Nucleon-Pion Spectroscopy from Sparsened Correlators

Fermilab

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Motivation

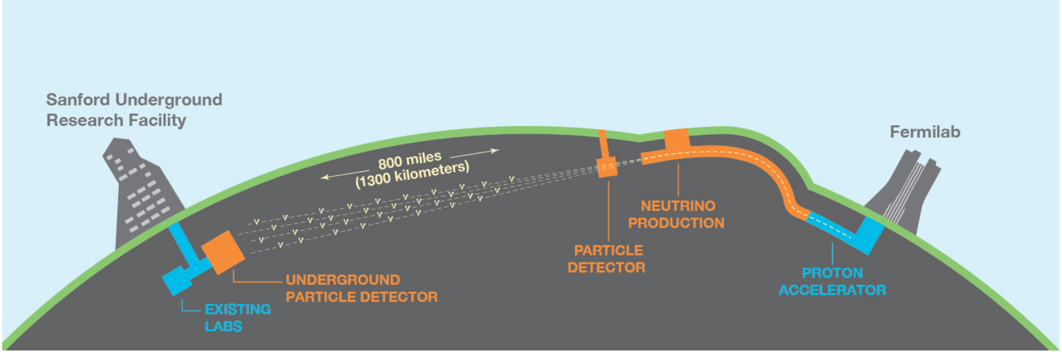


Image credit: Fermilab

Deep Underground Neutrino Experiment

- Beam from Fermilab to South Dakota to study ν oscillations
- Oscillation parameters depend on $P(\nu_\mu \rightarrow \nu_e)$ as function of L/E
- Experimental ν beams inherently broadband
- Will require reconstruction of E_ν
- Need energy-dependent cross-sections for ν-nucleus interactions

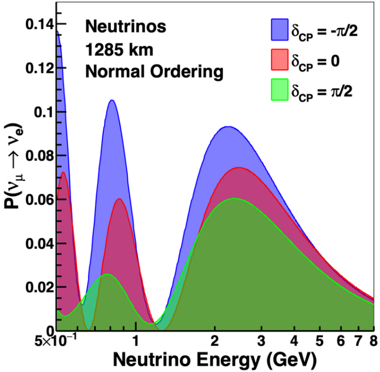


Image credit: B. Abi et al. (DUNE Collaboration), 2006.16043

ν-N Cross-Sections

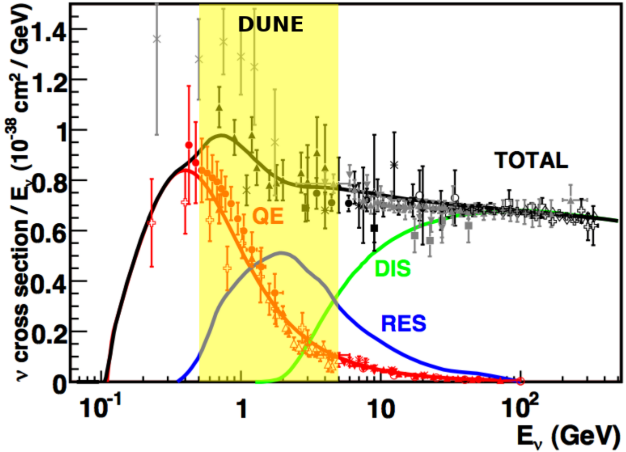


Image credit: Adapted from J. A. Formaggio, G. P. Zeller (1305.7513)

- DUNE beam peaked at a couple GeV – in resonant region

ν-Ar Cross Sections

- Nuclear many body methods relate neutrino-nucleus cross-sections to nucleon form factors (N. Rocco, 11:00; R. Gupta, 11:30)
- Quasi-elastic regime – based on nucleon elastic form factor
  - Great work in previous talks toward estimating this precisely
- DIS regime – perturbative
  - Factorization theorems write this in terms of nucleon PDFs
- Resonant regime – largest uncertainty is $N \to \Delta$ transition
  - Current estimates from electroproduction have $> 10\%$ uncertainties (E. Hernández et al., 1001.4416)
  - Need 3% uncertainty for DUNE target precision (D. Simons et al., 2210.02455)

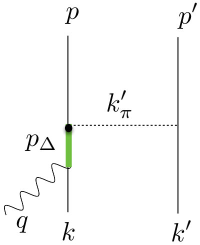
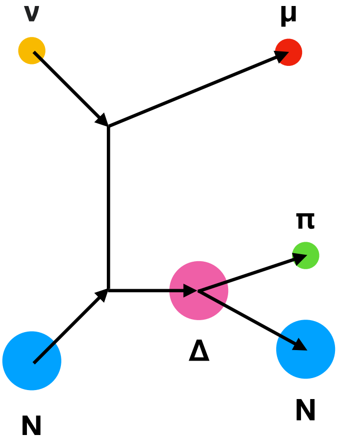


Figure credit: 2210.02455

Δ Neutrinoproduction

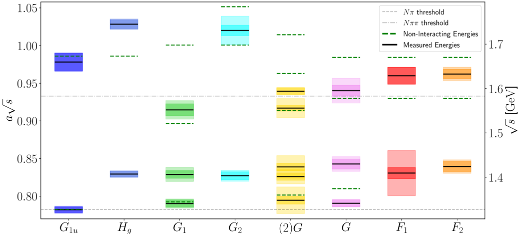
$$\nu_\mu N \to \mu\Delta$$

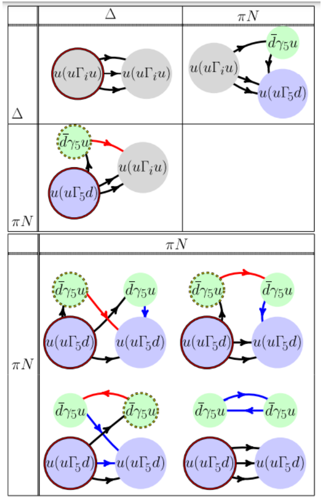
- Mediated through electroweak current
$$\bar{N}(\gamma_\mu - \gamma_\mu\gamma_5)\Delta$$
- Vector component known from $eN \to e\Delta$
- Axial component difficult to measure experimentally
- Δ resonance above $N\pi\pi$ threshold
$$\Delta \to N\pi, N\pi\pi$$
- Goal: Understand $N\pi$, $N\pi\pi$ spectrum up to m_Δ



Related Work

- Long history of studying $N \to \Delta$ on lattice (C. Alexandrou et al., hep-lat/0607030)
- Much exciting recent work in $N\pi$ spectroscopy and scattering
    - L. Barca et al. (2211.12278), Bulava et al. (2208.03867), Silvi et al. (2101.00689, source of figures), Andersen et al. (1710.01557)
- Physical point calculations now possible (Alexandrou et al., 2307.12846)
- Can probe Δ resonance via $N\pi$ phase shifts
- $N\pi\pi$ systems still unexplored



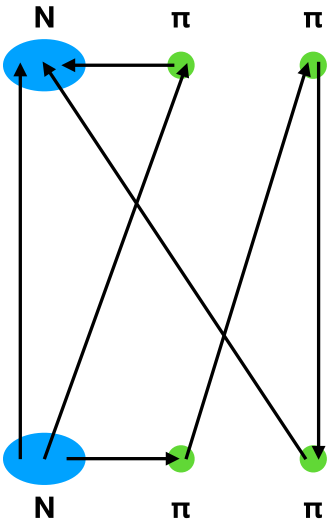


Methodology

- Want to compute

$$\langle N(\tau)\pi(\tau)\pi(\tau)\bar{N}(0)\bar{\pi}(0)\bar{\pi}(0)\rangle$$

- Naïvely requires all-to-all propagators (timeslice-to-self π loops)
- Cost: $O(V^2)$ for inversions, $O(V^6)$ for contractions
- Contraction cost reduced to $O(V^3)$ by computing sequential propagators through π
- Contraction cost further reduced by eightfold by parity projecting all quarks



Propagator Sparsening

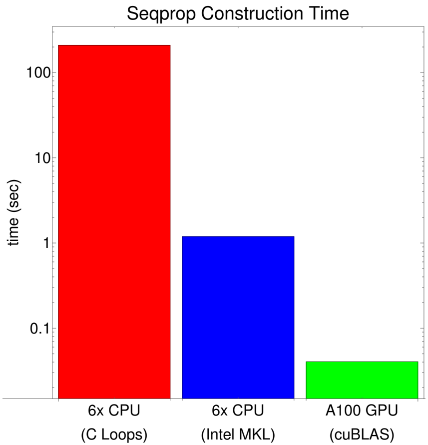
- Nearby sites on lattices highly correlated
- Can compute propagators on coarse grid without much loss of information (Detmold et al., 1908.07050; Yuan Li, 2009.01029; Amarasinghe et al., 2108.10835)
    - In momentum space, corresponds to incomplete Fourier projection
- Loss of information further reduced by Gaussian smearing
- Sparsening by factor of f in each direction reduces inversion costs by f^3 and seqprop construction cost in contractions by f^9

Ensemble Details

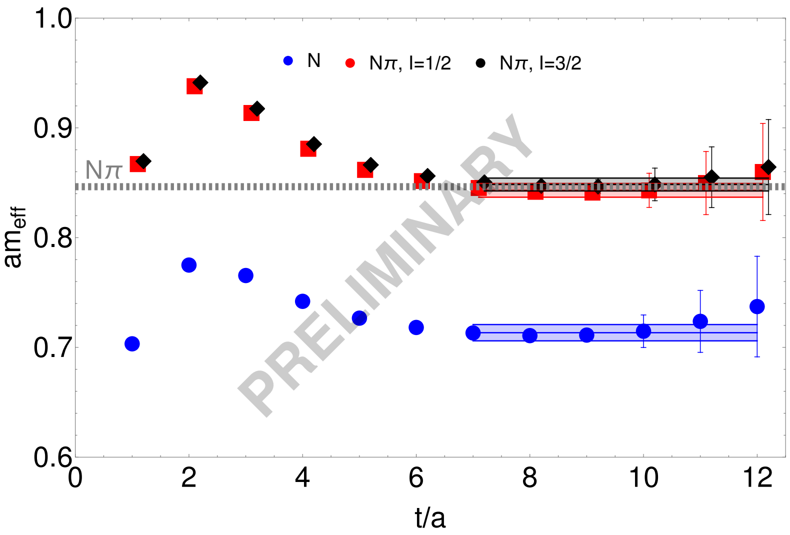
- $a = 0.15$ fm, $L = 4.8$ fm, $m_{\pi,P} = 135$ MeV HISQ ensemble from FNAL/MILC
- Clover fermions used for valence quarks ($m_{\pi,\text{val}} \approx 170$ MeV)
- Gradient flow smearing used to reduce mixed-action artifacts
- Propagators computed using QUDA multigrid inverter (M. Clark et al., 0911.3191, 1612.07873) on 8^3 grid on each timeslice
- Gaussian smearing applied at source and sink

Contraction Code

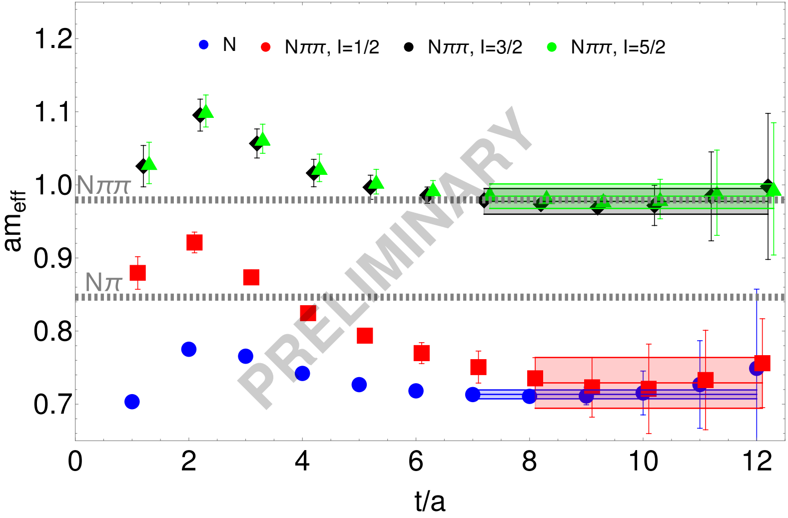
- Standalone code to read in propagators from QUDA and compute $N\pi$, $N\pi\pi$ contractions
- Designed to support CPU and GPU targets
- Leverages MKL BLAS or cuBLAS for sequential propagator construction
- Performs all Wick contractions from these sequential propagators



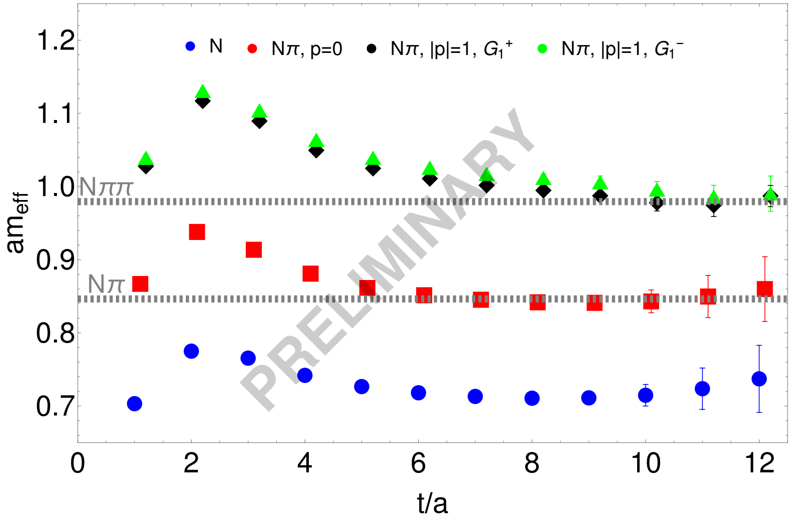
$N\pi$, $\mathbf{p} = 0$



$N\pi\pi$, $\mathbf{p} = 0$



$N\pi$, $I = 1/2$, $|\mathbf{p}| = 1$



Conclusions

- $N \to \Delta$ and therefore $N \to N\pi, N\pi\pi$ axial transitions needed for DUNE
- Spectroscopy calculations – first step in producing good $N\pi(\pi)$ interpolators
- Future plans:
  - Increased statistics
  - GEVP to study states in same parity/isospin sectors
  - Finite-volume phase shifts to study Δ resonance
  - 3-point functions for axial/vector form factors

Isospin Splitting in $N\pi$