The Status of the Axial-vector Form Factor and its Uncertainties in Lattice QCD

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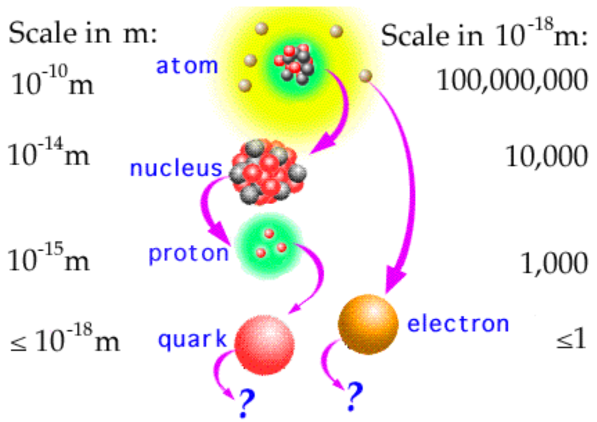

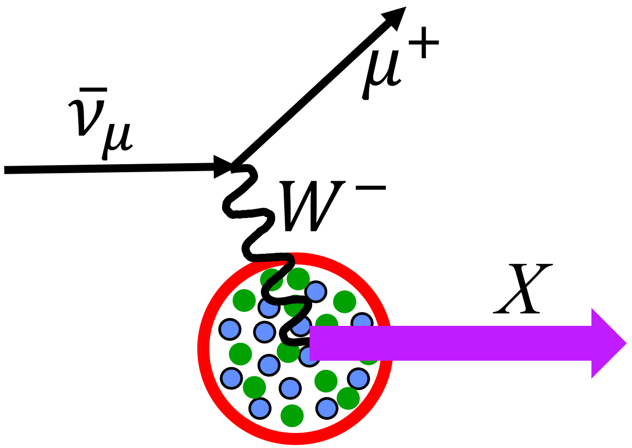

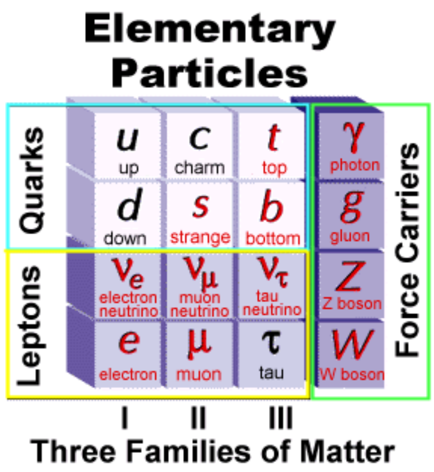

Theoretical Physics Uncertainties to Empower Neutrino Experiments,
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Acknowledgements

Thanks to my collaborators (PNDME and NME collaborations)

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Thanks for computer resources

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- USQCD Community white paper:
  Lattice QCD and Neutrino-Nucleus Scattering, *Eur.Phys.J.A* 55 (2019) 11, 196
- Snowmass 2021 White Paper
  Theoretical tools for neutrino scattering: interplay between lattice QCD, EFTs, nuclear physics, phenomenology, and neutrino event generators. e-Print: 2203.09030 [hep-ph]

Publications on Form Factors

AFF: R. Gupta et al, (PNDME) PhysRevD.96.114503 (2017)

VFF: Y-C Jang, et al, (PNDME) PhysRevD.101.014507 (2020)

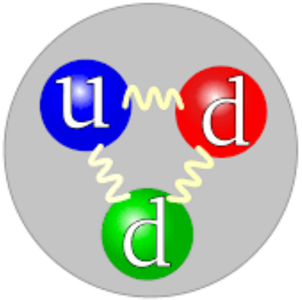
AFF: Y-C Jang et al, (PNDME) PRL 124 (2020) 072002

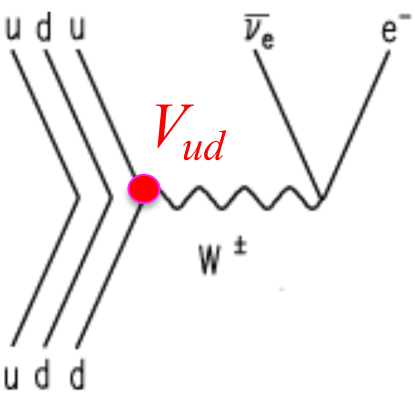
Both: S. Park, et al, (NME) PRD 105, 054505 (2022)

AFF: Y-C Jang, et al, (PNDME) arXiv:2305:11330

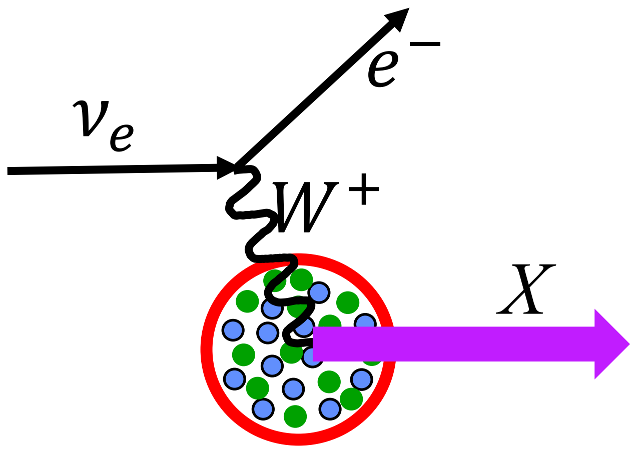
Outline:

- What LQCD can provide for ν-nucleus oscillation experiments
  - Axial and vector form factors of nucleons [nuclei are much more challenging]
  - Nuclear corrections in nuclei: $(p, n) \rightarrow (C^{12}, O^{16}, Ar^{40})$
- Challenges to the calculations of nucleon matrix elements
  - Signal-to-noise falls as $e^{-(M_N - 1.5 M_\pi)\tau}$
  - Excited states in nucleon correlation functions
  - Extrapolation in $\{a, M_\pi, M_\pi L\}$
- FF must satisfy PCAC
  - What we learned from $\langle N(p_f) | A_4(q) | N(p_i) \rangle$
  - Towers of $N\pi$, $N\pi\pi$, states contribute to axial and PS correlators
- Comparison of published results for g_A, G_A
- Comparison with MINERvA and ν-D analyses
- Summary of unpublished results for g_A, G_A
- Transition matrix elements
- Results for G_E , G_M
- Future



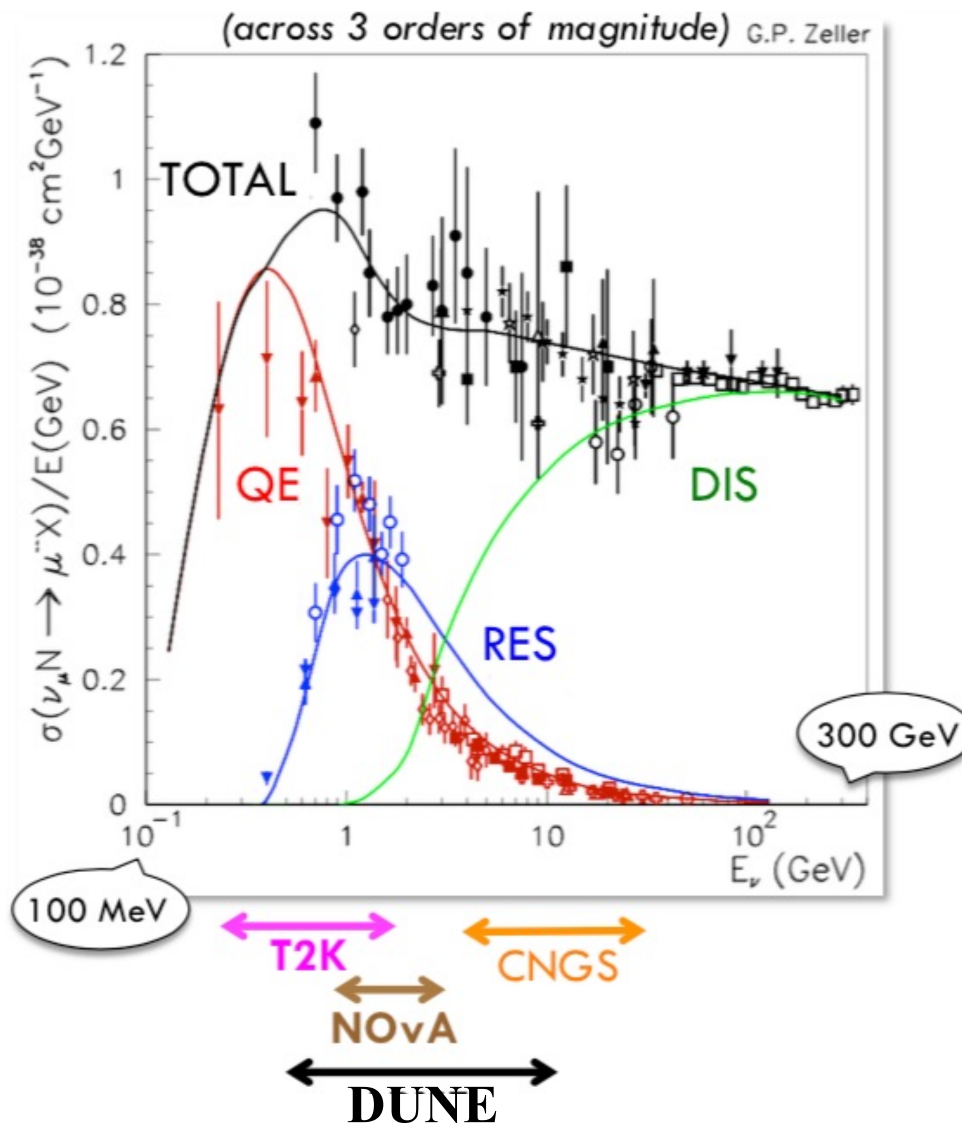


ν energy range covers complex physics



- Incoming neutrino energy and flux not known precisely

- Dynamics of struck Argon nucleus is too complex to simulate directly and connect to final states seen in the detectors



Goal: Inputs for DUNE

Matrix elements (form factors) for $\nu - {}^{40}Ar$ scattering

$$\langle X \,|\, A_\mu(q) \,|\, {}^{40}Ar \rangle$$

$$\langle X \,|\, V_\mu(q) \,|\, {}^{40}Ar \rangle$$

Building blocks:

Starting with nucleons and different energy regions:

$\langle p \,|\, J_\mu^W(q) \,|\, n \rangle$ Quasi-elastic

$\langle n\pi \,|\, J_\mu^W(q) \,|\, n \rangle, \langle \Delta \,|\, J_\mu^W(q) \,|\, n \rangle$ Resonant

$\langle \mathrm{X} \,|\, J_\mu^W(q) \,|\, n \rangle$ DIS

Including nuclear effects in scattering off complex nuclear targets

Nuclear many body Hamiltonian takes as input matrix elements involving successively more multi-particles

– One nucleon $\langle\, p \,|\, J_\mu^+(q) \,|\, n \,\rangle$

– Transition $\langle\, n\pi \,|\, J_\mu^W(q) \,|\, n \,\rangle$, $\langle\, \Delta |\, J_\mu^W(q) \,|\, n \,\rangle$

– Two nucleon $\langle\, n\, p \,|\, J_\mu^{W+}(q) \,|\, n\, n \,\rangle$

See Snowmass 2021 white paper: 2203.09030 [hep-ph]

The ν-n differential cross-section:

$$\frac{d\sigma}{dQ^2}\begin{pmatrix} \nu_l + n \to l^- + p \\ \bar{\nu}_l + p \to l^+ + n \end{pmatrix} = \frac{M^2 {G_F}^2 cos^2\theta_c}{8\pi {E_\nu}^2}\left\{A(Q^2) \pm B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\},$$

$$A(Q^2) = \frac{(m^2+Q^2)}{M^2}\Big[(1+\tau)F_A^2 - (1-\tau)F_1^2 + \tau(1-\tau)F_2^2 + 4\tau F_1 F_2 - \frac{m^2}{4M^2}\left((F_1+F_2)^2 + (F_A+2F_P)^2 - 4\left(1+\frac{Q^2}{4M^2}\right)F_P^2\right)\Big],$$

$$B(Q^2) = \frac{Q^2}{M^2}F_A(F_1+F_2),$$

$$C(Q^2) = \frac{1}{4}(F_A^2 + F_1^2 + \tau F_2^2).$$

$\langle N A_\mu N \rangle \to$ linear combination of F_A , $\tilde{F}_P$

$\langle N V_\mu N \rangle \to G_E$, G_M

F_A = axial form factor
$G_E = F_1 - \tau F_2$ Electric
$G_M = F_1 + F_2$ Magnetic
$\tau = Q^2/4M^2$
$M = M_p$ = 939 MeV
m=mass of the lepton

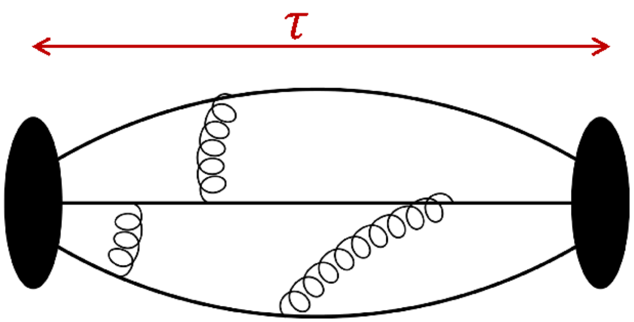
Analysis of (e, μ, ν)-n scattering involves 5 Form Factors & 3 charges g_A, μ, g_p^*

- $G_E(Q^2)$ Electric
- $G_M(Q^2)$ Magnetic
- $G_A(Q^2)$ Axial
- $\tilde{G}_P(Q^2)$ Induced pseudoscalar
- $G_P(Q^2)$ Pseudoscalar (extracted from $\langle NPN \rangle$)
- Lattice methodology is common: all calculated at the same time
- Precise experimental data exist for $G_E(Q^2)$ and $G_M(Q^2)$
- Axial ward identity (PCAC) relates $G_A(Q^2)$, $\tilde{G}_P(Q^2)$, $G_P(Q^2)$

- $G_E(Q^2 = 0)$ $= 1$ Conserved vector charge
- $G_M(Q^2 = 0)$ $= \mu = 4.7058$ Magnetic moment
- $G_A(Q^2 = 0)$ $= g_A = 1.276(2)$ Axial charge
- $\tilde{G}_P(Q^2 = 0.88 m_\mu^2) = g_p^* = 8.06(55)$ Induced pseudoscalar charge

Lattice QCD gives us

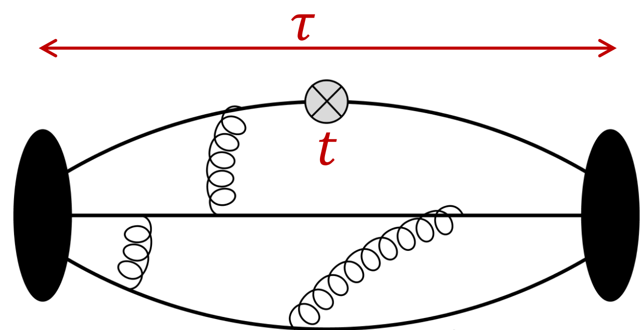
2-point function



$$\langle \Omega \mid \widehat{N_\tau}^\dagger \; \widehat{N}_0 \mid \Omega \rangle$$

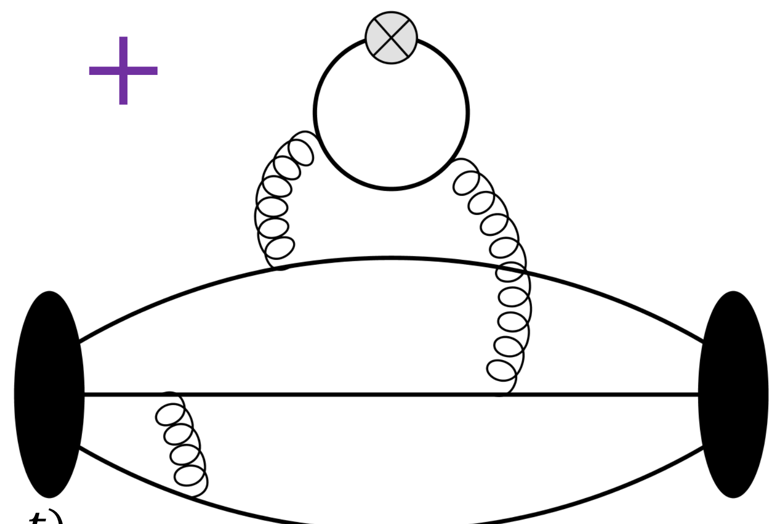
$$\Gamma^{2pt}(\tau) \quad = \sum_i |A_i|^2 e^{-E_i \tau}$$

3-point functions



Connected

$+$

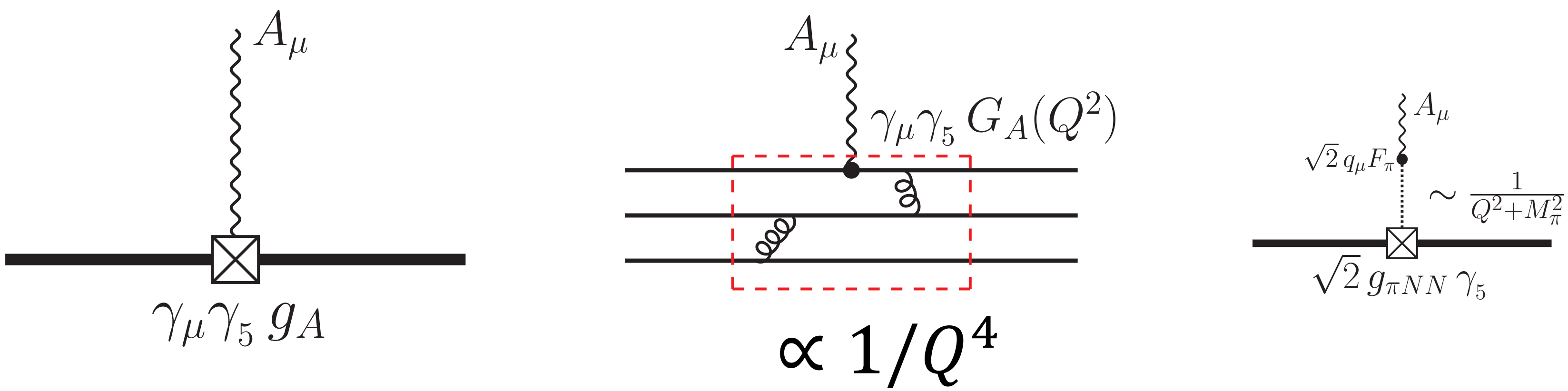


Disconnected

$$\langle \Omega \mid \widehat{N_\tau}^\dagger \; O(t) \; \widehat{N}_0 \mid \Omega \rangle$$

$$\Gamma_O^{3pt}(t,\tau) = \sum_{i,j} A_i^* A_j \langle i|O|j\rangle e^{-E_i t - E_j(\tau - t)}$$

$\Gamma^n \to ME \to$ Axial-vector Form Factors, $G_A, \tilde{G}_P, G_P$



On each ensemble characterized by $\{a, M_\pi, M_\pi L\}$

$$\langle N(p_f) | A^\mu(q) | N(p_i) \rangle = \bar{u}(p_f) \left[\gamma^\mu G_A(q^2) + q_\mu \frac{\tilde{G}_P(q^2)}{2M} \right] \gamma_5 u(p_i)$$

$$\langle N(p_f) | P(q) | N(p_i) \rangle = \bar{u}(p_f) G_P(q^2) \gamma_5\, u(p_i)$$

PCAC [$\partial_\mu A_\mu = 2mP$] relates G_A, $\tilde{G}_P$, G_P

Essential steps in the analysis

- Remove ESC from correlation functions Γ^n to obtain ME within ground-state nucleon
- Decompose ME into form factors $G(Q^2)$ on each ensemble $\{a, M_\pi, M_\pi L\}$
- Parameterize this $G(Q^2)|_{a,M_\pi,M_\pi L}$
- Perform CCFV extrapolation to get $G(Q^2)|_{cont}$
- Parameterize this $G(Q^2)|_{cont}$

Model averaging should include model choices at each step that have significant effect on result

Calculations of nucleon 2,3-point functions using LQCD are mature

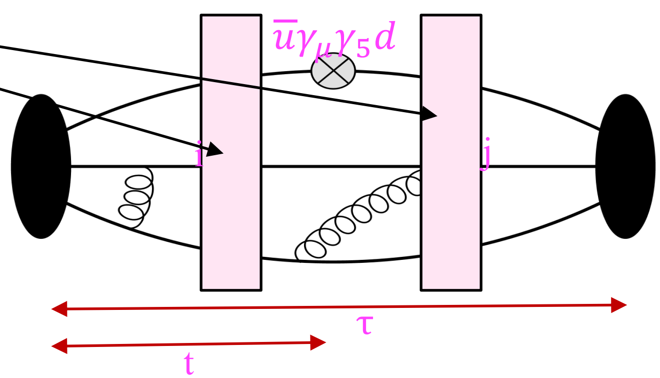
Spectrum (energies E_i & amplitudes A_i) and ME are extracted from fits to the spectral decomposition of 2- and 3-point functions

$$\Gamma^{2pt}(\tau) = \sum_i |A_i|^2 e^{-E_i \tau}$$

$$\Gamma_O^{3pt}(t,\tau) = \sum_{i,j} A_i^* A_j \langle i|O|j\rangle e^{-E_i t - E_j(\tau - t)}$$

Extract $\langle 0|\, O \,|\, 0 \rangle$

All states $|i\rangle$ with the same quantum numbers as N contribute unless A_i (or A_j) is zero



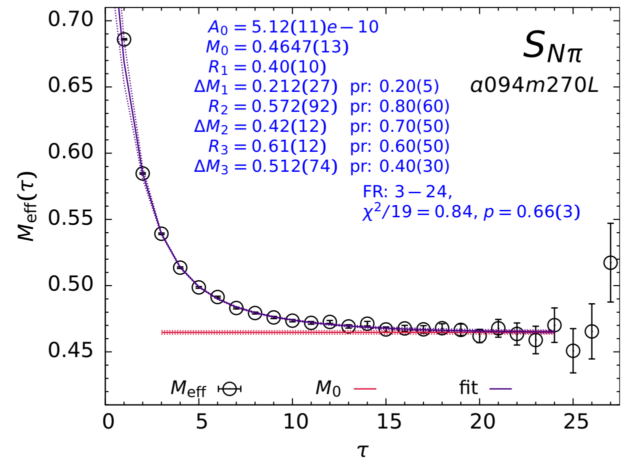
Radial excited States:
N(1440), N(1710)
Towers of multihadrons states
$N(\vec{k})\pi(-\vec{k})$ > 1200 MeV
$N(0)\pi(\vec{k})\pi(-\vec{k})$ > 1200 MeV

but removing ESC from multihadron states remains a challenge

Challenges for nucleon ME

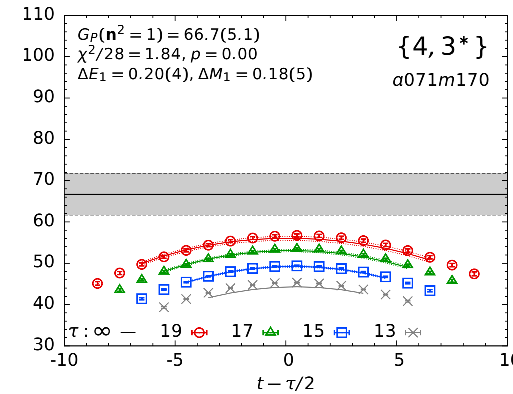
- Need large τ to "kill" states with <u>*small*</u> mass gap ($\Delta M\ \sim 300$)

- Cannot go to large enough $\boldsymbol{\tau}$ because the signal/noise degrades as $e^{-(M_N - 1.5 M_\pi)\tau}$
  - Signal: 2-pt: $\tau \sim$ 2fm ; 3-pt: $\tau \sim$ 1.5fm



- Typical interpolating operator $\widehat{N}$ couples to the nucleon, its excitations and multi-hadron states with the same quantum numbers

- As $\vec{q}\ \rightarrow 0$, the towers of $N\pi$, $N\pi\pi$, states become arbitrarily dense above ~1230 MeV (the **Δ** region)

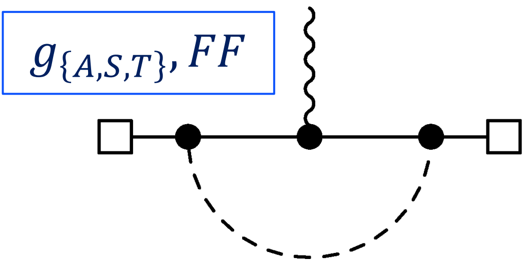


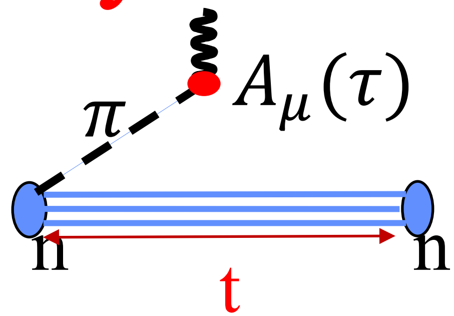
- Quantities impacted by $N\pi$, $N\pi\pi$, states should be analyzed on $M_\pi\ \lesssim 200\ MeV$ ensembles

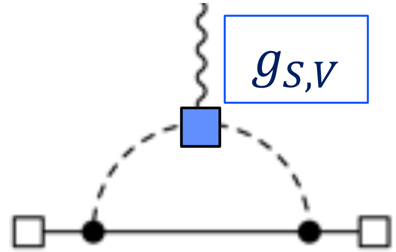
- Excited states giving significant contribution to a particular ME are not known *a priori*. *χPT is a very useful guide*

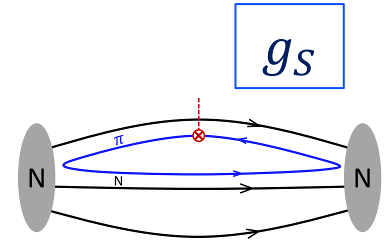
- *The potential of variational methods for isolating the ground state is just starting to be realized!*

χPT analysis of excited states



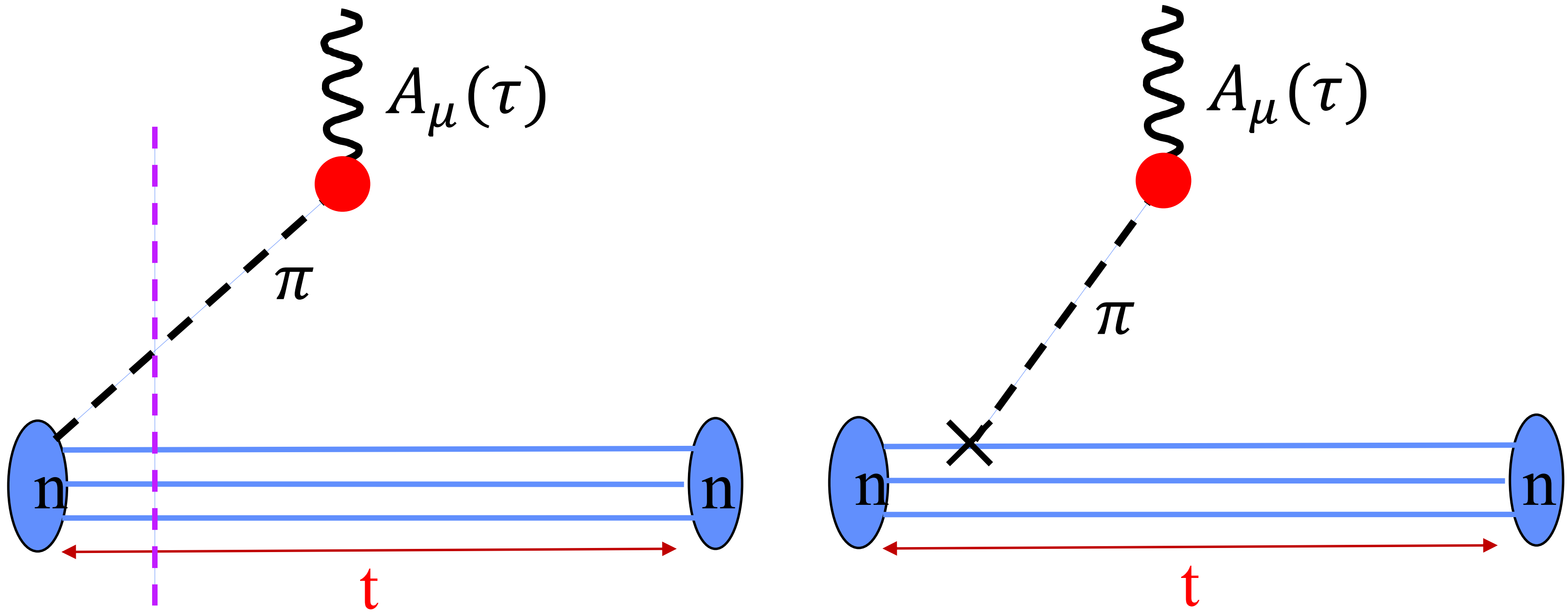






- Corrections from pion loops arise in all Γ^n
- Loops that originate or end at sources are ESC. These can be removed by a perfect nucleon source.
- Loops that originate on the nucleon line give rise to both: corrections to the physical result and excited state contributions (from pion going on-shell in Minkowski)
  - The latter are suppressed exponentially by the mass gap
  - Unless there are large cancellations, both should be considered in (i) removing excited state contamination in Γ^n to get ME (ii) Chiral fits to the data

χPT: $N\pi$ state coupling is large in the axial channel



Enhanced coupling to $N\pi$ state: Since the pion is light, the vertex ● can be anywhere in the lattice 3-volume

$$A_i^* \quad \langle i|A_4|j\rangle$$

$\sim V^{-1}$ (for A_i^*) $\qquad$ $\sim V$ (for $\langle i|A_4|j\rangle$)

Oliver Bär: Phys. Rev. D 99, 054506 (2019), Phys. Rev. D 100, 054507 (2019)

Decomposition of ground state matrix elements: $\langle N_\tau A_\mu(t) N_0 \rangle$ provides an over-determined set

Choosing "3" the direction of spin projection

$$\langle N(p_f)|A_{1,2}(q)|N(p_i)\rangle \to -\frac{q_{1,2}q_3}{2M}\,\tilde{G}_P$$

$$\langle N(p_f)|\,A_3(q)\,|N(p_i)\rangle \to -\left[\frac{q_3^2}{2M}\tilde{G}_P - (M+E)G_A\right]$$

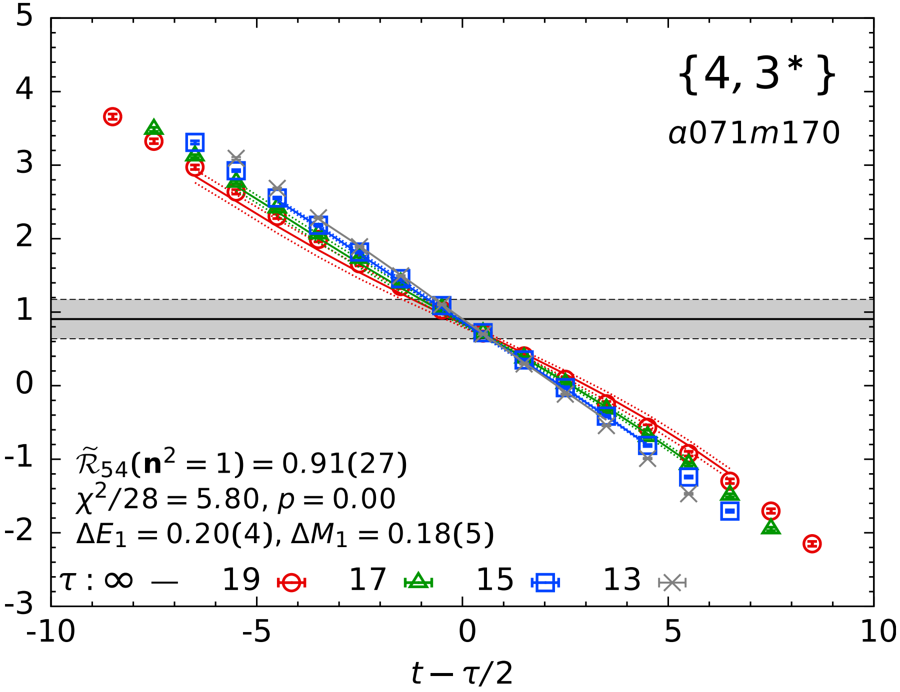
Gives both G_A, $\tilde{G}_P$

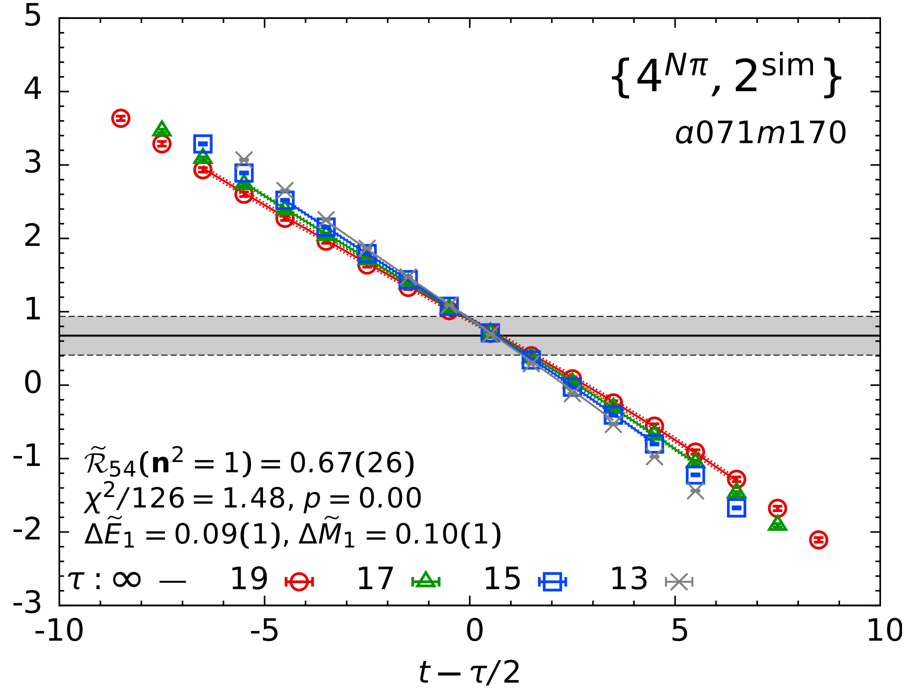
$$\langle N(p_f)|\,A_4(q)\,|N(p_i)\rangle \to -q_3\left[\frac{E-M}{2M}\tilde{G}_P - G_A\right]$$

Redundant. Dominated by excited states

Data driven evidence for $N\pi$ excited state

- $\langle N_\tau A_4(t) N_0 \rangle$ has large ESC
- Fits with $N\pi$ as the first excited state are preferred





FF obtained including $N\pi$ state satisfy PCAC

Gupta et al, PhysRevD.96.114503 (2017) → Jang et al, PRL 124 (2020) 072002

Constraints once FF are extracted from ground state matrix elements

1) PCAC ($\partial_u A_u = 2\hat{m}$P) requires

$$2\hat{m} G_P(Q^2) = 2M_N G_A(Q^2) - \frac{Q^2}{2M_N}\tilde{G}_P(Q^2)$$

2) In any [nucleon] ground state

$$\partial_4 A_4 = \left(E_q - M_0\right) A_4$$

3) G_A, $\tilde{G}_P$ extracted from $\langle N(p_f)|A_i(q)|N(p_i)\rangle$
must be consistent with $\langle N(p_f)|A_4(q)|N(p_i)\rangle$

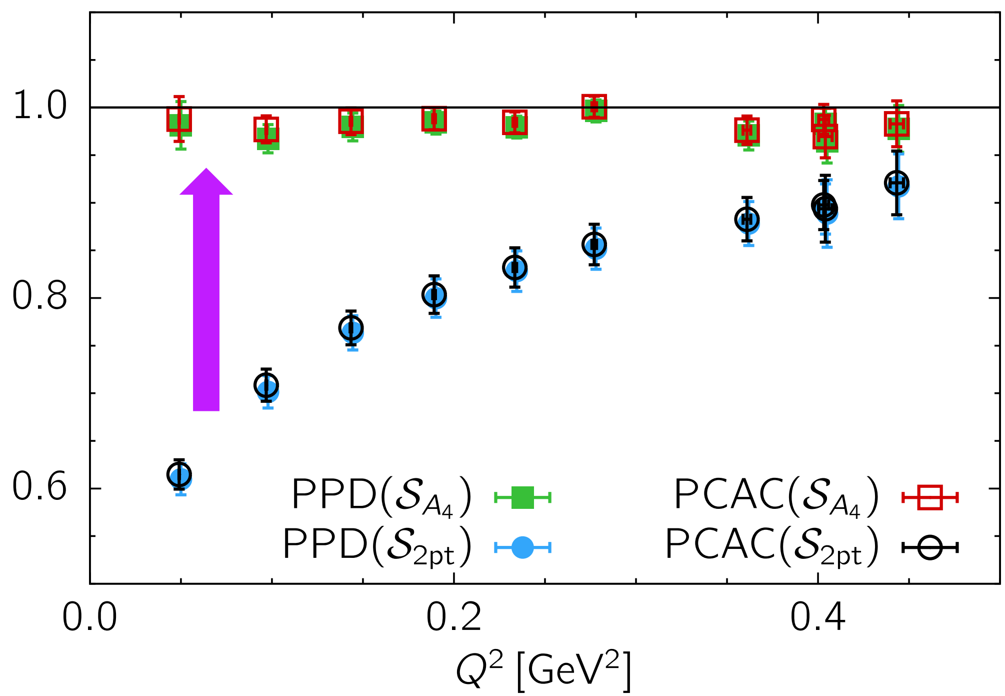
2017→ 2019: Resolution with PCAC and PPD

Gupta et al, PhysRevD.96.114503 → Jang et al, PRL 124 (2020) 072002

On including low mass $N_{p=0}\pi_p$ and $N_p\pi_{-p}$ excited states neglected in previous works, FF satisfy PCAC and PPD at ~5%

$$\frac{\hat{m} G_P}{M_N G_A} + \frac{Q^2 \tilde{G}_P}{4M_N^2 G_A} = 1$$

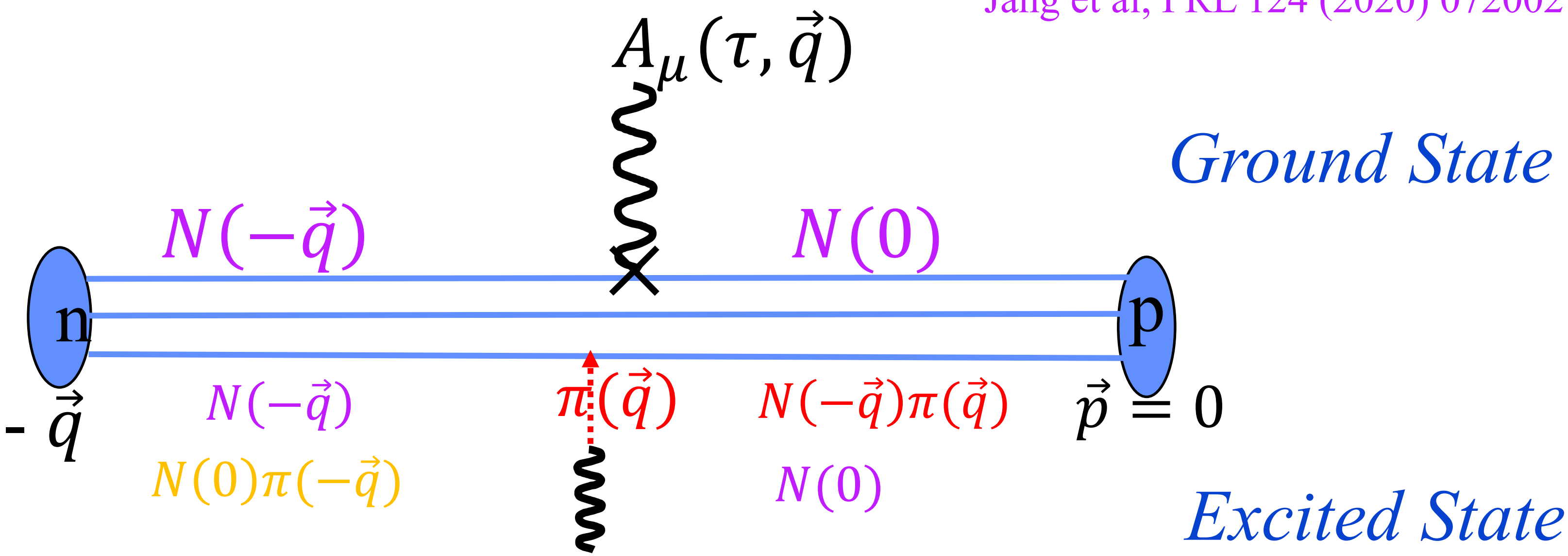
$$\frac{Q^2 + M_\pi^2}{4M_N^2} \frac{\tilde{G}_P(Q^2)}{G_A(Q^2)} = 1$$



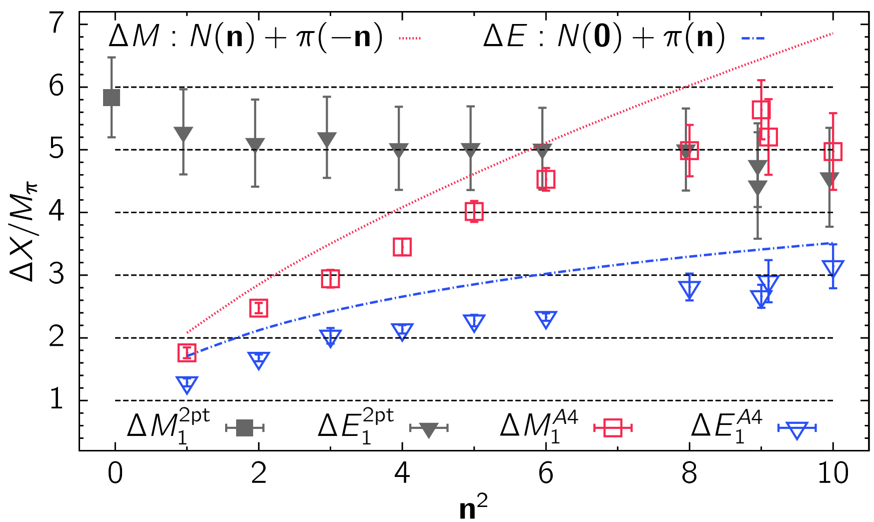
•Also see RQCD Collaboration: *JHEP* 05 (2020) 126, 1911.13150

$N\pi$ state in the axial channel

Jang et al, PRL 124 (2020) 072002



Mass gaps extracted from fits match the above picture

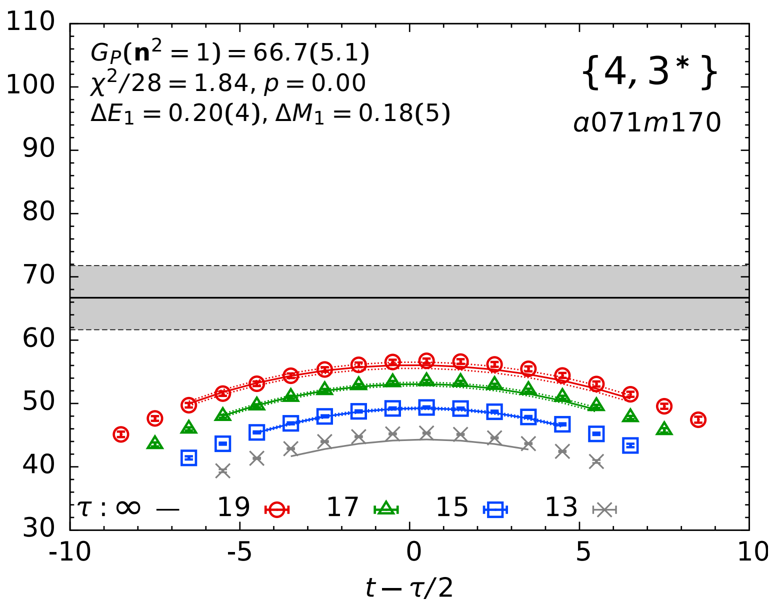


ΔM_1^{A4} and ΔE_1^{A4} are outputs of 2-state fits and not driven by priors

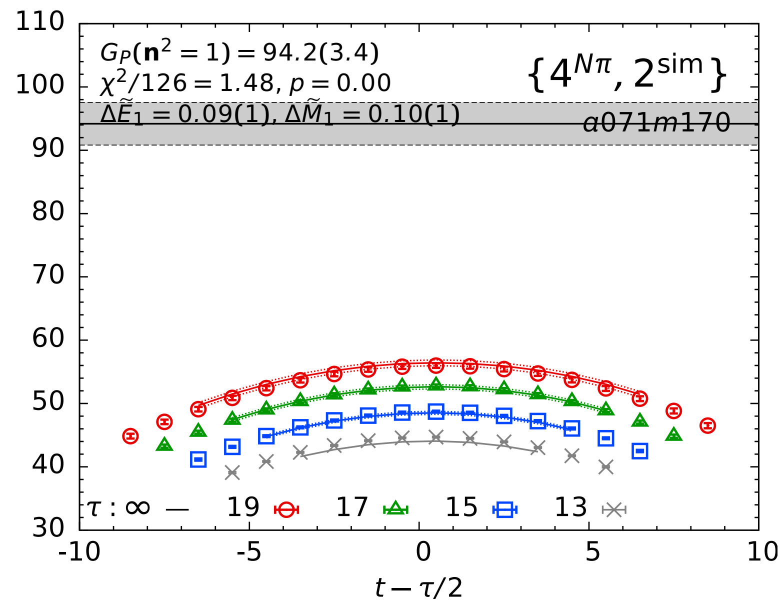
How large is the "$N\pi$" effect?

Output of a simultaneous fit to $\langle A_i \rangle, \langle A_4 \rangle, \langle P \rangle$ (called $\{4^{N\pi}, 2^{sim}\}$ fit) increases the form factors by:

$G_A \sim 5$ %
$\tilde{G}_P \sim 45$ %
$G_P \sim 45$ %



Standard 3-state fit to $\langle P \rangle$



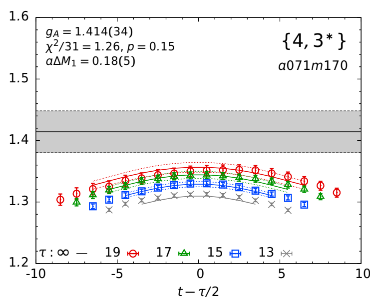
Simultaneous 2-state to $\langle A_i \rangle, \langle A_4 \rangle, \langle P \rangle$ correlators

Consistency in the extraction of g_A

- g_A from forward ME versus $g_A = G_A(Q^2 \to 0)$
- With / without including $N\pi$ state in the analysis
- PCAC

Spectrum from Γ^2

g_A (Forward ME): 1.22(5)

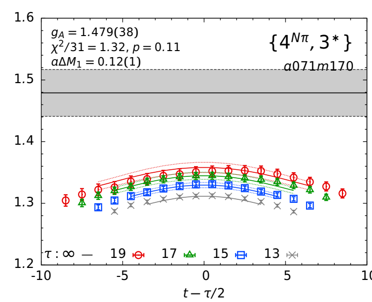


$g_A = G_A(Q^2 \to 0)$: 1.19(5)

$G_A, \tilde{G}_P, G_P$ do not satisfy PCAC

$N\pi$ included in fits (via A_4 or priors)

1.28(5)



1.32(6)

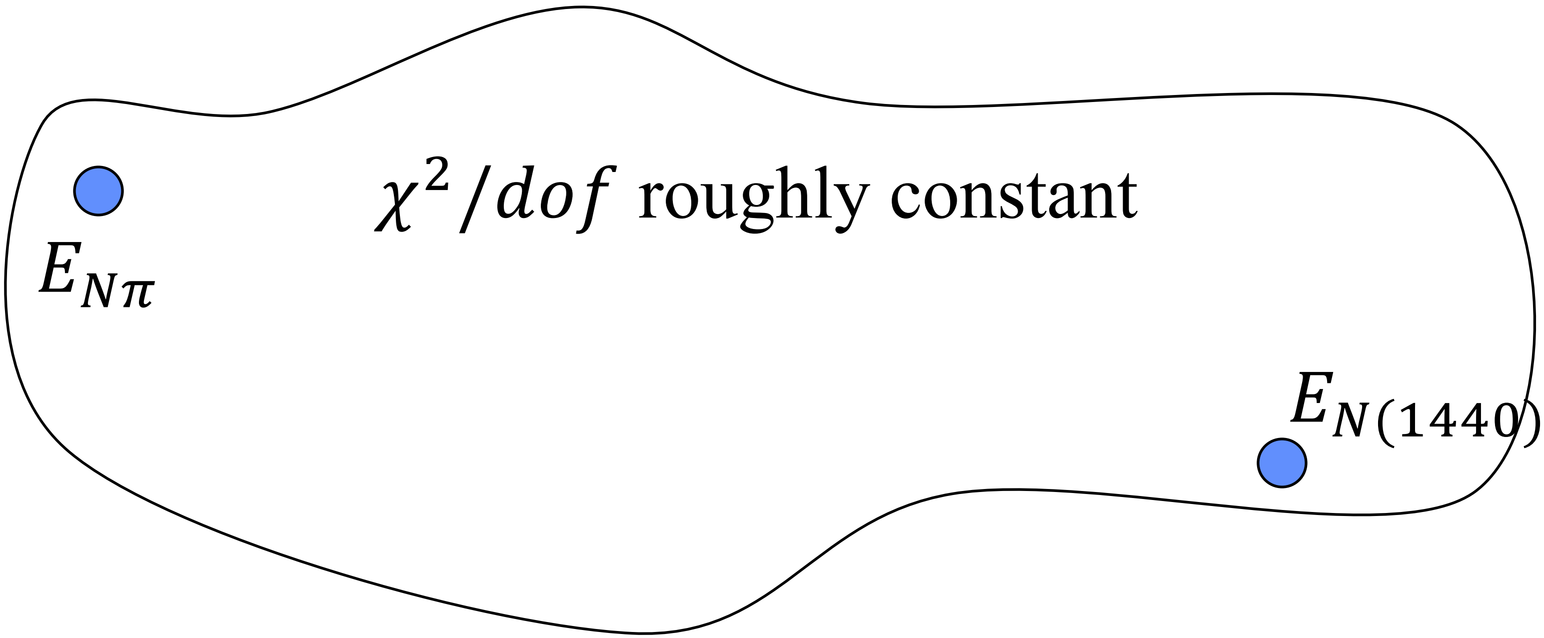
$G_A, \tilde{G}_P, G_P$ with $N\pi$ satisfy PCAC

Essential steps in the analysis

- Remove ESC from correlation functions Γ^n to obtain ME within ground-state nucleon
- Decompose ME into form factors $G(Q^2)$ on each ensemble $\{a, M_\pi, M_\pi L\}$
- Parameterize this $G(Q^2)|_{a,M_\pi,M_\pi L}$
- Perform CCFV extrapolation to get $G(Q^2)|_{cont}$
- Parameterize this $G(Q^2)|_{cont}$

Model averaging should include model choices at each step that have significant effect on result

If ESC is the largest systematic and fits do not select between $\{A_i, E_i\}$



- 2-state fit: Model average different E_1
- 3-state fit: Model average over $\{E_1, E_2\}$

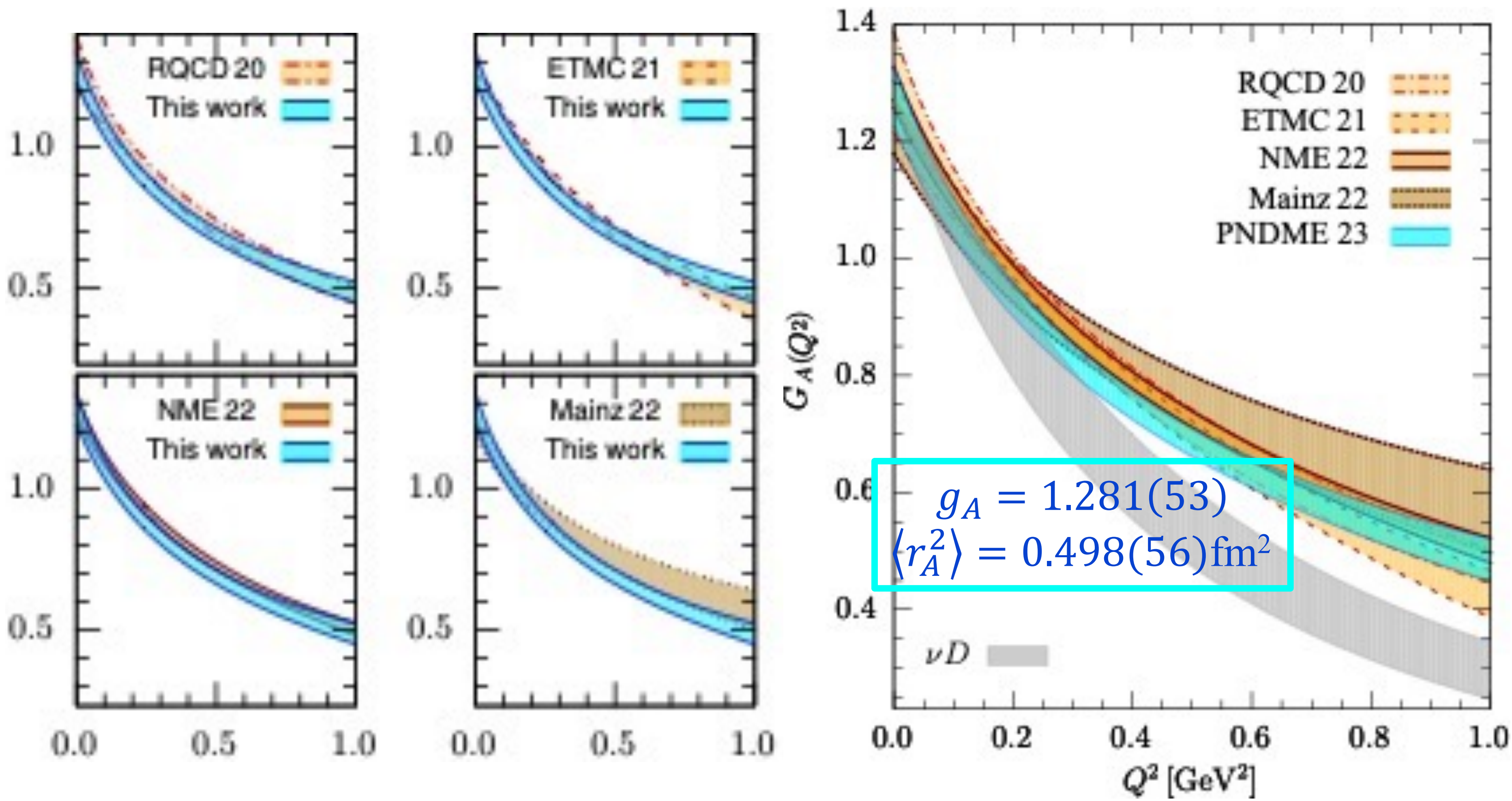
Calculations reviewed in 2305.11330

Collab.	**Ens**	**Lowest M_π (MeV)**	**Excited State**	Q^2	**Continuum-chiral-finite-volume extrap**	g_A
PNDME 23	13	2 physical	With $N\pi$	$z^2 + z^2$	CCFV	1.292(53)(24)
Mainz 22	14	2 physical	Simultaneous ESC and Q^2	z^2	CCFV	1.225(39)(25)
NME 21*	7 (13)	2 @ 170 ⟶1 Phy	With $N\pi$	z^2	Ignore $\{a, M_\pi^2, M_\pi^2 \mathrm{L}\}$ dependence	1.32(6)(5)
ETMC 20*	1 (3)	1⟶3 physical	Without $N\pi$	Only data for G_A	$\{a\}$	1.283(22)
RQCD* 19/23	36 (47)	2 Phy 2 Phy	With $N\pi$ only for $\tilde{G}_P, G_P$	Only data for G_A		1.229—1.302 $[1.284^{28}_{27}]$

PNDME: arXiv:2305.11330,
NME: PRD 105, 054505 (2022),
RQCD: JHEP 05, 126 (2020), PRD 107, 051505 (2023)

Mainz: PRD 106, 074503 (2022)
ETMC: PRD 103, 034509 (2021)
*New data in the pipeline

Comparing axial form factor from LQCD



A consensus is emerging

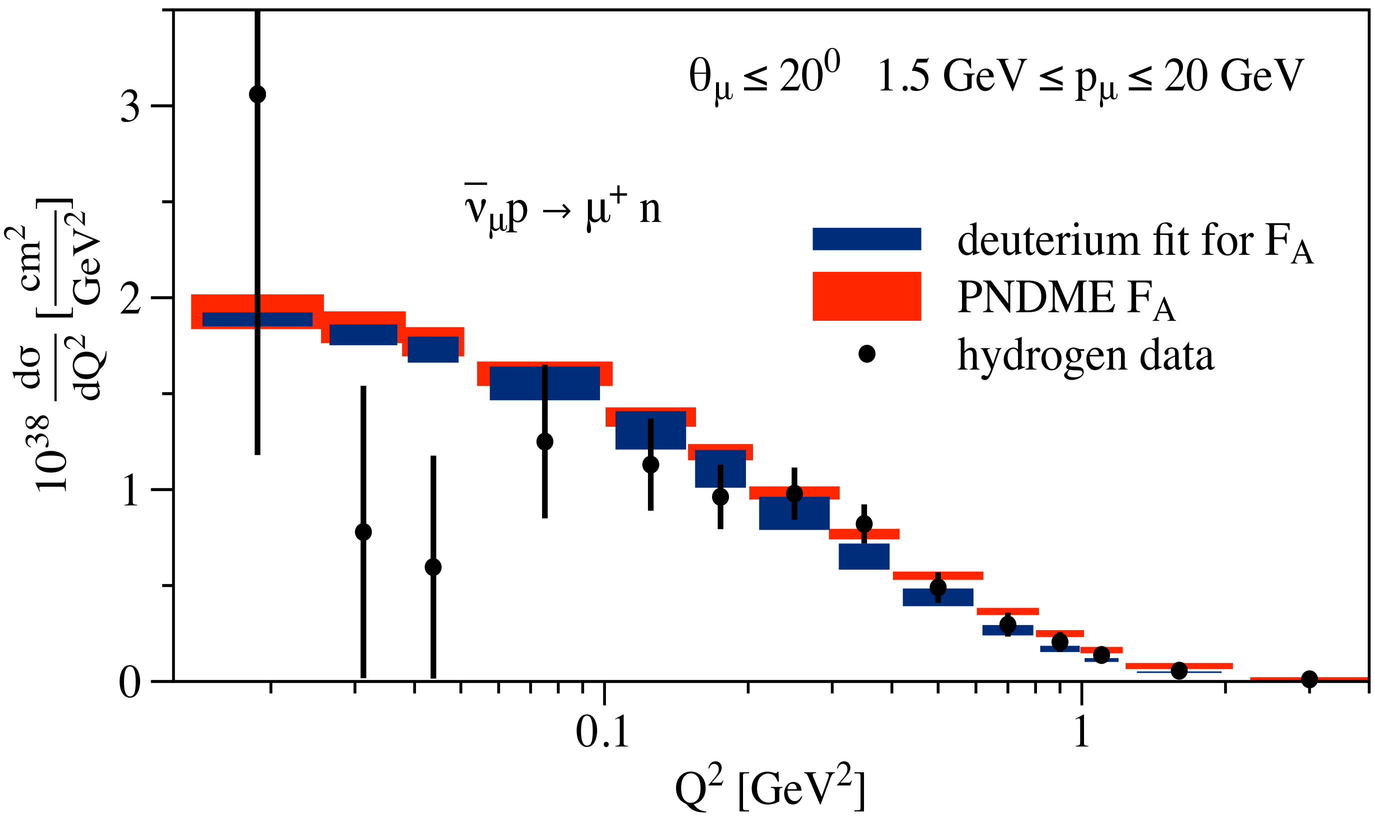
Expected improvements in lattice calculations

$M_\pi \to 135$; $a \to 0$; $L \to \infty$

- $Q^2 = p^2 - (E(p) - M)^2$
- $p = \frac{2\pi}{La} n = \frac{2\pi}{La}(i, j, k)$
- Fixed $\beta = 6/g^2$ (fixed a)
  - $M_\pi \to 135$ MeV keeping $M_\pi L$ fixed $\Rightarrow Q^2$ decreases
- Fixed M_π , take $a \to 0$ keeping L in fermi fixed
  - La fixed $\Rightarrow Q^2$ stays constant
- Fixed M_π and a: take $L \to \infty$
  - p decreases $\Rightarrow Q^2$ decreases

Q^2_{max} in lattice data will decrease but DUNE requires larger Q^2_{max}

Comparing prediction of x-section using AFF from $\nu - D$ and PNDME with MINERvA data



$Q^2 < 0.2$ GeV^2 $\quad 0.2 < Q^2 < 1 \quad$ $Q^2 > 1$ GeV^2

T. Cai, et al., (MINERvA) Nature **volume 614**, pages 48–53 (2023); Phys. Rev. Lett. 130, 161801 (2023)

Oleksandr Tomalak, Rajan Gupta, Tanmoy Bhattacharya, arXiv:2307.14920

Mapping the AFF

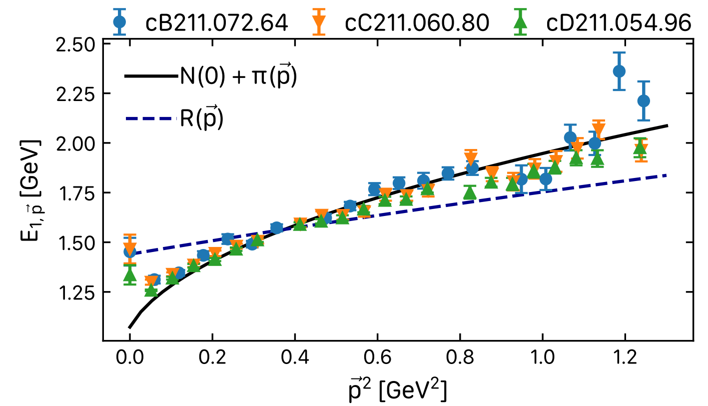
- $0 < Q^2 < 0.2$ GeV^2
  - This region will get populated by simulations with $M_\pi \approx 135$ MeV , a → 0, $M_\pi L > 4$
  - MINERνA data has large errors
  - Characterized by g_A and $\langle r_A^2 \rangle$ and $G_A(Q^2)$ parameterized by a z-expansion with a few terms
- $0.2 < Q^2 < 1$ GeV^2
  - Lattice data mostly from $M_\pi > 200$ MeV simulations
  - Competitive with MINERνA data. Cross check of each other
- $Q^2 > 1$ GeV^2
  - Lattice needs new ideas
  - MINERνA and future experiments

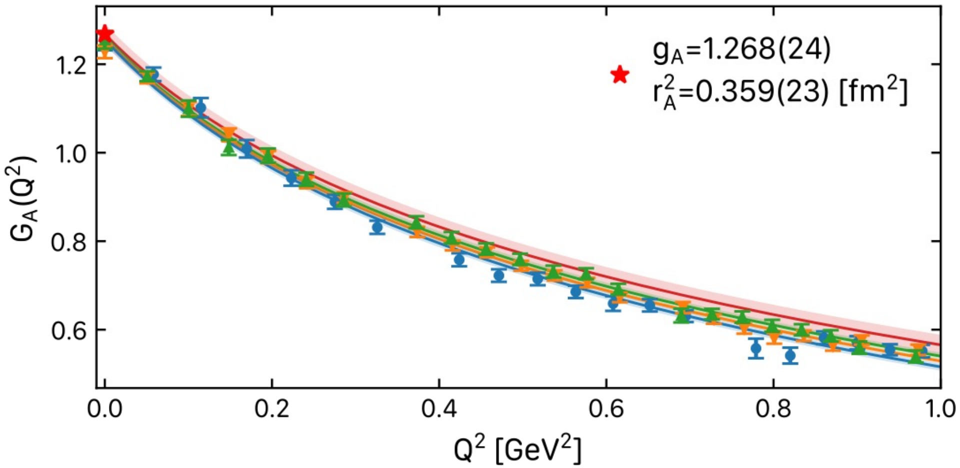
Unpublished data and looking ahead

Update from ETMC (3 $M_\pi \approx 135$ MeV ensembles)

2+1+1-flavor twisted mass ensembles

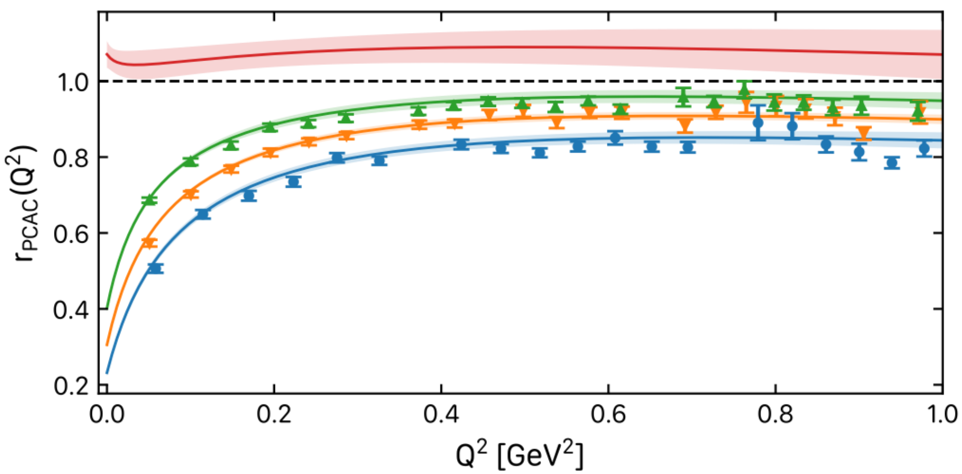
Ens. ID	latt. Vol.	a [fm]	Lm_π
cB211.072.64 (cB64)	$64^3 \times 128$	0.080	3.62
cC211.060.80 (cC80)	$80^3 \times 160$	0.069	3.78
cD211.054.96 (cD96)	$96^3 \times 192$	0.057	3.90





Excited state fits

- 2-state checked against 3-state
- $N\pi$ state not included
- 1[st] excited state mass ≈ *xx* MeV



PCAC test of form factors

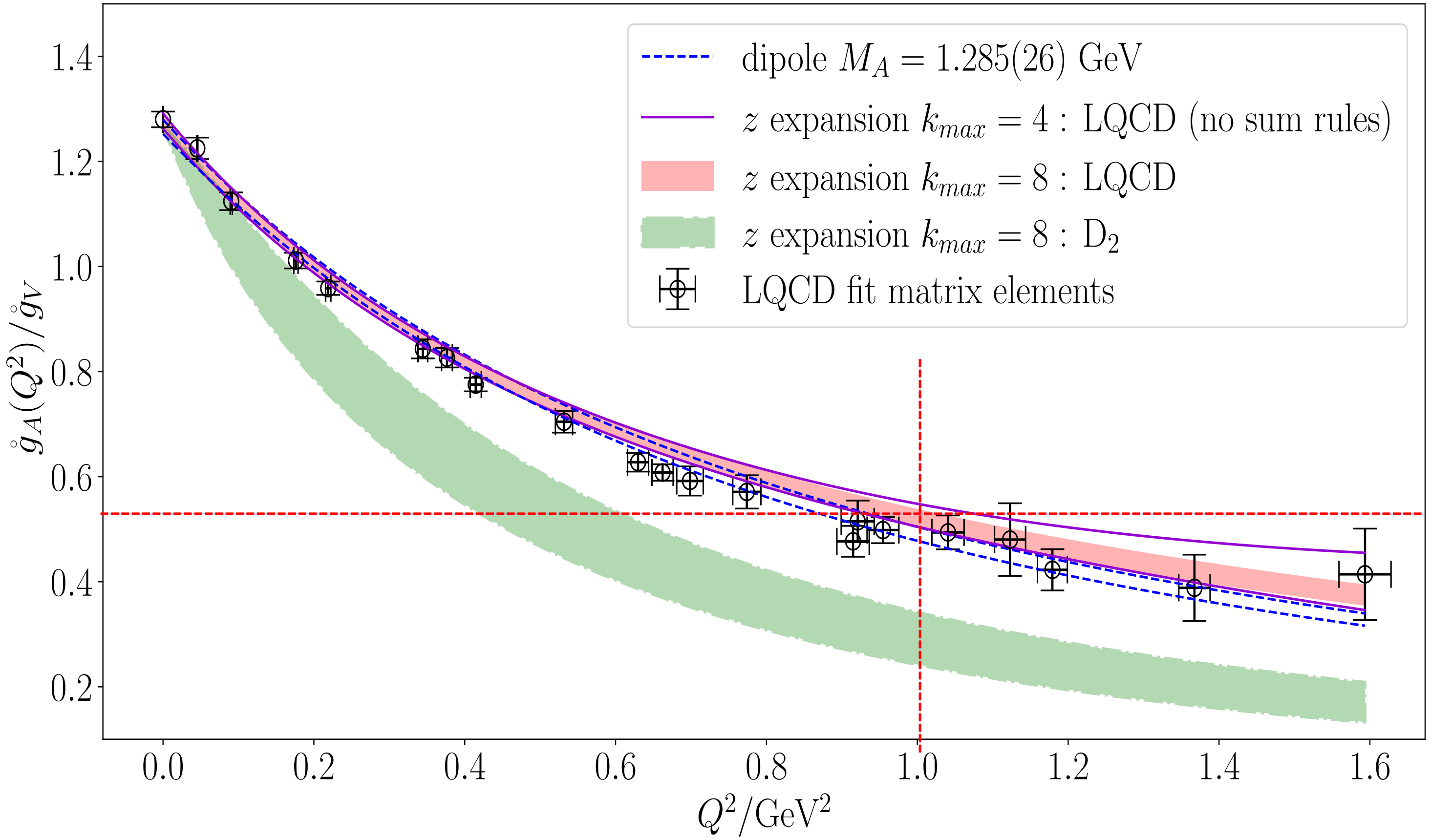
$$r_{\mathrm{PCAC}} = \frac{\frac{m_q}{m_N} G_5(Q^2) + \frac{Q^2}{4m_N^2} G_P(Q^2)}{G_A(Q^2)}$$

Large cut-off effects in twisted mass involving pions

Update from CalLAT Collaboration

(A. Meyer, A. Walker-Loud)

domain-wall on HISQ calculation using sequential prop through sink
$48^3 \times 64$ ensemble (a12m130): $a^{-1} = 1.66$ GeV; $M_\pi = 132$ MeV
Gaussian sources for quark propagators
1000 X 32 (configurations X measurements)

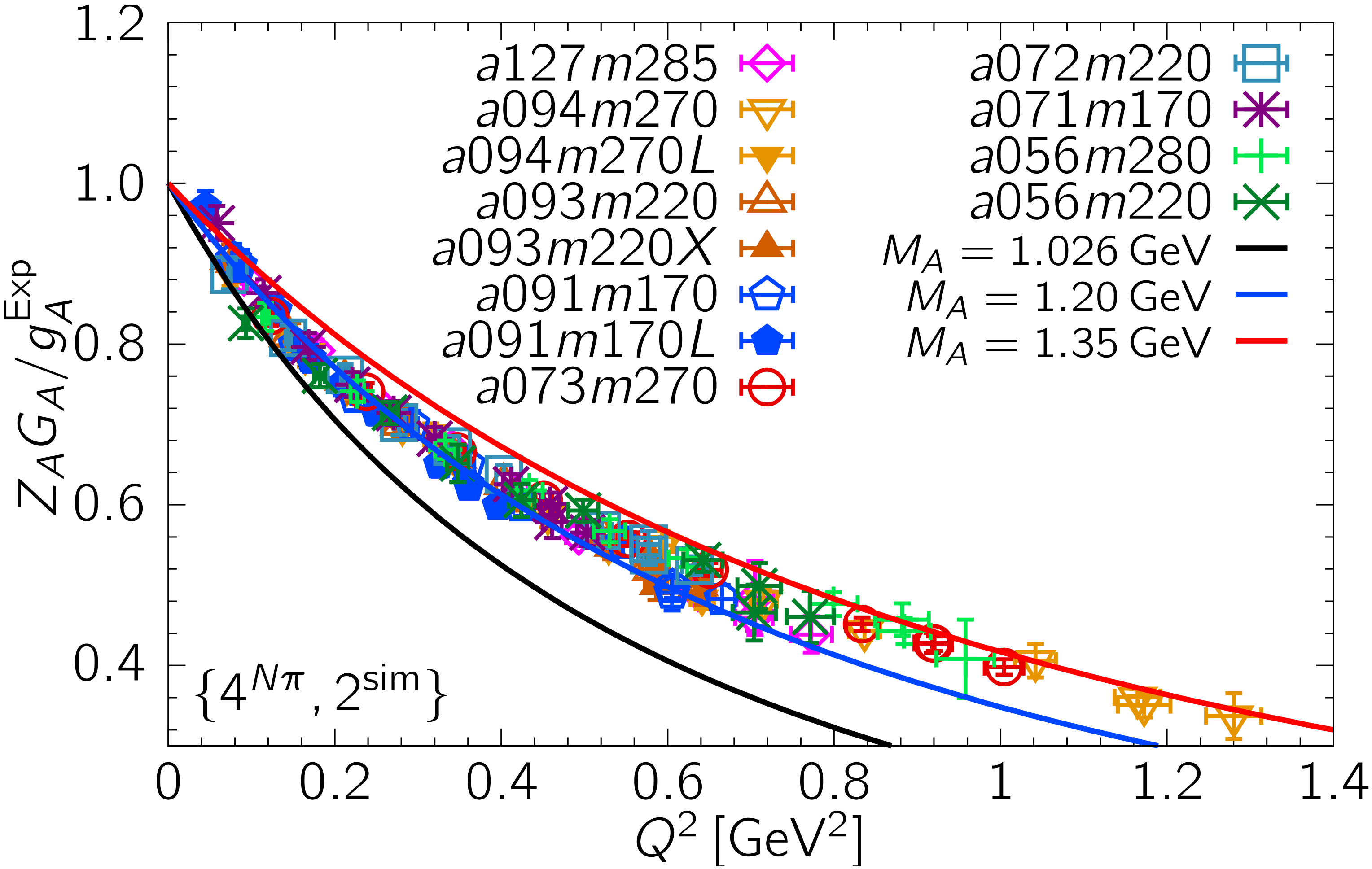


Update from NME Collaboration

(Sungwoo Park, R.G., …)

2+1-flavor clover fermions using sequential prop through sink

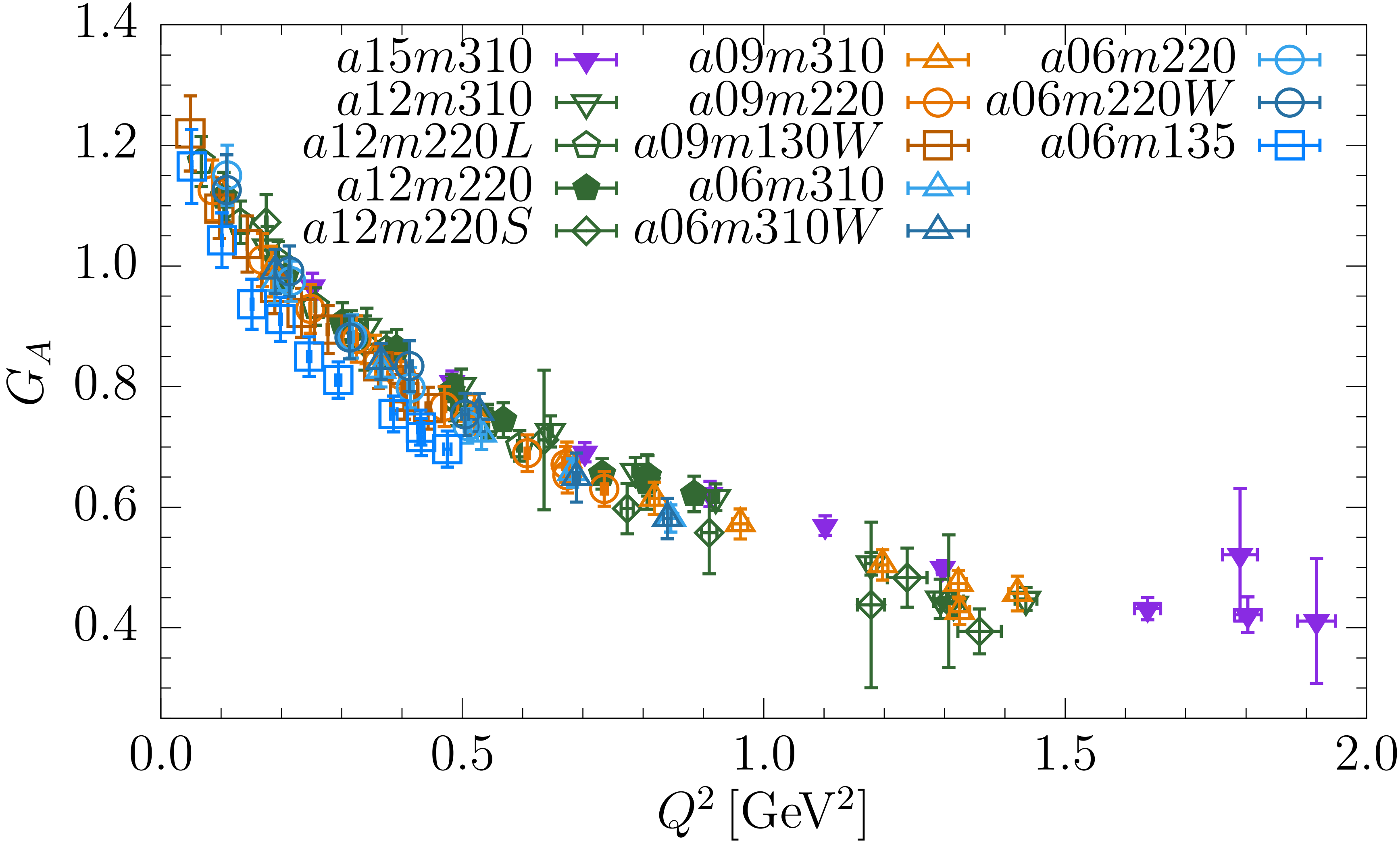
12 Ensembles; Gaussian sources for quark propagators



Update from PNDME Collaboration

(Y-C Jang, R.G., …arXiv:2305:11330)

Clover-on-HISQ calculation. Thirteen 2+1+1-flavor HISQ ensembles. Sequential propagators through nucleon sink; Wuppertal sources for quark propagators

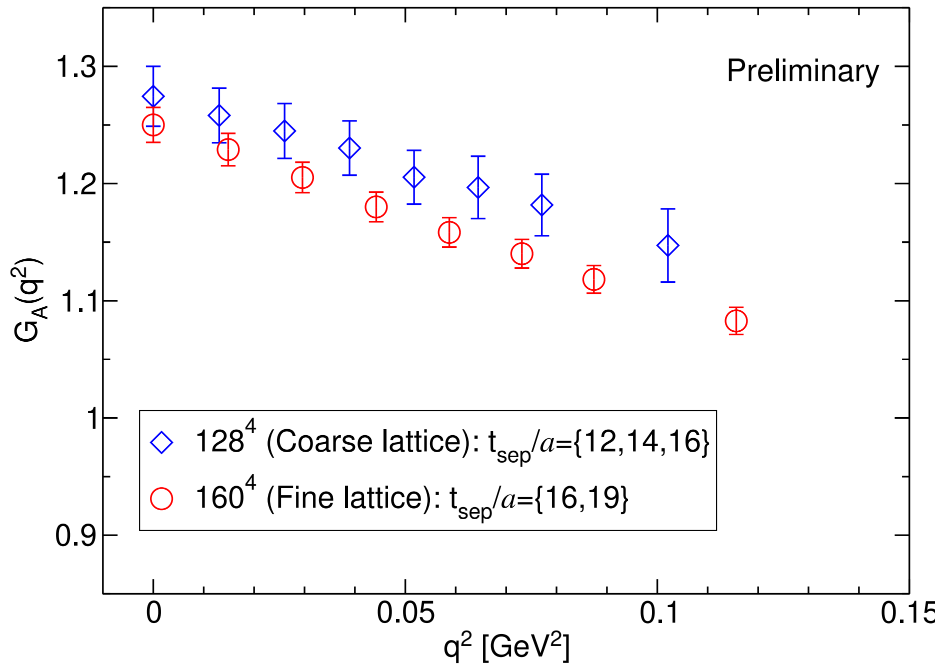


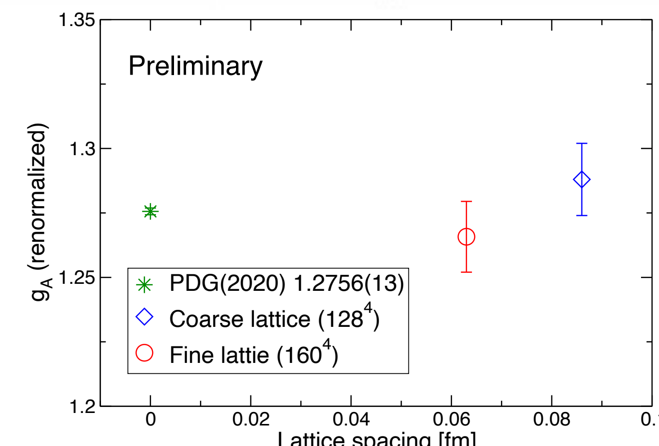
Updates from PACS

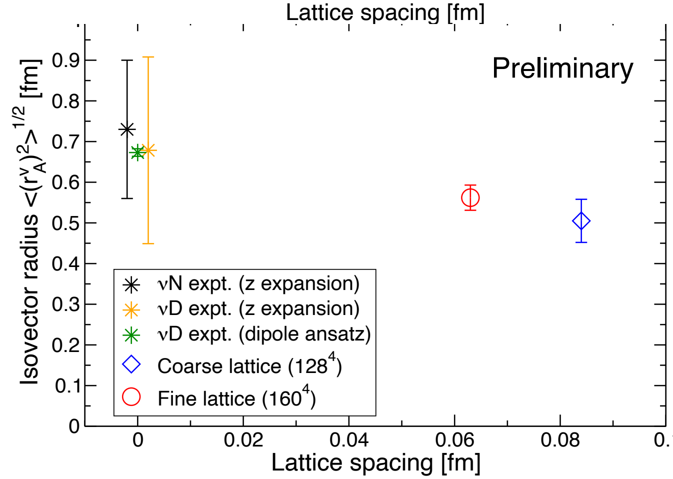
Talk by Ryutaro Tsuji

Stout smeared O(a) improved Wilson quark and Iwasaki gauge actions. 2+1 flavors

Lattice size	128^4	160^4
Spatial volume	$(10.9\ \text{fm})^3$	$(10.1\ \text{fm})^3$
Pion mass	135 MeV	135 MeV
Nucleon mass	0.935(11) GeV	0.946(3) GeV
Lattice spacing	0.086 fm	0.063 fm
$\lvert t_{\text{sink}} - t_{\text{src}} \rvert / a$	10, 12, 14, 16	13, 16, 19
Renormalization	SF, RI-MOM/SMOM	SF







Tuned exponential sources show very little excited-state effects in axial

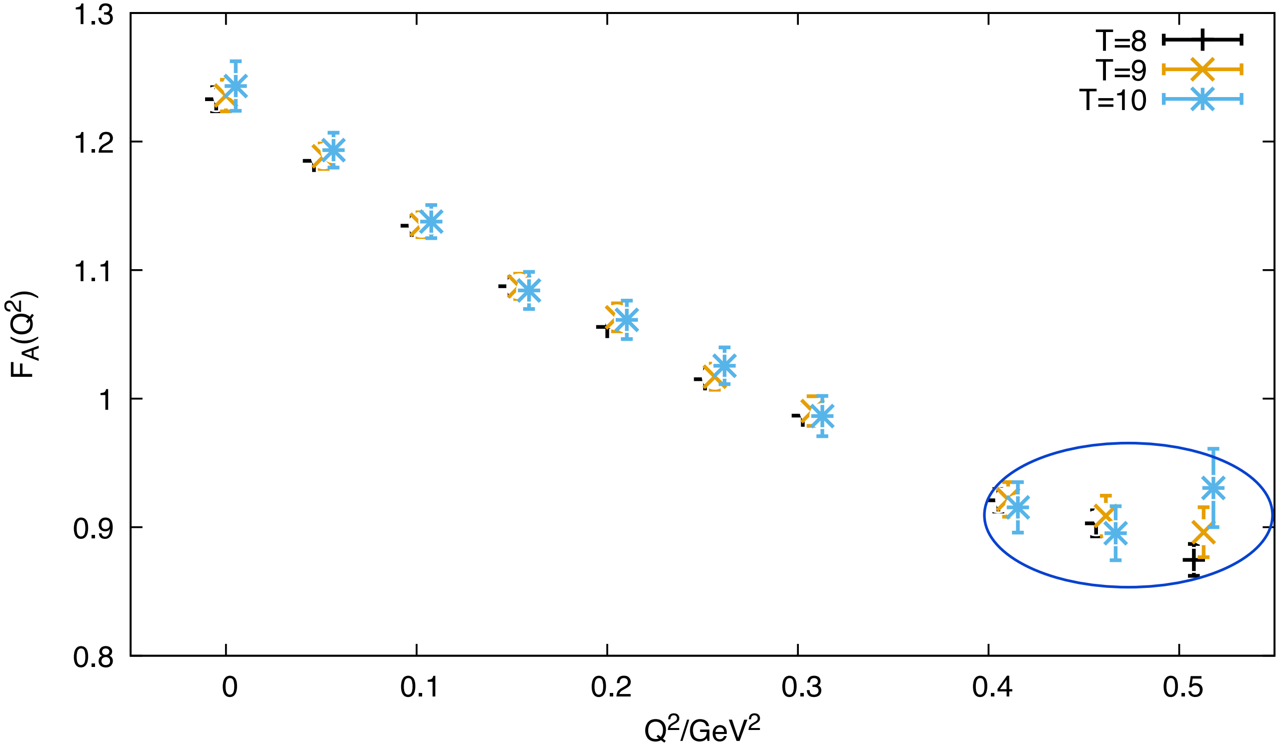
Update from LHP/RBC/UKQCD Collaboration

(S. Ohta arXiv:2211.16018)

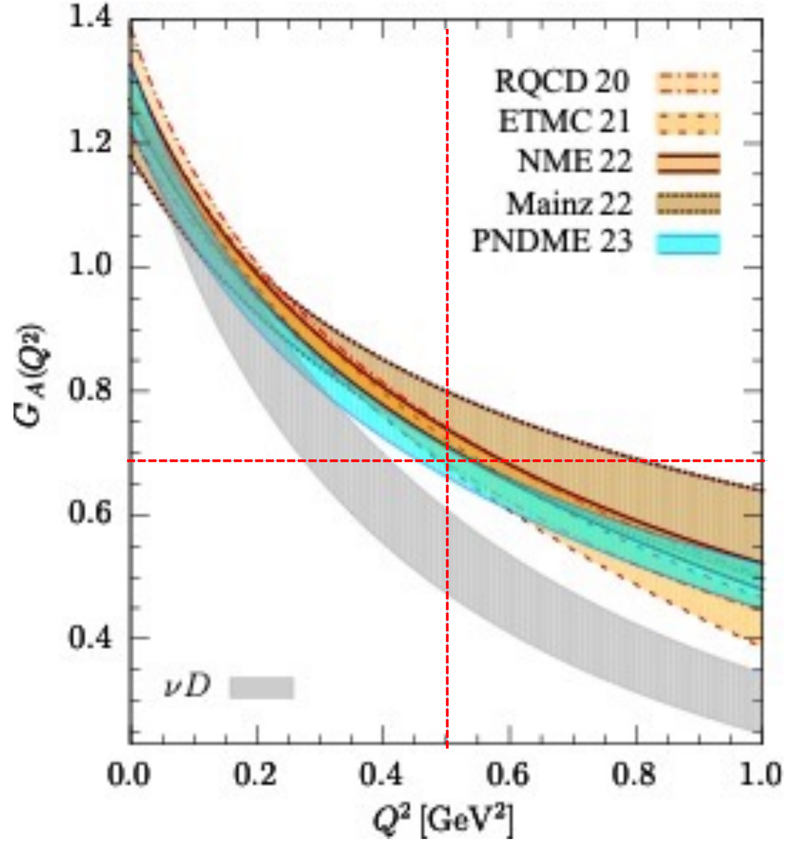
2+1-flavor domain-wall-fermions
$48^3 \times 96$ ensemble: $a^{-1} = 1.730(4)$ GeV
Gaussian sources for quark propagators
120 configurations, ## measurements

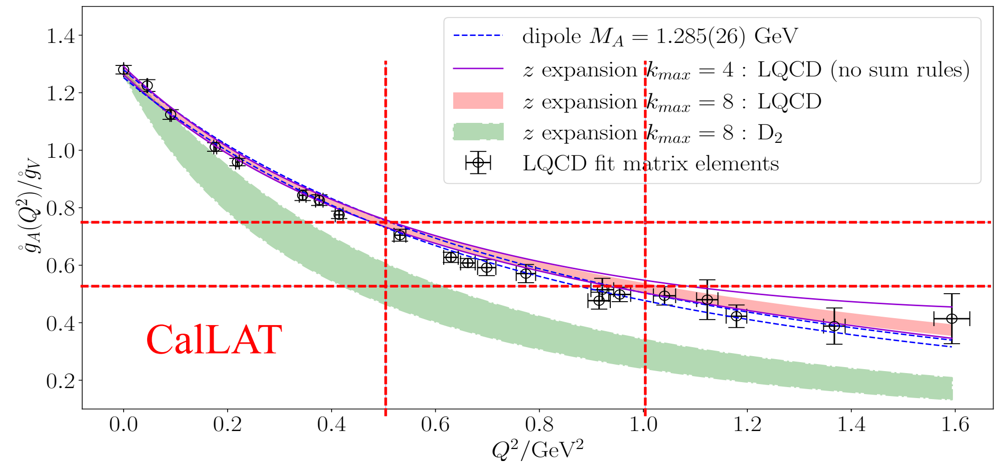
Data at $\tau = 8,9,10$ do not show significant change indicating small excited state effect

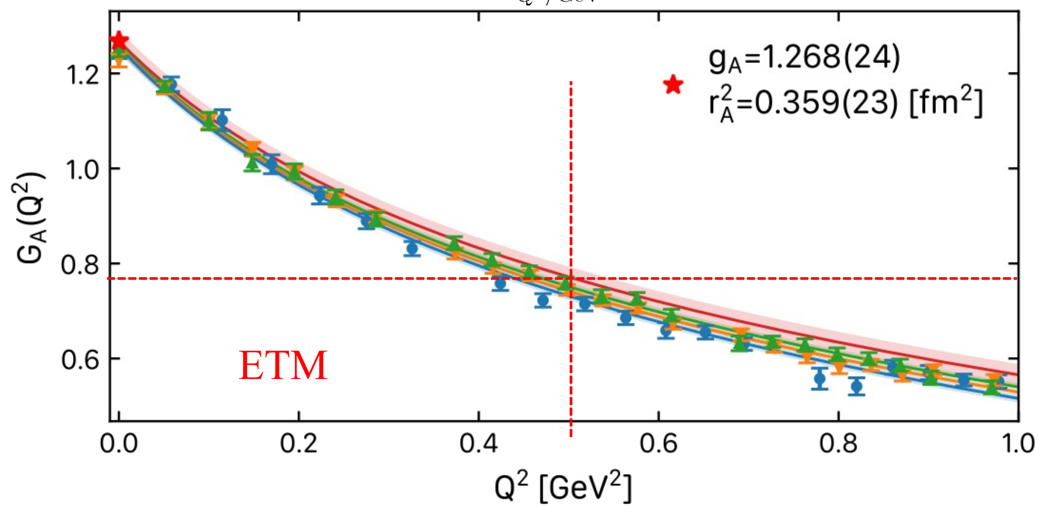
Slower fall-off than PNDME 23 data

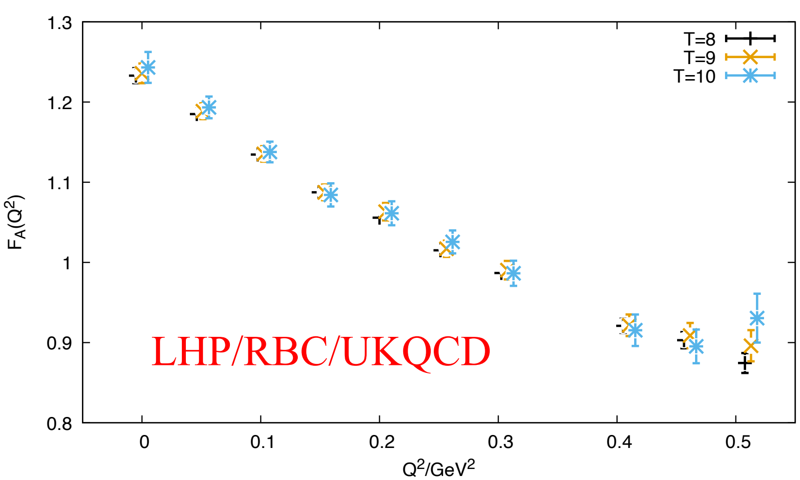


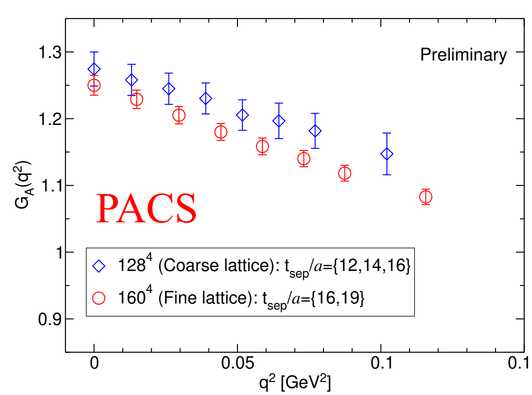
Comparison with unpublished data



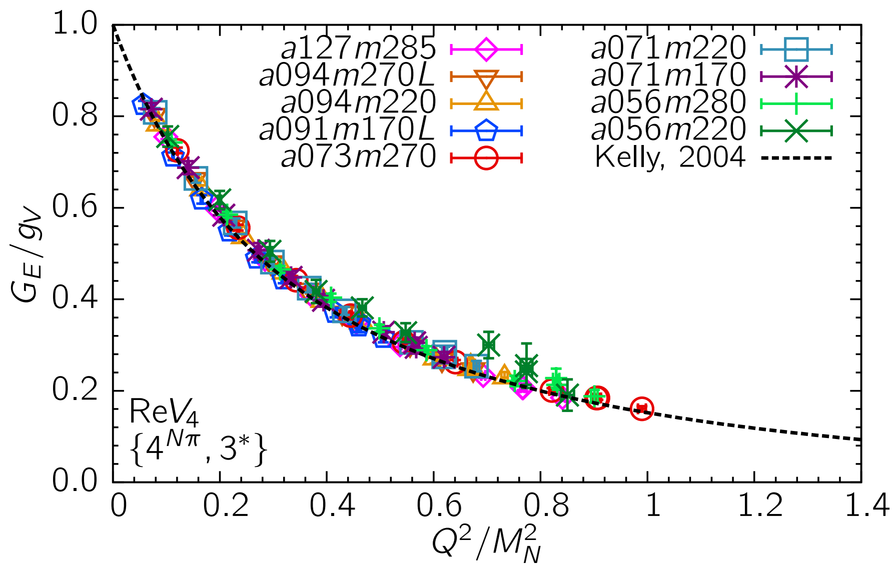




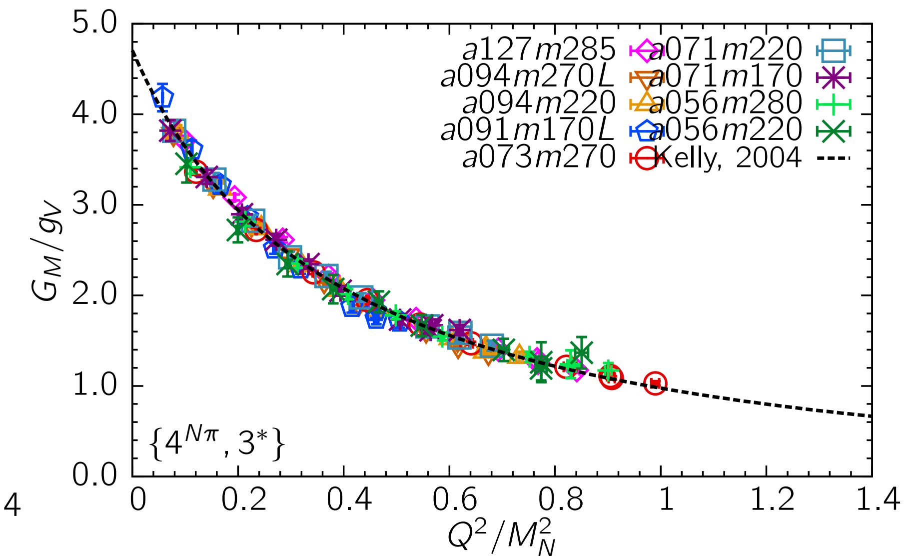




Electric & Magnetic FF



Electric



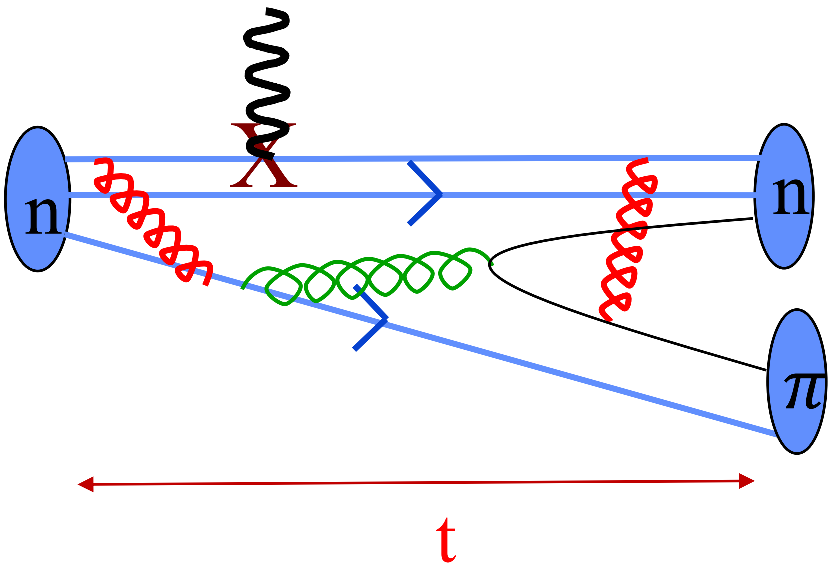
Magnetic

- The extraction of electric and magnetic form factors is insensitive to the details of the excited states
- Vector meson dominance → $N\pi\pi$ state should contribute (some evidence)
- The form factors do not show significant dependence on the lattice spacing or the quark mass
- Good agreement with the Kelly curve. Validates the lattice methodology
- Improve precision and get data over larger range of parameter values

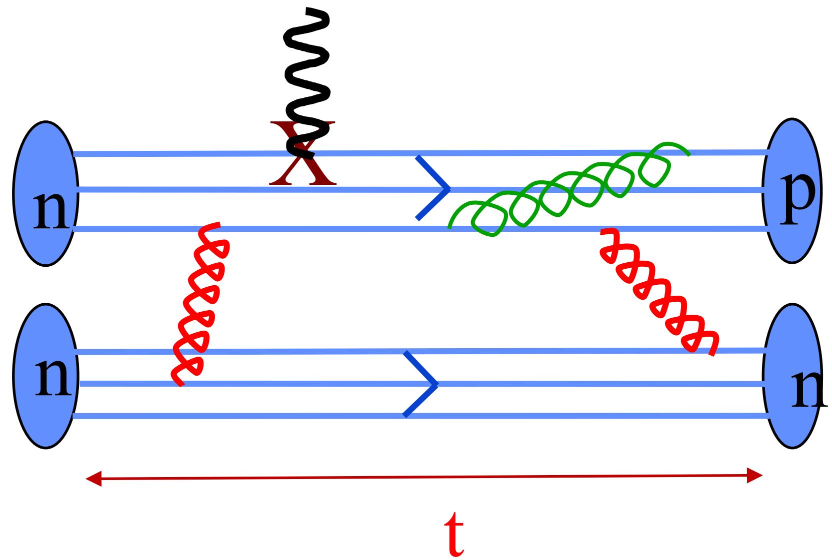
Variational with Multi-hadron states

NPB205 [FS5] (1982) 188

$$\widehat{N} \rightarrow \widehat{N} + c\,\widehat{N\pi}$$



$$\langle\, n\, \pi^{+} \,|\, J_{\mu}^{+}(q) \,|\, n \,\rangle$$



$$\langle\, n\, p \,|\, J_{\mu}^{+}(q) \,|\, n\, n \,\rangle$$

See

- Barca et al, 2211.12278 , 2110.11908
- NPLQCD Collaboration, *Phys.Rev.Lett.* 120 (2018) 15, 152002
- Nuclear matrix elements from lattice QCD for electroweak and beyond-Standard-Model processes, 2008.11160 [hep-lat]

Summary

- Challenges in lattice calculations of nucleon matrix elements:
  - Signal to noise degrades as $e^{-(M_N - 1.5 M_\pi)t}$
  - removing multi-hadrons excited states to get ground state ME
  - including multi-hadrons in initial and/or final state for transition ME
- Continue to develop a robust analysis strategy for removing dominant excited states in various nucleon matrix elements
- Improve chiral and continuum extrapolation. Simulate at more $\{a, M_\pi\}$
- Current $0.04 < Q^2 < 1$ GeV^2. Extend to larger Q^2 for DUNE
- Transition matrix elements
- Goal: Perform a comprehensive analysis of scattering data with input of lattice results for $g_A, G_E(Q^2), G_M(Q^2), G_A(Q^2), \tilde{G}_P(Q^2)$

Improvements in algorithms and computing power are needed to reach few percent precision