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Nuclear Parity Violation from Lattice QCD

LLNL-PRES-490285

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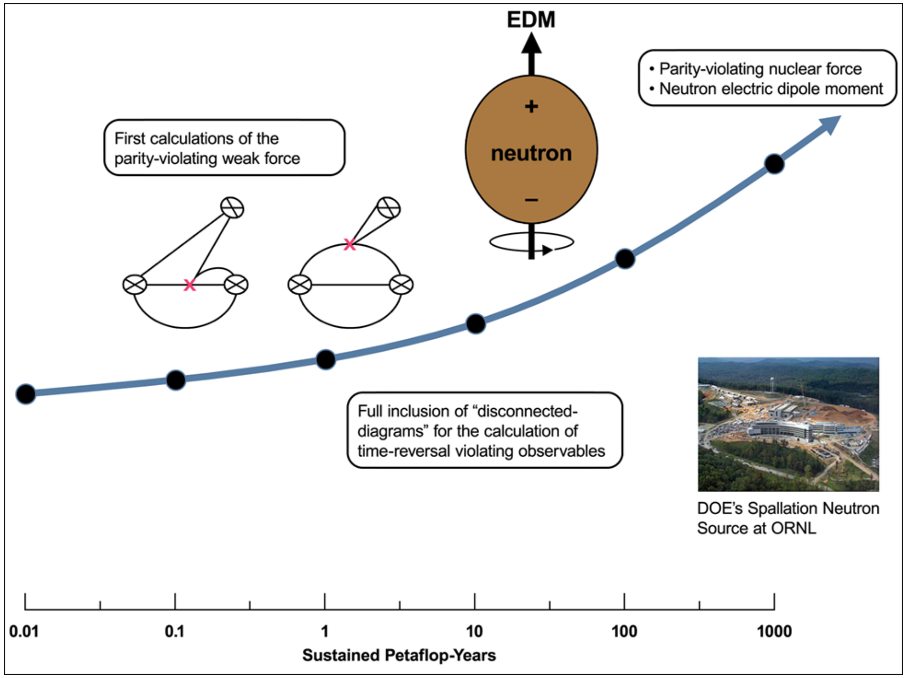
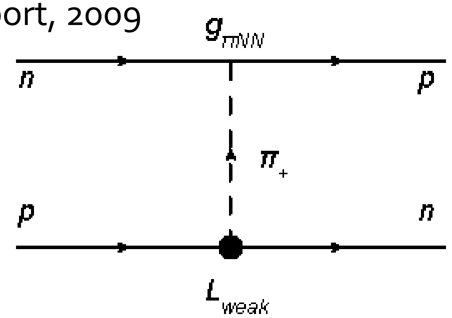
Into the Future with LQCD

- Faster computers & better algorithms
  - Precise calculations
  - Use of GPUs
  - Calculation of poorly known observables
- Nuclear Parity Violation

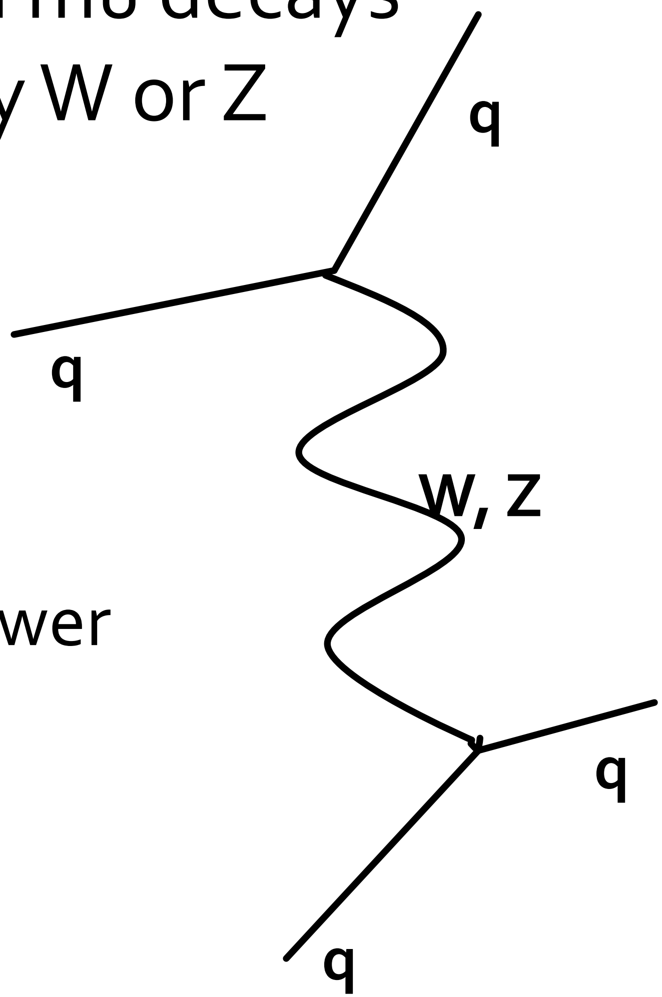


Scientific Grand Challenges Office of Nuclear Physics Workshop Report, 2009



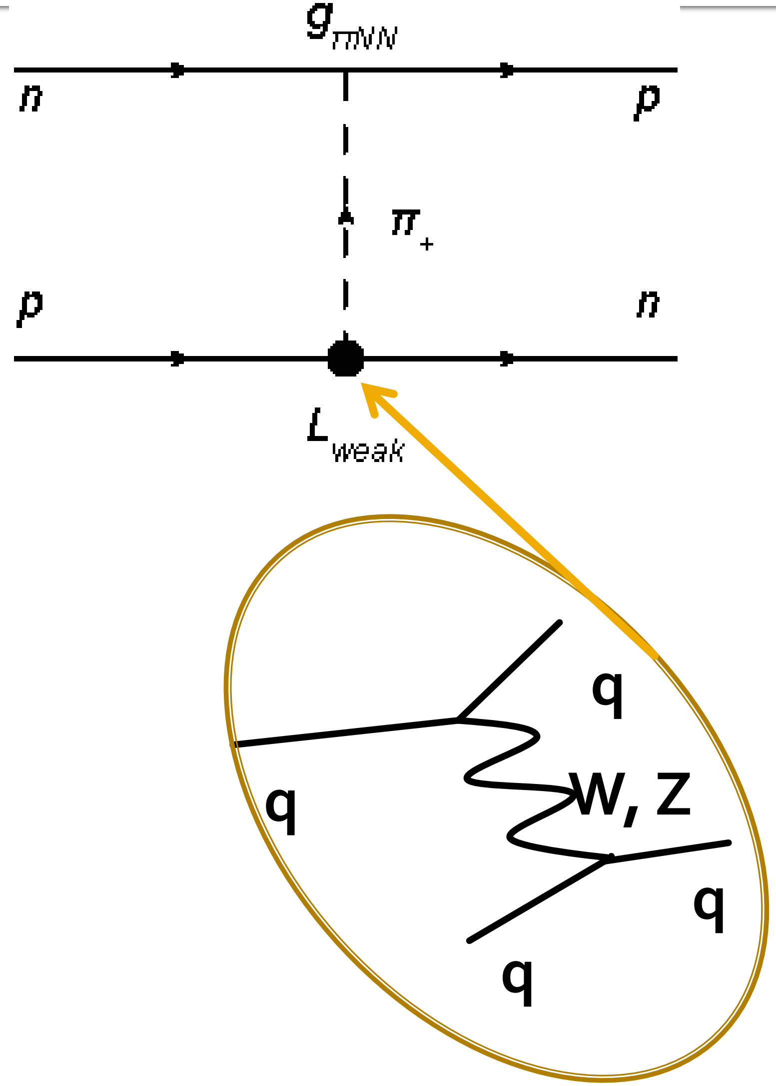
Parity Violation

- Discovered in 1957 in beta and mu decays
- Weak force effect mediated by W or Z
- Tested extensively in leptonic and semileptonic processes
- What about the quarks?
  - Neutral current interactions
  - NN interactions are the only answer
  - Hadronic PV much harder



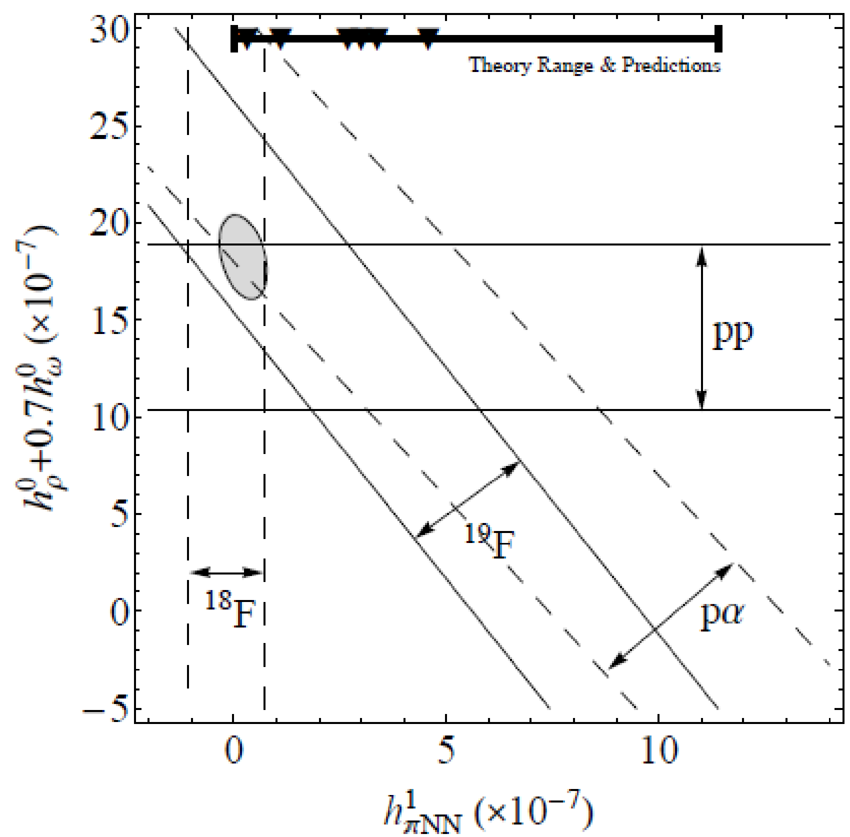
NN Parity Violating Interaction

- Predicted 1958, confirmed experimentally 1967
- 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 $h_{\pi NN}$

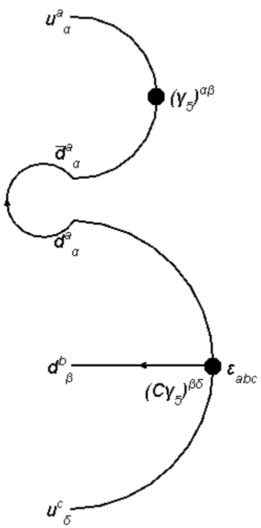
- NPDGamma (LANL & ORNL) want to extract at the 20% level
- Lattice QCD needs to match this precision…

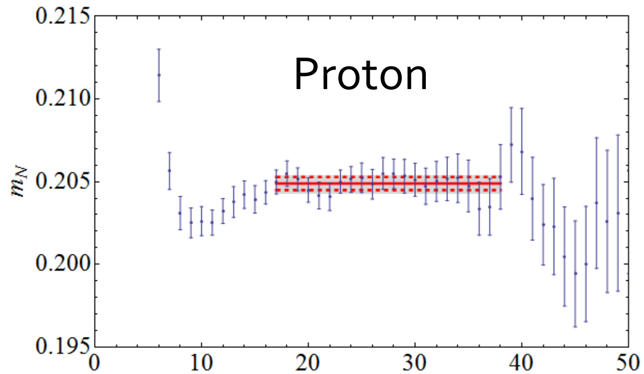


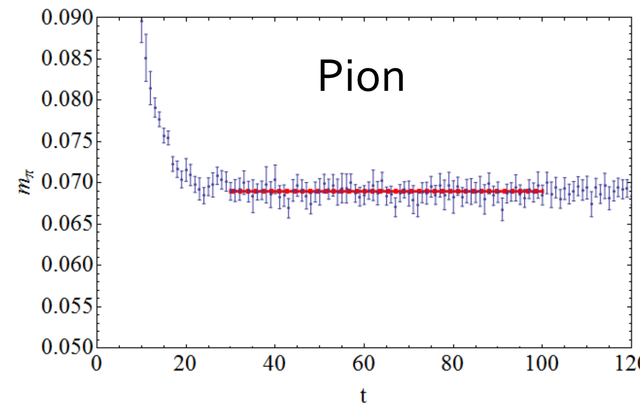
Configurations

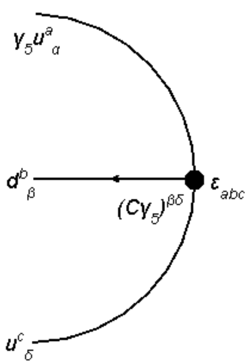
- Anisotropic Clover Lattices
  - Aniso parameters generated by Jlab
  - $20^3 \times 256$ generated at LLNL on BGL
  - $a_x \sim 0.125$ fm, $a_t \sim 0.036$ fm
  - $m_\pi \sim 390$ MeV
  - 1150 thermalized configs.
- Good lattices for 1st attempt

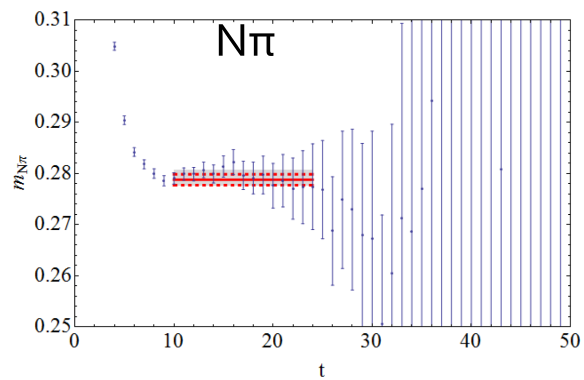
Sources and Sinks











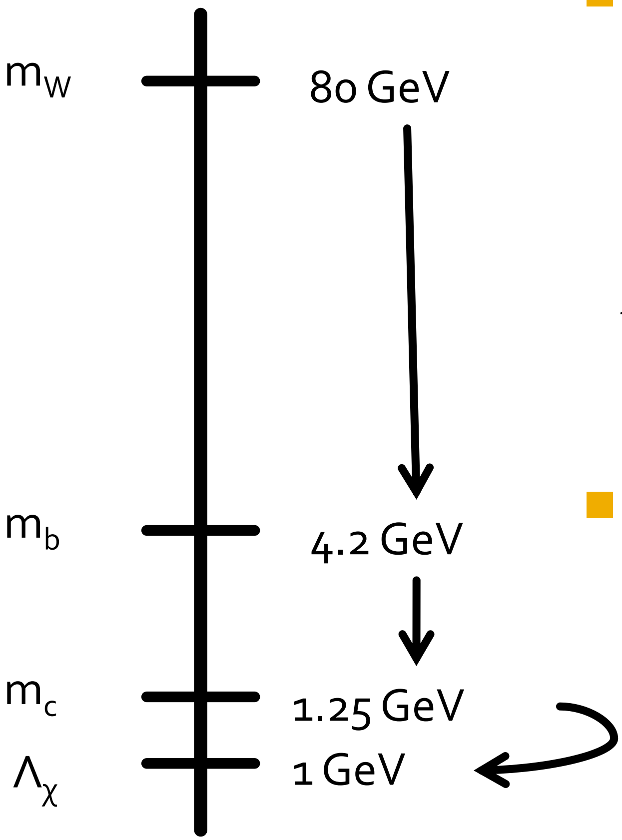
$$m_\pi = 0.06901 \pm 0.00004^{+0.00016}_{-0.00019}$$

$$m_p = 0.20489 \pm 0.00040^{+0.00049}_{-0.00064}$$

$$m_{N\pi} = 0.27882 \pm 0.00107^{+0.00203}_{-0.00114}$$

- Avoid quark loop contributions, use N* interpolator

Quark & Hadron Level PV Operators

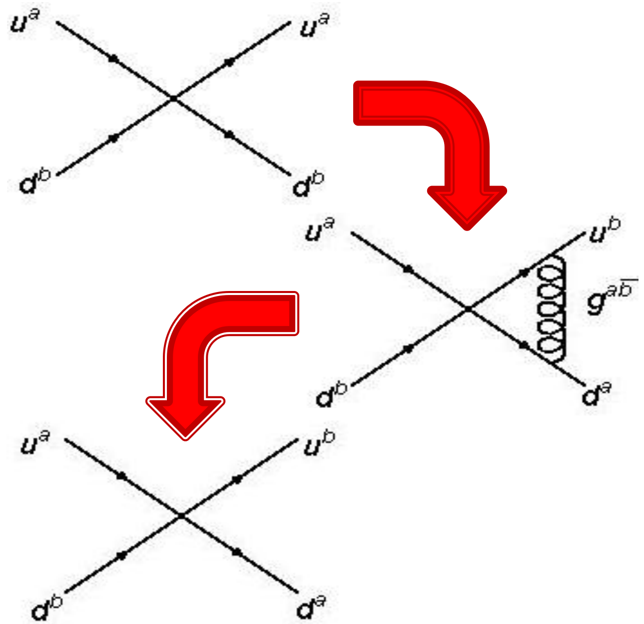


- Quark operators known at W, Z scale

$$L_{PV} = -\frac{G_F \sin^2(\theta_w)}{3\sqrt{2}} \sum_i C_i(\lambda, m_c, m_b)\theta_i$$

- Operator coefficients are scale-dependent

Quark & Hadron Level PV Operators



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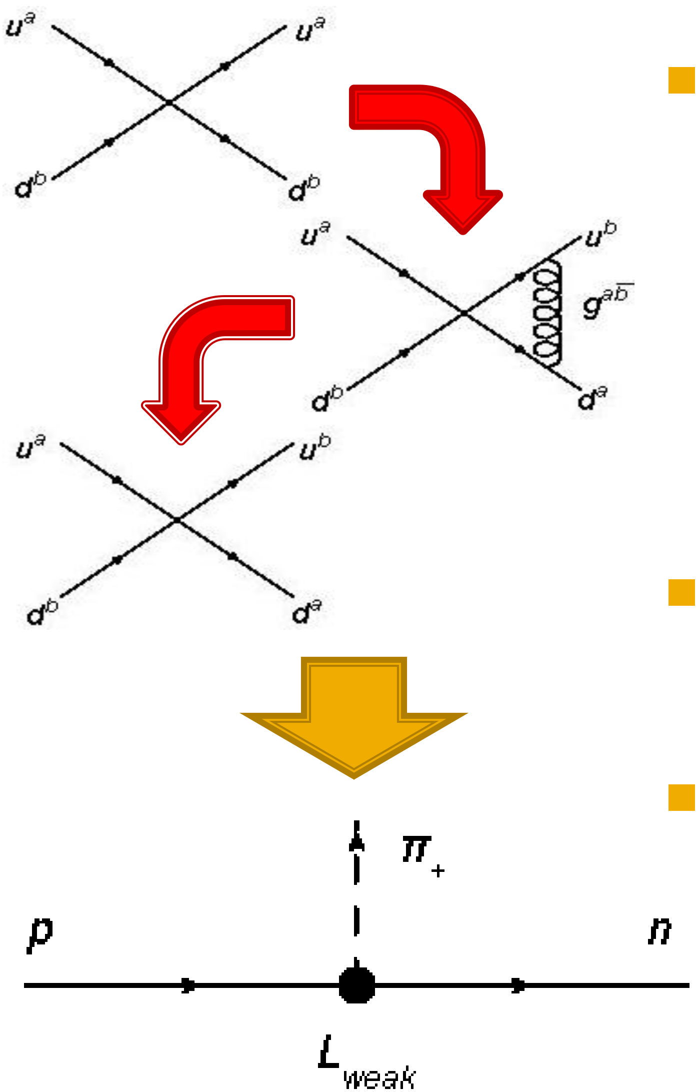


- Quark operators known at W, Z scale

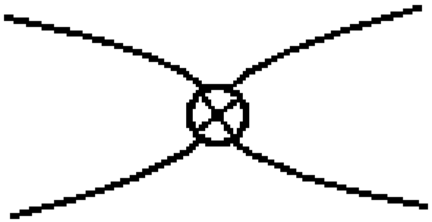
$$L_{PV} = -\frac{G_F \sin^2(\theta_w)}{3\sqrt{2}} \sum_i C_i(\lambda, m_c, m_b)\theta_i$$

- Operator coefficients are scale-dependent
- Match to dominant LO hadron interaction: $h_{\pi NN}$

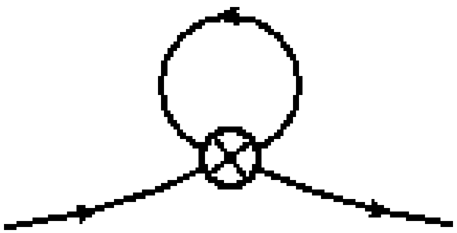
$$L_{weak}^{\Delta I=1} \sim h_{\pi NN}\left(\bar{p} n \pi^+ - \bar{n} p \pi^-\right)$$

The Weak Operator

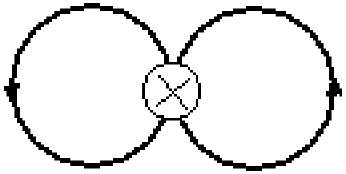
- 8 operators, Fierz transformation eliminates 1
- Three ways to put together:
  - Connected:



  - Quark Loop:

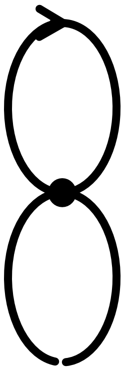


  - Disconnected:



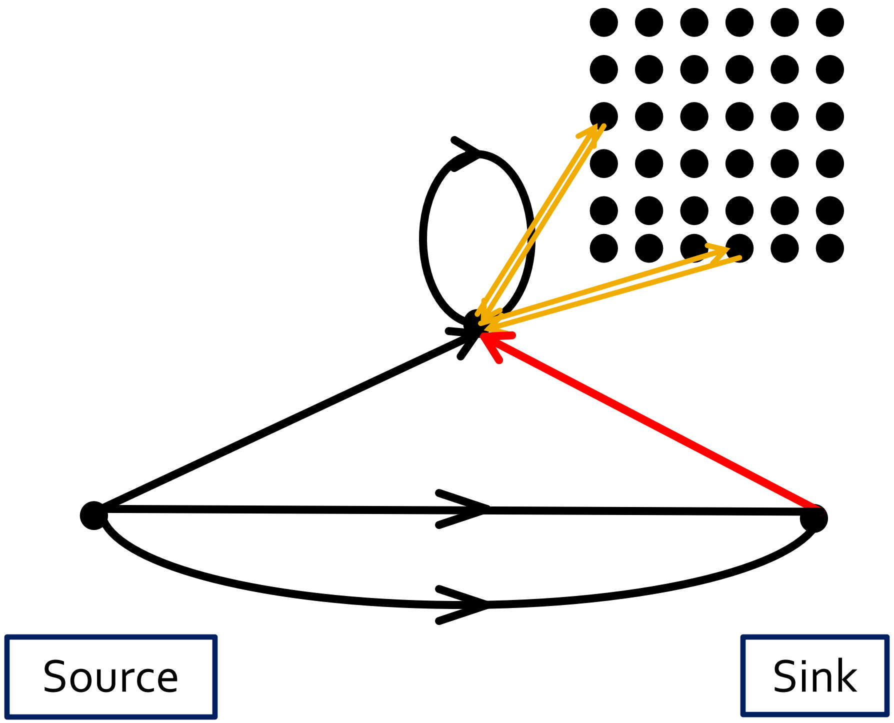
The Weak Operator

- Disconnected diagrams are zero in isospin limit.



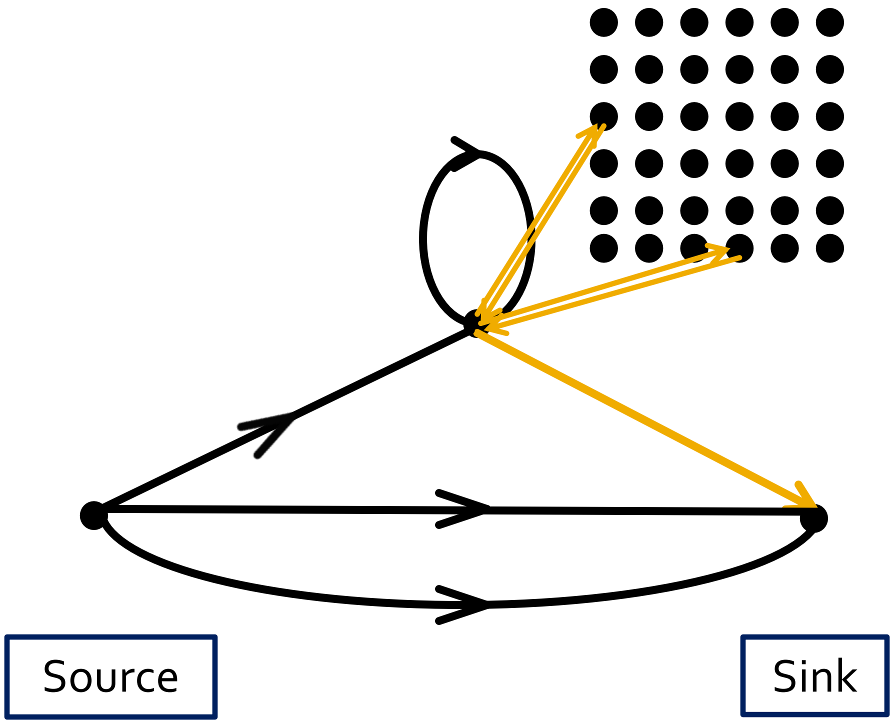
$$\left[\bar{q}\Gamma_{A,V}q\right]\left[\bar{u}\Gamma_{A,V}u-\bar{d}\Gamma_{A,V}d\right]$$

The Weak Operator



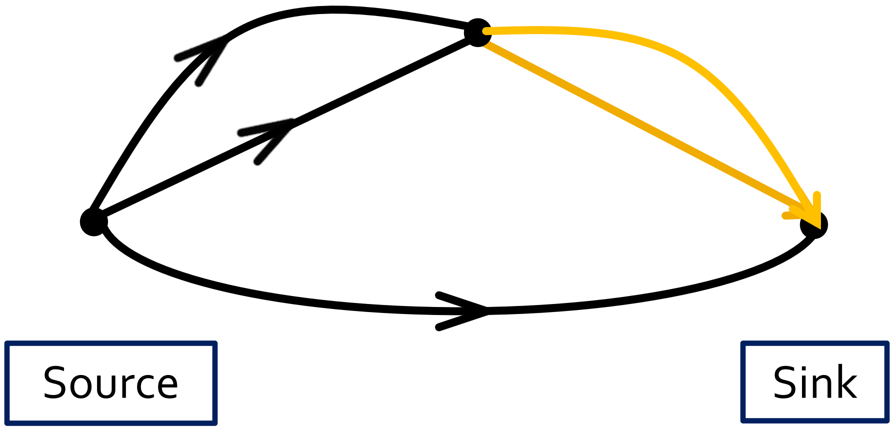
- Quark loop diagrams require point-to-all propagator on operator timeslice
  - Different from normal 3 point calcs.

The Weak Operator



- Quark loop diagrams require point-to-all propagator on operator timeslice
  - Different from normal 3 point calcs.
  - Restricted to single point on ops timeslice.
  - Sample all spatial points over full calc.

The Weak Operator



- Connected diagrams cannot use sequential props
- Can use previous propagators
- 3 propagators/meas:
  - Light quark from srce
  - Light/strange quark for quark loop and to sink

Calculation Requirements

- $\mathcal{O}$(100k) measurements for anisotropic clover
  - $\mathcal{O}$(700k) 3 pt. contractions, one set for each operator
  - ~10 CPU-minutes per contraction
- $\mathcal{O}$(300k) propagators
  - $\mathcal{O}$(10M) CPU-hours with normal inverters
  - Use of GPUs needed to make significant progress

The Edge Cluster

- 200 nodes
  - 12 CPUs/node (Intel Westmere)
  - 2 GPUs/node (NVIDIA Tesla M2050)
  - 96 GB/node
  - 3 GB/GPU
- Turns 10M CPU-hours into 100k GPU-hours
- Running only standby, still able to achieve 100k measurements in ~4 months.
- Thanks to BU and Balint Joo for GPU code help…

Matrix Element Extraction

- Standard 3 pt ratio function (source at t=0):

$$R_{A\to B} = \frac{C_3(t_{snk},t_{ops})}{C_B(t_{ops})}\left[\frac{C_A(t_{snk}-t_{ops})C_B(t_{snk})C_B(t_{ops})}{C_B(t_{snk}-t_{ops})C_A(t_{snk})C_A(t_{ops})}\right]^{1/2}$$

  - C_A the 2 pt. function for state A
  - C_B the 2 pt. function for state B
- t_{ops}=24
  - Chosen to be well into the proton/n-π plateau

Matrix Element Extraction

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

$$= \left(h_{\pi NN} + \Delta E \cdot h_a\right) + Z\left(h'_{\pi NN} + \Delta E' \cdot h'_a\right)e^{-\delta(t_{snk}-t_{ops})}$$

- Remove inserted energy contribution.

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

$$\Rightarrow M = \tfrac{1}{2}\left(R_{p\to n\pi} - R_{n\pi\to p}\right) = h_{\pi NN} + Zh'_{\pi NN}\, e^{-\delta(t_{snk}-t_{ops})}$$

Matrix Element Extraction

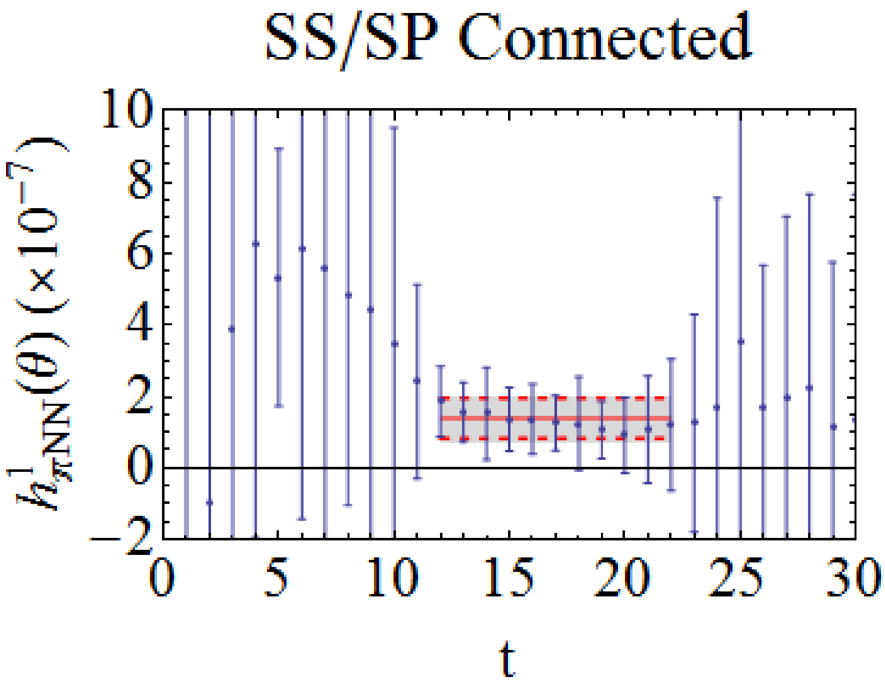
$$M_i = \tfrac{1}{2}\left(R_{p\to n\pi} - R_{n\pi\to p}\right) = h_{\pi NN} + Z_i h'_{\pi NN}\, e^{-\delta(t_{snk}-t_{ops})}$$

- Use matrix-prony methods with SS & SP meas. to remove (or lessen) excited states

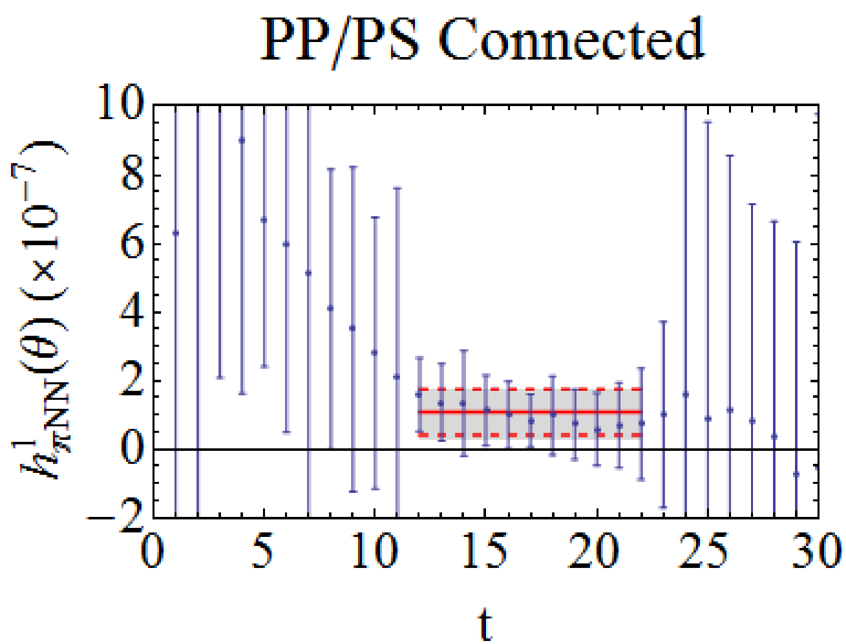
$$\frac{aM_{SS} + bM_{SP}}{a+b} = h_{\pi NN}$$

- Can do same thing for PP & PS
- Must rotate on sink, as source is “frozen”

Results



$h^1_{\pi NN}(\theta_{con}) = (1.394 \pm 0.563^{+0.138}_{-0.017}) \times 10^{-7}$

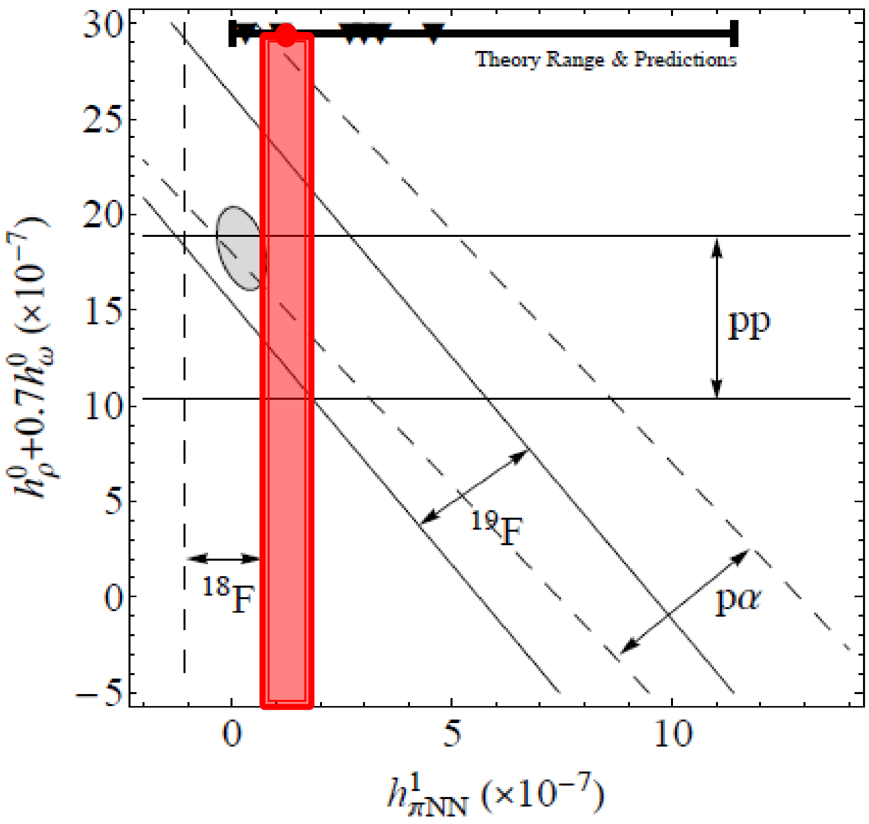


$h^1_{\pi NN}(\theta_{con}) = (1.069 \pm 0.669^{+0.153}_{-0.014}) \times 10^{-7}$

Results

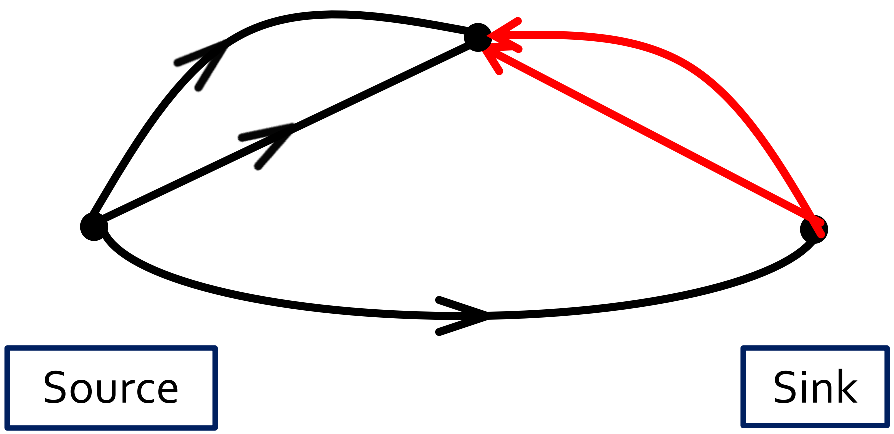
- Connected diagrams only!

$h^1_{\pi NN}(\theta_{con})=(1.232\pm0.437^{+0.146}_{-0.016})\times10^{-7}$



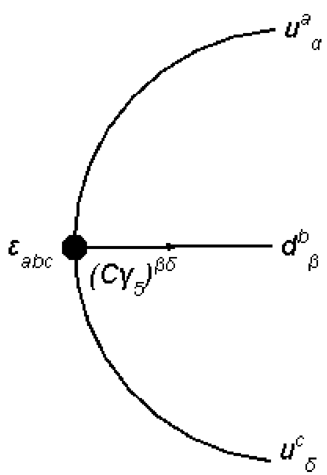
Contraction Improvments

- Need better way to do contractions for quark loop contributions
  - Similar to disconnected diagrams in scope
- Can we emulate sequential propagator method to get full spatial data?



Operator Improvements

- Use set of interpolating operators
  - Analytically does spin components (i.e. faster contractions)
  - Increased statistics (more operator combos)
  - 6 operators, 2×3×3=18 combinations



$$O_{p,\alpha} = \left(C\gamma_5\right)_{\beta\gamma} \varepsilon^{abc} u_a^\alpha u_b^\beta d_c^\gamma$$

$$\rightarrow \frac{1}{\sqrt{2}} \varepsilon^{abc} \left(u_1^a d_2^b - d_1^a u_2^b\right) u_1^c$$

Conclusions

- First calculation
  - Obtains non-zero answer consistent with experiment
  - Missing several important contributions…
- Need to Extract More
  - Longer run time
  - ORNL GPU Machine?
- Need to Extract More with Less
  - Better contractions