Nuclear Parity Violation from Lattice QCD

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Introduction

- Electroweak (EW) precision measurements at LEP, flavor mixing experiments at B-factories and the discovery of the Higgs Boson at LHC put tight constraints on possible new physics beyond the Standard Model
- but: hadronic EW neutral current

$$J^0_\mu = \bar{u}\gamma_\mu(1-\gamma_5)u - \bar{d}\gamma_\mu(1-\gamma_5)d - 4\sin^2\theta_W J^{\rm em}_\mu,$$

responsible for parity violation (PV) in hadronic processes is least constrained observable in the Standard Model
- intrinsic strength of weak interactions $\sim G_F F_\pi^2 = \mathcal{O}(10^{-7}) \Rightarrow$ processes dominated by $\mathcal{O}(1)$ QCD background
- can also exploit certain few-body and nuclear systems to test PV
- current analyses show enhanced isoscalar PV, suppressed isovector PV: neutral current contributes to the latter
- superficially similar to the octet enhancement ($\Delta I = 1/2$ rule) that governs strangeness changing decays
- could strong interaction explain both effects $\Rightarrow$ Lattice QCD

Model Parameters

- most common model used for nuclear PV is meson-exchange model by Desplanques, Donoghue and Holstein (DDH)
- PV interactions encoded in seven PV couplings

$$H_{\rm wk} = \frac{h^1_\pi}{\sqrt{2}}\bar{N}(\vec{\tau}\times\vec{\pi})_z N + \bar{N}\left(h^0_\rho \vec{\tau}\cdot\vec{\rho}^\mu + h^1_\rho \rho^\mu_z + \frac{h^2_\rho}{2\sqrt{6}}(3\tau_z\rho^\mu_z - \vec{\tau}\cdot\vec{\rho}^\mu)\right)\gamma_\mu\gamma_5 N$$
$$+\,\bar{N}(h^0_\omega\omega^\mu + h^1_\omega\tau_z\omega^\mu)\gamma_\mu\gamma_5 N - h^{1'}_\rho \bar{N}(\vec{\tau}\times\vec{\rho}^\mu)_z\frac{\sigma_{\mu\nu}k^\nu}{2m_N}\gamma_5 N.$$

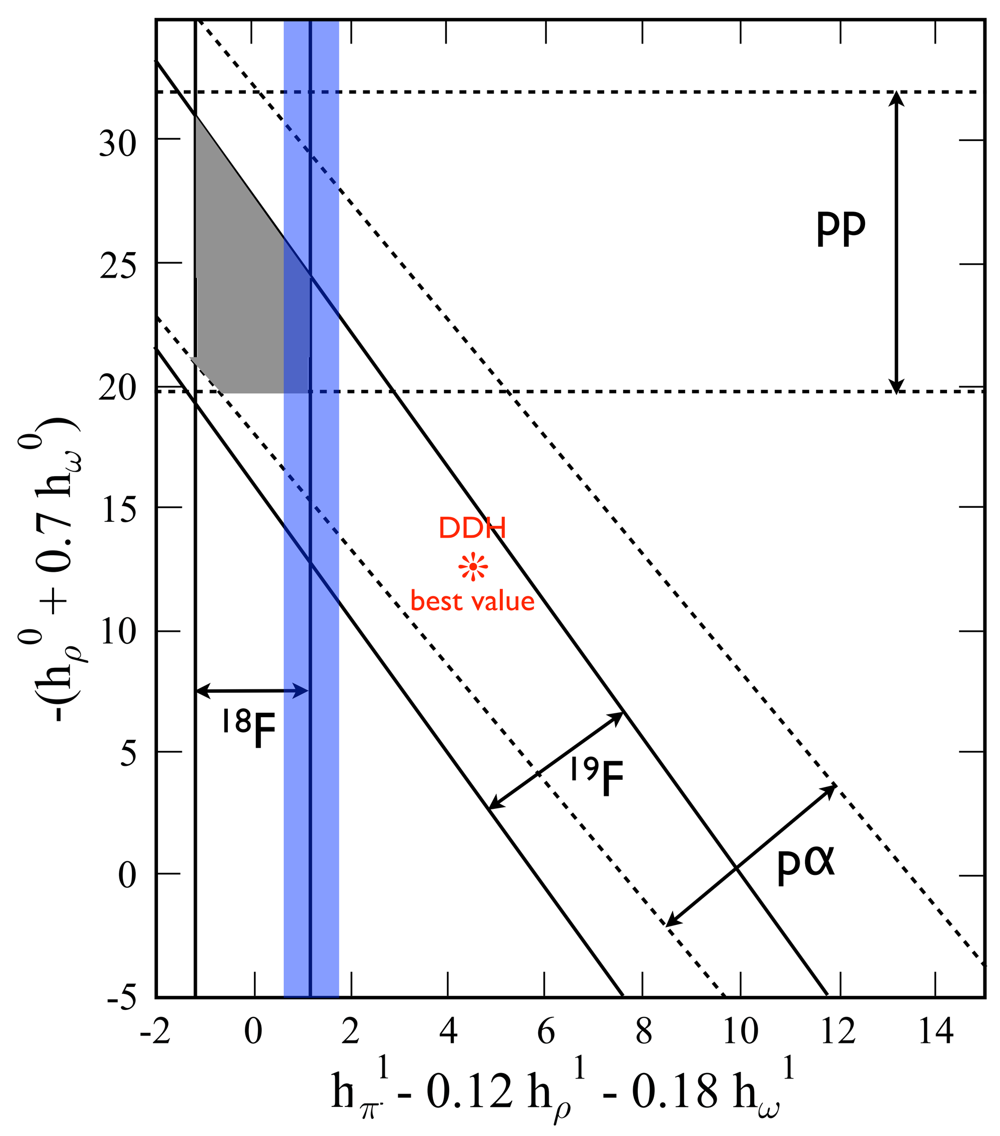

Figure: Experimental constraints on linear combinations of isoscalar and isovector DDH model.

- use Lattice QCD to compute $\vec{p}p$ PV matrix element directly $\Rightarrow$ improve constraints on isoscalar combination $(h^0_\rho + 0.7h^0_\omega)$

Lattice QCD Approach

- PV interactions described by short-range effective operators $\mathcal{O}^{\Delta I=0,1,2}$
- calculations of nuclear matrix elements for $\mathcal{O}^{\Delta I=0,1}$ involve expensive computations of quark-line disconnected diagrams $\Rightarrow$ we first study

$$\mathcal{O}^{\Delta I=2} \equiv \frac{1}{3}(\bar{q}\gamma_\mu\gamma_5\vec{\tau}q)\cdot(\bar{q}\gamma_\mu\vec{\tau}q) - (\bar{q}\gamma_\mu\gamma_5\tau^3 q)(\bar{q}\gamma_\mu\tau^3 q)$$

- the 5-point correlation function

$$C_{PS}(t;t_f,t_i) = \langle pp(^3P_1,t_f)\,\mathcal{O}^{\Delta I=2}(t)\,\bar{p}\bar{p}(^1S_0,t_i)\rangle$$

is proportional to desired proton-proton PV matrix element
- good: no operator mixing and only connected contributions in isospin limit
- challenges:
  - process features 2208 diagrams $\Rightarrow$ automatic code generation (see other poster)
  - interpolating operator for higher partial wave $^3P_1$ has to be constructed
  - many-point functions involving Baryons are extremely noisy $\Rightarrow$ code optimization for being able to gather huge amount of statistics
  - non-trivial finite volume dependence
  - exponential degradation of signal-to-noise ratio with decreasing pion mass
  - C_{PS} needs (re-)normalization

Normalization

- lattice interpolating operators have overlap with a tower of states $\Rightarrow$ euclidian correlation functions can be written as sums over exponentials, decaying with masses m_n:

$$C(t_f,t_i) = \langle p(t_f)\,\bar{p}(t_i)\rangle \sim \sum_{n=1}^{\infty} Z^{\rm snk*}_n Z^{\rm src}_n e^{-m_n(t_f-t_i)}$$

- factors Z_n represent the overlaps of the proton creation and annihilation operators $\bar{p}, p$ with corresponding state $|n\rangle$ at source or sink
- cancel vacuum overlaps by computing the ratio:

$$R(t;t_f,t_i) = \frac{C_{PS}(t;t_f,t_i)}{\sqrt{C_P(t_f,t_i)\,C_S(t_f,t_i)}}\sqrt{\frac{C_S(t_f,t)\,C_P(t,t_i)}{C_P(t_f,t)\,C_S(t,t_i)}}$$

where C_P, C_S are P- and S-wave di-proton correlation functions

Preliminary Results

- excited energy plots for C_P, C_S suggest region with insignificant excited state contaminations

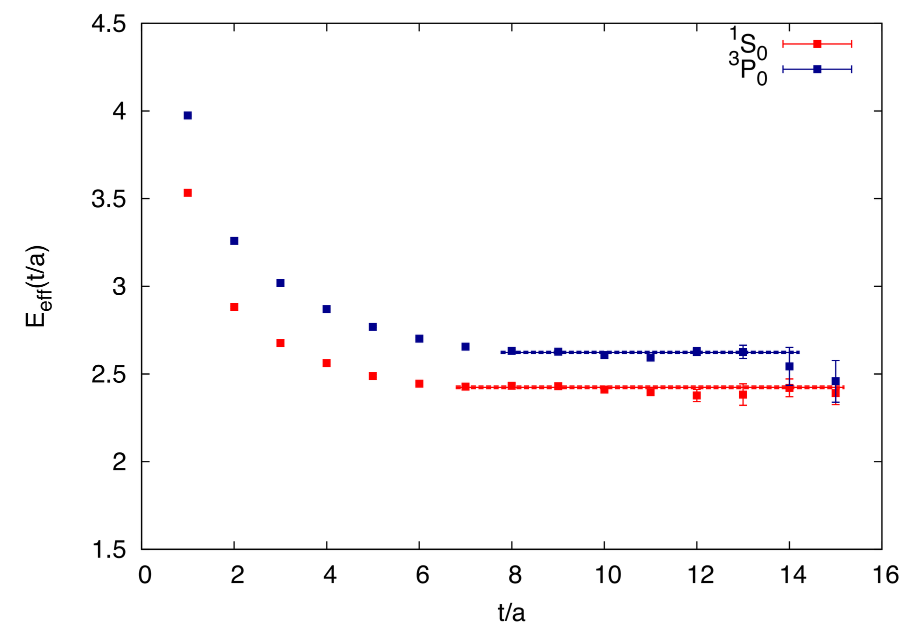

Figure: Effective energies $E_{\rm eff}(t) \equiv \log(C_X(t-1)/C_X(t+1))/2$ for S- and P-wave.

- plateau is linear in $t \Rightarrow$ possible $\mathcal{O}(e^{-\Delta E_{10}t})$ contaminations

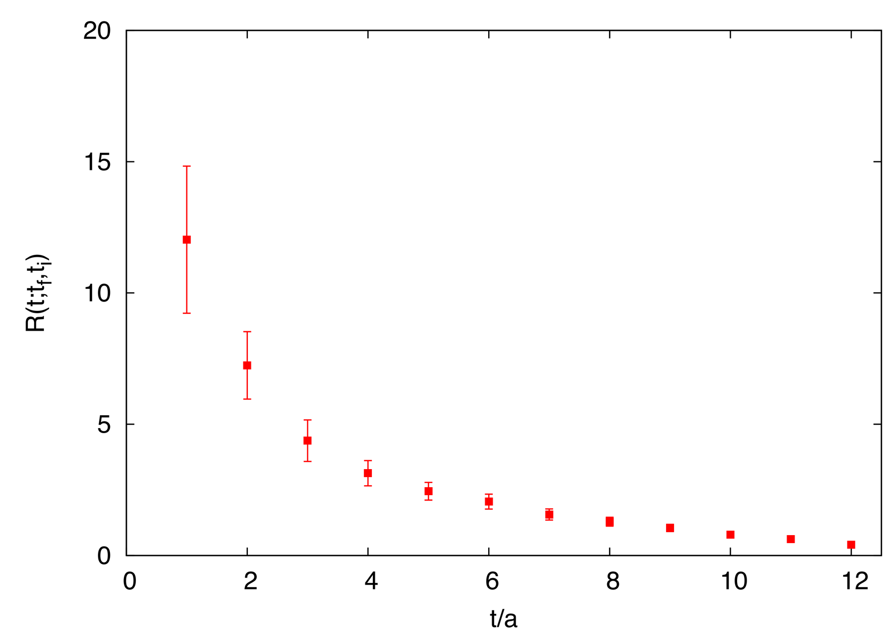

Figure: Ratio $R(t;t_f,t_i)$ shows linear dependence in t due to nearby energy levels.

Renormalization

- for targeted precision: NLO perturbative renormalization sufficient
- relevant diagrams on quark level are W and Z-exchange diagrams
- Wilson coefficient of $\mathcal{O}^{\Delta I=2}$:

$$C(\mu) = C^{(0)}_Z\left[1 + \left(4\log(\cos\theta_W)\log\frac{\mu}{M_W} - 3\right)\frac{\alpha_s(\mu)}{4\pi}\right] + C^{(0)}_W\left[1 - 3\frac{\alpha_s(\mu)}{4\pi}\right]$$

with known tree-level coefficients $C^{(0)}_Z, C^{(0)}_W$

Conclusion

- nuclear PV can be computed on the lattice for large m_π
- energy levels not well separated $\Rightarrow$ generalized eigenvalue techniques or summation method
- $\Delta I = 0, 1$ involve disconnected diagrams $\Rightarrow$ multigrid solver
- map out pion mass dependence

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