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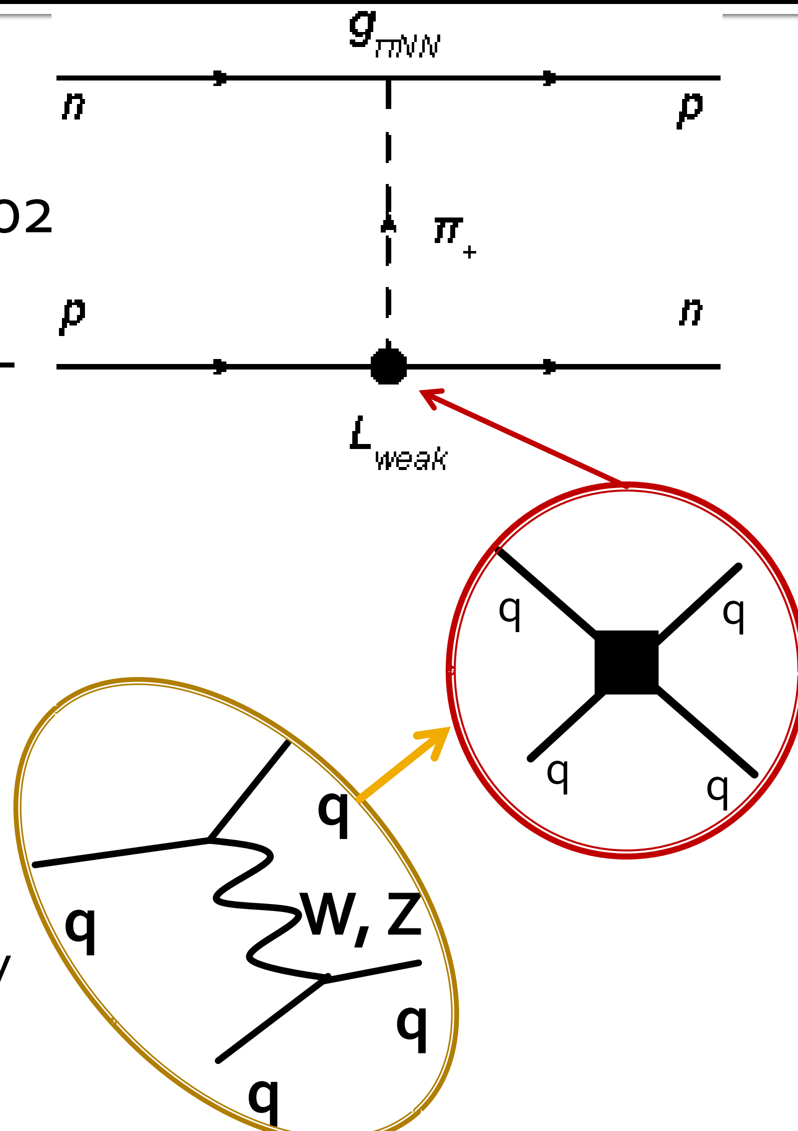
Lattice QCD Calculation of Nuclear Parity Violation

LLNL-PRES-490285

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

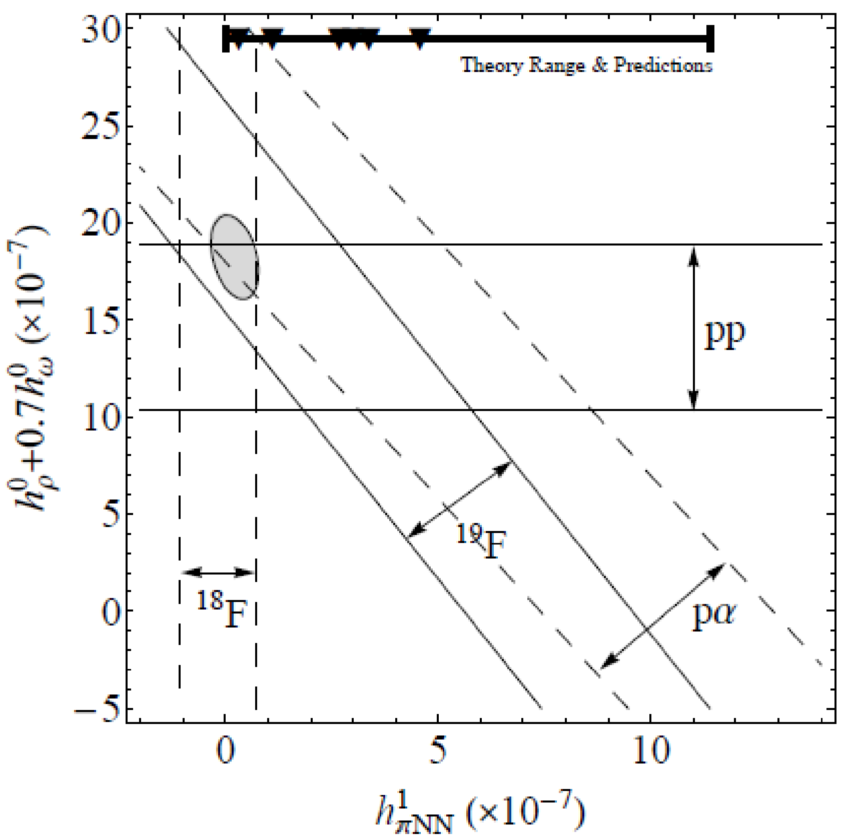
NN Parity Violating Interaction

- Predicted 1958, confirmed experimentally 1967
- Weak force PV interaction ~ 0.002 fm
- PV NN force dominated by long-range interactions
  - meson exchange models
  - weak physics encapsulated in weak vertex
- PV signal is dwarfed by QCD: $\mathcal{O}(10^{-7})$
  - Experimental ways around this
  - Large uncertainties and many-body effects



Extracting $h_{\pi NN}$

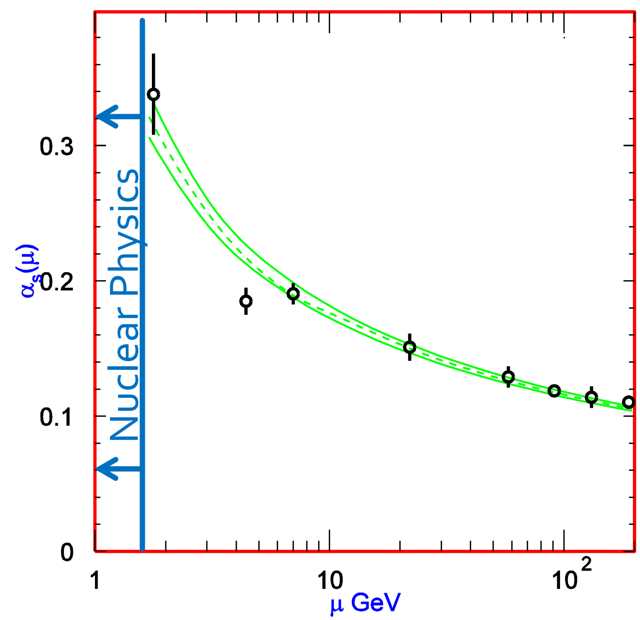
- $\Delta I=1$ dominated by $h_{\pi NN}$
- NPDGamma (see talk by M. Gericke) want to extract at the 20% level
- Lattice QCD needs to match this precision…



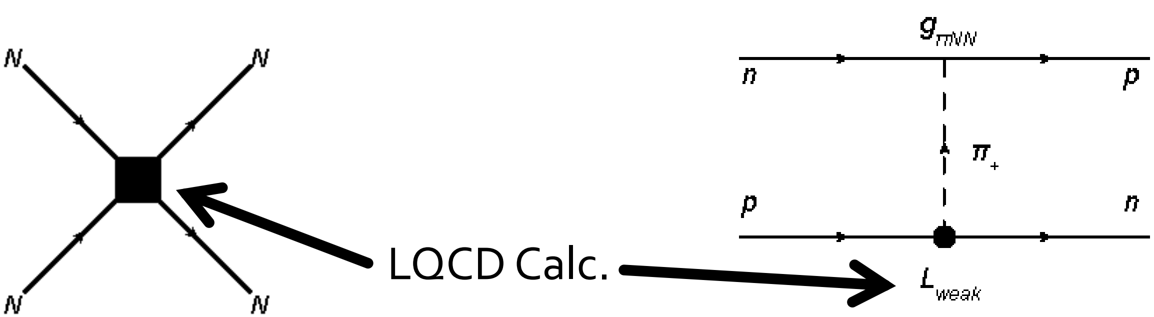
Lattice QCD & EFT

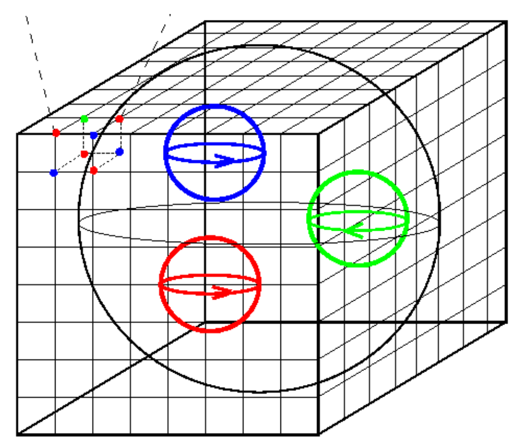
- QCD is nonperturbative in Nuclear Physics regime
- Discretize Space & Time
- Quarks on lattice sites, gluons on links

$$\Rightarrow \int [d\phi] \rightarrow \prod_n \int_{-\infty}^{\infty} d\phi_n$$

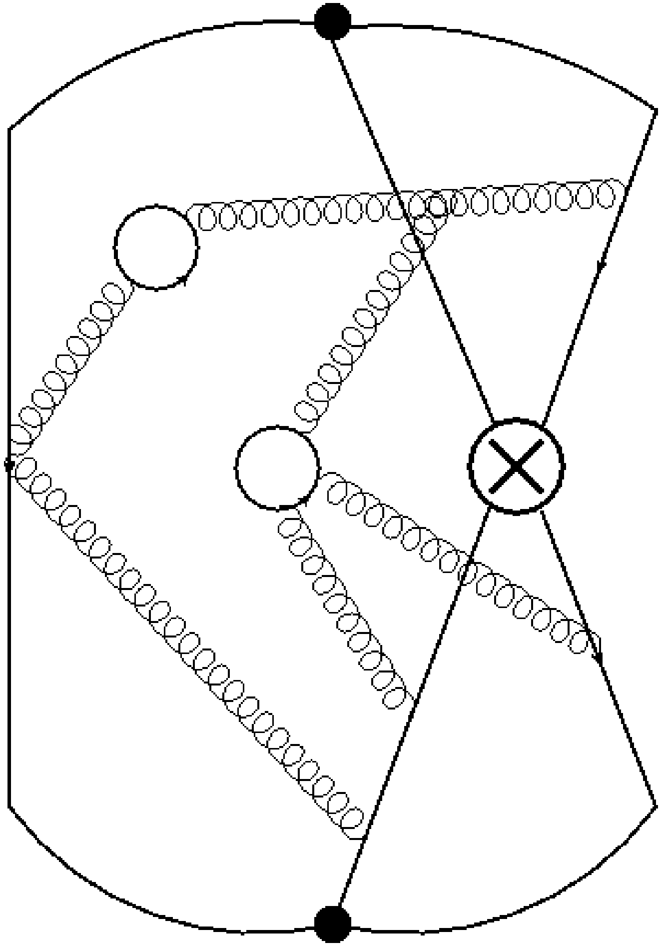


- Calc. ET coefficients



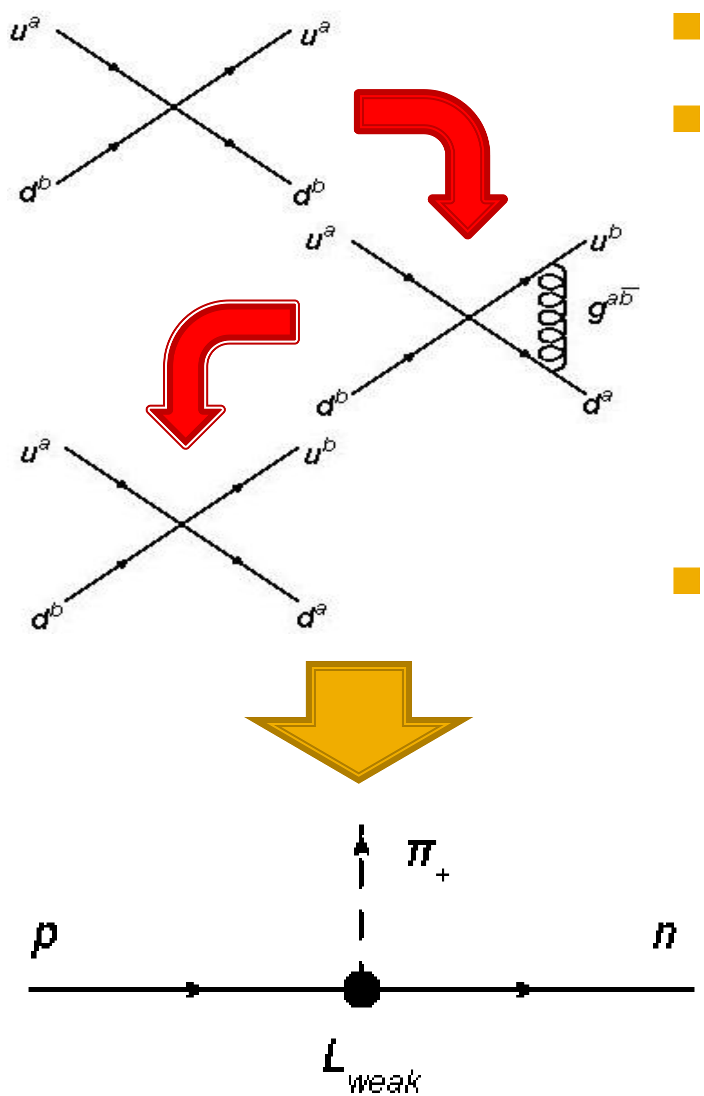


Steps to a Lattice Matrix Element



1. Gauge Configurations
   - Parameters from Jlab
   - $20^3 \times 256$ generated at LLNL on BGL
   - a_x~0.125 fm, a_t~0.036 fm
2. Propagator Generation
3. Quark Contractions

Quark & Hadron Level PV Operators



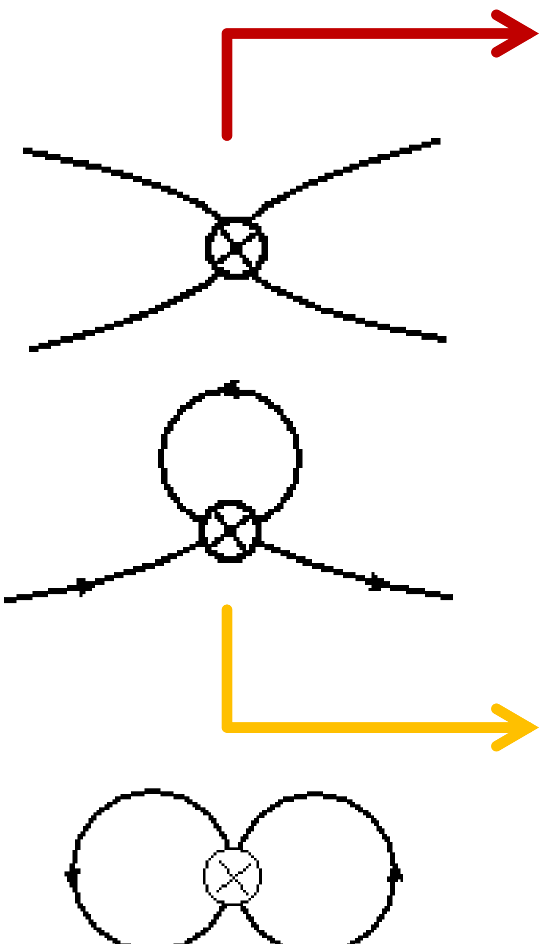
- 8 possible quark operators
- Operator coefficients are scale-dependent
  - J. Dai, et al., Phys. Lett. **B271, 403 (1991).**
  - B. Tiburzi (2012), 1207.4996.
- Match to dominant LO hadron interaction: $h_{\pi NN}$

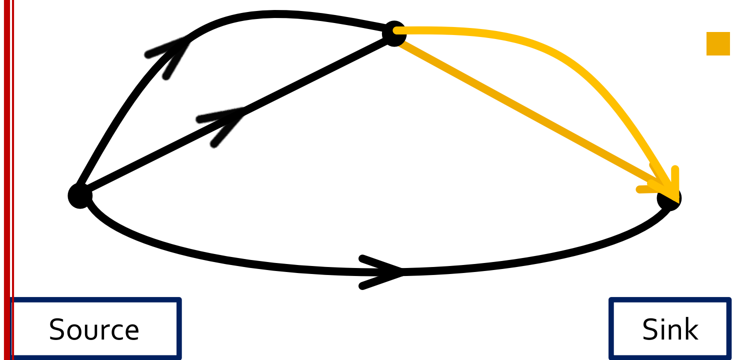
$$L_{weak}^{\Delta I=1} \sim h_{\pi NN}\left(\bar{p} n \pi^{+} - \bar{n} p \pi^{-}\right)$$

  - D. B. Kaplan and M. J. Savage, Nucl. Phys. **A556, 653 (1993).**

The Weak Operator

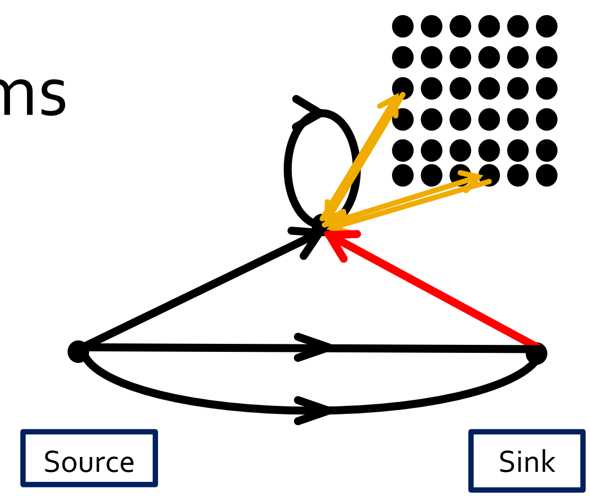
- Three ways to put together:





  - Connected diagrams cannot use sequential props

  - Quark loop diagrams require point-to-all propagator on operator timeslice



Matrix Element Extraction

$$R_{p\to n\pi} = \frac{C_3(t_{snk},t_{ops})}{C_{n\pi}(t_{ops})}\left[\frac{C_p(t_{snk}-t_{ops})C_{n\pi}(t_{snk})C_{n\pi}(t_{ops})}{C_{n\pi}(t_{snk}-t_{ops})C_p(t_{snk})C_p(t_{ops})}\right]^{1/2}$$

$$= \left(h_{\pi NN} + \Delta E \cdot h_a\right)$$

- Remove inserted energy contribution.

$$L_{weak}^{\Delta I=1} \sim h_{\pi NN}\left(\bar{p}n\pi^+ - \bar{n}p\pi^-\right) + h_a D_t\left(\bar{p}n\pi^+ - \bar{n}p\pi^-\right)$$

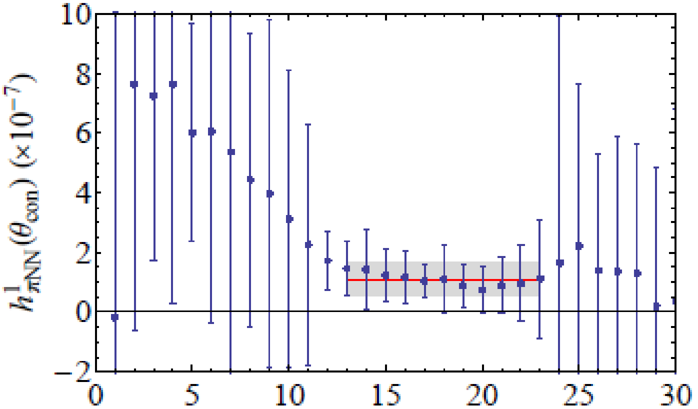
$$L_{PV}\Big|_{p\to n\pi} = -L_{PV}\Big|_{n\pi\to p}, \qquad \Delta E\Big|_{p\to n\pi} = -\Delta E\Big|_{n\pi\to p}$$

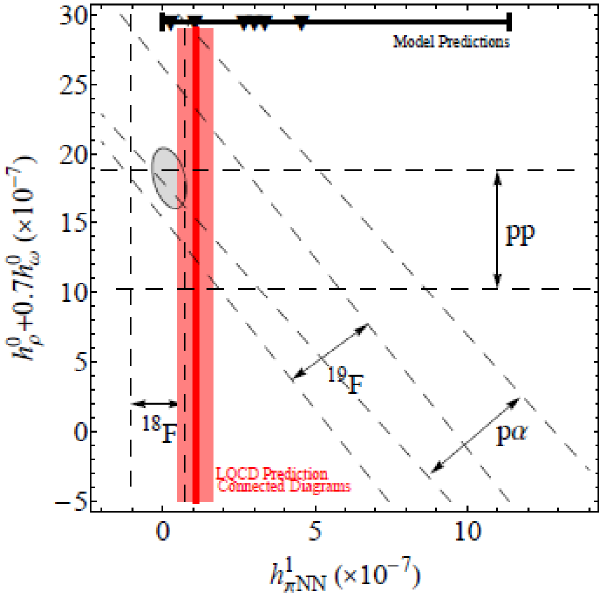
$$\Rightarrow M = \tfrac{1}{2}\left(R_{p\to n\pi} - R_{n\pi\to p}\right) = h_{\pi NN}$$

First Results

- First calculation
- Quark Loop Contributions
- Improved contraction code
- Better Nπ state
- Physical pion mass
- **Phys.Rev. C85 (2012) 022501**

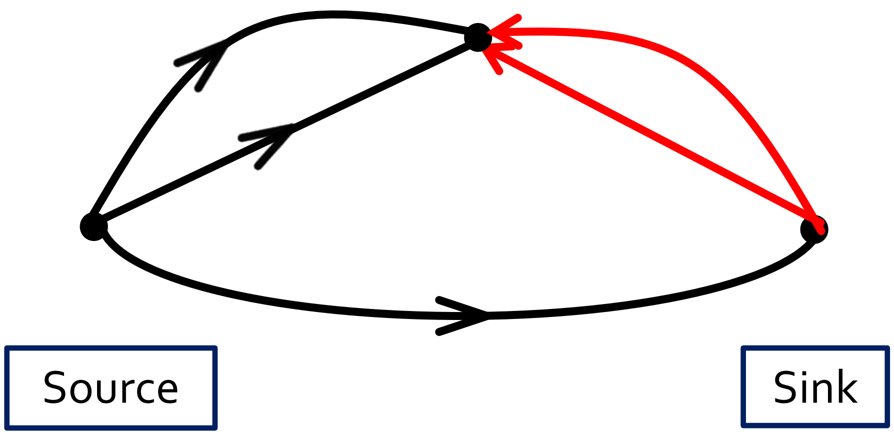
$h^1_{\pi NN}(\theta_{con}) = (1.099 \pm 0.505^{+0.058}_{-0.064}) \times 10^{-7}$





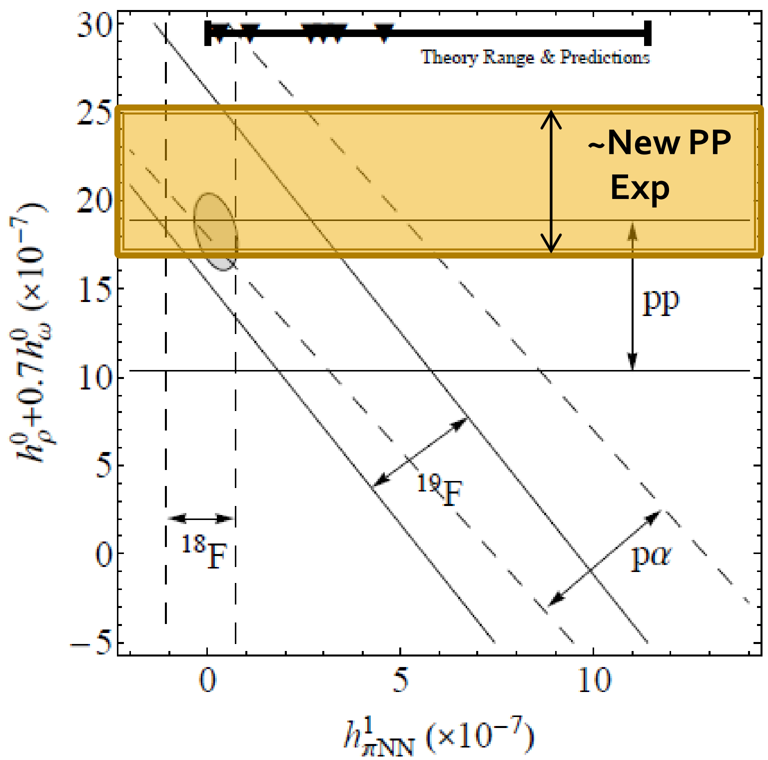
Next Generation

- Propagate from both ends:
  - Decrease sensitivity to single point fluctuations
  - Need separate loop propagator
- Multiple pion masses & volumes:
  - 390 MeV (20^3 & 32^3), 230 MeV (32^3), Physical Pt.?
- $\Delta I=2$



ΔI=2

- Perhaps least understood
- Affects experimental interpretation
  - Reanalysis of 2001/3 TRIUMF
  - Shift pp region up
- ΔI=2 analysis critical to understanding

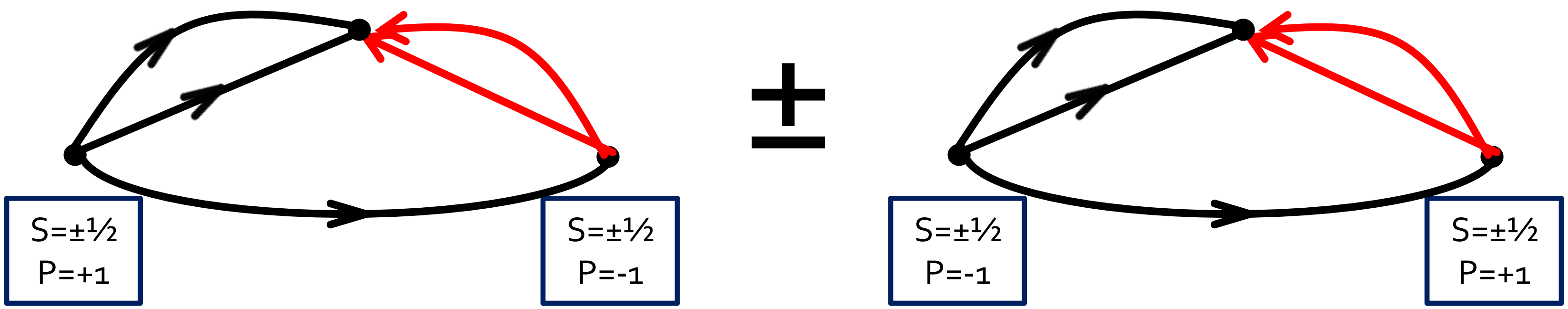


ΔI=2 & HBχPT

- Two leading order parameters

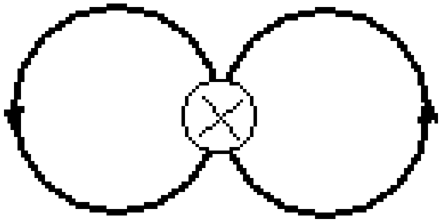
$$L_{\Delta I=2} \sim h_V^2 \overline{N}\left(X_R \gamma_\mu A^\mu X_R + X_L \gamma_\mu A^\mu X_L\right)N + h_A^2 \overline{N}\left(X_R \gamma_\mu \gamma_5 A^\mu X_R - X_L \gamma_\mu \gamma_5 A^\mu X_L\right)N$$
$$\sim h_V^2\left(\overline{p} n \partial_0 \pi_+ + \overline{n} p \partial_0 \pi_-\right) + h_A^2\left(\overline{p} S \cdot \vec{\partial} \pi_0 n \pi_+ - \overline{n} S \cdot \vec{\partial} \pi_0 p \pi_-\right)$$

- No quark loops!
- Note different relative signs and spin dependence



ΔI=0?

- Needs fully disconnected diagrams

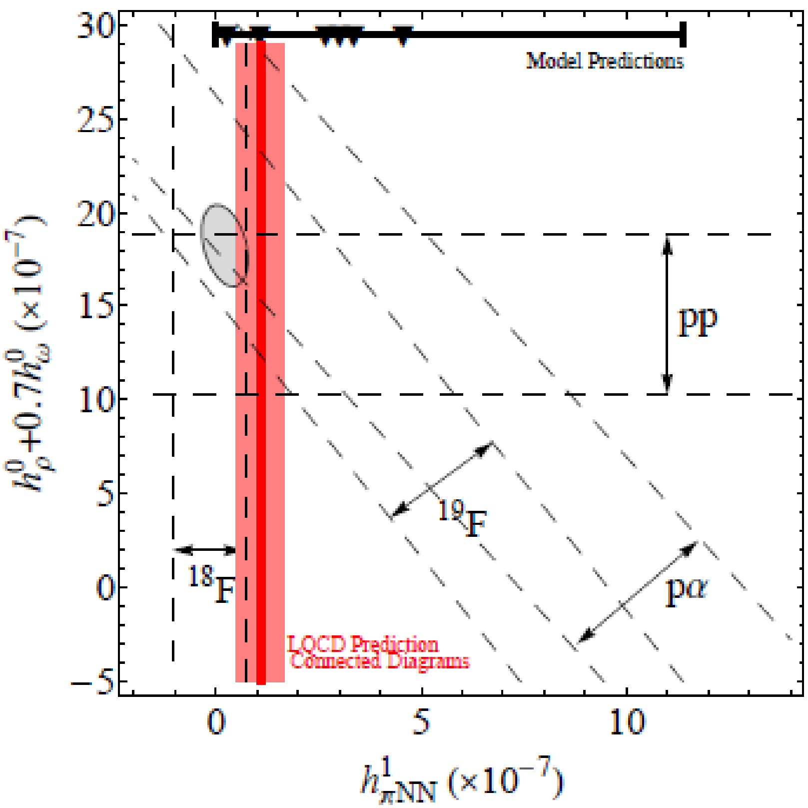


- Computationally expensive
- Stochastic estimation?
  - Noisy on an already noisy signal…

Conclusions

- First calculation
  - Obtains non-zero answer consistent with experiment
  - Missing several important contributions…
- Next Generation
  - More efficient running
  - More masses, volumes, better extraction

Understand PV Space



- Understand all 5 HBχPT PV parameters
- Connect to DDH formalism
- Connect to Danilov Amplitudes
- Use in experimental interpretation