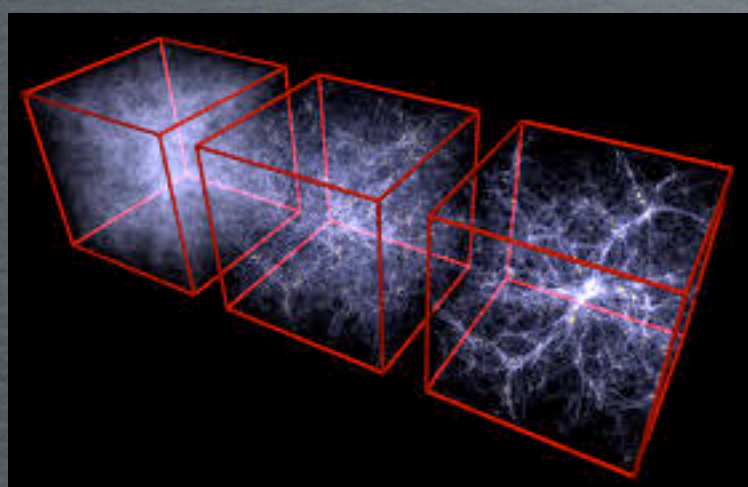
Bounding Dark Baryons: From Fermions to Bosons



LSD

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PRD 88 014502 (2013)

arXiv: 1312.???? (hep-ph)
arXiv: 1312.???? (hep-lat)

Graham Kribs +

Lattice Strong Dynamics Collaboration

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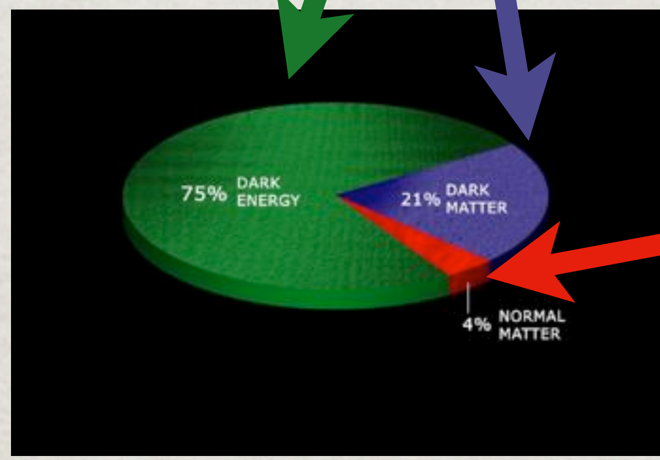
A slice of the Universe

??????

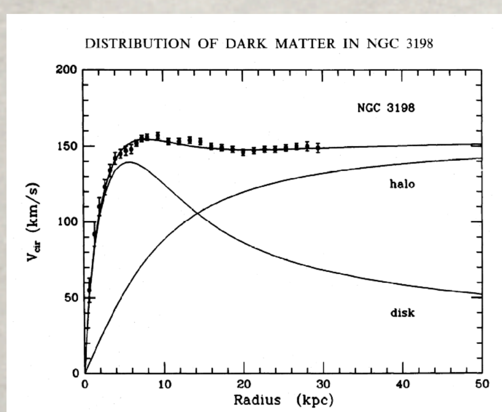
New Physics!!



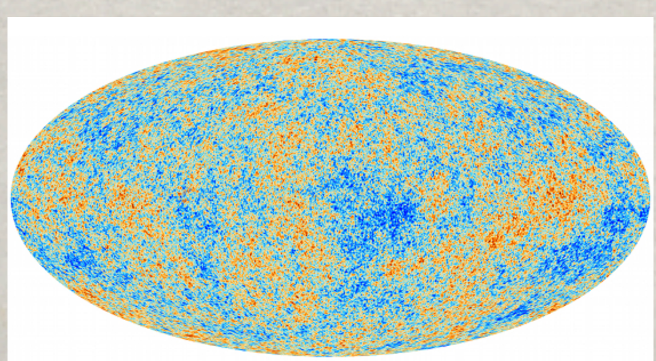
We Are Here

(QCD, EM, SM, etc.)

How do we know DM is there?



- Rotation Curves of Galaxies
- Gravitational Lensing



- Cosmological Backgrounds

Three Primary Properties of dark matter

1. Candidate should be Stable

- Explains why dark matter has survived to today

➡ Implies a new symmetry and/or charge

2. Candidate should be EW Charge Neutral

- Explains why there is no visible evidence

➡ Implies lightest stable particle is chargeless

3. Candidate should explain observed relic density

$$\rho_D \sim 0.2 \ \rho_c$$

How can
this come about?

Thermal Relic

Dark Matter Annihilates → How much do we see today?

One approach to DM theories:

Choose DM Mass
Choose DM Interactions → $\rho_D \sim 0.2\ \rho_c$

"WIMP Miracle"

Assume Interactions at/near EW Scale → $M_D \sim \text{TeV}$

An Asymmetric alternative?

S.Nussinov (1985) S.M. Barr, R.S.Chivukula, E. Farhi (1990) R.S.Chivukula, T.P.Walker (1990) D.B.Kaplan (1992)

Observe a different relation:

$$\rho_D \sim 5\rho_B$$

$$M_D n_D \sim 5 M_B n_B$$

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Asymmetry

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$$M_D n_D \sim 5 M_B n_B$$

If DM density is thermal: **Unjustified Accident**

Natural if DM density is also tied to asymmetry

$$n_D \sim n_B \Longrightarrow M_D \sim 5 \text{ GeV}$$

$$M_D \gg M_B \Longrightarrow n_B \gg n_D \sim e^{-M_D/T_{sph}}$$

Sphaleron connection $\Rightarrow$ Direct or Indirect coupling to EW

Thermal vs. asymmetric

However:

Asymmetric relic density
suggests negligible thermal abundance

Small Thermal Abundance → Large Annihilation rate → Strong Couplings

Tricky to achieve for perturbative, elementary DM

Strongly-coupled composite theories most interesting...

...this is where the lattice can play significant role!

Asymmetric Models

We Want:

- ★ Lightest stable composite chargeless (EM + weak)
- ★ Constituents that communicate with electroweak

Direct:

Subset of constituents that are non-singlet under $SU(2)_L$

Indirect:

Neutral, but couples to heavy, charged particles yet to be observed

Bai, Schwaller 2013

Worth Noting

The composite theories discussed here are NOT designed to be solutions to EW symmetry breaking!

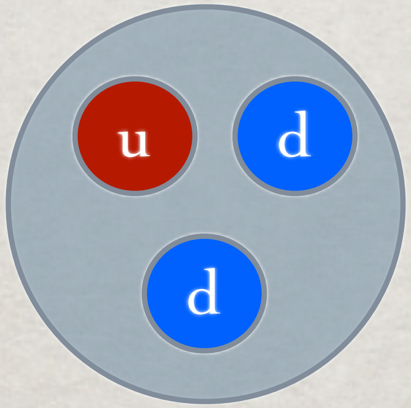
- ★ Theories studied here are not technicolor
  - ✳ No Goldstone modes becoming longitudinal vector components
  - ✳ Minimal contribution to vector masses and Higgs vev (ala QCD)
- ★ Interactions considered here for stable, confinement-scale baryons:
  - ✳ Odd Nc: Only EM interactions
  - ✳ Even Nc: EW interactions with SM Higgs

Baryon Flavor Symmetry

Invariant under $SU(N_f)$ transformations

★ Flavor Non-symmetric

Example: (3-color neutron ala QCD)



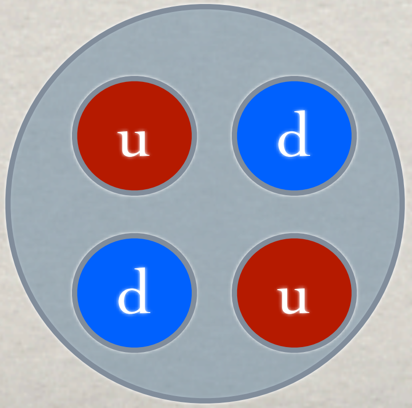
$$Q_u = Q_d$$

or

$$Q_u \neq Q_d$$

★ Flavor Symmetric

Example: (4-color neutron)



$$Q_u = -Q_d$$

only

How we might see it?

	Dim-5	Dim-6	Dim-7
	$\overline{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}$	$(\overline{\psi}\psi)v_\mu\partial_\nu F^{\mu\nu}$	$(\overline{\psi}\psi)F_{\mu\nu}F^{\mu\nu}$
	Magnetic Moment	Charge Radius	Polarizability
Odd Nc No baryon flavor sym.	✓	✓	✓
Odd Nc Baryon flavor sym.			✓
Even Nc No Baryon flavor sym.		✓	✓
Even Nc Baryon flavor sym.			✓

Focus of Previous work

- Direct detection exclusions for odd number of colors

Explore:

- 3-colors
- Multiple degenerate masses
- 2 and 6 light flavors

Explores a range of confining theories for odd Nc theory

Focus of Previous work

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QCD
sanity check

Something
different…

Explores a range of confining theories for odd Nc theory

Cross-Section Calc.

$$\frac{d\sigma}{dE_R} = \frac{\overline{|\mathcal{M}_{\rm SI}|^2} + \overline{|\mathcal{M}_{\rm SD}|^2}}{16\pi(M_\chi + M_T)^2 E_R^{\rm max}}$$

$$E_R^{\rm max} = \frac{2M_\chi^2 M_T v^2}{(M_\chi + M_T)^2}$$

$$\overline{|\mathcal{M}_{\rm SI}|^2} = e^4\left[ZF_c(Q)\right]^2\left(\frac{M_T}{M_\chi}\right)^2\left[\frac{4}{9}M_\chi^4\langle r_{E\chi}^2\rangle^2 + \kappa_\chi^2\left(1+\frac{M_\chi}{M_T}\right)^2\left(\frac{E_R^{\rm max}}{E_R}-1\right)\right]$$

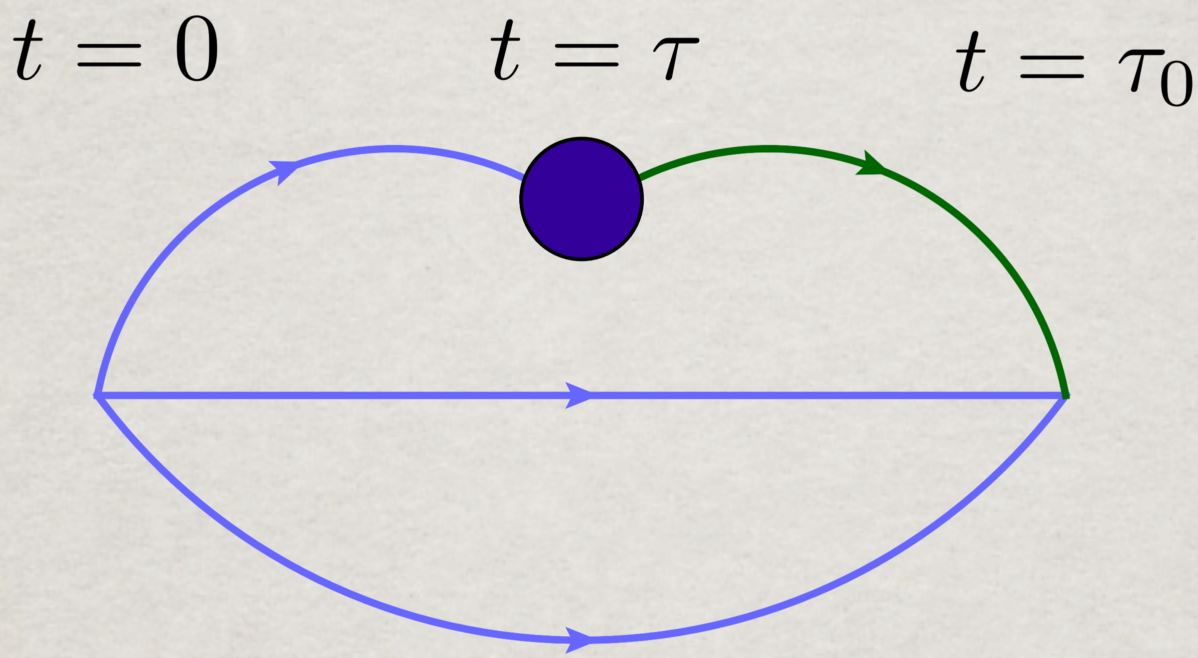
$$\overline{|\mathcal{M}_{\rm SD}|^2} = e^4\,\frac{2}{3}\left(\frac{J+1}{J}\right)\left[\left(A\frac{\mu_T}{\mu_n}\right)F_s(Q)\right]^2\kappa_\chi^2$$

$$R = \frac{M_{\rm detector}}{M_T}\frac{\rho_{\rm DM}}{M_\chi}\int_{E_{\rm min}}^{E_{\rm max}} dE_R\,\mathcal{A}cc(E_R)\left\langle v'\,\frac{d\sigma}{dE_R}\right\rangle_f$$

*Non-perturbative lattice input

Xenon100: $E_{min}^{Xe} = 6.6\ \mathrm{keV}$ $E_{max}^{Xe} = 30.5\ \mathrm{keV}$

Three-Point Calculation

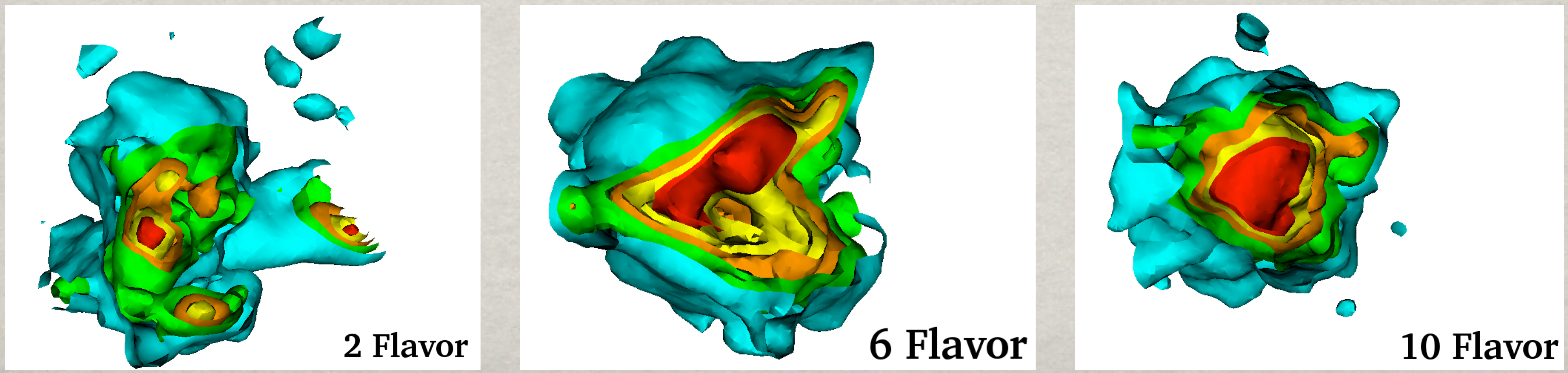


Disconected diagrams omitted in current calculation

2 Propagators → One measurements
One time insertion

Transverse charge density:

(courtesy of J. Wasem)



Scale Setting

How do we define lattice spacing in physical units?

Lattice QCD:

Hadron Masses, HQ potentials, etc.

(Example) $$aM_\Omega = \# \quad \Rightarrow \quad a \approx \frac{\#}{1670\ \mathrm{MeV}}$$

Technicolor:

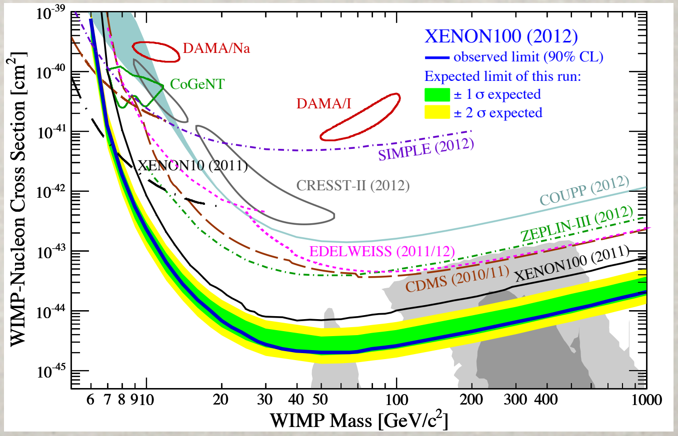
"Higgs" vev

$$af_\pi \xrightarrow{m_f \to 0} \# \quad \Rightarrow \quad a \approx \frac{\#}{246\ \mathrm{GeV}}$$

Dark Matter:

Dark Matter Mass

$$aM_B = \# \quad \Rightarrow \quad a \approx \frac{\#}{M_B}$$



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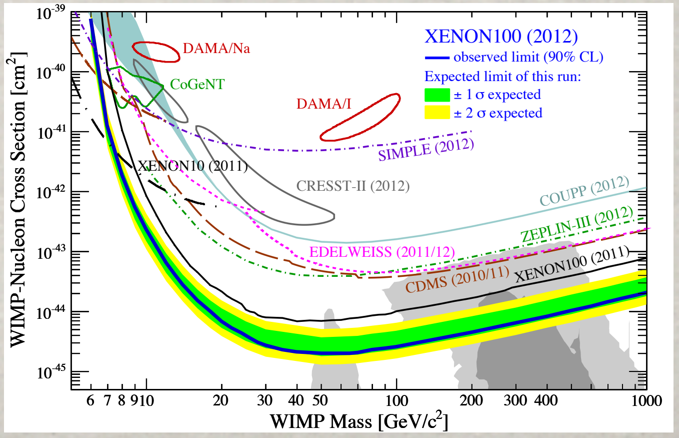
Dark Matter:

Dark Matter Mass

$aM_B = \#$ $\Rightarrow$ $a \approx \dfrac{\#}{M_B}$

Vary this value



Calculation Details

10 DWF Ensembles:

- $32^3 \times 64 \times 16$ lattices

$$am_\rho \sim \frac{1}{5}$$

2 flavor: $m_f =$ 0.010 - 0.030

6 flavor: $m_f =$ 0.010 - 0.030

Table 1: 2 Flavor

m_q	# Configs	# Meas
0.010	564	1128
0.015	148	296
0.020	131	262
0.025	67	268
0.030	39	154

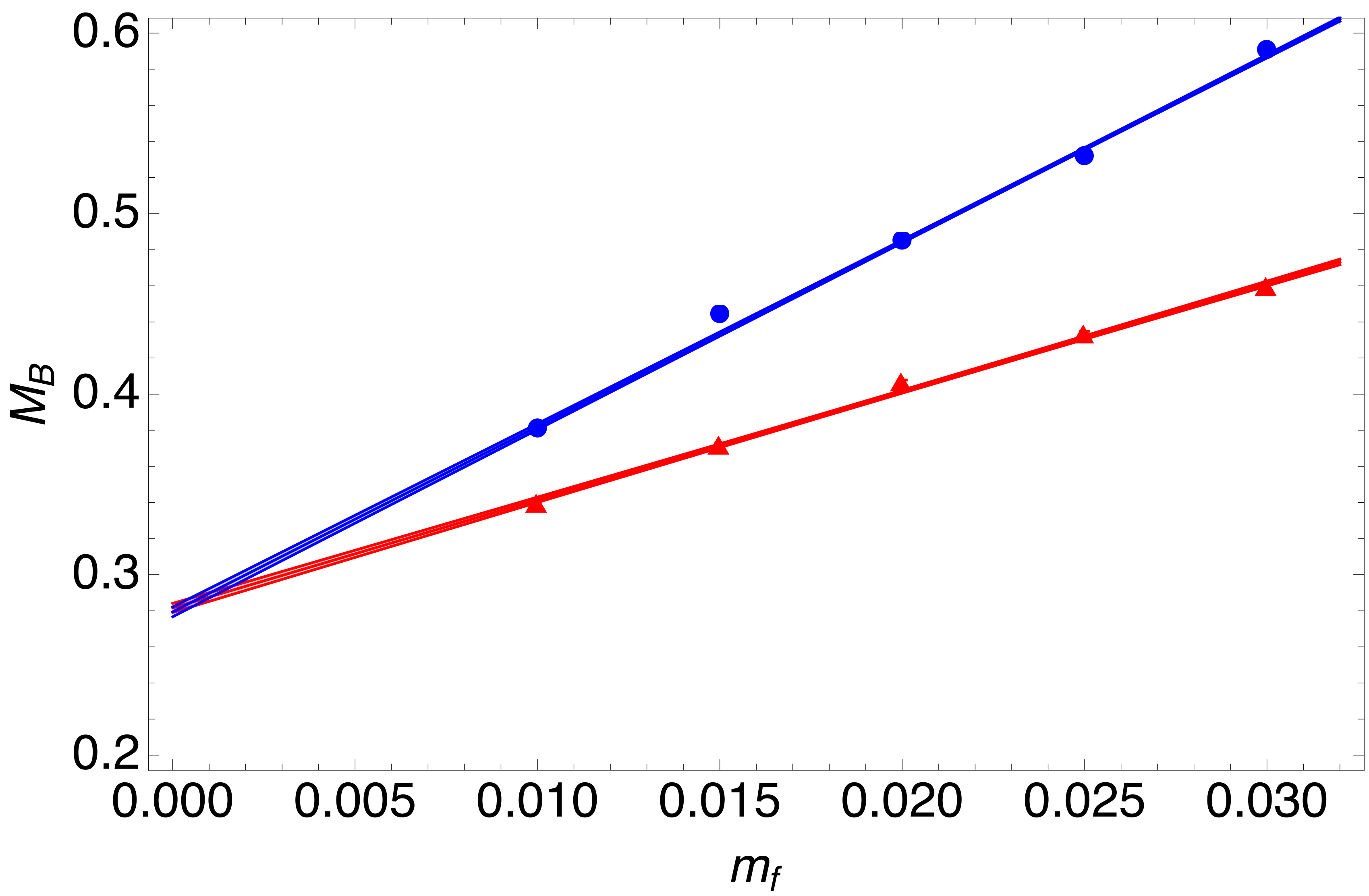
Table 1: 6 Flavor

m_q	# Configs	# Meas
0.010	221	442
0.015	112	224
0.020	81	162
0.025	89	267
0.030	72	259

Baryon Mass

Red - 2 Flavor

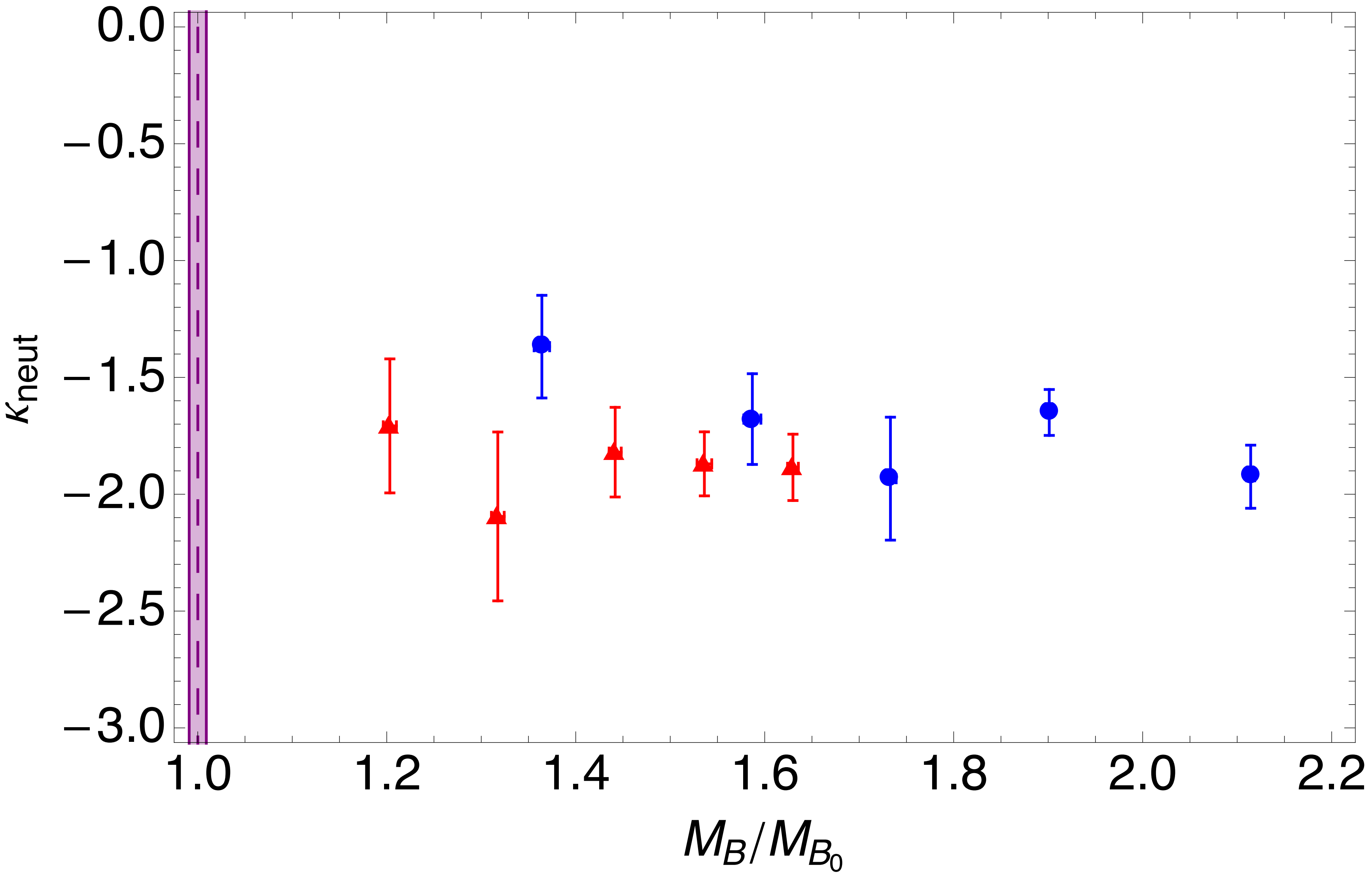
Blue - 6 Flavor



Magnetic Moment

Red - 2 Flavor

Blue - 6 Flavor



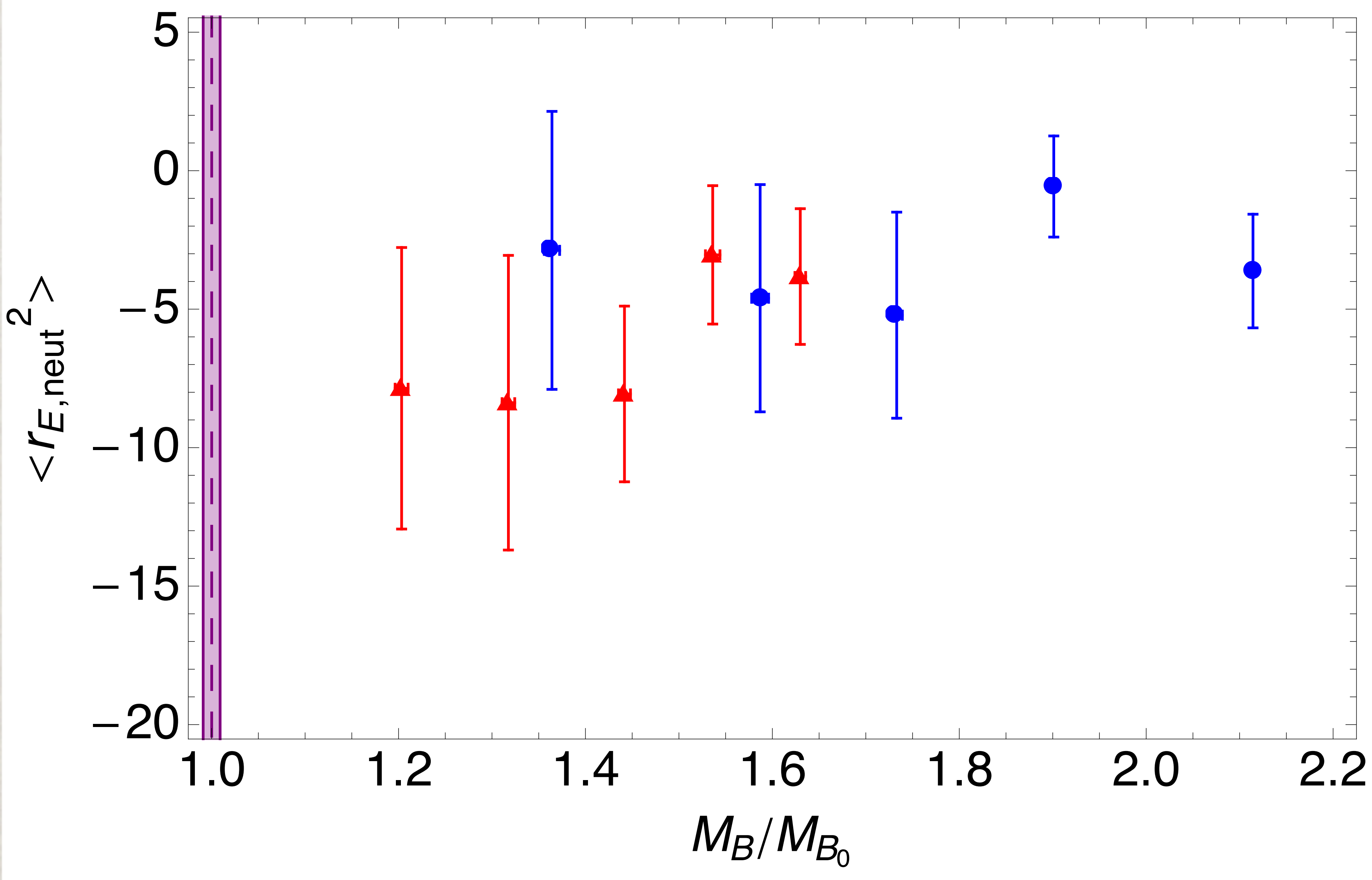
$$\mu = \frac{\kappa}{2M_B}$$

$$\kappa_{\rm neut} = \frac{1}{6}\kappa_s - \frac{1}{2}\kappa_v$$

Charge Radius

Red - 2 Flavor

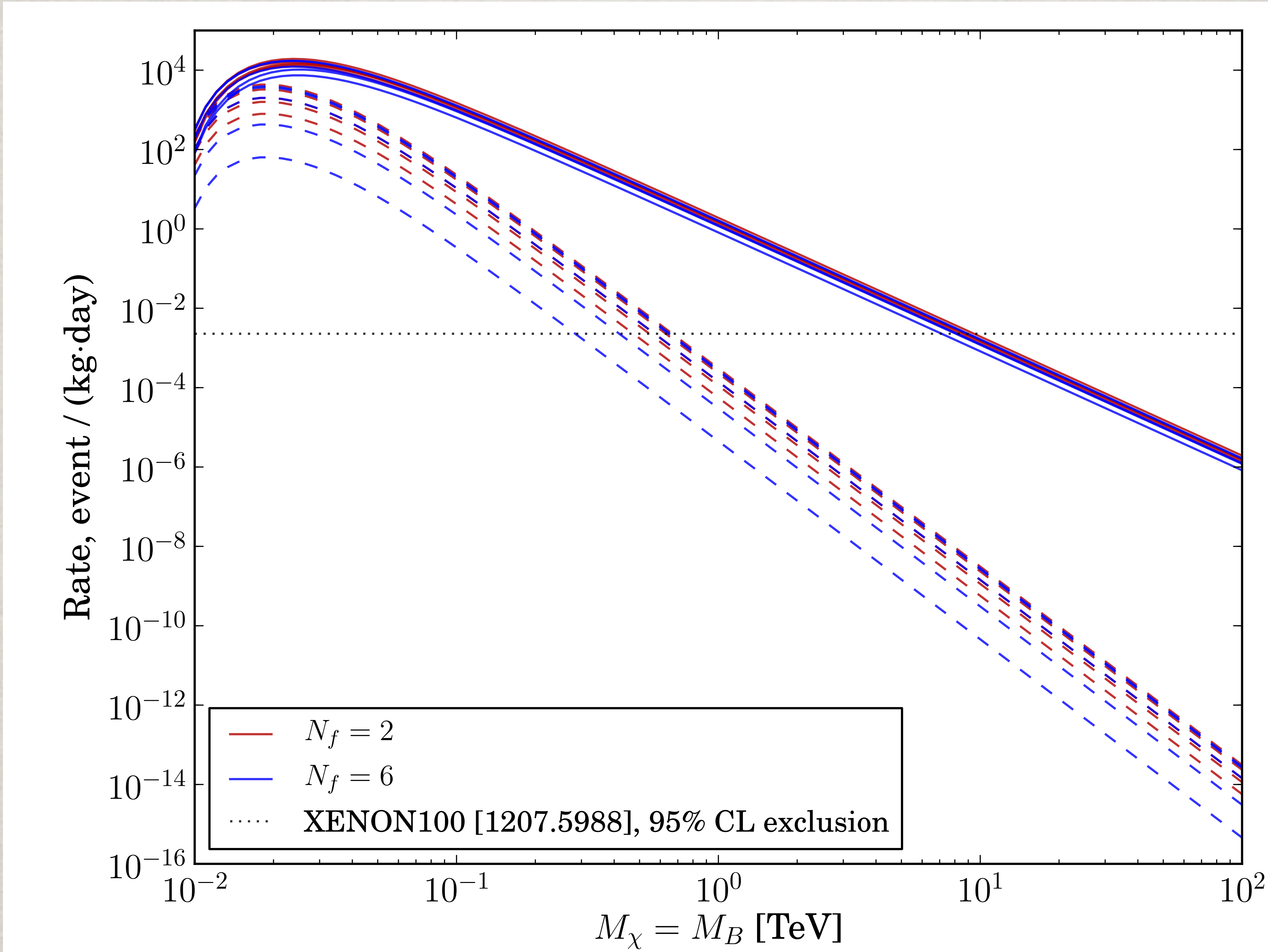
Blue - 6 Flavor



$$\langle r^2 \rangle = \frac{1}{V} \int d^3r \ \rho(r) r^2$$

$$\langle r^2_{\mathrm{E,neut}} \rangle = \frac{1}{2} \langle r^2_{\mathrm{E},s} \rangle - \frac{1}{2} \langle r^2_{\mathrm{E},v} \rangle$$

Exclusion Plots



Dashed horizontal line - Xenon100

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Focus of Current work

- Direct detection exclusions for even number of colors

Explore:

- 4-colors
- Multiple degenerate masses (quenched)
- Baryon spectra and sigma term

Allows for cross-section bounds from Higgs exchange

Model Basics

- Four Dirac Flavors

$$Q = T_{3,L} + Y$$

$$Y = T_{3,R}$$

$$Q = \pm\frac{1}{2}$$

Field	$SU(4)_D$	$(SU(2)_L, SU(2)_R)$
F_1	$\mathbf{4}$	$(\mathbf{2},\mathbf{1})$
F_2	$\bar{\mathbf{4}}$	$(\bar{\mathbf{2}},\mathbf{1})$
F_3	$\mathbf{4}$	$(\mathbf{1},\mathbf{2})$
F_4	$\bar{\mathbf{4}}$	$(\mathbf{1},\bar{\mathbf{2}})$

Kinetic:

$$\mathcal{L}_{\mathcal{D}} = iF_1^\dagger \bar{\sigma}^\mu \nabla_{\mu,L} F_1 + iF_2^\dagger \bar{\sigma}^\mu \nabla^*_{\mu,L} F_2 + iF_3^\dagger \bar{\sigma}^\mu \nabla_{\mu,R} F_3 + iF_4^\dagger \bar{\sigma}^\mu \nabla^*_{\mu,R} F_4$$

$$\nabla_L^\mu = \partial^\mu + igA^{a,\mu}(\tau_L^a/2)$$

$$(\nabla_L^\mu)^* = \partial^\mu - igA^{a,\mu}(\tau_L^a/2)$$

$$\nabla_R^\mu = \partial^\mu + ig'B^\mu(\tau_R^3/2)$$

$$(\nabla_R^\mu)^* = \partial^\mu - ig'B^\mu(\tau_R^3/2)$$

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F_1	$\mathbf{4}$	$(\mathbf{2},\mathbf{1})$
F_2	$\bar{\mathbf{4}}$	$(\bar{\mathbf{2}},\mathbf{1})$
F_3	$\mathbf{4}$	$(\mathbf{1},\mathbf{2})$
F_4	$\bar{\mathbf{4}}$	$(\mathbf{1},\bar{\mathbf{2}})$

Mass:

$$\mathcal{L}_M = \underbrace{m_{12}F_1F_2 + m_{34}F_3F_4}_{\text{Vector-like}} + \underbrace{y_{14}F_1HF_4 + y_{23}F_2H^\dagger F_3}_{\text{Chiral}} + \text{h.c.}$$

$$\langle H \rangle = \begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix} \quad \Longrightarrow \quad \mathcal{L}_M \to (F_1\ F_3)\begin{pmatrix} m_{12} & y_{14}v \\ y_{23}v & m_{34} \end{pmatrix}\begin{pmatrix} F_2 \\ F_4 \end{pmatrix}$$

Why vector-like masses?

- Primary Motivation:

  Pure chiral masses 2-color (Quirky) theories in heavy fermion limit excluded by Higgs exchange

  G.D. Kribs, T.S. Roy, J. Terning, K.M. Zurek (2009)

  Other composite theories of this kind likely to follow suit...

- Vector-like masses have unique properties

  Lots of recent focus in context of Higgs to two photons

  N. Arkani-Hamed, K. Blum, R.T. D'Agnolo, J. Fan (2012) M. Voloshin (2012) . . .

  Can vector-like masses suppress Higgs exchange?

Higgs Exchange

- Higgs-nucleon cross-section:

Extract This

$$\sigma = \frac{\mu(m_B, m_n)^2}{4\pi A^2 m_h^4}(Zf_p + (A-Z)f_n)^2 \times g_h^2$$

$$g_h = f_B = \frac{\sigma_h}{M_B} = \left[\frac{yh}{M_B}\frac{\partial \sigma_f}{\partial(yh)}\right]_{h=v} \qquad \sigma_f = m_f\langle B|\overline{q}q|B\rangle = m_f\frac{\partial M_B}{\partial m_f}$$

$$f_B = \underbrace{\left[\frac{yh}{m_f}\frac{\partial m_f}{\partial(yh)}\right]_{h=v}}_{\text{Pert.}} \underbrace{\left[\frac{m_f}{M_B}\frac{\partial M_B}{\partial m_f}\right]}_{\text{Non-pert.}}$$

Vec. mass suppression?

- Simplified Mass Matrix:

$$M = \begin{pmatrix} \bar{M} + \Delta M/2 & yv \\ yv & \bar{M} - \Delta M/2 \end{pmatrix}$$

$$m_1 = \bar{M} + \frac{1}{2}\sqrt{\Delta M^2 + 4(yv)^2}$$

$$m_2 = \bar{M} - \frac{1}{2}\sqrt{\Delta M^2 + 4(yv)^2}$$

$$\frac{yh}{m_f}\frac{\partial m_f}{\partial(yh)} = \frac{1}{2\widetilde{M} + \sqrt{\widetilde{\Delta M}^2 + 1}} \frac{1}{\sqrt{\widetilde{\Delta M}^2 + 1}}$$

$$\widetilde{M} = \bar{M}/2yv$$

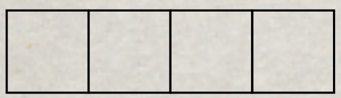
$$\widetilde{\Delta M} = \Delta M/2yv$$

$$\frac{yh}{m_f}\frac{\partial m_f}{\partial(yh)} \to \begin{cases} 1 & 2yv \gg \bar{M}, \Delta M \\ \dfrac{yv}{\bar{M}} & \bar{M} \gg 2yv \gg \Delta M \\ \dfrac{2(yv)^2}{\bar{M}\Delta M} & \bar{M} \gg \Delta M \gg 2yv \end{cases}$$

4-COLOR BARYONS

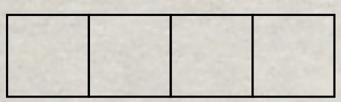
- Bosonic baryons

One Flavor: U

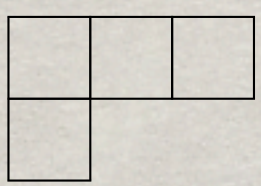


Spin-2: $\mathcal{O}^{N_F=1}_{B,S2} = (U^T C\gamma^i U)(U^T C\gamma^j U) \qquad i \neq j$

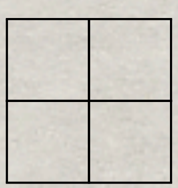
Two Flavors: $U \quad D$



Spin-2: $\mathcal{O}^{N_F=2}_{B,S2} = (U^T C\gamma^i U)(U^T C\gamma^j U) \qquad i \neq j$



Spin-1: $\mathcal{O}^{N_F=2}_{B,S1} = (U^T C\gamma^i U)(U^T C\gamma^5 D)$



Spin-0: $\mathcal{O}^{N_F=2}_{B,S1} = (U^T C\gamma^5 D)(U^T C\gamma^5 D)$

Calculation Details

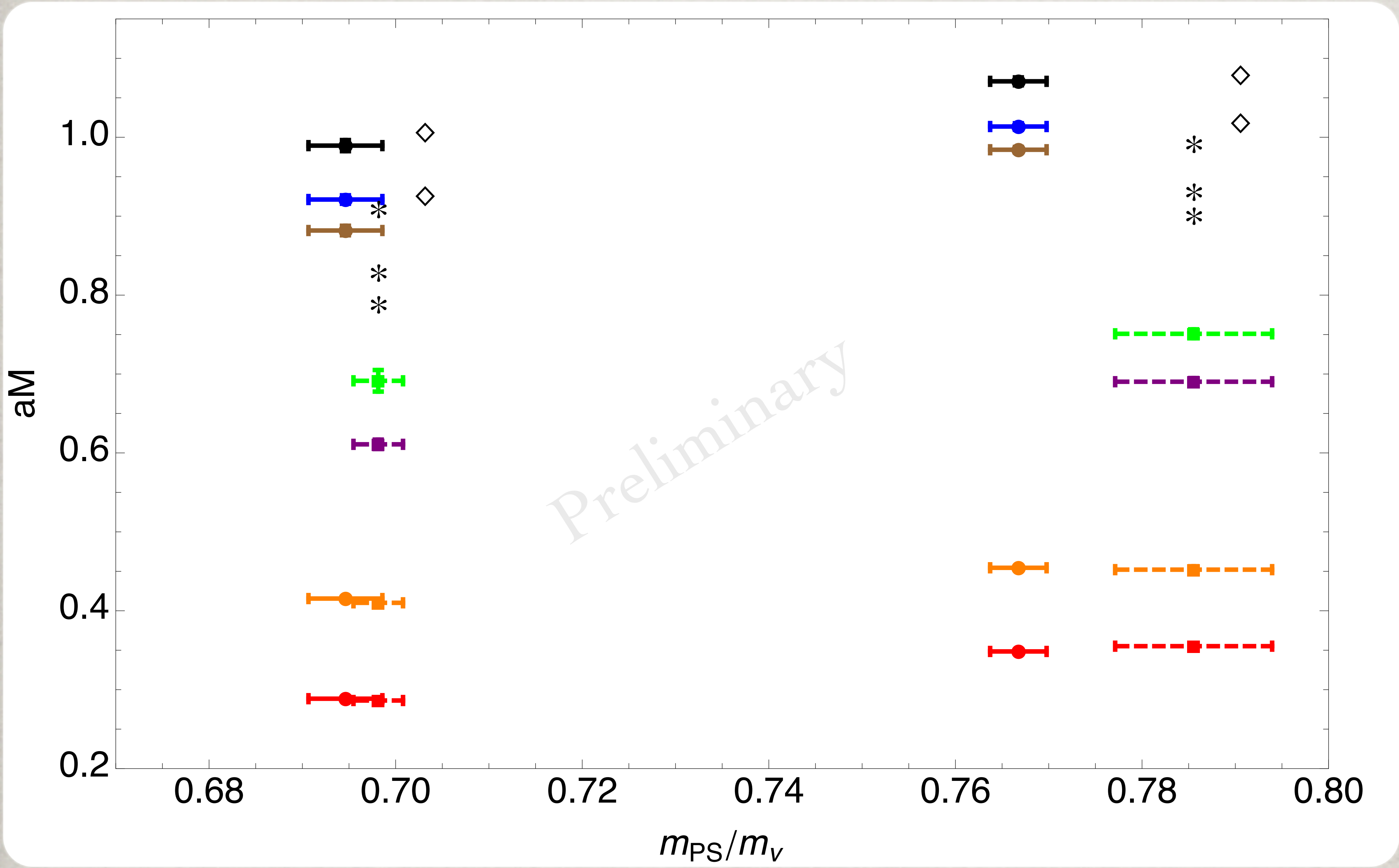
28 quenched Ensembles:

- Two # colors
- Four lattice volumes
- Three lattice spacings
- 3-6 fermion masses

N_c	β	κ	$N_s^3 \times N_t$	# Meas.
4	11.028	0.1554	$16^3 \times 32$	4878
			$32^3 \times 64$	1126
		0.15625	$16^3 \times 32$	4765
			$32^3 \times 64$	1146
			$48^3 \times 96$	1091
		0.1572	$32^3 \times 64$	1075
	11.5	0.1515	$16^3 \times 32$	2975
			$32^3 \times 64$	1057
		0.1520	$16^3 \times 32$	2872
			$32^3 \times 64$	1052
		0.1523	$16^3 \times 32$	2976
			$32^3 \times 64$	914
			$48^3 \times 96$	637
			$64^3 \times 128$	489
		0.1524	$16^3 \times 32$	2970
			$32^3 \times 64$	863
		0.1527	$32^3 \times 64$	1011
	12.0	0.1475	$32^3 \times 64$	1125
		0.1480	$32^3 \times 64$	1189
		0.1486	$32^3 \times 64$	1055
		0.1491	$16^3 \times 32$	411
		0.1491	$32^3 \times 64$	1050
		0.1491	$48^3 \times 96$	1150
		0.1491	$64^3 \times 128$	928
		0.1495	$32^3 \times 64$	1043
		0.1496	$32^3 \times 64$	1009
3	6.0175	0.1537	$32^3 \times 64$	1000
		0.1547	$32^3 \times 64$	1000

Table 1: Ensembles and number of measurements.

Large N Comparisons



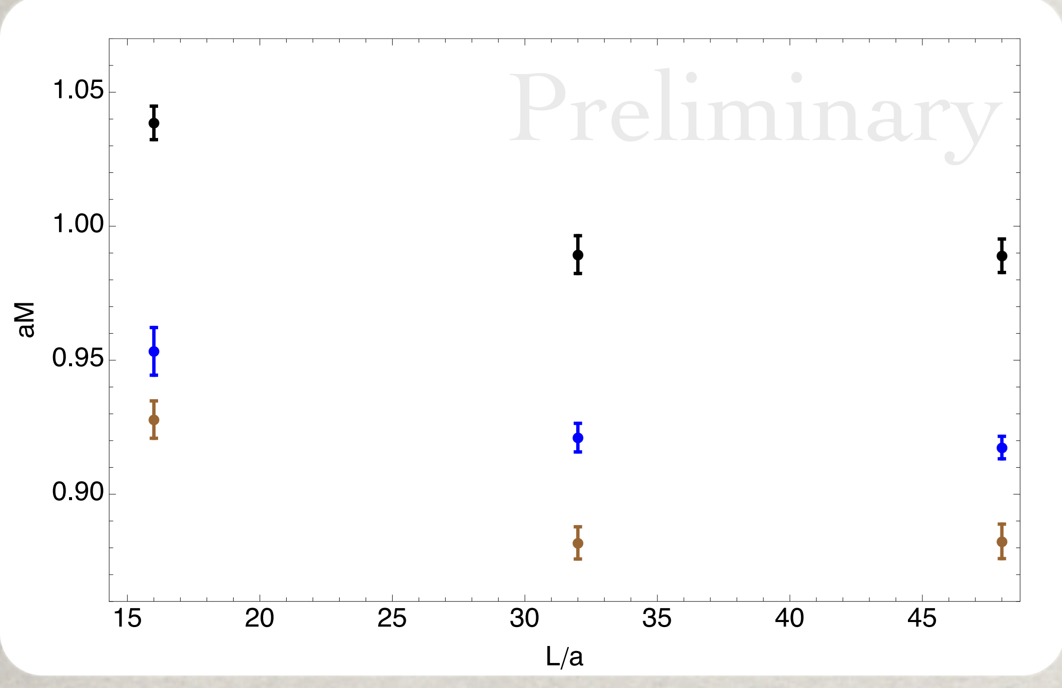
Solid - 4 colors
Dashed - 3 colors

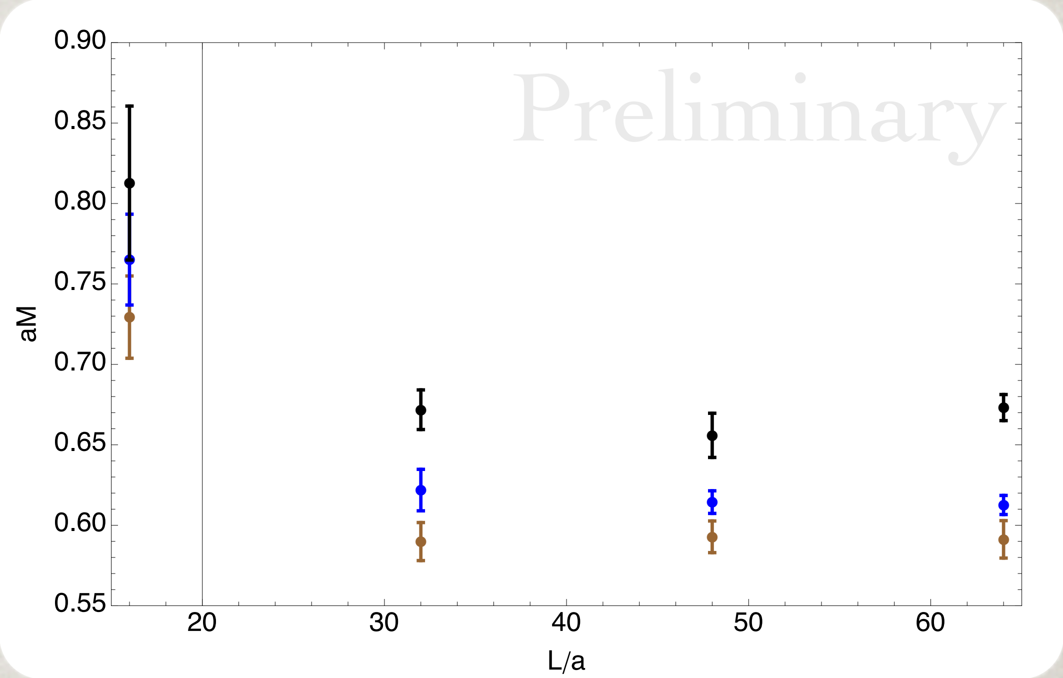
Black - Spin 2
Blue - Spin 1
Brown - Spin 0
Green - Spin 3/2
Purple - Spin 1/2
Orange - Vector
Red- Pseudoscalar

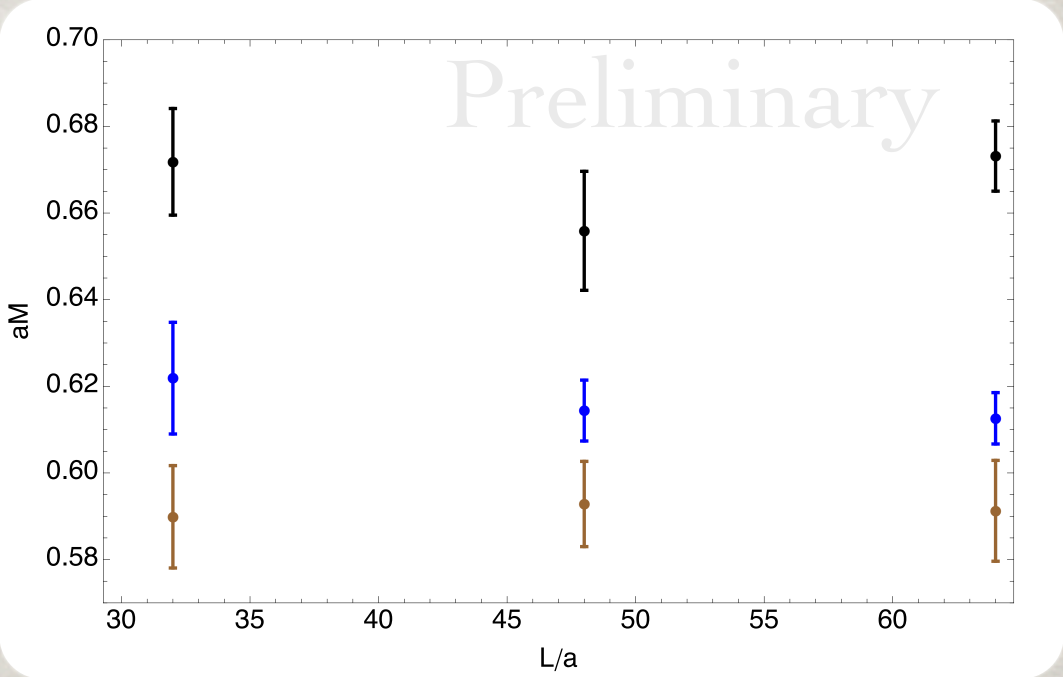
$$* : \quad M(N_c, J) = N_c m_0 + \frac{J(J+1)}{N_c} B + \mathcal{O}(1/N_c^2)$$

$$\diamond : \quad M(N_c, J) = N_c m_0^{(0)} + C + \frac{J(J+1)}{N_c} B + \mathcal{O}(1/N_c^2)$$

Volume effects



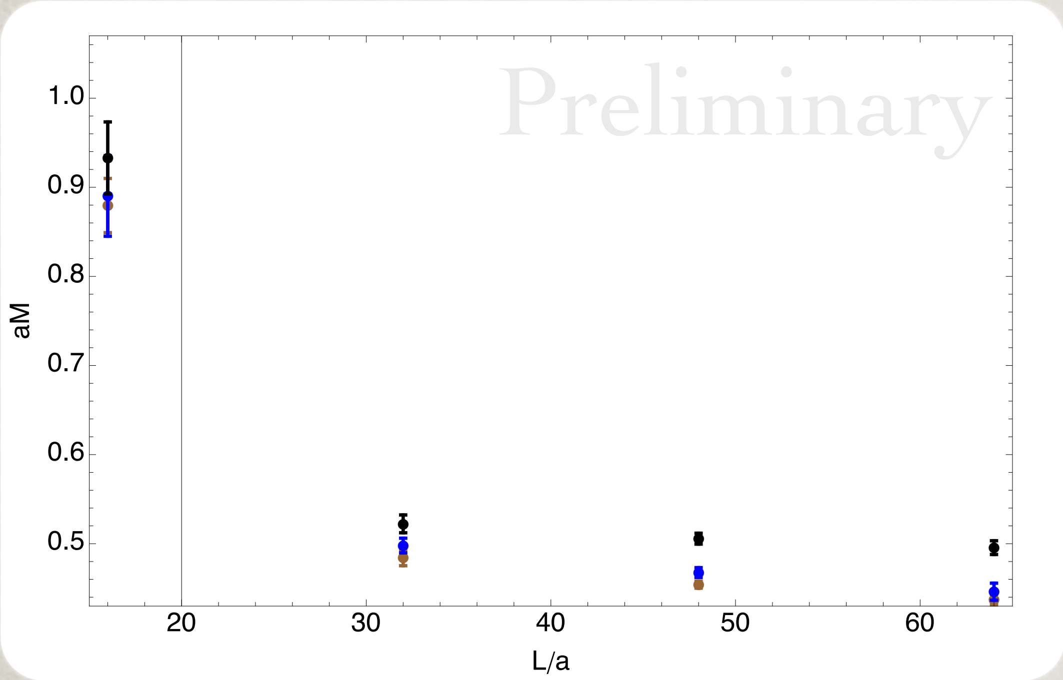


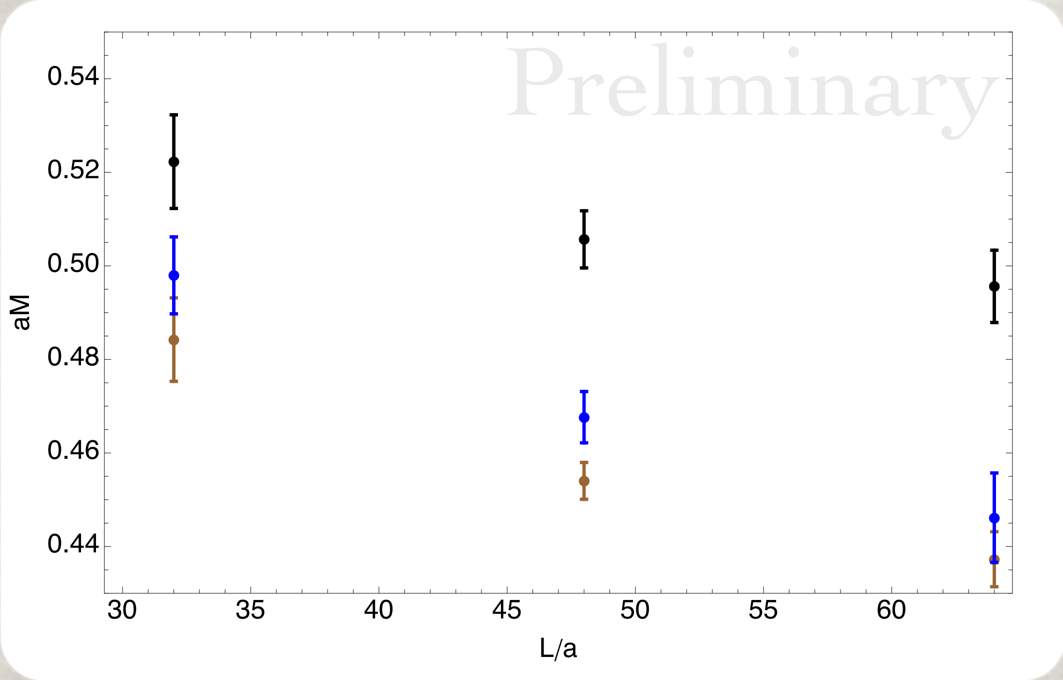


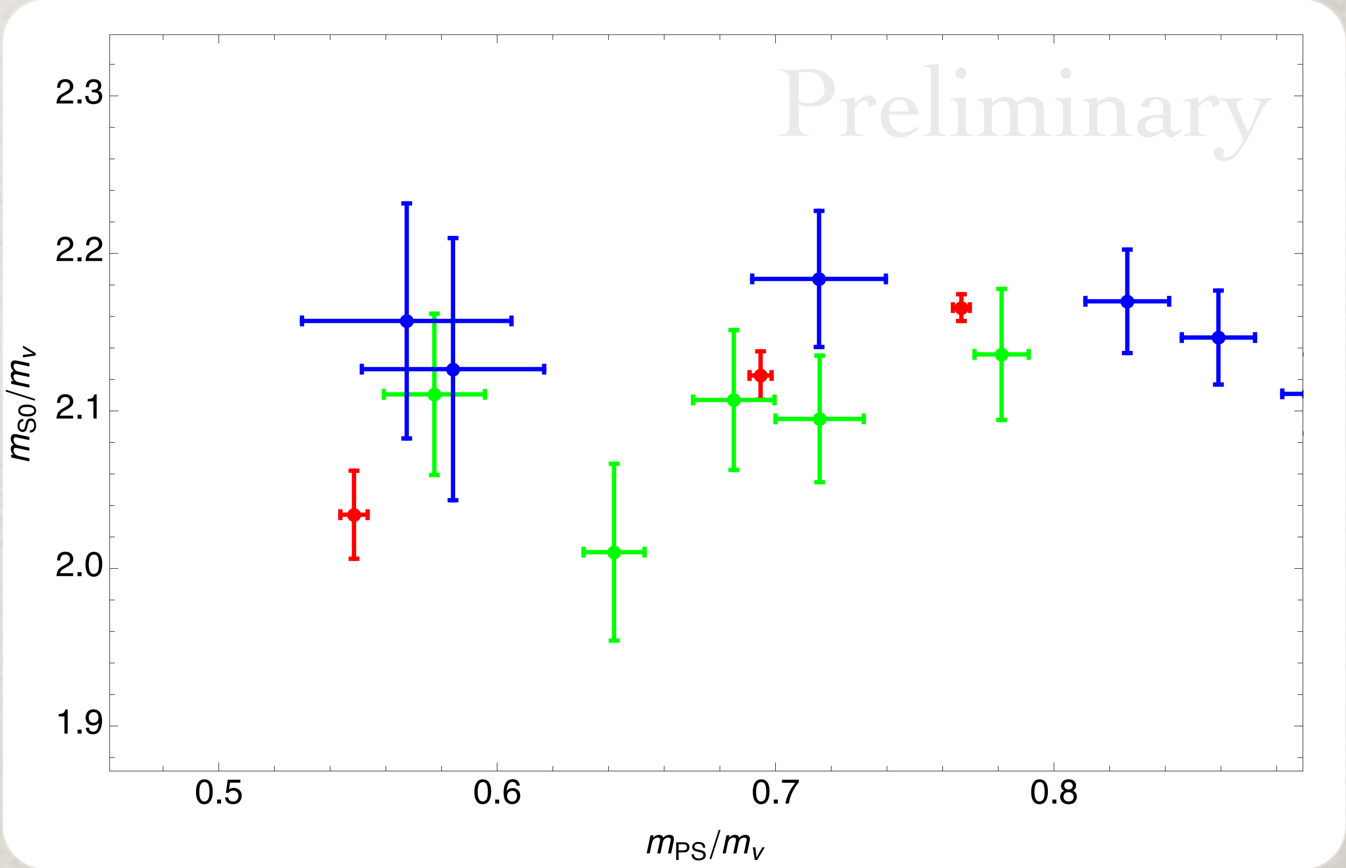
$\beta = 11.028$

$\beta = 11.5$

Volume effects

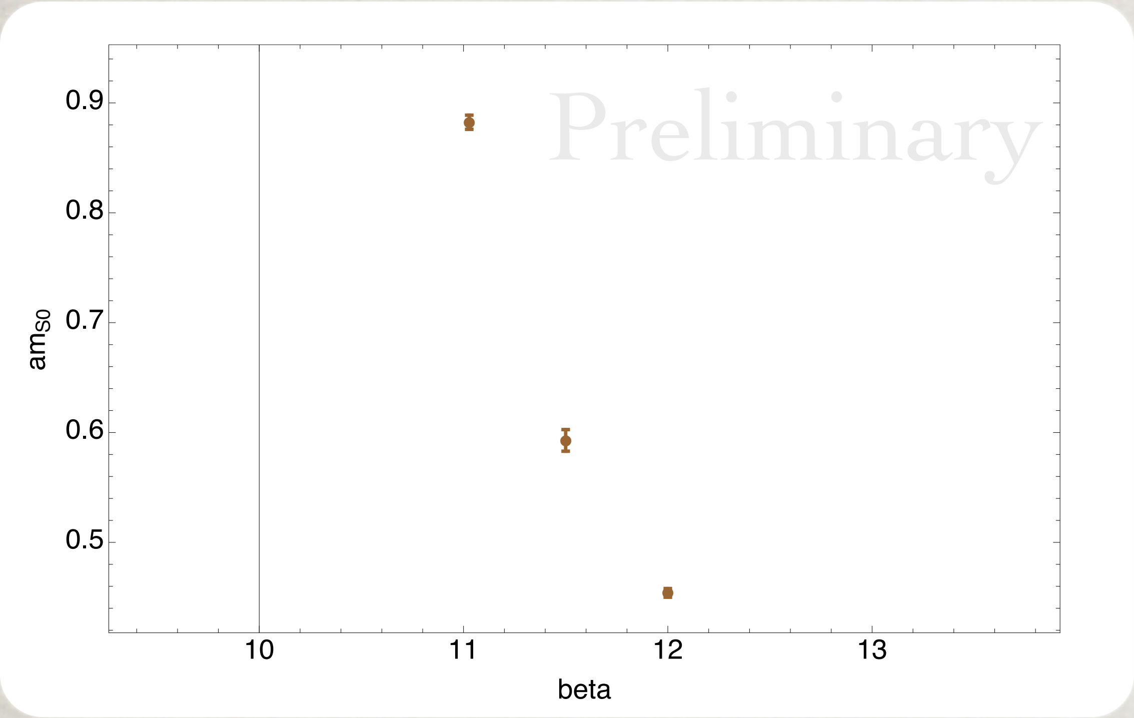


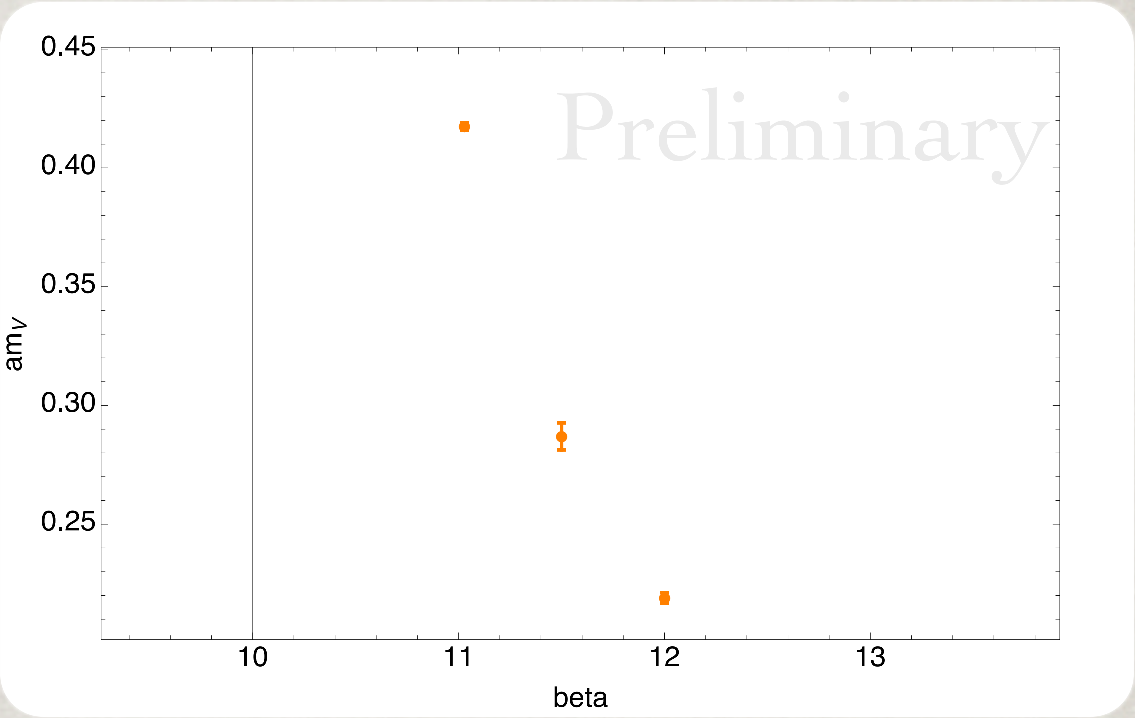


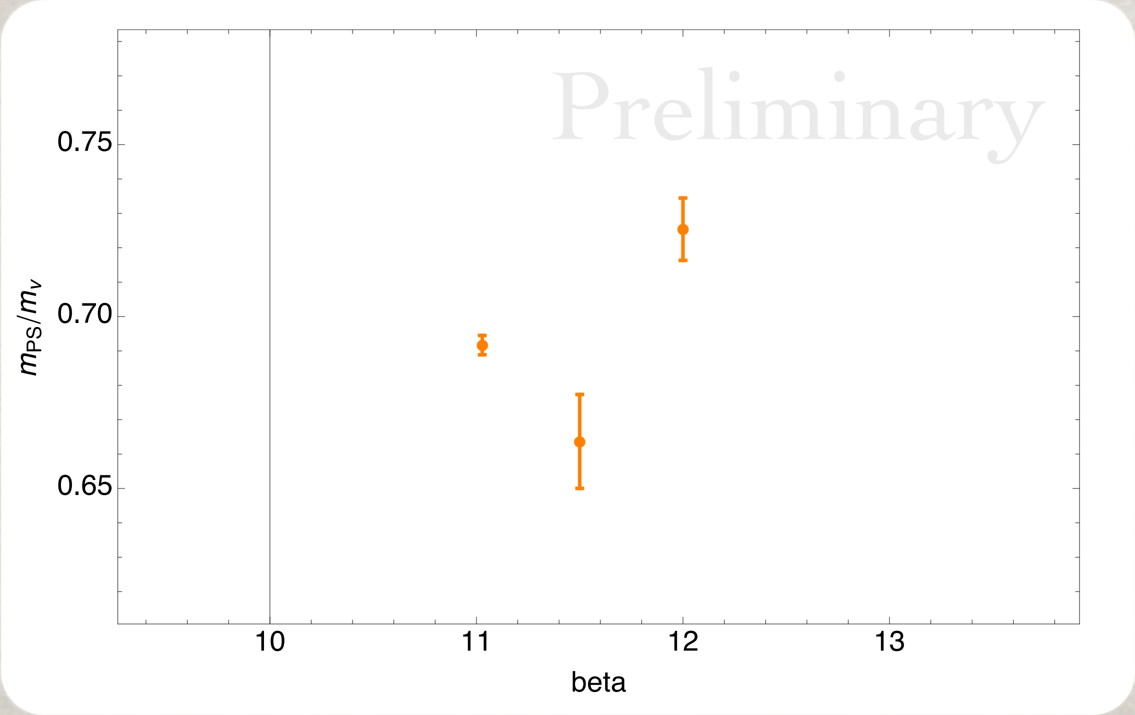


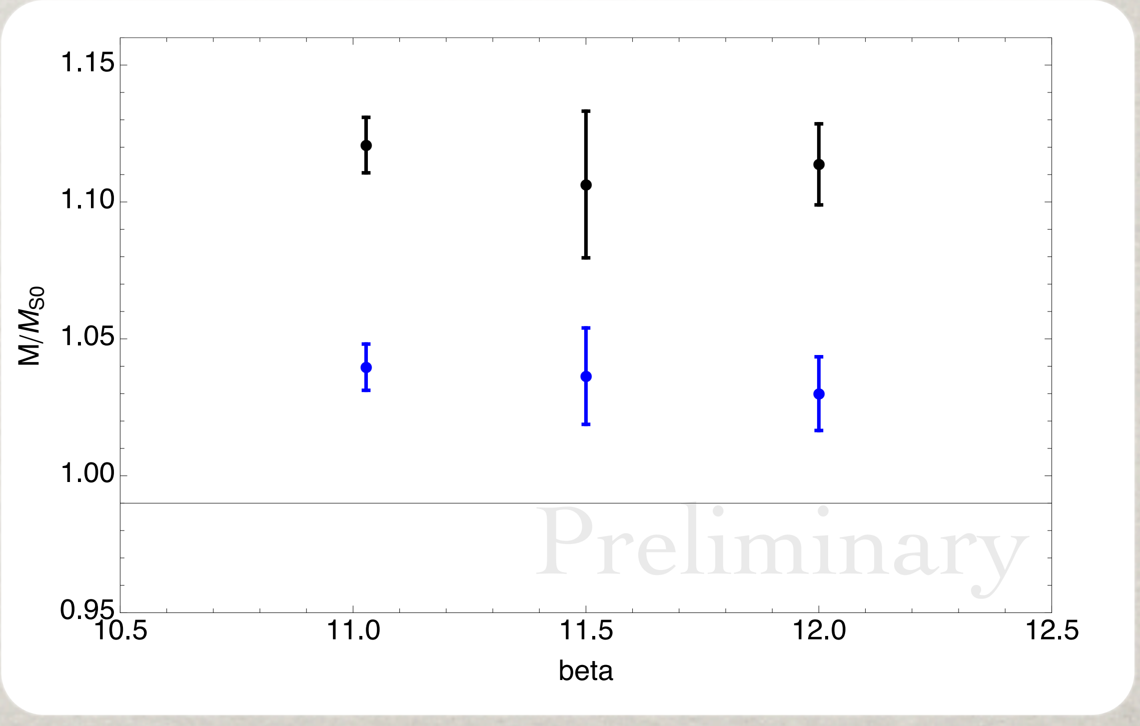
$$\beta = 12.0$$

Lattice spacing effects

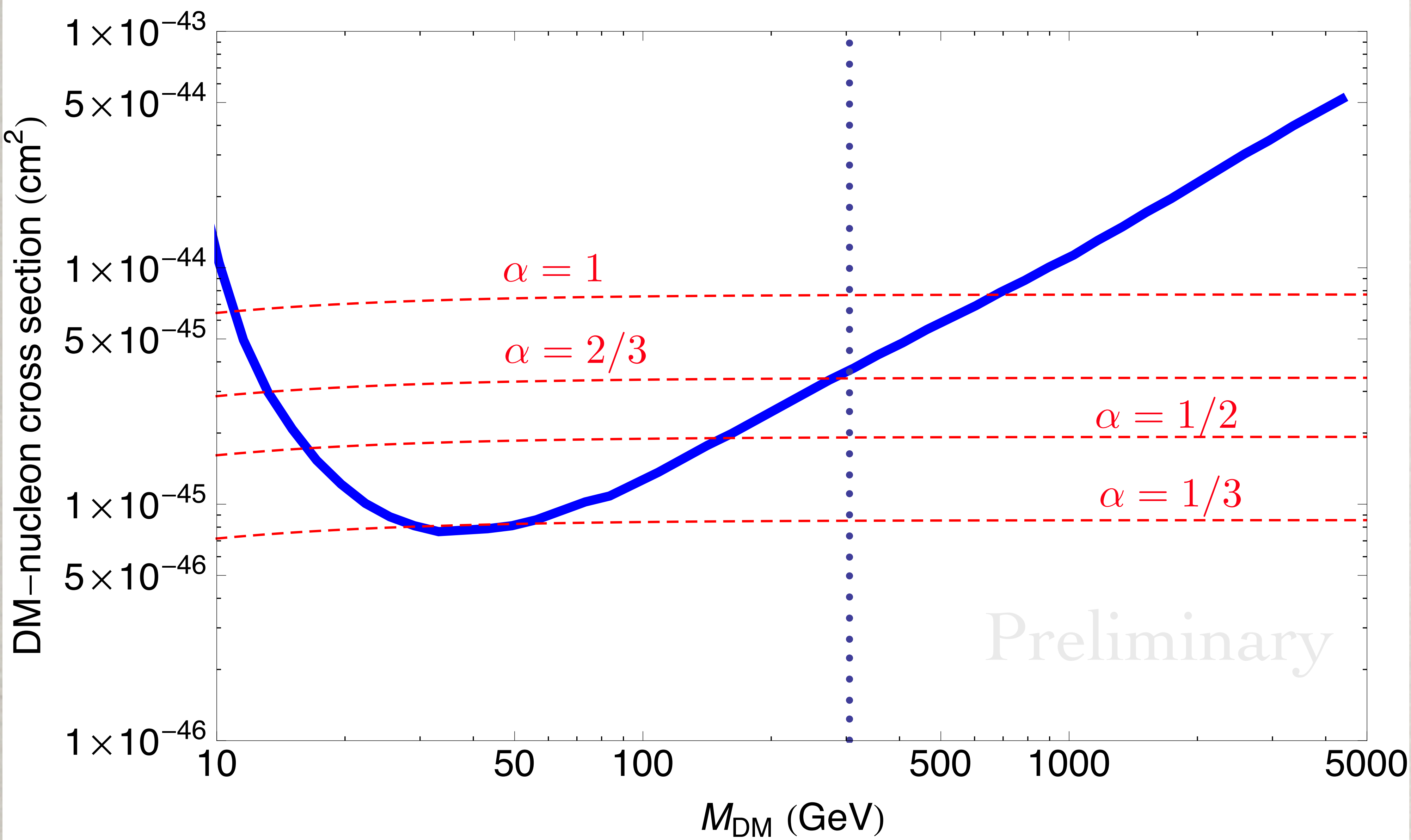








Sigma term & Higgs bound



LUX
arXiv:1310.8214

For $\dfrac{m_{PS}}{m_V} \approx 0.69$

$$\frac{m_f}{M_B}\frac{\partial M_B}{\partial m_f} = 0.262(16)$$

$$\alpha \equiv \frac{yh}{m_f}\frac{\partial m_f}{\partial(yh)} \to \begin{cases} 1 & 2yv \gg \bar{M}, \Delta M \\ \dfrac{yv}{\bar{M}} & \bar{M} \gg 2yv \gg \Delta M \\ \dfrac{2(yv)^2}{\bar{M}\Delta M} & \bar{M} \gg \Delta M \gg 2yv \end{cases}$$

Final Word

- Significant bounds exist for composite DM

  Fermions - Magnetic Moment $\Longrightarrow$ $M_{DM} \gtrsim 10$ TeV

  Boson - Pure Chiral masses Higgs Exchange $\Longrightarrow$ $M_{DM} \gtrsim 1$ TeV

- Additional vector-like masses can reduce constraint from Higgs exchange

  LUX Bound

$$\frac{yv}{\bar{M}} \lesssim 0.70 \quad \text{when} \quad \bar{M} \gg 2yv \gg \Delta M$$

$$\frac{2(yv)^2}{\bar{M}\Delta M} \lesssim 0.70 \quad \text{when} \quad \bar{M} \gg \Delta M \gg 2yv$$

Final Word

Big Question:

Does a minimum SM cross-section on composite DM

For charged constituents: Polarizabilities

Future work in this direction:

1) Lattice measurements of 4-color polarizabilities

- Background field method
- Large volumes, two lattice spacings
- High Statistics

2) DM-nucleon scattering via polarizabilities

- Improve on current methods accounting for nuclear physics
- Additional sensitivity to nuclear resonances?

The LLNL Multiprogrammatic and Institutional Computing program through the Tier 1 Grand Challenge award provided us the large amounts of necessary computing power.