Probing novel interactions at the TeV scale using precision measurements of neutron beta decay

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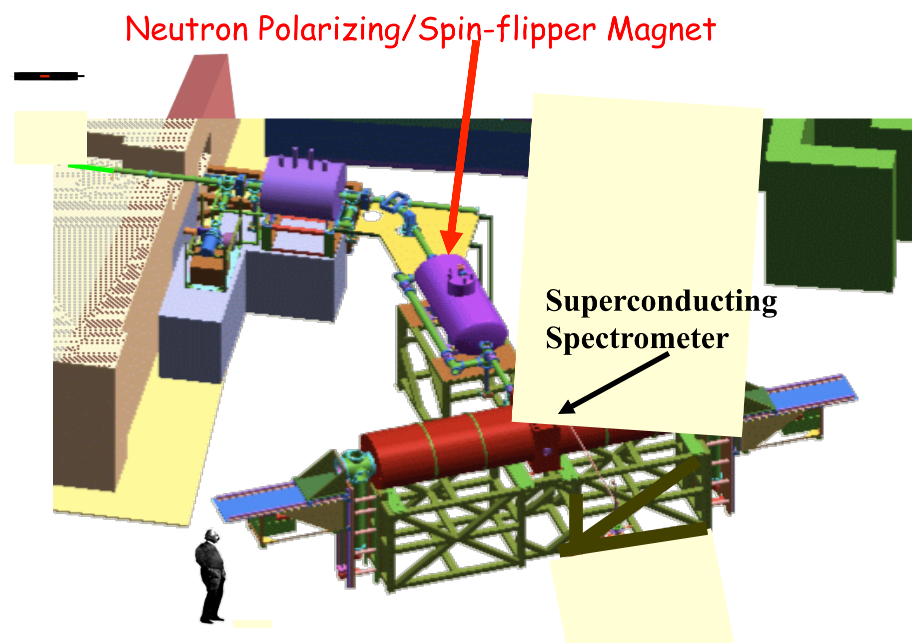

Theory and Experimental effort centered at LANL

Theory and Lattice QCD Collaboration (PNDME)

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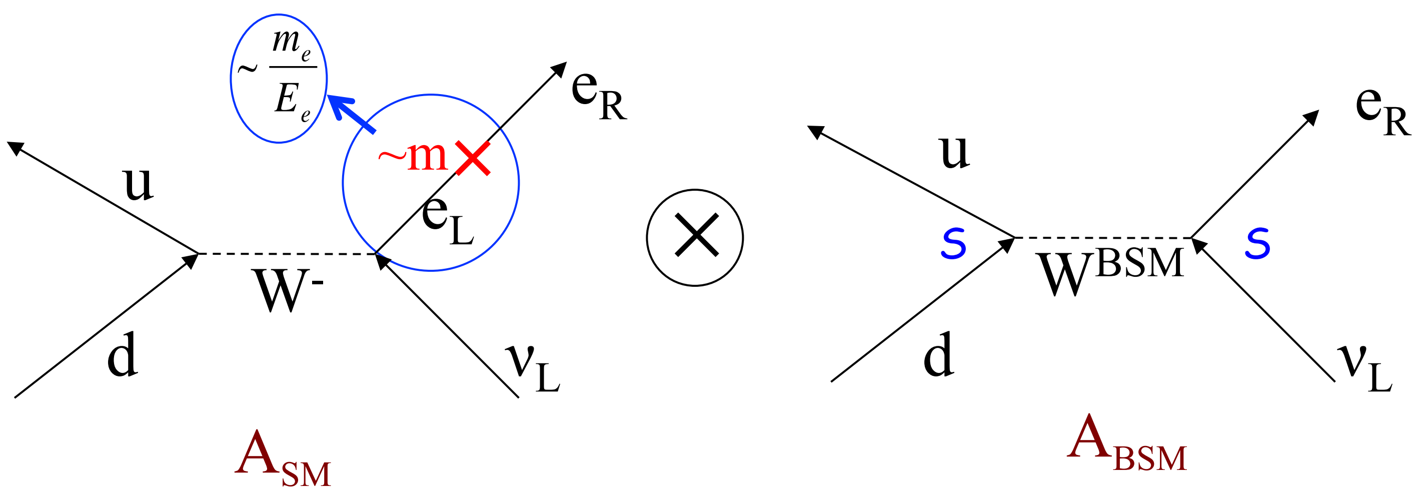
- Tanmoy Bhattacharya (LANL)
- Vincenzo Cirigliano (LANL)
- Saul Cohen (U of Washington)
- Alberto Filipuzzi (Valencia, Spain)
- Martin Gonzalez-Alonso (Madison, Wisconsin)
- Michael Graesser (LANL)
- Rajan Gupta (LANL)
- Anosh Joseph (LANL)
- Huey-Wen Lin (U of Washington)
- Kostas Originos (William and Mary)

Novel S and T interactions at TeV scale
⟶ Effective Theory at ~ 1 GeV

$$H_{\text{eff}} = G_F \left[J^{\text{lept}}_{V-A} \times J^{\text{quark}}_{V-A} + \sum_{n=1,10} \epsilon_n^{\text{BSM}}\, \hat{O}_n \right]$$

$$\epsilon_S \;\bar{u}d \times \bar{e}(1-\gamma_5)\nu_e \qquad\qquad \epsilon_T \;\bar{u}\sigma_{\mu\nu}d \times \bar{e}\sigma^{\mu\nu}(1-\gamma_5)\nu_e$$

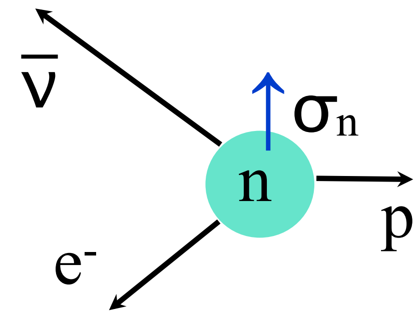
At leading order, contributions from BSM physics arise due to interference of A_{SM} and A_{BSM} and contribute to b and B_1 only through ε_S and ε_T



Ultra Cold Neutron Decay:

Parameters sensitive to new physics

Neutron decay can be parameterized as



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

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

B_1: Energy dependent part of antineutrino correlation with neutron spin

Physics Case: (BSM/SM) ~ O(1)

- Couplings $\varepsilon_{P,S,T}$ $\sim (\Lambda_{BSM})^2/G_F \sim (v/\Lambda_{BSM})^2 \sim 10^{-3}$
- Recoil corrections: $q/M_N \sim 10^{-3}$
- Radiative corrections: $\alpha/\pi \sim 10^{-3}$
- Isospin-breaking: $(M_N\text{-}M_P)/M_N \sim q/M_N \sim 10^{-3}$
- UCN: small Doppler broadening of *e* spectrum
- SM known to ($\sim 10^{-5}$): contribution is controlled by 2 small parameters $(M_n\text{-}M_p)/M_n$ and α/π
- Unique: scalar and tensor BSM interactions involve helicity-flip (m_e/E_e suppression) and are hard to detect in high energy experiments

Physics program

- *In order to bound ε_S and ε_T and quantify significance of the results, we are pursuing an integrated experimental and theoretical program*

$$\boxed{\begin{aligned} b &= f_b\,(\varepsilon_{S,T}\ \ g_{S,T}) \\ B_1 &= f_B\,(\varepsilon_{S,T}\ \ g_{S,T}) \end{aligned}}$$

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

Measure these quantities with UCNs

Calculate these hadronic matrix elements using Lattice QCD

Analyze bounds on ε_S and ε_T from multiple measurements (including LHC signals). Examine BSM extensions

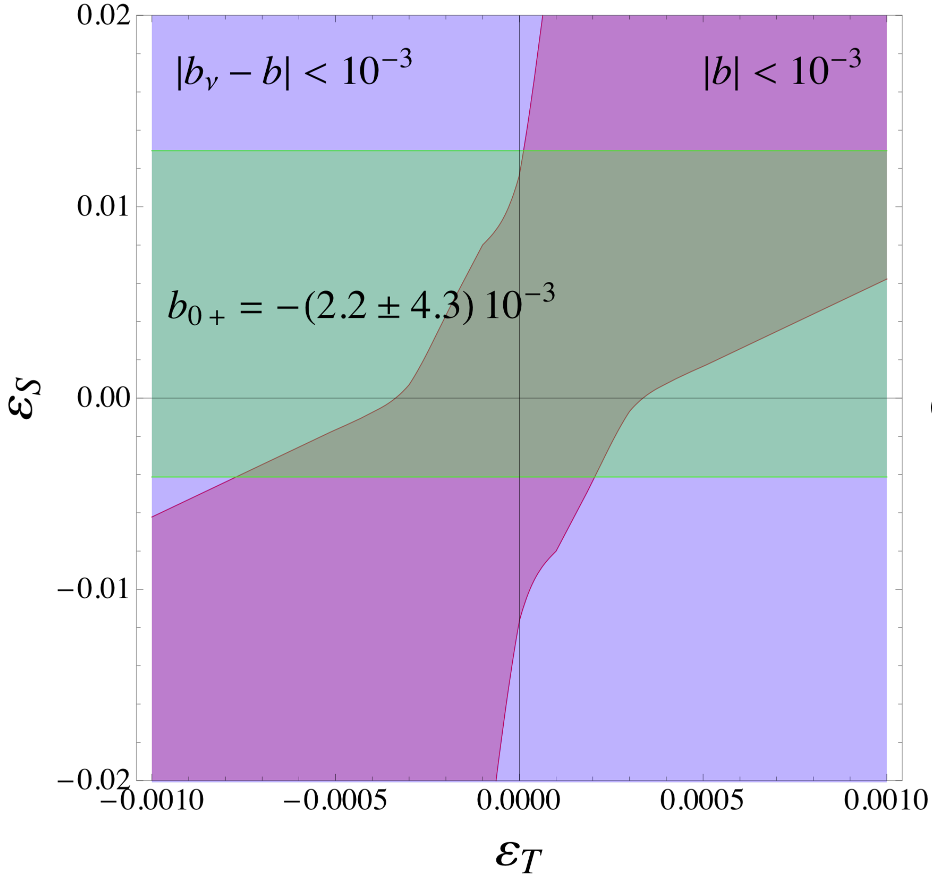
Relating *b* and *B₁* to BSM couplings

Linear order relations from n $\longrightarrow$ p e ν decay

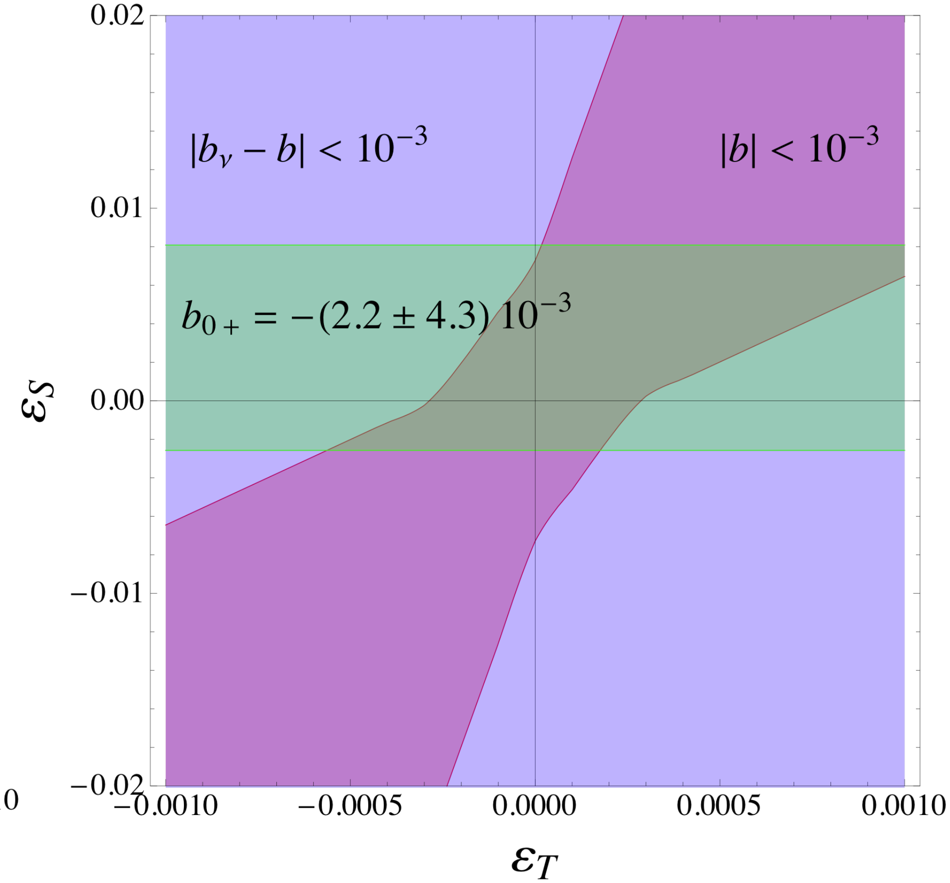
$$b^{BSM} \approx 0.34\, g_S \varepsilon_S - 5.22\, g_T \varepsilon_T$$

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

Constraining allowed region in ε_S and ε_T as estimates of g_S and g_T are improved



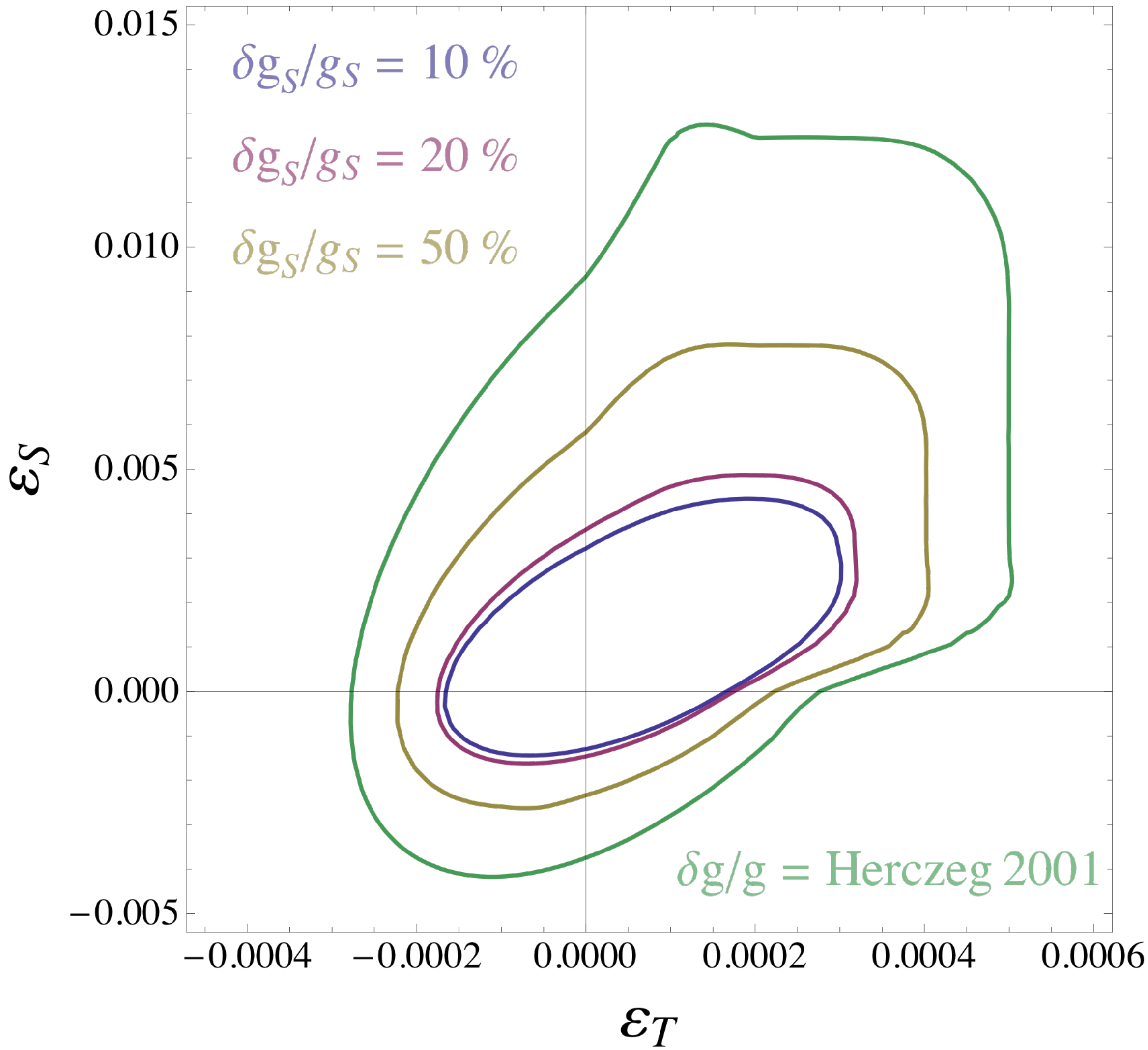
Herczeg–2001
$0.25 < g_S < 1.0$
$0.6 \quad < g_T < 2.3$



Lattice–2011
$g_S = 0.8(4)$
$g_T = 1.05(35)$

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

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



Expt. input

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

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

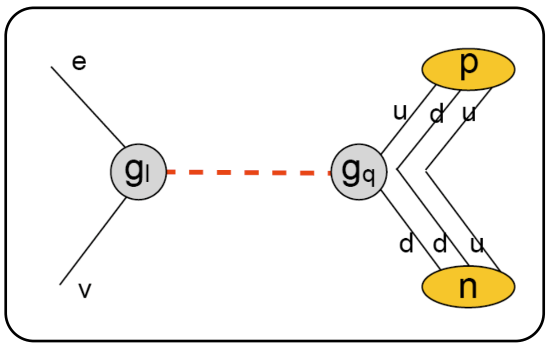
$b_{0+} = 2.6\ (4.3) * 10^{-3}$

Limited by precision of ME from Lattice QCD

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

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

Precision calculations of g_S, g_T using Lattice QCD



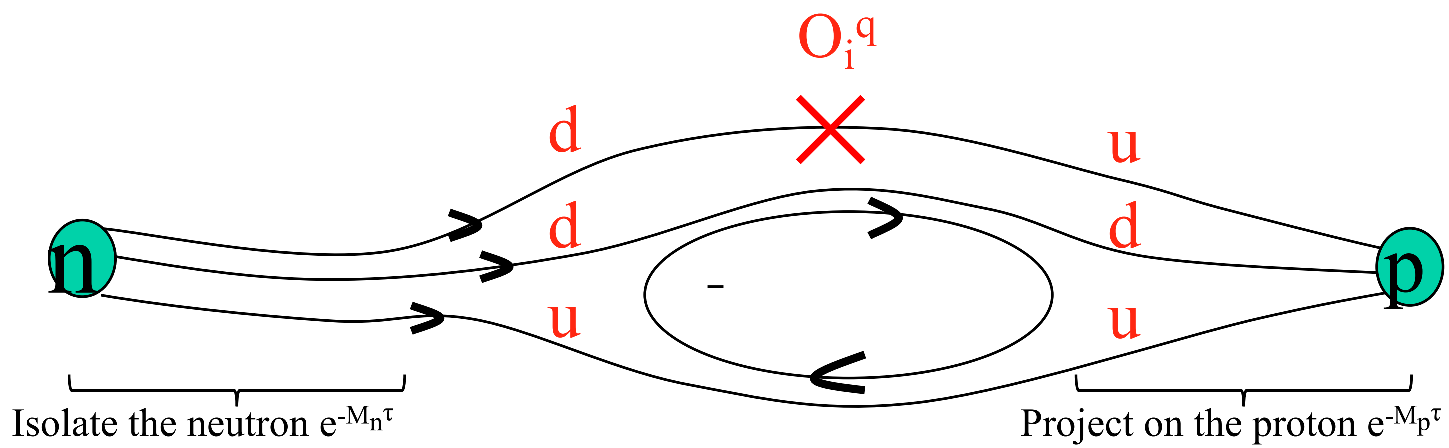
$$g_S \sim \langle p | \bar{u} d | n \rangle$$

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

Goal: 10-20% accuracy

T. Bhattacharya, S. Cohen, R. Gupta, A. Joseph, H-W Lin

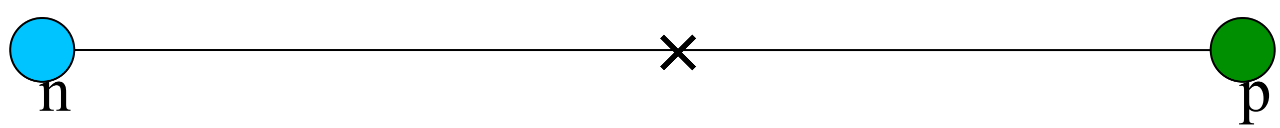
Lattice QCD calculation of $\langle p|\bar{u}\,\Gamma d|n\rangle$



- **Achieving 10-20% uncertainty is a realistic goal but requires:**
  - High Statistics: computer resources from USQCD, XSEDE, LANL
  - Controlling all Systematic Errors:
    - Finite volume effects
    - Contamination from excited states
    - Chiral Extrapolations to physical *u* and *d* quark masses
    - Extrapolation to the continuum limit (lattice spacing $a \to 0$)
    - Non-perturbative renormalization of bilinears using the RI_{mom} scheme

Lattice setup: Choices we made

- Gauge configurations with 2+1+1 flavor of dynamical quarks
  - HISQ lattices generated by the MILC collaboration (short-term)
  - Clover lattices generated by the JLab collaboration (longer-term)
- Analysis using clover fermions (Phase 1: Clover on HISQ)
  - Exceptional Configurations – extensive tests
- Improving Signal in Baryon Correlators – Source Smearing size
- Study multiple time separations between the source (neutron) and sink (proton) to study & reduce excited state contribution

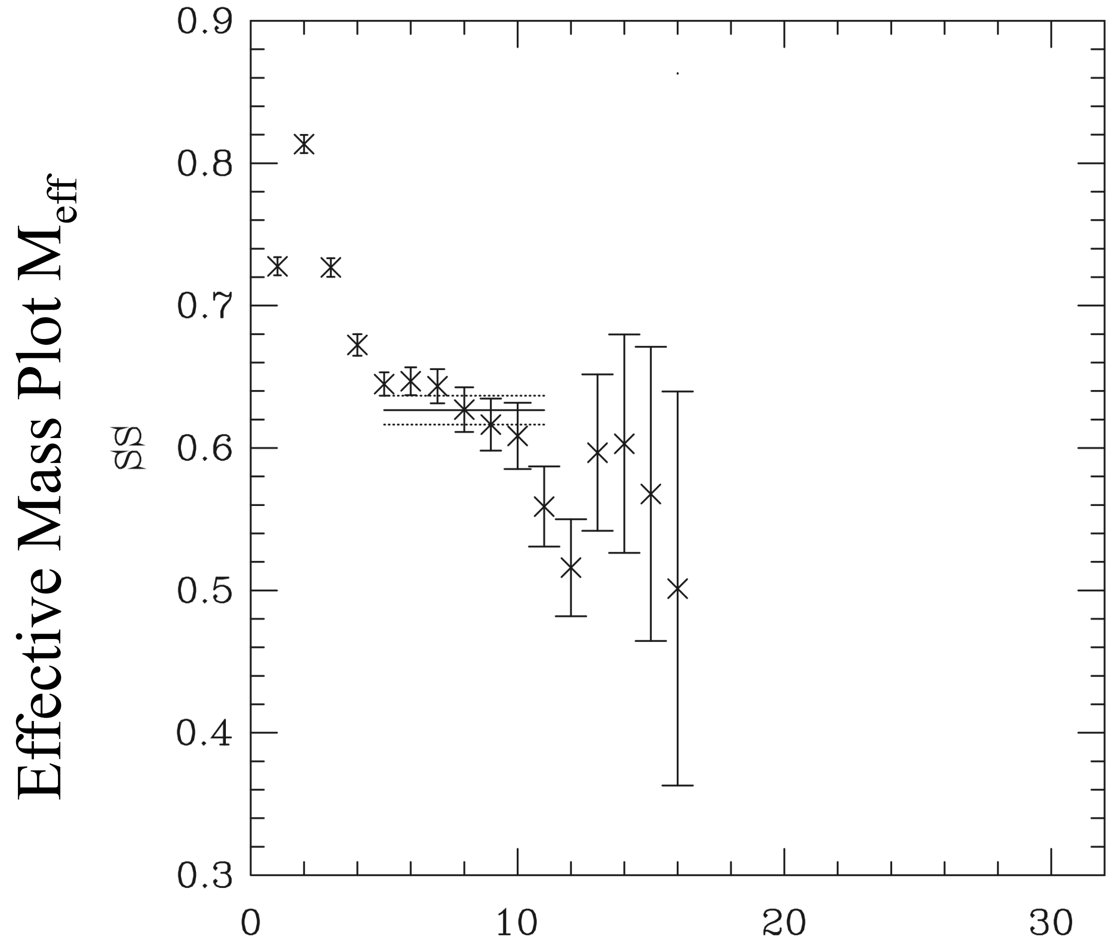


2+1+1 flavor HISQ lattices: goal 1000 configs

- m_s set to its physical value using $M_{\bar{s}s}$

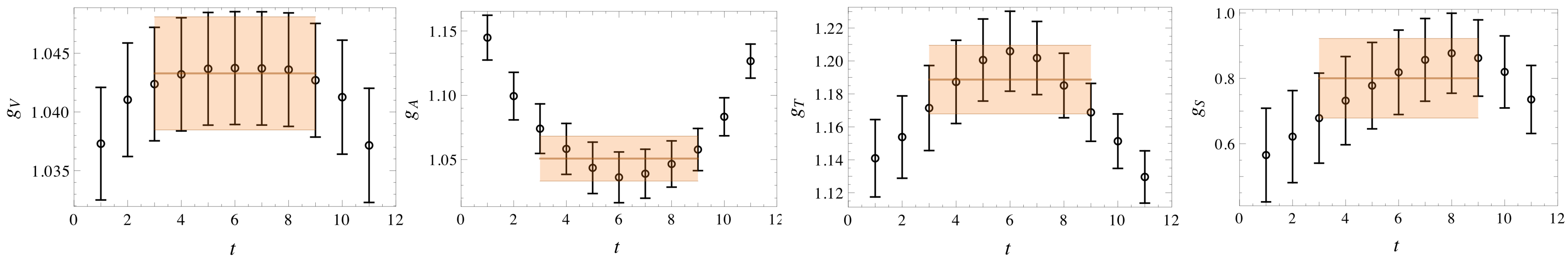
a(fm)	m_l/m_s	Lattice Volume	$M_\pi L$	M_π (MeV)	Configs. Analyzed
0.12	0.2	$24^3 \times 64$	4.54	305	507
0.12	0.1	$32^3 \times 64$	4.29	217	478
0.09	0.2	$32^3 \times 96$	4.5	313	391
0.09	0.1	$48^3 \times 96$	4.73	220	443
0.06	0.2	$48^3 \times 144$	4.53	320	330
0.06	0.1	$64^3 \times 144$	4.28	229	

Signal in 2-point baryon correlators



a = 0.12 fm lattices with M_π = 220 MeV
(225 lattices; each with 4 sources)

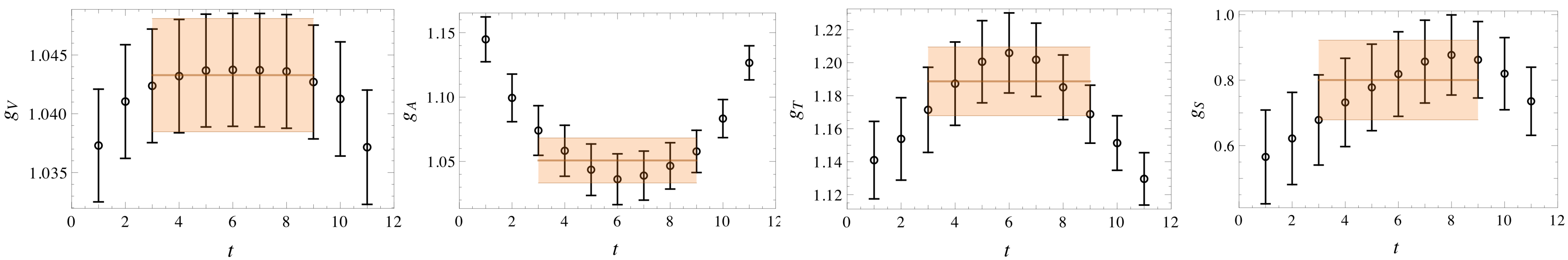
Signal in the ratio $\frac{g_\Gamma}{Z_\Gamma} = \frac{\langle p | \bar{u}\Gamma d | n \rangle}{\langle p | n \rangle}$



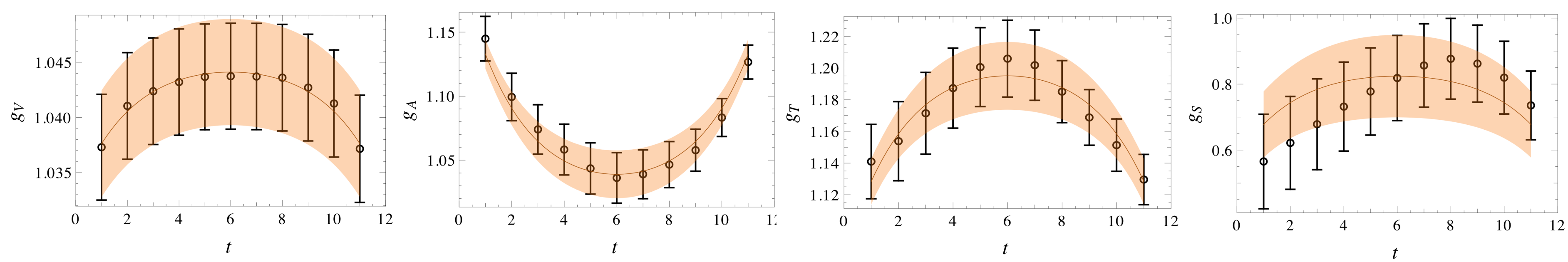
Preliminary data

- Statistics
- Plateau (result should be independent of *t*)
  - Otherwise eliminate excited state contribution
- Non-perturbative calculation of renormalization Z_Γ

Signal in the ratio $\frac{g_\Gamma}{Z_\Gamma} = \frac{\langle p | \bar{u} \Gamma d | n \rangle}{\langle p | n \rangle}$



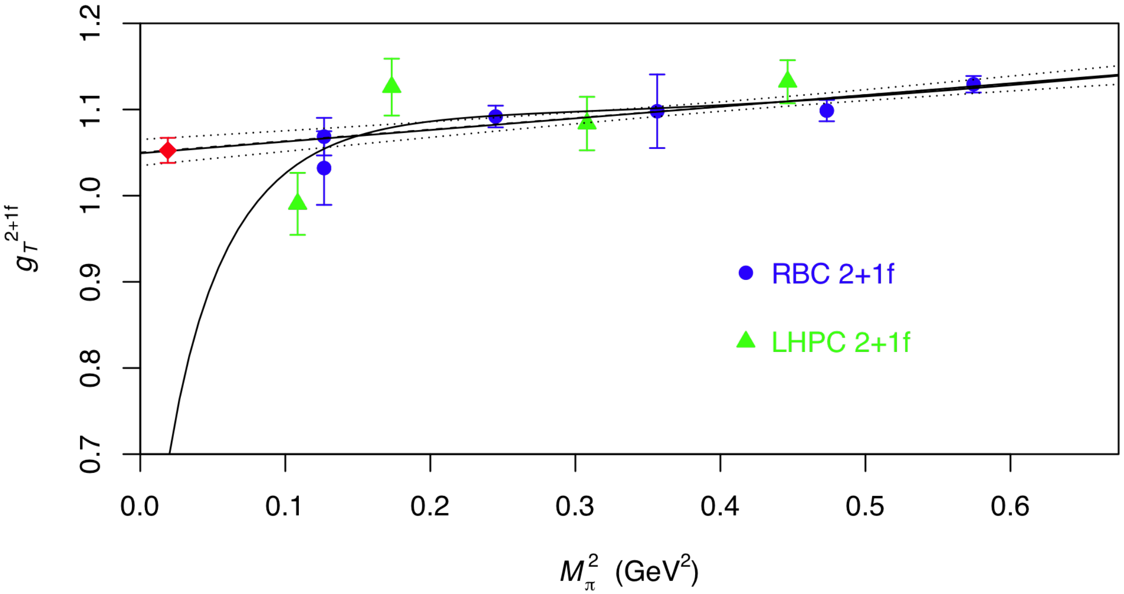
One-state versus two-state fit



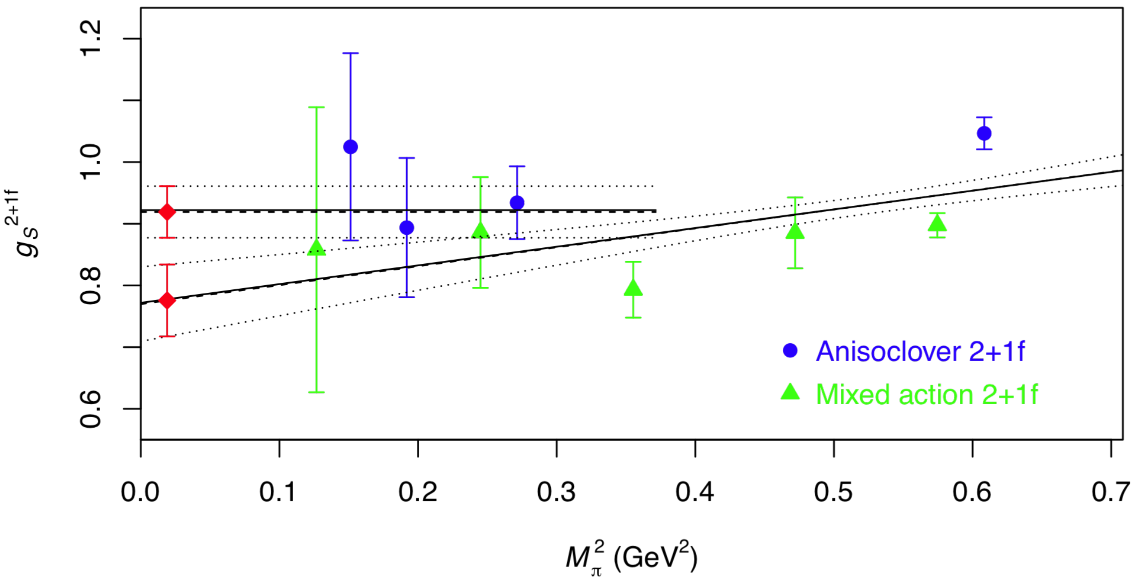
The calculation of g_S will dictate the statistics needed

Preliminary

Uncertainty in the chiral extrapolation



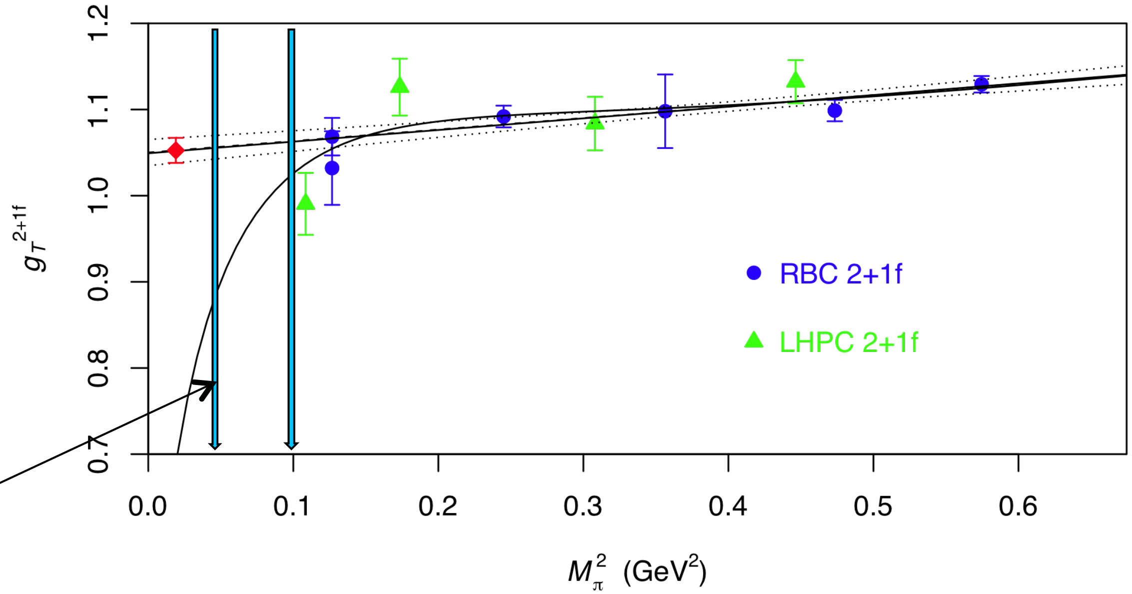
Do chiral logs dominate at lower M_π^2 ?

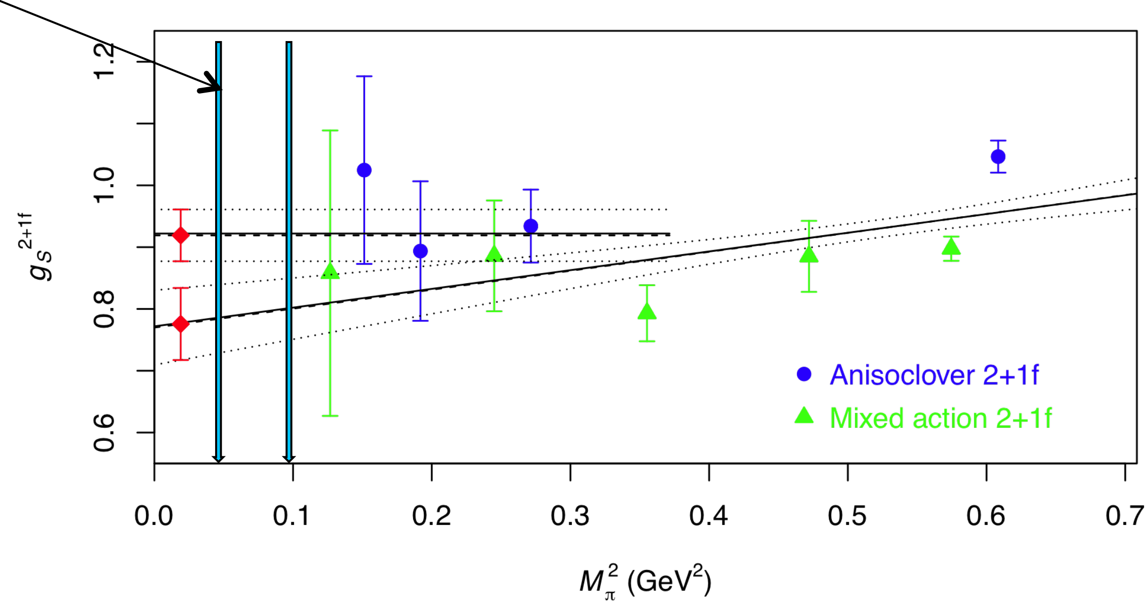


What M_π^2 interval should be used in the extrapolation?

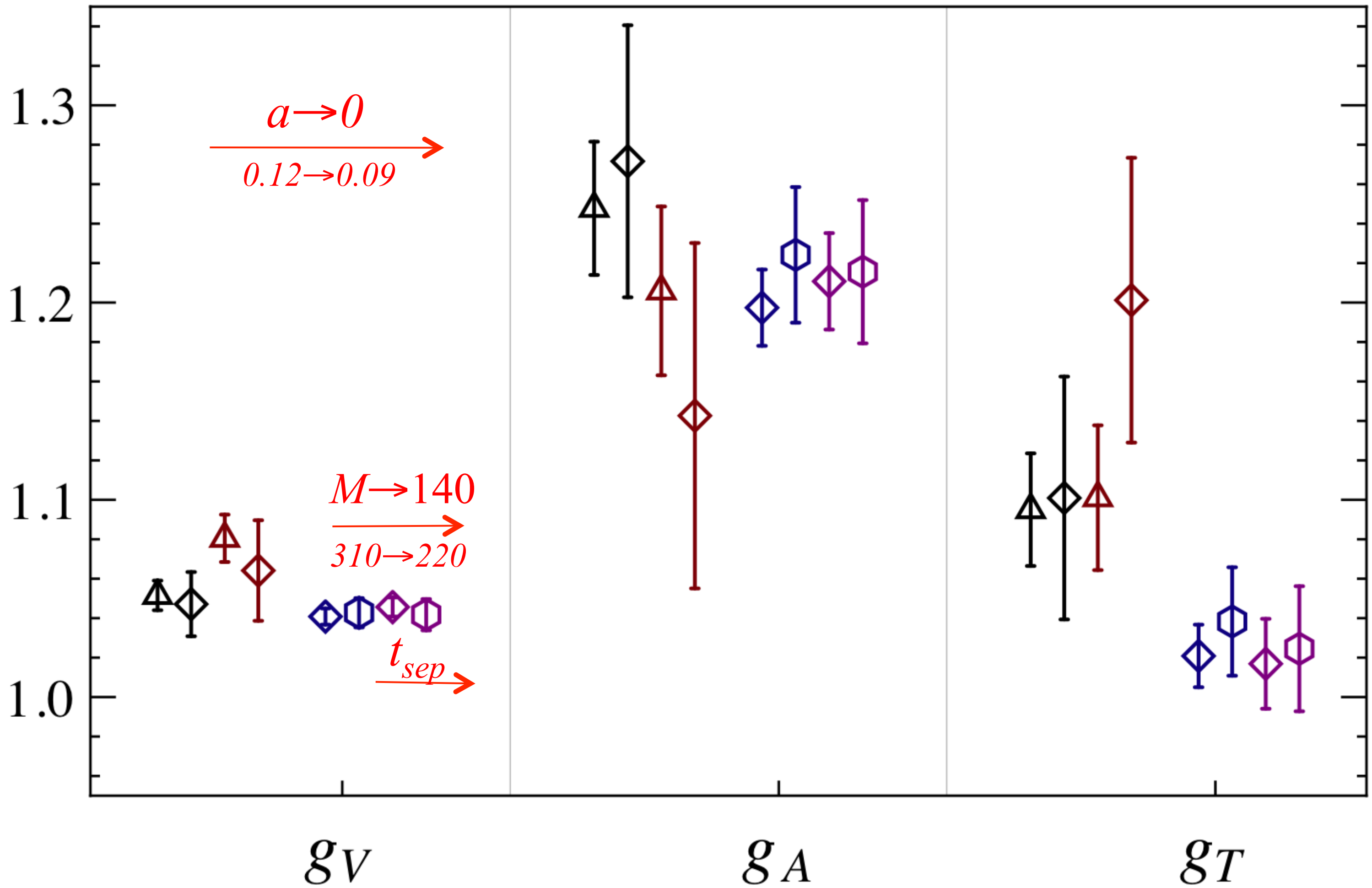
Reducing uncertainty in the chiral extrapolation

Ongoing simulations





New Preliminary Estimates

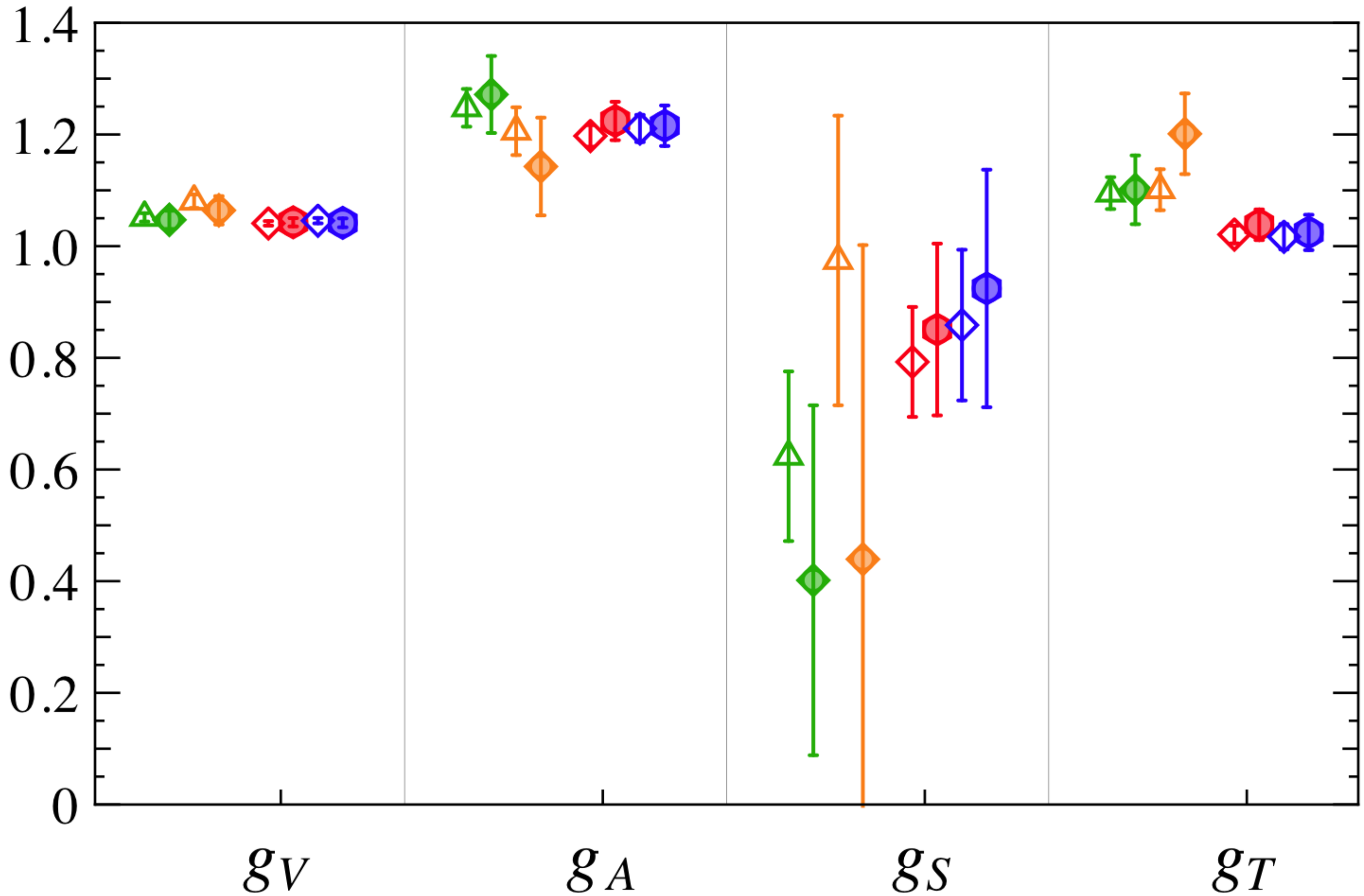


8 points

$2 \times a$
$2 \times m_l$
$2 \times t_{\text{sep}}$

{a (fm);M (MeV); t_sep} = {0.12; 310; 10}, {0.12; 310; 12}, {0.12; 220; 10}, {0.12; 220; 12}, {0.09; 310; 12}, {0.09; 310; 14}, {0.09; 220; 12}, {0.09; 220; 14}

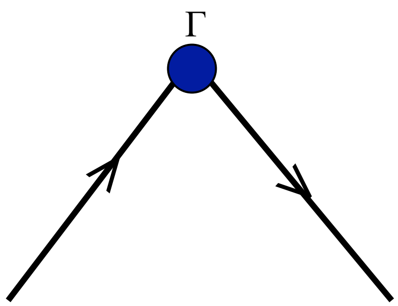
New Preliminary Estimates



The calculation of g_S will dictate the statistics needed

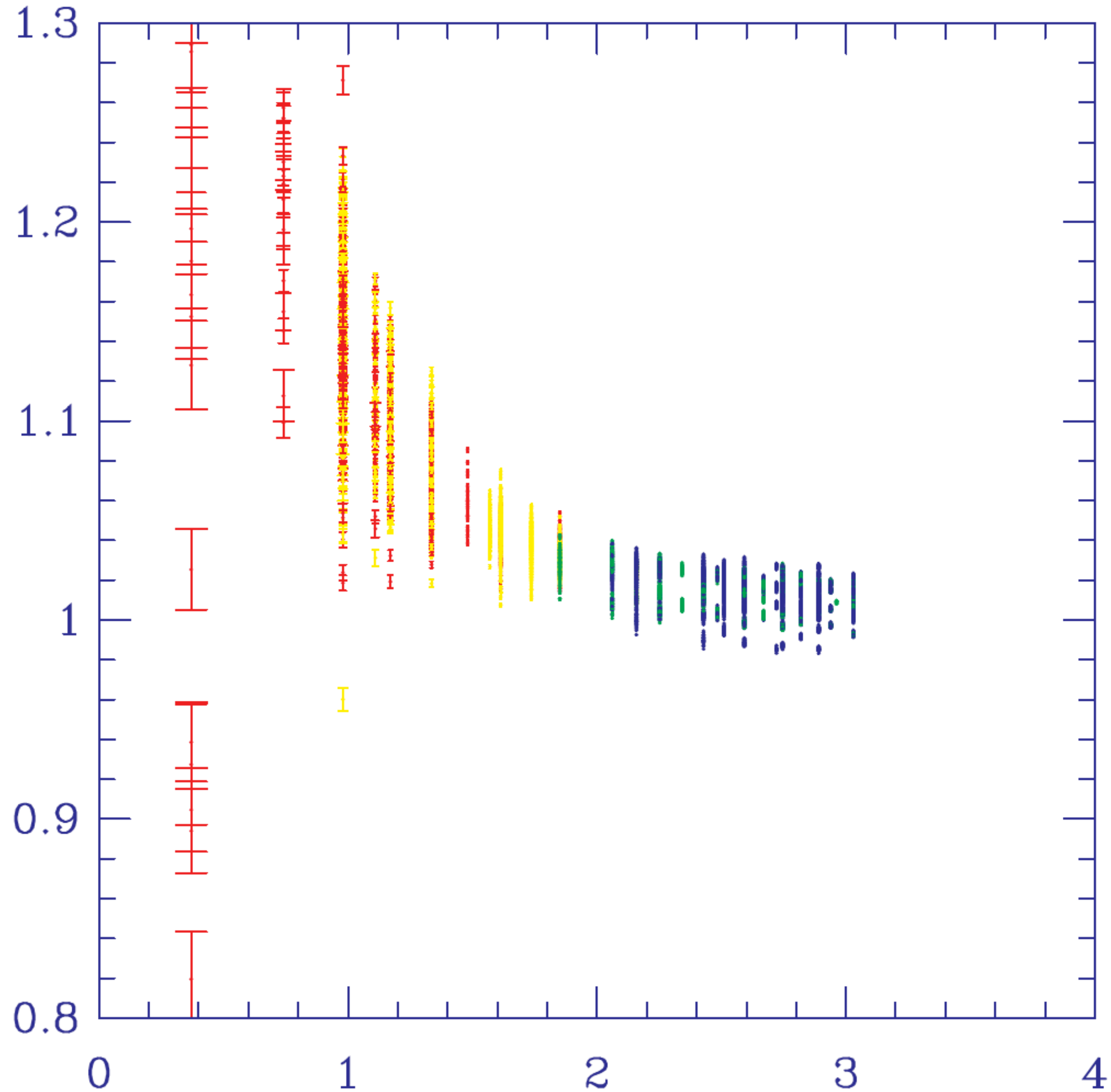
In Progress: Renormalization of Bilinears

- Non-perturbative renormalization Z_Γ using the RI_{smom} scheme
  - Need quark propagator in momentum space

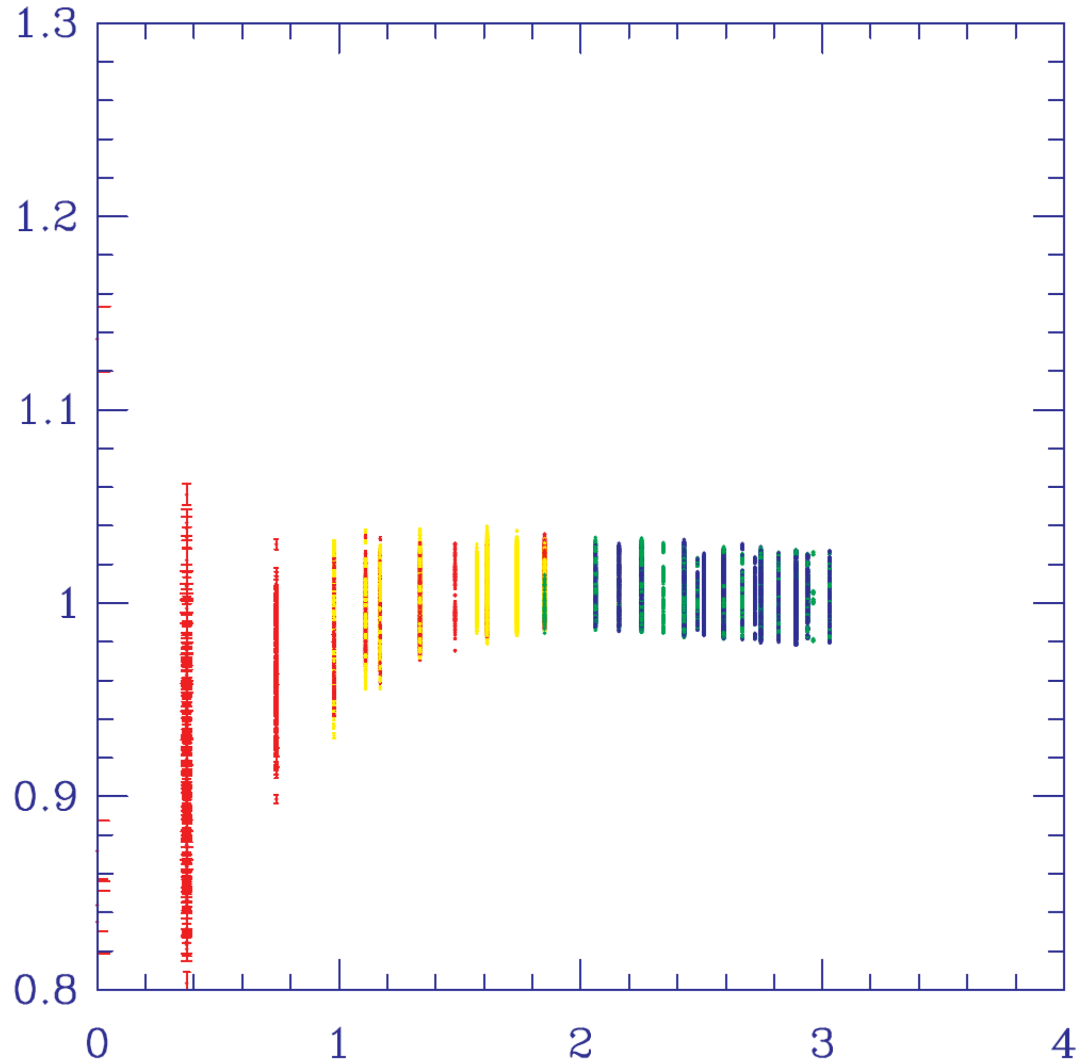


- Construct ratios with respect to charge ($\Gamma=\gamma_t$) to reduce systematic errors

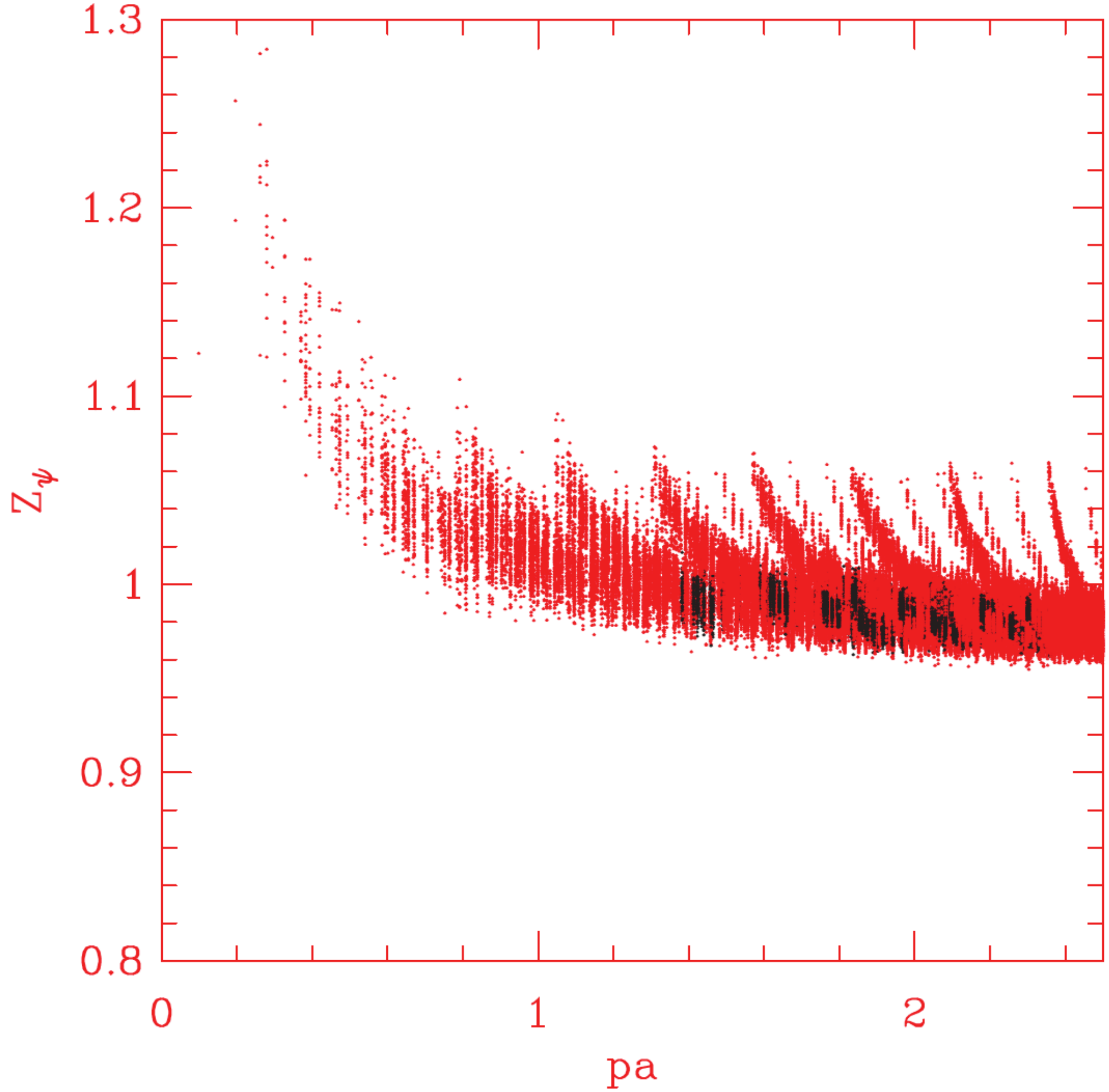
$Z_\psi Z_S$ (a=0.12, M_π=310 MeV)



$Z_\psi Z_T$ (a=0.12, M_π=310 MeV)



Z_ψ (a=0.12, M_π=310 MeV)



Continuum extrapolation

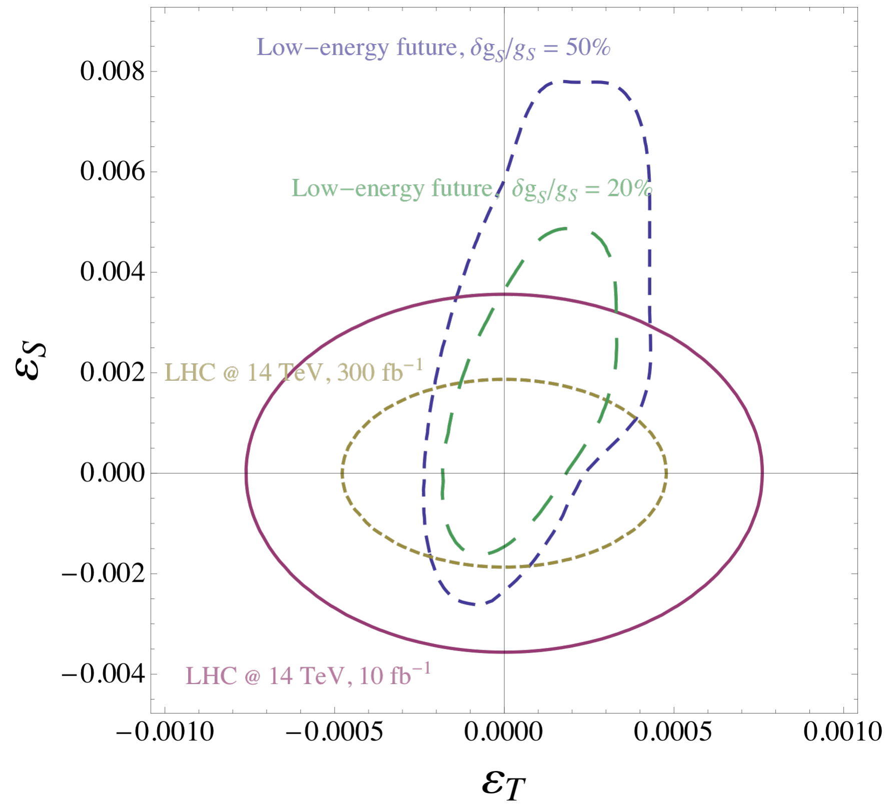
- Continuum extrapolation using a = 0.12, 0.09, 0.06 fm after Z_Γ have been calculated & included
- To quantify a dependence in g_S and g_T we need to reduce errors
  - need full 1000 configurations at $a=0.12$ fm

Summary

- GOAL: To use experimental measurements of b and b-b_ν at the 10^{-3} level to bound ε_S and ε_T requires calculation of g_T and g_S at the 10-20% level
- 2011: Lattice QCD estimates of g_S and g_T improved the bounds on ε_S and ε_T compared to previous estimates based on phenomenological models
- 2013: Lattice calculations are on track to providing g_T and g_S with 10-20% uncertainty

β-decay versus LHC constraints

- LHC @ 14 TeV and 300 fb^{-1}, will provide comparable constraints to low-energy ones with $\delta g_S/g_S$ ~20%



Acknowledgements

- Computing resources from
  - USQCD
  - XSEDE
  - LANL
- 2+1+1 HISQ lattices generated by the MILC collaboration
- Computer code uses CHROMA library
- Supported by DOE and LANL-LDRD