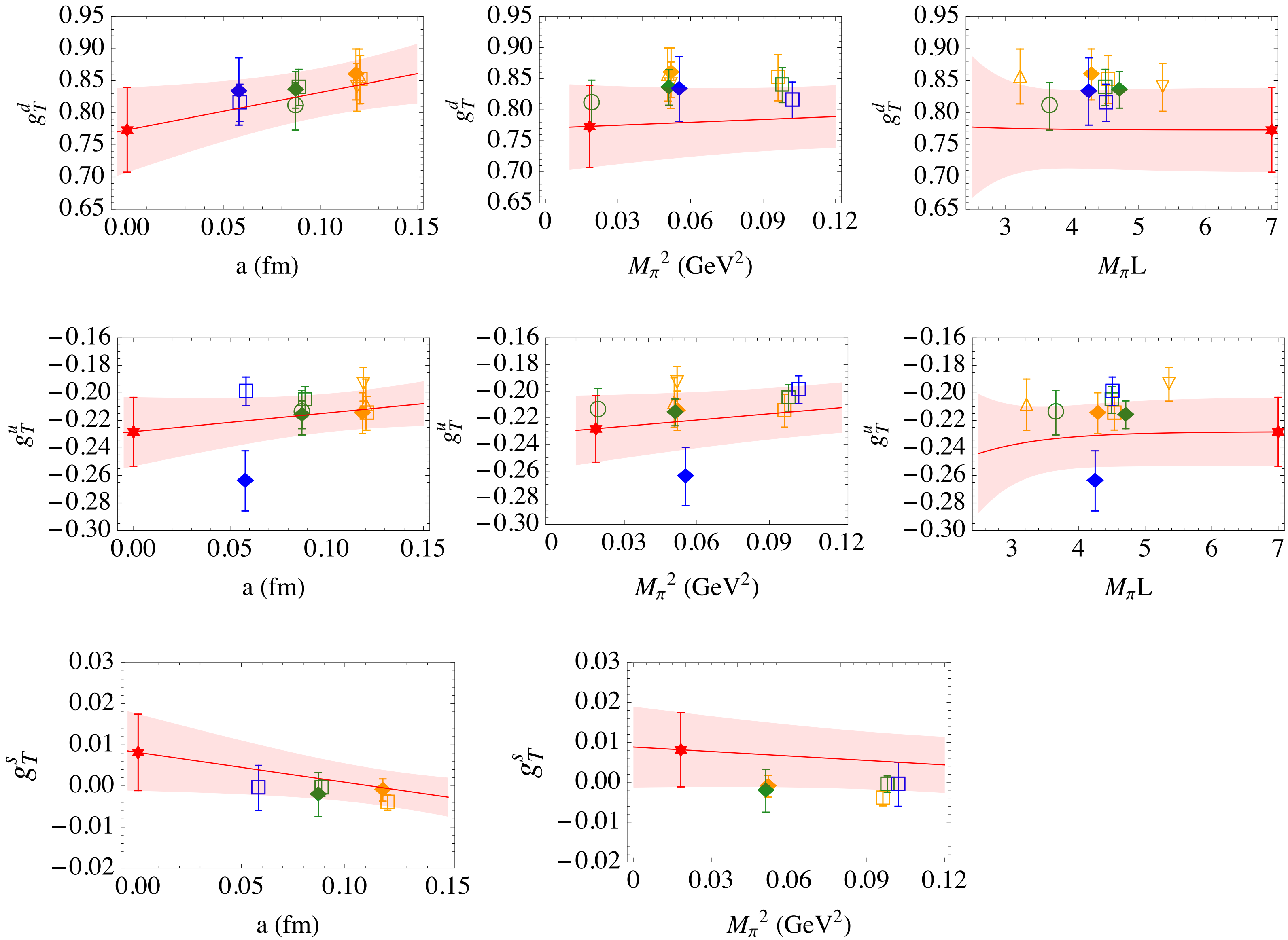




quark Chromo EDM
(4-pt function)

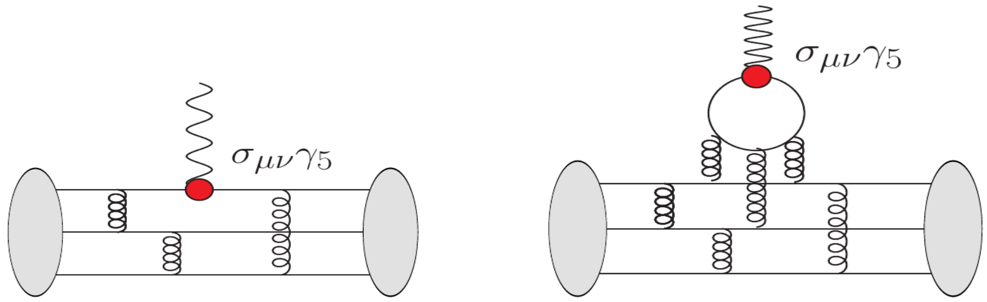


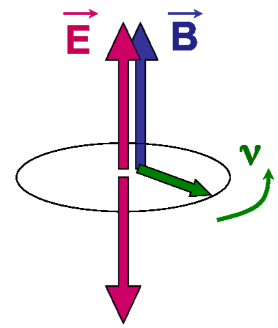
Flavor diagonal tensor charges



Constraining BSM using nEDM

quark EDM





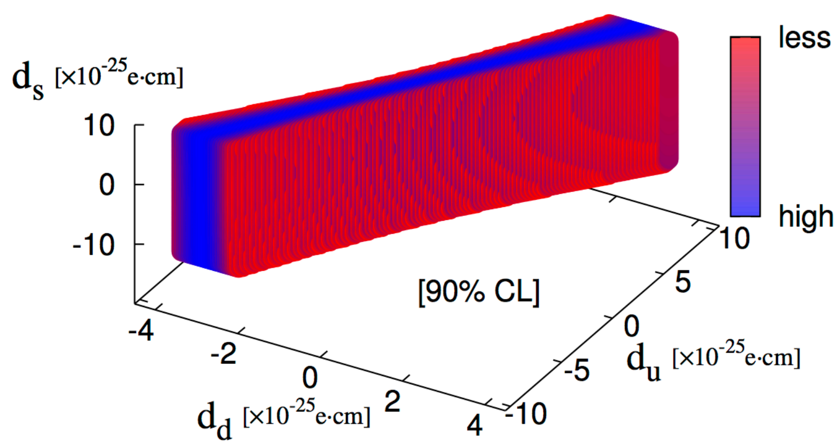
Assuming only quark EDM contribute to nEDM, then

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

g_T^u = -0.232(28)

g_T^d = 0.774(68)

g_T^s = 0.008(9)

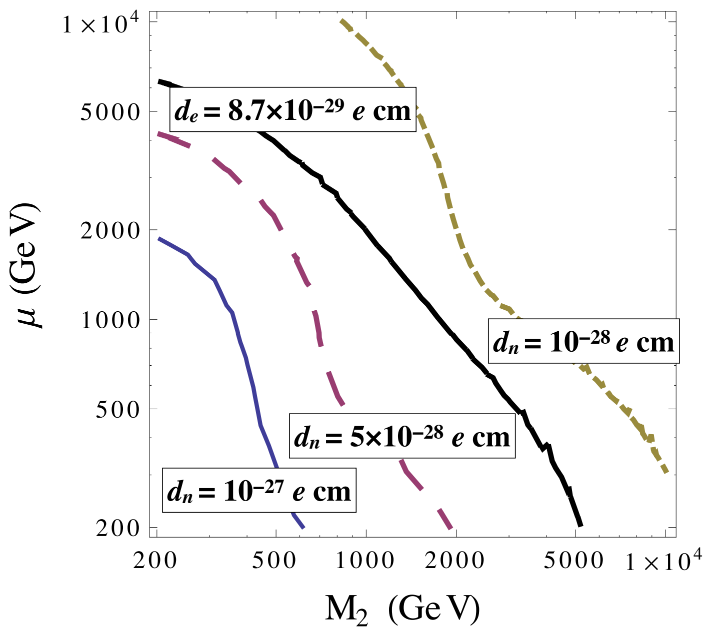


arXiv:1506:04196

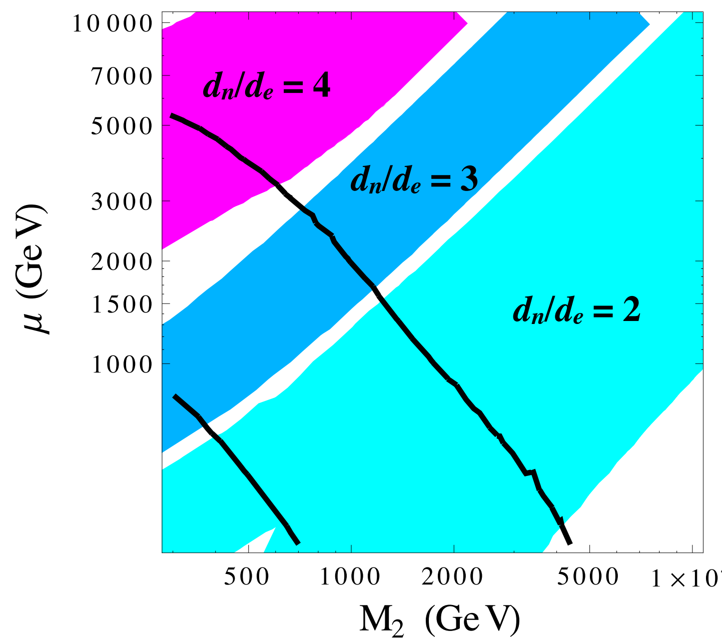
Split Supersymmetry

arXiv:1506:04196

- 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 with scalars
- Fermion EDMs arise at 2-loops via phases in gaugino-Higgsino sector



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 $d_e = 8.7\times10^{-29}$ *e* cm & sinϕ=0.2 and 1.

Split Supersymmetry

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

Vector and Axial Form Factors

- Vector ⟶ electric and magnetic charge radii:
  Resolve (i) discrepancy with and (ii) between
  (*e* scattering and μ-hydrogen) experiments

- Axial:
  Needed to improve estimates of neutrino cross-sections off nuclear targets

Vector and Axial Form-Factors

In the iso-spin limit

$$\left\langle n(p_f,s_f)\right|V_\mu(q)\left|n(p_i,s_i)\right\rangle = \bar{u}(p_f,s_f)\left[\gamma_\mu F_1(q^2)+\frac{\sigma_{\mu\nu}q_\nu}{2M}F_2(q^2)\right]u(p_f,s_i)$$

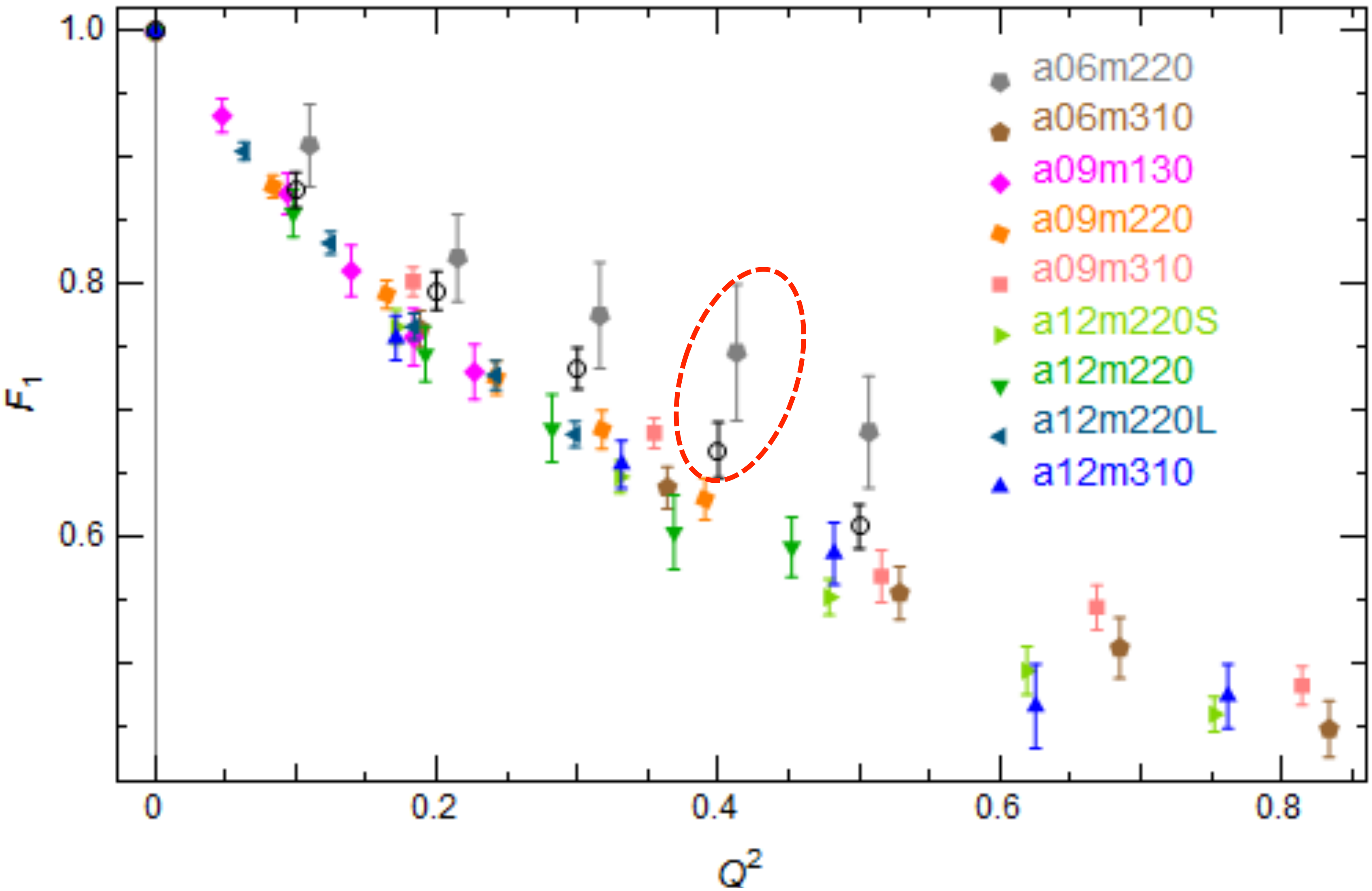
$$G_E(q^2)=F_1(q^2)-\frac{q^2}{4M_n}F_2(q^2)$$
$$G_M(q^2)=F_1(q^2)+F_2(q^2)$$

$$\left\langle n(p_f,s_f)\right|A_\mu(q)\left|n(p_i,s_i)\right\rangle = \bar{u}(p_f,s_f)\left[\gamma_\mu F_A(q^2)+\frac{q\mu}{2M_n}F_P(q^2)\right]\gamma_5 u(p_f,s_i)$$

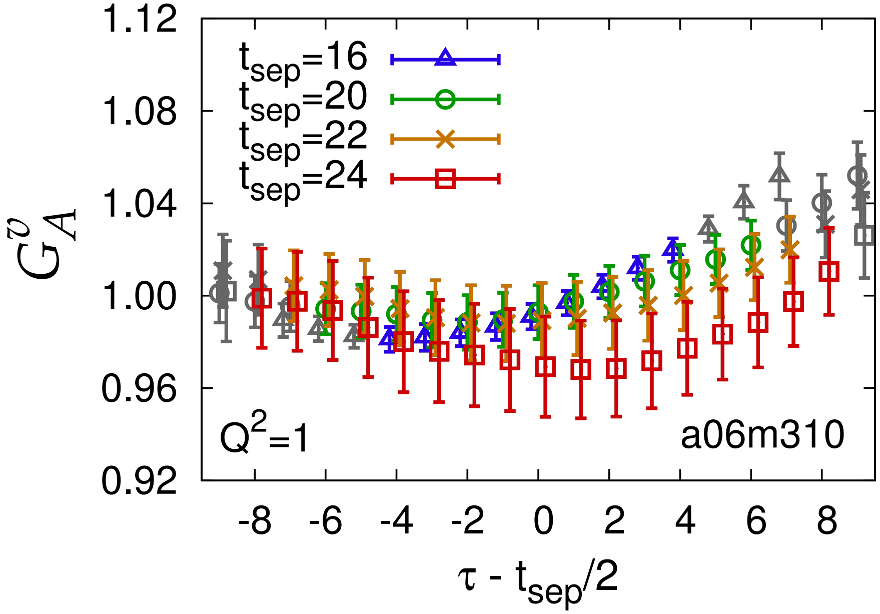
Additional Computational Challenge

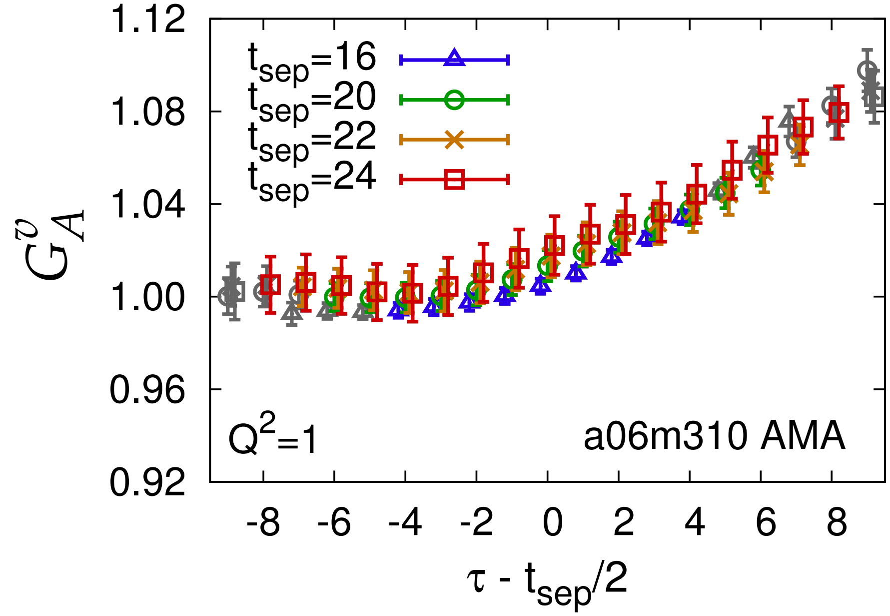
- Signal degrades very rapidly with increasing $q^2 = (p_f - p_i)^2$

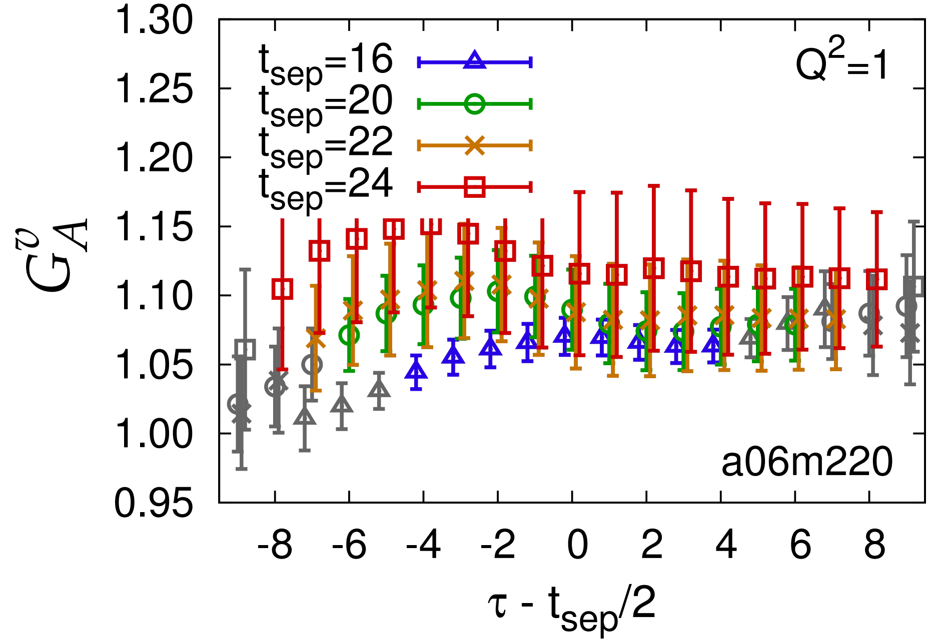
Vector Form-Factor (preliminary)

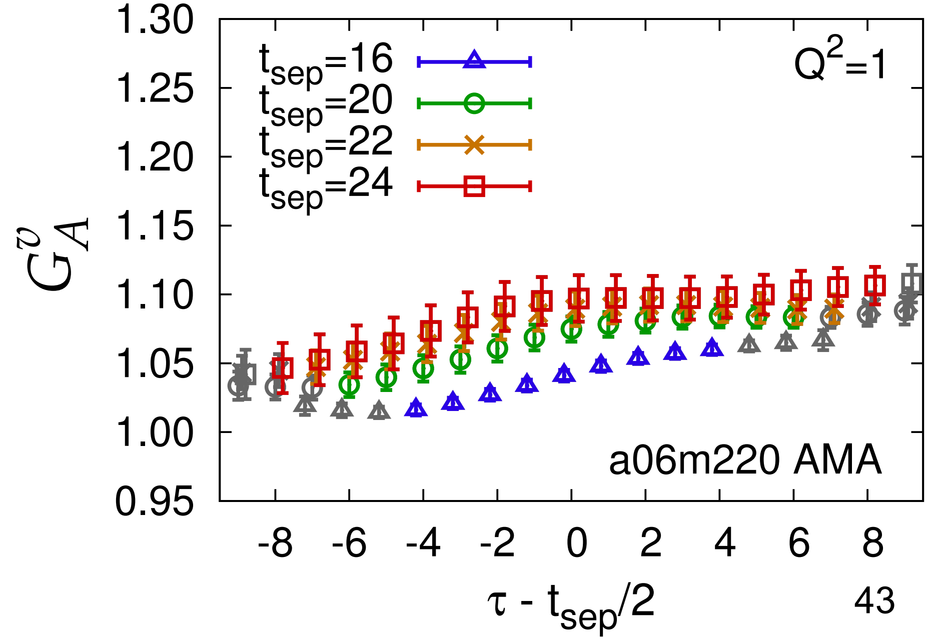


Some preliminary results









Axial Form-factor