Excited states and precision results for nucleon charges and form factors

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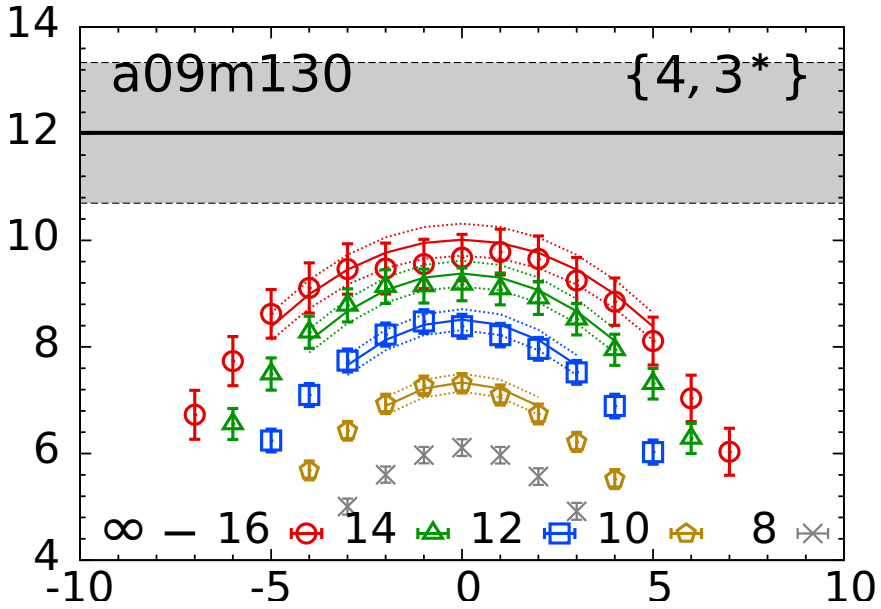
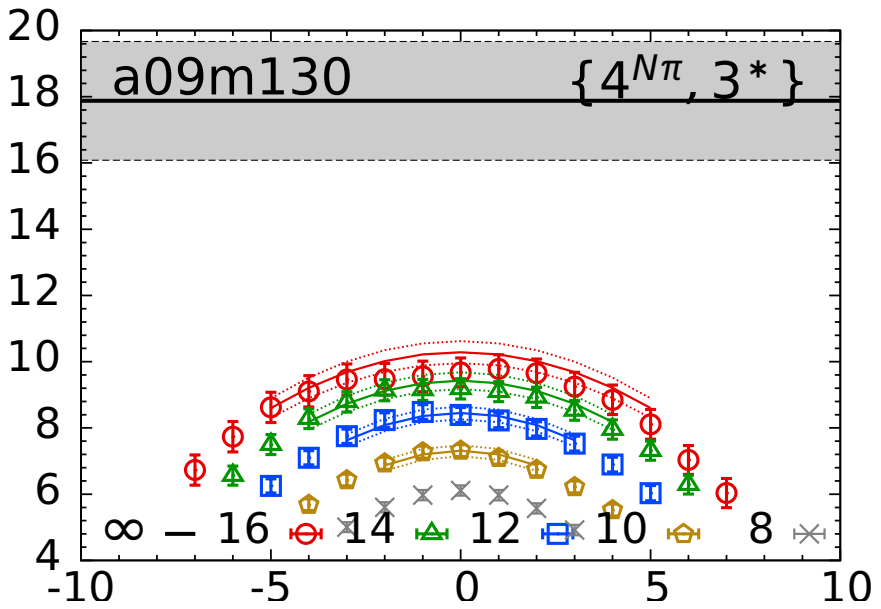
Work done with T. Bhattacharya, V. Cirigliano, M. Hoferichter, Y-C. Jang, B. Joo, H-W. Lin, E. Mereghetti, S. Mondal, S. Park, F. Winter, B. Yoon





LA-UR 21-27234

Discussion based on

- AFF: Phys Rev Lett 124 (2019) 072002
- Θ-term: Phys Rev D103 (2021) 114507
- σ-term: arXiv:2105.12095
- g_i and FF: arXiv:2103.05599

Outline

- Excited States (ES) in nucleon correlation functions
- Intuitive understanding of enhanced contributions from $N\pi$, $N\pi\pi$, ... states
- Three strategies
- Examples
  - PCAC relation and axial form factors
  - Axial charge
  - Electric and magnetic form factors
  - Nucleon σ-term
  - Θ-term contribution to neutron EDM
- Summary: Which ES contribute to which NME?

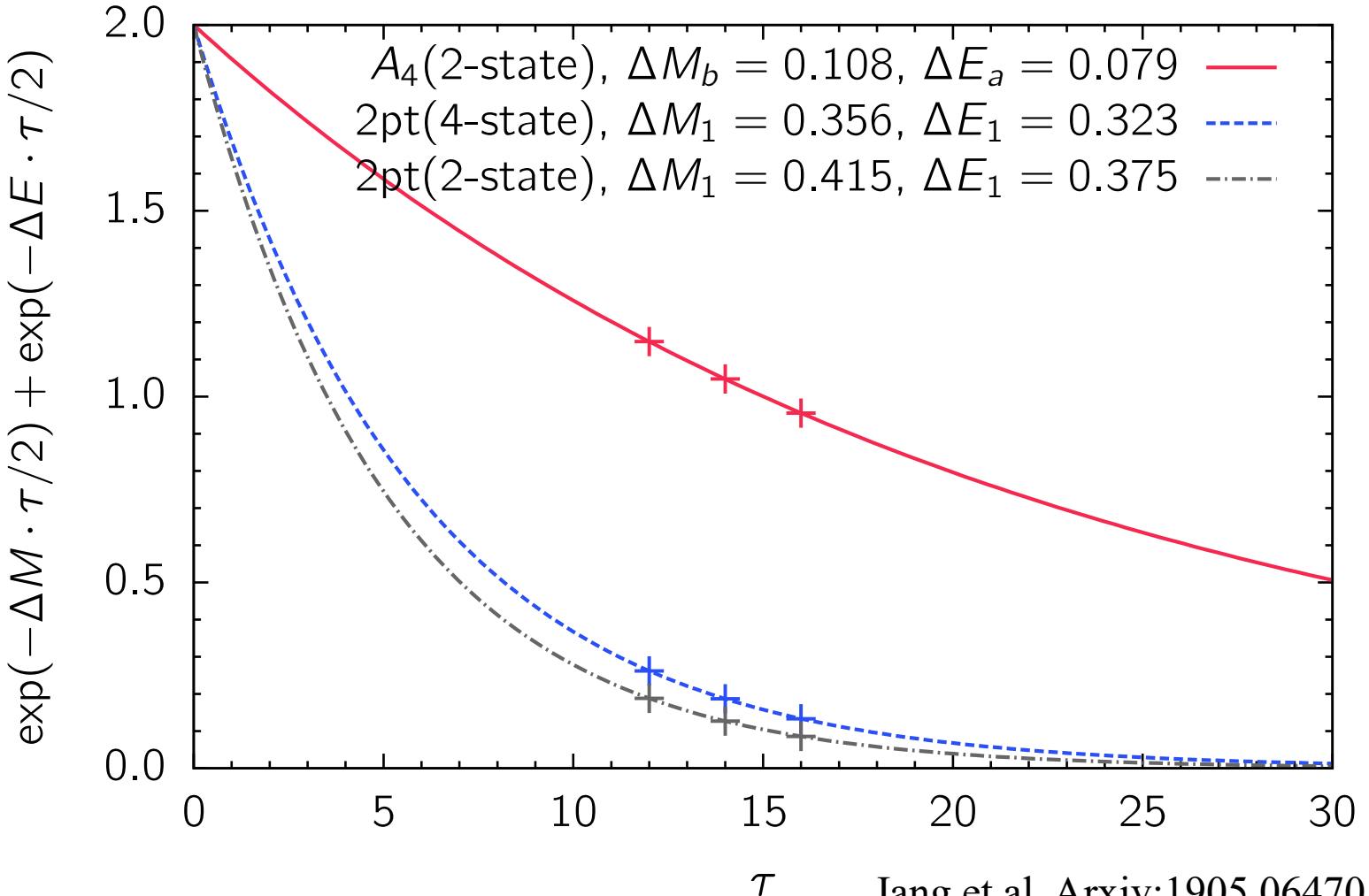
Excited States in Nucleon Correlation Functions

- Statistical signal dies as $e^{-(M_N - 1.5M_\pi)t}$
- Towers of multi-hadron excited states start at ~1200 MeV
  - $N\pi$, $N\pi\pi$, ...
  - Arbitrarily dense as $\vec{p} \to 0$
  - Difference in mass gap increases as $\vec{p} \to 0$ and $M_\pi \to 135$ MeV
  - Contribution increases as $M_\pi \to 135$ MeV
- Which states contribute significantly?
- With current statistics, can fit the spectral decomposition with up to 3 states. χ^2 does not discriminate between fits!

Fit χ^2 do not discriminate for $1 \lesssim \tau \lesssim 1.5$ fm

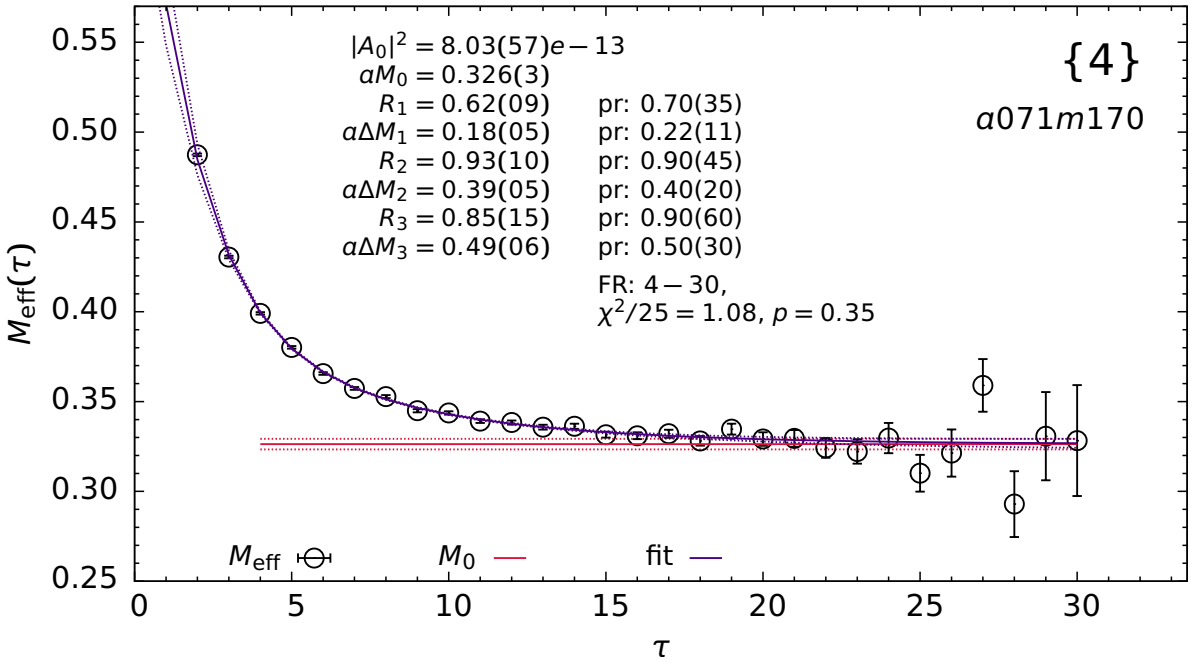
A cartoon of 1st ESC contribution assuming amplitude $A_1 = 1$

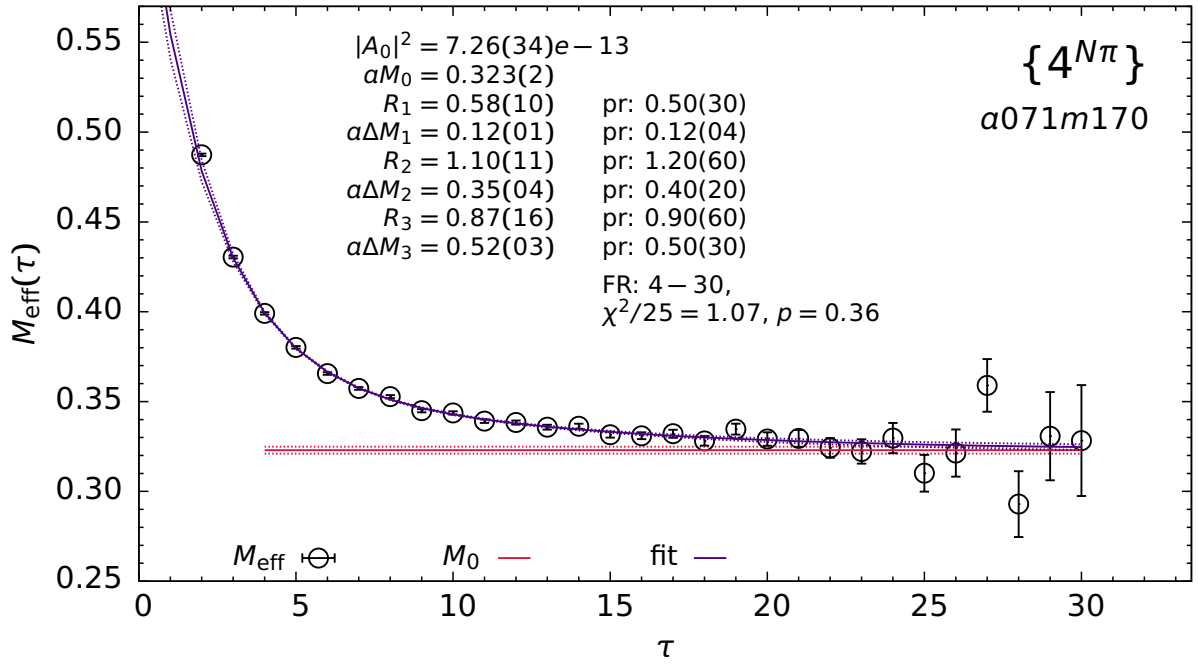
- $\tau = 12, 14, 16$
- The behavior is almost linear
- 3 curves differ in value
- At small τ need more states



Jang et al, Arxiv:1905.06470

Nucleon 2-point function

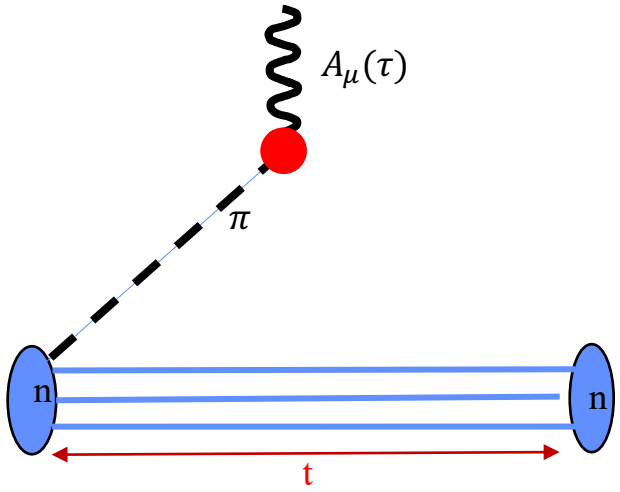




- Signal extends to ≈2 fm
- Even ground state mass M_0 sensitive (few %) to including $N\pi$ state
- A large region in M_i and A_i space that gives similar χ^2

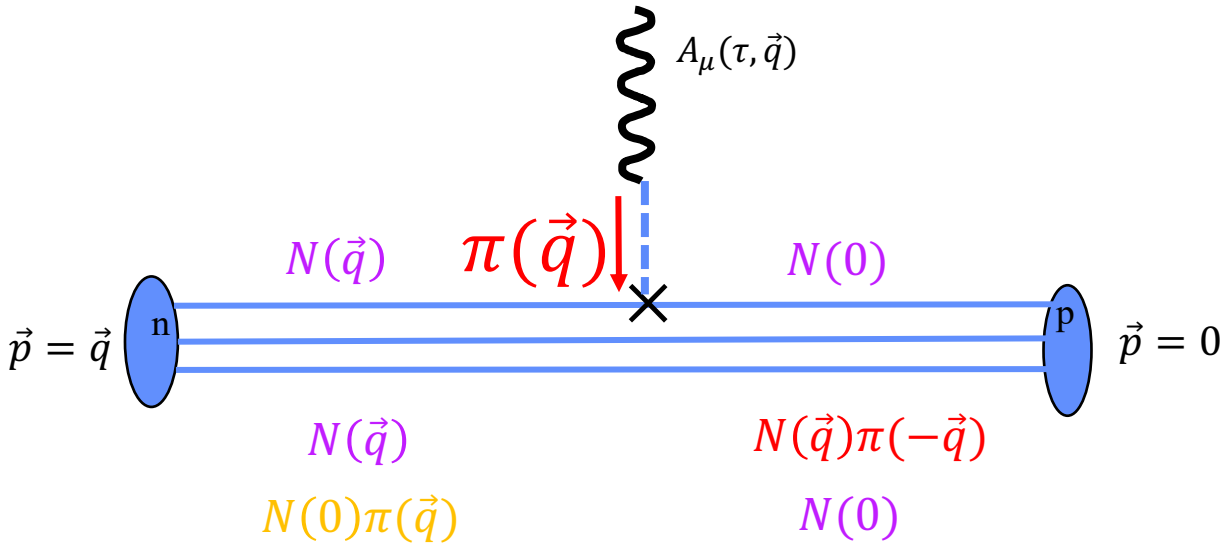
Intuitive understanding of enhancement

Axial Channel

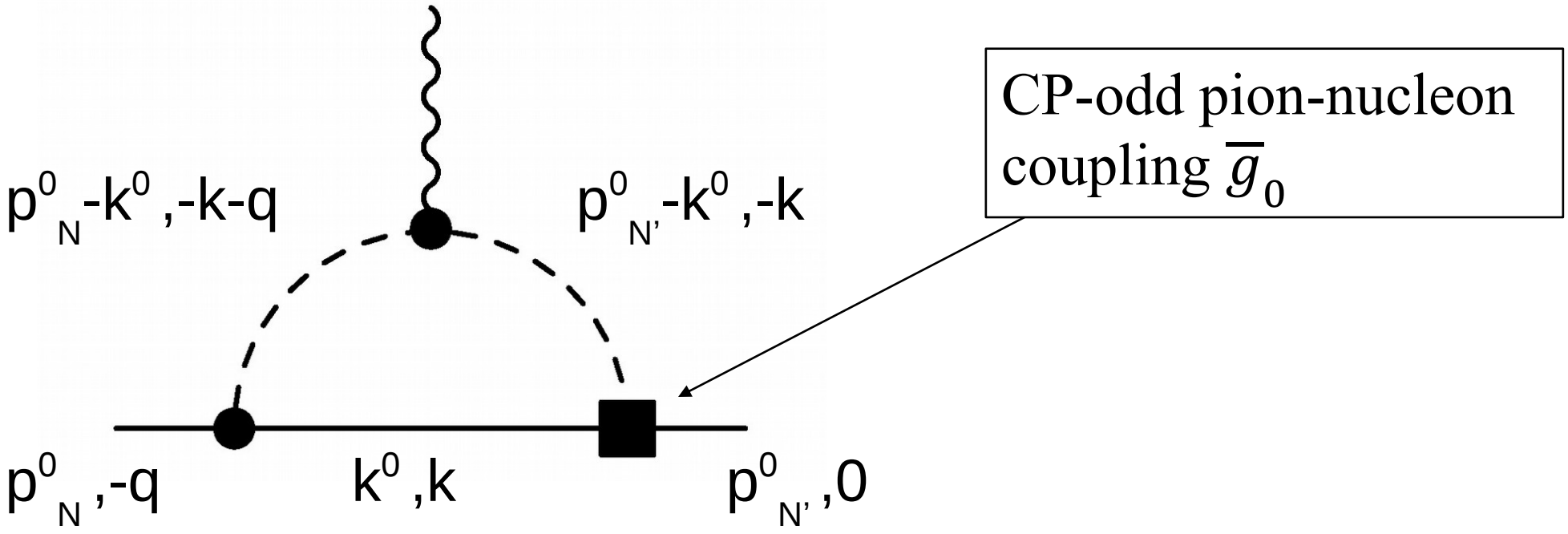


Since the pion is light, the vertex ● can be anywhere in the 3-volume

Pion Pole Dominance



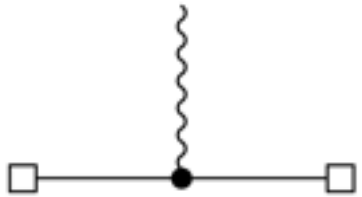
Θ-term contribution to neutron EDM



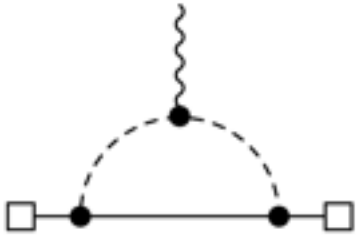
This loop term ($N\pi$ contribution) is not suppressed w.r.t the ground state

Phys Rev D103 (2021) 114507

Nucleon σ-term $\boldsymbol{\sigma_{ud}} = m_{ud}\, g_S^{u+d}$

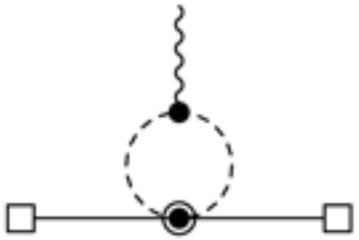


LO



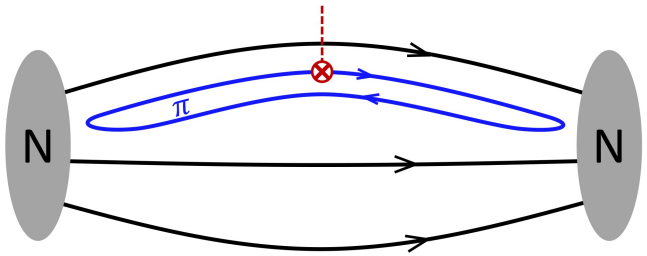
NLO

Large coupling of O_S to 2 pions



NNLO

Large LEC c_1, c_2, c_3



arXiv:2105.12095

3 Strategies

S1: Ward Identities

- AFF (PCAC/PPD)
- VFF (VMD)

S2: χPT

- AFF (PCAC)
- Θ-term
- Nucleon σ-term

S3: What if $N\pi$ contributes

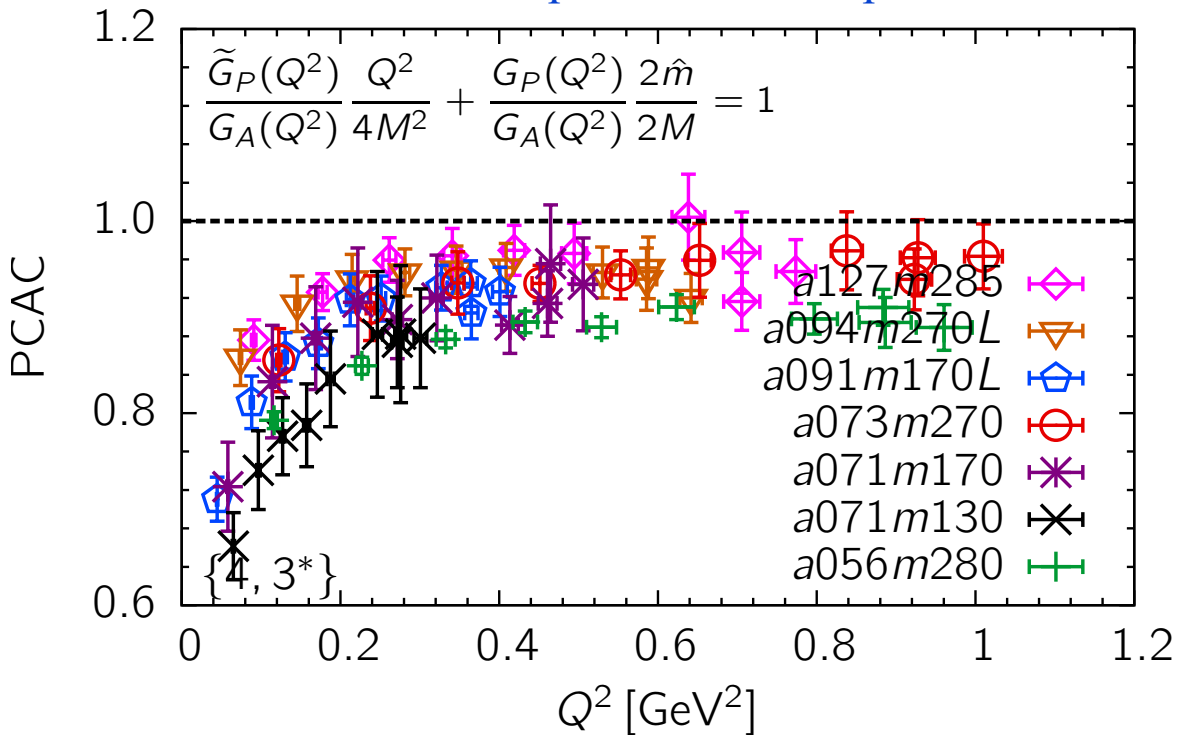
- All NME

S3 recognizes that $N\pi$, $N\pi\pi$, ... states are present at loop level in all NME and provides sensitivity to their contribution

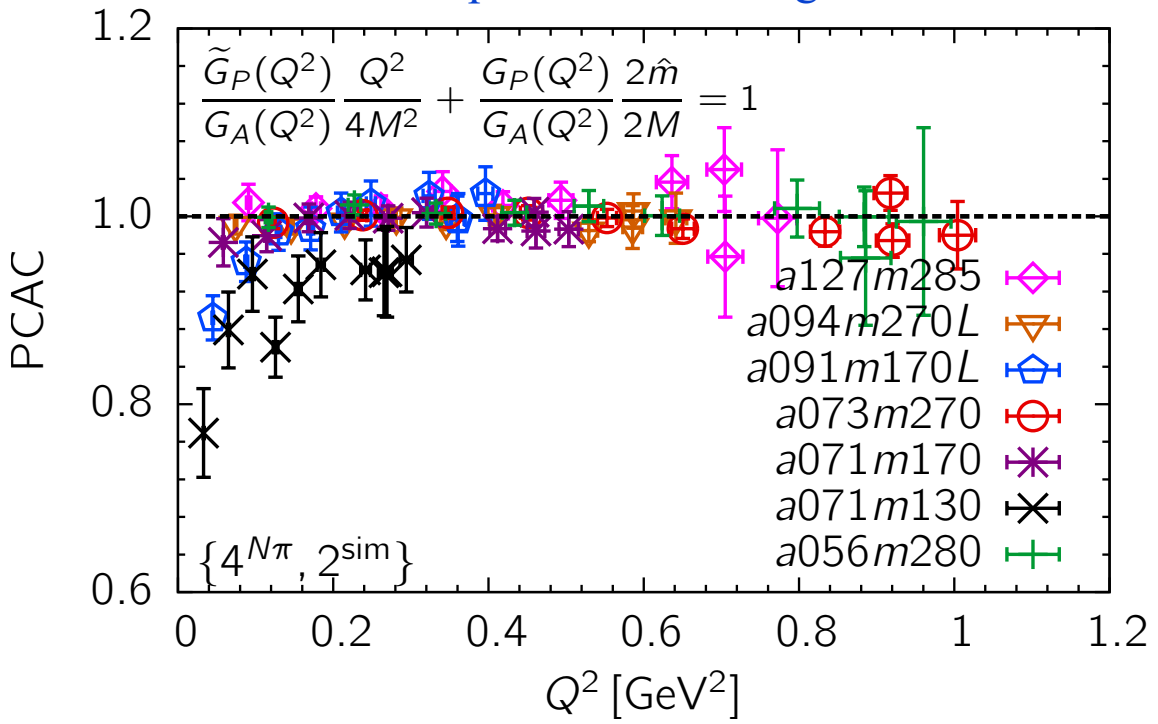
Axial Form Factors: Satisfying PCAC

Preliminary data from 2+1-flavor clover ensembles

Standard: spectrum from 2-pt



New: spectrum including $N\pi$ state

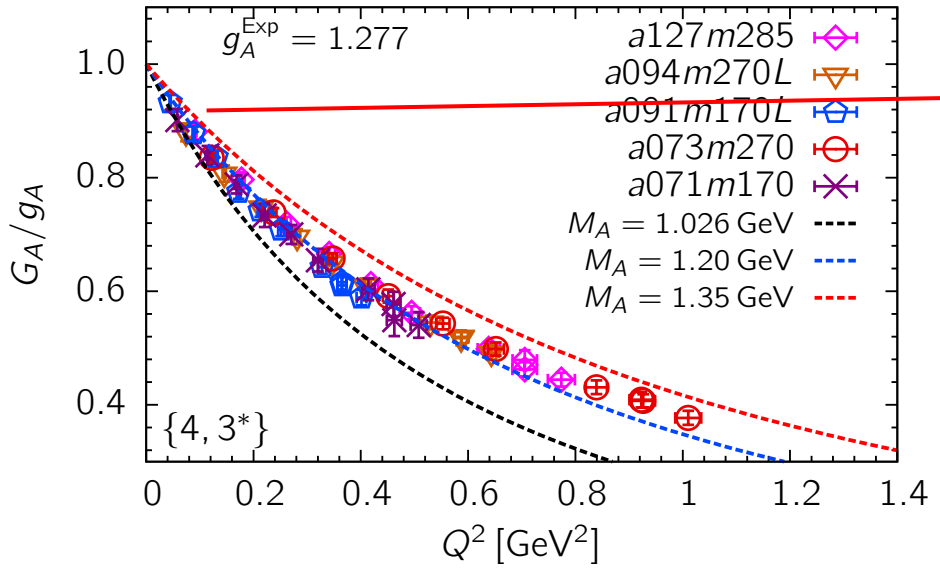


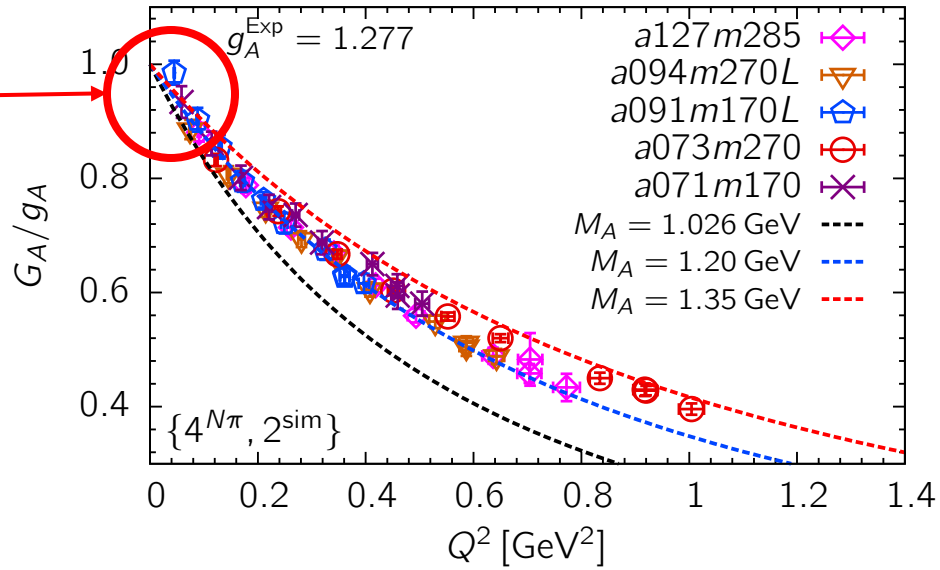
Update of plots in arXiv:2021.05599 with 2 additional ensembles

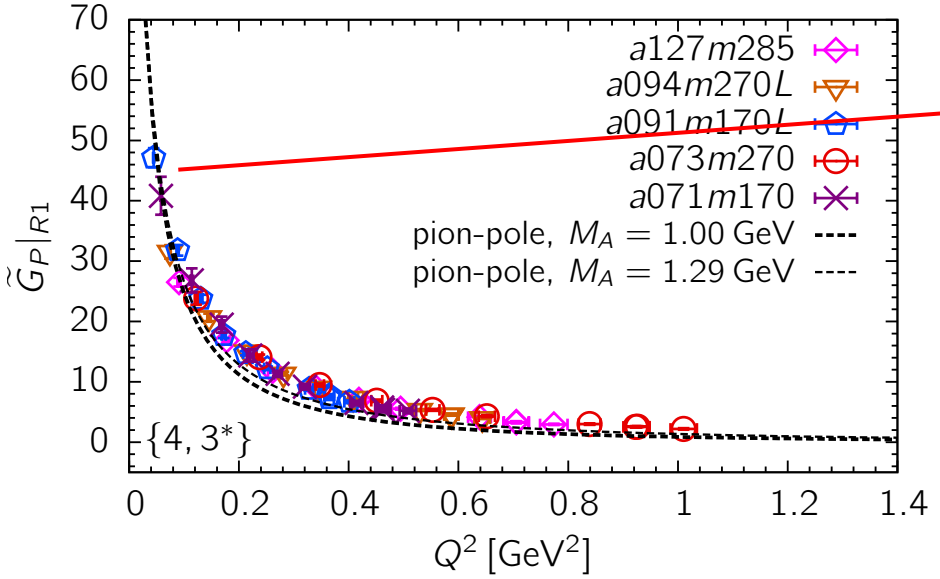
Change on removing $N\pi$ contamination: G_A (~5%) $\tilde{G}_P$ (~35%)

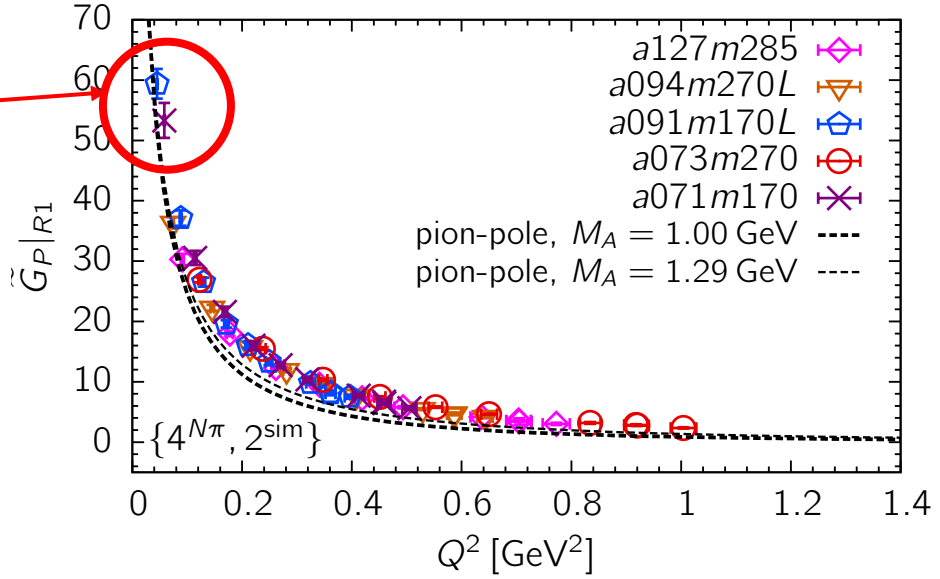
Standard: spectrum from 2-pt

New: spectrum including $N\pi$ state

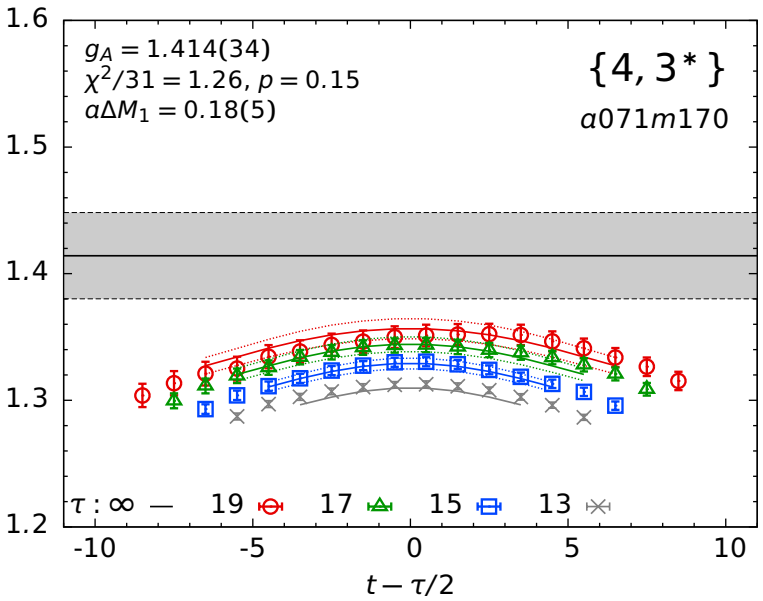


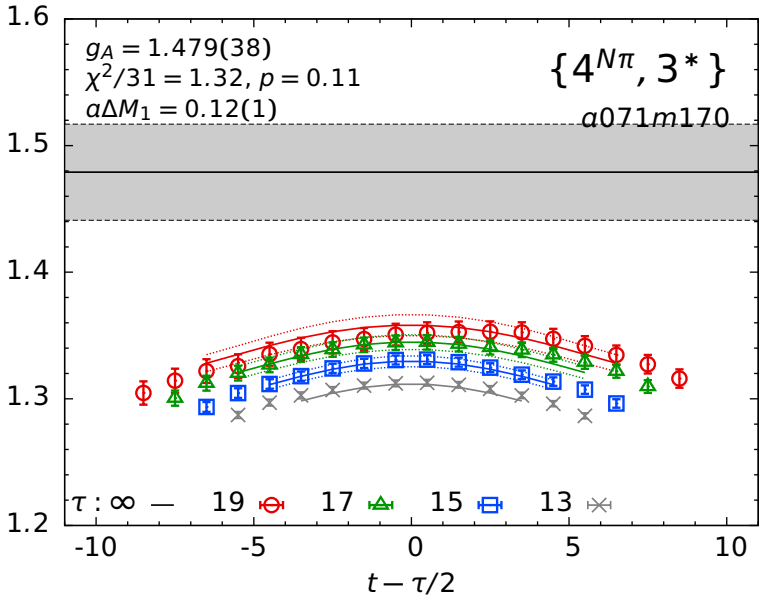


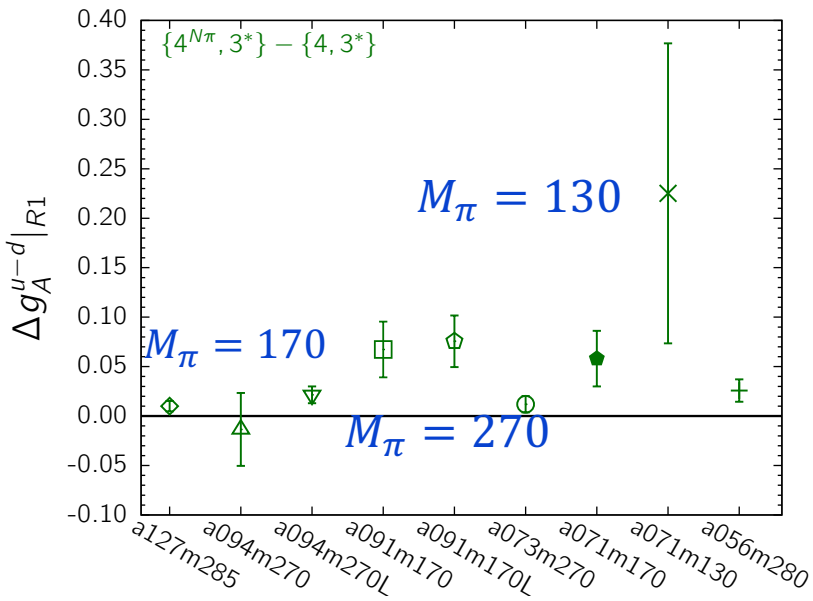




Axial charge g_A^{u-d} (Include $N\pi$ or not?): S3







The effect increases as $M_\pi \to 135$ MeV

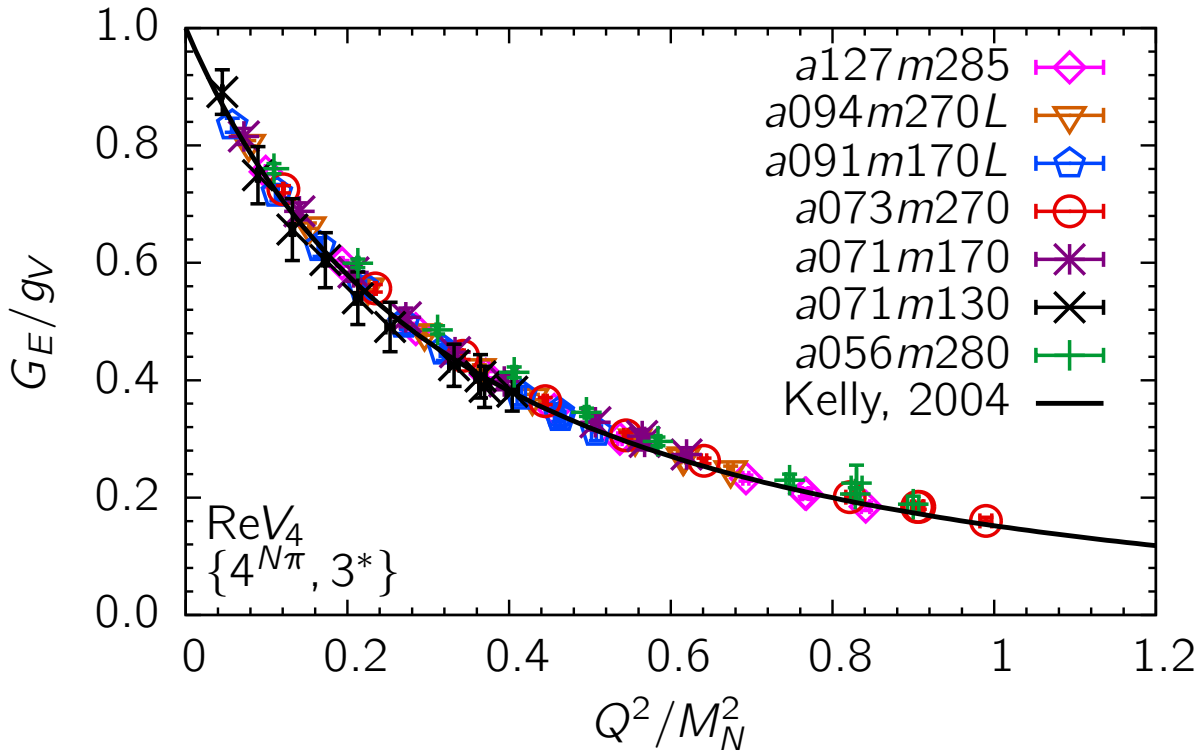
Including $N\pi$ state in the analysis increases g_A^{u-d} by ~8%

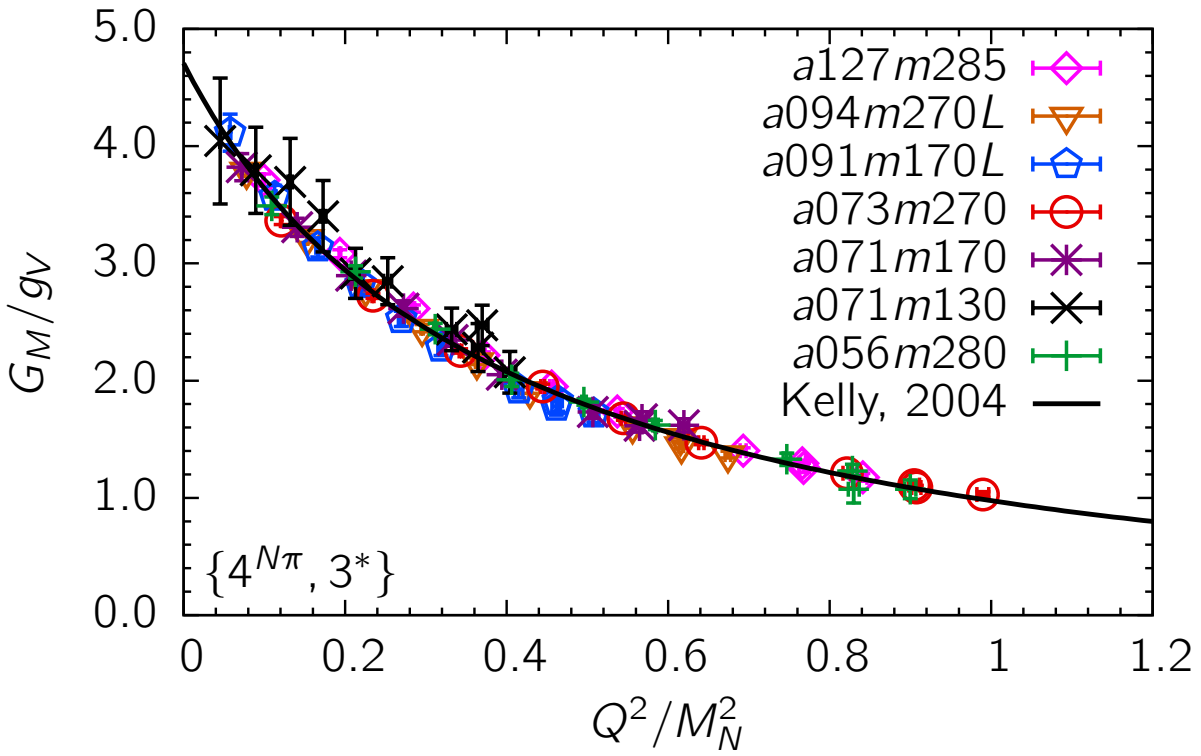
g_A^{u-d} $(N\pi)$ agrees with extrapolation of $G_A(Q^2 \to 0)$

Need to increase statistics on the $M_\pi = 130$ MeV ensemble

Electric and Magnetic Form Factors

Preliminary data from 2+1-flavor clover ensembles



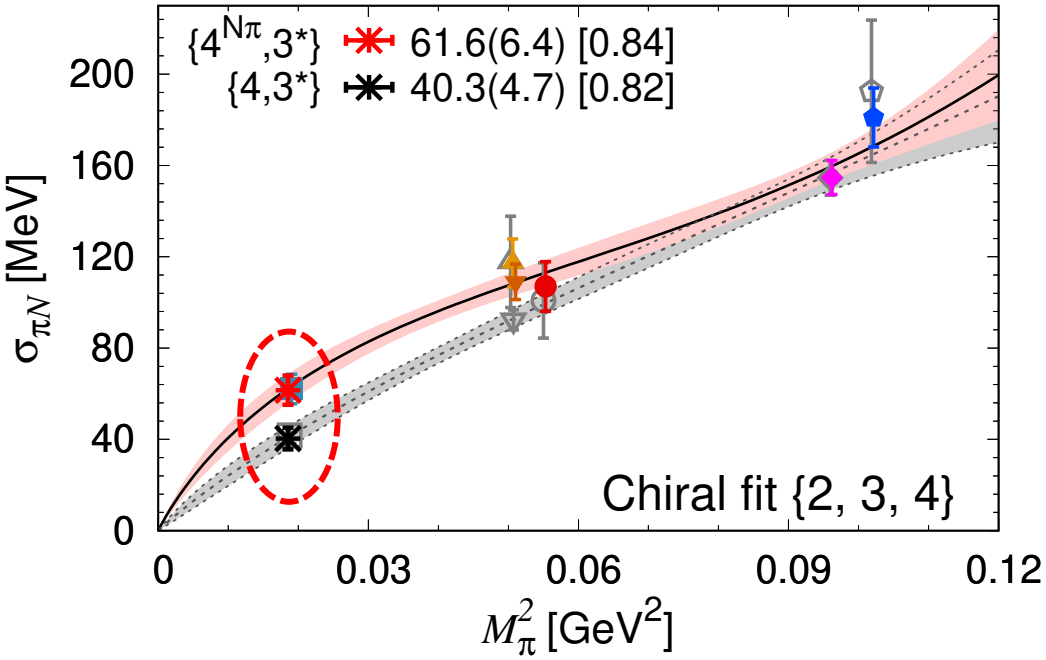


Update of arXiv:2021.05599 with 2 additional ensembles

Scalar matrix elements: nucleon σ-term $\sigma_{ud} = m_{ud}\, g_S^{u+d}$

arXiv:2105:12945

χPT analysis shows large contributions from $N\pi$ and $N\pi\pi$ excited states



Without $N\pi$: $\sigma_{ud} \approx 40$ MeV

With $N\pi$: $\sigma_{ud} \approx 60$ MeV.

Consistent with results using dispersion theory

See Sungwoo Park's talk

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Θ-term contribution to nEDM: χPT

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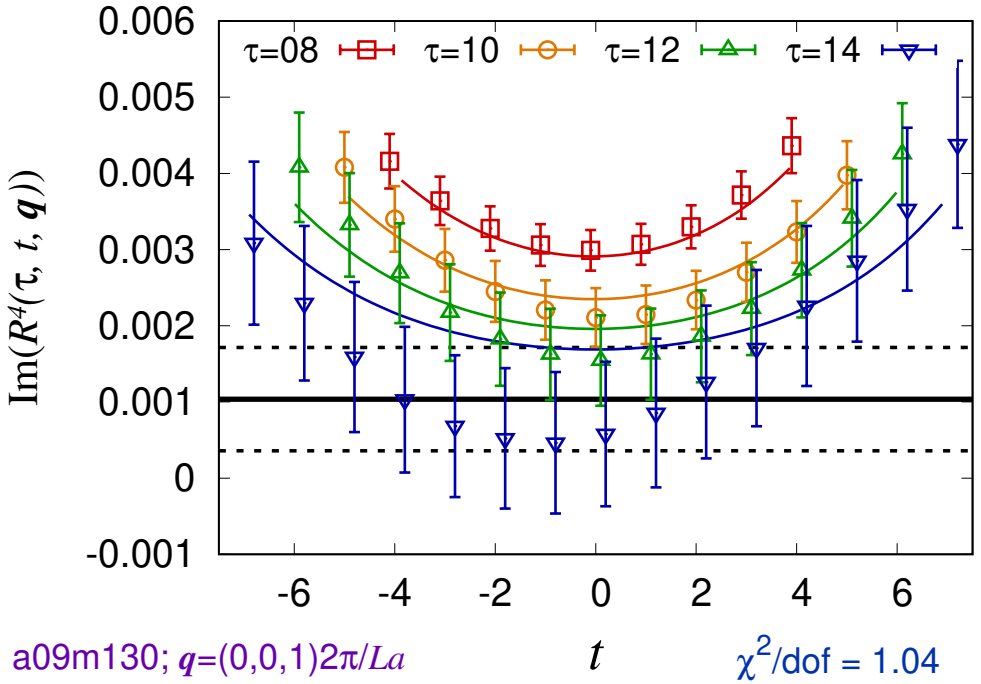
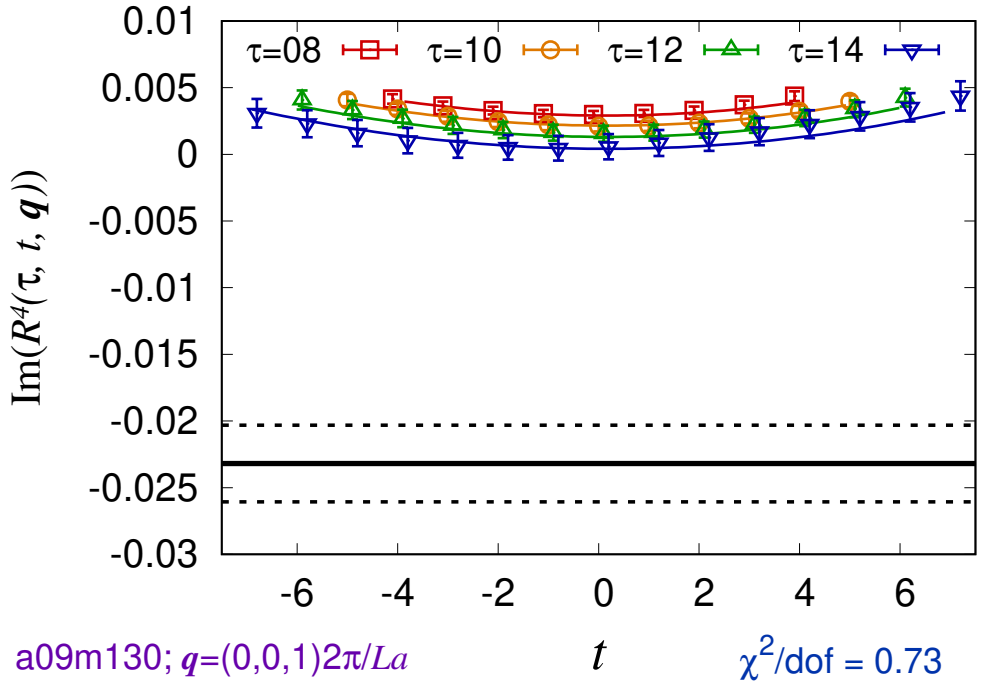
Standard: spectrum from 2-pt



d_n= -0.003(7)(30) $\bar{\Theta}$ e fm

New: spectrum including $N\pi$ state



d_n= -0.028(18)(54) $\bar{\Theta}$ e fm

See Tanmoy Bhattacharya's talk

Summary

- $N\pi$, $N\pi\pi$, ... excited states contribute to all NME
- χPT: these contributions are enhanced for a number of NME
  - Axial Form Factors & PCAC
  - g_A^{u-d} (≈8%?)
  - Nucleon σ-term
  - Θ-term contribution to nEDM
  - ???
- Contributions becomes more significant as $M_\pi \to 135$ MeV.
- $\sigma_{\pi N}$ changes from ~40 MeV to ~60 MeV [arXiv:2105.12095]
- Increase statistics, especially on the *a071m130* ensemble
- Increase $\{a, M_\pi\}$ points