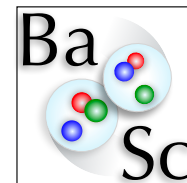


Coupled-channel dynamics in meson-baryon scattering from lattice QCD

John Bulava, for the Baryon Scattering Collaboration (BaSc)

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RUB



NSTAR 2026, Sevilla (ES), Sep. 10, 2026

Motivation:

- Many near-threshold (exotic?) excitations
- Coupled-channel dynamics
- Role of $SU(3)$ flavor and chiral symmetry
- Tools: Lattice QCD, experiment, chiral EFT
- Advantages of Lattice QCD:
 - First-principles solution to QCD
 - Finite-volume $\rightarrow$ discrete spectrum
 - Isospin + $SU(3)$ flavor symmetry
 - Varying quark masses $\rightarrow$ study threshold effects

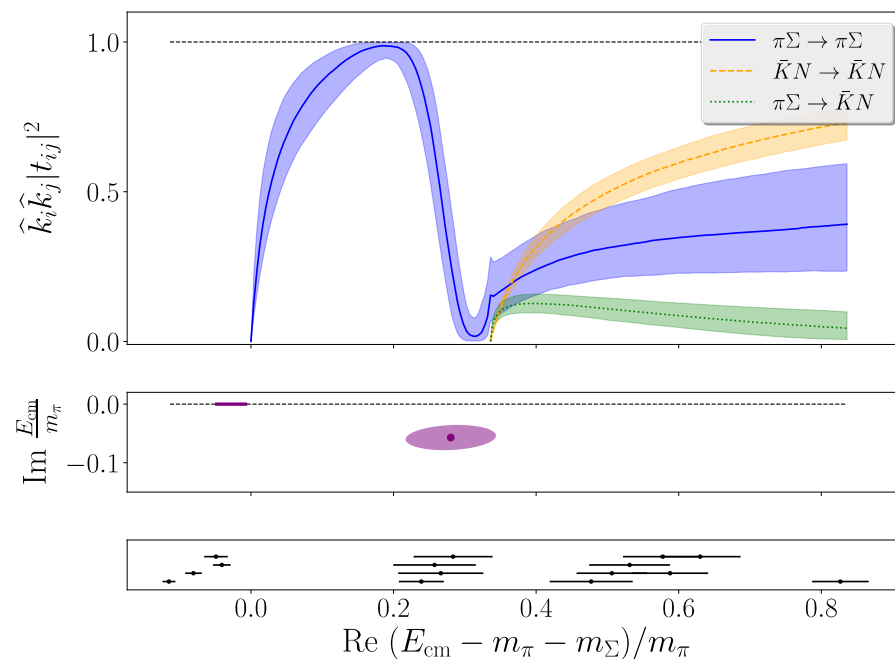
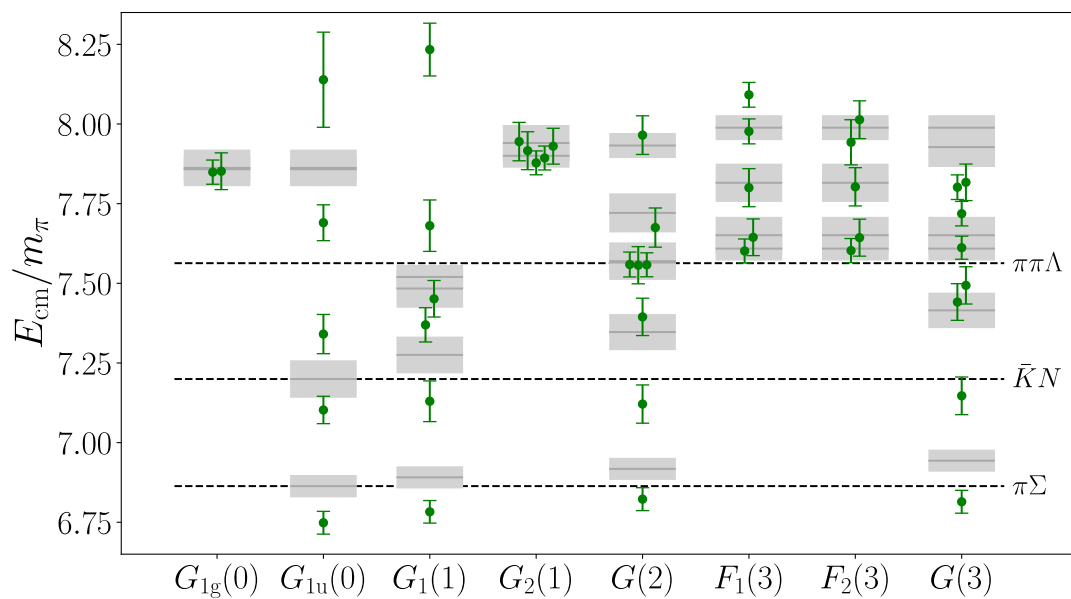
Finite-volume spectrum



Scattering amplitudes

$$\det[K^{-1}(E_{\text{cm}}^{\text{FV}}) - B(\mathbf{p}_{\text{cm}}^{\text{FV}})] = 0$$

M. Lüscher, Nucl. Phys. B 354, 531–578 (1991)



from Baryon Scattering Collaboration (BaSc), Phys.Rev.Lett. 132 (2024) 5, 051901
(See talks by C. Morningstar, B. Cid-Mora)

Spectrum from Euclidean Correlators:

- Operators control which states appear, are irreducible under symmetries of Hamiltonian.

$$E_{\text{eff}}(\mathbf{p}, \tau) = -\partial_{\tau} \ln C_{ij}(\mathbf{p}, \tau)$$

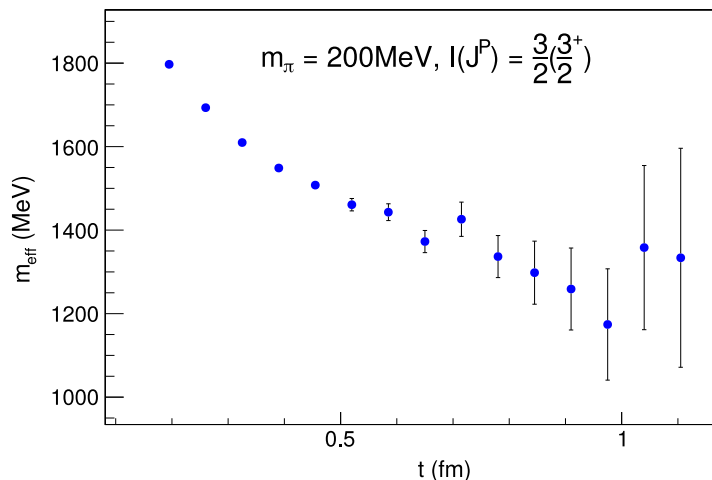
- Ground state dominance at large time:

$$= E_0 \times \left\{ 1 + O(e^{-(E_1 - E_0)\tau}) \right\}$$

- Fit to few-state ansatz:

$$C_{ij}[A, E](\tau) = \sum_{n=1}^{N_{\text{state}}} A_{in} A_{jn}^* e^{-E_n \tau}$$

- Signal-to-noise problem => 'Teufelspakt'



=>



Excited states:

M. Luescher, U. Wolff, Nucl.Phys.B 339 (1990) 222-252

- (convergent) perturbation theory at LO:

$$C_{ij}^{(0)}(\tau) = \sum_{n=1}^N e^{-E_n \tau} A_{ni} A_{nj}^* \quad (u_n, A_m) = \delta_{mn}$$

$$\begin{aligned} C^{(0)}(\tau) u_n &= e^{-E_n \tau} A_n = \lambda_n^{(0)}(\tau, \tau_0) C^{(0)}(\tau_0) u_n \\ \Rightarrow \lambda_n^{(0)}(\tau, \tau_0) &= e^{-E_n(\tau - \tau_0)} \end{aligned}$$

To all orders: effective energies approach excited states!

$$E_n^{\text{eff}}(\tau, \tau_0) = -\partial_\tau \ln \lambda_n(\tau, \tau_0) = E_n + \varepsilon_n(\tau, \tau_0)$$

Operator Wishlist: single-hadron operators

S. Basak, et al., Phys.Rev.D 72 (2005) 094506

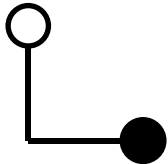
Meson configurations



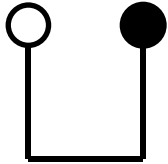
single-site



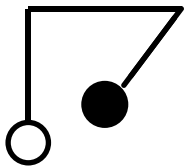
singly-displaced



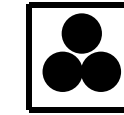
doubly-displaced-L



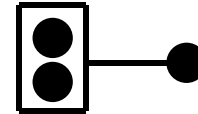
triply-displaced-U



triply-displaced-O



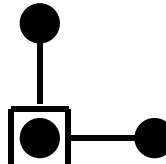
single-site



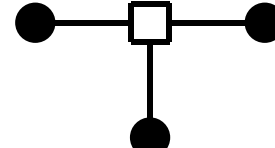
singly-displaced



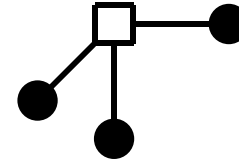
doubly-displaced-I



doubly-displaced-L



triply-displaced-T



triply-displaced-O

Operator Wishlist: multi-hadron operators

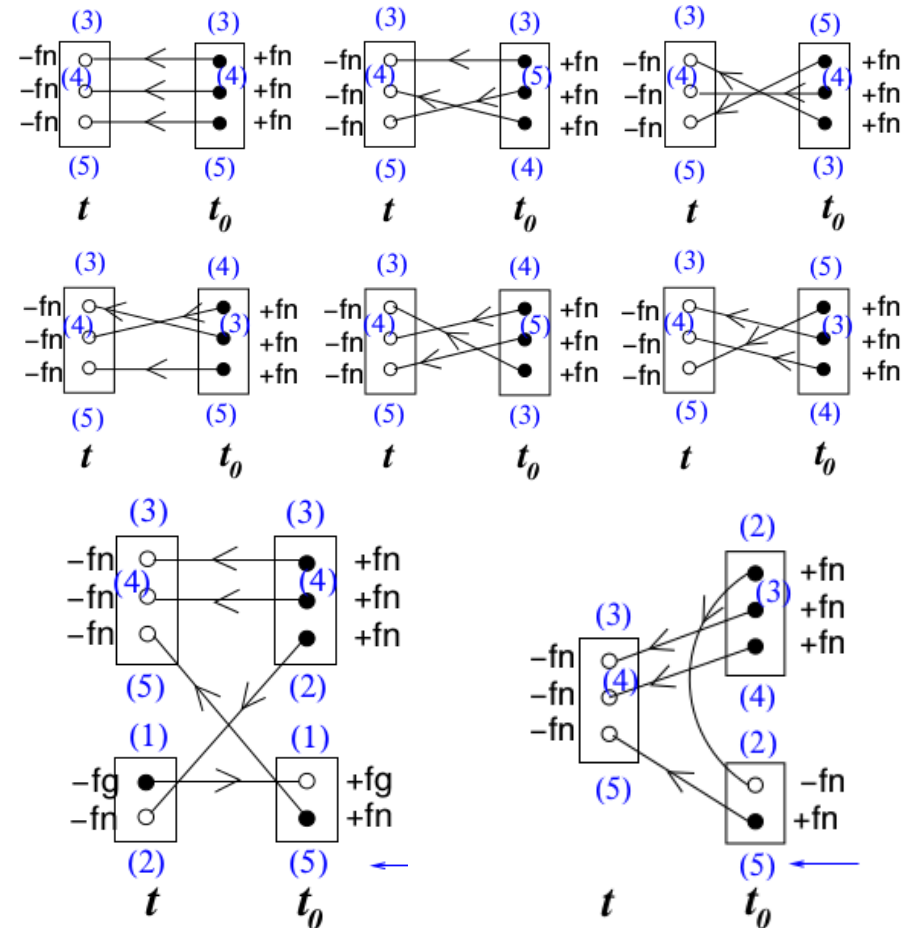
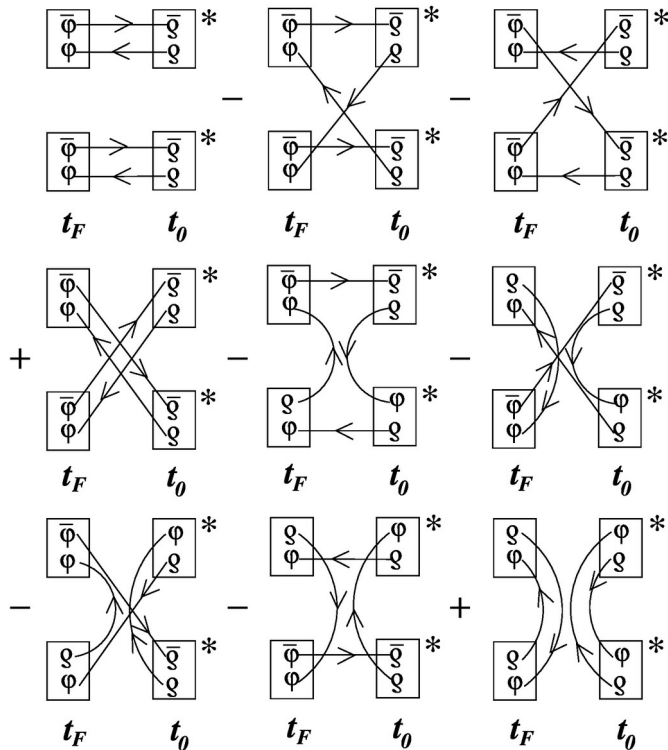
C. Morningstar, JB, B. Fahy, J. Foley, Y.-C. Jhang, K. J. Juge, D. Lenkner, C. H. Wong PRD 88 (2013);

C. Thomas, R. Edwards, J. Dudek PRD 85 (2012)

- Problem 1: momentum projection => 'all-to-all' quark props.

M. Peardon, JB, J. Foley, C. Morningstar, J. Dudek, R. Edwards, B. Joo, H.-W. Lin, D. Richards, K. J Juge PRD 80 (2009); C. Morningstar, JB, J. Foley, K. J. Juge, D. Lenkner, M. Peardon, C. H. Wong PRD 83 (2011)

- Problem 2: proliferation of Wick Contractions



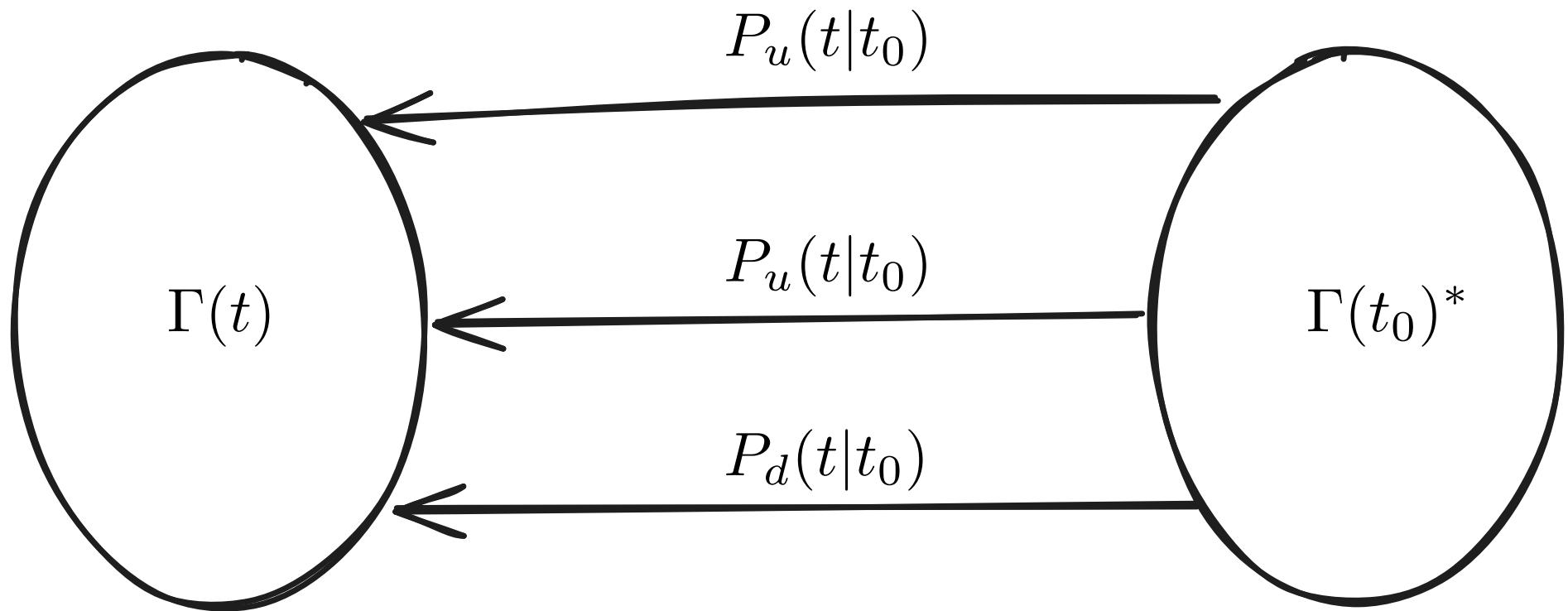
- Laplacian-Heaviside (LapH) quark smearing:

$$S_{ab}(\boldsymbol{x}, \boldsymbol{x}') = \Theta(\sigma_s^2 + \Delta) \approx \sum_{k=1}^{N_{\text{ev}}} v_a^{(k)}(\boldsymbol{x}) v_b^{(k)}(\boldsymbol{x}')^*$$

- Factorization of smeared quark propagator: $Q_f = S D_f^{-1} S$

$$Q_f(a, \alpha, \boldsymbol{y}, t | b, \beta, \boldsymbol{x}, t_0) = \sum_{k, k'=1}^{N_{\text{ev}}} v_a^{(k)}(\boldsymbol{y}, t) \times \\ P_f(k, \alpha, t | k', \beta, t_0) v_b^{(k')}(\boldsymbol{x}, t_0)^*$$

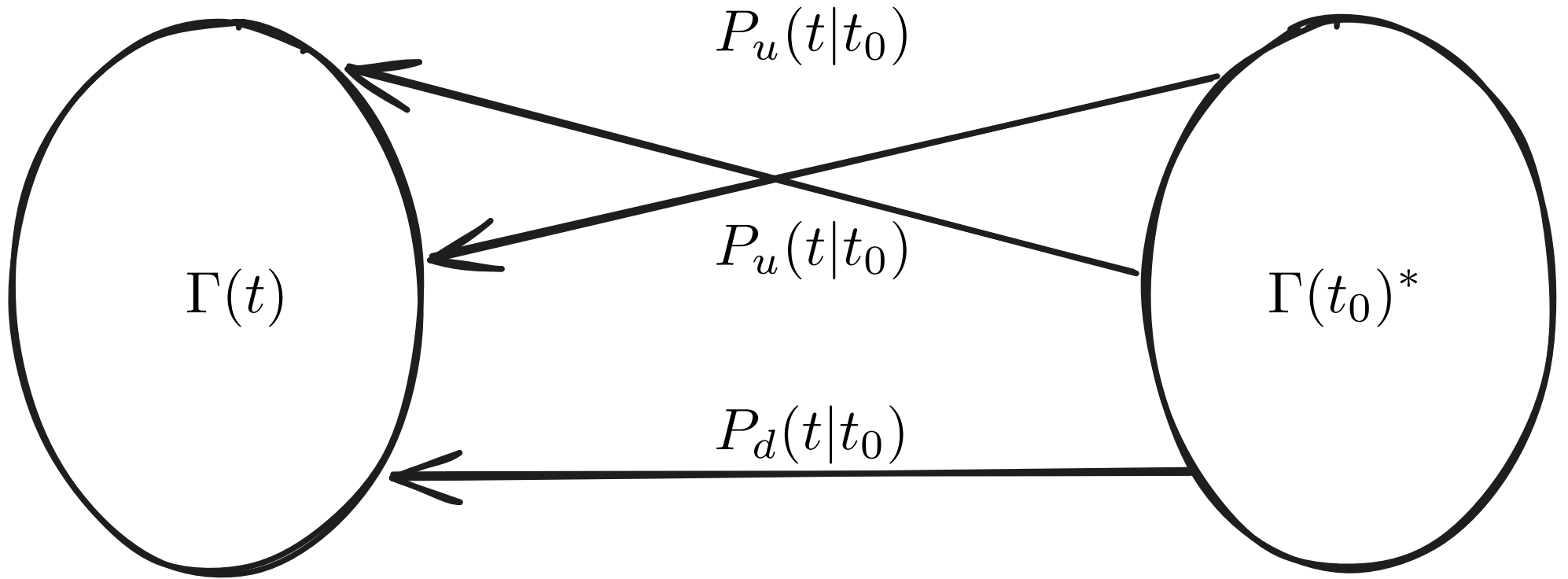
Correlator construction: nucleon



Mode triplet:

$$\Gamma_{ijk}(\mathbf{p}, t) = \sum_{\mathbf{x}} e^{i\mathbf{p} \cdot \mathbf{x}} \epsilon_{abc} v_a^{(i)}(\mathbf{x}, t) v_b^{(j)}(\mathbf{x}, t) v_c^{(k)}(\mathbf{x}, t)$$

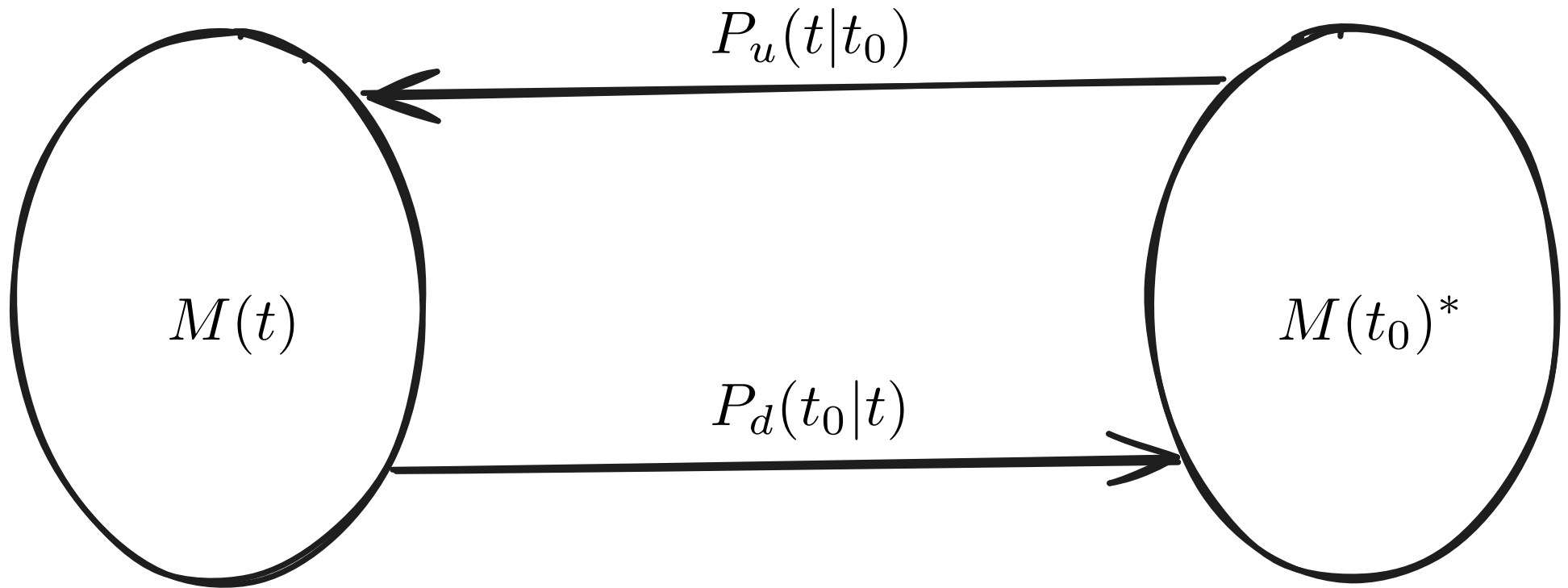
Correlator construction: nucleon



Mode triplet:

$$\Gamma_{ijk}(\mathbf{p}, t) = \sum_{\mathbf{x}} e^{i\mathbf{p} \cdot \mathbf{x}} \epsilon_{abc} v_a^{(i)}(\mathbf{x}, t) v_b^{(j)}(\mathbf{x}, t) v_c^{(k)}(\mathbf{x}, t)$$

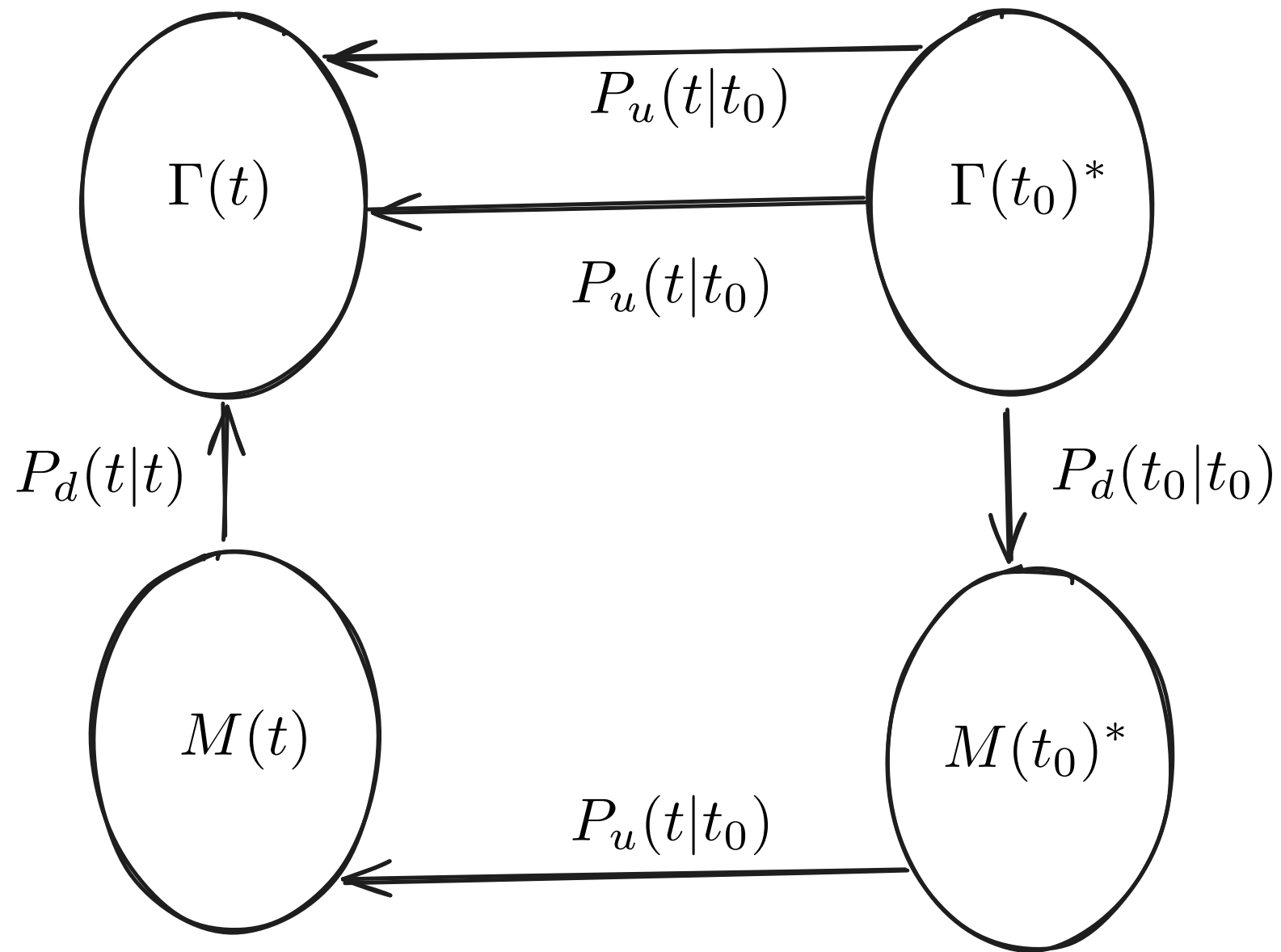
Correlator construction: pion



Mode doublet:

$$M_{ij}(\mathbf{p}, t) = \sum_{\mathbf{x}} e^{i\mathbf{p} \cdot \mathbf{x}} \delta_{ab} v_a^{(i)*}(\mathbf{x}, t) v_b^{(j)}(\mathbf{x}, t)$$

Correlator construction: pion-nucleon



- It's all tensor contraction!

Example spectrum determination (preliminary):

H. Alharazin, F. Alvarado, L. Barca, JB, D. Laudicina, C. Morningstar, F. Romero-Lopez, M. Salg for the BaSc collaboration
See also: A. Hackl, C. Lehner Phys.Rev.D 113 (2026) 11, 114502

- X252 ensemble from Coordinated Lattice Simulations (CLS):
$$N_f = 2 + 1, m_\pi = 280\text{MeV}, 36^3 \times 128, N_{\text{cfg}} = 26, N_{t_0} = 16$$
- Nucleon (Roper) channel at rest: $I=1/2$, $B=1$, $G1g$ irrep
- Operator list:
 - 3 Single-site nucleon (qqq)
 - $\pi(0)\pi(0)N(0)$
 - $\sigma(0)N(0)$
 - $\pi(1)N(1)$
 - $\pi(1)\Delta(1)$
 - $\eta(1)N(1)$

PyWick: automated enumeration of Wick contractions

H. Alharazin, F. Alvarado, JB, D. Laudicina, F. Romero-Lopez, M. Salg in prep.
see also: D. Djukanovic, Comput.Phys.Commun. 247 (2020) 106950
A. Hackl, C. Lehner, Phys.Rev.D 113 (2026) 11, 114502

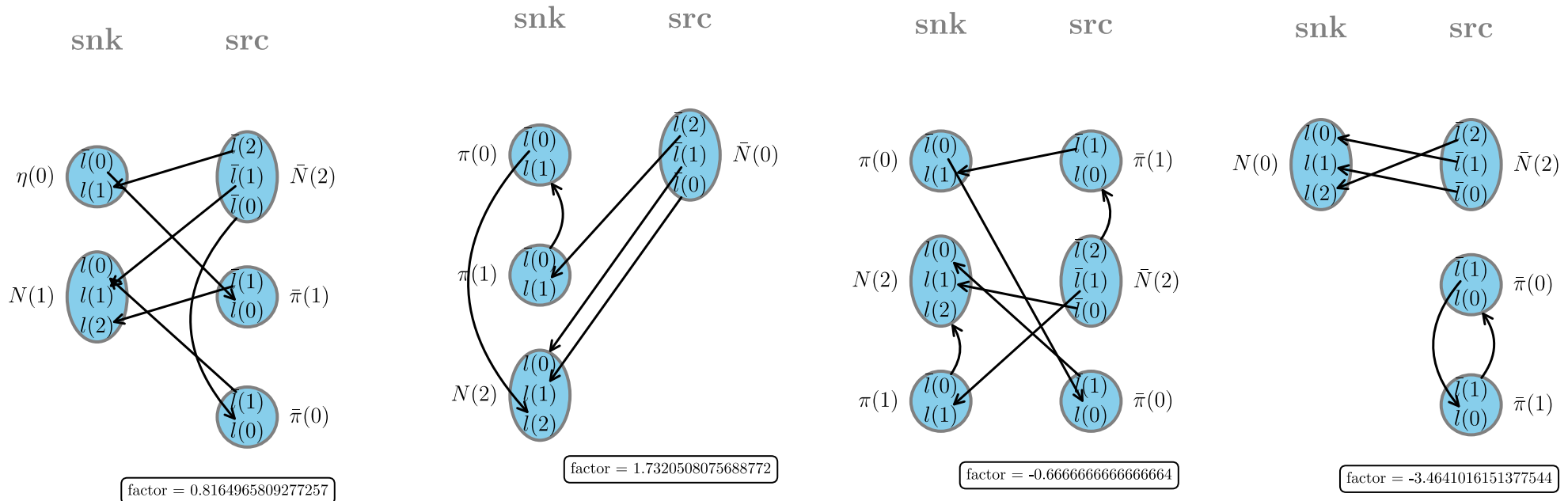
- Wick contraction encoded as integer array of quark lines :

[[[1, 0, 0], [0, 0, 1]], [[1, 0, 1], [0, 0, 0]], [[1, 0, 2], [0, 0, 2]]]

- Each quark line has format

[[tf, hadron_f, quark_f], [tO, hadron_O, quark_O]]

- States included:
 - Single hadrons
 - SU(2) and SU(3) multi-hadron multiplets (up to 3 hadrons)
- 736 (connected) contractions. Examples:

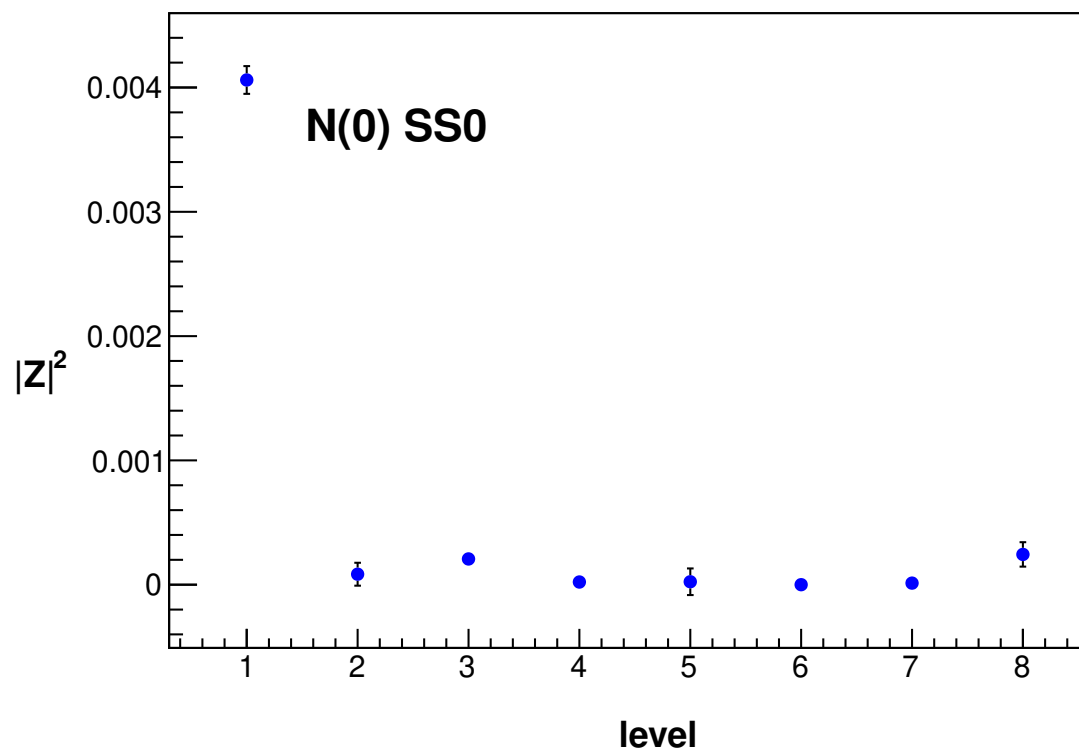
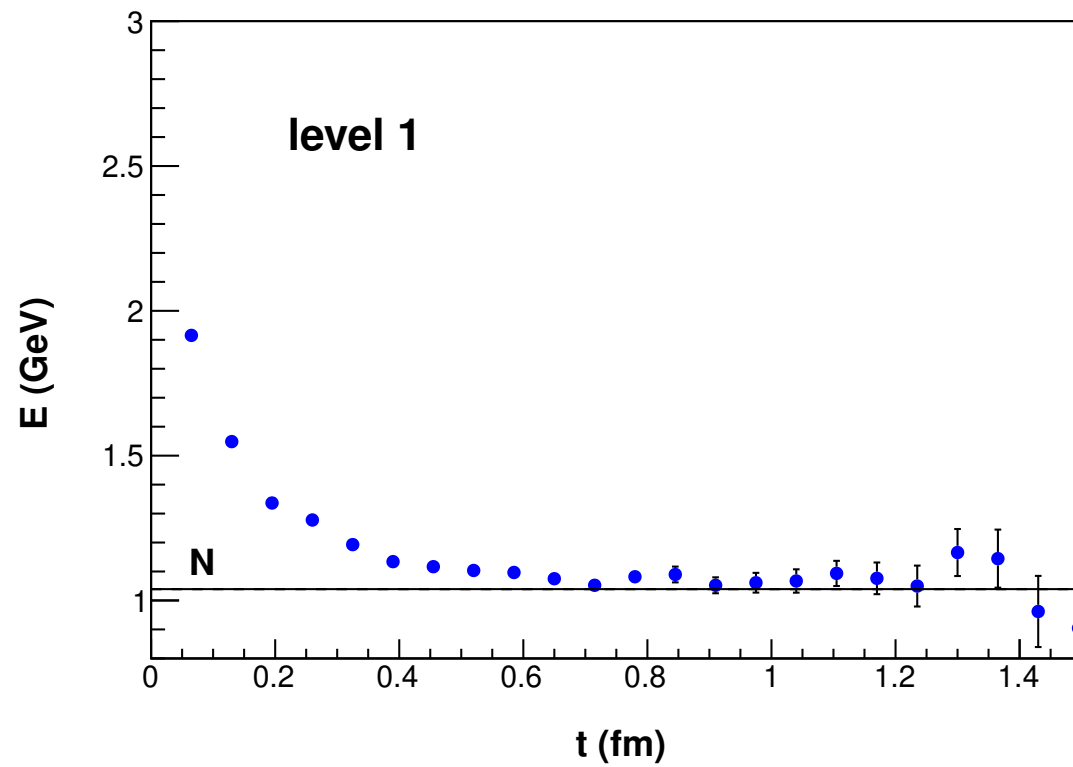


- Main driver with easy user interface:

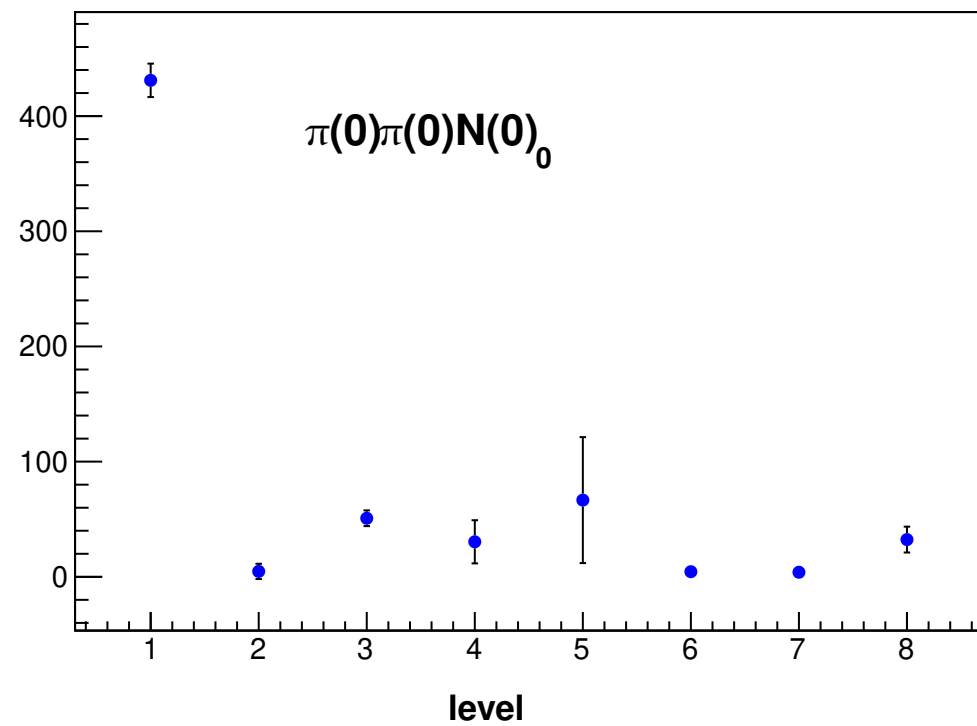
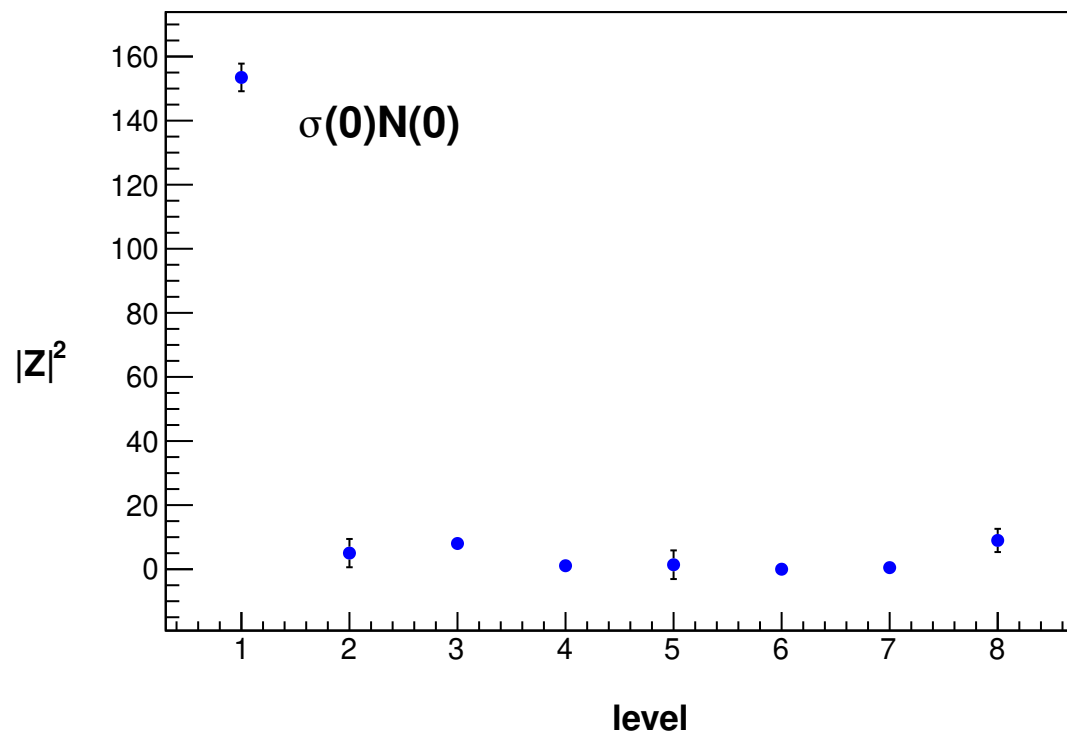
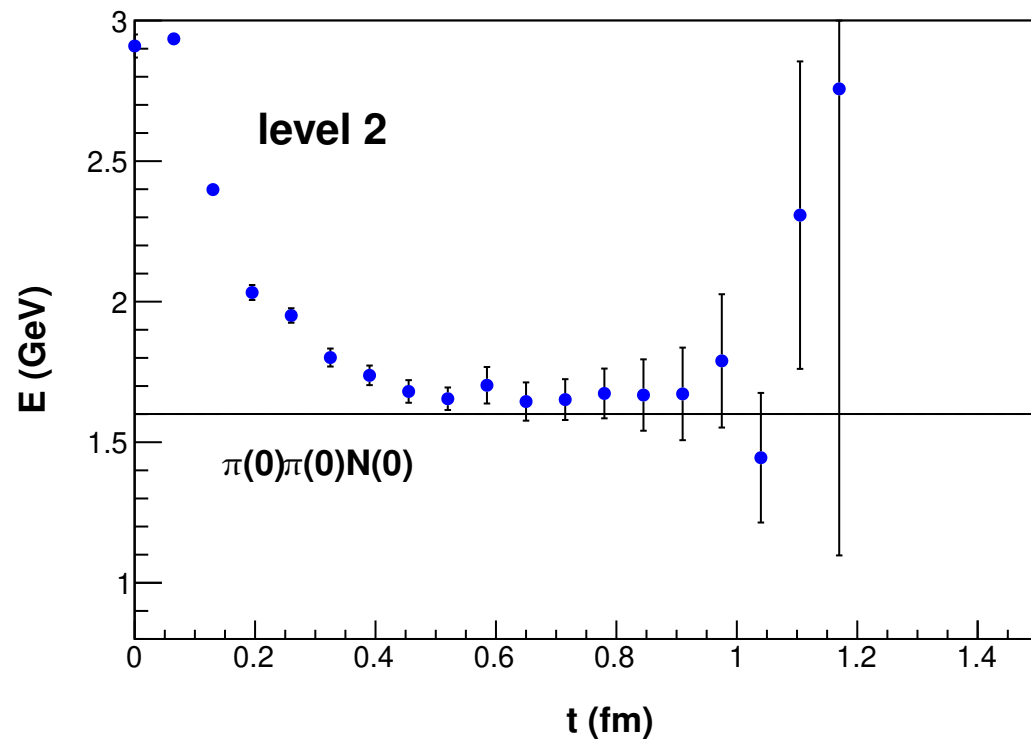
```
nucleon_psq0_g1g = [  
    [['N',0]], ← [hadron_name, psq]  
    [['Nstar',0]],  
    [['f0',0],['N',0]],  
    [['pi',1],['N',1]],  
    [['eta',1],['N',1]],  
    [['pi',1],['D',1]],  
    [['pi',0],['pi',0],['N',0]],  
    ]
```

- Setup: (single CPU) 736 connected graphs, stack sizes ~ 10-10,000
- Compute: ~1hr per source time on single NVIDIA H100
- Combine: (single CPU) combine graphs into correlators

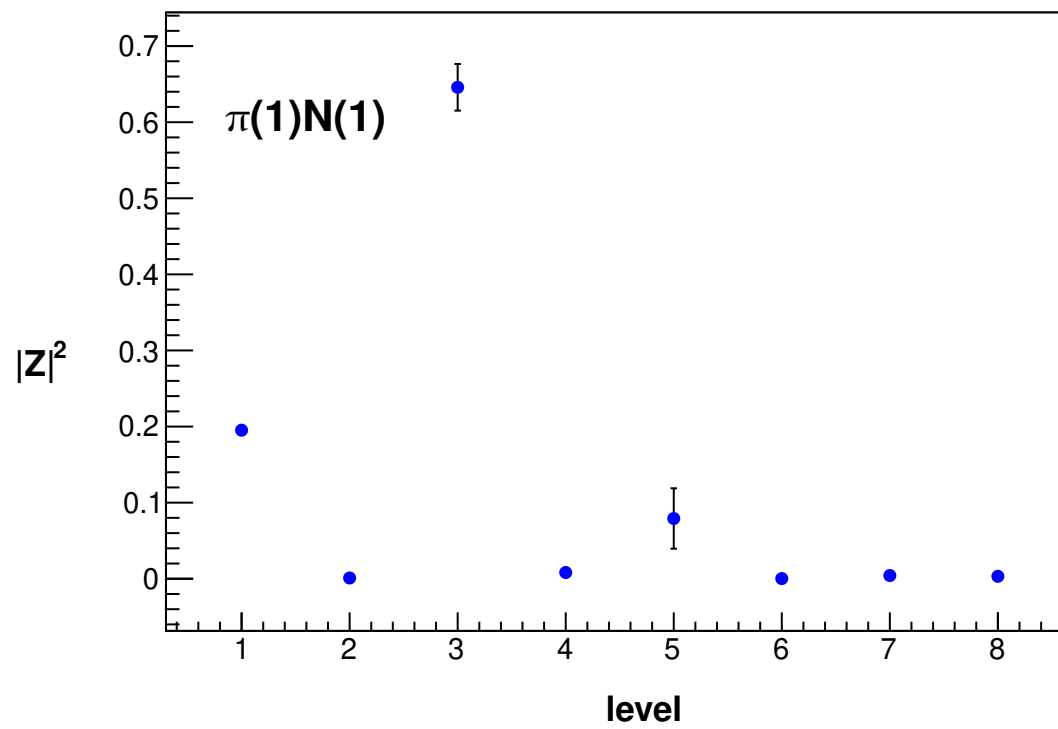
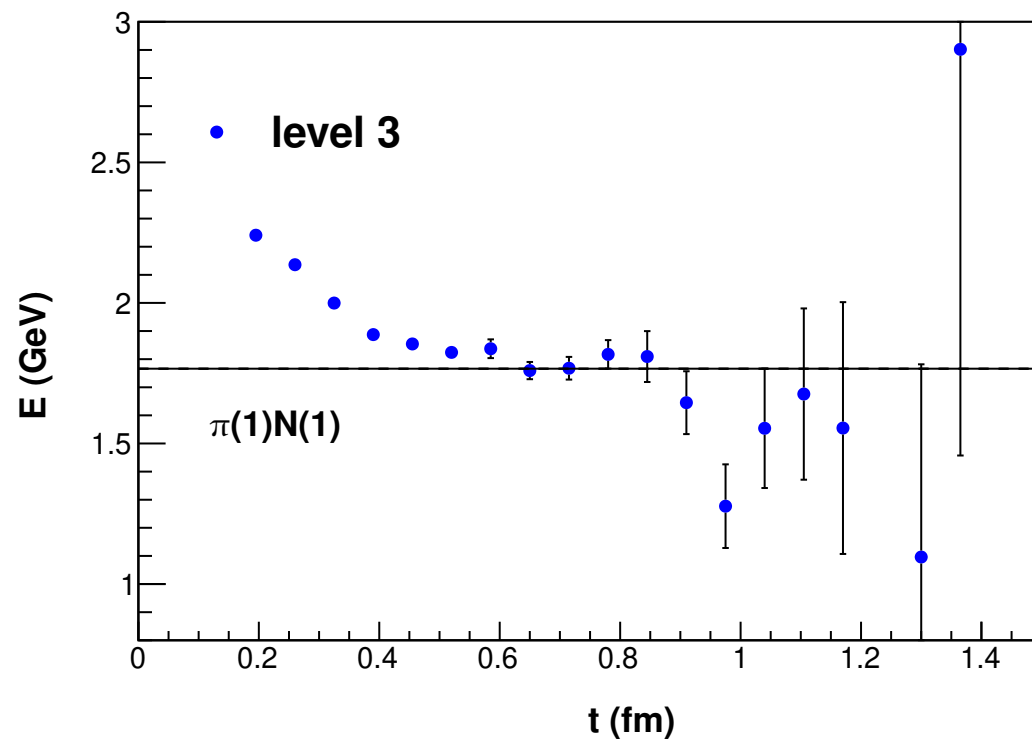
Results: level 1



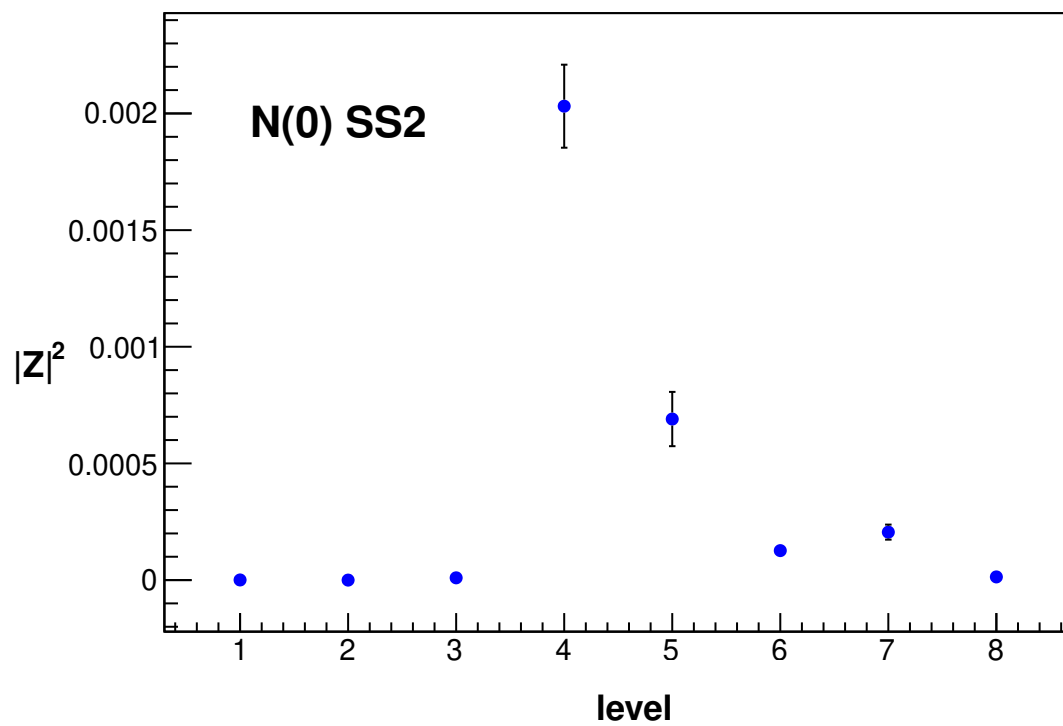
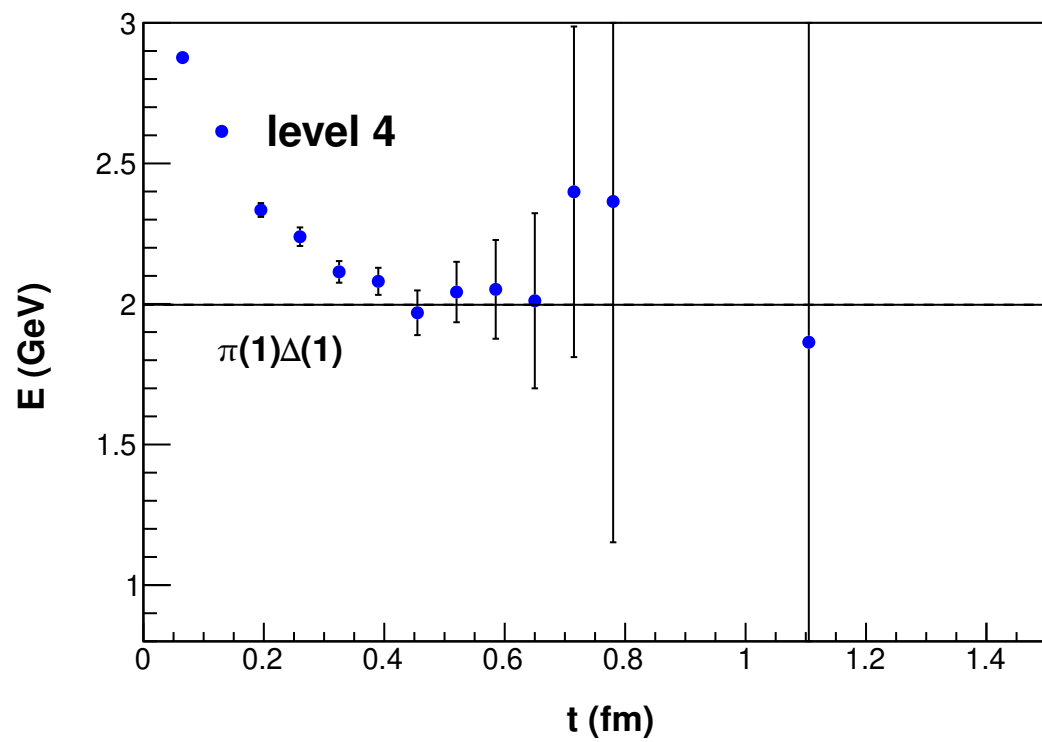
Results: level 2



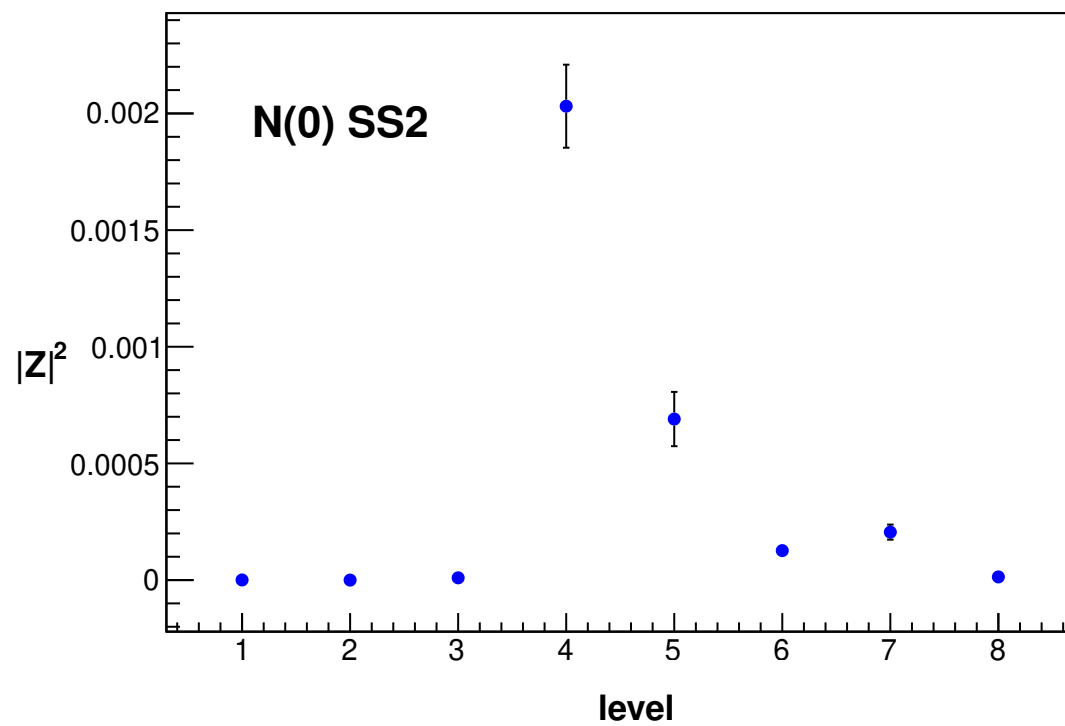
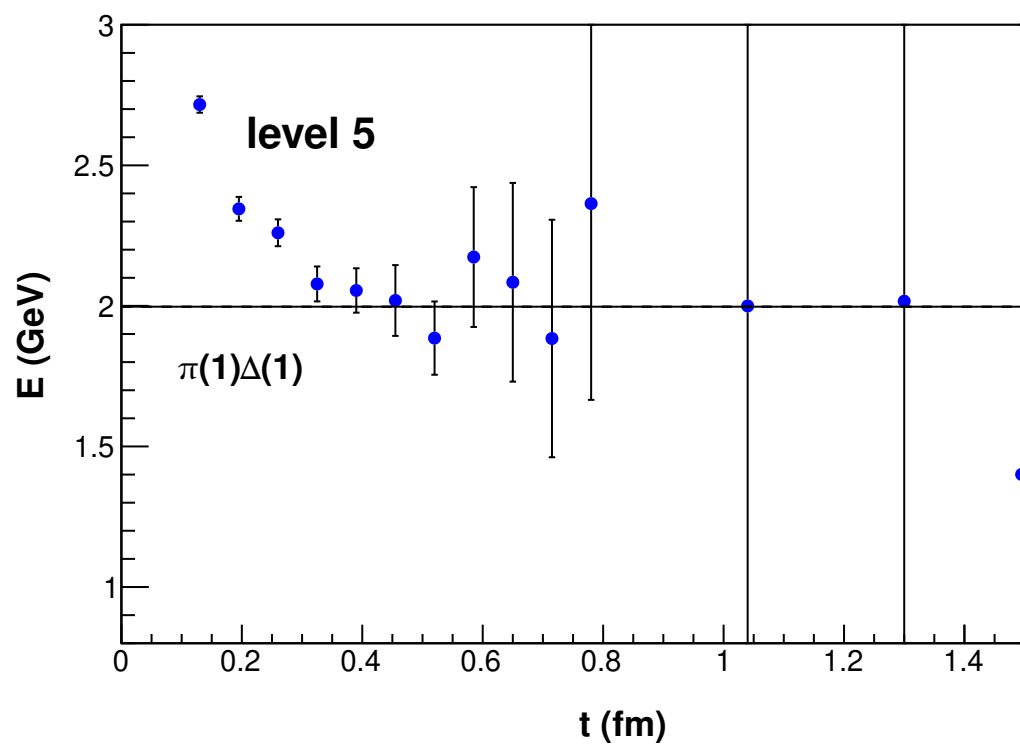
Results: level 3



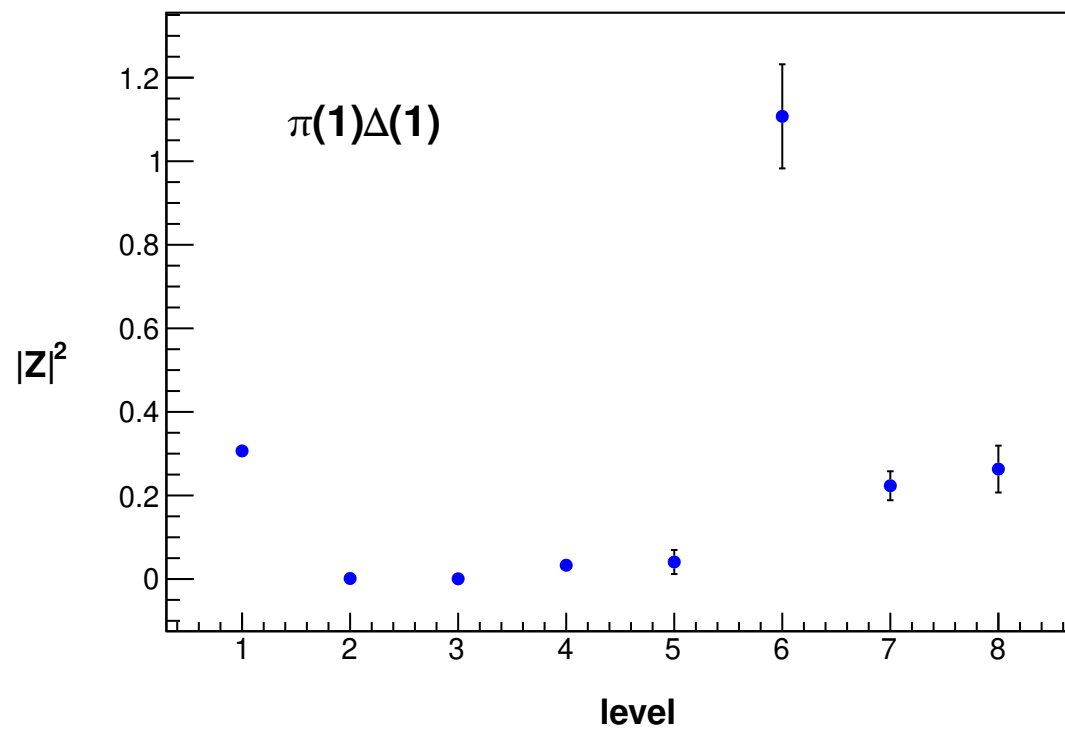
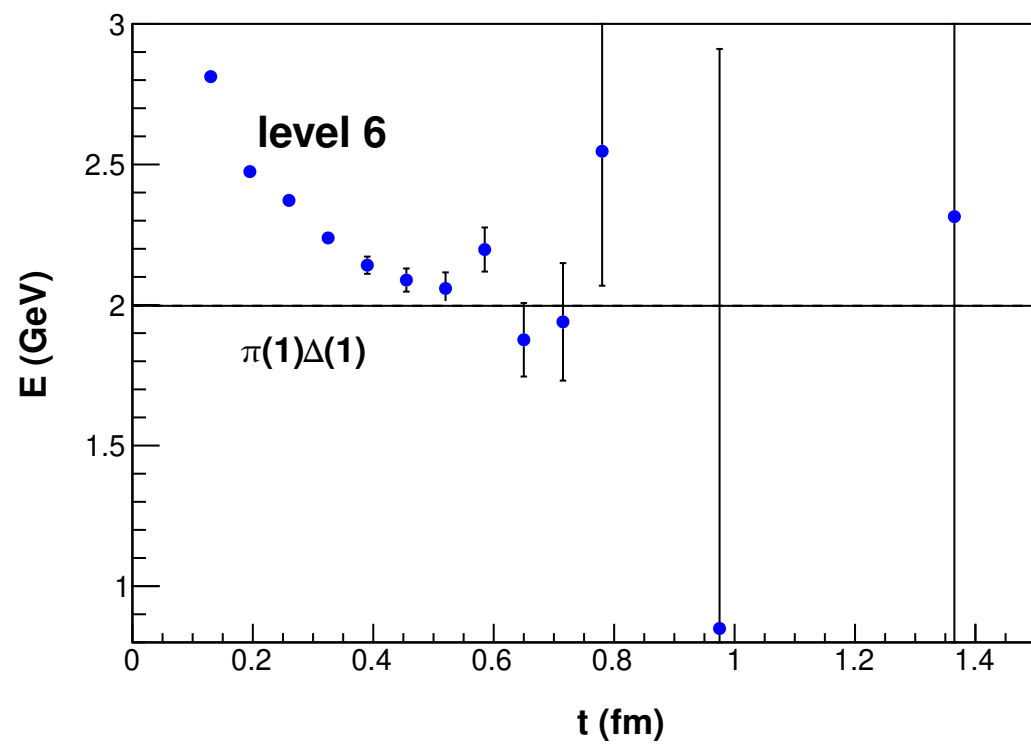
Results: level 4



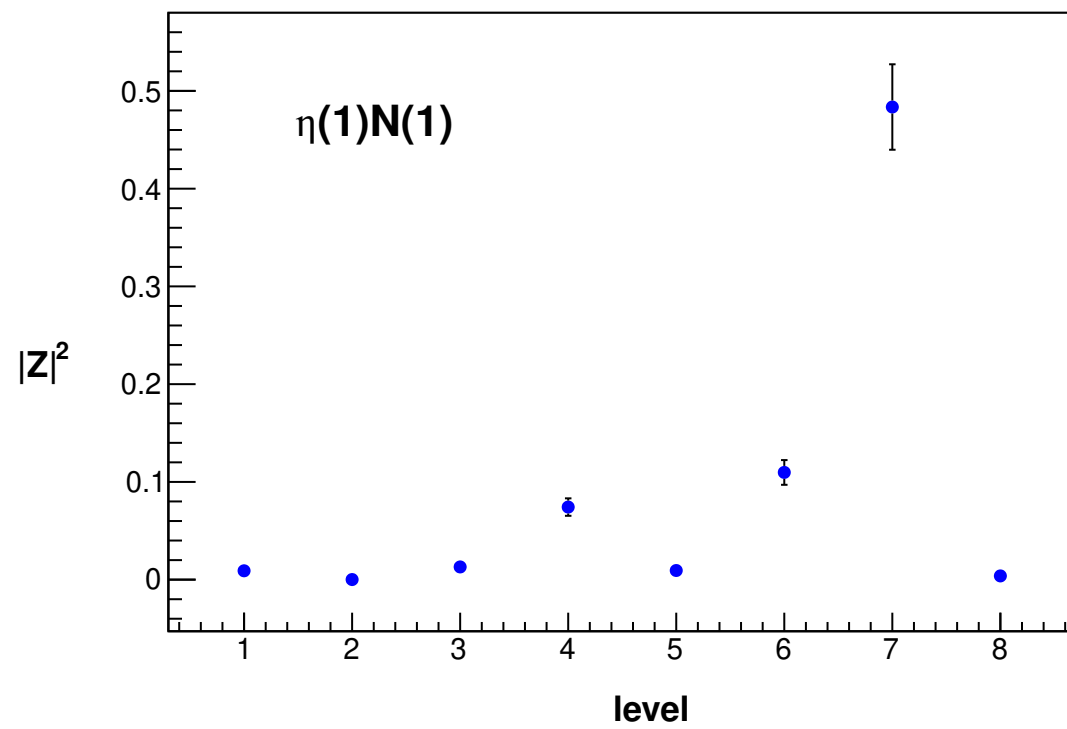
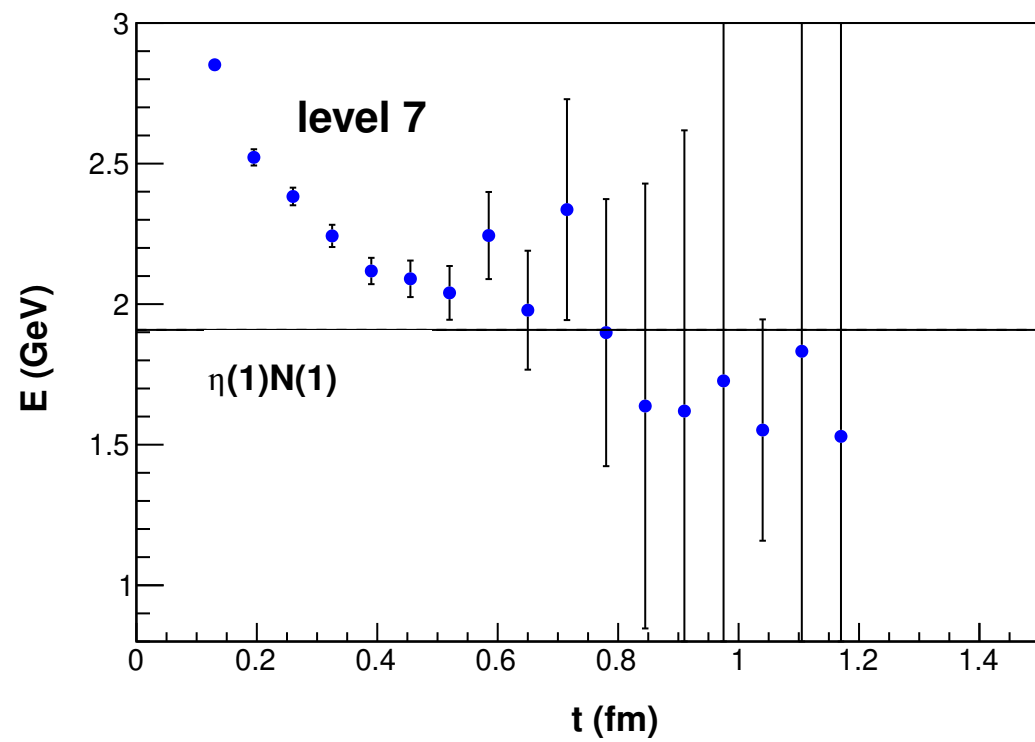
Results: level 5



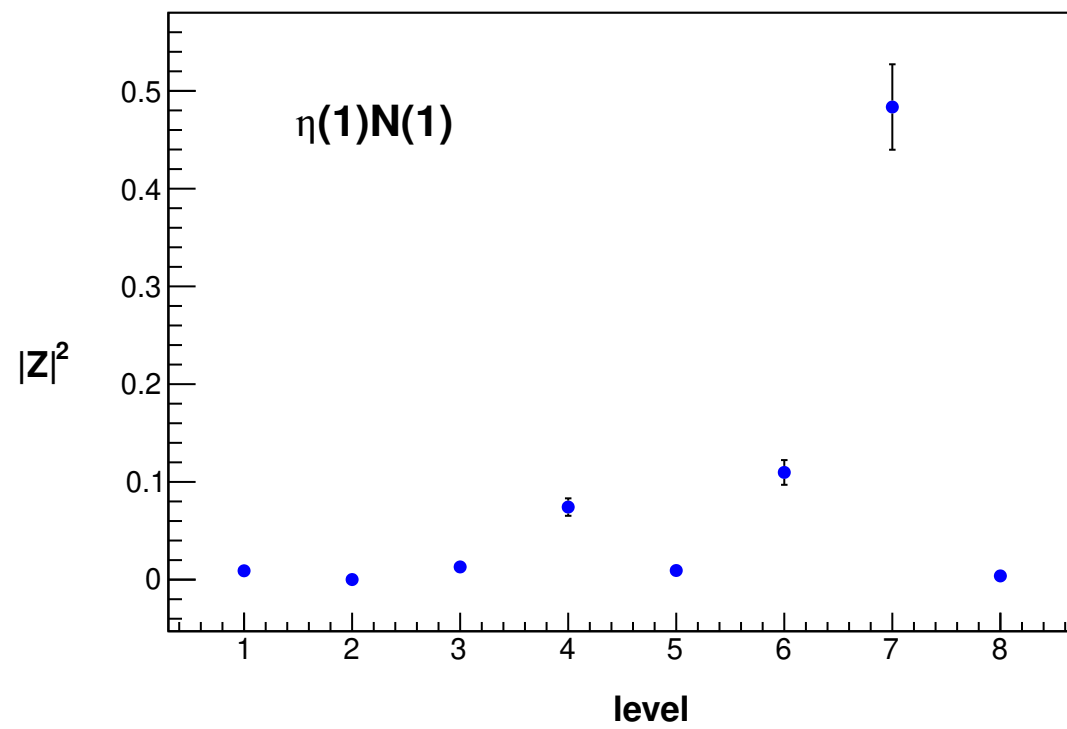
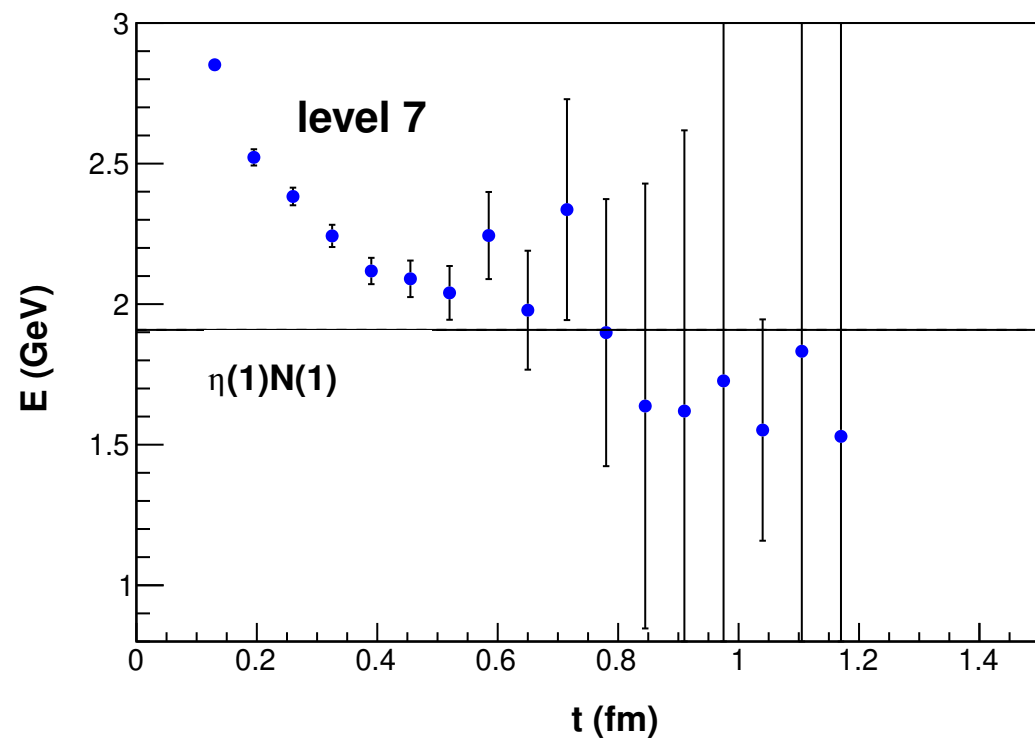
Results: level 6



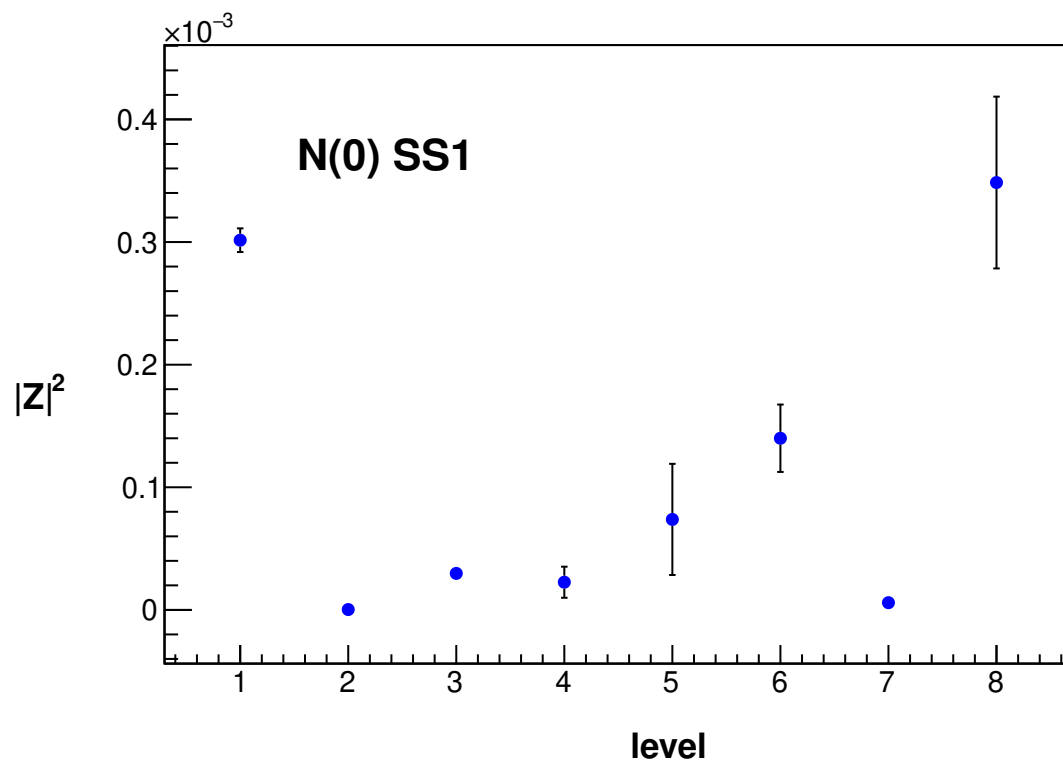
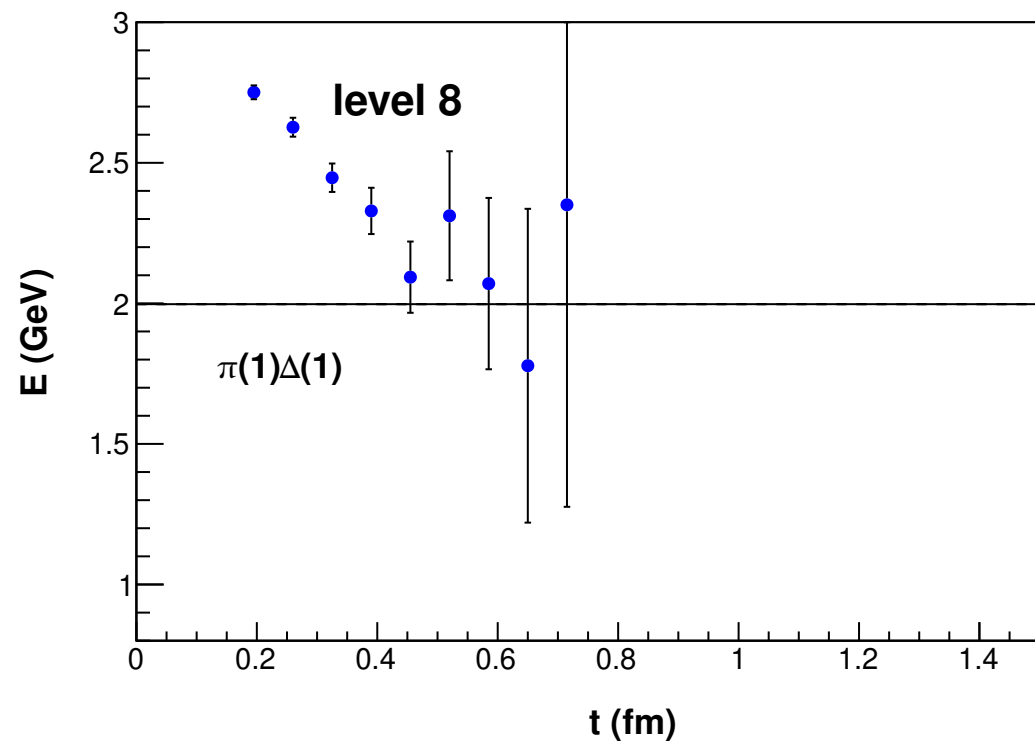
Results: level 7



Results: level 7



Results: level 8



Conclusions

- Coupled-channel meson-baryon scattering progress with lattice QCD
- Distillation framework allows for automated correlator construction from tensor contraction
- Example: N^* (Roper) channel
 - Preliminary GEVP with 8 operators
 - Still missing: ρN , ωN , $K\Lambda$, $K\Sigma$, $\pi K\Lambda$, ...
 - Displaced operators? Pentaquark operators?
 - Expect 20x increase in statistics → energy shifts
- Finite volume formalism does not yet exist. Recent work on $I=5/2$: