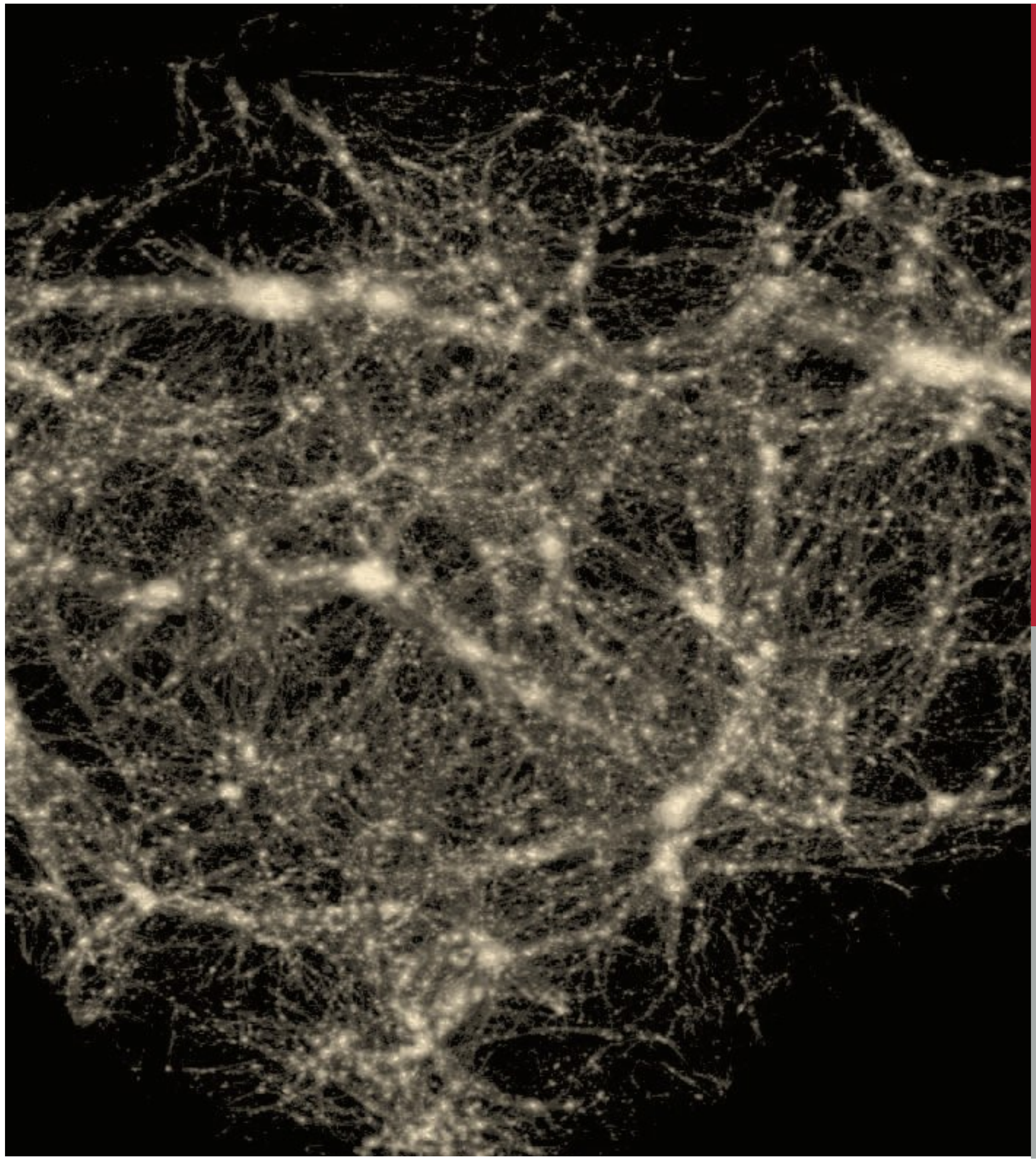


Dark nuclei

William Detmold
MIT

Dark nuclei

- Dark nuclear physics of QCD like theory with $N_c=2$ and $N_f=2$
- Based on two recent papers in collaboration with *Matthew McCullough* & *Andrew Pochinsky*
  - *Dark Nuclei I: Cosmology and Indirect Detection* —1406.2276
  - *Dark Nuclei II: Nuclear Spectroscopy* in Two-Colour QCD —1406.4116
- Motivation
  - Understand what is "nuclear physics" in a general context
    What are generic features, what is special?
  - Dark matter model building: interesting new phenomenology

Two-colour QCD

- Two-colour QCD with two flavours of fundamental fermions
  - Numerically feasible (simpler than QCD)
  - Emergent complexity: novel phenomenological aspects
- Single hadron aspects already considered in DM context
  [Lewis et al., Neil & Buckley, Hietanen et al.]
- Also lattice investigations of quenched $N_c=4$ QCD and other theories in this context [LSD collaboration]
  - Sigma terms, polarisabilities,…

Symmetries of two-colour QCD

- Global flavour symmetry $SU(2)_L \times SU(2)_R$ enlarges to SU(4)
  - Pseudo-reality of SU(2) - left and right handed quarks can be combined into multiplets

$$\Psi = \begin{pmatrix} u_L \\ d_L \\ -i\sigma_2 C \bar{u}_R^\top \\ -i\sigma_2 C \bar{d}_R^\top \end{pmatrix} \qquad \Psi \xrightarrow{SU(4)} \exp\left(i \sum_{j=1}^{15} \theta_j T_j \right) \Psi$$

- Strong interactions result in condensate that spontaneously breaks the global symmetry: SU(4)→ Sp(4)~SO(5) [Peskin 1980]
- Numerical calculations have significant explicit symmetry breaking: $m_u = m_d \sim \Lambda_{QC_2D}$

Spectrum

- Simplest colour singlets
  - "Pions": $\pi^- \sim \bar{u}\gamma_5 d$, $\pi^0 \sim \bar{u}\gamma_5 u + \bar{d}\gamma_5 d$, $\pi^+ \sim \bar{d}\gamma_5 u$ $J^P=0^-$
  - (anti-)"Nucleons": ud, $\bar{u}\bar{d}$ $J^P=0^+$

  } Degenerate SO(5) multiplet
  - "Rhos": $\rho^- \sim \bar{u}\gamma_\mu d$, $\rho^0 \sim \bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d$, $\rho^+ \sim \bar{d}\gamma_\mu u$ $J^P=1^-$
  - (anti-)"Deltas": $u\gamma_\mu\gamma_5 d$, $\bar{u}\gamma_\mu\gamma_5\bar{d}$ $J^P=1^+$

  } Degenerate SO(5) multiplet
  - Axial vector, scalar, tensor mesons + associated baryons
- Single hadron spectrum studied by [Hietanen et al. 1404.2794]
  - Pion multiplet are pseudoGoldstone bosons of χSB: $SU(4) \to Sp(4)$
  - Rho stable for masses considered

Spectrum

- Colour singlets can combine
  - Two-, three-, … particle scattering states
  - "Nuclei" for sufficiently attractive interactions–<u>not</u> *a priori* obvious
- Two "pions" combine to give 25 states: $\mathbf{5}\otimes\mathbf{5}=\mathbf{1}\oplus\mathbf{10}\oplus\mathbf{14}$
  - J=0 systems, contains B=2,1,0,-1,-2 states
- "pion"+ "rho": J=1 systems with same flavour breakdown

$$\boldsymbol{D}^\mu = \begin{pmatrix} S^\mu_+ & D^\mu_{2,0} & D^\mu_{1,0} & D^\mu_{1,-1} & D^\mu_{1,1} \\ \overline{D}^\mu_{2,0} & S^\mu_- & D^\mu_{-1,0} & D^\mu_{-1,-1} & D^\mu_{-1,1} \\ \overline{D}^\mu_{1,0} & \overline{D}^\mu_{-1,0} & S^\mu_0 & D^\mu_{0,-1} & D^\mu_{0,1} \\ \overline{D}^\mu_{1,-1} & \overline{D}^\mu_{-1,-1} & \overline{D}^\mu_{0,-1} & S^\mu_B & D^\mu_{0,2} \\ \overline{D}^\mu_{1,1} & \overline{D}^\mu_{-1,1} & \overline{D}^\mu_{0,1}+ & \overline{D}^\mu_{0,2} & S^\mu_{\overline{B}} \end{pmatrix}$$

$$\begin{aligned} \boldsymbol{D}^\mu_{\mathbf{1}} &= \mathrm{Tr}(\boldsymbol{D}^\mu)\ , \\ \boldsymbol{D}^\mu_{\mathbf{10}} &= \frac{i}{2}\left(\boldsymbol{D}^\mu - \boldsymbol{D}^{\mu T}\right)\ , \\ \boldsymbol{D}^\mu_{\mathbf{14}} &= \frac{1}{2}\left(\boldsymbol{D}^\mu + \boldsymbol{D}^{\mu T}\right) - \frac{1}{5}\mathrm{Tr}(\boldsymbol{D}^\mu)\mathbb{1}_5 \end{aligned}$$

- Higher body systems: J=0,1, flavour = $\underbrace{\square\square\square\cdots\square\square}_{n}$, n=2,…,8

Simulations

- Wilson gauge and fermion actions
- HMC using modified **`chroma`**
- 4 lattice spacings (β), 6 masses
  - Isospin symmetric
- 3 or 4 volumes per choice (β ,m_0)
- Long streams of configurations

Label	β	m_0	$L^3 \times T$	N_{traj}
A	1.8	−1.0890	$12^3 \times 72$	5,000
			$16^3 \times 72$	4,120
			$20^3 \times 72$	3,250
B	2.0	−0.9490	$12^3 \times 48$	10,000
			$16^3 \times 48$	4,000
			$20^3 \times 48$	3,840
			$24^3 \times 48$	2,930
C	2.0	−0.9200	$12^3 \times 48$	10,000
			$16^3 \times 48$	9,780
			$20^3 \times 48$	10,000
D	2.0	−0.8500	$12^3 \times 48$	9,990
			$16^3 \times 48$	5,040
			$16^3 \times 72$	5,000
			$20^3 \times 48$	5,000
			$24^3 \times 48$	5,050
E	2.1	−0.7700	$12^3 \times 72$	5,000
			$16^3 \times 72$	5,000
			$20^3 \times 72$	4,300
F	2.2	−0.6000	$12^3 \times 72$	5,000
			$16^3 \times 72$	5,000
			$20^3 \times 72$	5,000
			$24^3 \times 72$	5,070

Multi-baryon contractions

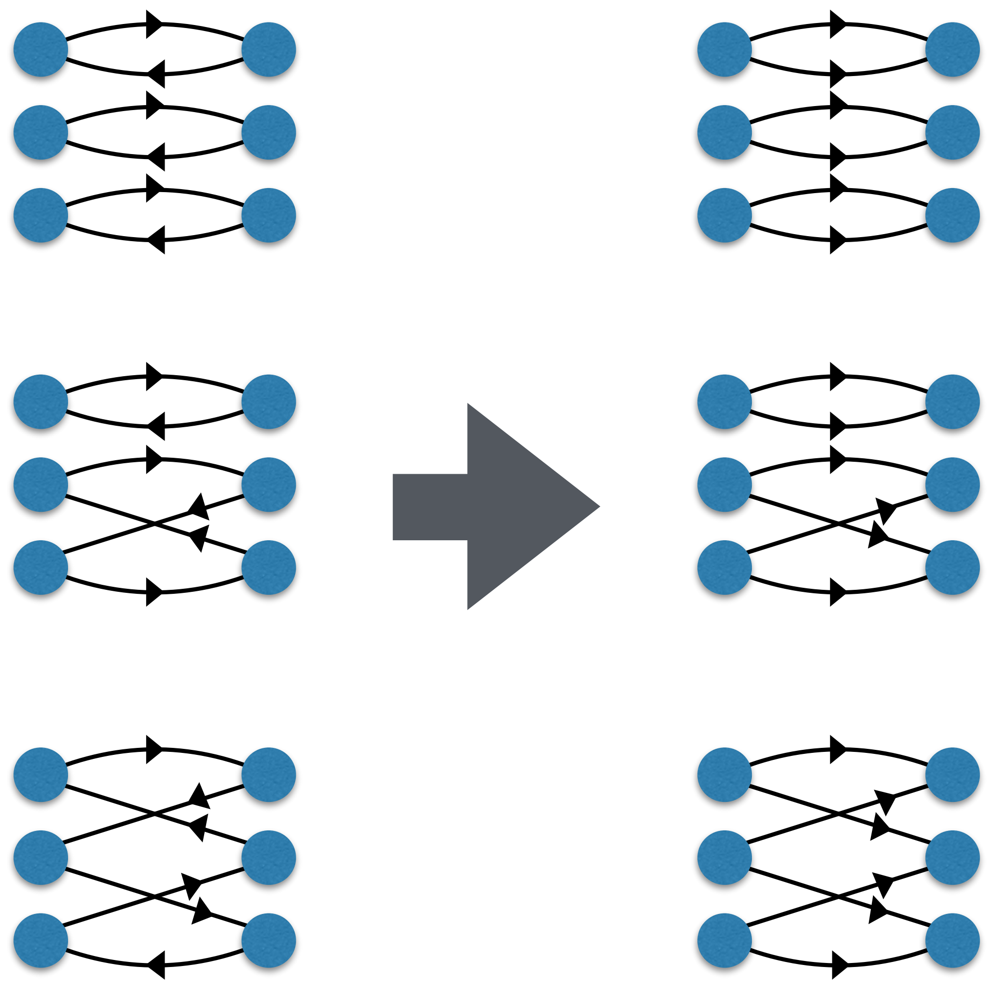
- SU(2) multi-baryon contractions equivalent to maximal isospin multi-meson contractions
  - Clear from degeneracies but explicitly

$$S(y,x) = C^\dagger(-i\sigma_2)^\dagger S(x,y)^T(-i\sigma_2)C$$
$$S(y,x) = \gamma_5 S^\dagger(x,y)\gamma_5$$

  first relation specific to N_c=2

- Use algorithms from N_c=3 QCD
  [WD & Savage 2011,;WD, Orginos, Shi 2012]

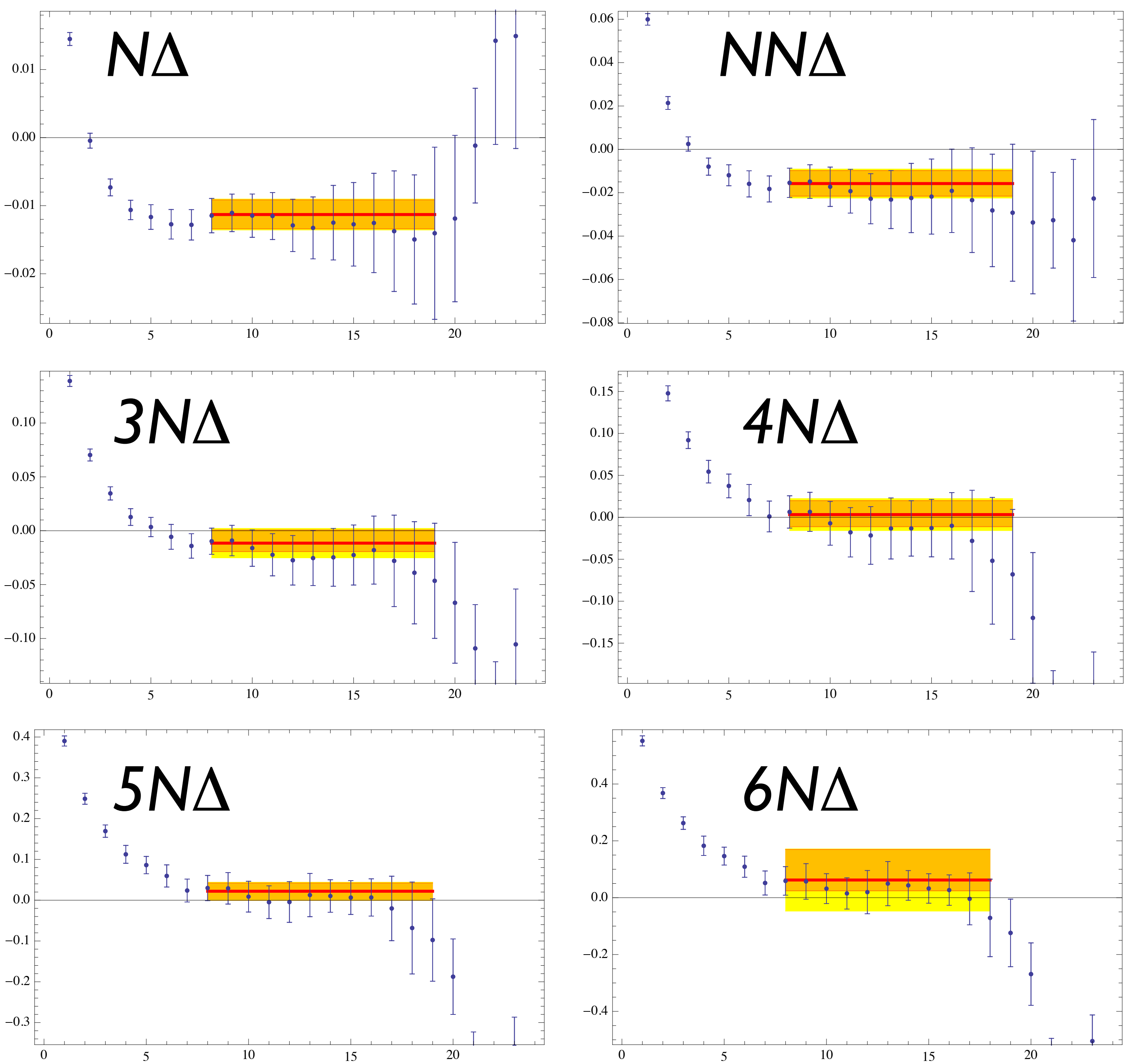
- (n-1)$N\Delta$ ~ mixed pion-kaon contractions
  [WD & Smigielski 2011]



Ex:: three types of contractions
for I=3 $\pi\pi\pi$ and *NNN*

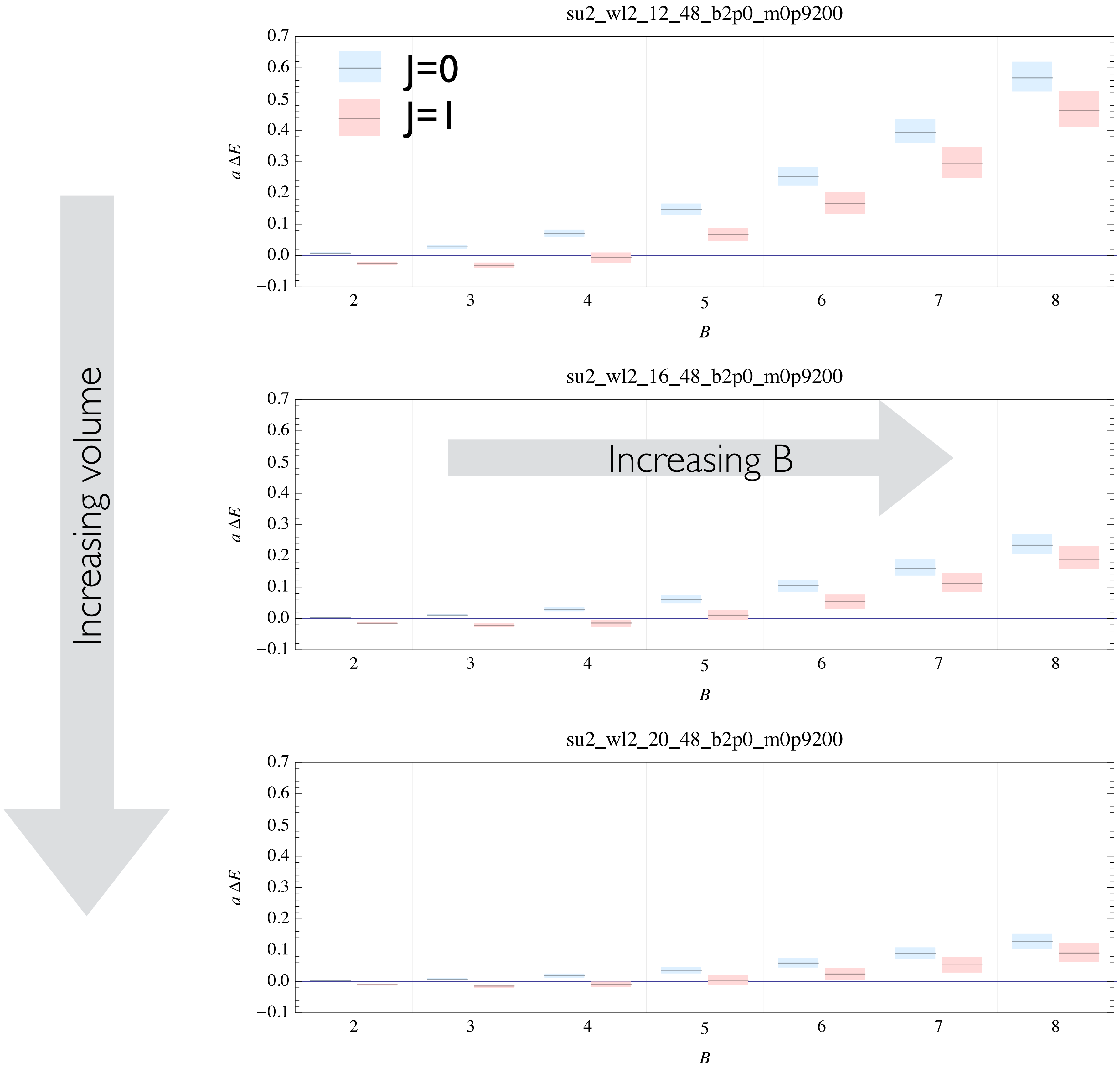
Example effective mass shift plots

$$R_{nN}(t) \equiv \frac{C_{nN}(t)}{[C_{1N}(t)]^n}, \qquad R_{nN,\Delta}(t) \equiv \frac{\sum_i C^{(i,i)}_{nN,\Delta}(t)}{[C_{1N}(t)]^n \sum_i C^{(i,i)}_{0N,\Delta}(t)}$$



su2_wl2_20_48_b2p0_m0p9200

Energy shifts for different volumes



To be bound or not to be bound…

- Bound/scattering state hypotheses (Lüscher):

$$H_1: \quad \Delta E_{\text{bound}}(L) = -\Delta E_\infty \left[1 + C\,\frac{e^{-\kappa L}}{L}\right],$$

$$H_2: \quad \Delta E_{\text{scatter}}(L) = \frac{2\pi A}{\mu L^3}\binom{n}{2}\left[1 - \left(\frac{A}{\pi L}\right)\mathcal{I} + \left(\frac{A}{\pi L}\right)^2 [\mathcal{I}^2 + (2n-5)\mathcal{J}]\right] + \frac{B}{L^6}$$

- Assess support for each hypothesis using the Bayes factor

$$K = \frac{P(D|H_1)}{P(D|H_2)} = \frac{\int P(D|H_1, p_1)P(p_1|H_1)dp_1}{\int P(D|H_2, p_2)P(p_2|H_2)dp_2}$$

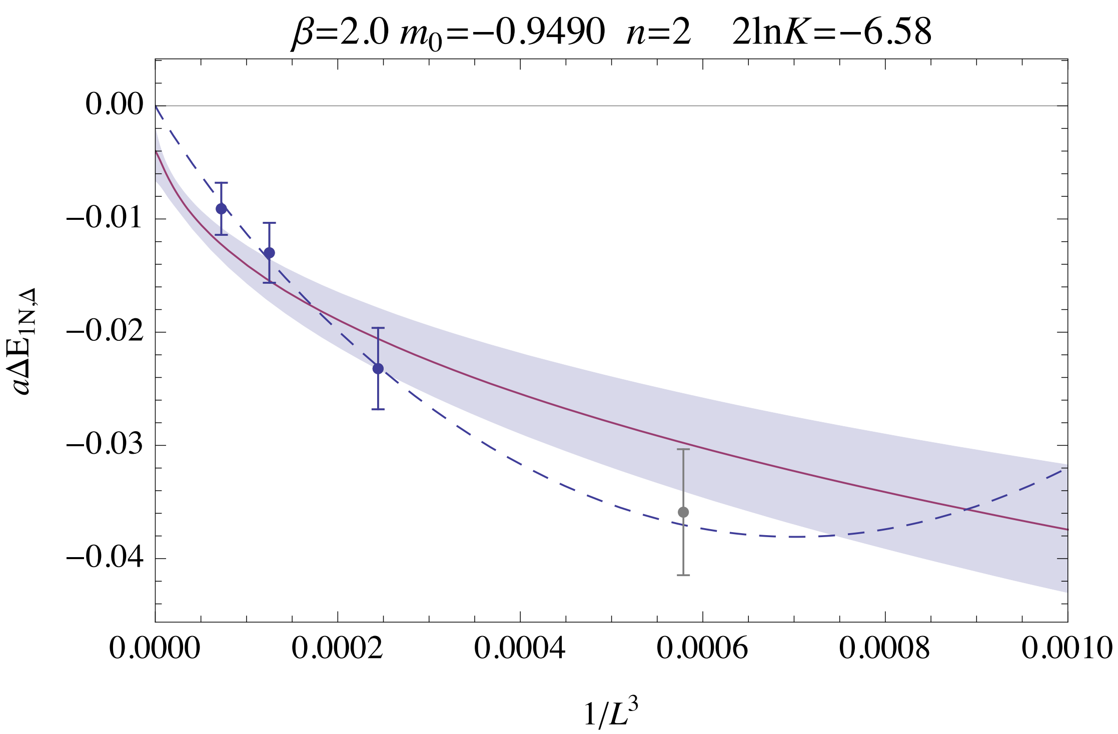
where $\log P(D|H_i, p_i) = -\frac{1}{2}\sum_{j=1}^{N}\frac{[d_j - H_i(x_j; p_i)]^2}{\sigma_j^2}$

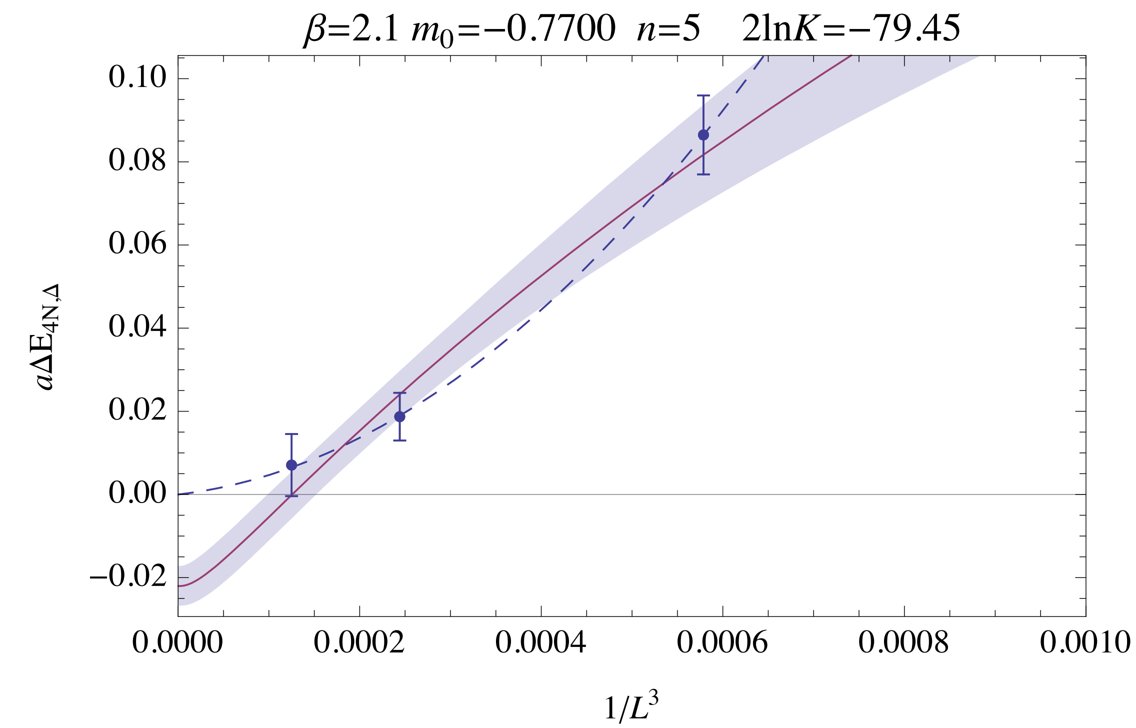
and $P(p_i|H_i)$ are broad prior distributions for convergence

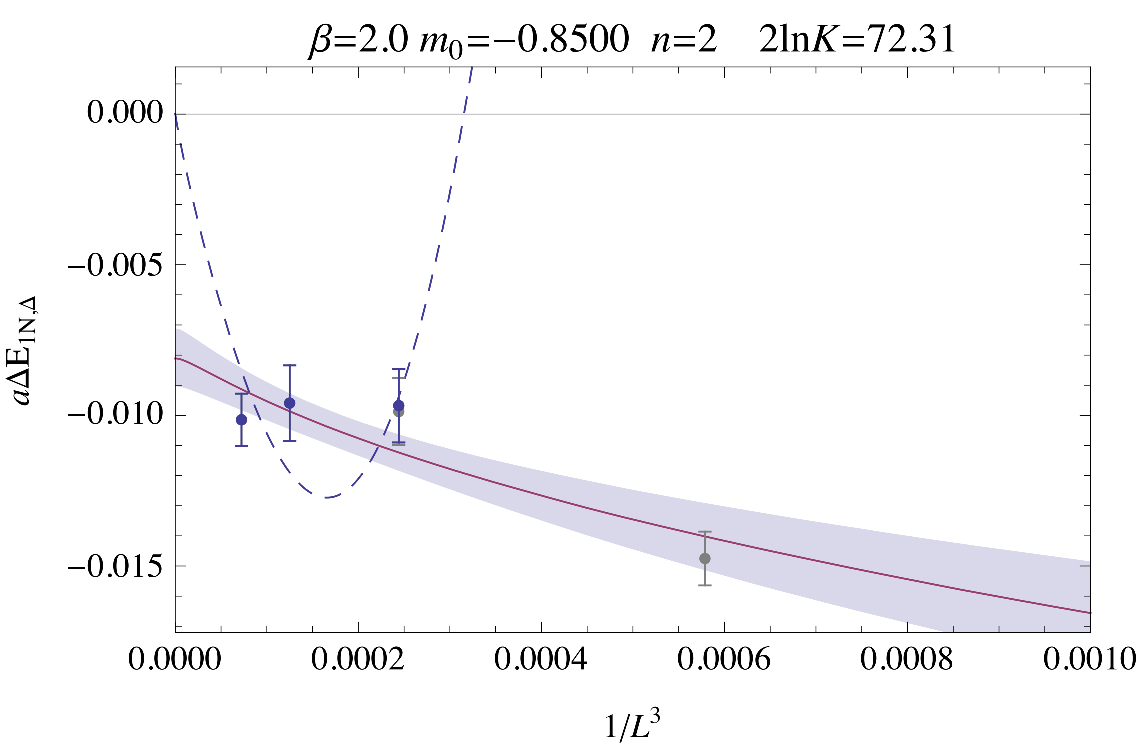
- If 2 *ln[K]* > 6 : "strong evidence" of preference for H_1 over H_2 then ask what are the bounds on the binding energy

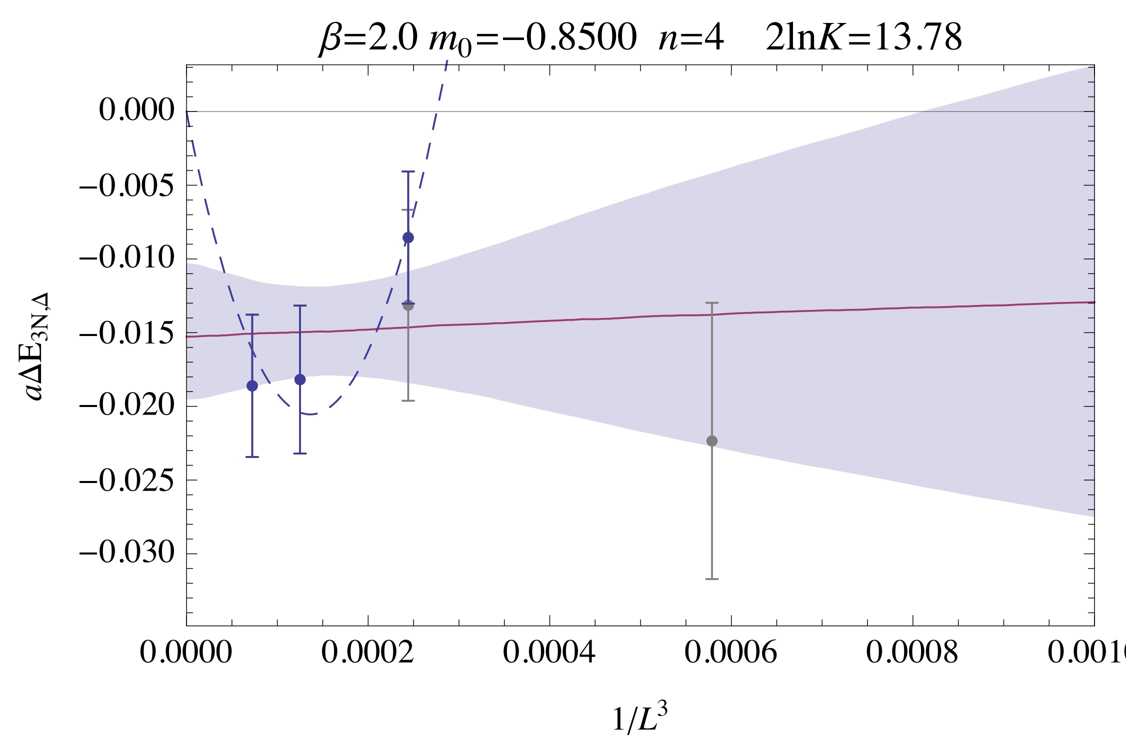
Kass and Raftery (1995). *Journal of the American Statistical Association* **90** (430): 791.

Infinite volume extrapolations



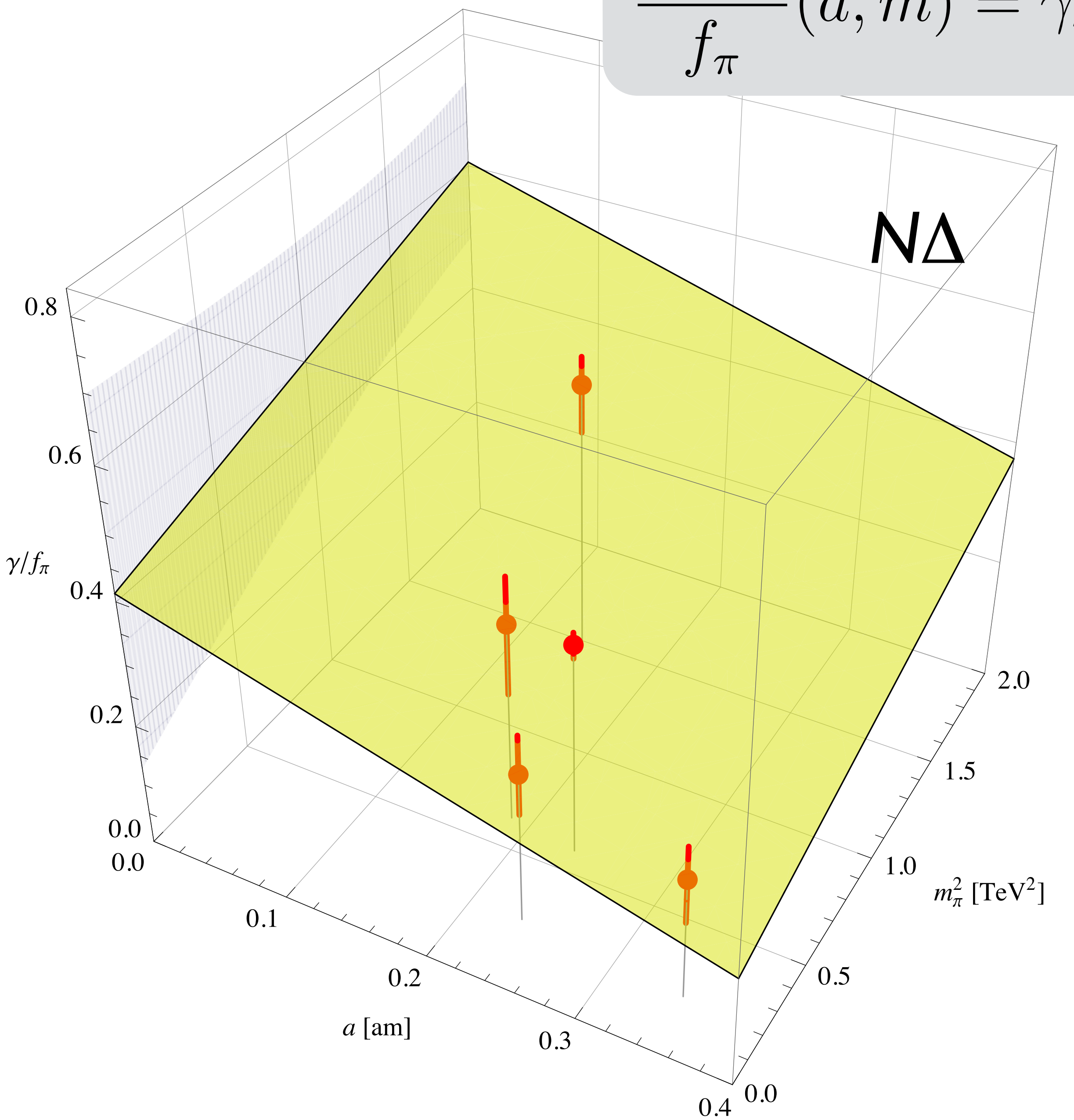


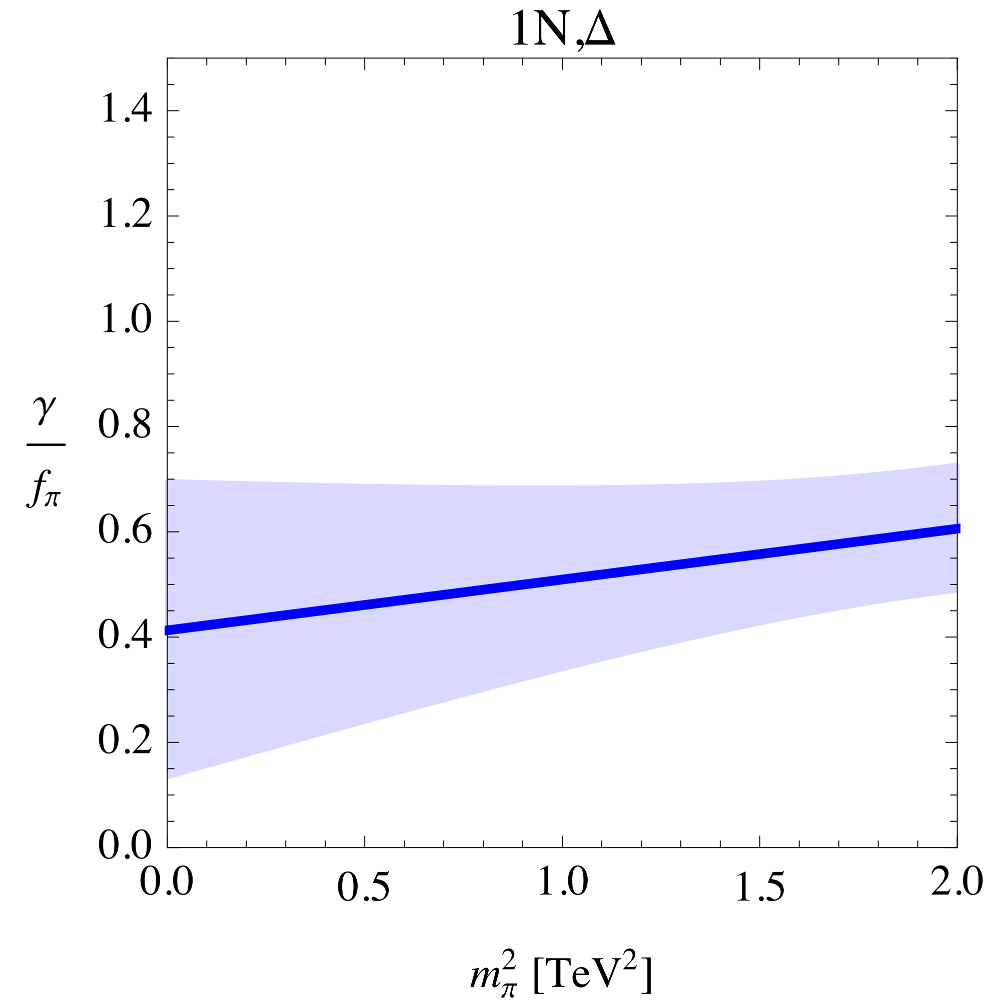




- Simple continuum limit extrapolation of binding momentum, γ

$$\frac{\gamma_{nN,\Delta}}{f_\pi}(a,m) = \gamma^{(0)}_{nN,\Delta} + a\ \delta^{(a)}_n + {m_\pi}^2 \delta^{(m)}_n$$

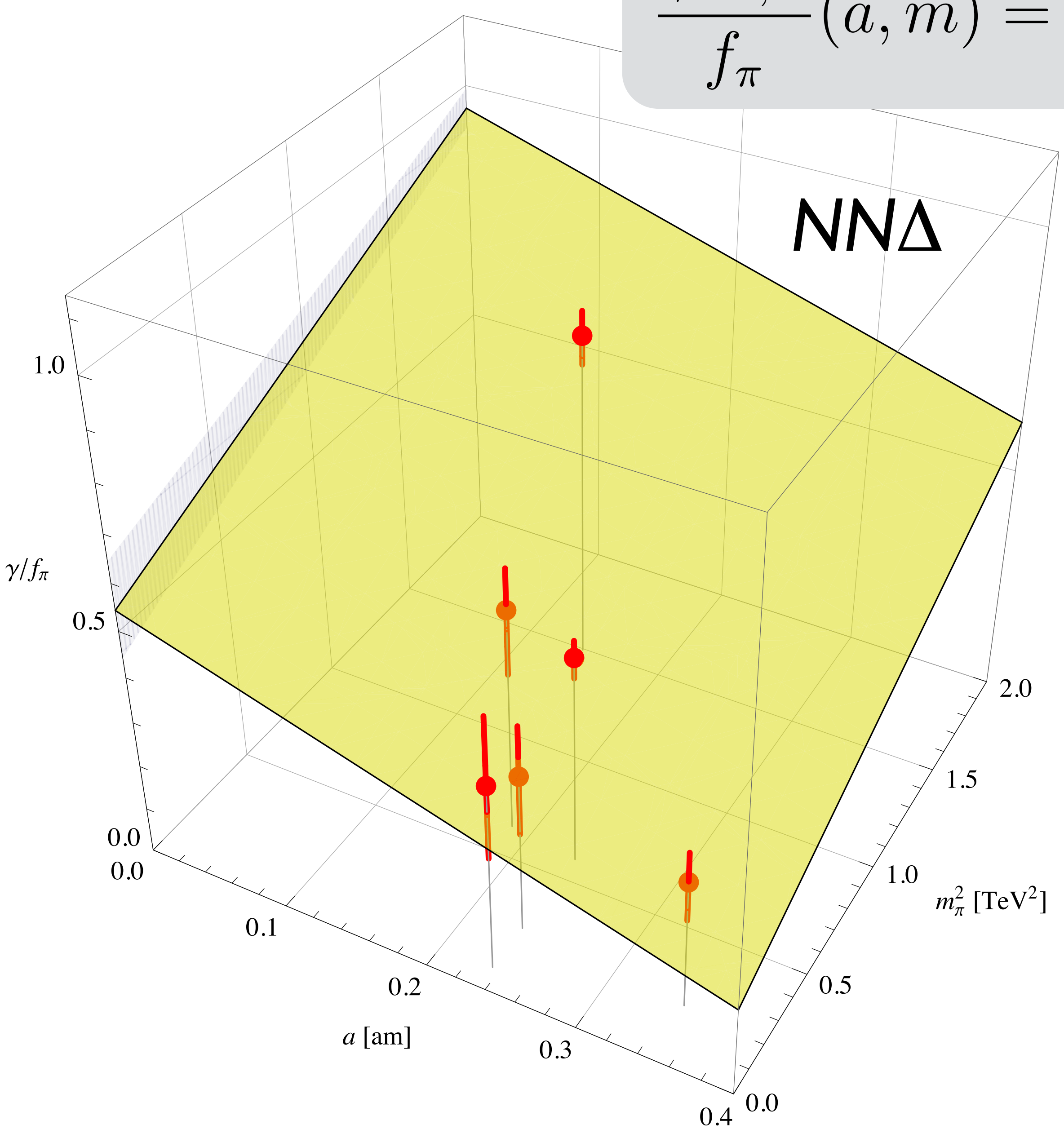


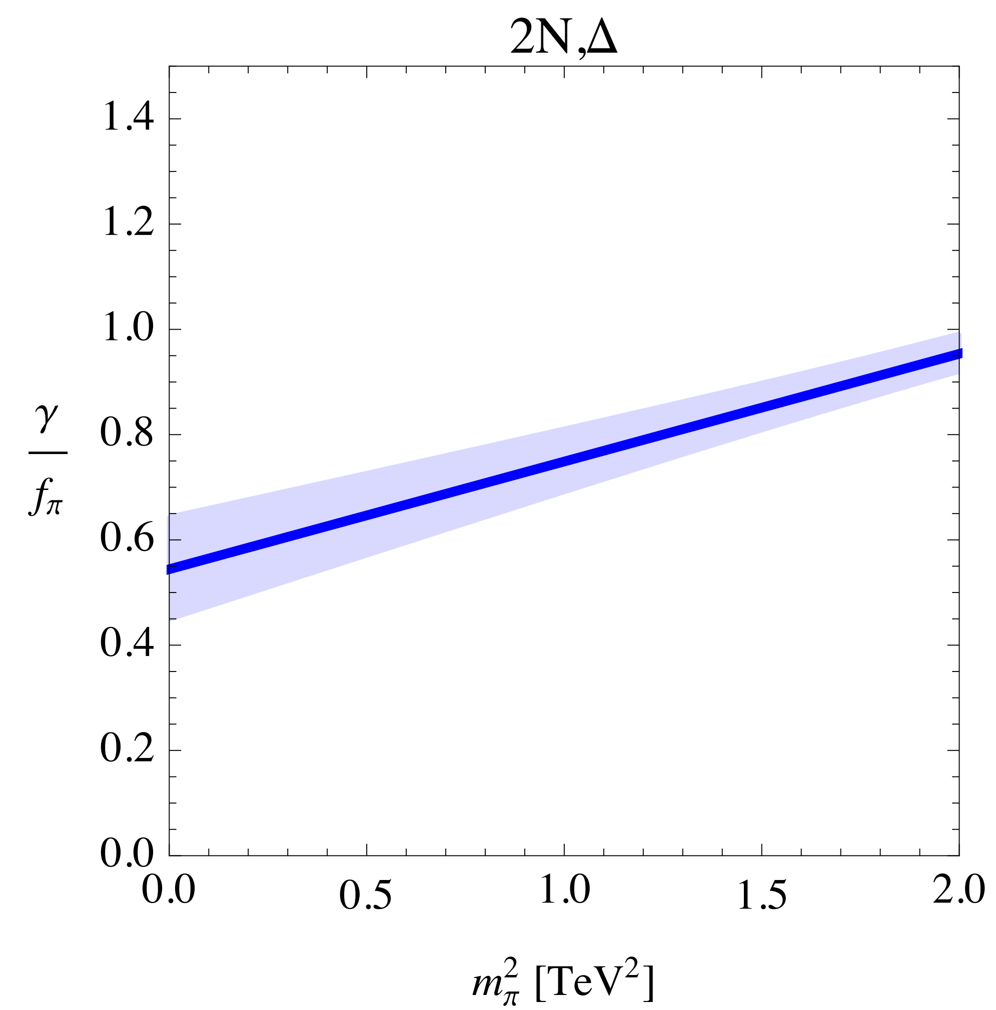


NB: physical scale set by demanding f_π=246 GeV (arbitrary)

- Simple continuum limit extrapolation of binding momentum, γ

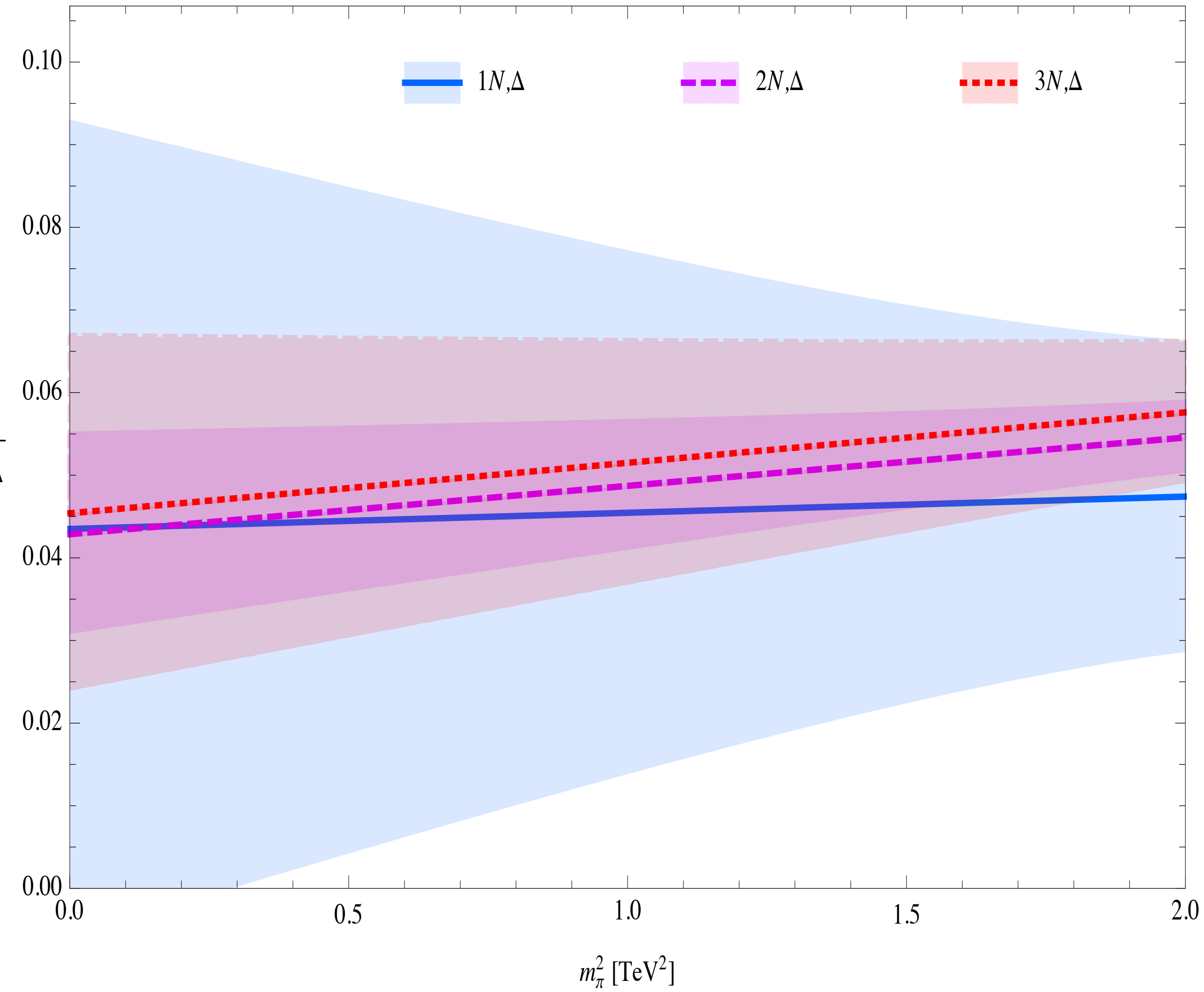
$$\frac{\gamma_{nN,\Delta}}{f_\pi}(a,m) = \gamma^{(0)}_{nN,\Delta} + a\,\delta^{(a)}_n + {m_\pi}^2\delta^{(m)}_n$$



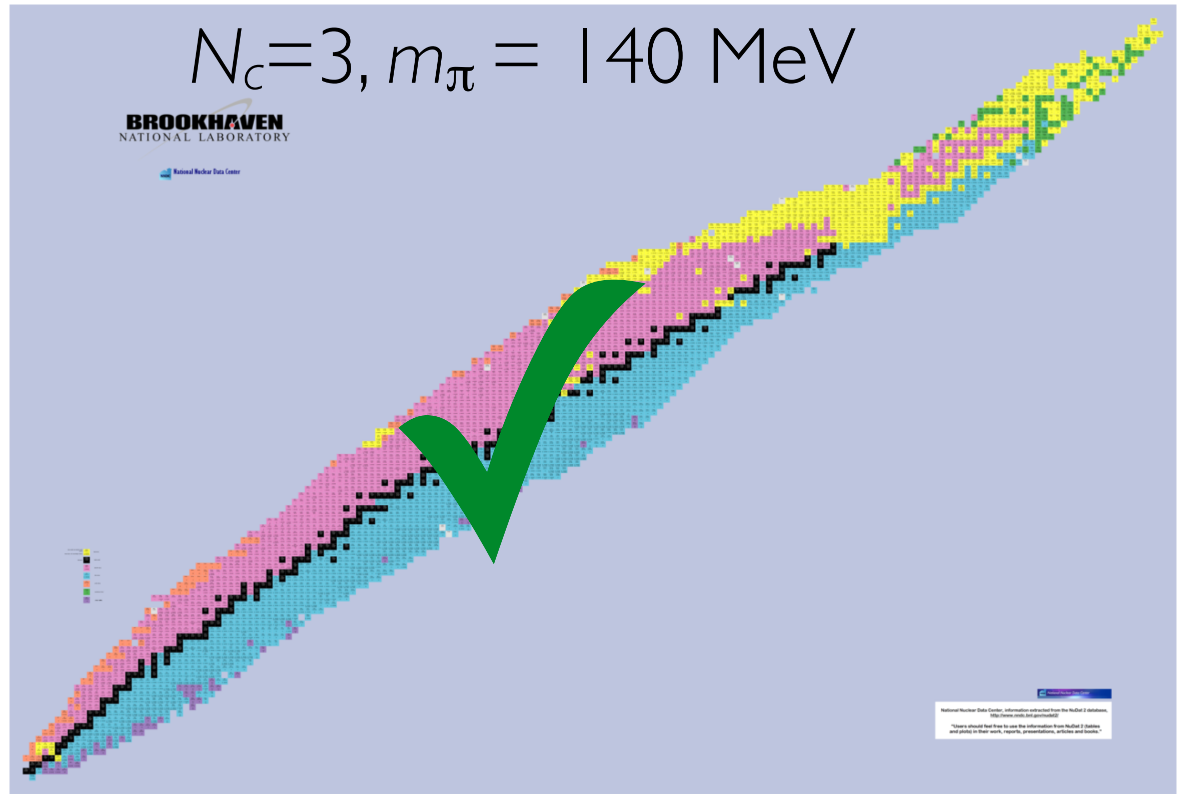


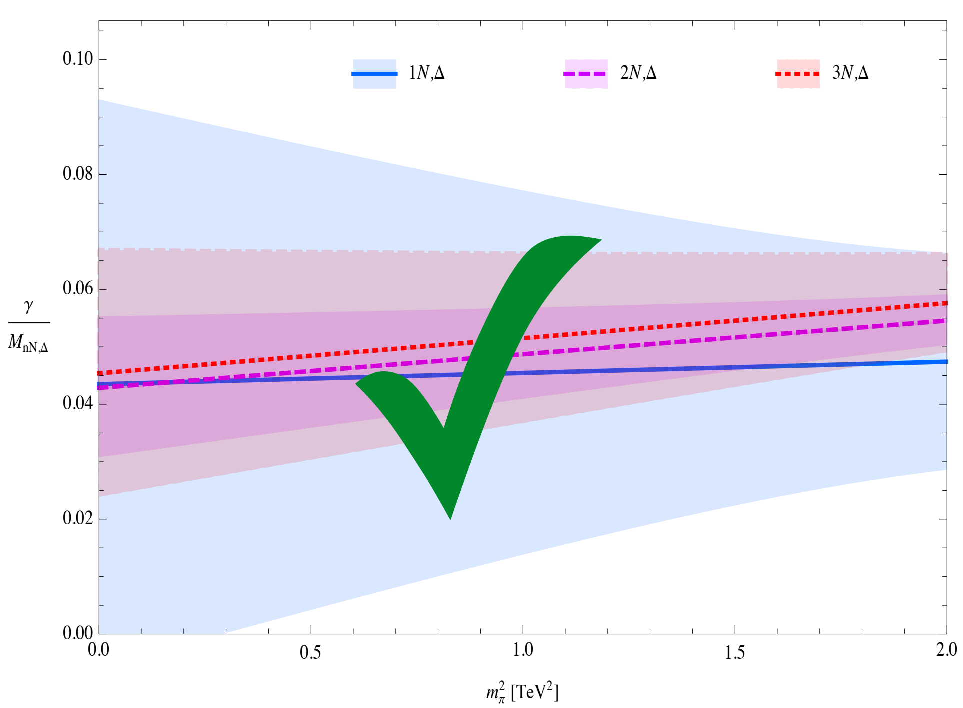
Dark nuclei

- J=0 nuclei: very likely unbound (all positively shifted)
- **J=1, strong evidence for bound states for B=2,3, 4(?)**
  B=5,..,8 seem unbound
  - Bindings decrease with quark mass and increase towards continuum
  - Binding is few % w.r.t. mass $\frac{\gamma}{M_{\mathrm{nN},\Delta}}$
- Nuclear states with other quantum #s may also be bound

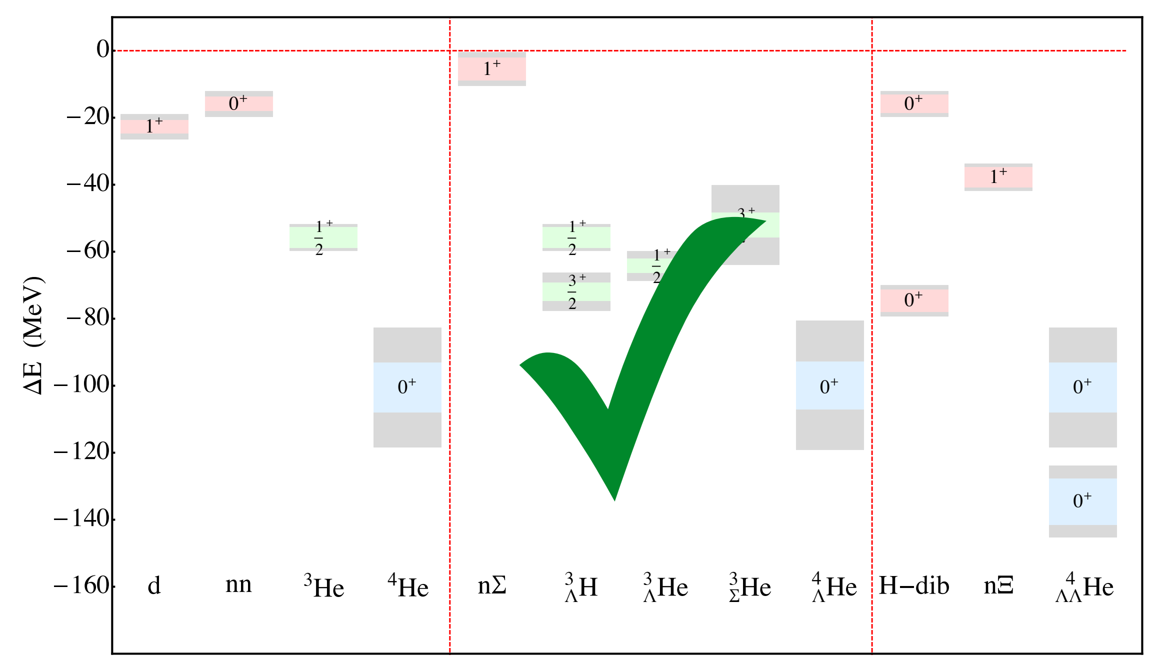


The ubiquity of nuclei?





N_c=2, m_π = 1 TeV



N_c=3, m_π = 400–800 MeV
NPLQCD/PACS-CS

The ubiquity of nuclei?

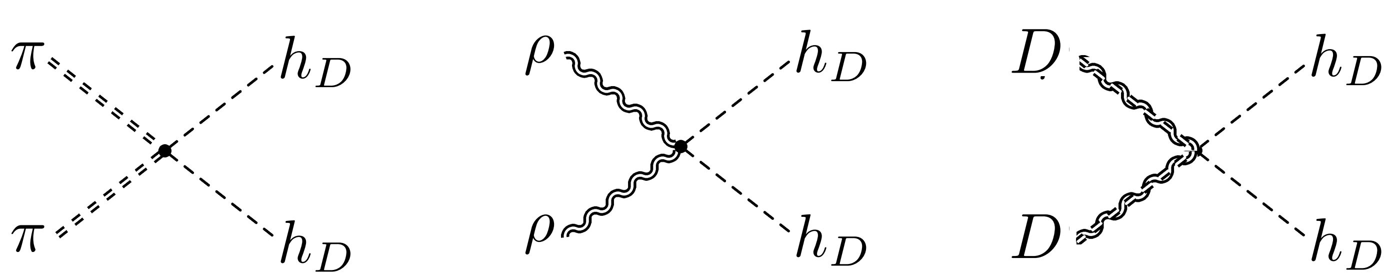
- So far appears that nuclei are rather generic and not an accident of parameters
- What are nuclei? e.g. shell-model like states vs quark blobs
  - More detailed studies necessary (eg magnetic moments)
- How generic are layers of effective degrees of freedom?
  - nucleons → alpha clusters → nuclei ….

Dark matter model building

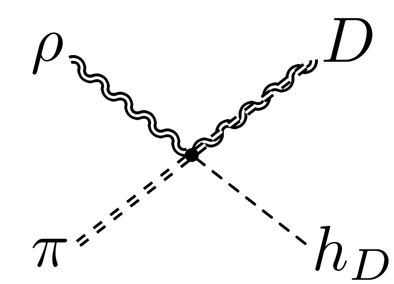
- Extend strongly-interacting dark sector to talk minimally to SM
  - Simple extension: add scalar particle that kinematically mixes with Higgs

$$\mathcal{L} = \mathcal{L}_{\text{strong}} - \frac{\lambda}{4}\left(v_D - H_D^2\right)^2 - \left(\kappa H_D (u_R^\dagger u_L + d_L^\dagger d_R) + h.c.\right) + \delta\, H_D^2 |H|^2$$

    - Dark Higgs vev gives quark masses
    - Kinematic mixing controlled by δ: must be small $\sim 10^{-3}$
- Hadronic theory: consider only pions, rhos, "deuterons" (LQCD calculations provide motivation to consider deuterons)
- Interactions



Annihilation



Nucleosynthesis

Cosmology & Indirect detection signals

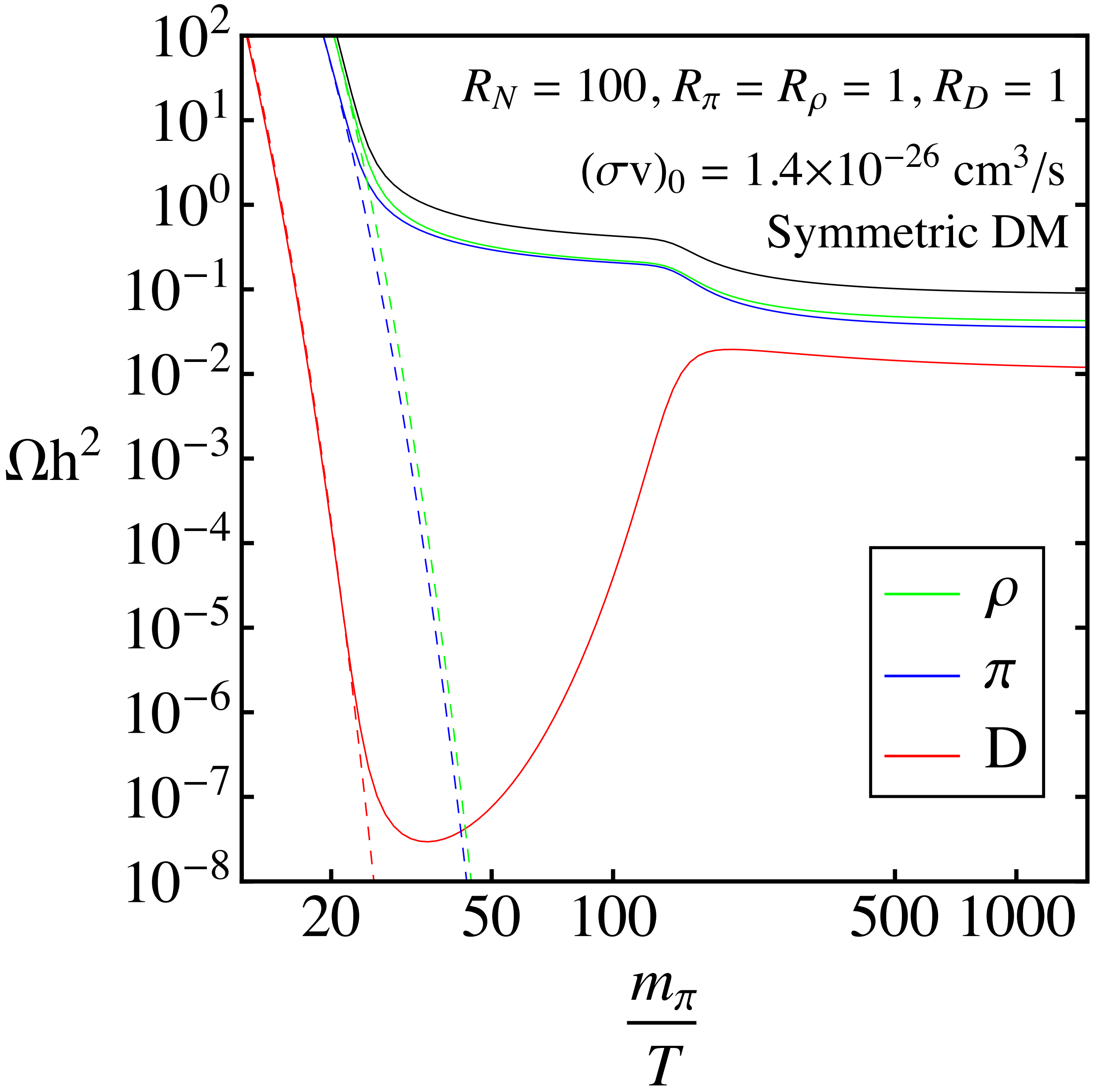
- Dark nucleosynthesis, dark capture processes modify early universe cosmology (both symmetric & asymmetric scenarios)
- Presence of nuclear binding energies: new scale for phenomenology is significantly different than M, Λ_{QC_2D}

Signature	Collider	Direct Detection	Annihilation	Nucleosynthesis	Capture
Sym-DM	$M, 2M$	$M, 2M$	$M, 2M$	$B_D \ll M$	M
Asym-DM	$M, 2M$	$M, 2M$	—	$B_D \ll M$	—

- For symmetric DM, additional scale/process may lead to signals at multiple different energy scales with identical spatial morphology
- For asymmetric DM scenarios (only dark baryon number carrying states remain) nucleosynthesis allows indirect detection signals

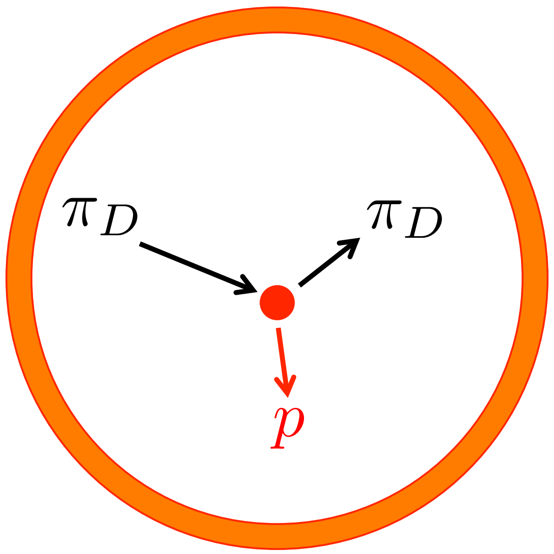
An example of relic denstiies

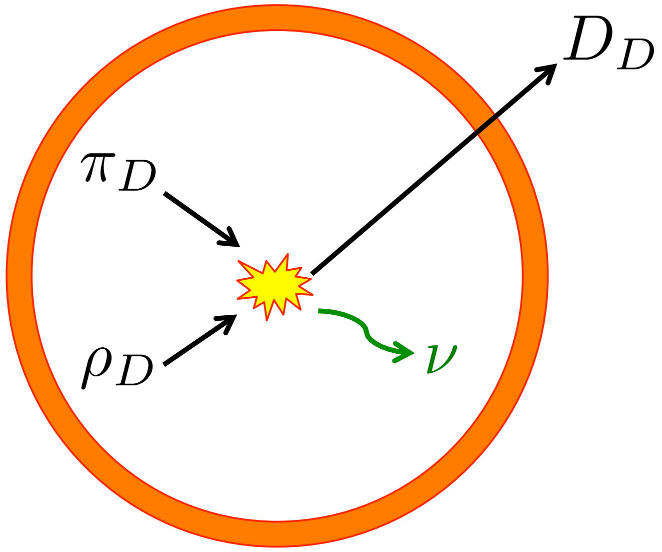
- Dark nucleosynthesis beaten out by annihilation at high densities
- Becomes dominant at lower temperatures $B_D/20 < T < M/20$
- Repopulates the nuclear state



Compact Objects

- Significant modifications to physics of astrophysical bodies
  - Dark matter gravitationally captured after scattering on visible matter
  - Helioseismology and neutron star lifetimes strongly modified – strongly constrains asymmetric DM models
- Very rich phenomenology!
  - Liberation of binding energy may allow ejection of dark matter
- Star develops a co-located dark nuclear process site





Summary

- Two-flavour, two-colour QCD has a complex spectrum exhibiting the analogues of nuclei
  - Ubiquity of nuclei?
- Composite dark matter is a natural scenario to consider
  - Composite doesn't just mean simple hadrons
    Need to consider "nuclei"
  - Nuclear binding provides a scale for free that is small relative to the QCD scale in a natural way
  - Predicts a range of different phenomenology that beyond what is possible in simpler models

fin