

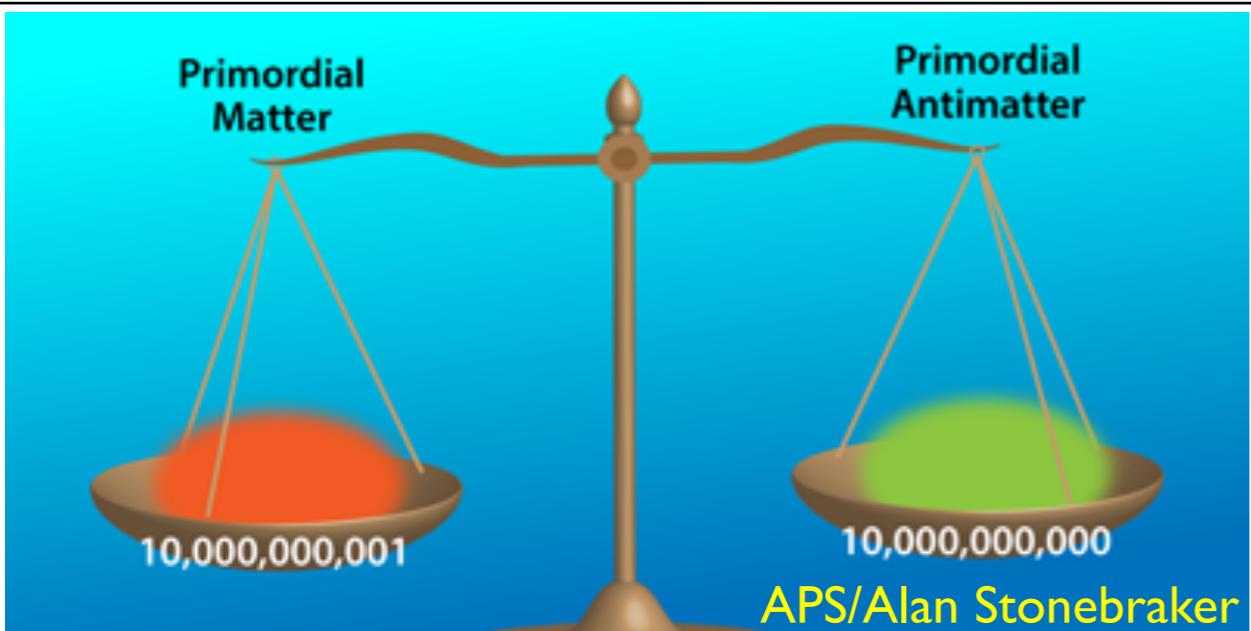
Lattice QCD Spectroscopy for Hadronic CP Violation



André Walker-Loud

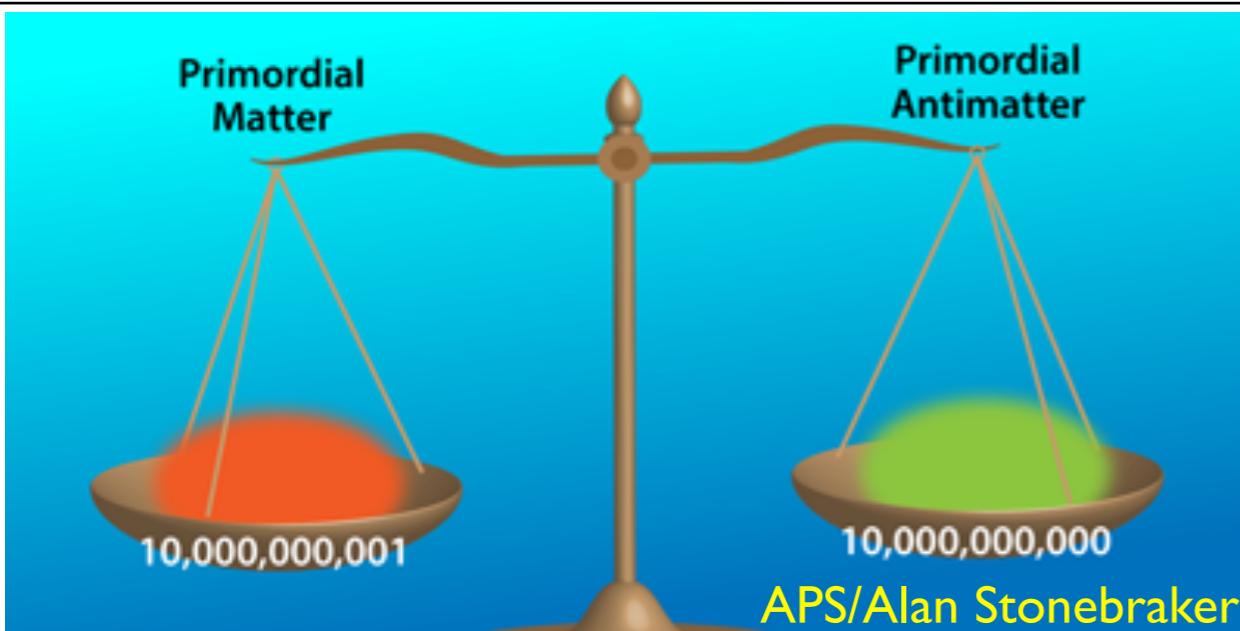


Fundamental Symmetries and Low-Energy Nuclear Physics



- The Universe is matter dominated at roughly 1 ppb:
$$\eta \equiv \frac{X_{p+n}}{X_\gamma} = 6.19(15) \times 10^{-10}$$
- Sources of CP-violation beyond the Standard Model (SM) are needed to generate this observed asymmetry
- Assuming nature is CPT symmetric, this implies T-violation which implies fermions will have permanent electric dipole moments (EDMs)
- This has motivated significant experimental efforts to search (or plan to search) for permanent EDMs in a variety of systems e, n, p, deuteron, triton, ^3He , ..., ^{199}Hg , ^{225}Ra , ^{229}Pa ,...

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- There are now a number of groups working on computing EDMs from the QCD-theta term. If we can determine the couplings - they can be used in the chiral extrapolations, removing a free parameter from their analysis

| | | |
|--------------|---|------------|
| Mereghetti | : | Mon 10:00 |
| Bhattacharya | : | Mon 14:40 |
| Dragos | : | Tues 14:00 |
| Kim | : | Tues 14:20 |
| Liang | : | Tues 6:45 |
| Walker-Loud | : | NOW |
| Yoon | : | Thur 8:30 |
| Syritsyn | : | Thur 8:50 |

Fundamental Symmetries and Low-Energy Nuclear Physics

- In a large nucleus, the long-range pion exchange will dominate the nuclear EDM

$$\mathcal{L}_{CPV} = -\frac{\bar{g}_0}{2F_\pi} \bar{N} \vec{\pi} \cdot \vec{\tau} N - \frac{\bar{g}_1}{2F_\pi} \bar{N} \pi_3 N - \frac{\bar{g}_2}{2F_\pi} \pi_3 \bar{N} \left(\tau_3 - \frac{\pi_3}{F_\pi} \vec{\pi} \cdot \vec{\tau} \right) N$$

- For the QCD theta term

$$\{\bar{g}_1, \bar{g}_2\} \sim \bar{g}_0 \frac{m_\pi^2}{\Lambda_\chi^2}$$

- For more generic CP Violating operators

$$\bar{g}_2 \sim \{\bar{g}_0, \bar{g}_1\} \frac{m_\pi^2}{\Lambda_\chi^2} \quad \bar{g}_1 \sim \bar{g}_0$$

Fundamental Symmetries and Low-Energy Nuclear Physics

- The nuclear EDM is proportional to the Schiff moment

$$S = \sum_{i \neq 0} \frac{\langle \Phi_0 | S_z | \Phi_i \rangle \langle \Phi_i | H_{CPV} | \Phi_0 \rangle}{E_0 - E_i} + c.c.$$

$$S = \frac{2M_N g_A}{F_\pi} (a_0 \bar{g}_0 + a_1 \bar{g}_1 + a_2 \bar{g}_2)$$

- The Schiff parameters $\{a_0, a_1, a_2\}$ are computed with nuclear models under the assumption the CPV operator does not significantly distort the nuclear wave-function
- For a QCD theta term only $\bar{g}_1 \sim \bar{g}_2 \sim 0$ and thus a constraint on $\bar{\theta}$ can be made through the relation

$$\bar{g}_0 = \frac{\delta M_{n-p}^{m_d - m_u}}{m_d - m_u} \frac{2m_d m_u}{m_d + m_u} \bar{\theta} = \alpha \frac{2m_d m_u}{m_d + m_u} \bar{\theta}$$

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Gaffney et al. Nature 497 (2013)

- ^{225}Ra is interesting nucleus as it is *pear-shaped* (octupole deformed)

- “stiff” core making nuclear model calculations more reliable
- nearly degenerate parity partner state

$$E_{1/2}^- - E_{1/2}^+ = 55 \text{ KeV}$$

- $10^2 - 10^3$ enhancement of a_0, a_1, a_2



Fundamental Symmetries and Low-Energy Nuclear Physics

- Sources of CP-Violation in quark sector:

| Operator | [Operator] | No. Operators |
|------------------|------------|---------------|
| $\bar{\theta}$ | 4 | 1 |
| quark EDM | 6 | 2 |
| quark Chromo-EDM | 6 | 2 |
| Weinberg (GGG) | 6 | 1 |
| 4-quark | 6 | 2 |
| 4-quark induced | 6 | 1 |

Fundamental Symmetries and Low-Energy Nuclear Physics

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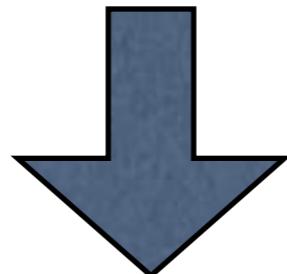
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$$\mathcal{L}_{CPV} = -\frac{g_s^2 \bar{\theta}}{32\pi^2} \tilde{G}_{\mu\nu} G^{\mu\nu} - \frac{i}{2} \bar{q} \sigma^{\mu\nu} \gamma_5 (\tilde{d}_0 + \tilde{d}_3 \tau_3) G_{\mu\nu} q$$



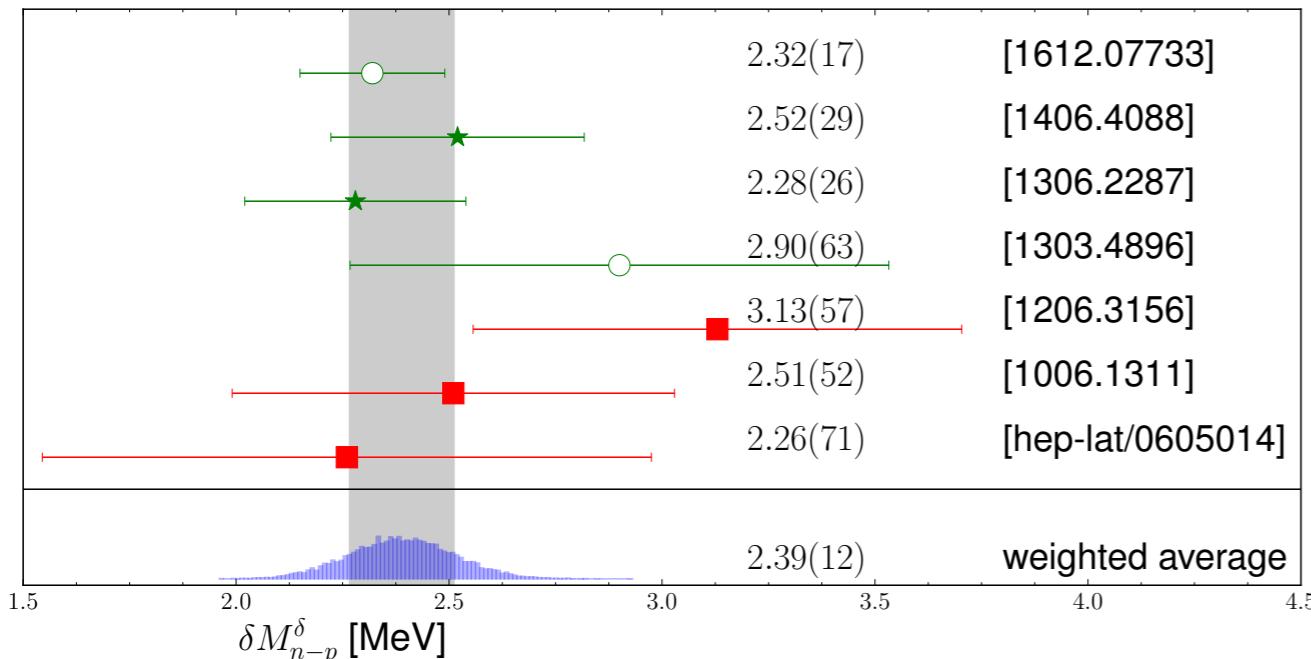
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QCD Isospin Violation and CP-violating π -N

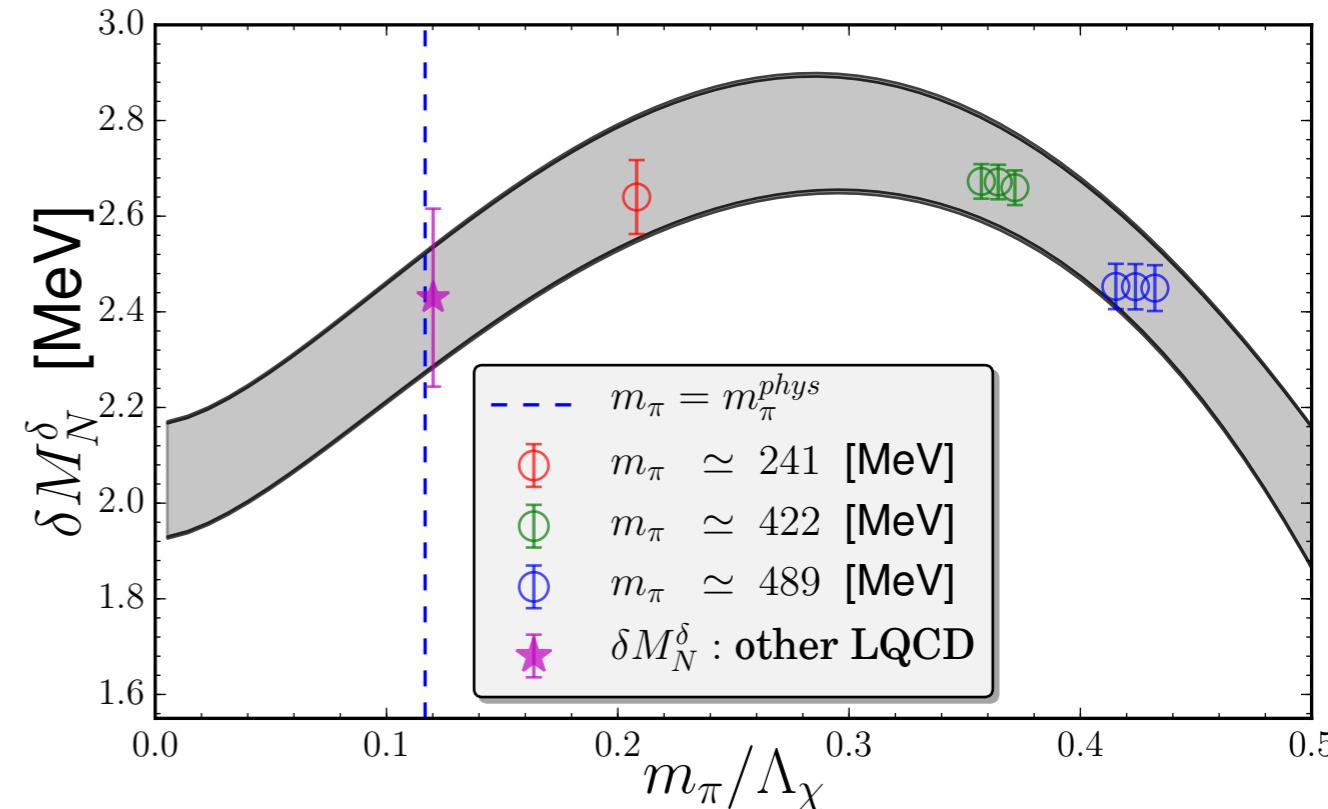
- A precise determination of the strong isospin breaking contribution to Mn-Mp teaches us about CP-violation
Crewther, Vecchia, Veneziano, Witten, Phys.Lett. 91B (1980)

$$\bar{g}_0 = \frac{\delta M_{n-p}^{m_d - m_u}}{m_d - m_u} \frac{2m_d m_u}{m_d + m_u} \bar{\theta} = \alpha \frac{2m_d m_u}{m_d + m_u} \bar{\theta}$$

QCD Isospin Violation and CP-violating π -N



Heffernan, Banerjee, Walker-Loud [1706.04991]



Brantley, Joo, Mastropas, Mereghetti, Monge-Camacho, Tiburzi, Walker-Loud [1612.07733]

Using
de Vries, Mereghetti, Walker-Loud
Phys. Rev. C92 (2015) [1506.06247]

$$\frac{\bar{g}_0}{\sqrt{2}f_\pi} = (14.7 \pm 1.8 \pm 1.4) \cdot 10^{-3} \bar{\theta}$$

NNLO χ PT Walker-Loud [0904.2404]

$$\delta M_{n-p}^{m_d - m_u} = \delta \left\{ \alpha \left[1 - \frac{m_\pi^2}{(4\pi f_\pi)^2} (6g_A^2 + 1) \ln \left(\frac{m_\pi^2}{\mu^2} \right) \right] \right. \\ \left. (g_A = 1.27, f_\pi = 130 \text{ MeV}) \quad + \beta(\mu) \frac{2m_\pi^2}{(4\pi f_\pi)^2} \right\}$$

Computational Strategy

• QCD Theta term

$$\mathcal{L}_{CPV} = -\frac{g_s^2 \bar{\theta}}{32\pi^2} \tilde{G}_{\mu\nu} G^{\mu\nu} \rightarrow \mathcal{L}_{CPV}^\chi = -\frac{\bar{g}_0}{2F_\pi} \bar{N} \vec{\pi} \cdot \vec{\tau} N$$

Symmetries $\rightarrow \bar{g}_0 = \frac{\delta M_{n-p}^{m_d - m_u}}{m_d - m_u} \frac{2m_d m_u}{m_d + m_u} \bar{\theta}$

$$\delta M_{n-p}^{m_d - m_u} = \alpha(m_d - m_u)$$

Simple spectroscopic calculation allows us to determine this long-range CP-Violating pion-nucleon coupling

This relation holds to NNLO in the chiral expansion up to small corrections

de Vries, Mereghetti, Walker-Loud
Phys. Rev. C92 (2015) [1506.06247]

Computational Strategy

de Vries, Mereghetti, Seng, Walker-Loud
Phys. Lett. B766 (2017) [1612.01567]

● Quark Chromo-EDM Operators

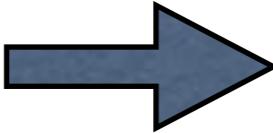
$$\mathcal{L}_{\bar{q}q}^6 = -\frac{i}{2}\bar{q}\sigma^{\mu\nu}\gamma_5(\tilde{d}_0 + \tilde{d}_3\tau_3)G_{\mu\nu}q - \frac{1}{2}\bar{q}\sigma^{\mu\nu}(\tilde{c}_3\tau_3 + \tilde{c}_0)G_{\mu\nu}q$$

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Symmetries  $\bar{g}_0 = \delta_q M_N \frac{\tilde{d}_0}{\tilde{c}_3} + \delta M_N \frac{\Delta_q m_\pi^2}{m_\pi^2} \frac{\tilde{d}_3}{\tilde{c}_0}$

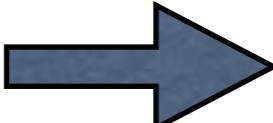
$$\bar{g}_3 = -2\sigma_{\pi N} \left(\frac{\Delta_q M_N}{\sigma_{\pi N}} - \frac{\Delta_q m_\pi^2}{m_\pi^2} \right) \frac{\tilde{d}_3}{\tilde{c}_0}$$

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Again, all that is needed are simple spectroscopic quantities

δM_N = nucleon mass splitting induced by $\mathcal{O} = \delta \bar{q} \tau_3 q$,

$\sigma_{\pi N}$ = nucleon sigma-term induced by $\mathcal{O} = -\bar{m} \bar{q} q$,

$\delta_q M_N$ = nucleon mass splitting induced by $\mathcal{O} = -(\tilde{c}_3/2) \bar{q} \sigma^{\mu\nu} \tau_3 G_{\mu\nu} q$,

$\Delta_q M_N$ = nucleon sigma-term induced by $\mathcal{O} = -(\tilde{c}_0/2) \bar{q} \sigma^{\mu\nu} G_{\mu\nu} q$,

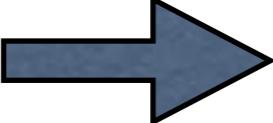
$\Delta_q m_\pi^2$ = pion sigma-term induced by $\mathcal{O} = -(\tilde{c}_0/2) \bar{q} \sigma^{\mu\nu} G_{\mu\nu} q$,

Computational Strategy

de Vries, Mereghetti, Seng, Walker-Loud
Phys. Lett. B766 (2017) [1612.01567]

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Symmetries 

$$\bar{g}_0 = \delta_q M_N \frac{\tilde{d}_0}{\tilde{c}_3} + \delta M_N \frac{\Delta_q m_\pi^2}{m_\pi^2} \frac{\tilde{d}_3}{\tilde{c}_0}$$

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Actually, there are subtle difficulties with the simple relations

Seng and Ramsey-Musolf, Phys. Rev. C96 (2017)

which require a modified relation in order to maintain the relations to NNLO (up to small NNLO corrections)

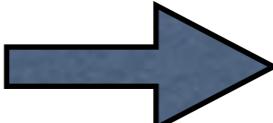
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$$\bar{g}_3 = -2\sigma_{\pi N} \left(\frac{\Delta_q M_N}{\sigma_{\pi N}} - \frac{\Delta_q m_\pi^2}{m_\pi^2} \right) \frac{\tilde{d}_3}{\tilde{c}_0}$$

$$\bar{g}_0 = \tilde{d}_0 \left(\frac{d}{d\tilde{c}_3} + r \frac{d}{d(\bar{m}\varepsilon)} \right) \delta m_N + \delta m_{N,\text{QCD}} \frac{1-\varepsilon^2}{2\varepsilon} (\bar{\theta} - \bar{\theta}_{\text{ind}})$$

$$\bar{g}_3 = -2\tilde{d}_3 \left(\frac{d}{d\tilde{c}_0} - r \frac{d}{d\bar{m}} \right) \Delta m_N , \quad r = \frac{1}{2} \frac{\langle 0 | \bar{q} g_s \sigma_{\mu\nu} G^{\mu\nu} q | 0 \rangle}{\langle 0 | \bar{q} q | 0 \rangle}$$

An additional benefit of these relations - the quadratic $1/a^2$ mixing of the mass operator into the CDM cancels, leaving a residual logarithmic mixing

On the Feynman–Hellmann Theorem in Quantum Field Theory and the Calculation of Matrix Elements

Chris Bouchard, Chia Cheng Chang, Thorsten Kurth, Kostas Orginos, Andre Walker-Loud

(Submitted on 21 Dec 2016 (v1), last revised 5 Jul 2017 (this version, v2))

Feynman-Hellmann theorem $\partial_\lambda E_n|_{\lambda=0} = \langle n | H_\lambda | n \rangle$

“Feynman-Hellmann” correlation function

$$\begin{aligned} \frac{\partial m_\lambda^{eff}(t, \tau)}{\partial \lambda} \Big|_{\lambda=0} &= \frac{1}{\tau} \left[\frac{-\partial_\lambda C_\lambda(t + \tau)}{C_\lambda(t + \tau)} - \frac{-\partial_\lambda C_\lambda(t)}{C_\lambda(t)} \right]_{\lambda=0} \\ &= g_\lambda + O(e^{-\Delta t}) \end{aligned}$$

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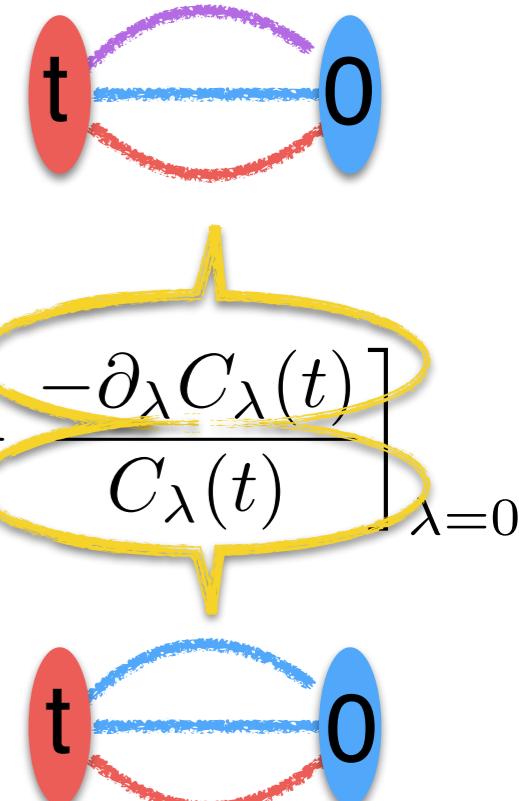
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Feynman-Hellmann theorem $\partial_\lambda E_n|_{\lambda=0} = \langle n | H_\lambda | n \rangle$

derivative correlation function

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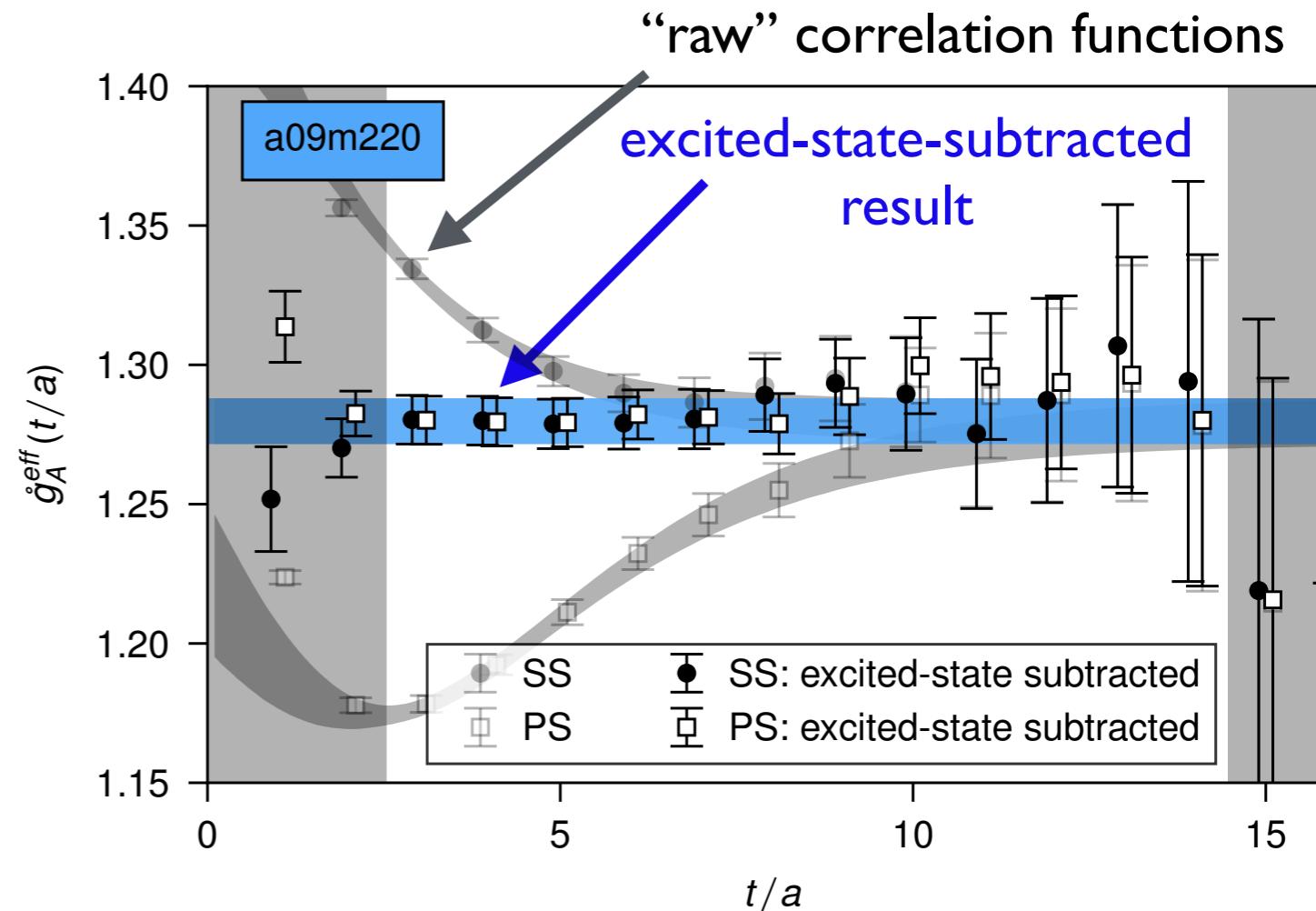


“Feynman-Hellmann” propagator = $\int dt_{\mathcal{O}} \mathcal{O}(t_{\mathcal{O}}) \int dt_{\mathcal{O}} \mathcal{O}(t_{\mathcal{O}})$

standard 2-point function

our unconventional method

$$\frac{\partial m_\lambda^{eff}(t, \tau)}{\partial \lambda} \Big|_{\lambda=0} = \frac{1}{\tau} \left[\frac{-\partial_\lambda C_\lambda(t + \tau)}{C(t + \tau)} - \frac{-\partial_\lambda C_\lambda(t)}{C(t)} \right]$$



Key features of this method

- The correlation function is given by $\partial_\lambda m_\lambda^{eff}(t) \Big|_{\lambda=0} = g_{00} + z(e^{-(t+1)\Delta_{10}} - e^{-t\Delta_{10}}) + \dots$
- excited state contamination is demonstrably controlled
- we can access very early Euclidean time, allowing the use of exponentially more precise numerical points

our unconventional method

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“Feynman-Hellmann” propagator

$$\text{---} = \int dt_O \quad \square \quad O(t_O)$$

$$= S_{FH}(y, x) = \sum_z S(y, z) \Gamma(z) S(z, x)$$

Our unconventional method is similar too

- traced back to Maiani, Martinelli, Paciello and Taglienti **Nucl. Phys. B293 (1987)**: Güsken, Low, Mutter, Sommer, Patel, Schilling **PLB227 (1989)** first computed $-\partial_\lambda C_\lambda(t)$
- Bulava, Donnellan, Sommer, **JHEP 1201 (2012)**: combined above with GEVP
- de Divitiis, Petronzio, Tantalo, **PLB718 (2012)**: computed derivatives of form factors
- Chambers et al. **PRD90 (2014)**, **PRD92 (2015)** Savage et al. **PRL199 (2017)**; used unconventional method with background field (λ) varying strength of field to extract derivative
- **Our method:**
 - uses analytic representation of derivative correlator instead of background field (cheaper)
 - uses complete spectral decomposition of correlator, including contact operators
 - analysis was pushed to greater detail, showing stability of analysis (**PRD96** [1612.06963], [1704.01114], **Nature 558** [1805.12130])

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We have improved our method to allow for arbitrary current insertion
see talk by Arjun Gambhir
Thurs. 11:00, Structure

Our Lattice QCD Action

Möbius Domain Wall Fermions on gradient flowed 2+1+1 HISQ ensembles

Berkowitz et al. PRD96 (2017) [1701.07559]

- ❑ Approximate chiral symmetry, many finite lattice spacing operators not allowed
- ❑ Leading discretization errors begin at $O(a^2)$

To control the three standard systematics for LQCD calculations, need

- ❑ multiple lattice spacings
- ❑ multiple volumes
- ❑ pion masses at/near the physical pion mass

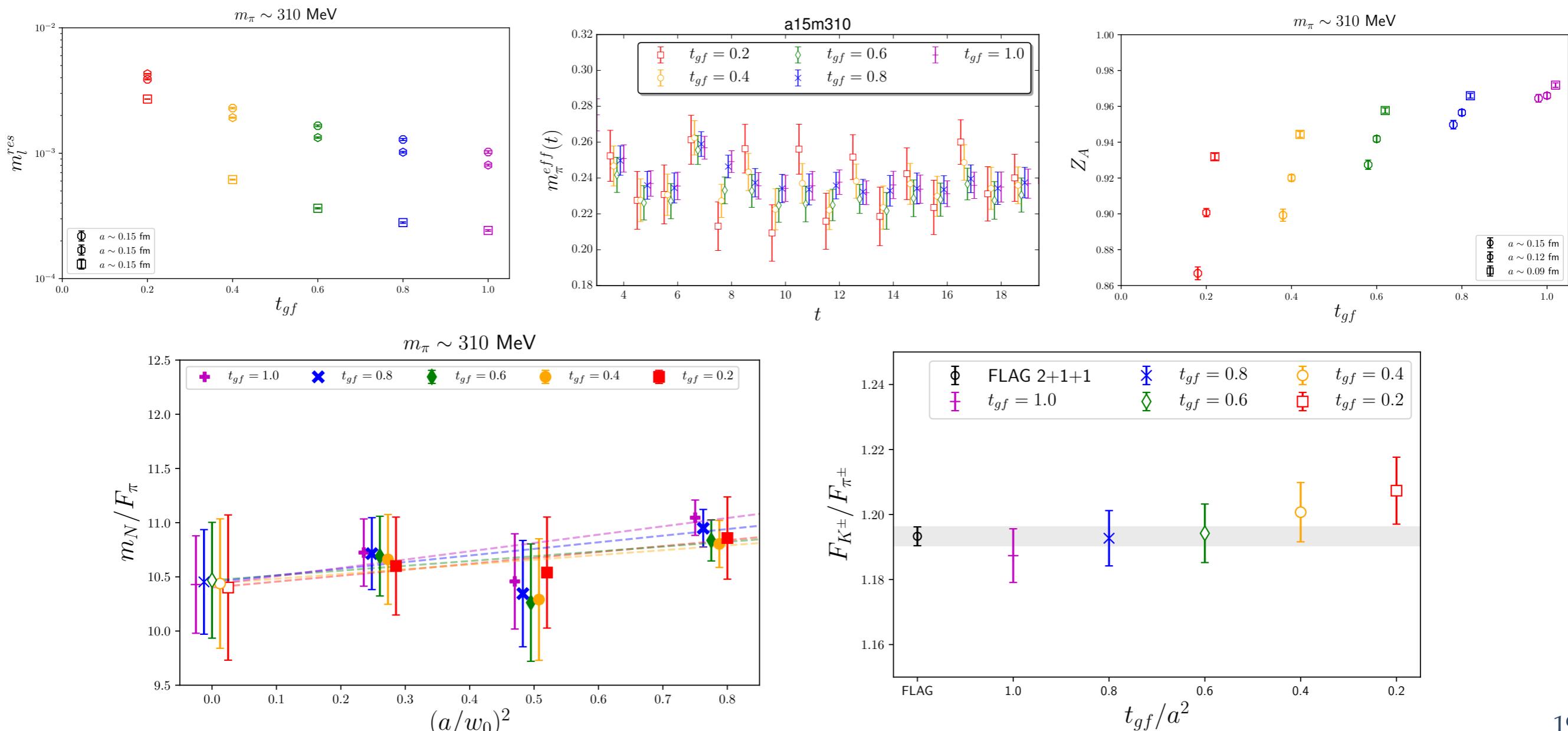
The only set of publicly available ensembles which satisfy these criteria are the
Nf=2+1+1 Highly Improved Staggered Quark (HISQ: Follana et al. PRD75 (2007) [hep-lat/0610092])
ensembles generated by the MILC Collaboration Bazavov et al. PRD82 (2010) [1004.0342], PRD87
(2013) [1212.4768]

The DWF on asqtad action (Renner et al. [LHPC] NPPS 140 (2005) [hep-lat/0409130])
was used very successfully: LHPC; NPLQCD; Aubin, Laiho, Van de Water; ...

- ❑ Fully developed Mixed-Action EFT: Bar, Bernard, Rupak, Shores; Tiburzi;
Chen, O'Connell, Van de Water, Walker-Loud; ...
- ❑ This motivated us to use an improved version of this action

Our Lattice QCD Action

- Möbius Domain Wall Fermions on gradient flowed 2+1+1 HISQ ensembles **Berkowitz et al. PRD96 (2017) [1701.07559]**
- Gradient Flow smearing of HISQ cfgs more effective at reducing residual chiral symmetry breaking than the HYP smearing used in DWF on asqtad
 $m_{\text{res}} < 0.1 m_l$ on all ensembles for small-to-moderate L_5 and $M_5 \leq 1.3$



Our Lattice QCD Action

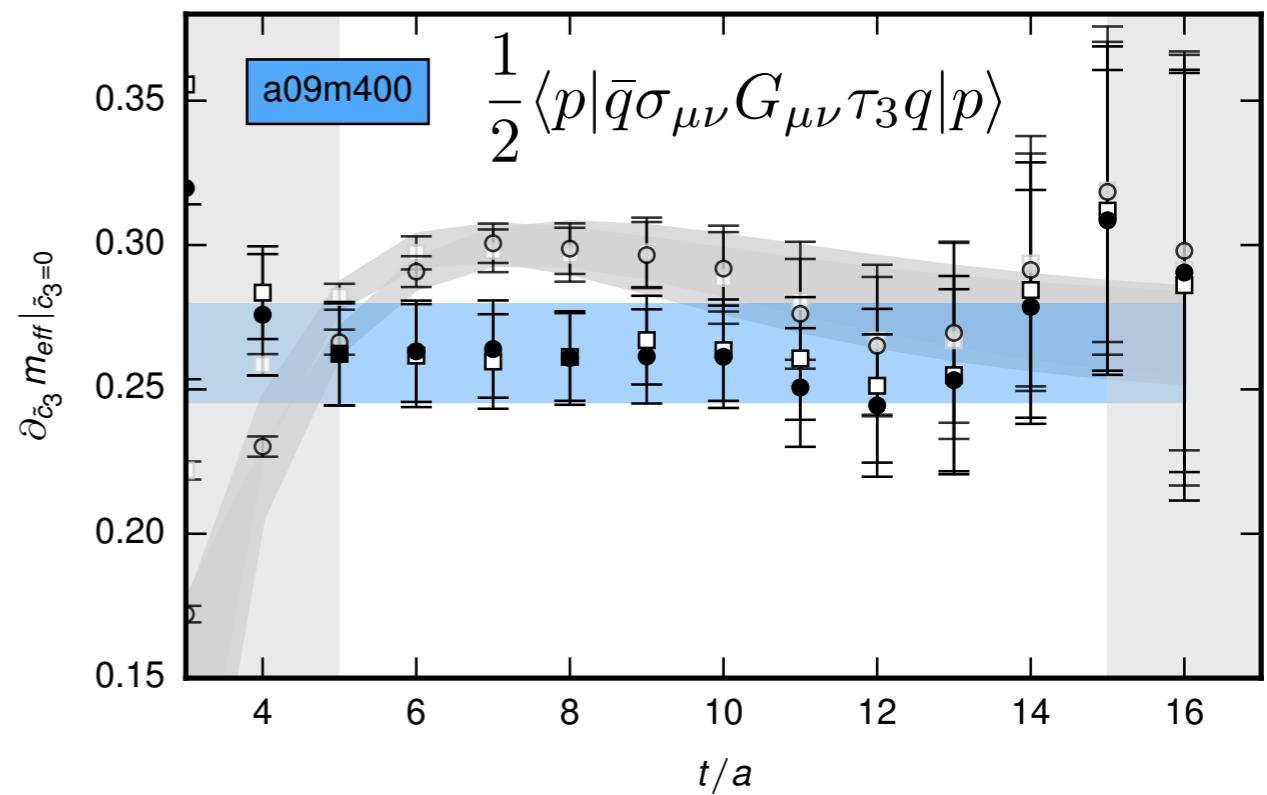
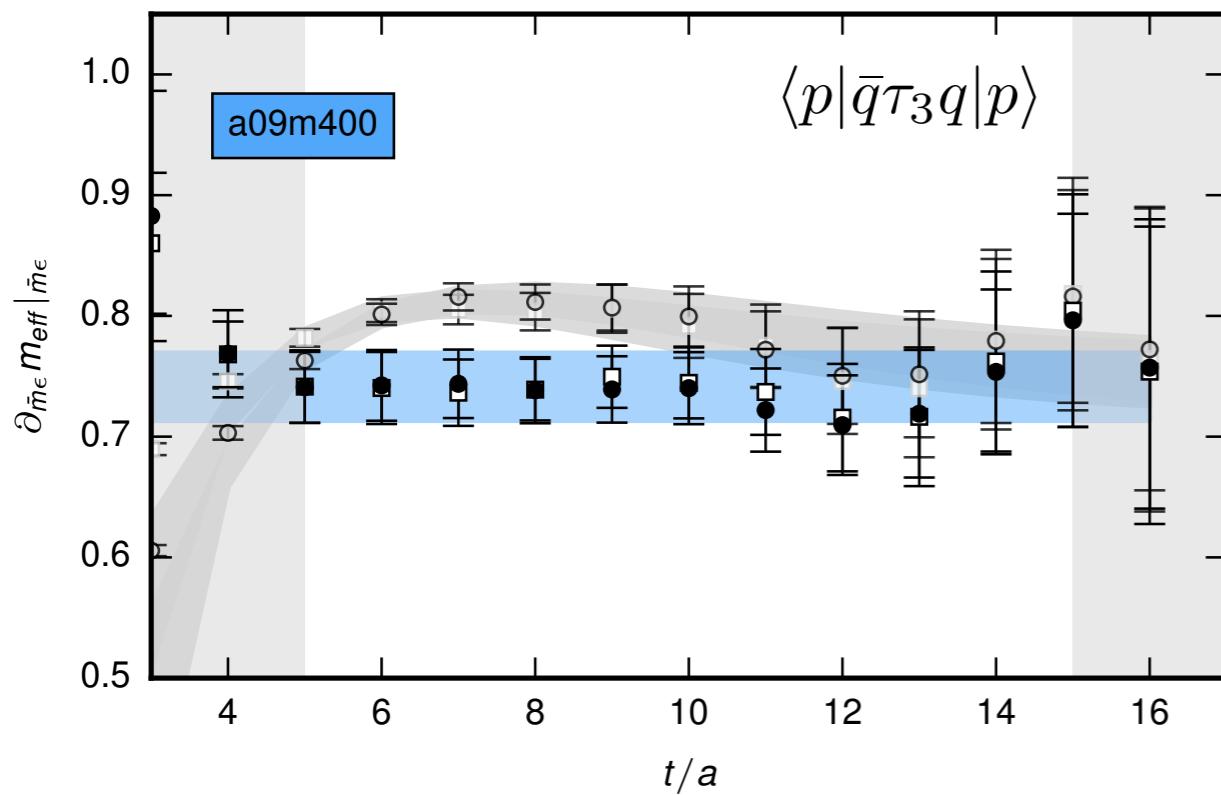
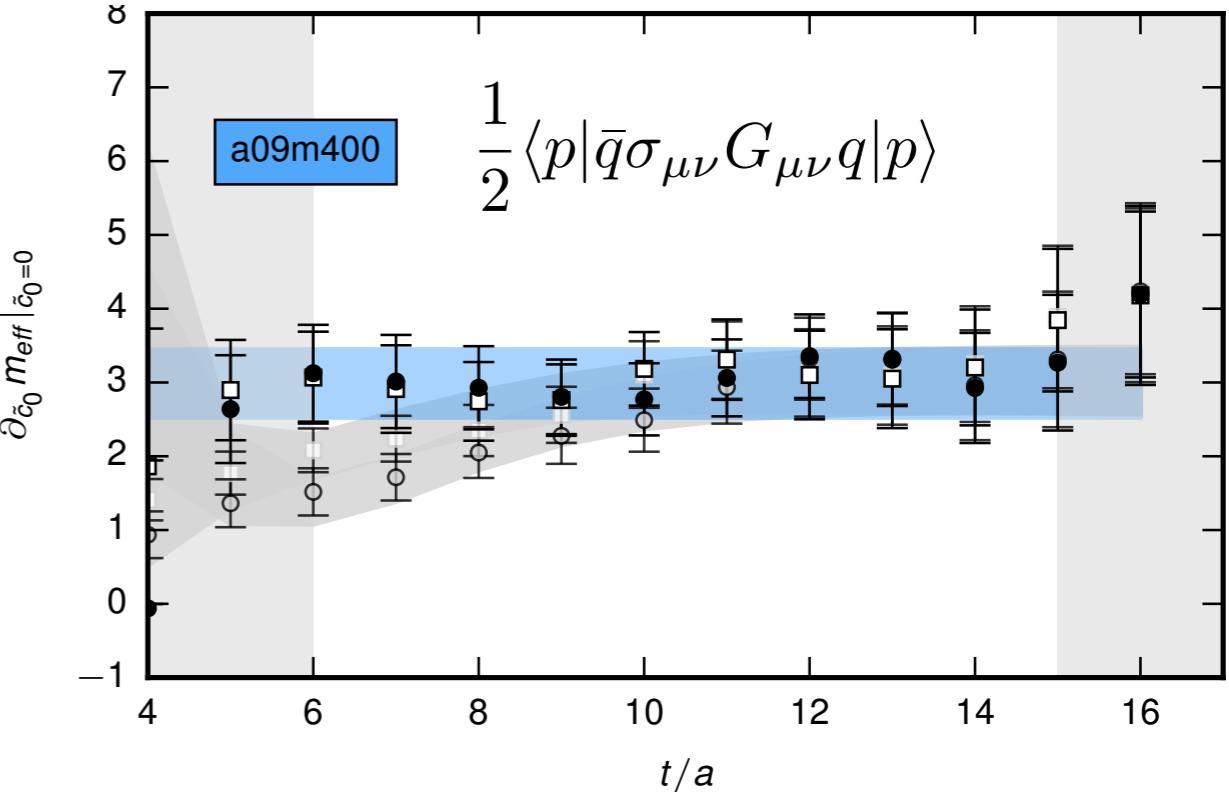
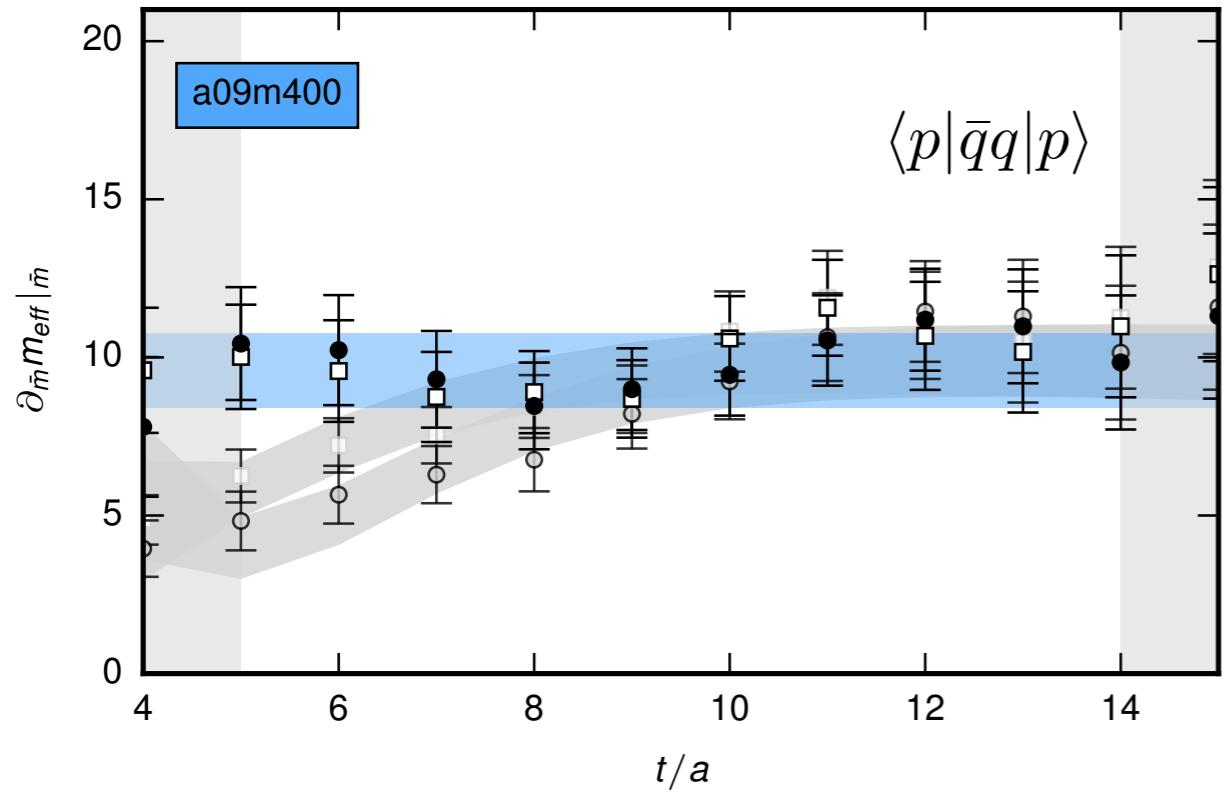
| HISQ gauge configuration parameters | | | | | | | valence parameters | | | | | | | |
|-------------------------------------|------------------|------------------|------------------|-----------|---------------------------|-------------------|--------------------|---------|--------|-------|-------|----------------------|-----------------------|------------------|
| abbr. | N_{cfg} | volume | $\sim a$ [fm] | m_l/m_s | $\sim m_{\pi_5}$ [MeV] | $\sim m_{\pi_5}L$ | N_{src} | L_5/a | aM_5 | b_5 | c_5 | $am_l^{\text{val.}}$ | σ_{smr} | N_{smr} |
| a15m400 | 1000 | $16^3 \times 48$ | 0.15 | 0.334 | 400 | 4.8 | 8 | 12 | 1.3 | 1.5 | 0.5 | 0.0278 | 3.0 | 30 |
| a15m350 | 1000 | $16^3 \times 48$ | 0.15 | 0.255 | 350 | 4.2 | 16 | 12 | 1.3 | 1.5 | 0.5 | 0.0206 | 3.0 | 30 |
| a15m310 | 1960 | $16^3 \times 48$ | 0.15 | 0.2 | 310 | 3.8 | 24 | 12 | 1.3 | 1.5 | 0.5 | 0.01580 | 4.2 | 60 |
| a15m220 | 1000 | $24^3 \times 48$ | 0.15 | 0.1 | 220 | 4.0 | 12 | 16 | 1.3 | 1.75 | 0.75 | 0.00712 | 4.5 | 60 |
| a15m130 | 1000 | $32^3 \times 48$ | 0.15 | 0.036 | 130 | 3.2 | 5 | 24 | 1.3 | 2.25 | 1.25 | 0.00216 | 4.5 | 60 |
| a12m400 | 1000 | $24^3 \times 64$ | 0.12 | 0.334 | 400 | 5.8 | 8 | 8 | 1.2 | 1.25 | 0.25 | 0.02190 | 3.0 | 30 |
| a12m350 | 1000 | $24^3 \times 64$ | 0.12 | 0.255 | 350 | 5.1 | 8 | 8 | 1.2 | 1.25 | 0.25 | 0.01660 | 3.0 | 30 |
| a12m310 | 1053 | $24^3 \times 64$ | 0.12 | 0.2 | 310 | 4.5 | 8 | 8 | 1.2 | 1.25 | 0.25 | 0.01260 | 3.0 | 30 |
| a12m220S | 1000 | $24^3 \times 64$ | 0.12 | 0.1 | 220 | 3.2 | 4 | 12 | 1.2 | 1.5 | 0.5 | 0.00600 | 6.0 | 90 |
| a12m220 | 1000 | $32^3 \times 64$ | 0.12 | 0.1 | 220 | 4.3 | 4 | 12 | 1.2 | 1.5 | 0.5 | 0.00600 | 6.0 | 90 |
| a12m220L | 1000 | $40^3 \times 64$ | 0.12 | 0.1 | 220 | 5.4 | 4 | 12 | 1.2 | 1.5 | 0.5 | 0.00600 | 6.0 | 90 |
| a12m130 | 1000 | $48^3 \times 64$ | 0.12 | 0.036 | 130 | 3.9 | 3 | 20 | 1.2 | 2.0 | 1.0 | 0.00195 | 7.0 | 150 |
| a09m400 | 1201 | $32^3 \times 64$ | 0.09 | 0.335 | 400 | 5.8 | 8 | 6 | 1.1 | 1.25 | 0.25 | 0.0160 | 3.5 | 45 |
| a09m350 | 1201 | $32^3 \times 64$ | 0.09 | 0.255 | 350 | 5.1 | 8 | 6 | 1.1 | 1.25 | 0.25 | 0.0121 | 3.5 | 45 |
| a09m310 | 784 | $32^3 \times 96$ | 0.09 | 0.2 | 310 | 4.5 | 8 | 6 | 1.1 | 1.25 | 0.25 | 0.00951 | 7.5 | 167 |
| a09m220 | 1001 | $48^3 \times 96$ | 0.09 | 0.1 | 220 | 4.7 | 6 | 8 | 1.1 | 1.25 | 0.25 | 0.00449 | 8.0 | 150 |

Our Lattice QCD Action

| HISQ gauge configuration parameters | | | | | | | valence parameters | | | | | | | |
|-------------------------------------|------------------|------------------|------------------|-----------|---------------------------|-------------------|--------------------|---------|--------|-------|-------|----------------------|-----------------------|------------------|
| abbr. | N_{cfg} | volume | $\sim a$ [fm] | m_l/m_s | $\sim m_{\pi_5}$ [MeV] | $\sim m_{\pi_5}L$ | N_{src} | L_5/a | aM_5 | b_5 | c_5 | $am_l^{\text{val.}}$ | σ_{smr} | N_{smr} |
| a15m400 | 1000 | $16^3 \times 48$ | 0.15 | 0.334 | 400 | 4.8 | 8 | 12 | 1.3 | 1.5 | 0.5 | 0.0278 | 3.0 | 30 |
| a15m350 | 1000 | $16^3 \times 48$ | 0.15 | 0.255 | 350 | 4.2 | 16 | 12 | 1.3 | 1.5 | 0.5 | 0.0206 | 3.0 | 30 |
| a15m310 | 1960 | $16^3 \times 48$ | 0.15 | 0.2 | 310 | 3.8 | 24 | 12 | 1.3 | 1.5 | 0.5 | 0.01580 | 4.2 | 60 |
| a15m220 | 1000 | $24^3 \times 48$ | 0.15 | 0.1 | 220 | 4.0 | 12 | 16 | 1.3 | 1.75 | 0.75 | 0.00712 | 4.5 | 60 |
| a15m130 | 1000 | $32^3 \times 48$ | 0.15 | 0.036 | 130 | 3.2 | 5 | 24 | 1.3 | 2.25 | 1.25 | 0.00216 | 4.5 | 60 |
| a12m400 | 1000 | $24^3 \times 64$ | 0.12 | 0.334 | 400 | 5.8 | 8 | 8 | 1.2 | 1.25 | 0.25 | 0.02190 | 3.0 | 30 |
| a12m350 | 1000 | $24^3 \times 64$ | 0.12 | 0.255 | 350 | 5.1 | 8 | 8 | 1.2 | 1.25 | 0.25 | 0.01660 | 3.0 | 30 |
| a12m310 | 1053 | $24^3 \times 64$ | 0.12 | 0.2 | 310 | 4.5 | 8 | 8 | 1.2 | 1.25 | 0.25 | 0.01260 | 3.0 | 30 |
| a12m220S | 1000 | $24^3 \times 64$ | 0.12 | 0.1 | 220 | 3.2 | 4 | 12 | 1.2 | 1.5 | 0.5 | 0.00600 | 6.0 | 90 |
| a12m220 | 1000 | $32^3 \times 64$ | 0.12 | 0.1 | 220 | 4.3 | 4 | 12 | 1.2 | 1.5 | 0.5 | 0.00600 | 6.0 | 90 |
| a12m220L | 1000 | $40^3 \times 64$ | 0.12 | 0.1 | 220 | 5.4 | 4 | 12 | 1.2 | 1.5 | 0.5 | 0.00600 | 6.0 | 90 |
| a12m130 | 1000 | $48^3 \times 64$ | 0.12 | 0.036 | 130 | 3.9 | 3 | 20 | 1.2 | 2.0 | 1.0 | 0.00195 | 7.0 | 150 |
| a09m400 | 1201 | $32^3 \times 64$ | 0.09 | 0.335 | 400 | 5.8 | 8 | 6 | 1.1 | 1.25 | 0.25 | 0.0160 | 3.5 | 45 |
| a09m350 | 1201 | $32^3 \times 64$ | 0.09 | 0.255 | 350 | 5.1 | 8 | 6 | 1.1 | 1.25 | 0.25 | 0.0121 | 3.5 | 45 |
| a09m310 | 784 | $32^3 \times 96$ | 0.09 | 0.2 | 310 | 4.5 | 8 | 6 | 1.1 | 1.25 | 0.25 | 0.00951 | 7.5 | 167 |
| a09m220 | 1001 | $48^3 \times 96$ | 0.09 | 0.1 | 220 | 4.7 | 6 | 8 | 1.1 | 1.25 | 0.25 | 0.00449 | 8.0 | 150 |

additional HISQ ensembles generated @ LLNL
available to interested parties

Results: Preliminary



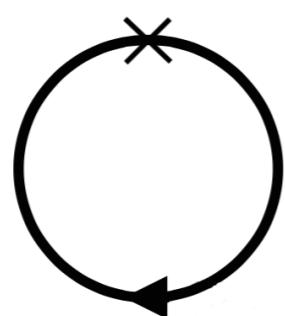
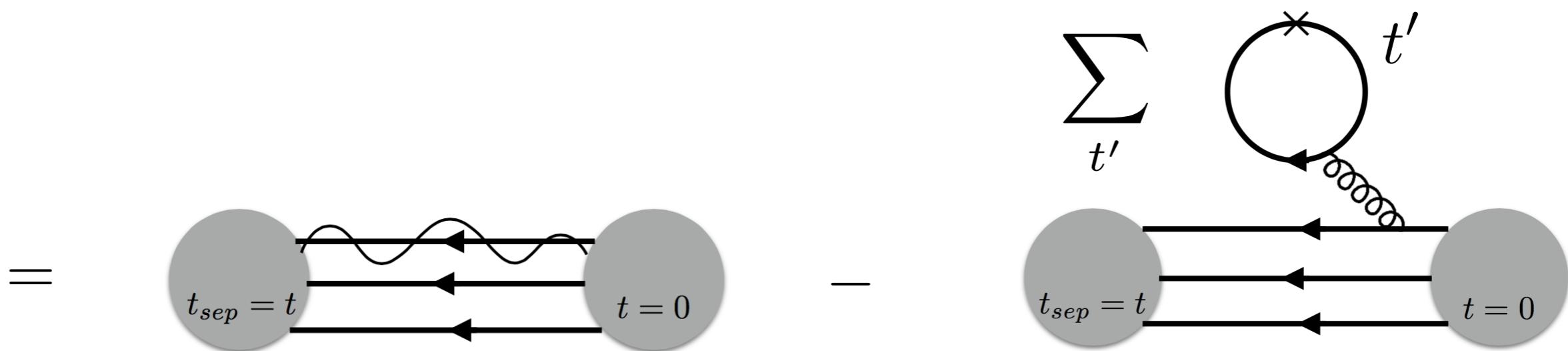
Disconnected Diagrams

see talk by Arjun Gambhir
Thurs. 11:00, Structure

Iso-vector CPV pion-nucleon coupling dependent on iso-scalar quantities.

$$\bar{g}_1 = -2\tilde{d}_3 \left(\frac{d}{d\tilde{c}_0} - r \frac{d}{d\bar{m}} \right) \Delta m_N$$

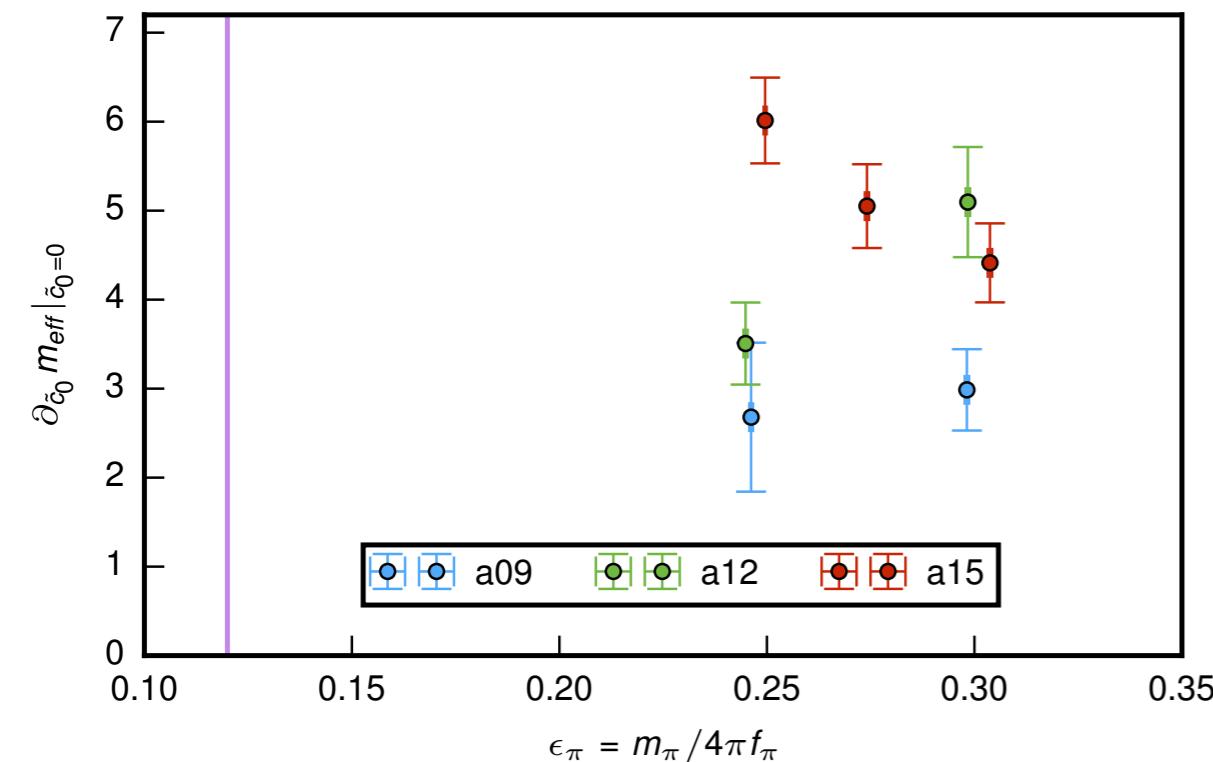
$$\frac{\partial}{\partial \tilde{c}_0} C_{\tilde{c}_0}(t) \Big|_{\tilde{c}_0=0} = \int dt' \langle \Omega | T\{\mathcal{O}(t) \left(\frac{1}{2} \bar{q} \sigma_{\mu\nu} G^{\mu\nu} q(t') \right) \mathcal{O}^\dagger(0)\} | \Omega \rangle$$



$$= -\text{tr}[\sigma_{\mu\nu} G^{\mu\nu} S(x|x)]$$

Requires information of all-to-all

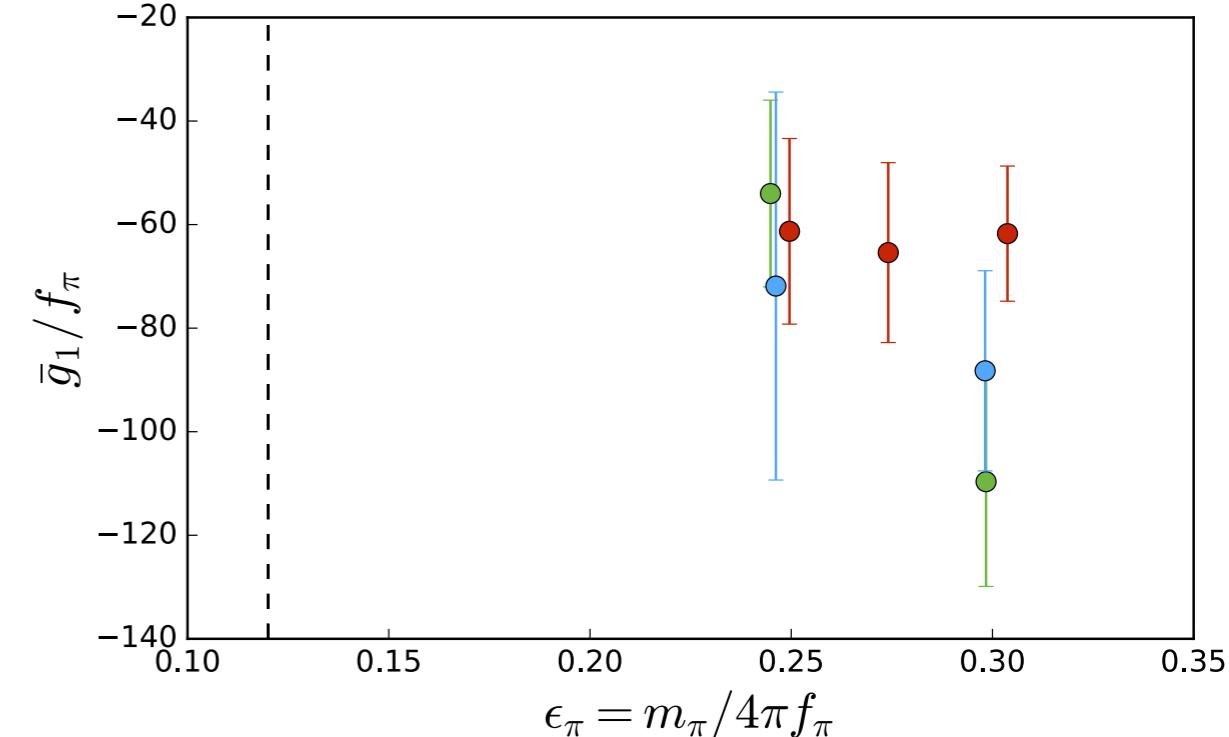
Results: Preliminary



Bare matrix element

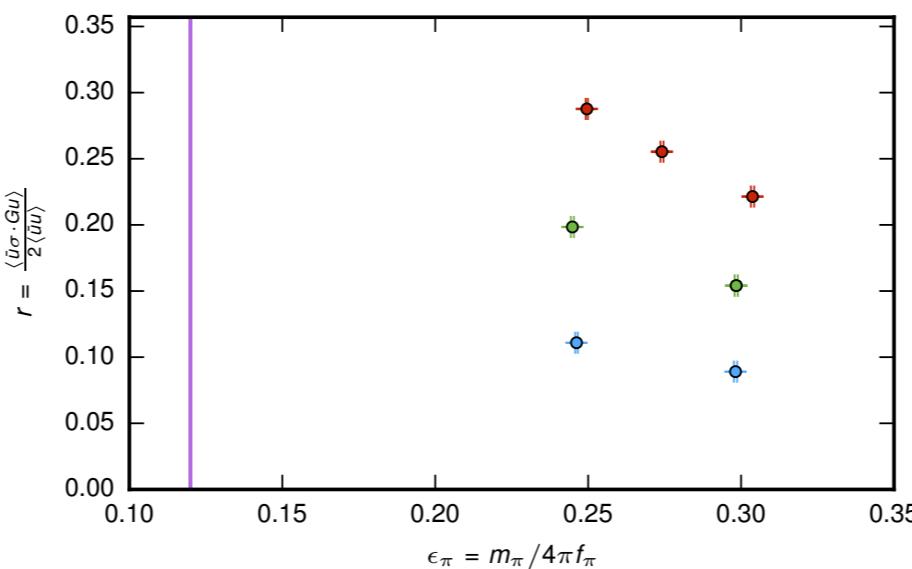
$$\langle p | \bar{q} \sigma_{\mu\nu} G_{\mu\nu} q | p \rangle_{latt}$$

$$r = \frac{\langle \Omega | \bar{q} \sigma_{\mu\nu} G_{\mu\nu} q | \Omega \rangle}{2 \langle \Omega | \bar{q} q | \Omega \rangle}$$

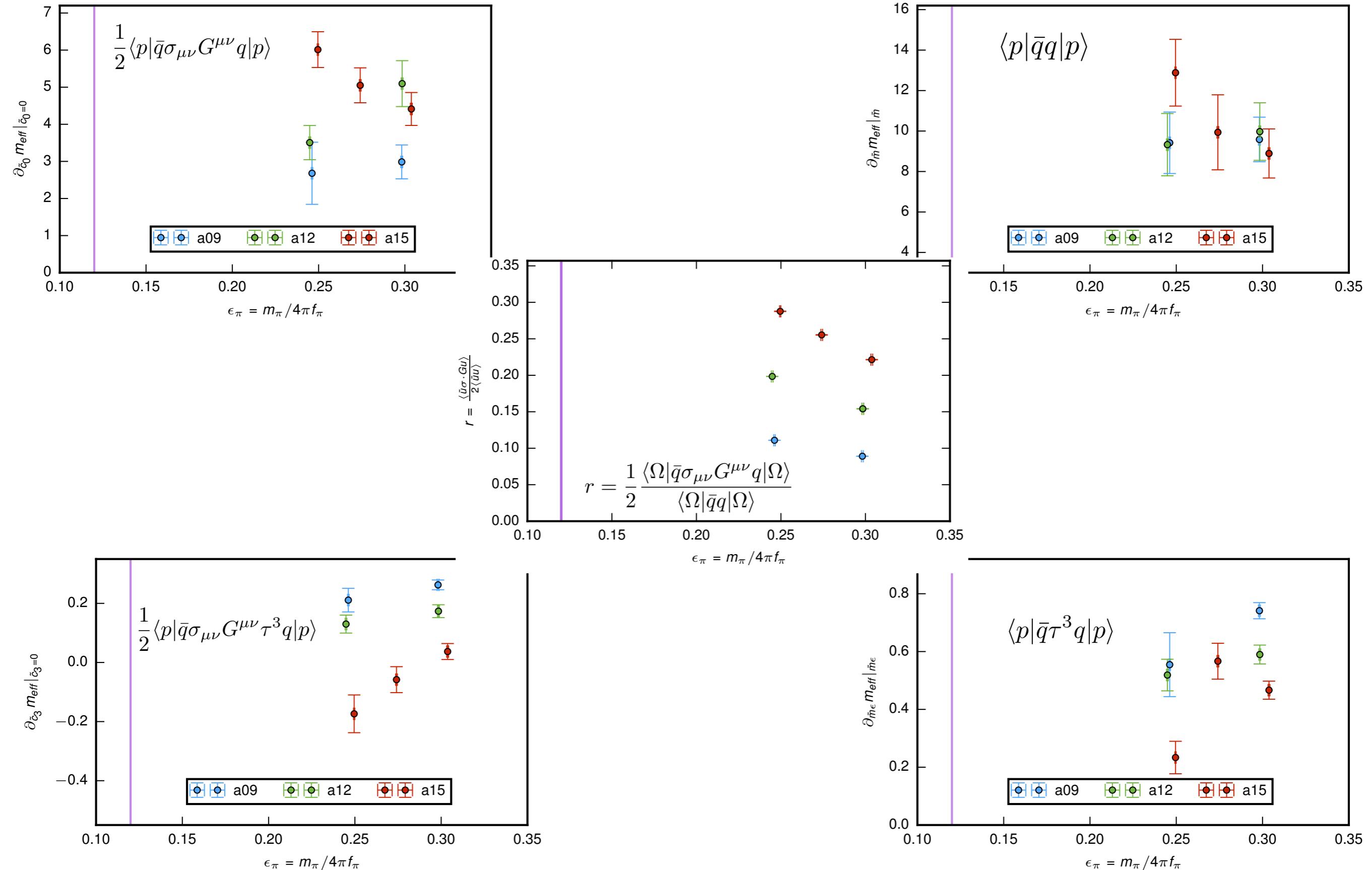


r-subtracted matrix element

$$-\frac{2}{f_\pi} (\langle p | \bar{q} \sigma_{\mu\nu} G_{\mu\nu} q | p \rangle_{latt} - r \langle p | \bar{q} q | p \rangle)$$



Putting it all Together



Renormalization

RI/SMOM Renormalization: MANY extra operators needed for complete renormalization

$$\mathcal{O}_1 \equiv C = \bar{\psi} \sigma^{\mu\nu} g G_{\mu\nu} t^a \psi,$$

$$\mathcal{O}_2 \equiv \partial^2 S = \partial^2 (\bar{\psi} t^a \psi),$$

$$\mathcal{O}_3 \equiv E = \frac{e}{2} \bar{\psi} \sigma^{\mu\nu} F_{\mu\nu} \{Q, t^a\} \psi,$$

$$\mathcal{O}_4 \equiv mFF = \text{Tr}[\mathcal{M} Q^2 t^a] F_{\mu\nu} F^{\mu\nu},$$

$$\mathcal{O}_5 \equiv mGG = \text{Tr}[\mathcal{M} t^a] G_{\mu\nu}^b G^{b\mu\nu},$$

$$\mathcal{O}_8 \equiv (m^2 S)_1 = \frac{1}{2} \bar{\psi} \{ \mathcal{M}^2, t^a \} \psi,$$

$$\mathcal{O}_9 \equiv (m^2 S)_2 = \text{Tr}[\mathcal{M}^2] \bar{\psi} t^a \psi,$$

$$\mathcal{O}_{10} \equiv (m^2 S)_3 = \text{Tr}[\mathcal{M} t^a] \bar{\psi} \mathcal{M} \psi,$$

$$\mathcal{O}_{11} \equiv S_{EE} = \bar{\psi}_E t^a \psi_E,$$

$$\mathcal{O}_{12} \equiv (\partial \cdot V)_E = i \partial_\mu (\bar{\psi} \gamma^\mu t^a \psi_E - \bar{\psi}_E t^a \gamma^\mu \psi),$$

$$\mathcal{O}_{13} \equiv V_\partial = \bar{\psi} t^a (i \overrightarrow{\partial}) \psi_E + \bar{\psi}_E (-i \overleftarrow{\partial}) t^a \psi,$$

$$\mathcal{O}_{14} \equiv V_{A_\gamma} = \frac{e}{2} \bar{\psi} \{Q, t^a\} A_\gamma \psi_E + \frac{e}{2} \bar{\psi}_E \{Q, t^a\} A_\gamma \psi,$$

$$\mathcal{O}_{15} \equiv (mS_E)_1 = \frac{1}{2} (\bar{\psi} \{ \mathcal{M}, t^a \} \psi_E + \bar{\psi}_E \{ \mathcal{M}, t^a \} \psi_E),$$

$$\mathcal{O}_{16} \equiv (mS_E)_2 = \text{Tr}[\mathcal{M} t^a] (\bar{\psi} \psi_E + \bar{\psi}_E \psi),$$

$$\mathcal{O}_{17} \equiv (mDG) = \text{Tr}[\mathcal{M} t^a] (D_\mu^{bc} G_{\mu\nu}^b) A^\nu{}^c.$$

$$\psi_E \equiv (i D^\mu \gamma_\mu - \mathcal{M}) \psi ,$$

$$\bar{\psi}_E \equiv -\bar{\psi} (i \overleftarrow{D}^\mu \gamma_\mu + \mathcal{M}) ,$$

$$D_\mu = \partial_\mu - ig A_\mu^a T^a - ie Q A_\mu^{(\gamma)}$$

$$\overleftarrow{D}_\mu = \overleftarrow{\partial}_\mu + ig A_\mu^a T^a + ie Q A_\mu^{(\gamma)}$$

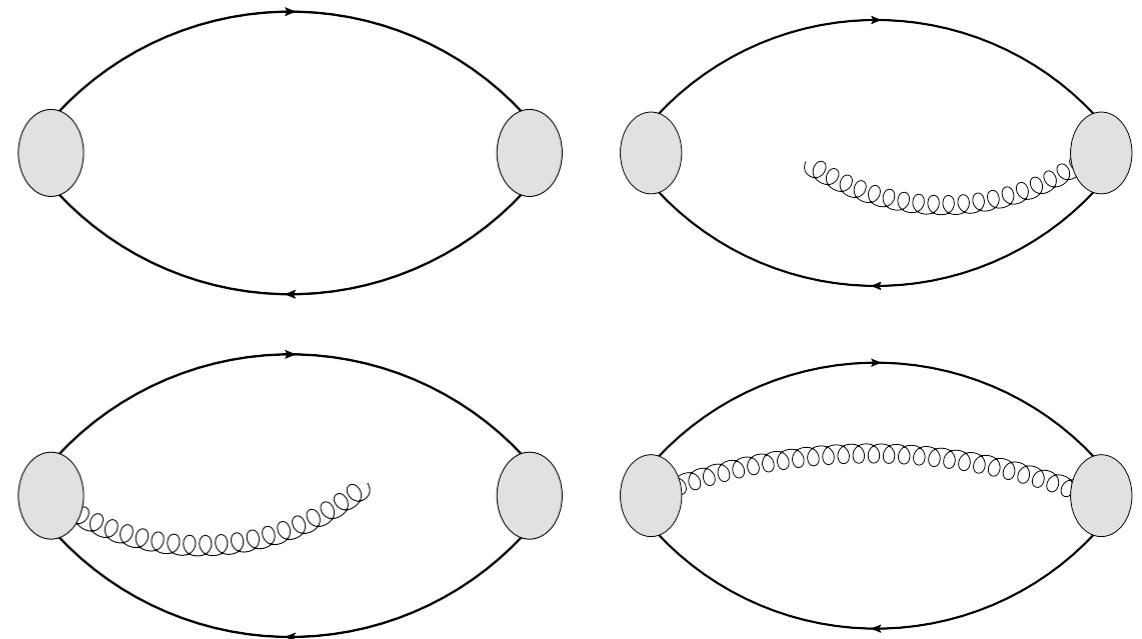
Renormalization

Coordinate space renormalization? (Thanks Sergey Syritsyn)

Gimenez, Giusti, Guerriero, Lubicz, Martinelli, Petrarca, Reyes, Taglienti, Trevigne

Phys.Lett. B598 (2004) [hep-lat/0406019]

- Only two operators needed
- qq-qq graphs already determined in perturbation theory
- Imposing tree-level condition - off-diagonal graphs vanish
- Tree-level renormalization condition for CMDM-CMDM is already a two-loop calculation



$$\begin{pmatrix} \bar{q}q(x) & \bar{q}q(0) \\ 0 & \bar{q}\sigma_{\mu\nu}G_{\mu\nu}q(x) \end{pmatrix}_R = Z_x \begin{pmatrix} \bar{q}q(x) & \bar{q}q(0) \\ \bar{q}\sigma_{\mu\nu}G_{\mu\nu}q(x) & \bar{q}q(0) \end{pmatrix}_{bare} Z_x$$

Outlook

- By exploiting symmetries, we can study the modification of the nucleon spectrum in the presence of CP conserving operators which will then determine the values of the CP-violating π -N couplings which arise from the quark chromo-EDM operators
- The long-range CPV pion-nucleon couplings could allow for a direct connection with fundamental coefficients in dimension-6 quark operators and real nuclear physics, ^{225}Ra
- The calculations are simplified through a non-standard matrix-element calculation technique
- We need to decide upon and complete a renormalization scheme
- We plan to compute at smaller pion masses to control the physical pion mass extrapolation

Lattice QCD Team



plus a few
friends

[David Brantley](#): almost single handedly wrote the code and performed all the calculations for the project (he would be here giving this talk except for life-interference)

Jason Chang
Jordy de Vries
Arjun Gambhir
Nicolas Garron
Emanuele Mereghetti
Sergey Syritsyn

Evan Berkowitz
Kate Clark
Bálint Joó
Thorsten Kurth
Henry Monge-Camacho
Amy Nicholson
Kostas Orginos
Enrico Rinaldi
Pavlos Vranas
AWL