Understanding the axial structure of the nucleon from QCD

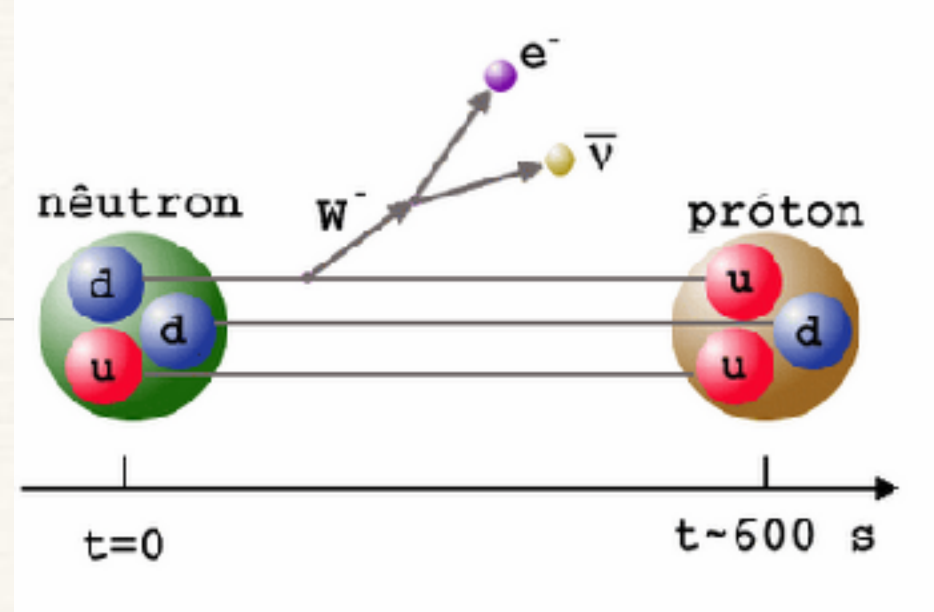
André Walker-Loud

Frontiers in Lattice QCD and related topics

Yukawa Institute for Theoretical Physics

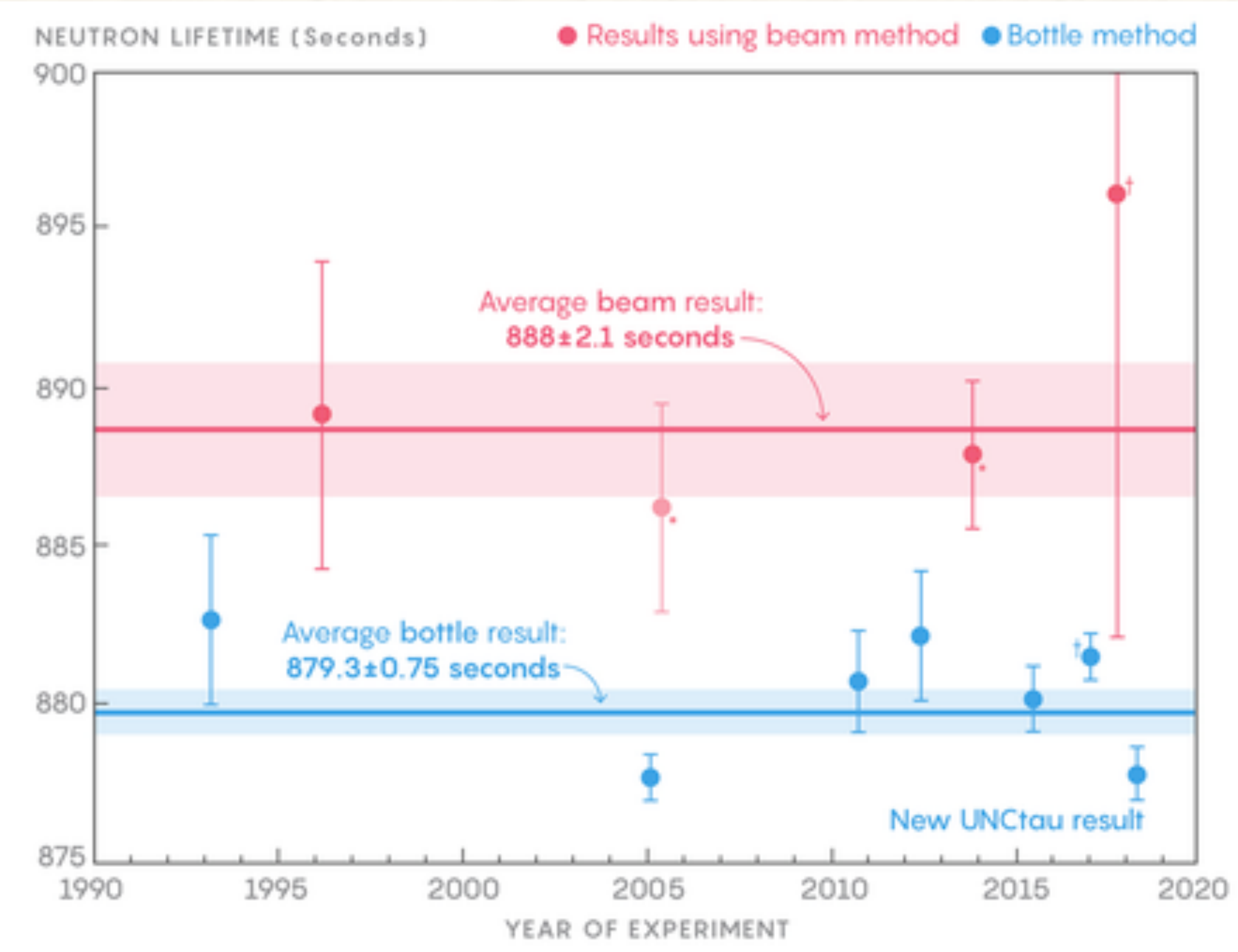
April 2019

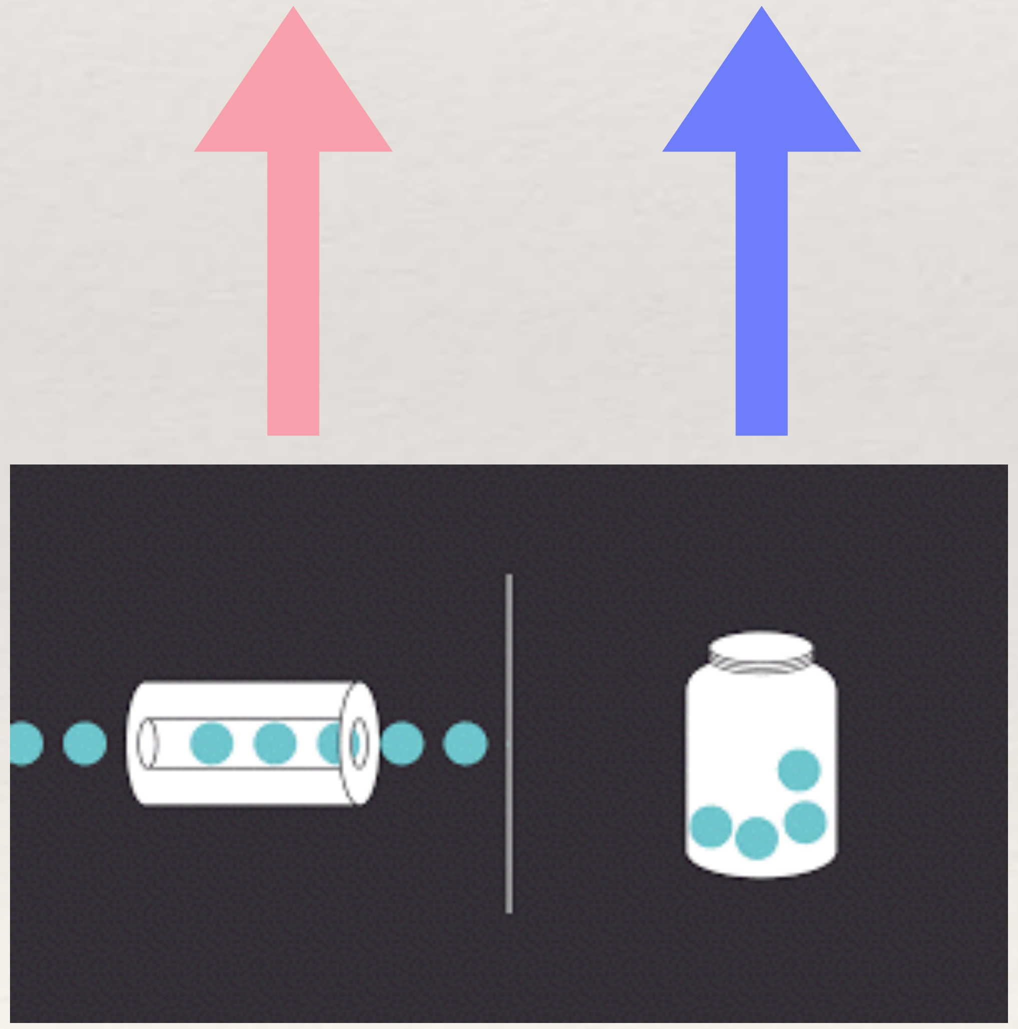
Neutron lifetime and the axial coupling



Czarnecki, Marciano, Sirlin
Phys.Rev.Lett. 120 (2018)
[arXiv:1802.01804]

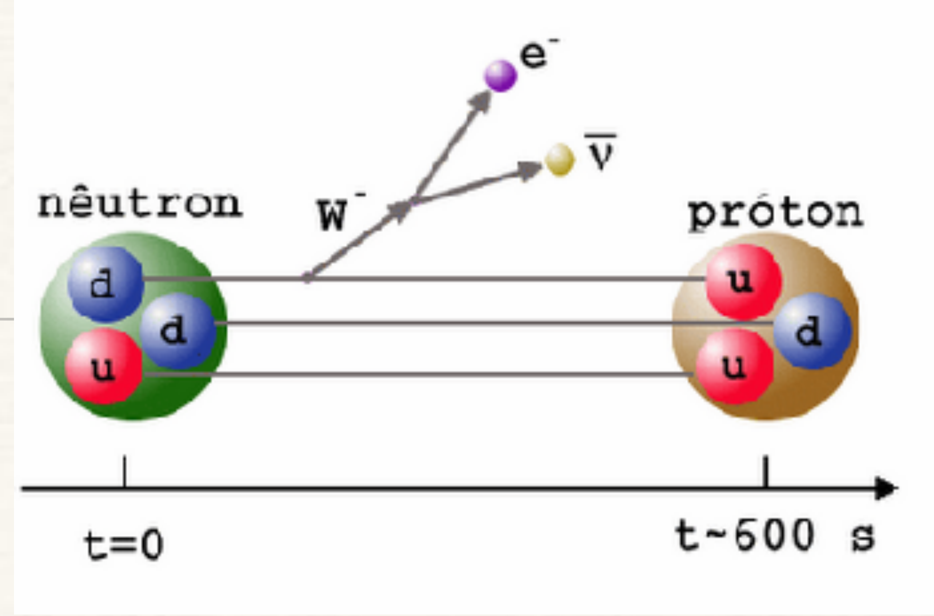
$$\tau_n = \frac{5172.0 \pm 1.1 \text{ seconds}}{(1+3g_A^2)}$$

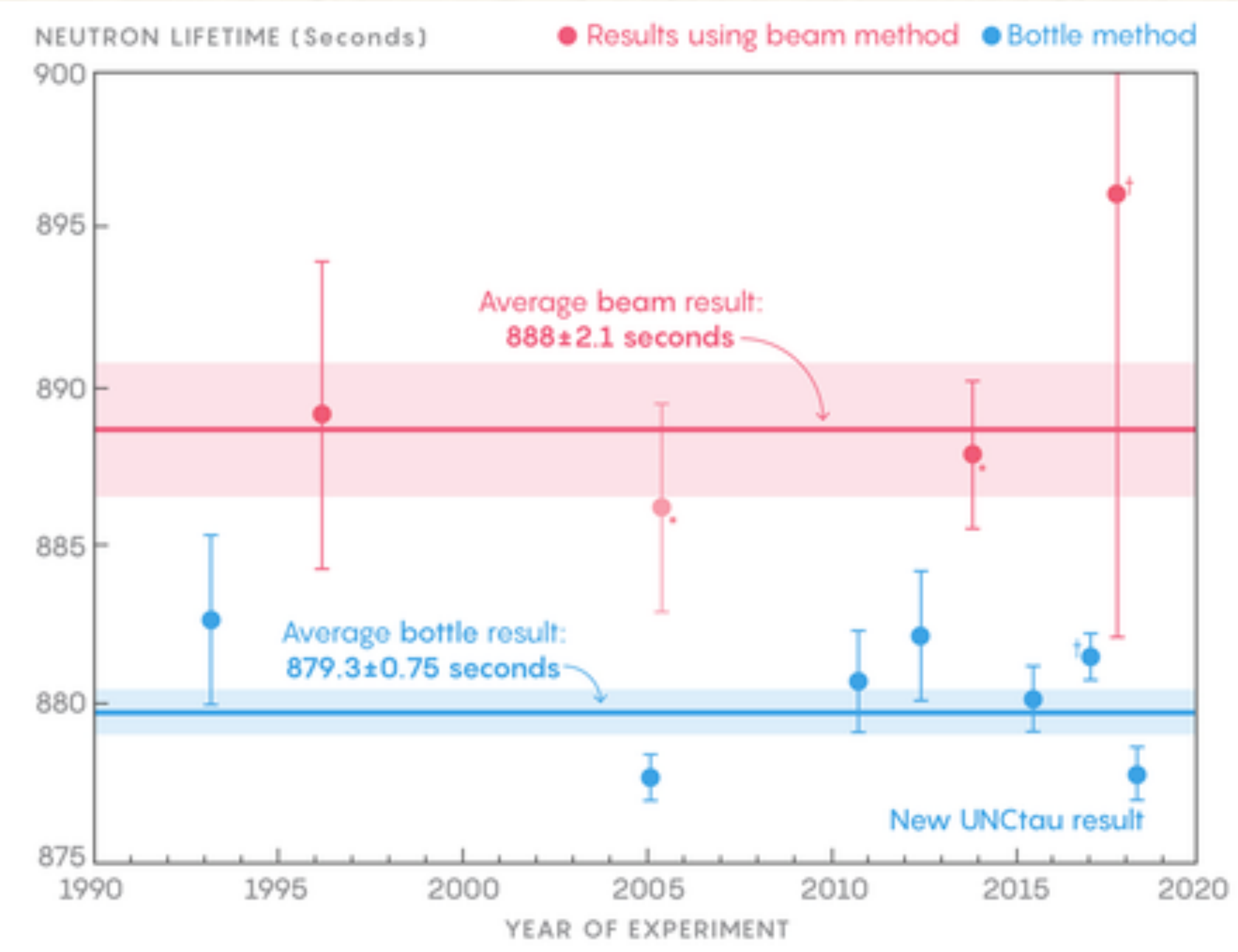


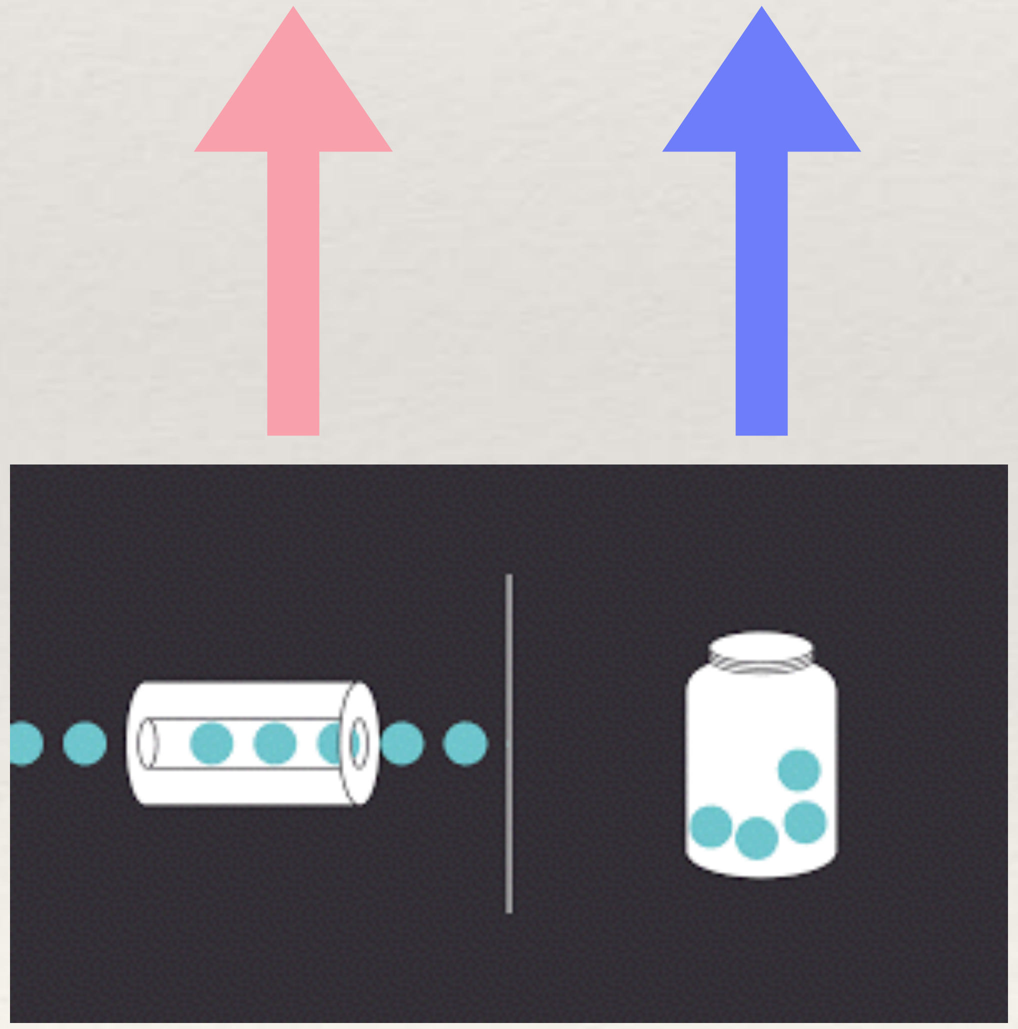


- There is currently a 4-sigma discrepancy between the **beam** and **bottle** measurements of the neutron lifetime
$$\tau_n^{\text{beam}} = 888.0(2.0)s \quad \tau_n^{\text{bottle}} = 879.4(0.6)s$$
- This has generated a lot of interest that the discrepancy could be caused by new physics (hidden decay mode)
- The numerator, 5172.0(1.1), depends upon several quantities which must be measured experimentally - almost all of which are receiving new scrutiny given this discrepancy $$\frac{1}{\tau_n} = \frac{G_\mu^2 |V_{ud}|^2}{2\pi^3} m_e^5 (1+3g_A^2)(1+RC)f$$
- In particular, the radiative corrections (RC) have been updated with a multi-sigma shift
Seng, Gorchtein, Patel, Ramsey-Musolf: PRL 121 (2018) [1807.10197]
Seng, Gorchtein, Ramsey-Musolf: 1812.03352
- It is also important to have a Standard Model prediction for g_A - LQCD

Neutron lifetime and the axial coupling







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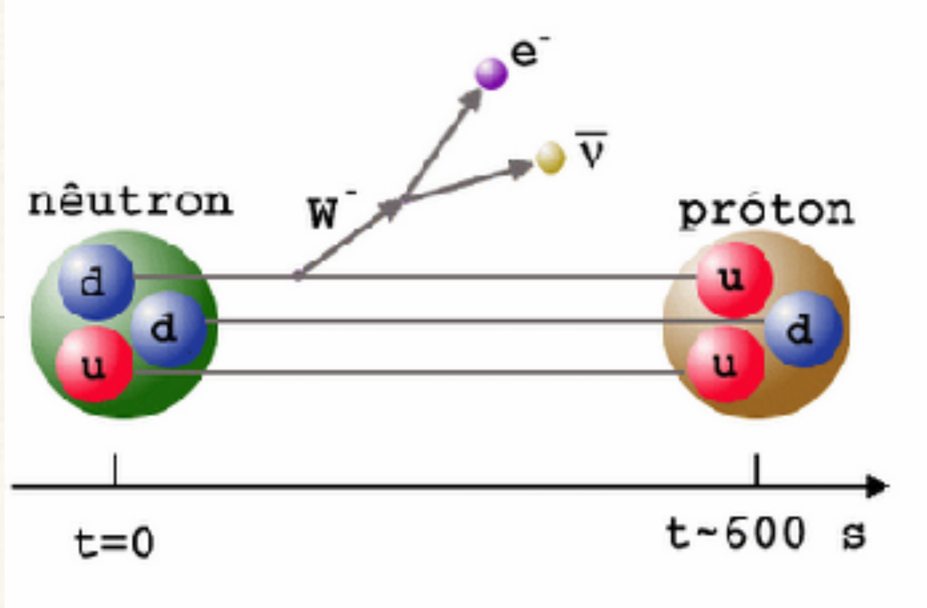
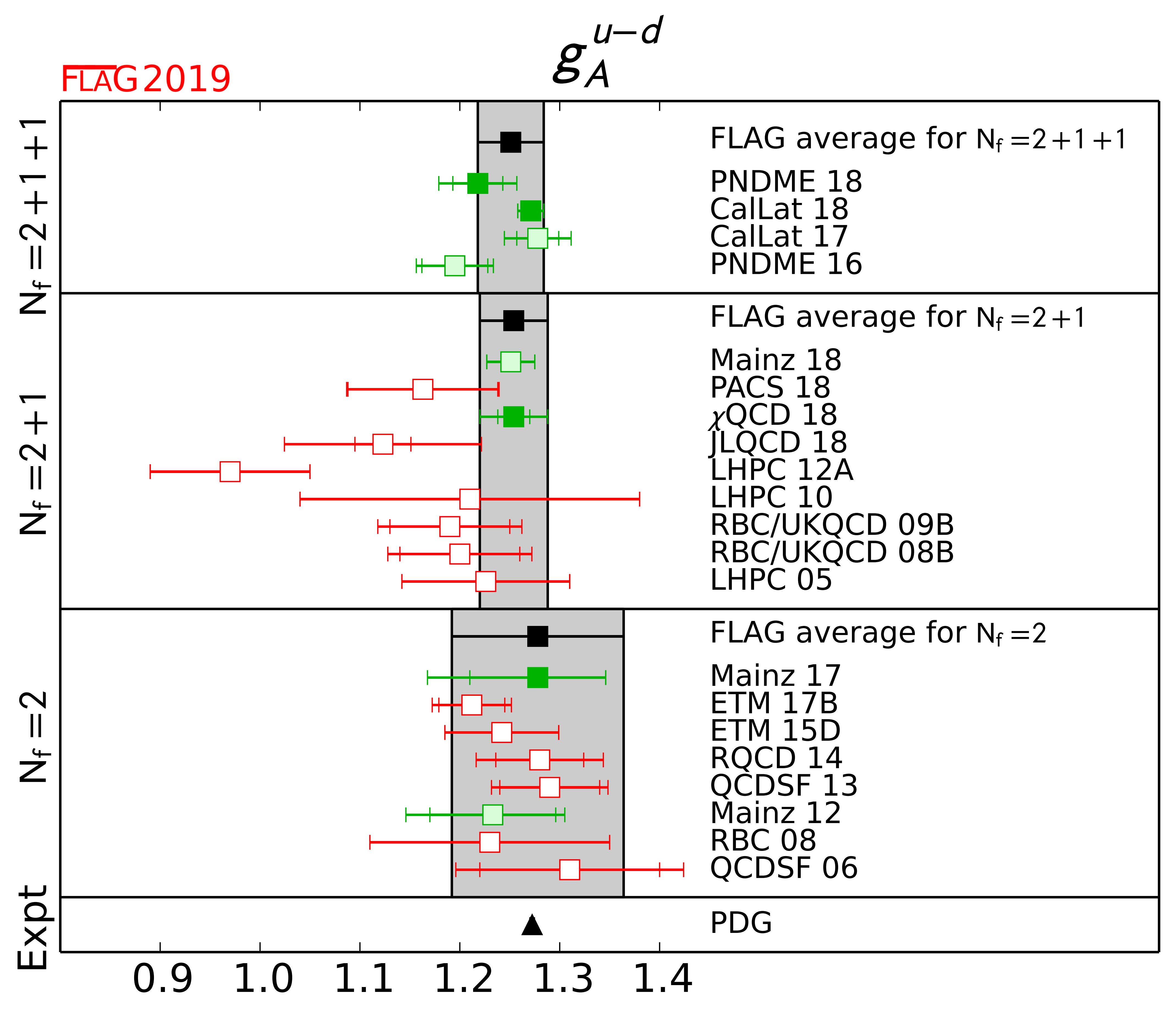
multi-sigm
10197]

We need a 0.13% uncertainty to be comparable to experimental uncertainty

- It is also important to have a Standard Model prediction for g_A - LQCD

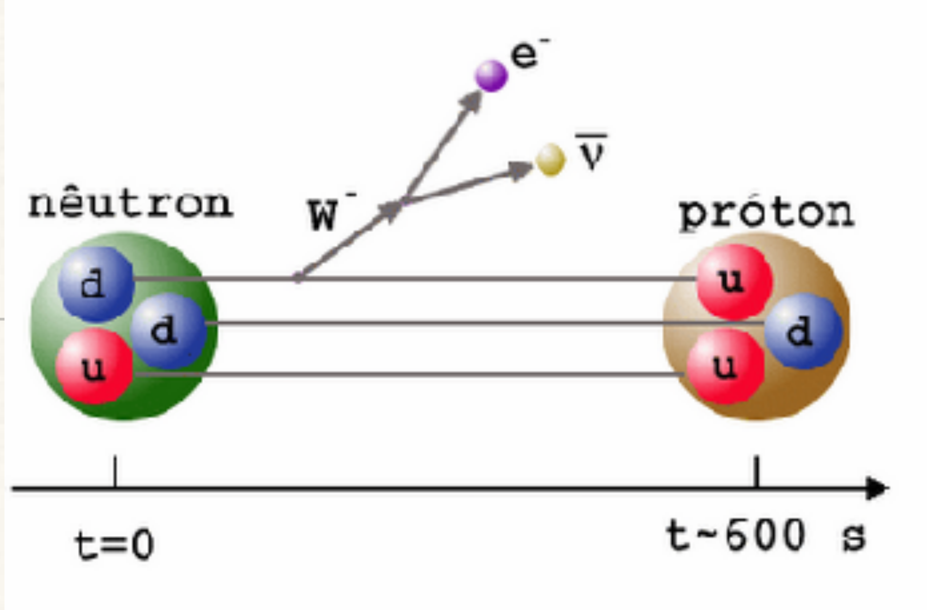
nucleon axial coupling from LQCD

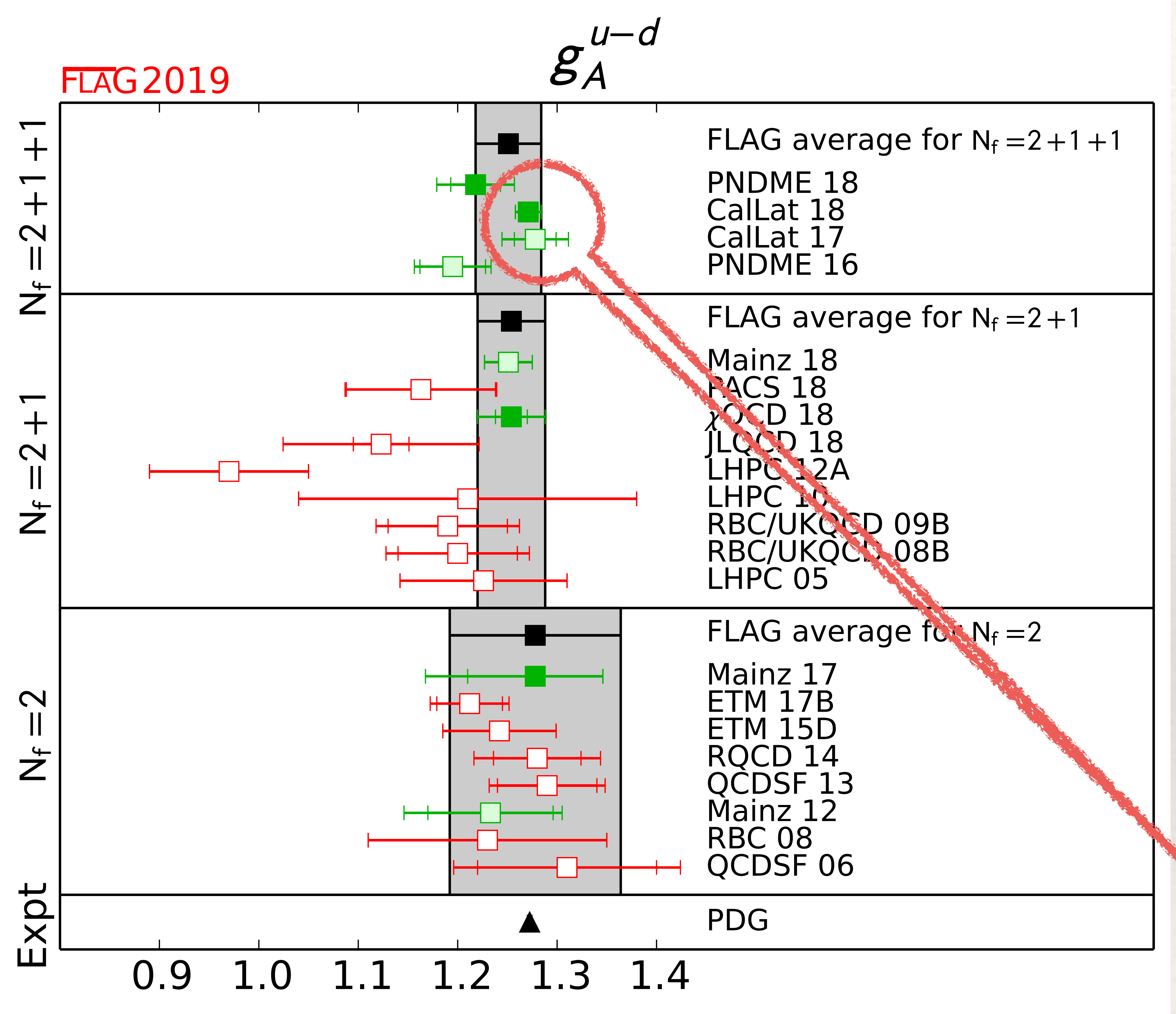




- To gain confidence in the application of Lattice QCD to nuclear physics, we must benchmark (calibrate) our calculations against well known quantities of interest
- g_A was supposed to be a good benchmark calculation for single nucleon structure - but it proved to have significant systematic challenges, preventing results with the precision anticipated
- FLAG 2019 has included single nucleon quantities in their averaging for the first time

nucleon axial coupling from LQCD





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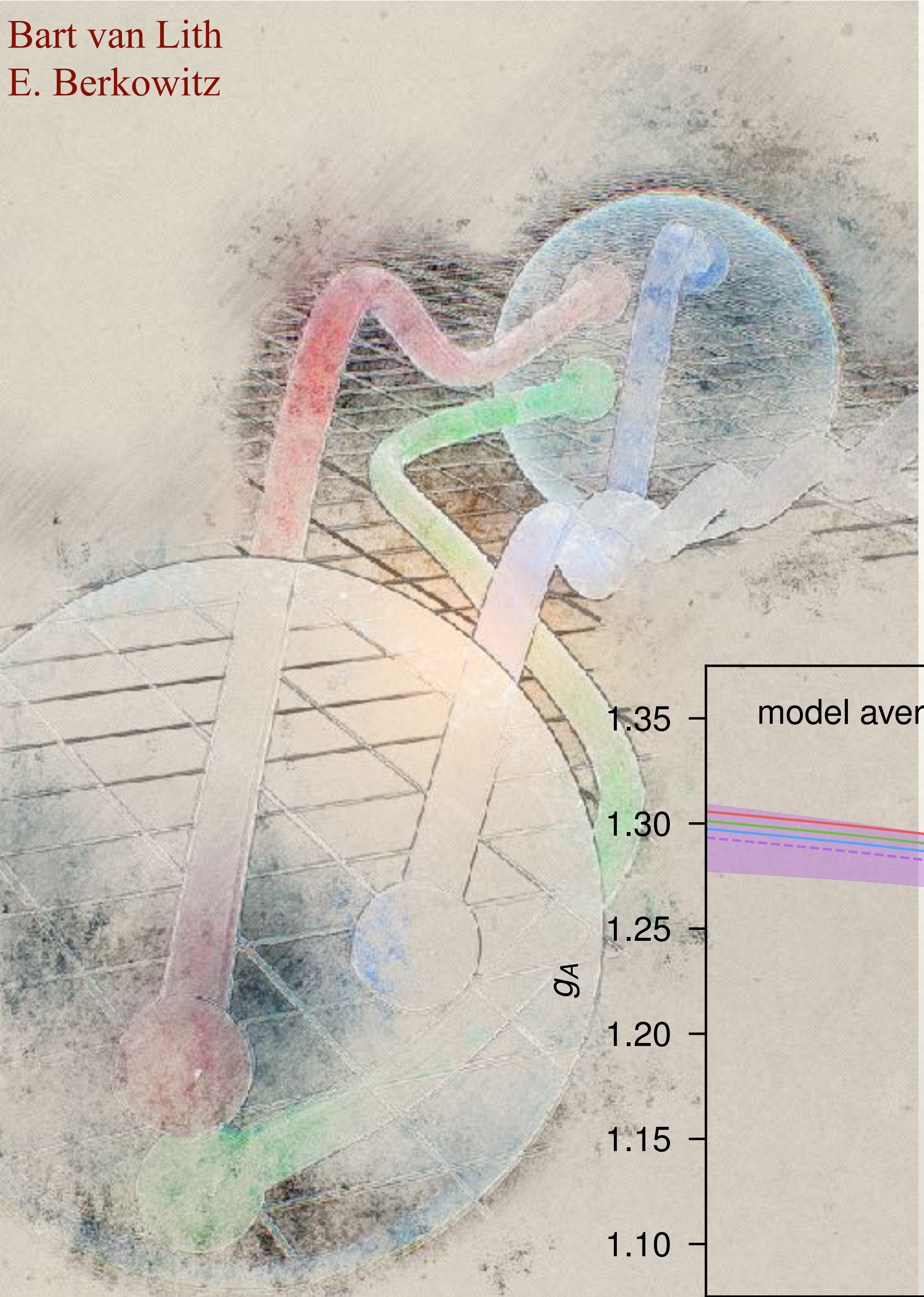
- ❑ FLAG 2019 has included single nucleon quantities in their averaging for the first time
- ❑ Notice one result is significantly more precise than the others

Bart van Lith
E. Berkowitz



LETTER

https://doi.org/10.1038/s41586-018-0161-8

Nature 558 (2018) no.7708, 91-94 [arXiv:1805.12130]

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

https://github.com/callat-qcd/project_gA

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(postdoc, grad student)

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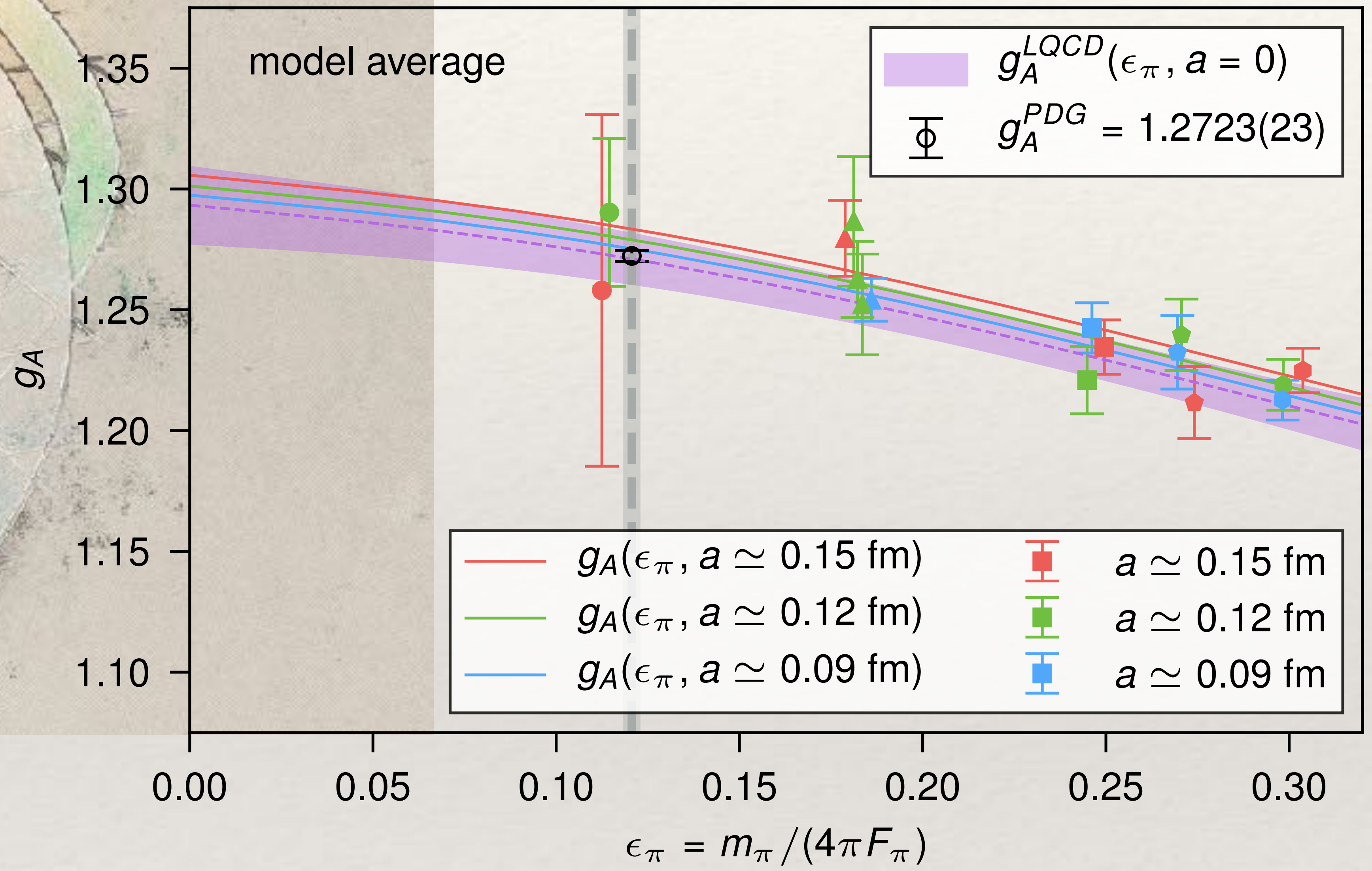
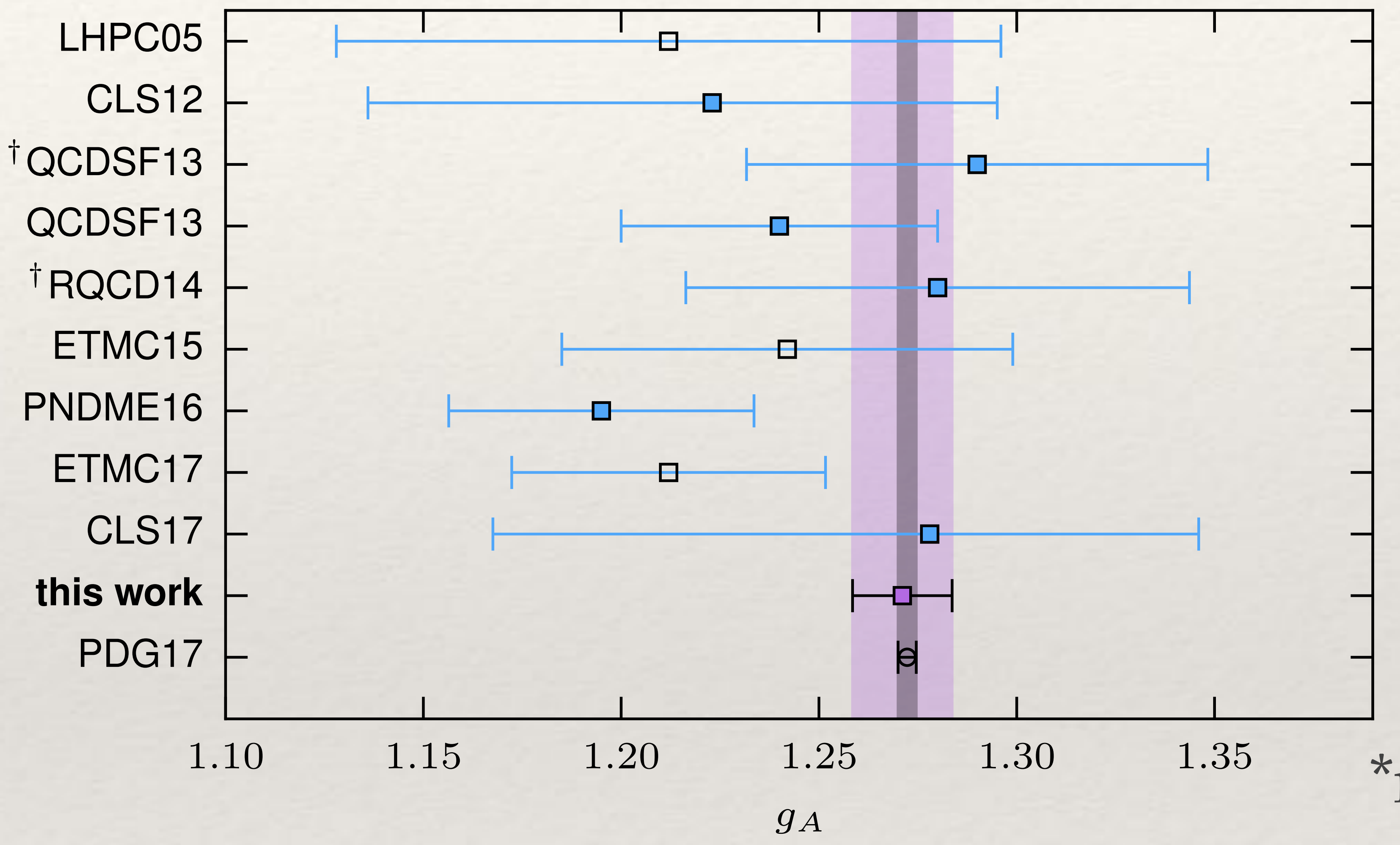
previously estimated to achieve 2% by 2020



LQCD results



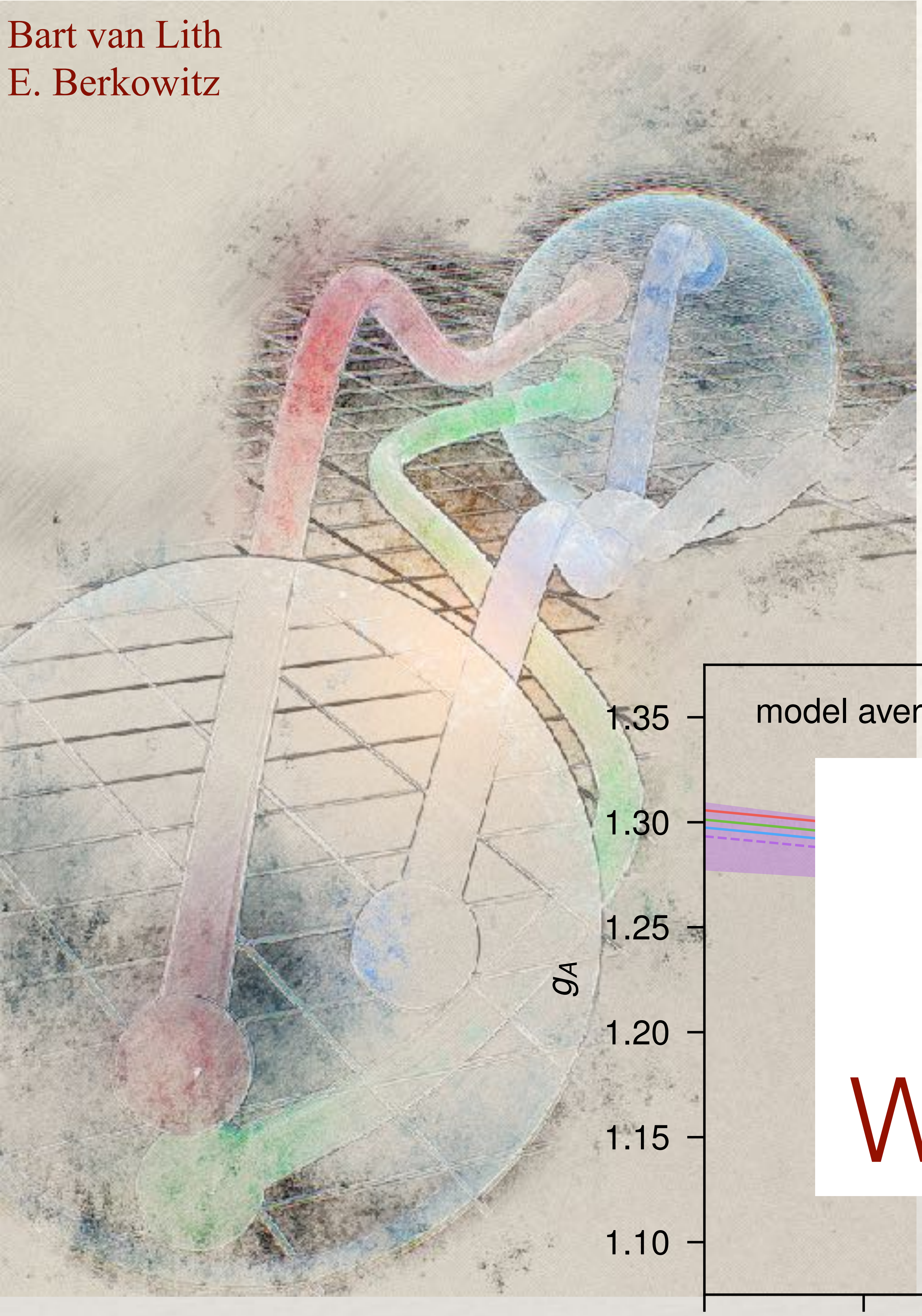
(CalLat)
*not all in California

$$g_A^{\rm QCD} = 1.2711(103)^s(39)^\chi(15)^a(19)^V(04)^I(55)^M$$
$$= 1.2711(126)$$
$$g_A^{\rm UCNA} = 1.2772(020)$$

experiment factor of 6 more precise

DOE Topical Collaboration
Double Beta Decay

Bart van Lith
E. Berkowitz



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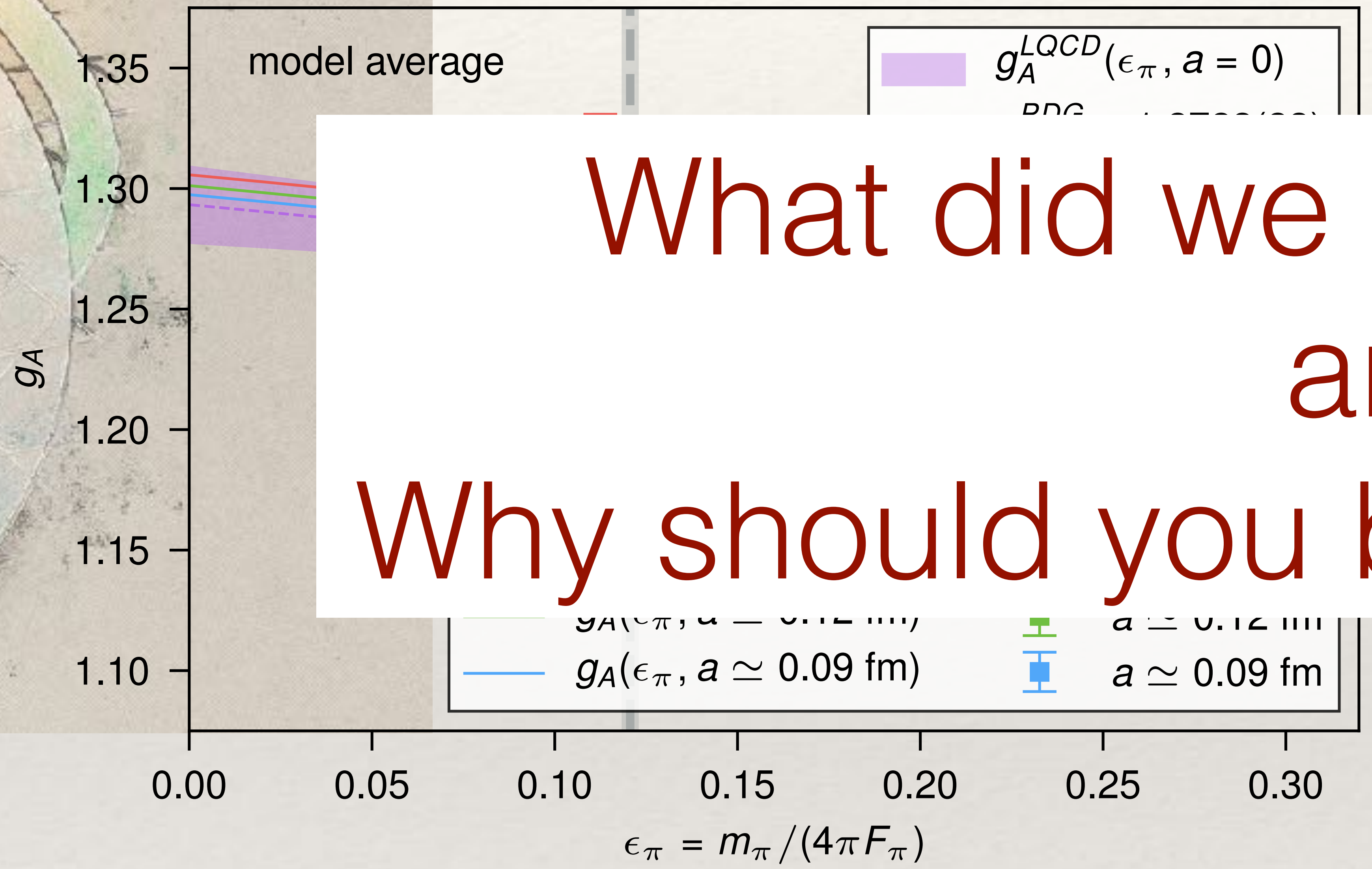

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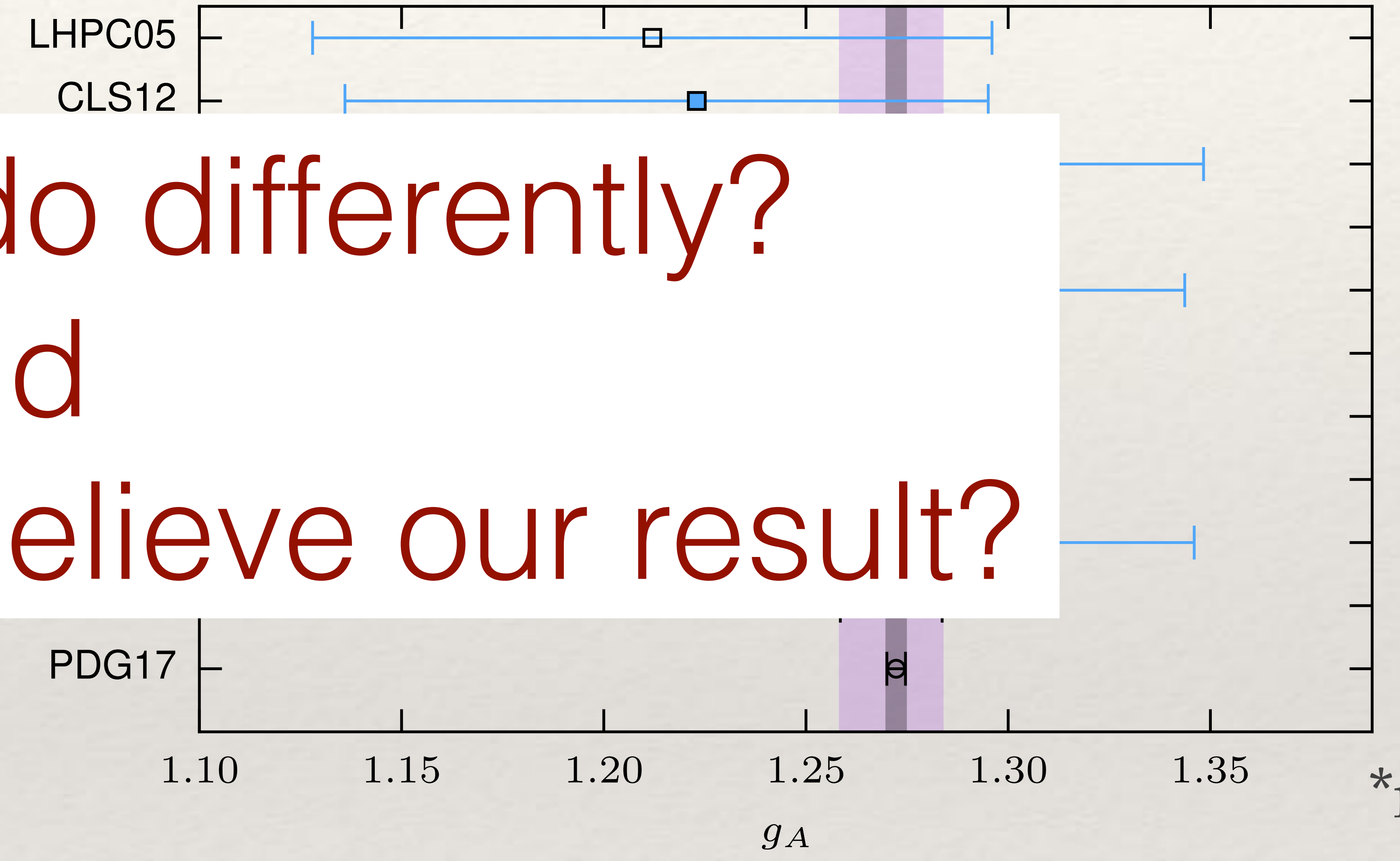

What did we do differently?
and
Why should you believe our result?

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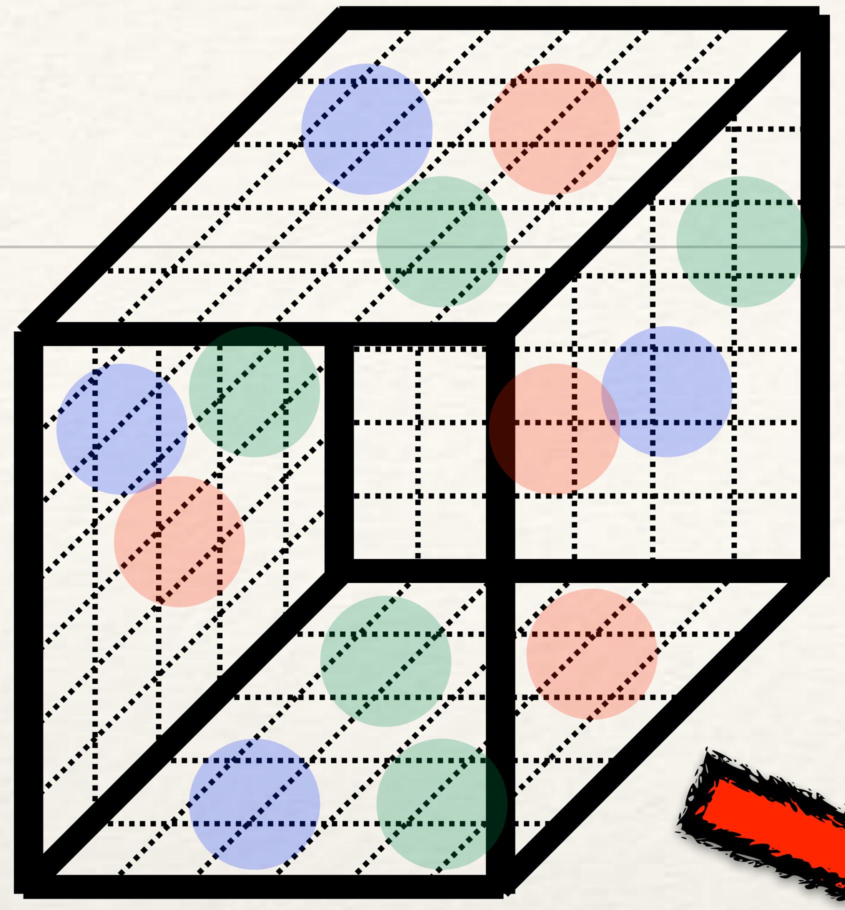
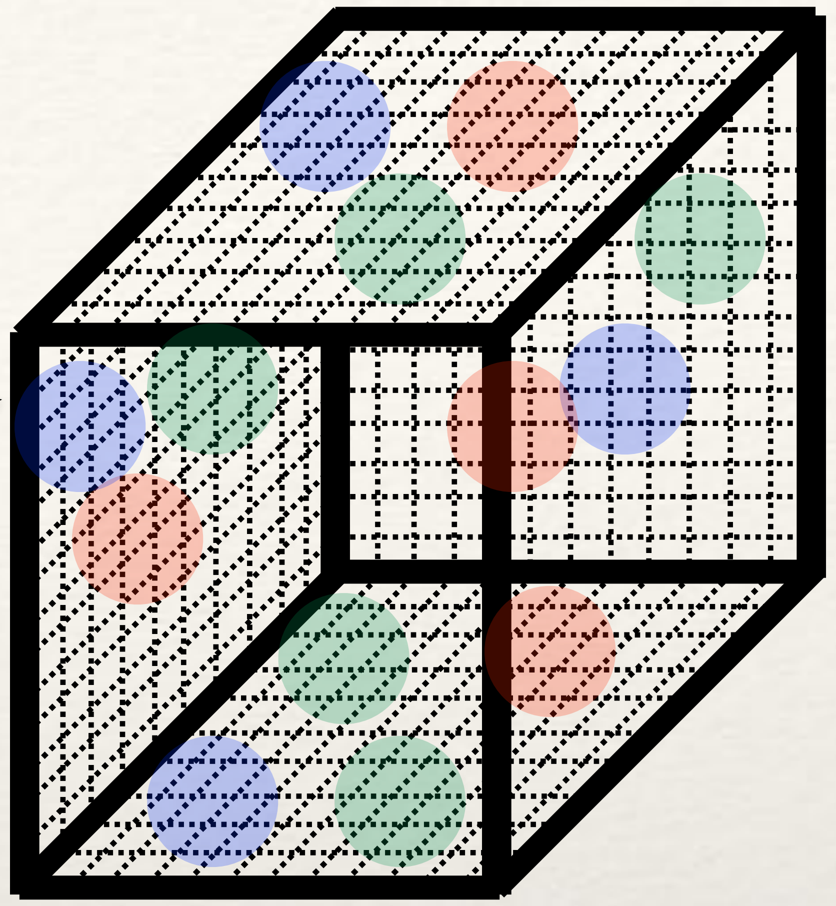
Standard Systematics



continuum limit
need 3 or more
lattice spacings

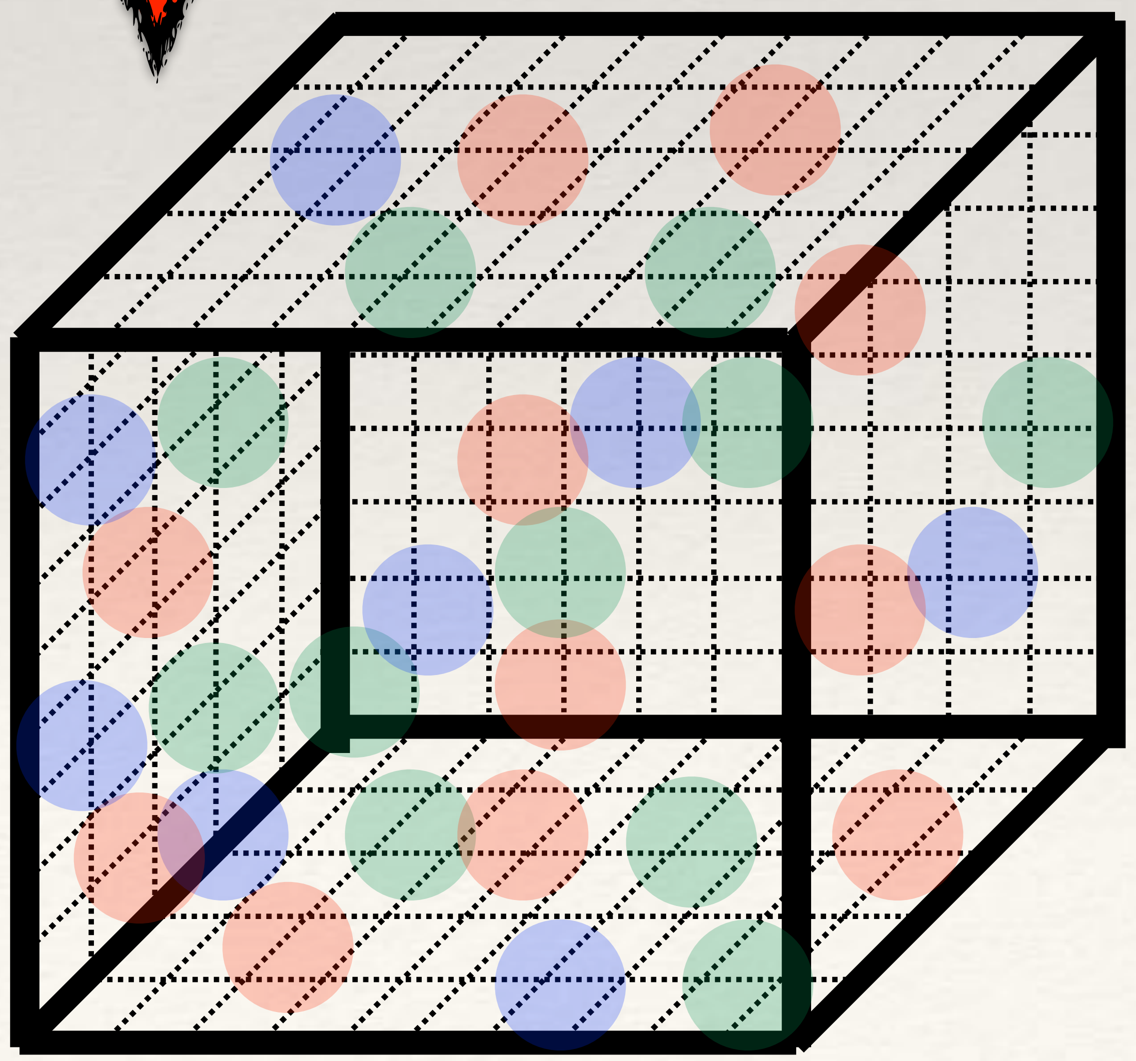
$$t_{comp} \propto \frac{1}{a^6}$$



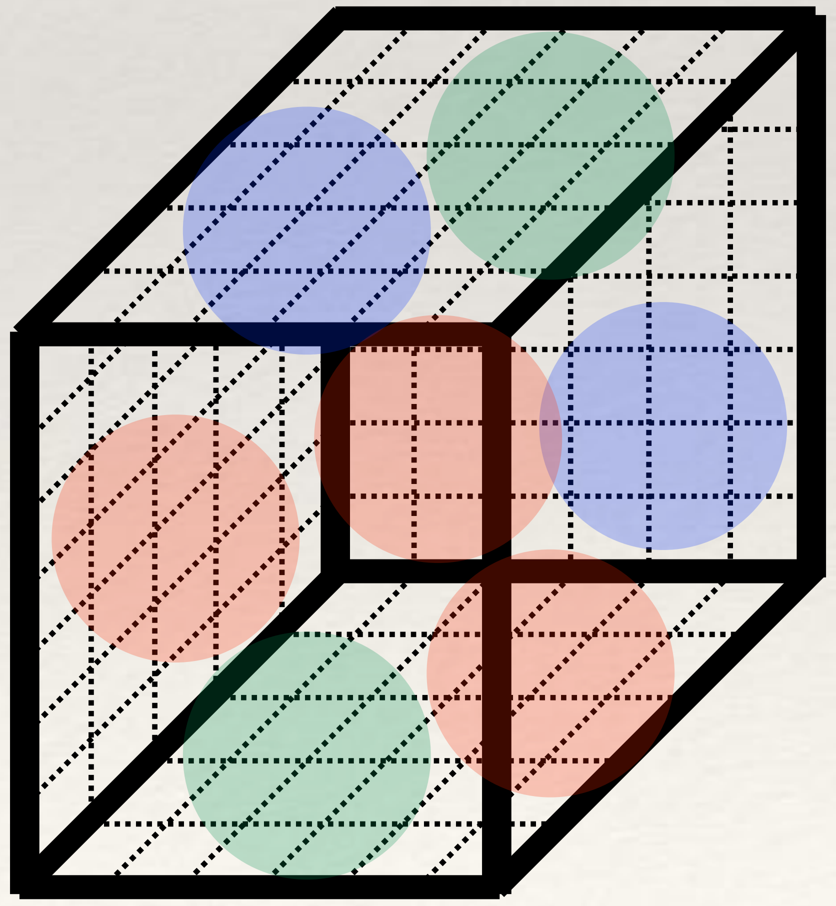
infinite volume limit

$$t_{comp} \propto V^{5/4}$$

$$V = N_L^3 \times N_T$$



physical pion masses
exponentially bad
signal-to-noise problem

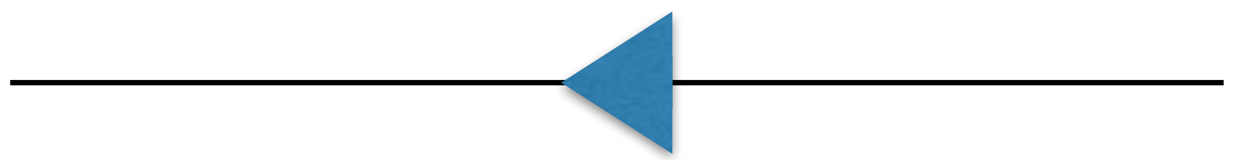


Slide adapted from E. Berkowitz

LQCD challenges for NP

Most difficult challenge: an exponentially bad signal-to-noise problem

Parisi, Phys. Rep. 103 (1984) 203



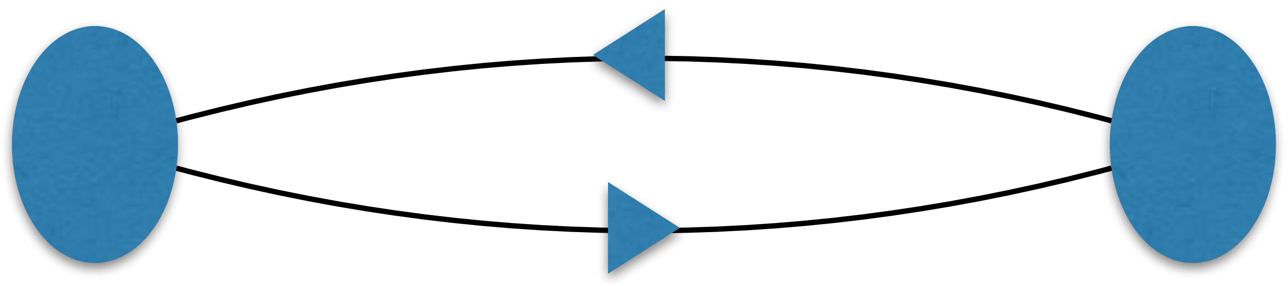
$$\sim e^{-\frac{1}{2}m_\pi t} + e^{-\frac{1}{3}m_N t} + \cdots$$

Lepage, TASI 1989

Each **quark propagator** carries information about pions and nucleons (conversations with David Kaplan)

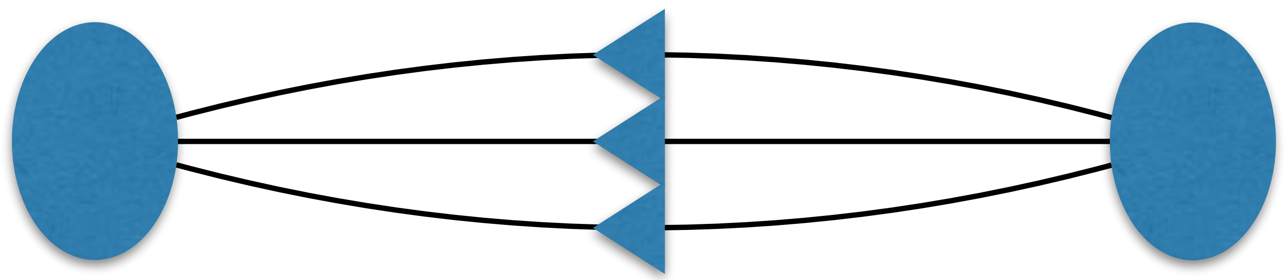
$$\lambda_\pi(t) \gg \lambda_N(t)$$

$$\lambda_i(t) \sim e^{-E_i t}$$



$$\bar{d}\gamma_5 u : C(t) = A_\pi e^{-m_\pi t} + \cdots$$

Large pion eigenvalues must cancel to expose small nucleon eigenvalues



$$(u^T C\gamma_5 d)u : C(t) = A_N e^{-m_N t} + \cdots$$

$$\frac{\text{Signal}}{\text{Noise}} \sim \sqrt{N} \exp\left[-A\left(m_N - \frac{3}{2}m_\pi\right)t\right]$$

exponential noise
power-law statistics

LQCD challenges for NP

2-point correlation function

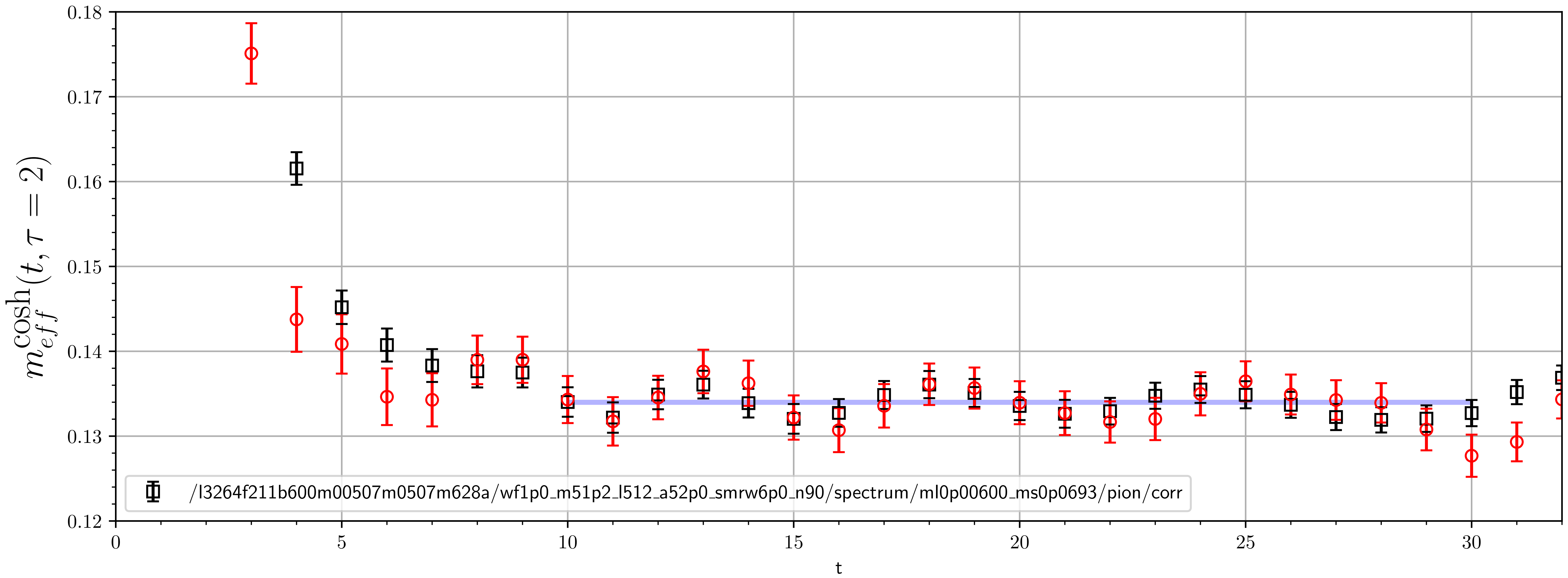
$$C(t) = \sum_n z_n z_n^\dagger e^{-E_n t}$$

$$m_{eff}(t) = \frac{1}{\tau} \ln\left(\frac{C(t)}{C(t+\tau)}\right)$$

For pions, need to consider leading finite temperature effects

$$C(t) = \sum_n z_n z_n^\dagger \left(e^{-E_n t} + e^{-E_n (T-t)}\right)$$

$$m_{eff}^{\cosh}(t,\tau) = \frac{1}{\tau}\cosh^{-1}\left(\frac{C(t+\tau)+C(t-\tau)}{2C(t)}\right)$$

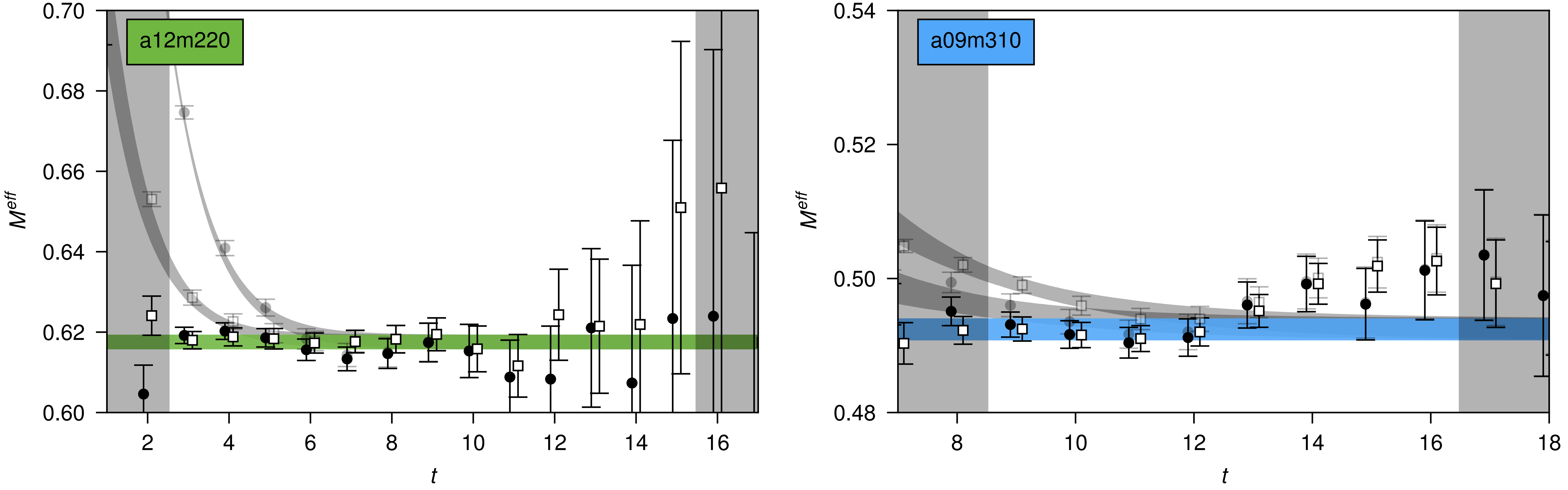


Effective mass of Pion 2-point correlation function
red and black “data” are from different choices of *interpolating* operators

Noise is constant in time - can determine very clean ground state (blue band)

LQCD challenges for NP

2-point correlation function



Two examples of nucleon effective mass

Noise is growing in time - can not simply go to the long-time limit without exponentially increasing the amount of statistics needed

$$\frac{Signal}{Noise} \rightarrow \sqrt{N_{state}}e^{-(m_N - \frac{3}{2}m_\pi)t}$$

Correlated late-time fluctuations… what is the ground state?

Need sophisticated analysis to ensure you are not susceptible to correlated fluctuations

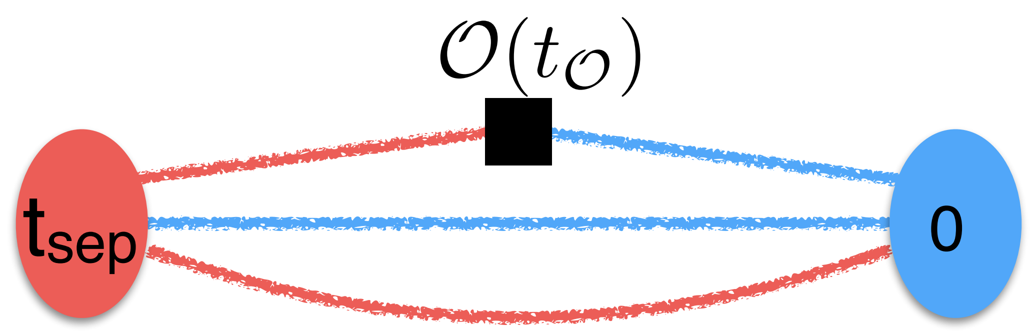
This problem is exacerbated with form-factor calculations (g_A) and 2+ nucleons

- quark contraction cost becomes dominant
- density of excited states grows significantly and gap becomes small (nuclear interaction energies instead of pion mass gap)

LQCD challenges for NP

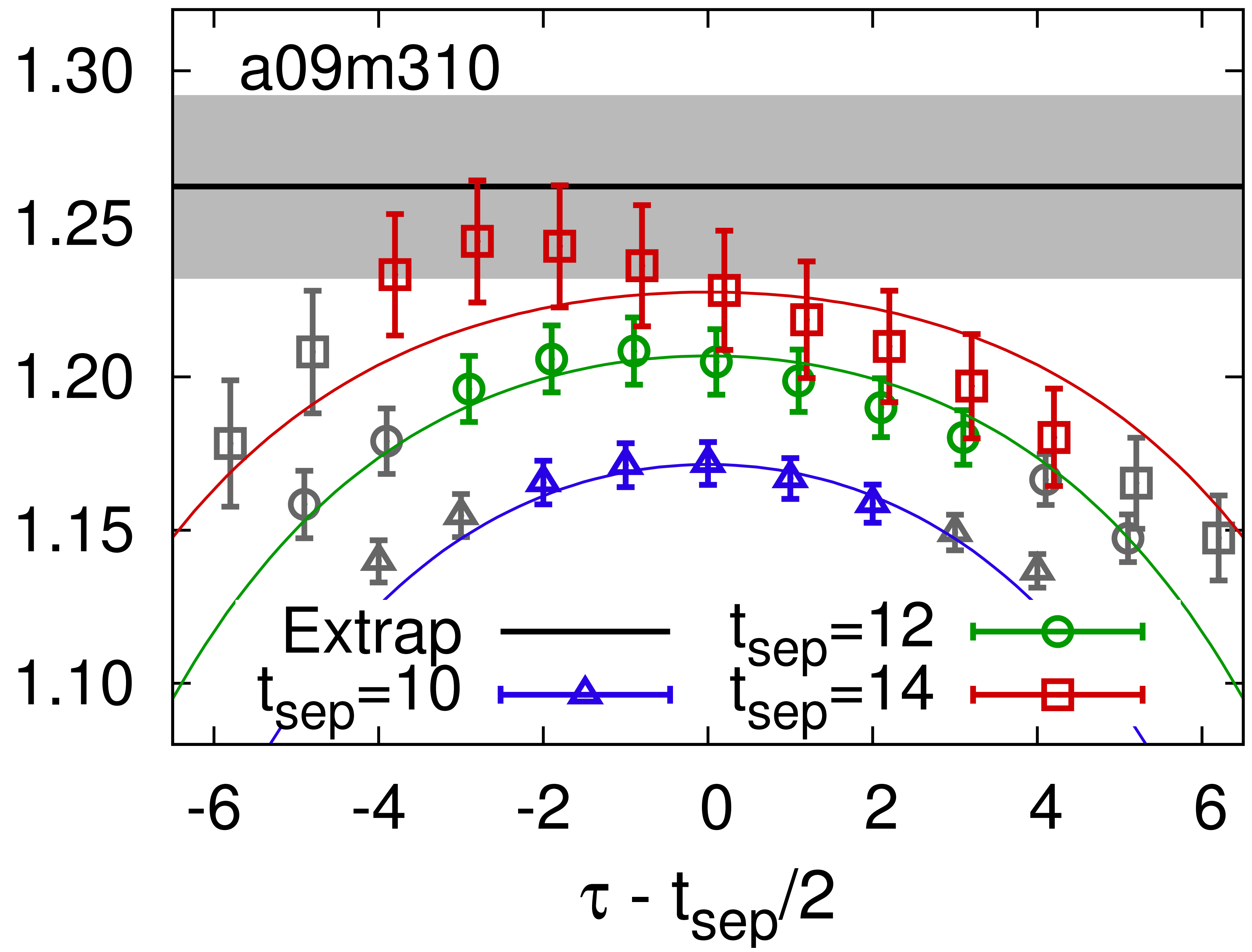
Nucleon axial charge calculation

fixed source-sink separation time, t_{sep}



$$R_3 = g_\lambda + z_1 e^{-t_{sep}\Delta_{10}} + z_{10} e^{-(\tau - t_{sep}/2)\Delta_{10}} + \cdots$$

in long-time (**t_{sep}**) limit - should be flat



Repeat for multiple values of **t_{sep}**

Extrapolate to **t_{sep}** $\to \infty$

t_{sep}	**fm**
14	**1.22**
12	**1.05**
10	**0.875**

typical calculation

Bhattacharya, Cirigliano, Cohen, Gupta, Lin, Yoon

Phys.Rev.D 94 (2016)

LQCD challenges for NP

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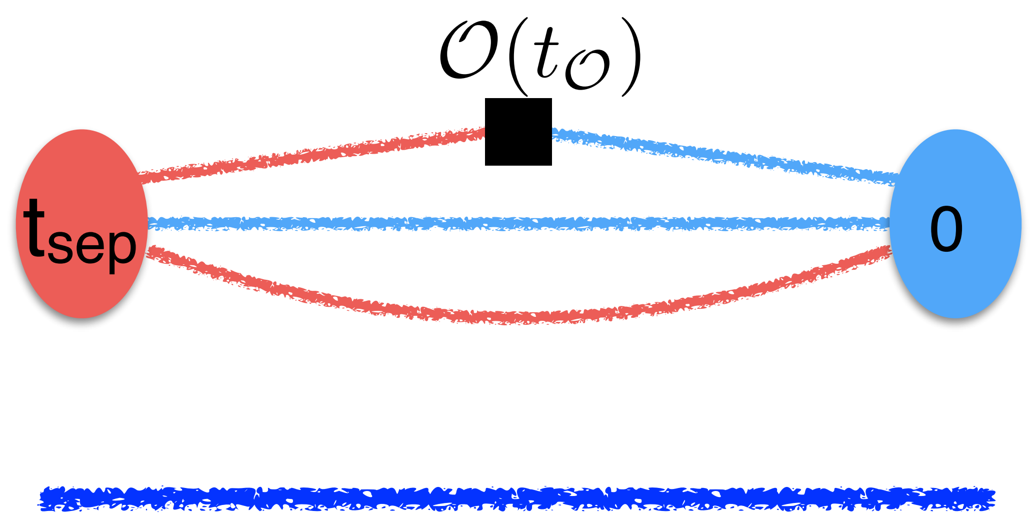

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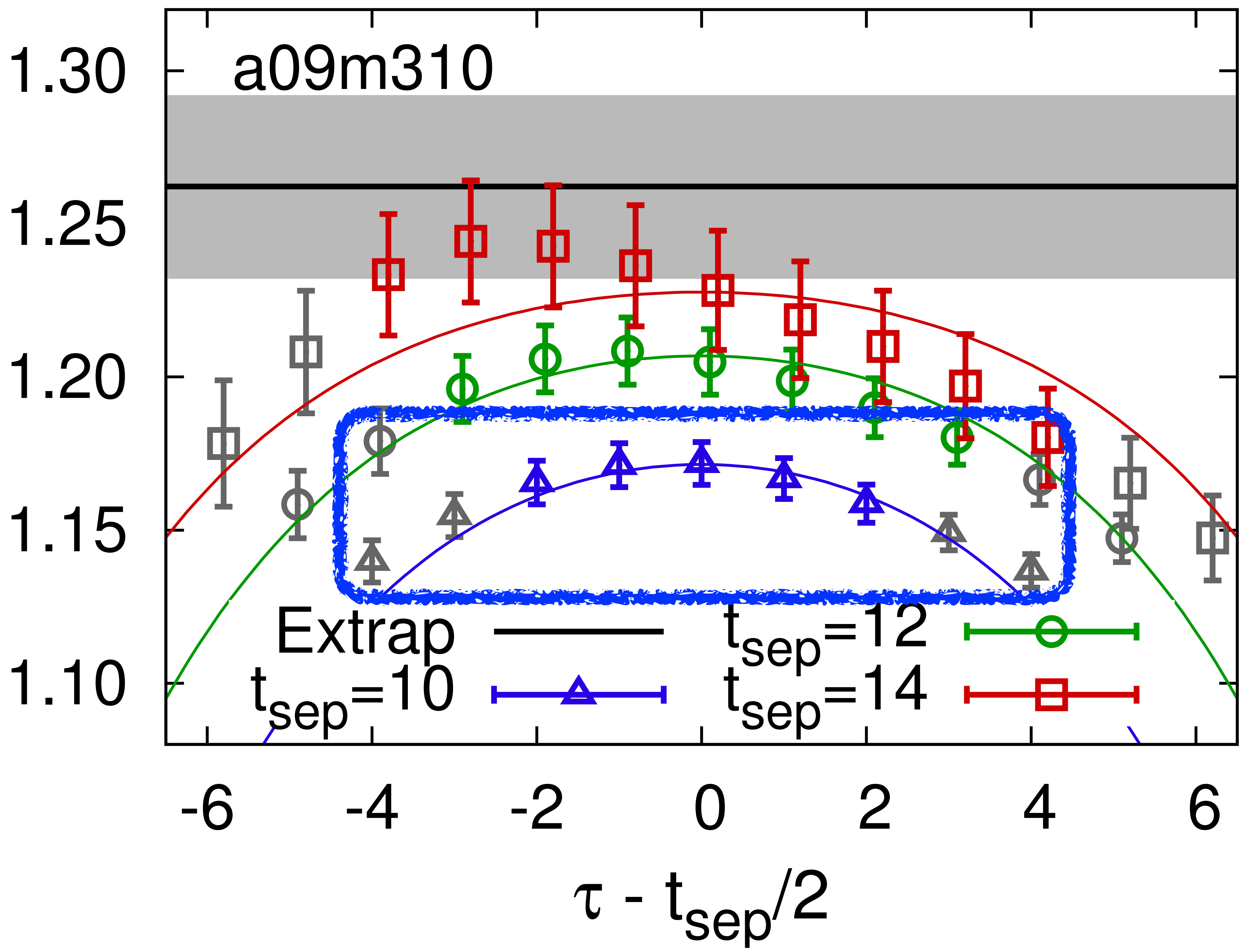

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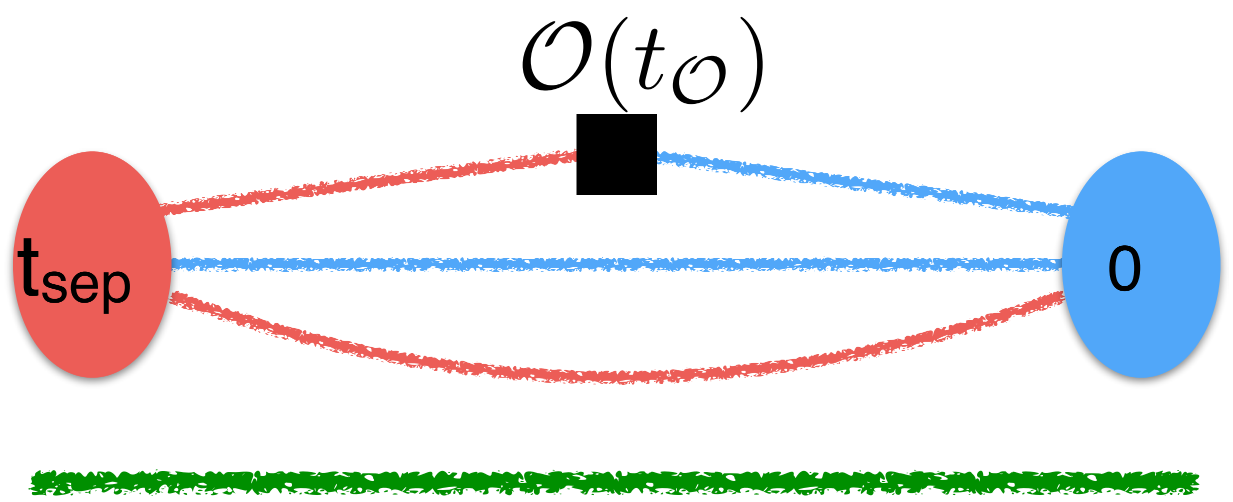

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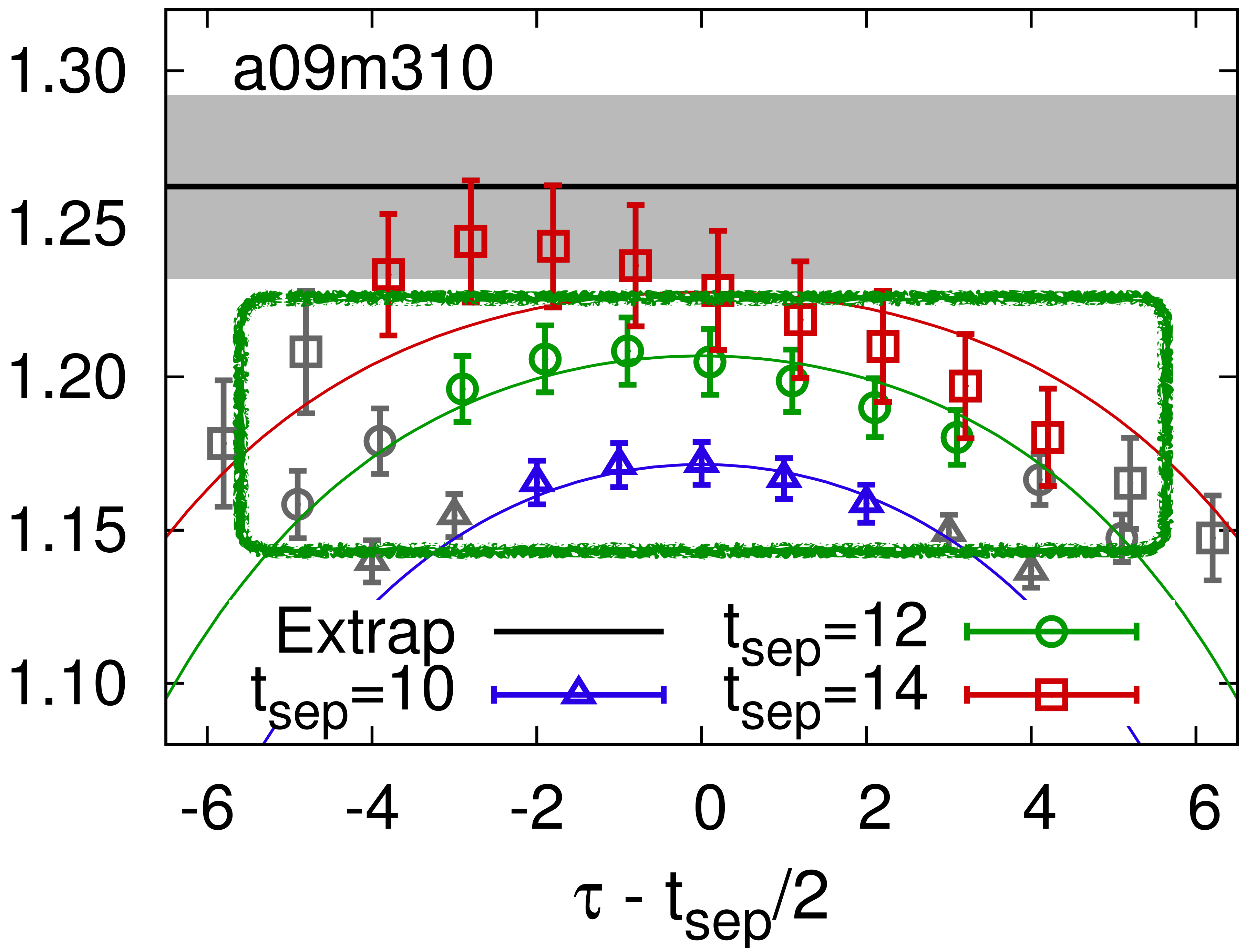

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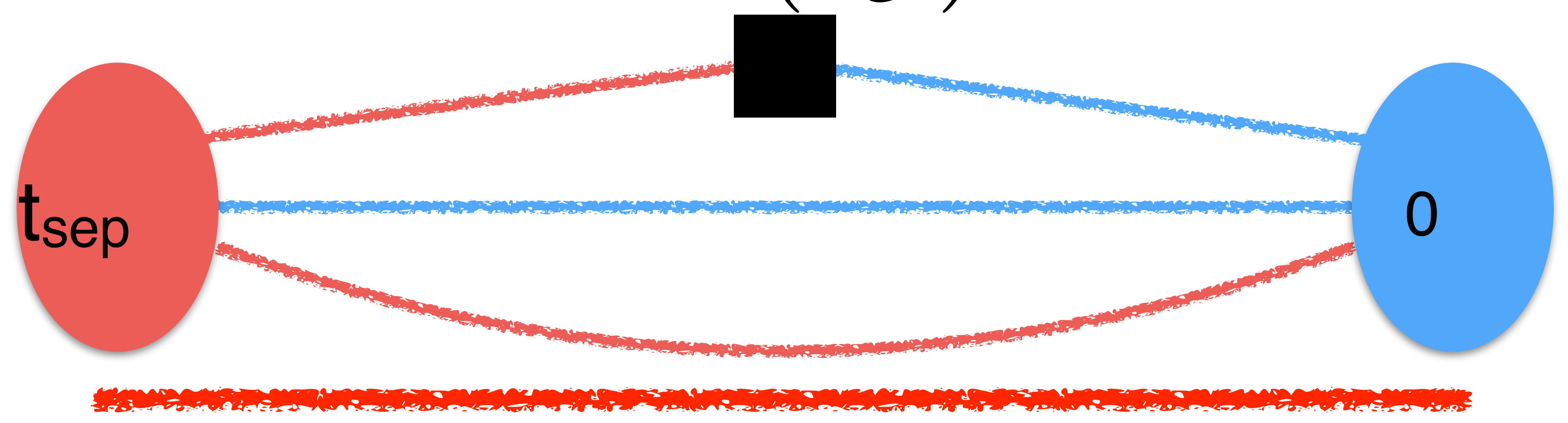
$\mathcal{O}(t_{\mathcal{O}})$



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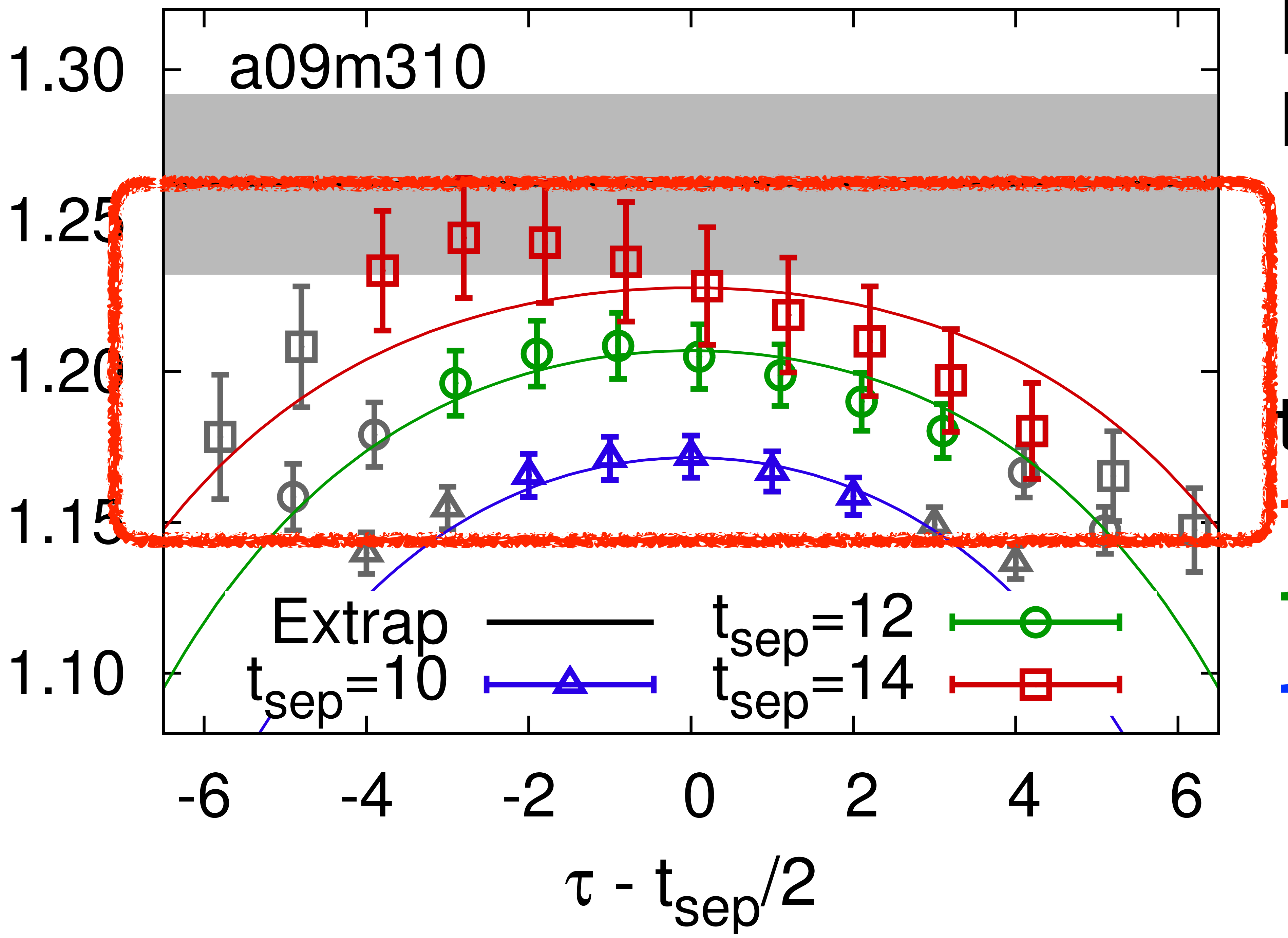

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arXiv.org > hep-lat > arXiv:1612.06963
Phys. Rev. D96 (2017)

High Energy Physics – Lattice

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

$$\partial_\lambda E_n\big|_{\lambda=0} = \langle n|H_\lambda|n\rangle$$

"Follow your nose" in QFT

"Feynman-Hellmann" correlation function

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

$$= g_\lambda + z\left(e^{-(t+1)\Delta_{10}} - e^{-t\Delta_{10}}\right) + \cdots$$

$\Delta_{10} = E_1 - E_0$ more than exponentially suppressed arXiv.org > hep-lat > arXiv:1612.06963

Phys. Rev. D96 (2017)

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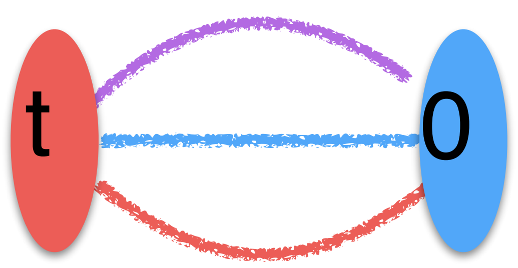
derivative correlation function



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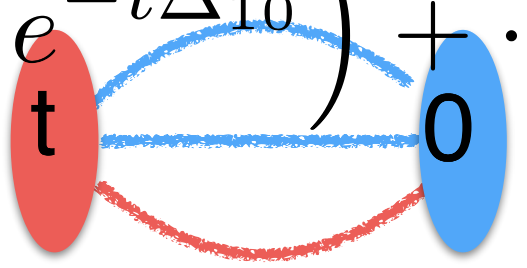
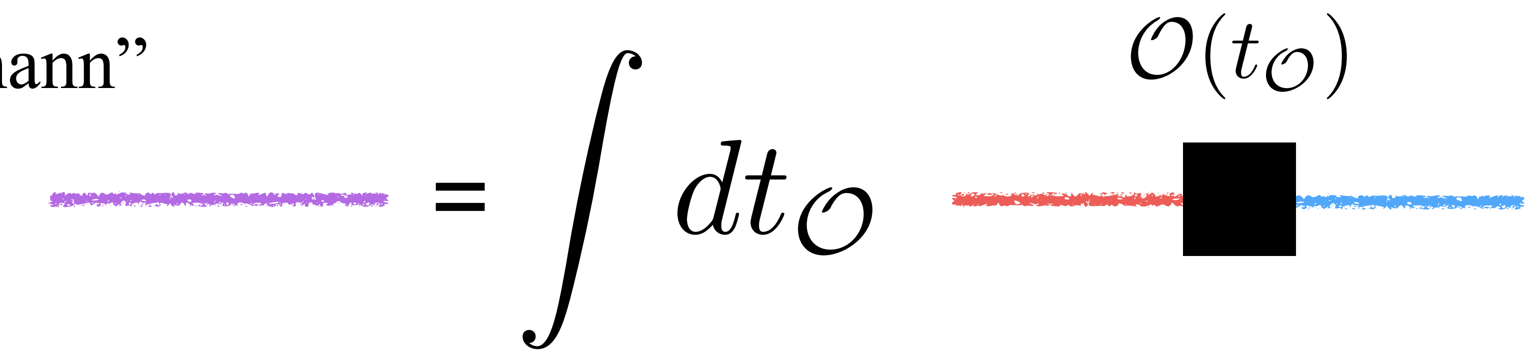


"Feynman-Hellmann" propagator

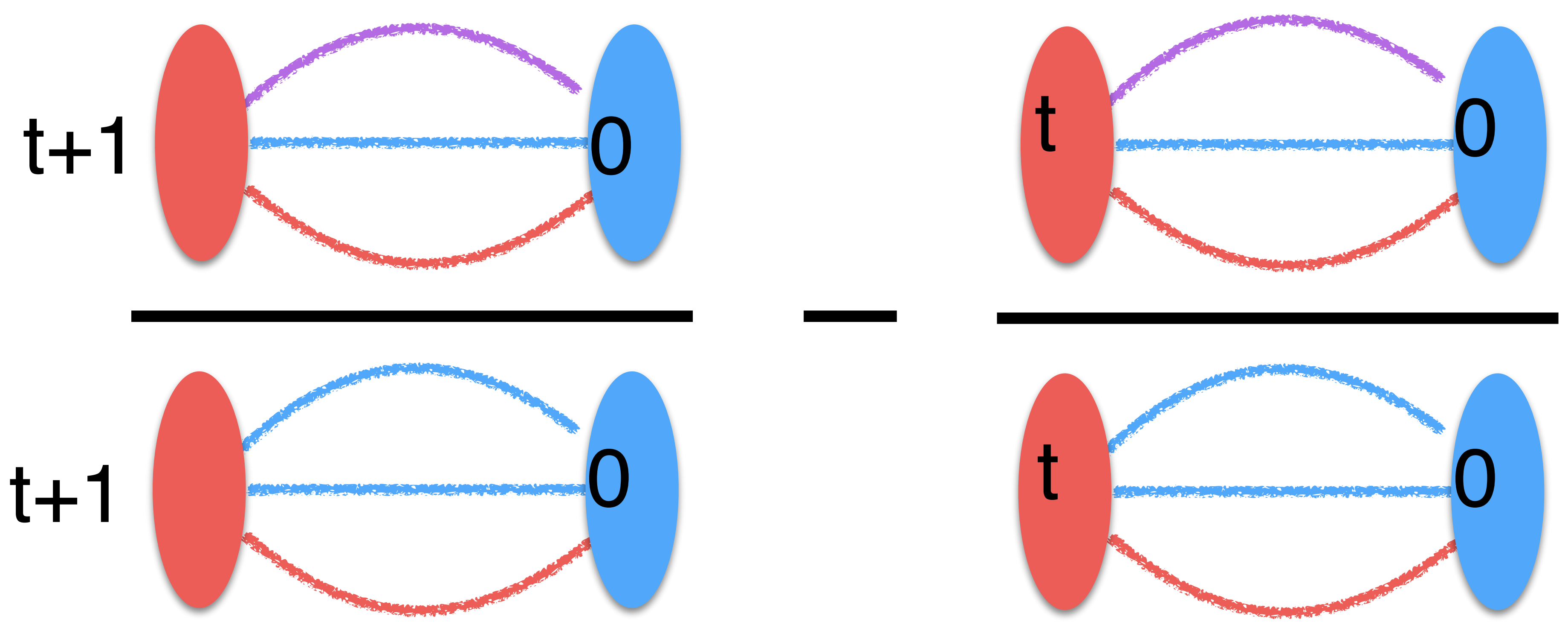


standard 2-point function

On the Feynman-Hellmann Theorem in QFT and the calculation of matrix elements

Phys. Rev. D96 (2017)
arXiv:1612.06963

our unconventional method



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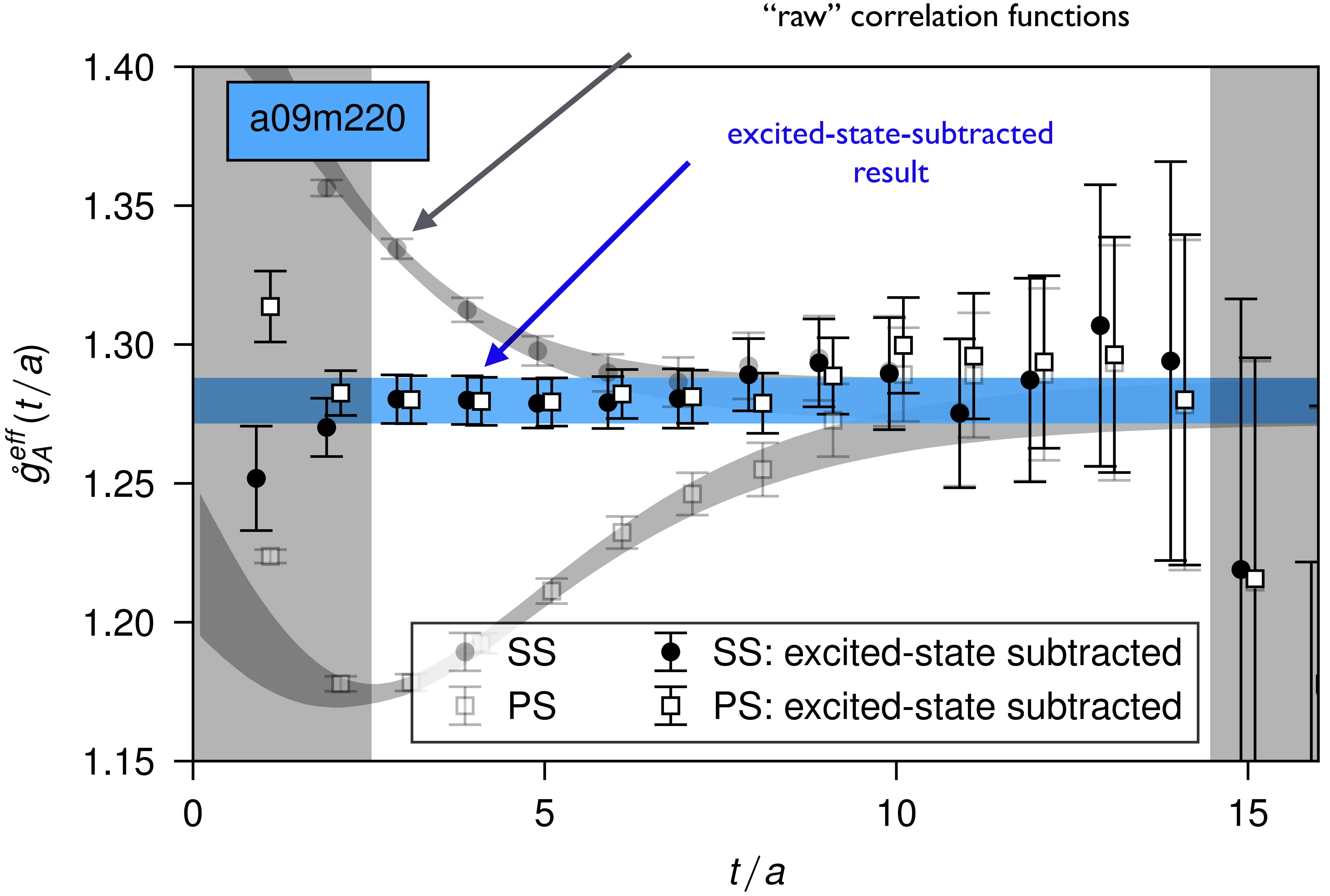

$$\left.\partial_\lambda m_\lambda^{eff}(t)\right|_{\lambda=0} = g_{00} + z(e^{-(t+1)\Delta_{10}} - e^{-t\Delta_{10}}) + \cdots$$

Key features of this method

- The correlation function is given by
- excited state contamination is demonstrably controlled
- we can access very early Euclidean time, allowing the use of exponentially more precise numerical points
- **No background field is used** - the FH-theorem is used to "derive" our "Feynman-Hellmann Correlation function" analytically

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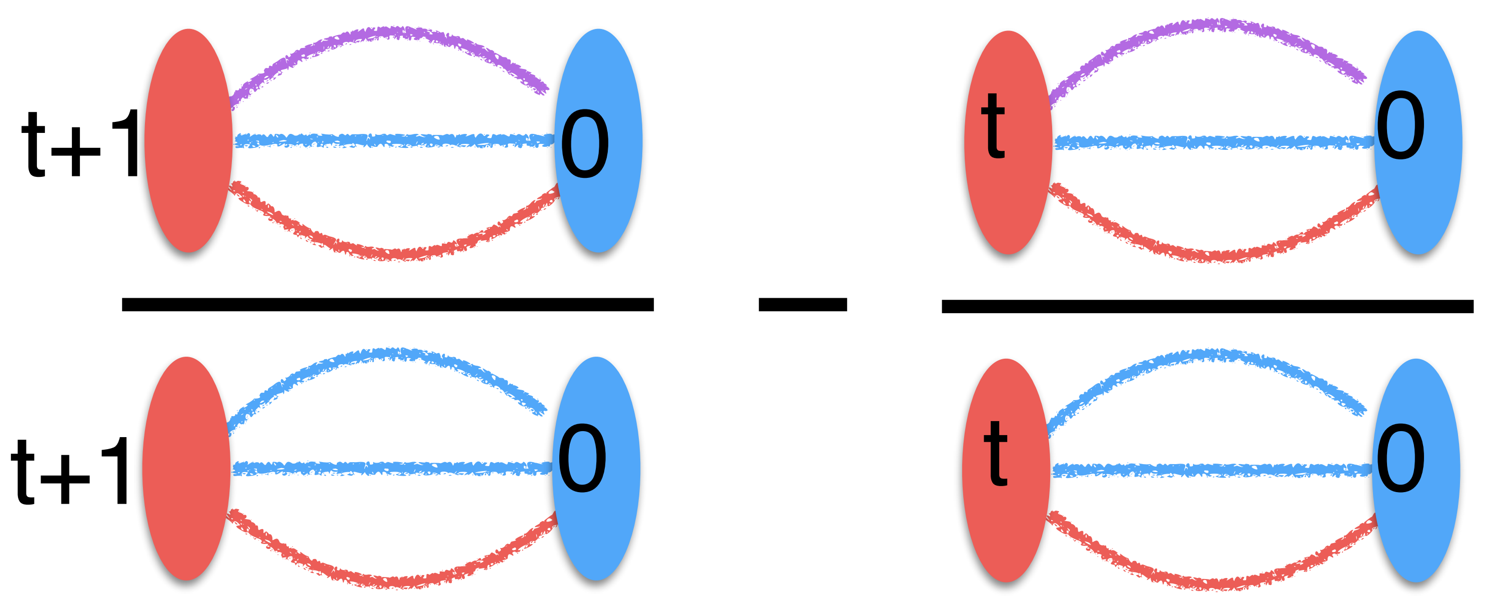
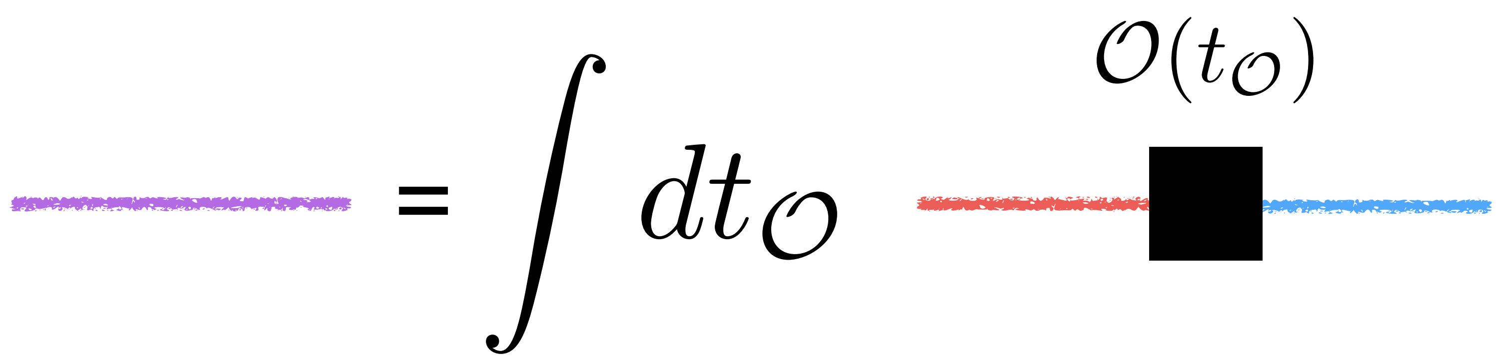
arXiv:1612.06963

our unconventional method



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

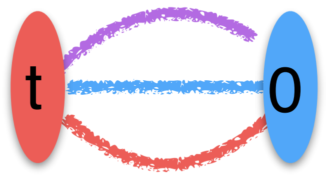
"Feynman-Hellmann" propagator



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

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 $-\partial_\lambda C_\lambda(t)$

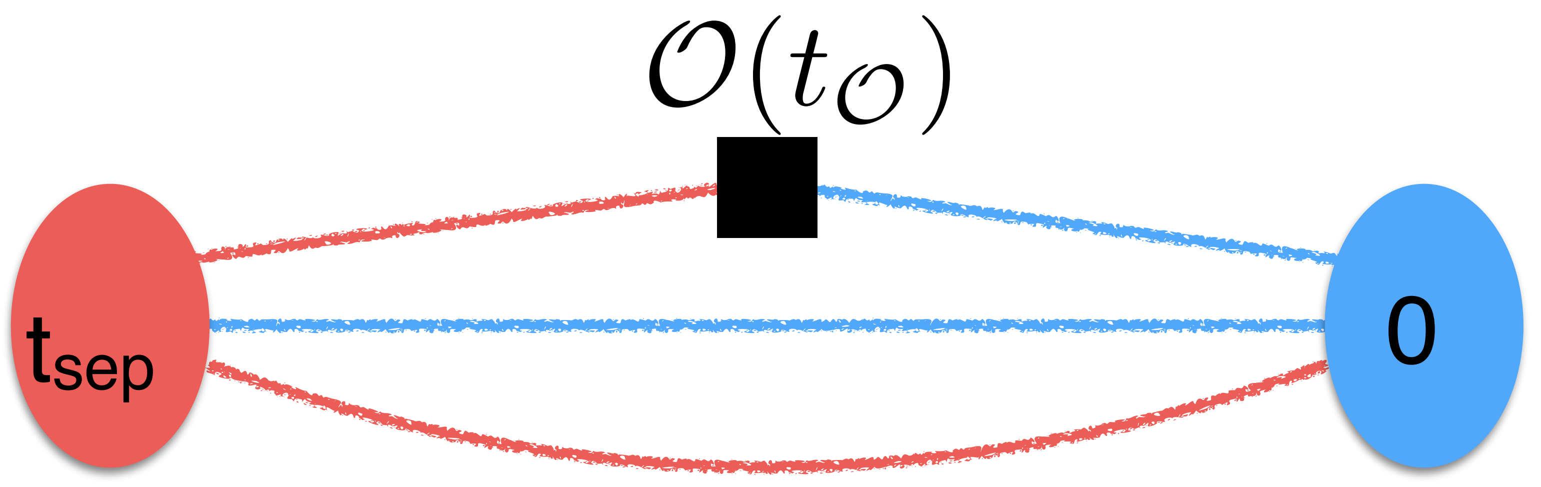


- Bulava, Donnellan, Sommer, **JHEP 1201 (2012):** combined above with GEVP
- de Divitiis, Petronzio, Tantalo, **PLB718 (2012):** computed derivatives of form factors
- Chambers et al. **PRD90 (2014), PRD92 (2015)** Savage et al. **PRL199 (2017);** used unconventional method with background field (λ) 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])

On the Feynman-Hellmann Theorem in QFT and the calculation of matrix elements

Phys. Rev. D96 (2017)
arXiv:1612.06963

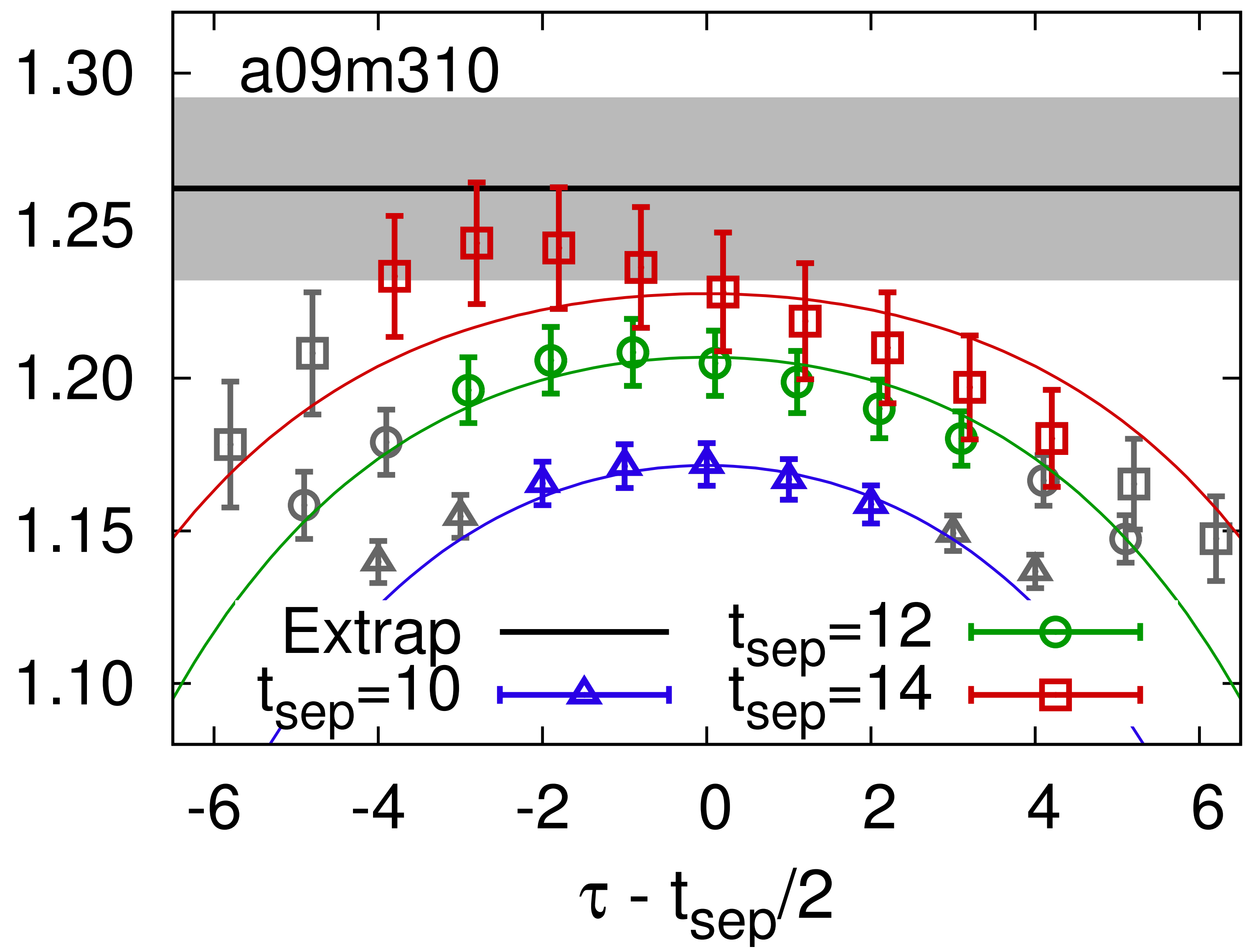
standard method



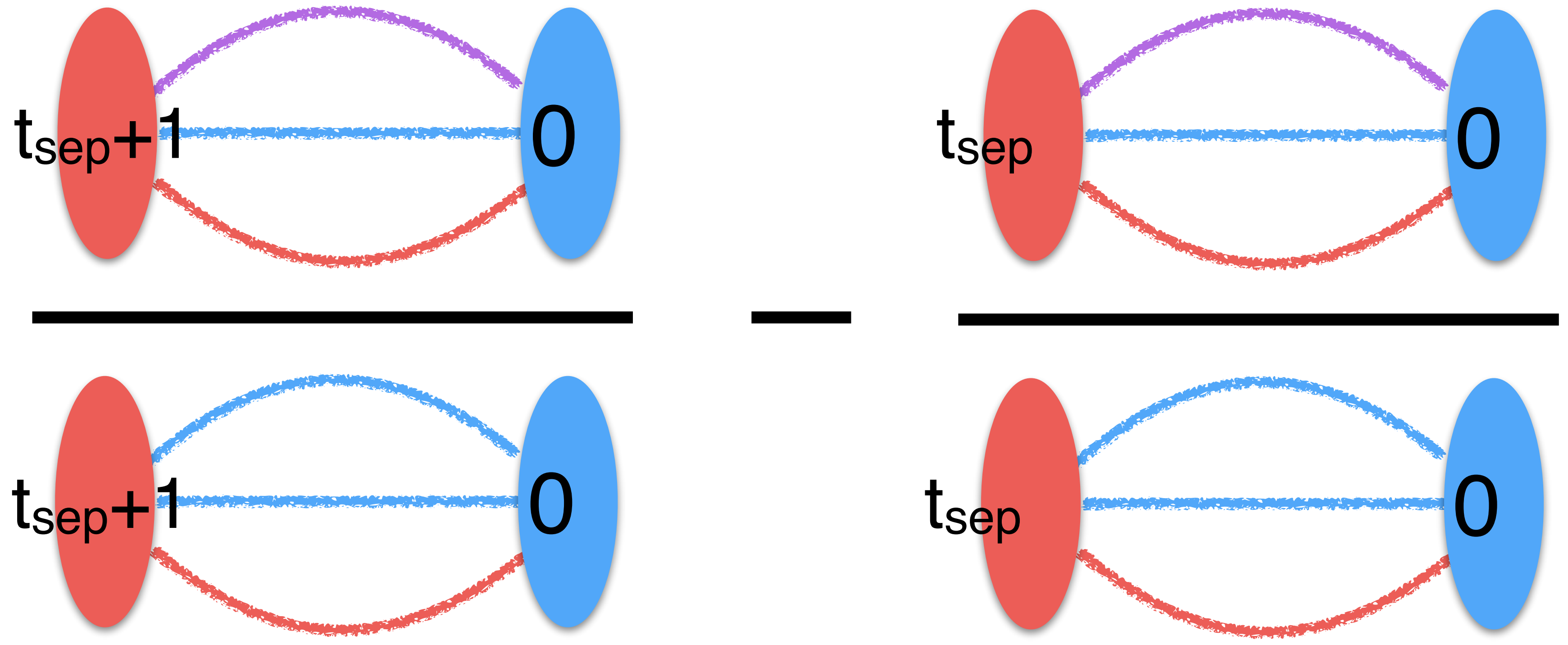
fixed source-sink separation time, **t_{sep}**
repeat for a few different t_{sep}

$$R_3 = g_\lambda + z_1 e^{-t_{sep}\Delta_{10}} + z_{10} e^{-(\tau - t_{sep}/2)\Delta_{10}} + \cdots$$

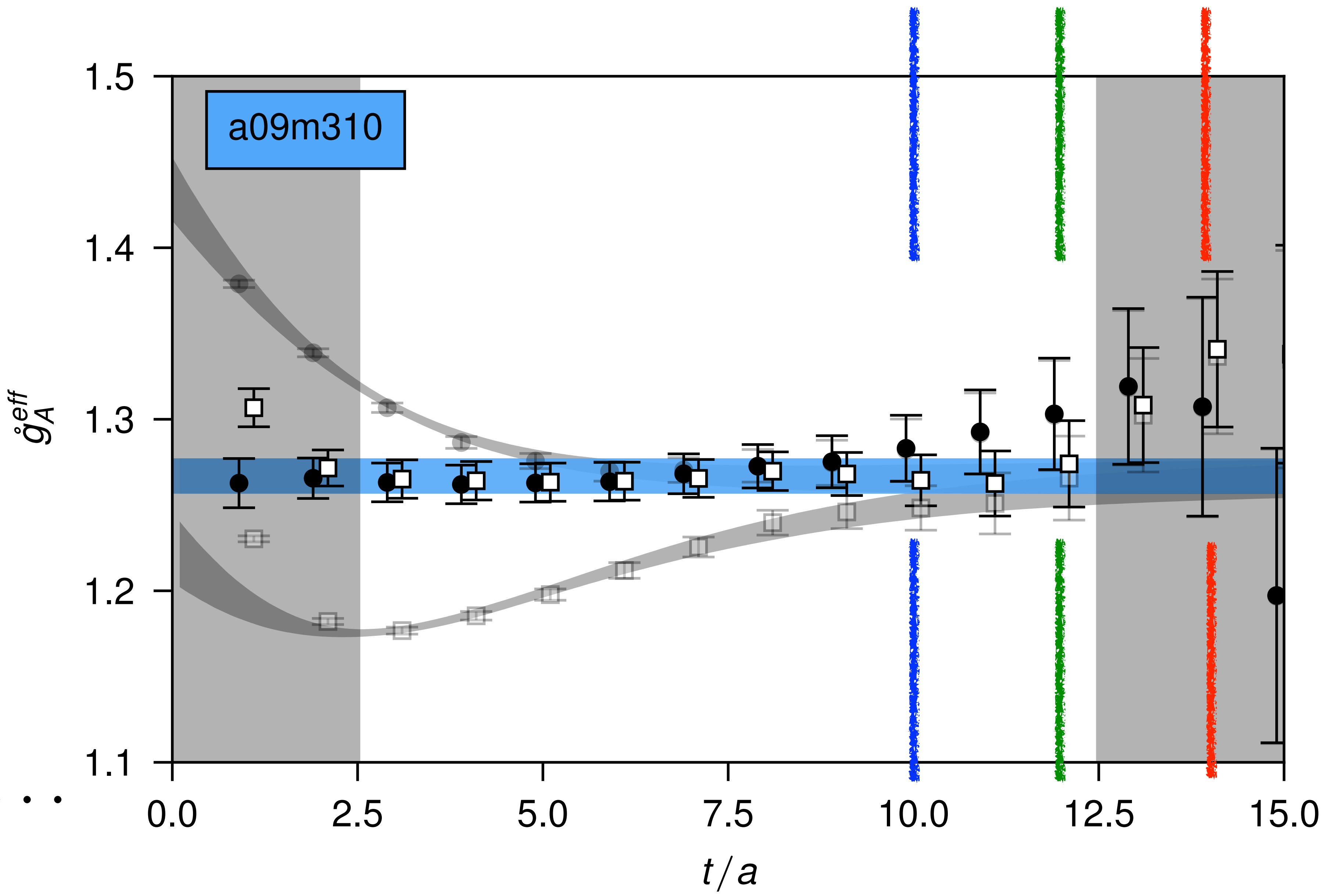
PNDME arXiv:1606.07049



our unconventional method



$$\partial_\lambda m_\lambda \Big|_{\lambda=0} = g_\lambda + z\left(e^{-(t_{sep}+1)\Delta_{10}} - e^{-t_{sep}\Delta_{10}}\right) + \cdots$$



Some Lattice QCD Details

Berkowitz et al. PRD96 (2017) [1701.07559]

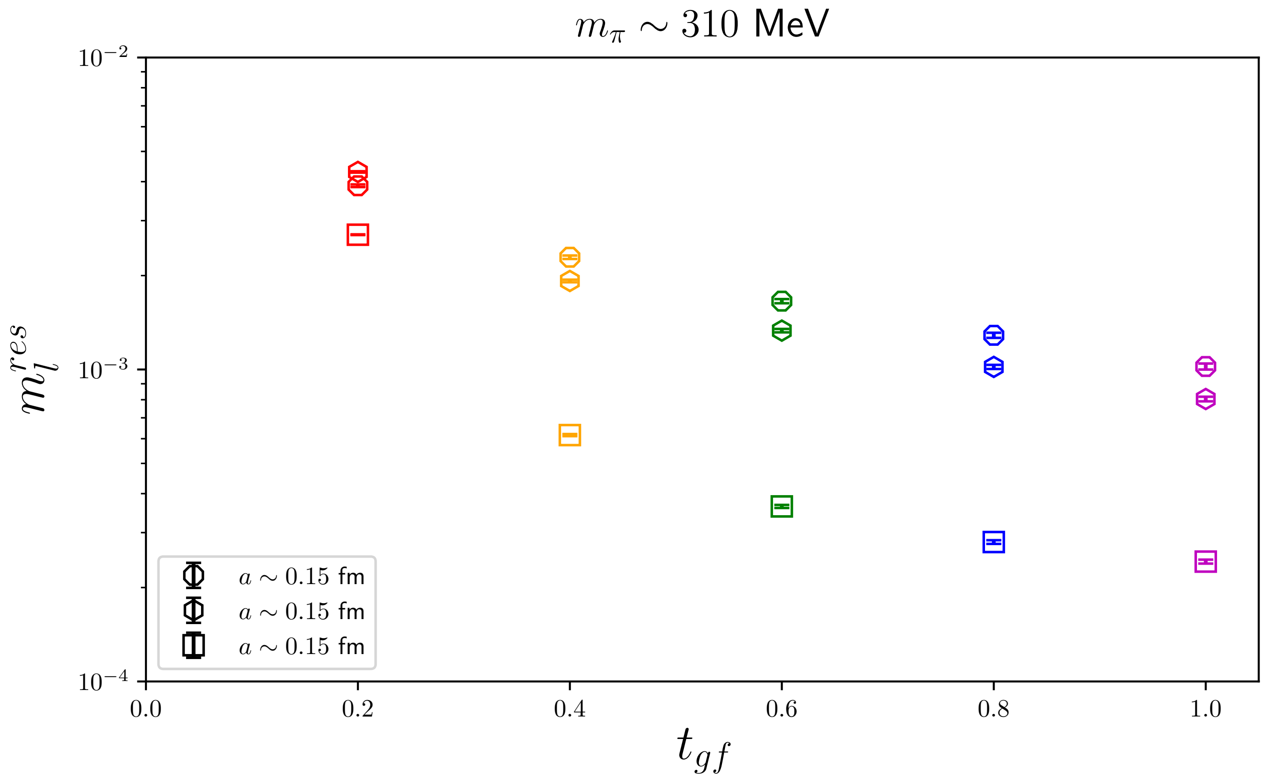
- Möbius Domain Wall Fermions on gradient flowed 2+1+1 HISQ ensembles Berkowitz et al. PRD96 (2017) [1701.07559]
  - Approximate chiral symmetry, many finite lattice spacing operators not allowed
  - Leading discretization errors begin at $O(a^2)$
- To control the three standard systematics for LQCD 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, Shoresh; Tiburzi; Chen, O'Connell, Van de Water, Walker-Loud; …
  - This motivated us to use an improved version of this action

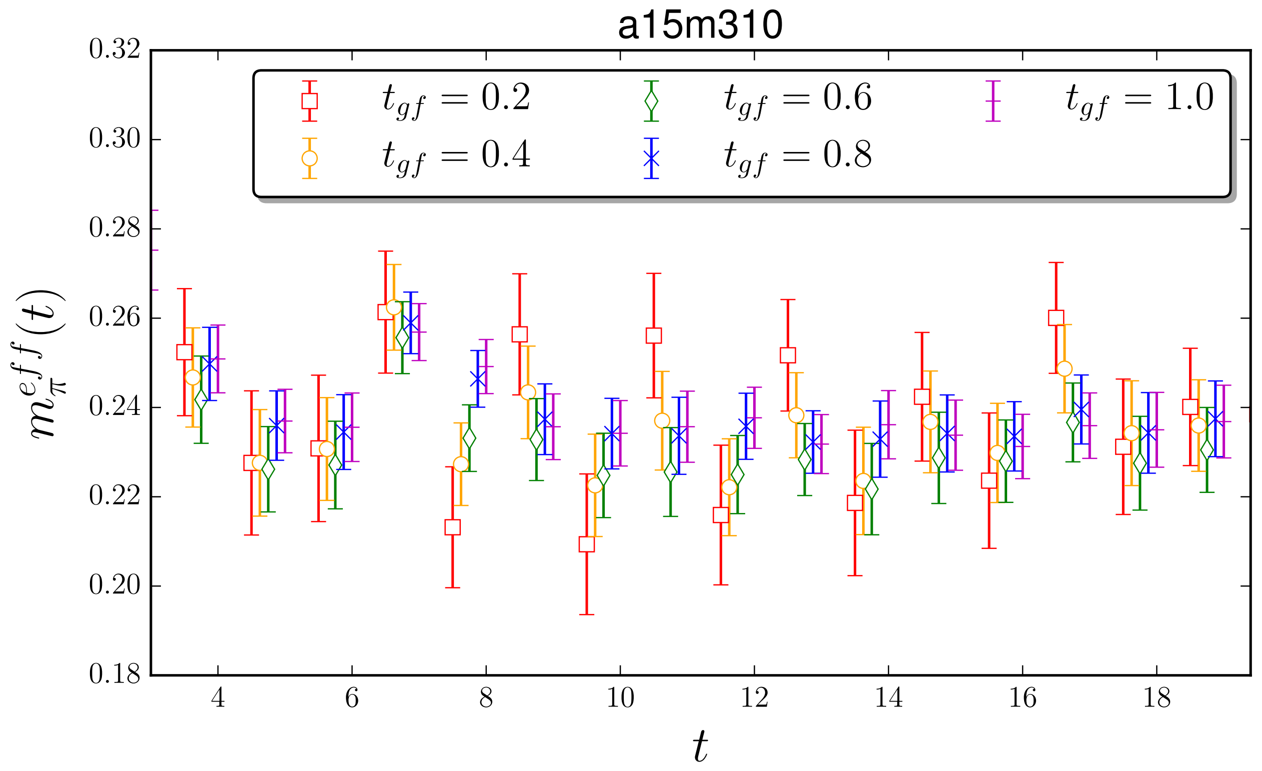
Some Lattice QCD Details

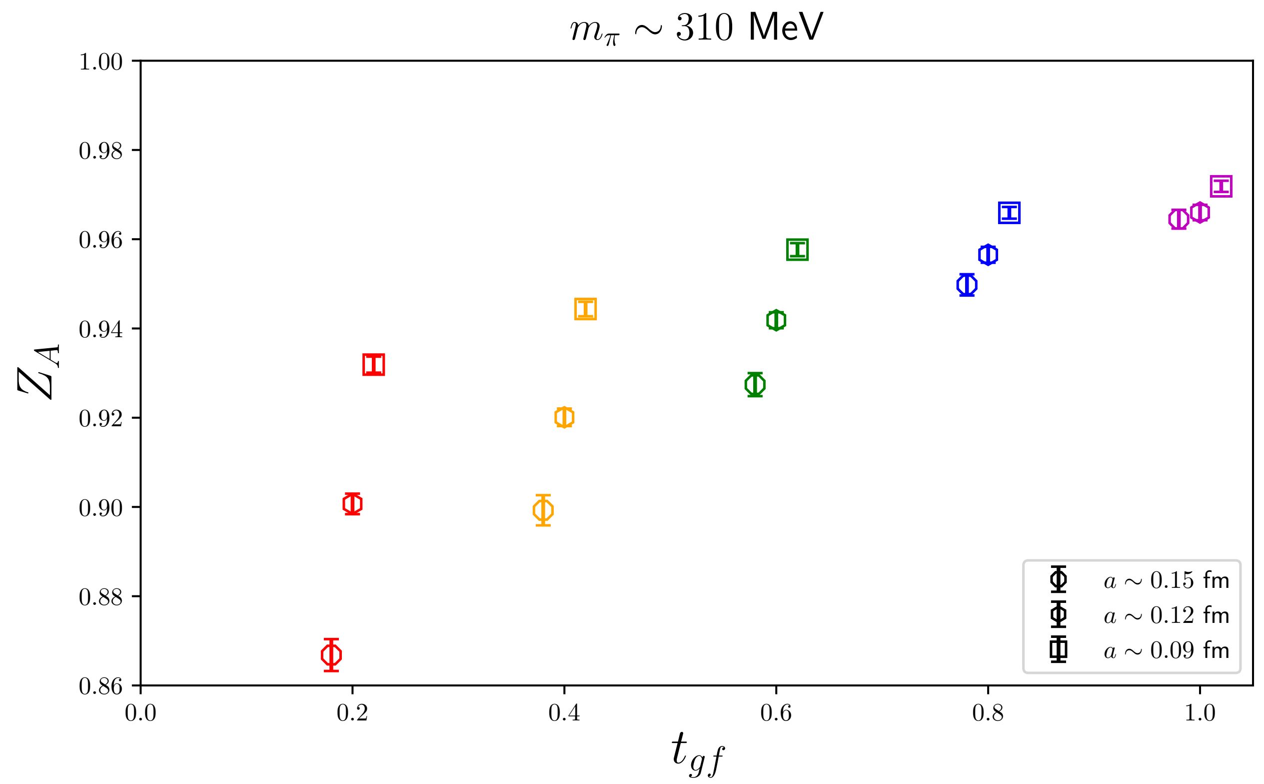
Berkowitz et al. PRD96 (2017) [1701.07559]

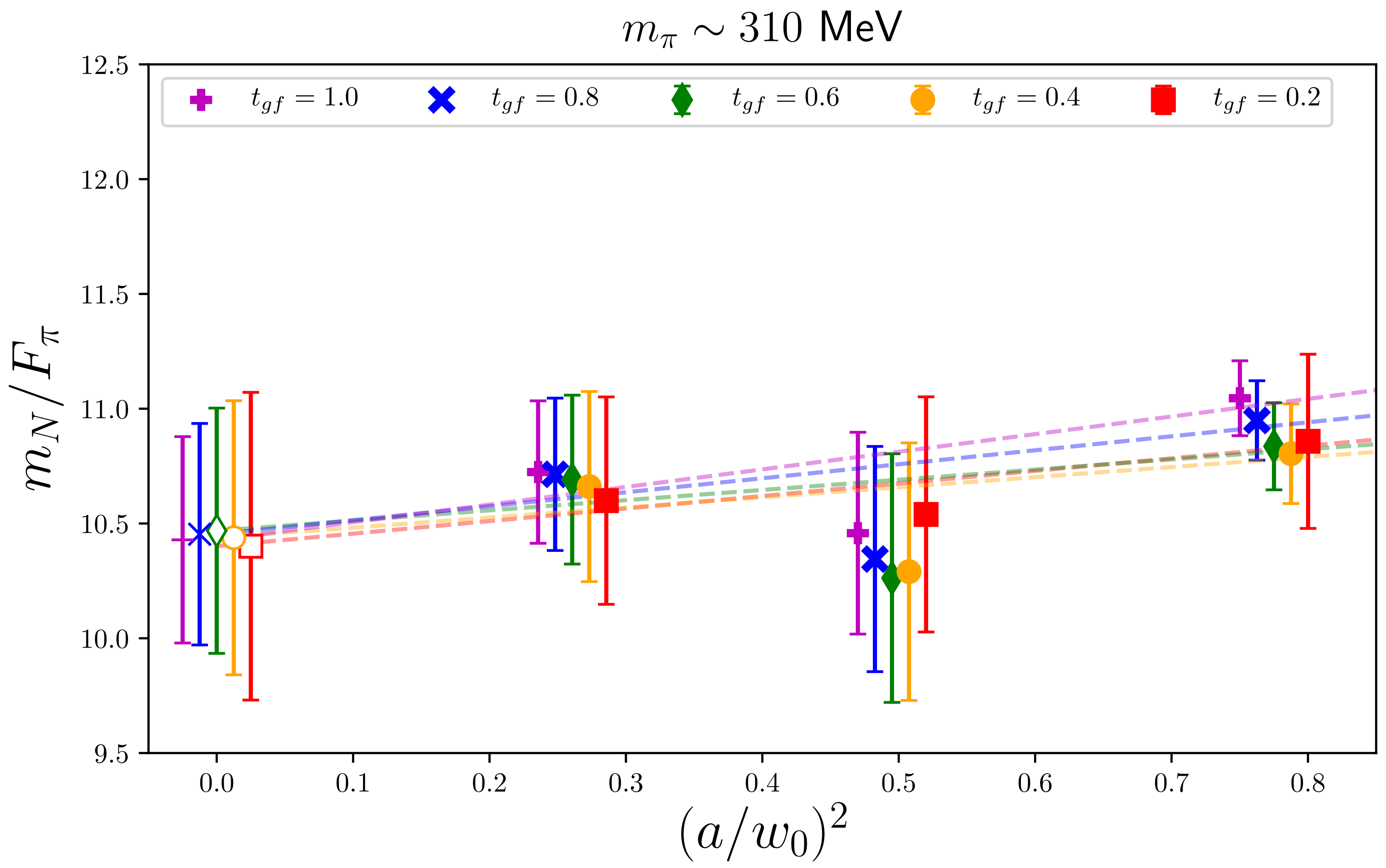
- Möbius Domain Wall Fermions on gradient flowed 2+1+1 HISQ ensembles Berkowitz et al. PRD96 (2017) [1701.07559]
- Gradient Flow smearing of HISQ cfgs more effective at reducing residual chiral symmetry breaking than the HYP smearing used in DWF on asqtad

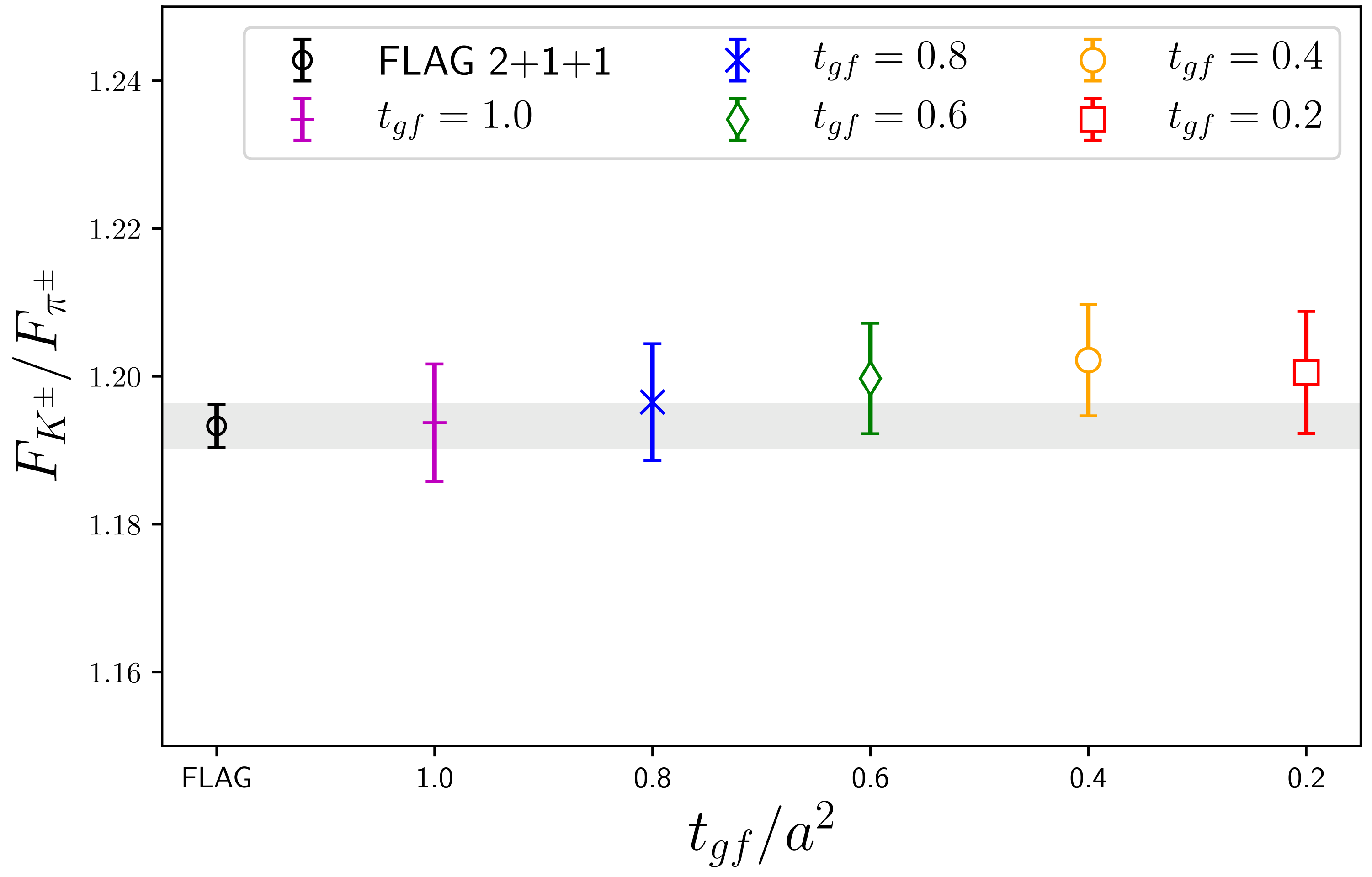
  $m_{res} < 0.1\ m_l$ on all ensembles for small-to-moderate L_5 and $M_5 \leq 1.3$











Some Lattice QCD Details

Berkowitz et al. PRD96 (2017) [1701.07559]

Renormalization

- The currents used in the calculation must be renormalized to match physical currents
- By definition

$$Z_V \mathring{g}_V = 1$$

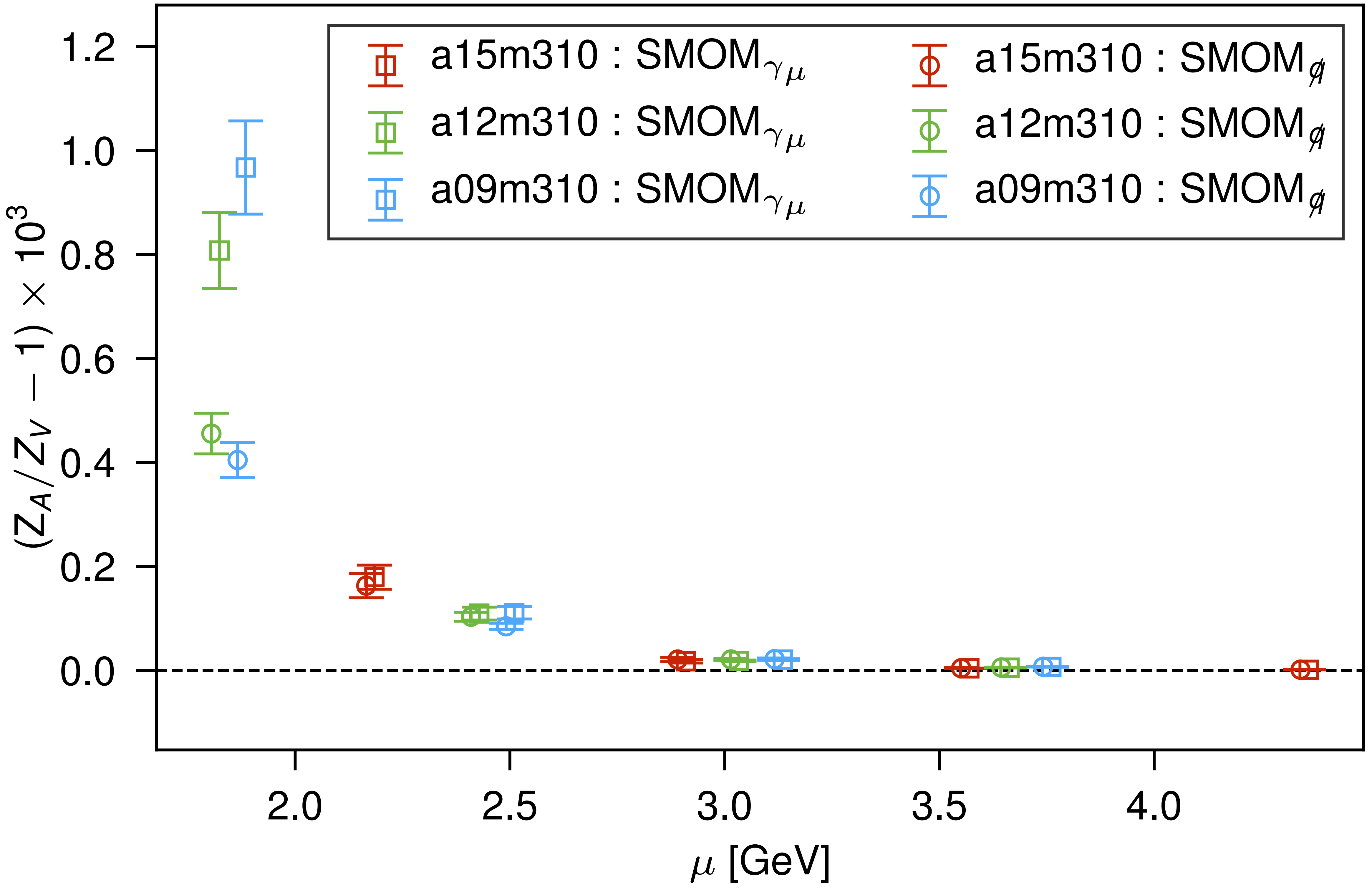
- The renormalized value of the axial coupling

$$g_A = \frac{Z_A}{Z_V} \frac{\mathring{g}_A}{\mathring{g}_V}$$

- Our action uses (Möbius) Domain-Wall fermions, which have very good chiral symmetry properties
- Using the RI/SMOM non-perturbative renormalization scheme, we find

$$\frac{Z_A}{Z_V} = 1$$ **to 1 part in 10^4**

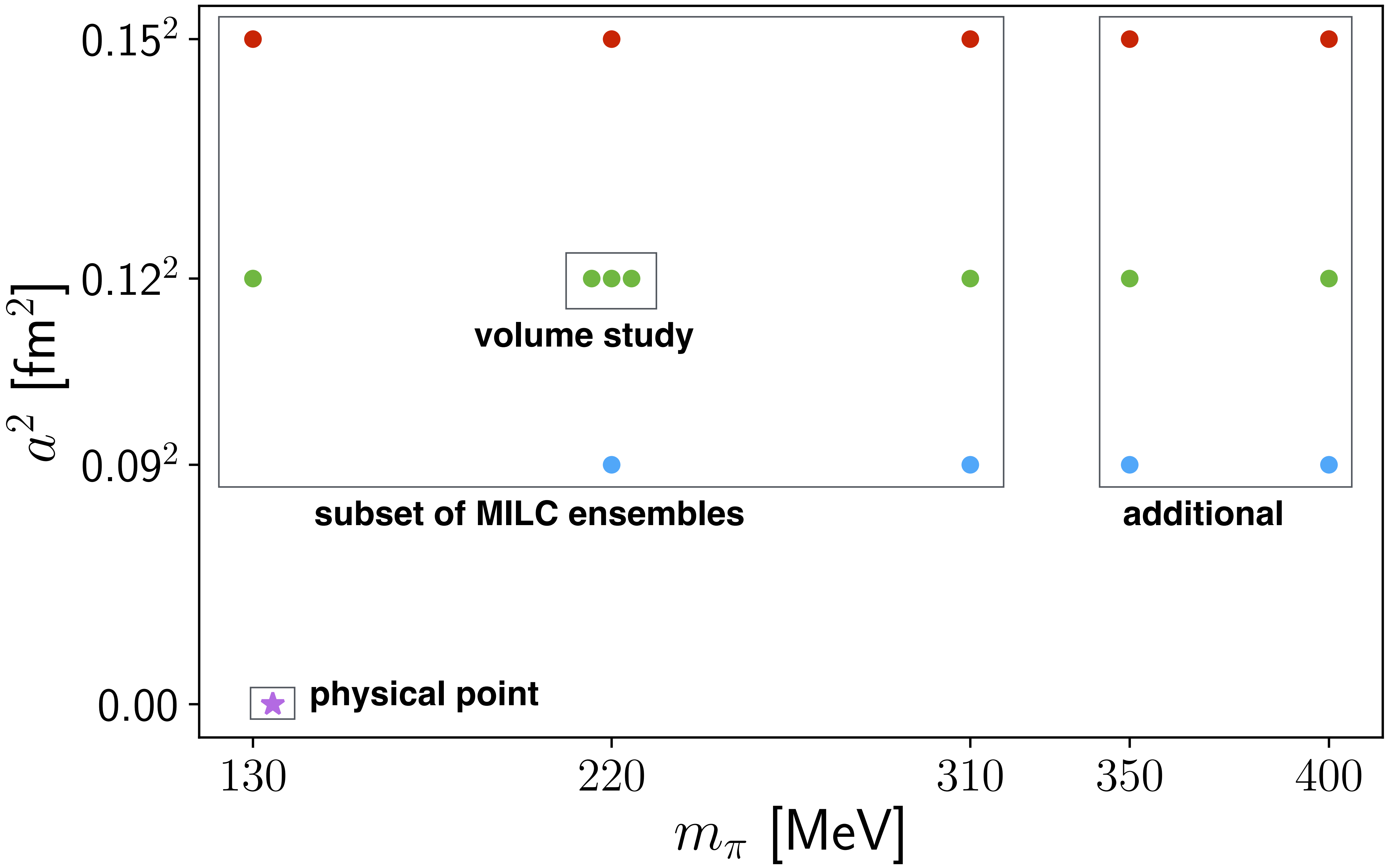
a confirmation that our action respects chiral symmetry to a good degree.

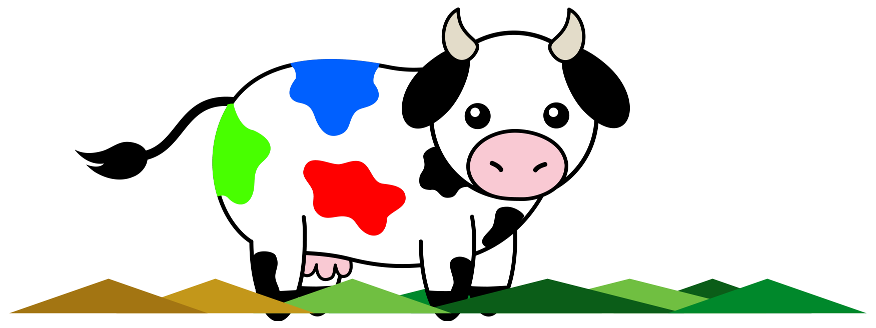


Some Lattice QCD Details

Berkowitz et al.
PRD96 (2017) [1701.07559]

HISQ gauge configurations and mixed action





unofficial MILC cow
MILC = MIMD Lattice Computation
(the acronym has an acronym in the acronym)

MILC configurations are the only publicly available dataset capable of

- chiral extrapolation to physical pion mass
- continuum extrapolation
- infinite volume extrapolation

HISQ action
Errors starting at $\mathrm{O}(\alpha_s a^2, a^4)$

Lüscher-Weisz action
Errors starting at $\mathrm{O}(\alpha_s^2 a^2, a^4)$

Möbius domain-wall valence quarks

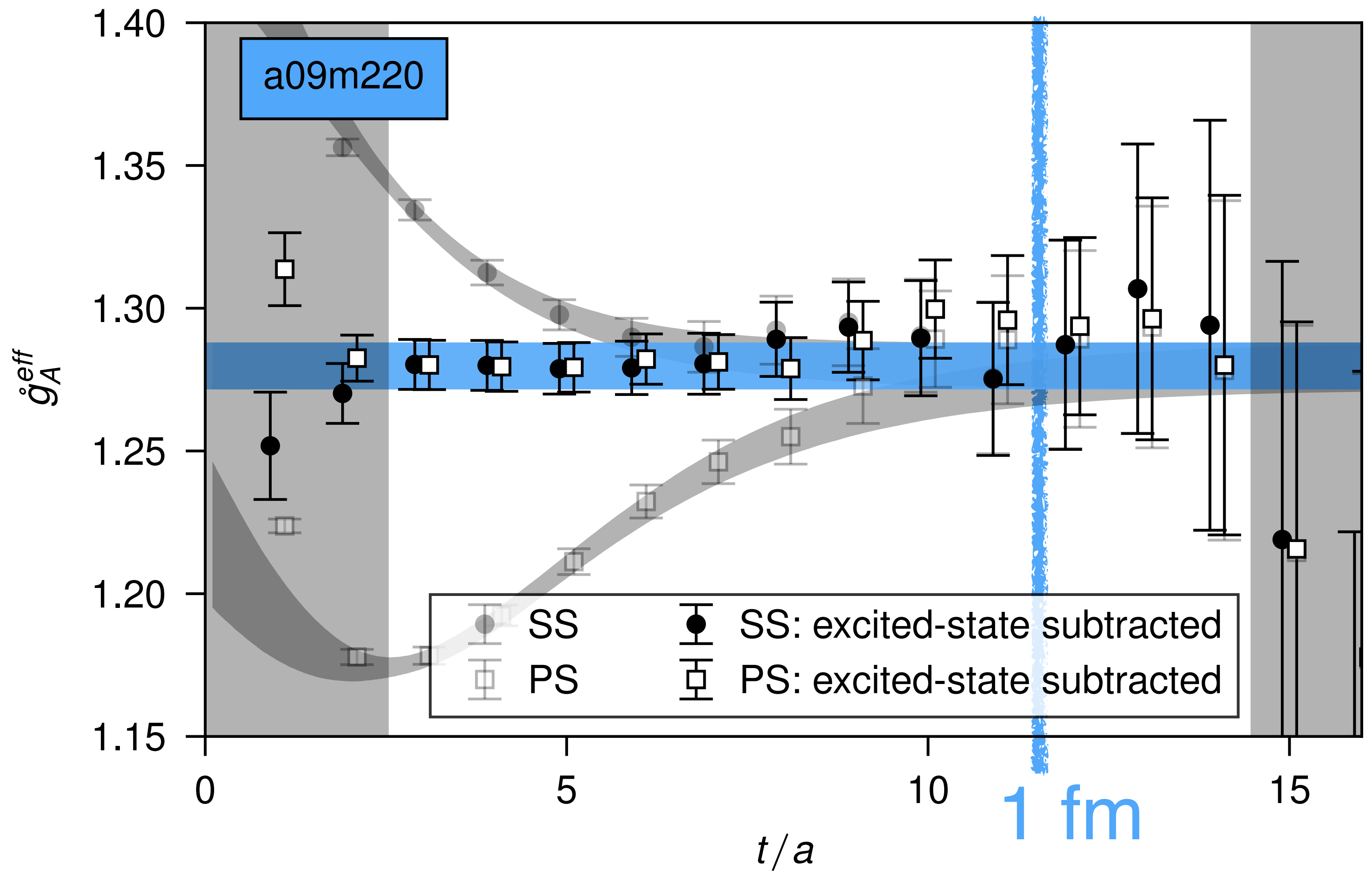
- chiral symmetry at finite lattice spacing
- *Ludicrously* fast GPU solver (QUDA)

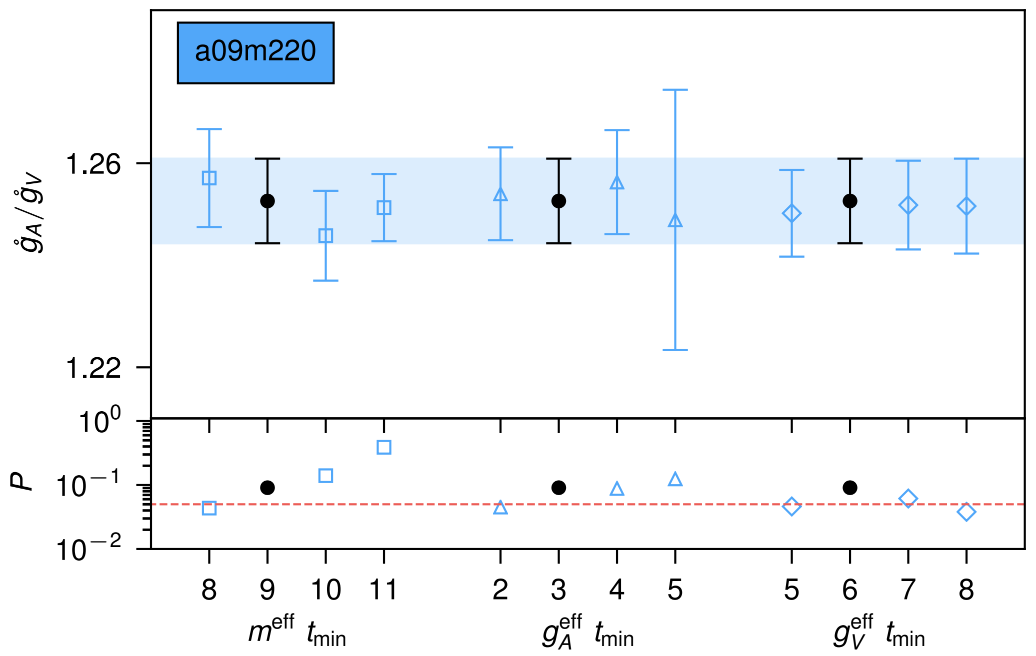
Slide adapted from CC. Chang

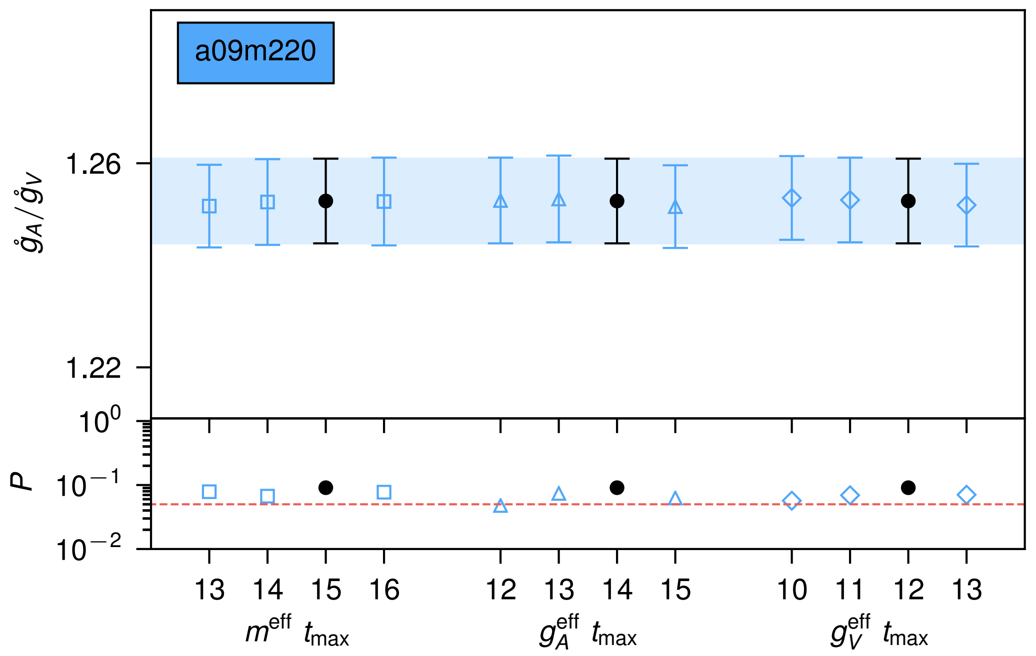
Analysis Details

Correlation function analysis

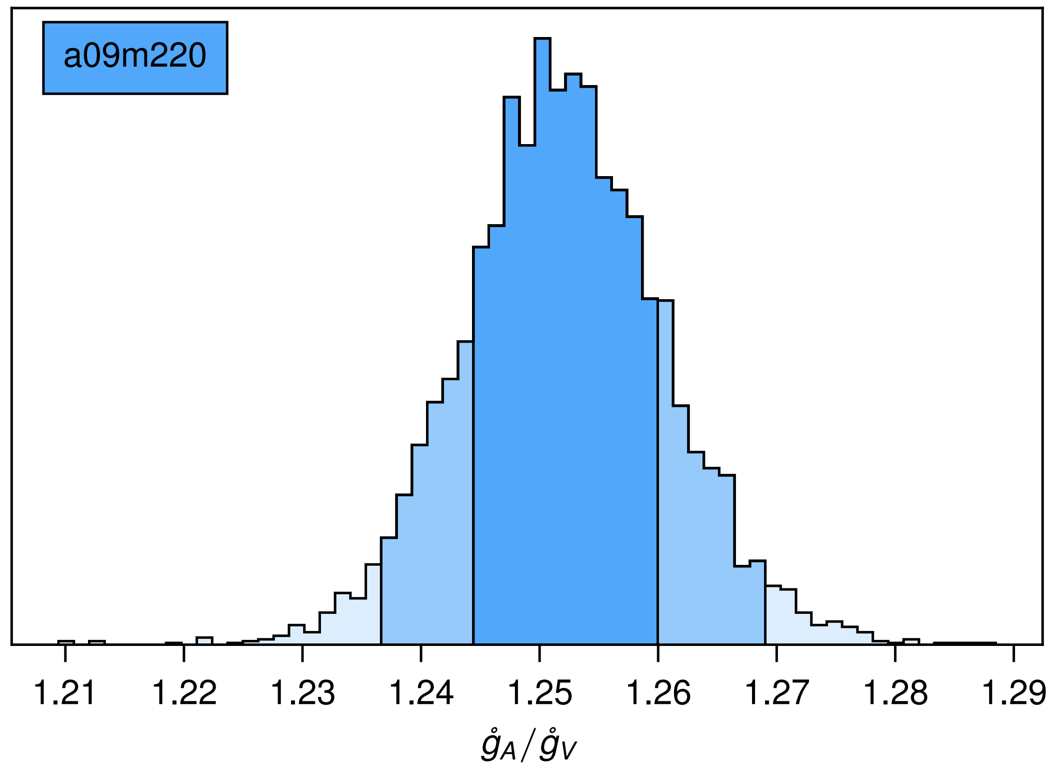
- Simultaneous fit to 6 correlation functions, 2-point, g_A, g_V (SS and PS)
- Complete 2-state fit (g.s. and 1 excited state, including transitions)
- Bayesian constrained fit as a pre-conditioner for unconstrained non-linear regression
- Stability analysis is performed varying min and max time in the correlator analysis







- early time has excited state contamination
- late time susceptible to correlated fluctuations
- excited state subtracted results are constant in fit region
- resulting bootstrap distributions (N_{bs}=5000) are Gaussian and show no outliers



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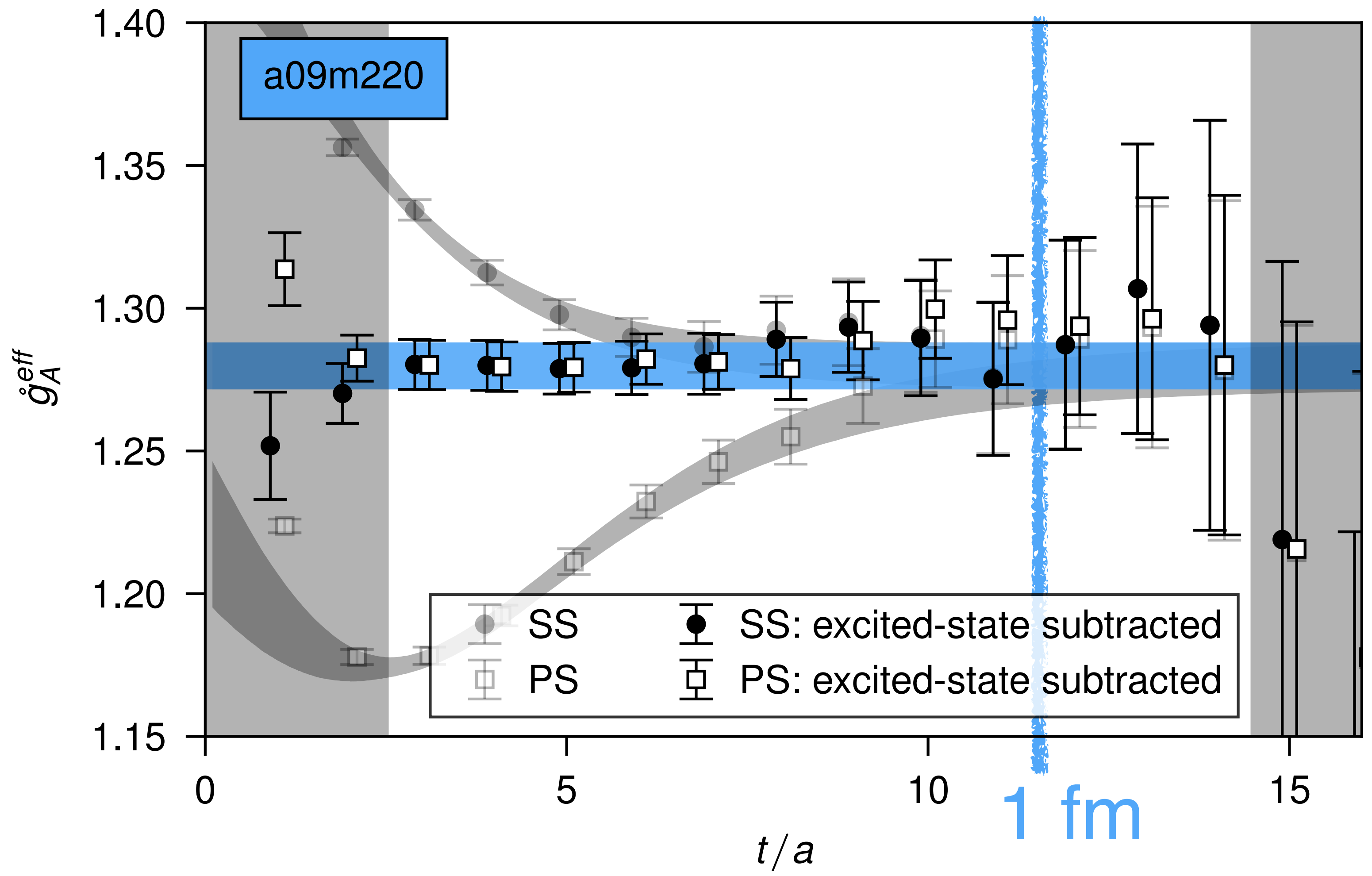

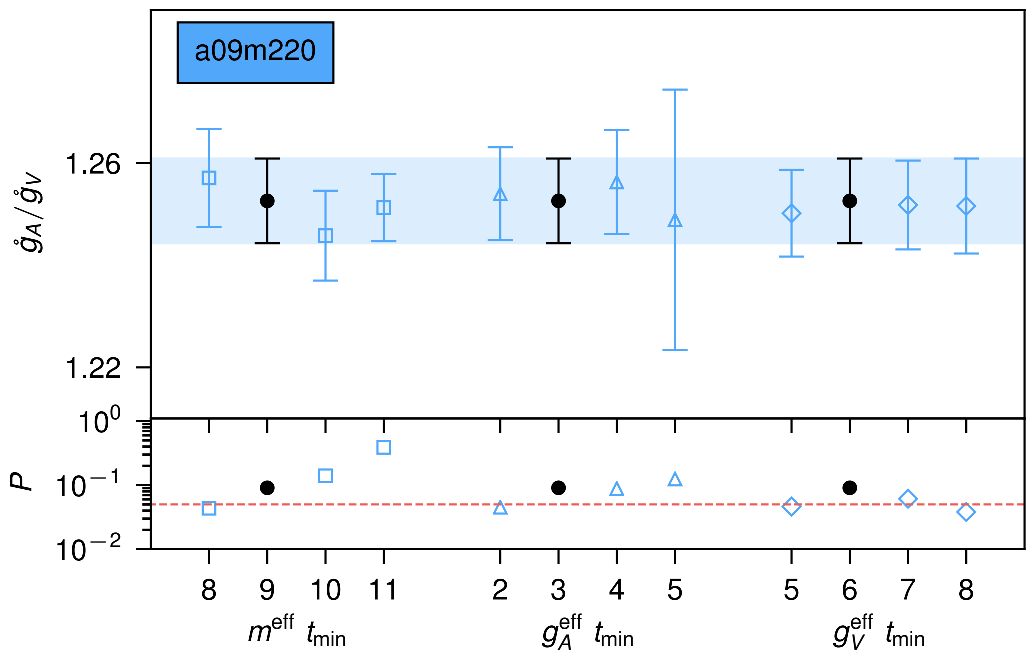

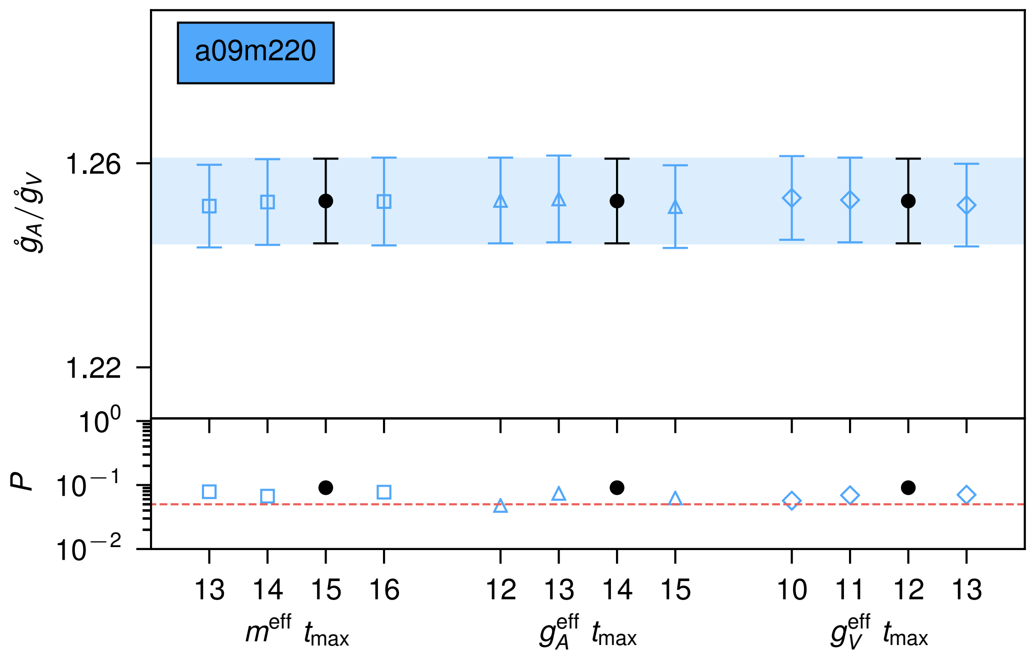

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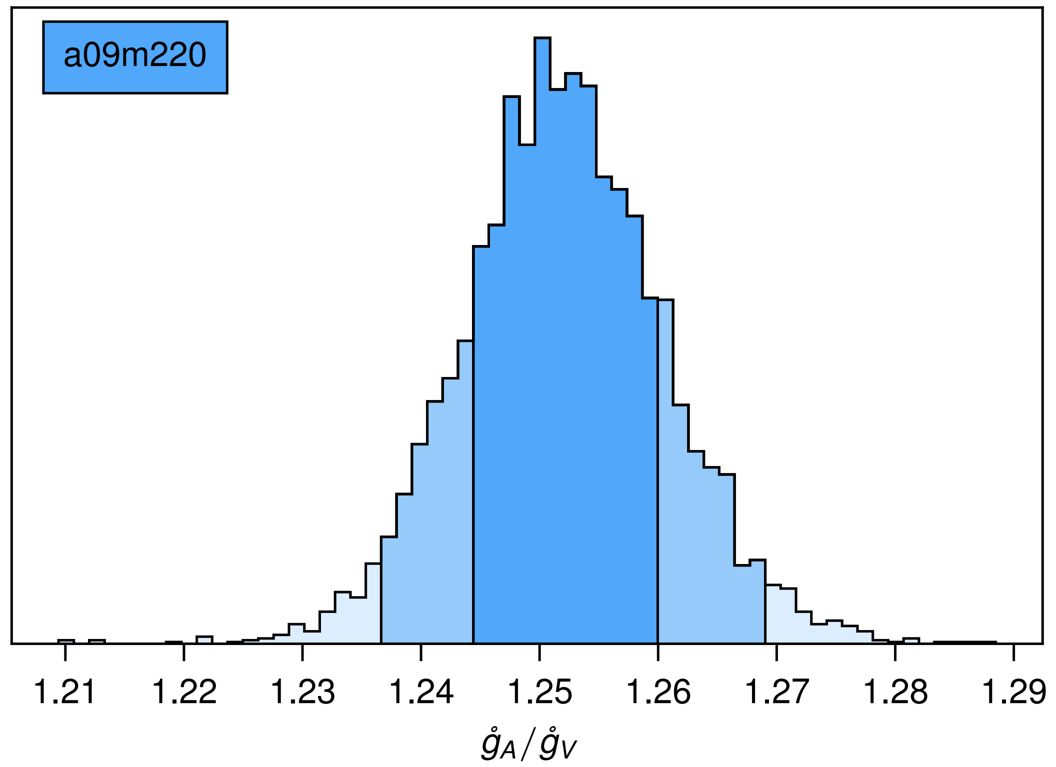
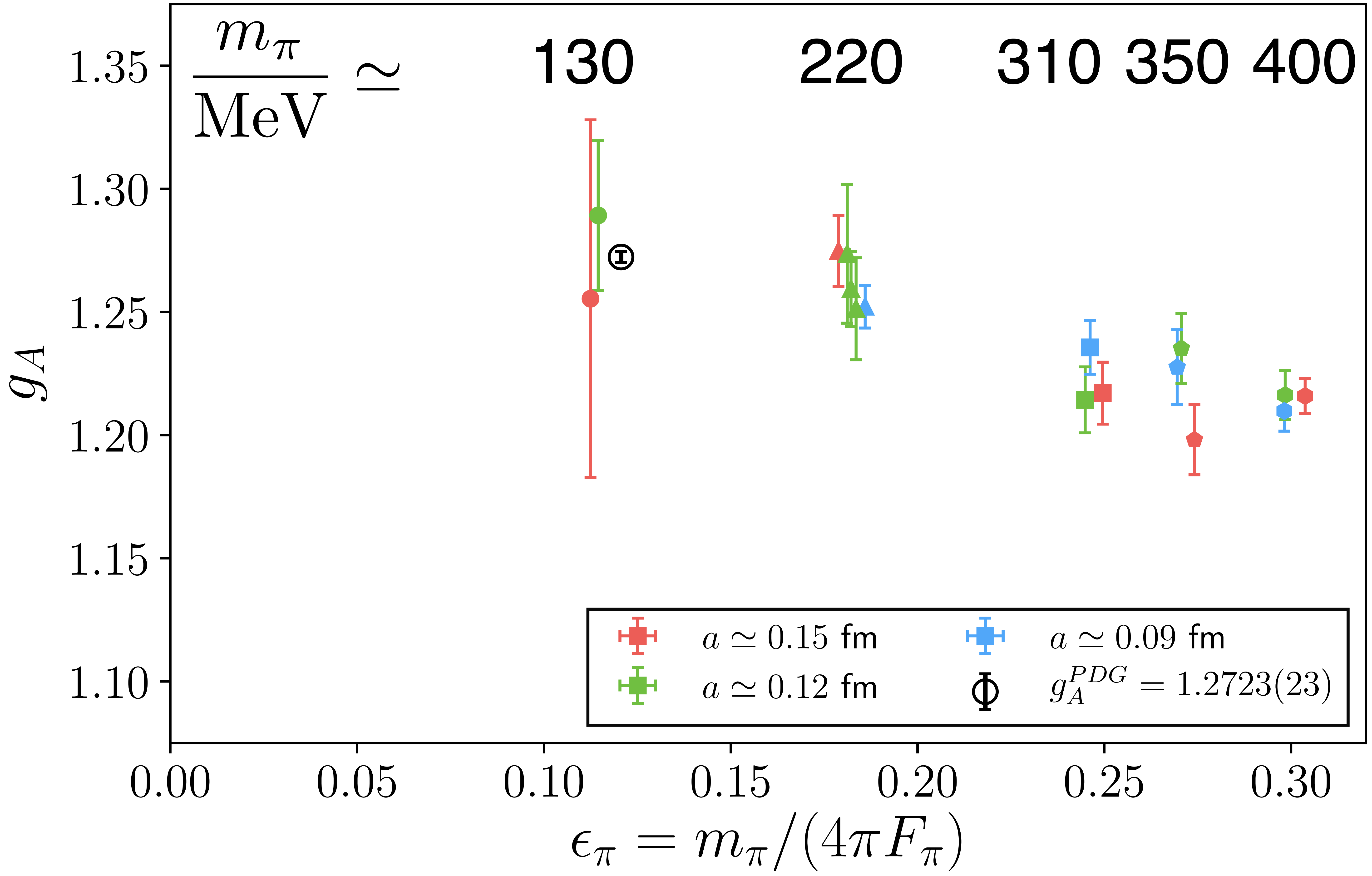
Nature 558 (2018) no.7708, 91-94

Download the arXiv version or supplemental material - 36 pages of detail



Analysis Details

Renormalized LQCD results

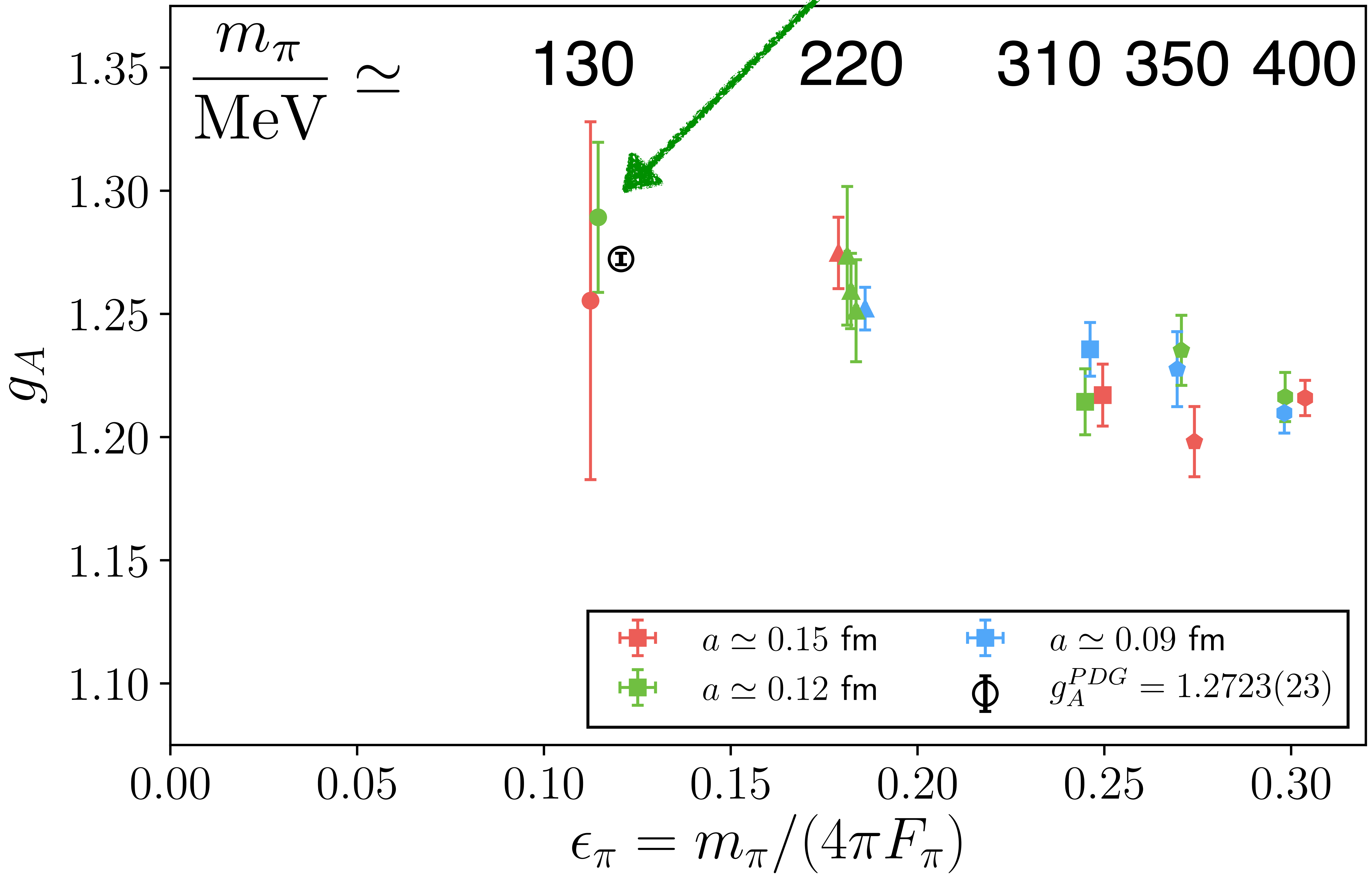


Analysis Details

Renormalized LQCD results

$g_A^{a12m130} = 1.292(30)$

2.3% uncertainty



Analysis Details

Extrapolations

Dimensionless parameters:

lattice spacing, volume, pion mass

$$\epsilon_a^2 = \frac{1}{4\pi}\frac{a^2}{w_0^2} \qquad m_\pi L \qquad \epsilon_\pi = \frac{m_\pi}{4\pi F_\pi}$$

- ChiPT: EFT expanding around m_π= 0
  - best hope for model-independent extrapolation
  - not guaranteed to converge around m_π 135 MeV
- Mild m_π a dependence
  - Taylor expansion works well for extrapolation/interpolation

Slide adapted from A. Nicholson

Analysis Details

Extrapolations

Dimensionless parameters:

lattice spacing, volume, pion mass

$$\epsilon_a^2 = \frac{1}{4\pi}\frac{a^2}{w_0^2} \qquad m_\pi L \qquad \epsilon_\pi = \frac{m_\pi}{4\pi F_\pi}$$

$$\begin{aligned}
\text{NNLO } \chi\text{PT}: &\quad \text{Eq. (S8)} + \delta_a + \delta_L \\
\text{NNLO+ct } \chi\text{PT}: &\quad \text{Eq. (S8)} + c_4\epsilon_\pi^4 + \delta_a + \delta_L \\
\text{NLO Taylor } \epsilon_\pi^2: &\quad c_0 + c_2\epsilon_\pi^2 + \delta_a + \delta_L \\
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\end{aligned}$$

Slide adapted from A. Nicholson

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$$g_A = g_0 + c_2\epsilon_\pi^2 - \epsilon_\pi^2\left(g_0 + 2g_0^3\right)\ln\left(\epsilon_\pi^2\right) + g_0 c_3 \epsilon_\pi^3$$

NNLO XPT

NNLO χPT :	Eq. (S8) $+ \delta_a + \delta_L$
NNLO+ct χPT :	Eq. (S8) $+ c_4\epsilon_\pi^4 + \delta_a + \delta_L$
NLO Taylor ϵ_π^2 :	$c_0 + c_2\epsilon_\pi^2 + \delta_a + \delta_L$
NNLO Taylor ϵ_π^2 :	$c_0 + c_2\epsilon_\pi^2 + c_4\epsilon_\pi^4 + \delta_a + \delta_L$
NLO Taylor ϵ_π :	$c_0 + c_1\epsilon_\pi + \delta_a + \delta_L$
NNLO Taylor ϵ_π :	$c_0 + c_1\epsilon_\pi + c_2\epsilon_\pi^2 + \delta_a + \delta_L$

Slide adapted from A. Nicholson

Analysis Details

Extrapolations

Dimensionless parameters:

lattice spacing, volume, pion mass

$$\epsilon_a^2 = \frac{1}{4\pi}\frac{a^2}{w_0^2} \qquad m_\pi L \qquad \epsilon_\pi = \frac{m_\pi}{4\pi F_\pi}$$

$$\delta_a = a_2\varepsilon_a^2 + b_4\varepsilon_a^2\varepsilon_\pi^2 + a_4\varepsilon_a^4 + [a_1\sqrt{4\pi}\varepsilon_a + s_2\alpha_S\alpha_a^2]$$

$$g_A = g_0 + c_2\epsilon_\pi^2 - \epsilon_\pi^2\left(g_0 + 2g_0^3\right)\ln\left(\epsilon_\pi^2\right) + g_0c_3\epsilon_\pi^3$$

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NLO Taylor ϵ_π :	$c_0 + c_1\epsilon_\pi + \delta_a + \delta_L$
NNLO Taylor ϵ_π :	$c_0 + c_1\epsilon_\pi + c_2\epsilon_\pi^2 + \delta_a + \delta_L$

Slide adapted from A. Nicholson

Analysis Details

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$$F_1(x) = \sum_{\mathbf{n}\neq 0}\left[K_0(x|\mathbf{n}|) - \frac{K_1(x|\mathbf{n}|)}{x|\mathbf{n}|}\right]$$

$$\delta_L = \underline{\frac{8}{3}\varepsilon_\pi^2\left[g_0^3 F_1(m_\pi L) + g_0 F_3(m_\pi L)\right]} + \underline{f_3\varepsilon_\pi^3 F_1(m_\pi L)}$$

$$F_3(x) = -\frac{3}{2}\sum_{\mathbf{n}\neq 0}\frac{K_1(x|\mathbf{n}|)}{x|\mathbf{n}|}$$

Beane and Savage
Phys.Rev.D70 [hep-ph/0404131]

$$g_A = g_0 + c_2\epsilon_\pi^2 - \epsilon_\pi^2\left(g_0 + 2g_0^3\right)\ln\left(\epsilon_\pi^2\right) + g_0 c_3\epsilon_\pi^3$$

NNLO XPT

parameterization of higher order volume corrections

NNLO χPT :	Eq. (S8) $+ \delta_a + \delta_L$
NNLO+ct χPT :	Eq. (S8) $+ c_4\epsilon_\pi^4 + \delta_a + \delta_L$
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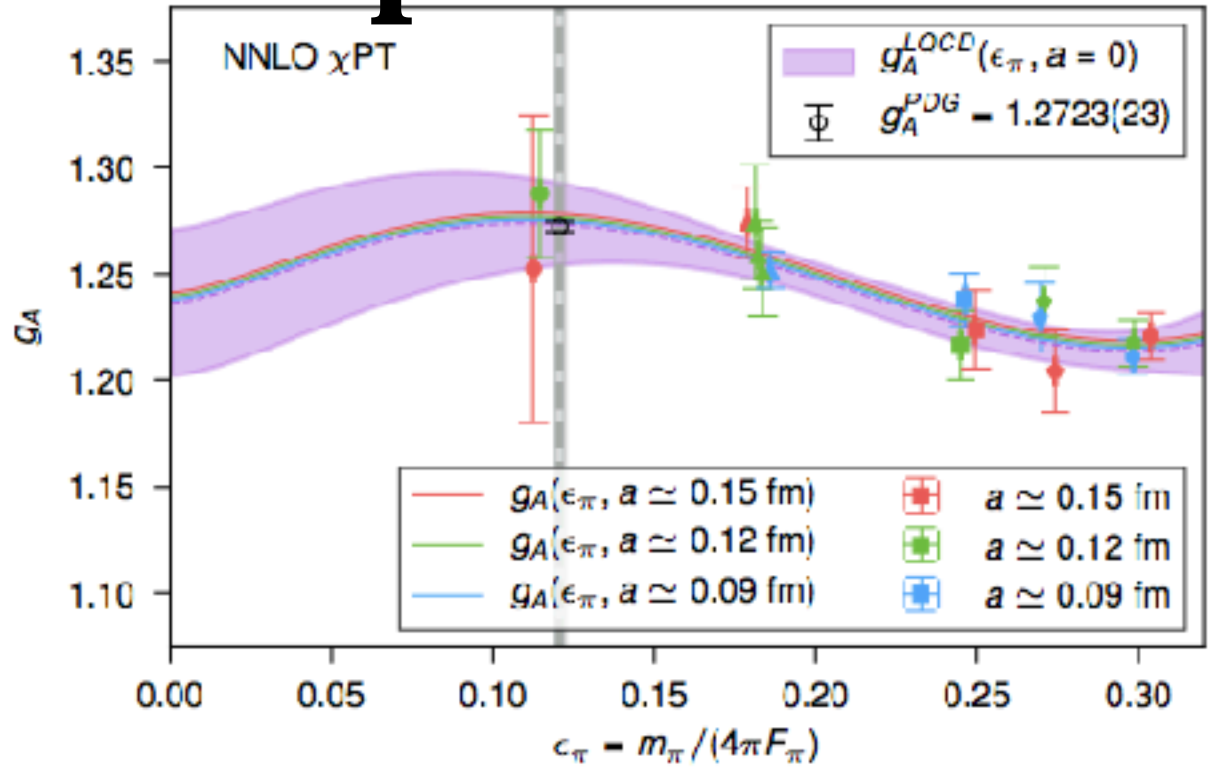
NLO Taylor ϵ_π :	$c_0 + c_1\epsilon_\pi + \delta_a + \delta_L$
NNLO Taylor ϵ_π :	$c_0 + c_1\epsilon_\pi + c_2\epsilon_\pi^2 + \delta_a + \delta_L$

Slide adapted from A. Nicholson

Analysis Details

Extrapolations



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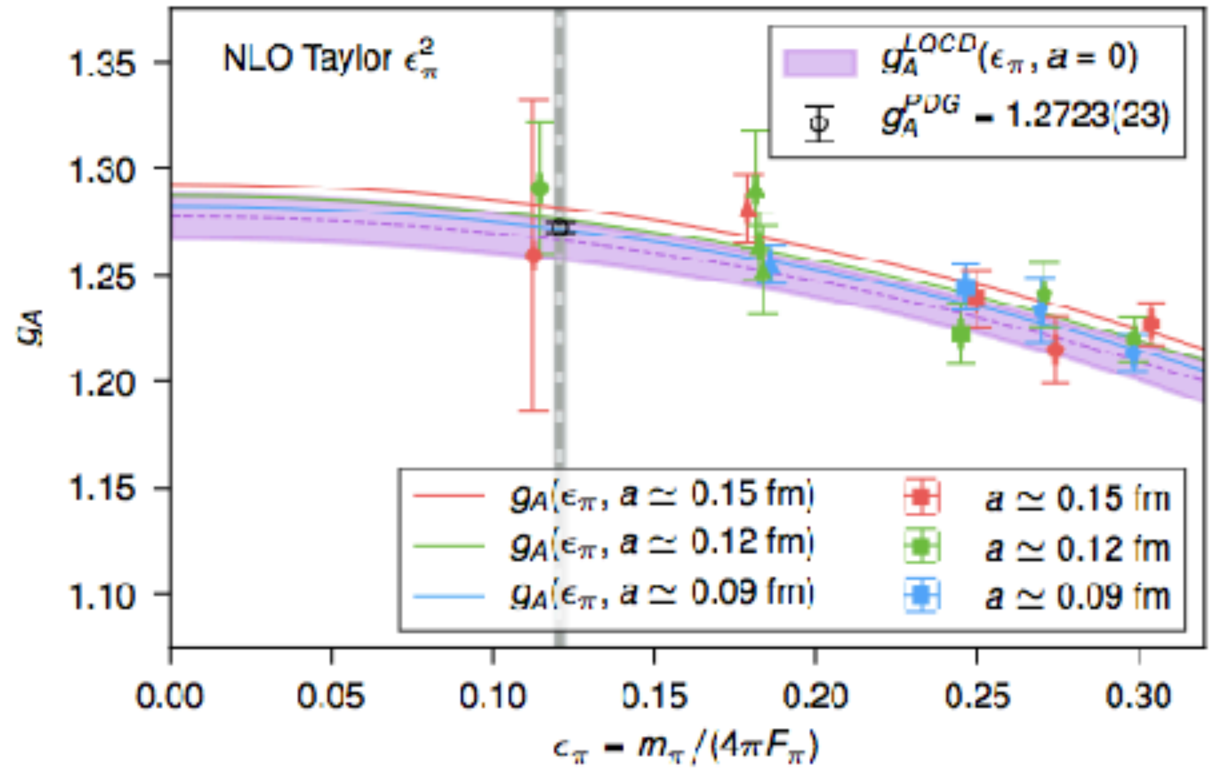

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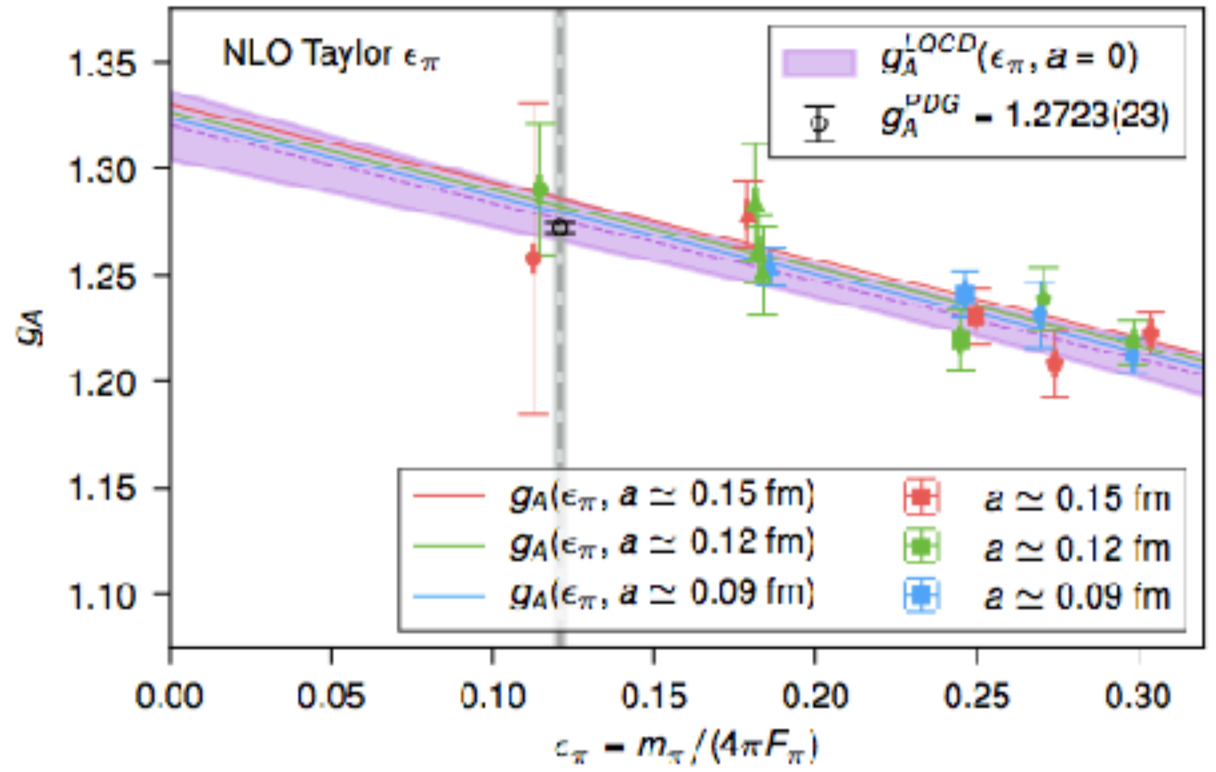

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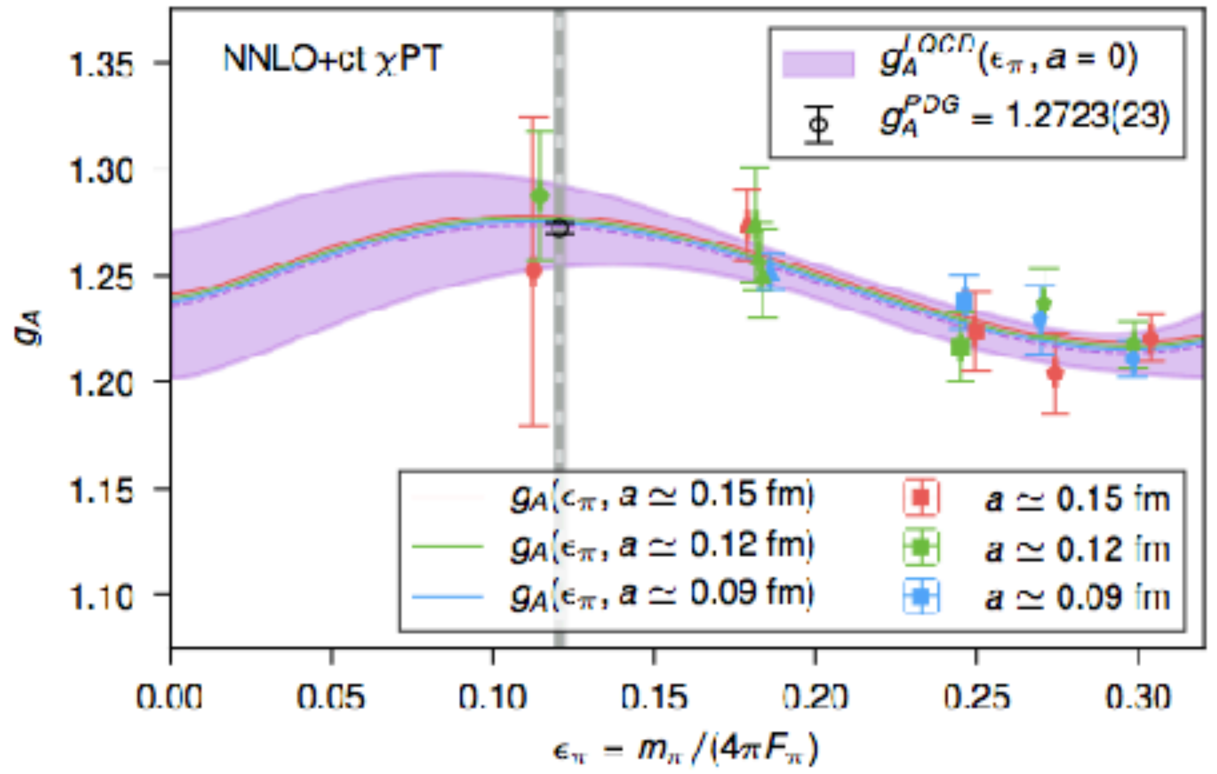

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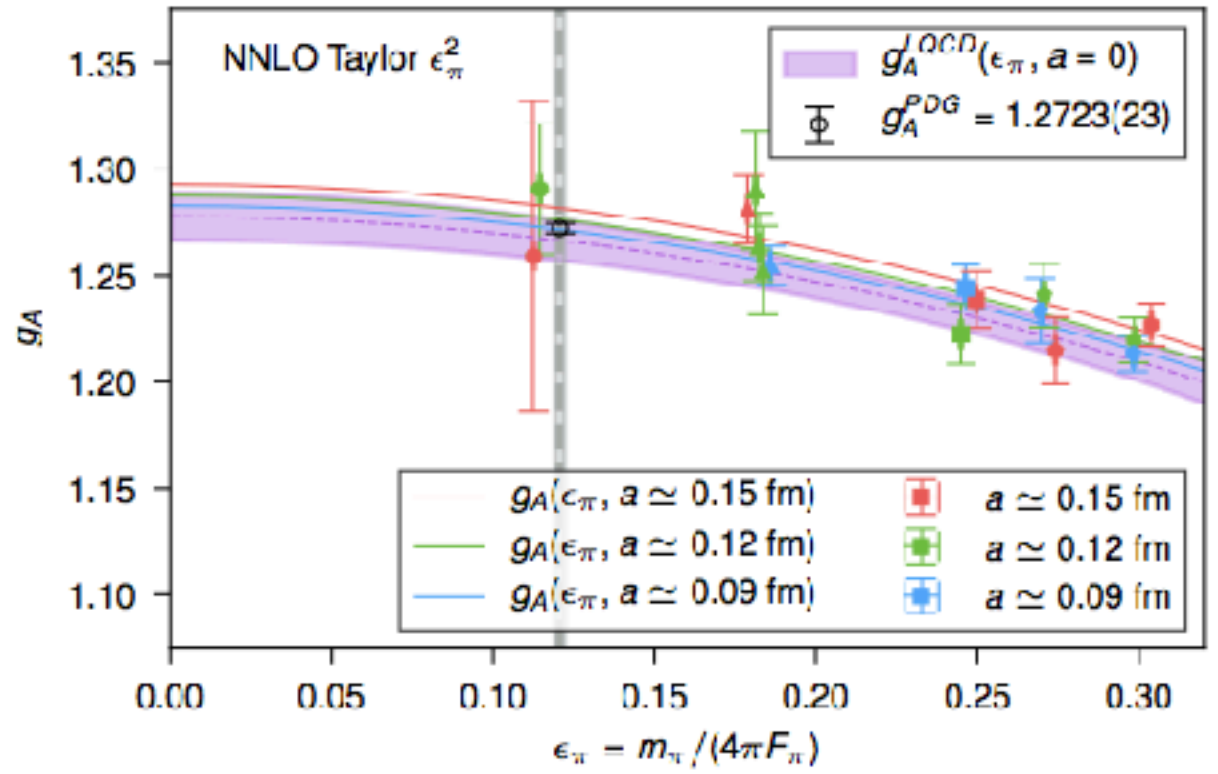

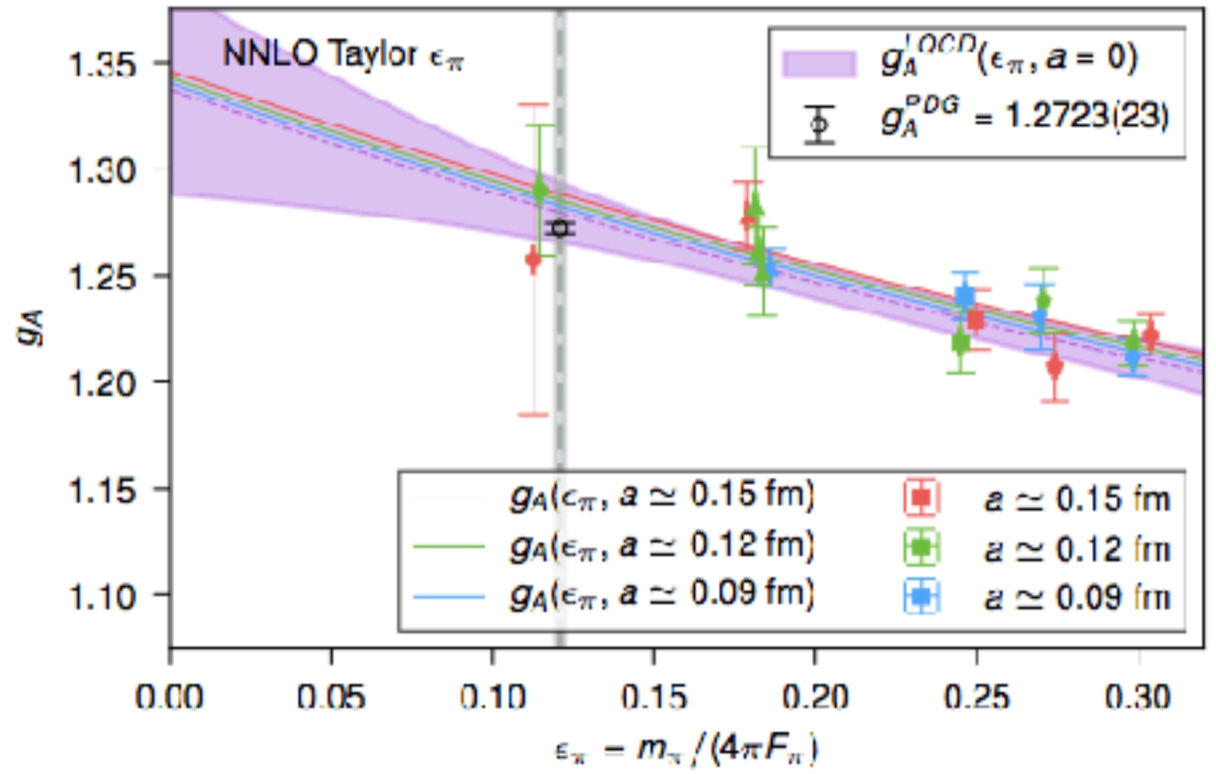

h

$$
\begin{aligned}
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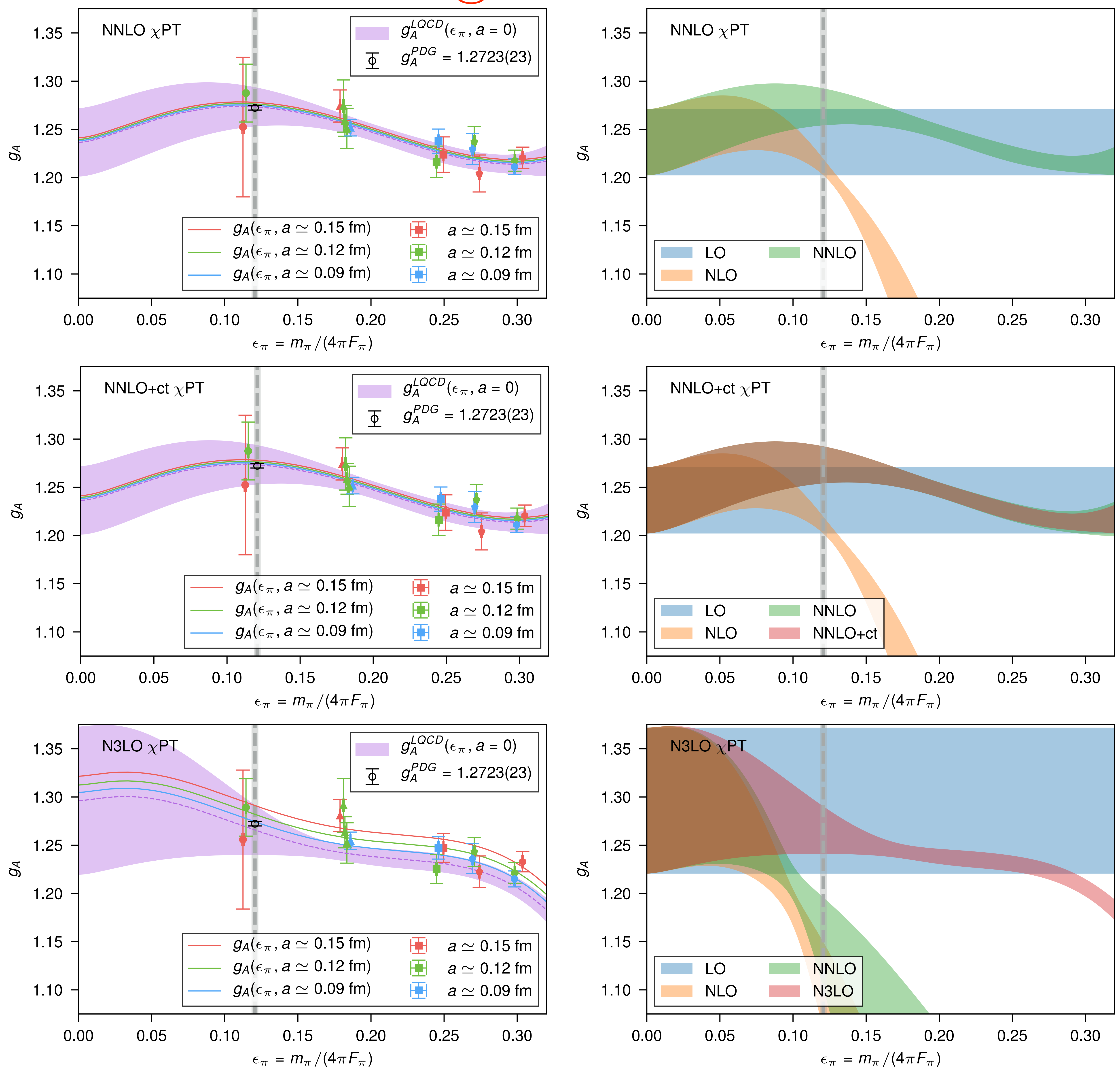
\text{NNLO Taylor } \epsilon_\pi: &\quad c_0 + c_1\epsilon_\pi + c_2\epsilon_\pi^2 + \delta_a + \delta_L
\end{aligned}
$$

convergence of the chiral expansion…



$$g_A = g_0 - \epsilon_\pi^2(g_0 + 2g_0^3)\ln(\epsilon_\pi^2) + c_2\epsilon_\pi^2 + g_0 c_3 \epsilon_\pi^3$$

$$\epsilon_\pi = \frac{m_\pi}{4\pi F_\pi}$$

$$g_A = g_0 - \epsilon_\pi^2(g_0 + 2g_0^3)\ln(\epsilon_\pi^2) + c_2\epsilon_\pi^2 + g_0 c_3 \epsilon_\pi^3 + c_4\epsilon_\pi^4$$

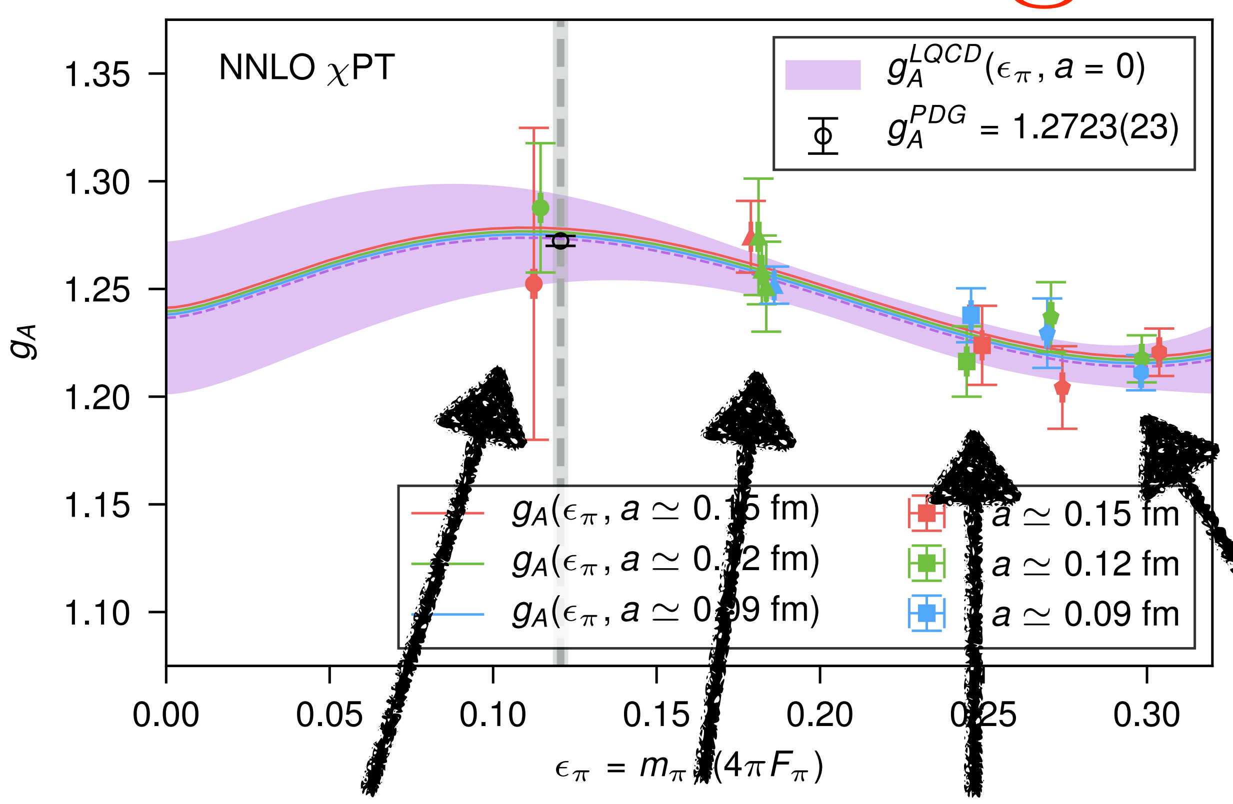
$$g_A = g_0 - \epsilon_\pi^2(g_0 + 2g_0^3)\ln(\epsilon_\pi^2) + c_2\epsilon_\pi^2 + g_0 c_3 \epsilon_\pi^3 + \epsilon_\pi^4\left[c_4 + \tilde{\gamma}_4 \ln(\epsilon_\pi^2) + \left(\frac{2}{3}g_0 + \frac{37}{12}g_0^3 + 4g_0^5\right)\ln^2(\epsilon_\pi^2)\right]$$

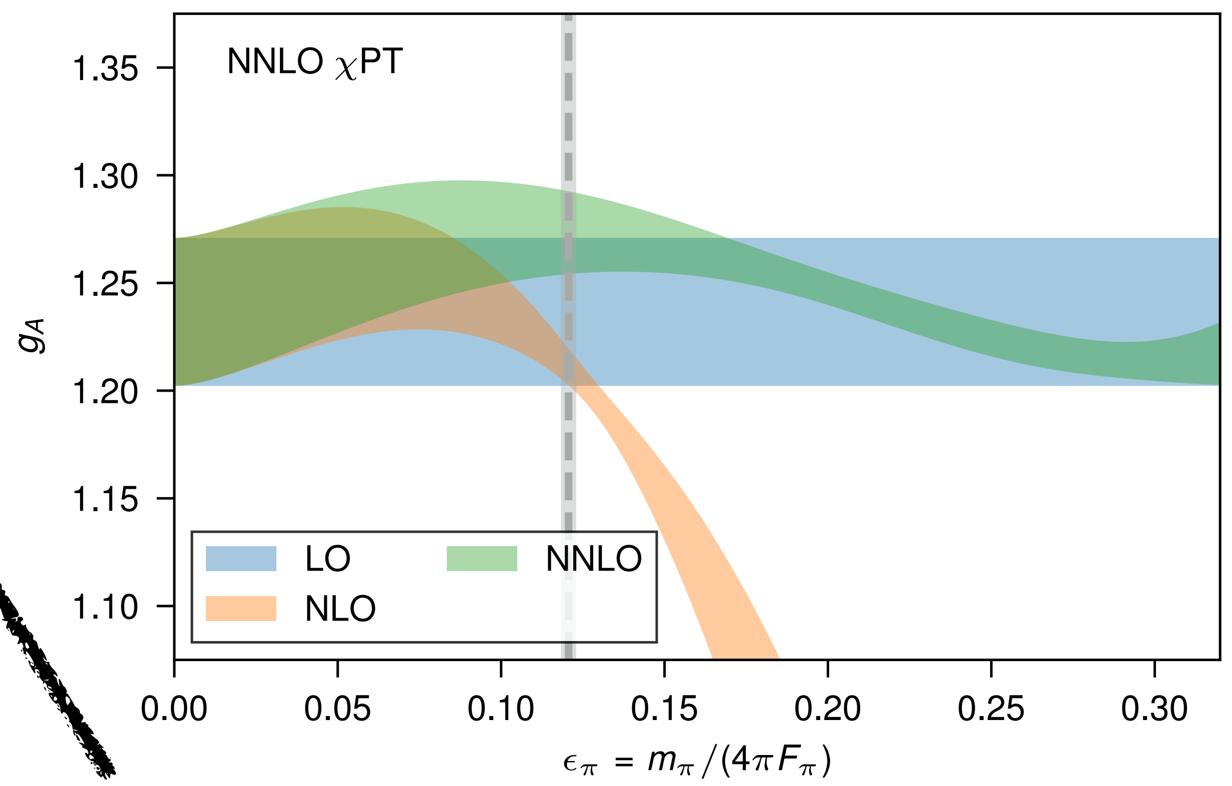
Bernard and Meissner (CD06)

Phys.Lett.B639 [hep-lat/0605010]

F —> F_π

convergence of the chiral expansion…





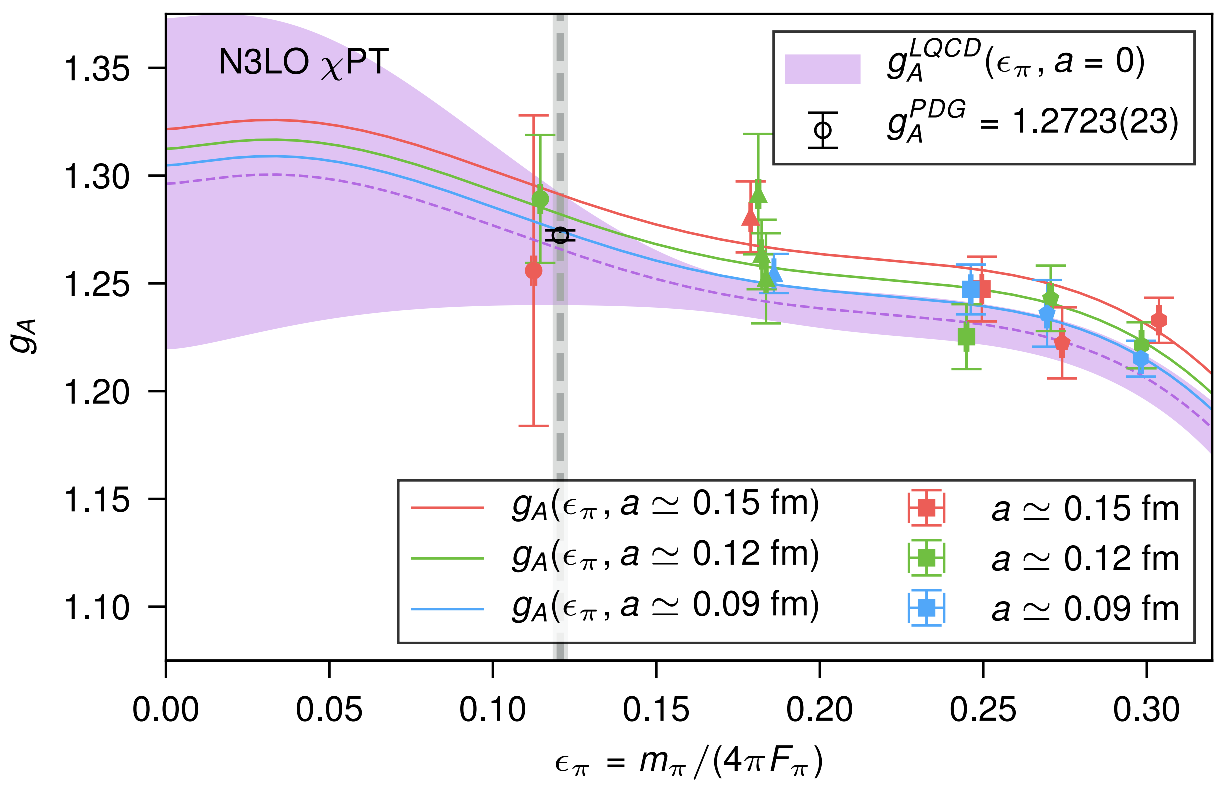
$$g_A = g_0 - \epsilon_\pi^2 (g_0 + 2g_0^3) \ln(\epsilon_\pi^2) + c_2 \epsilon_\pi^2 + g_0 c_3 \epsilon_\pi^3$$

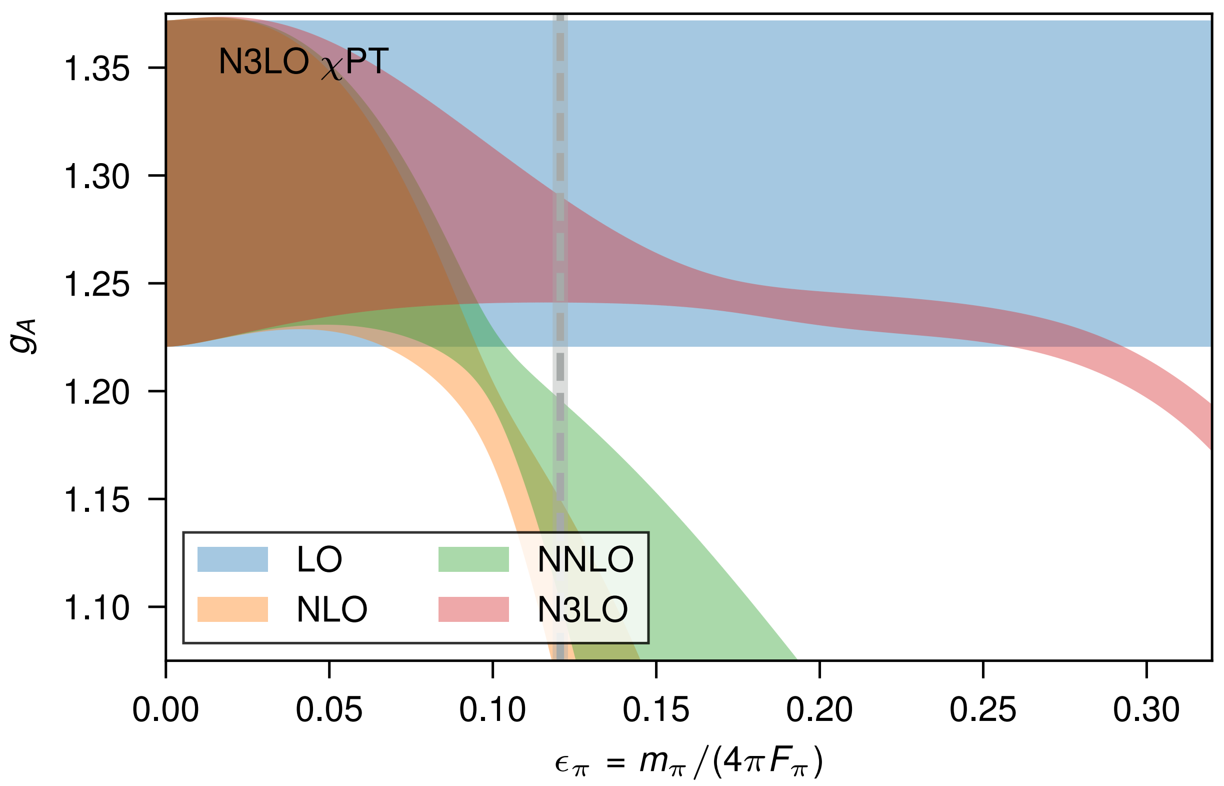
$$\epsilon_\pi = \frac{m_\pi}{4\pi F_\pi}$$

$m_\pi \sim 130$ MeV 220 310 400

can we trust extrapolation of quantities with chiraly-enhanced behavior?

if the single nucleon is not converging, would you trust chiral extrapolations of two or more nucleons?



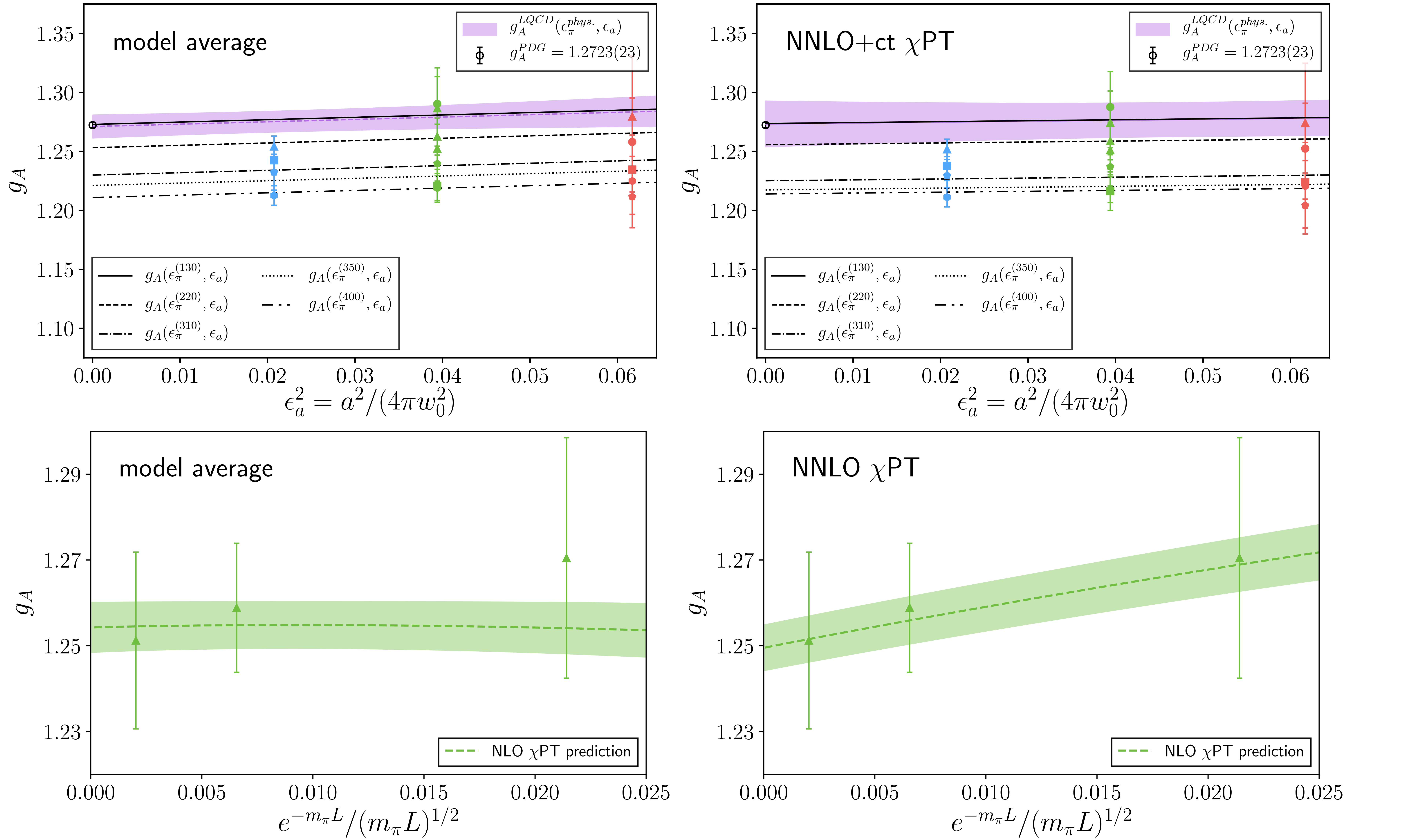


$$g_A = g_0 - \epsilon_\pi^2 (g_0 + 2g_0^3) \ln(\epsilon_\pi^2) + c_2 \epsilon_\pi^2 + g_0 c_3 \epsilon_\pi^3 + \epsilon_\pi^4 \left[c_4 + \tilde{\gamma}_4 \ln(\epsilon_\pi^2) + \left(\frac{2}{3} g_0 + \frac{37}{12} g_0^3 + 4 g_0^5 \right) \ln^2(\epsilon_\pi^2) \right]$$

Bernard and Meissner (CD06)
Phys.Lett.B639 [hep-lat/0605010]
F —> F_π

Analysis Details

Continuum and infinite volume extrapolation



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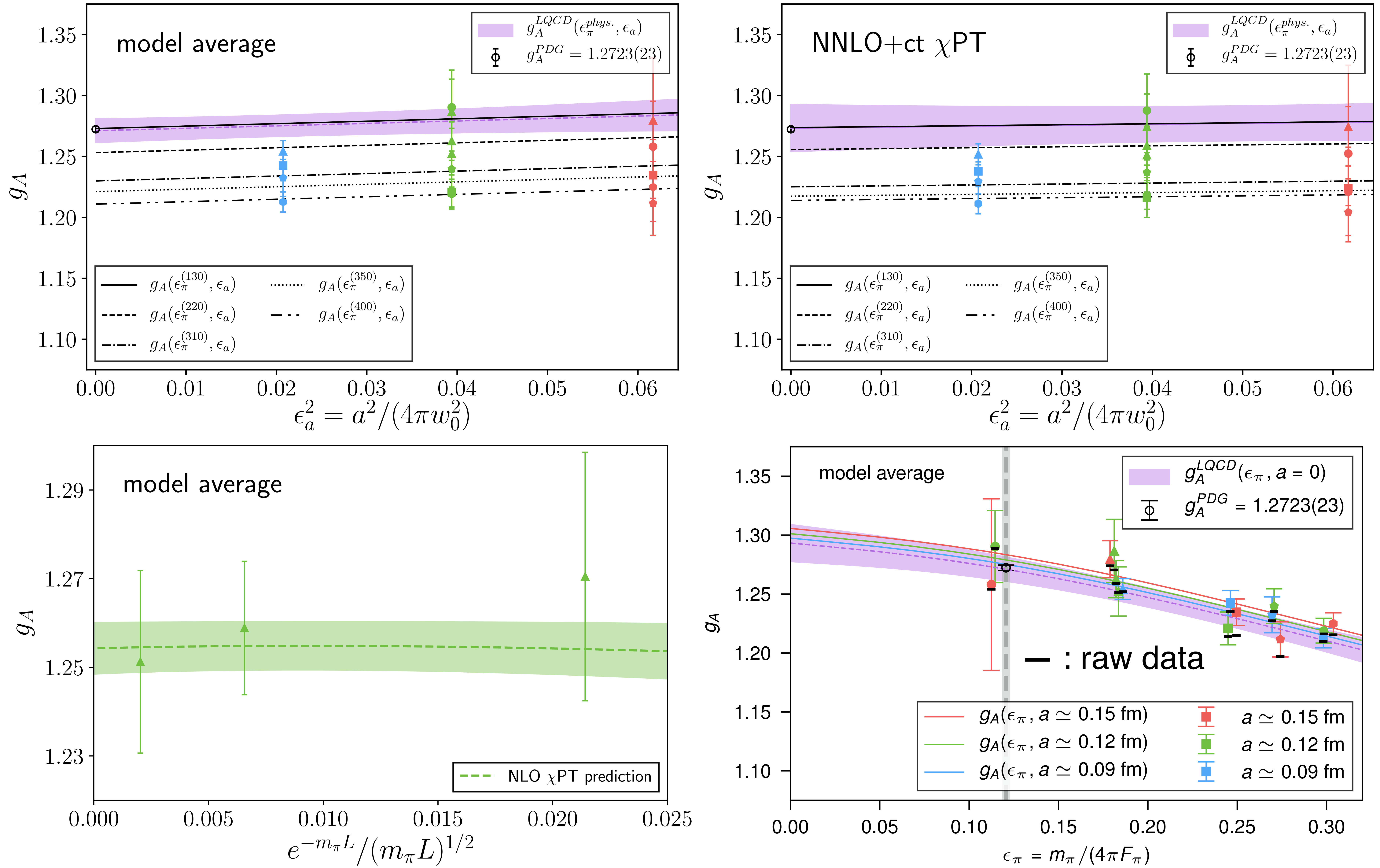
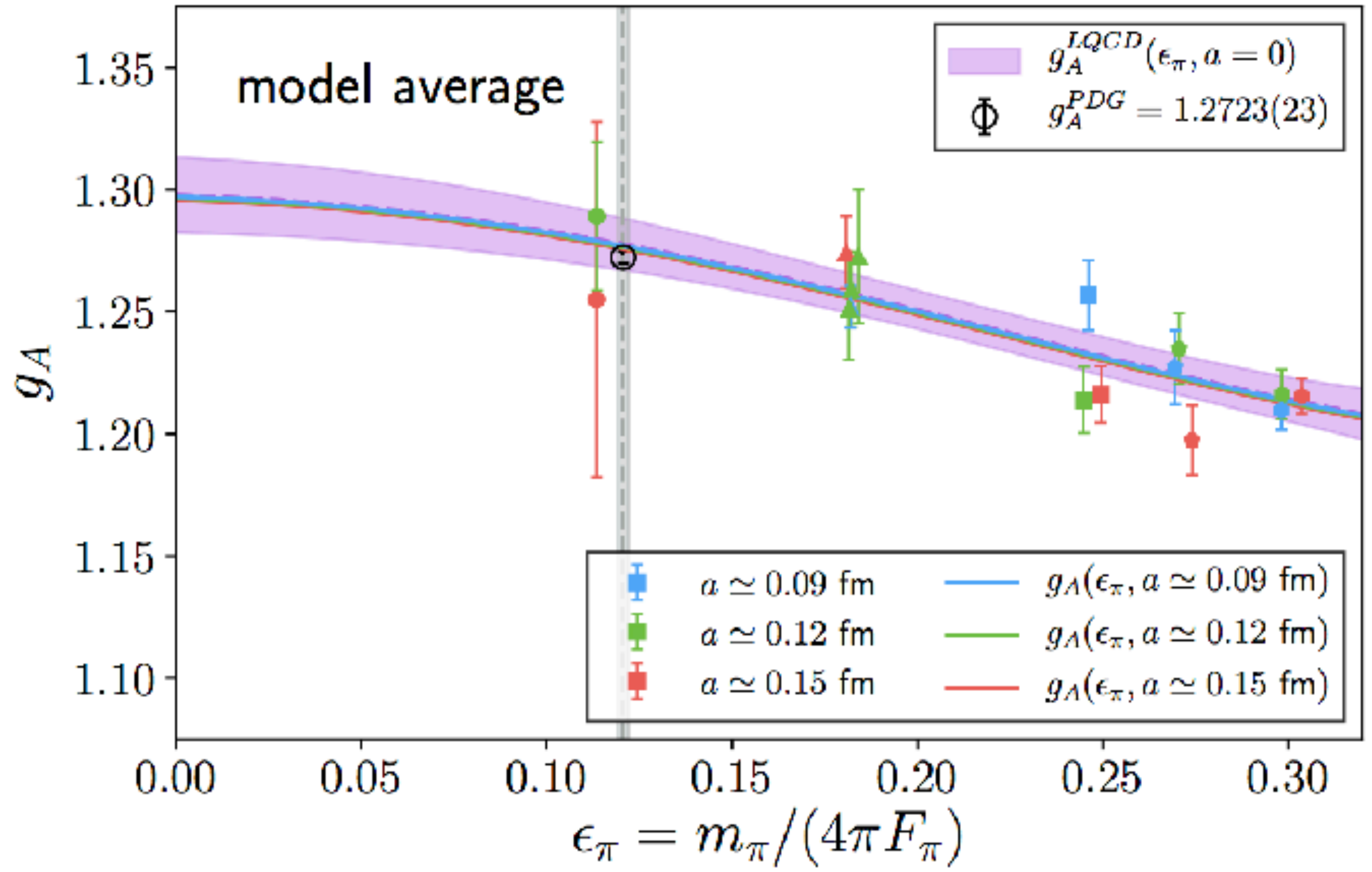
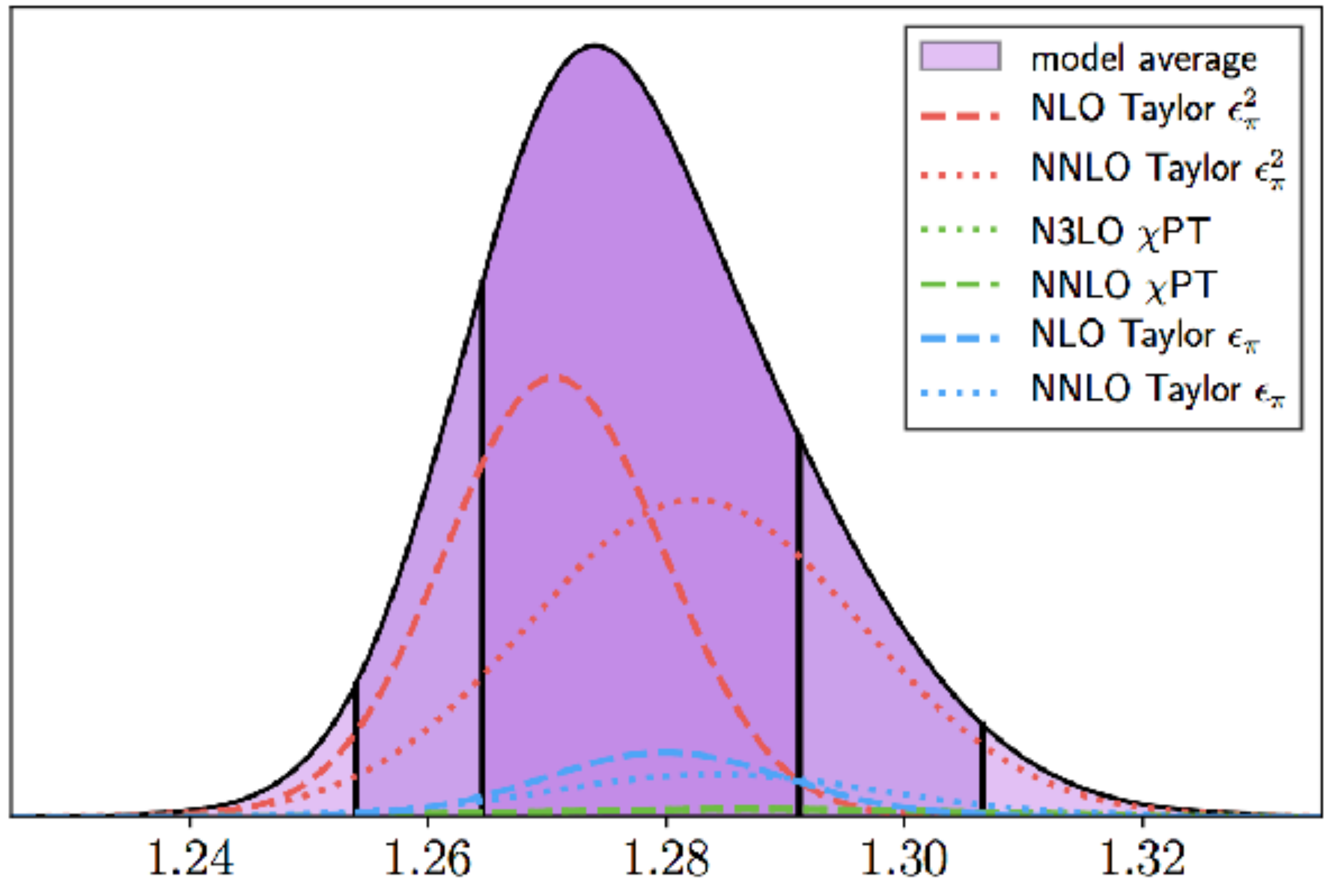


Analysis Details

Model average extrapolation





Fit	χ^2/dof	$\mathcal{L}(D\|M_k)$	$P(M_k\|D)$	$P(g_A\|M_k)$
NNLO χPT	0.727	22.734	0.033	1.273(19)
NNLO+ct χPT	0.726	22.729	0.033	1.273(19)
NLO Taylor ϵ_π^2	0.792	24.887	0.287	1.266(09)
NNLO Taylor ϵ_π^2	0.787	24.897	0.284	1.267(10)
NLO Taylor ϵ_π	0.700	24.855	0.191	1.276(10)
NNLO Taylor ϵ_π	0.674	24.848	0.172	1.280(14)
average				1.271(11)(06)

$$\text{NNLO } \chi\text{PT}: \quad \text{Eq. (S8)} + \delta_a + \delta_L$$

$$\text{NNLO+ct } \chi\text{PT}: \quad \text{Eq. (S8)} + c_4\epsilon_\pi^4 + \delta_a + \delta_L$$

$$\text{NLO Taylor } \epsilon_\pi^2: \quad c_0 + c_2\epsilon_\pi^2 + \delta_a + \delta_L$$

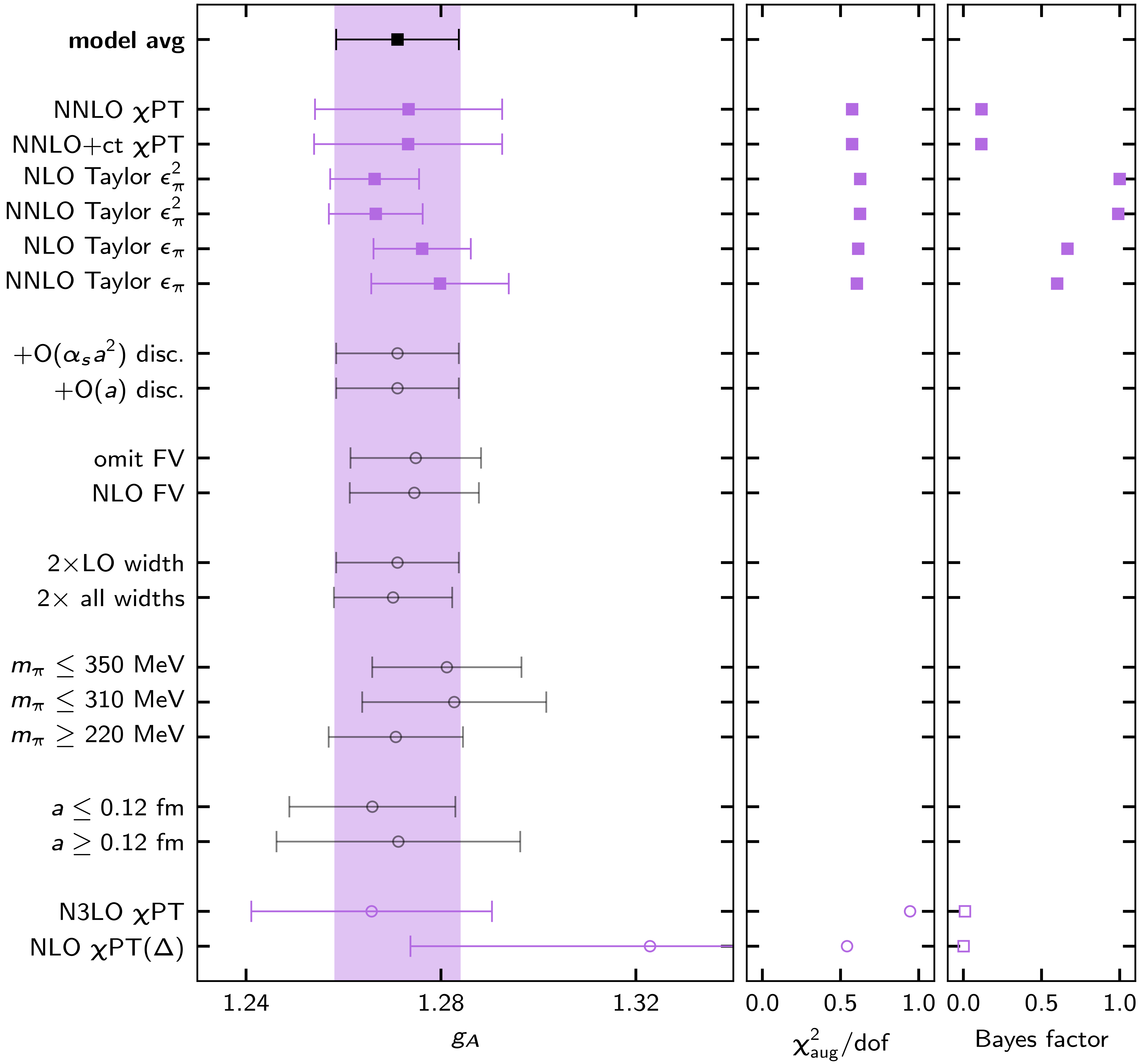
$$\text{NNLO Taylor } \epsilon_\pi^2: \quad c_0 + c_2\epsilon_\pi^2 + c_4\epsilon_\pi^4 + \delta_a + \delta_L$$

$$\text{NLO Taylor } \epsilon_\pi: \quad c_0 + c_1\epsilon_\pi + \delta_a + \delta_L$$

$$\text{NNLO Taylor } \epsilon_\pi: \quad c_0 + c_1\epsilon_\pi + c_2\epsilon_\pi^2 + \delta_a + \delta_L$$

Analysis Details

Stability of Extrapolation Analysis



Final result

6 fits included in the model average and their relative weights

discretization corrections

finite volume corrections

sensitivity to prior width

sensitivity to pion mass cuts

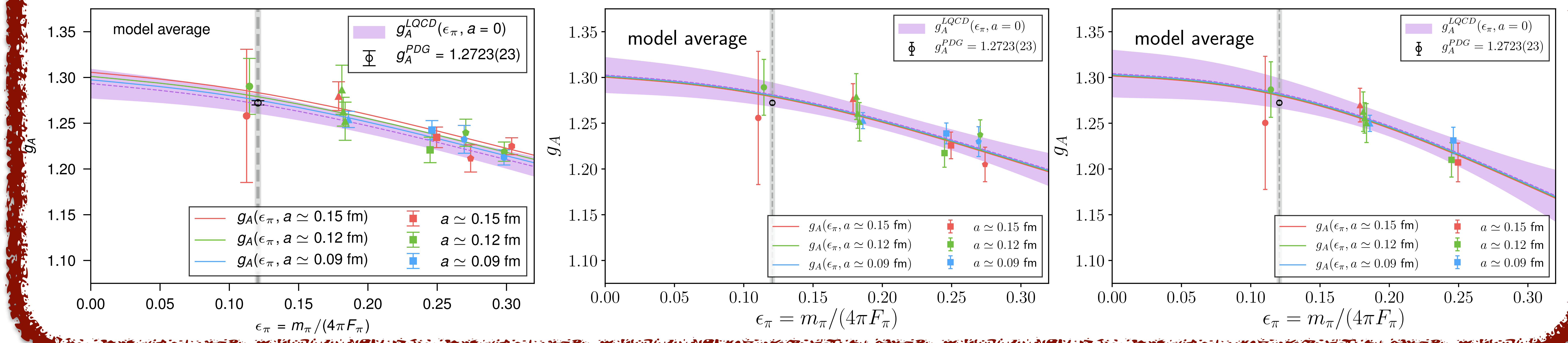
sensitivity to lattice spacing cuts

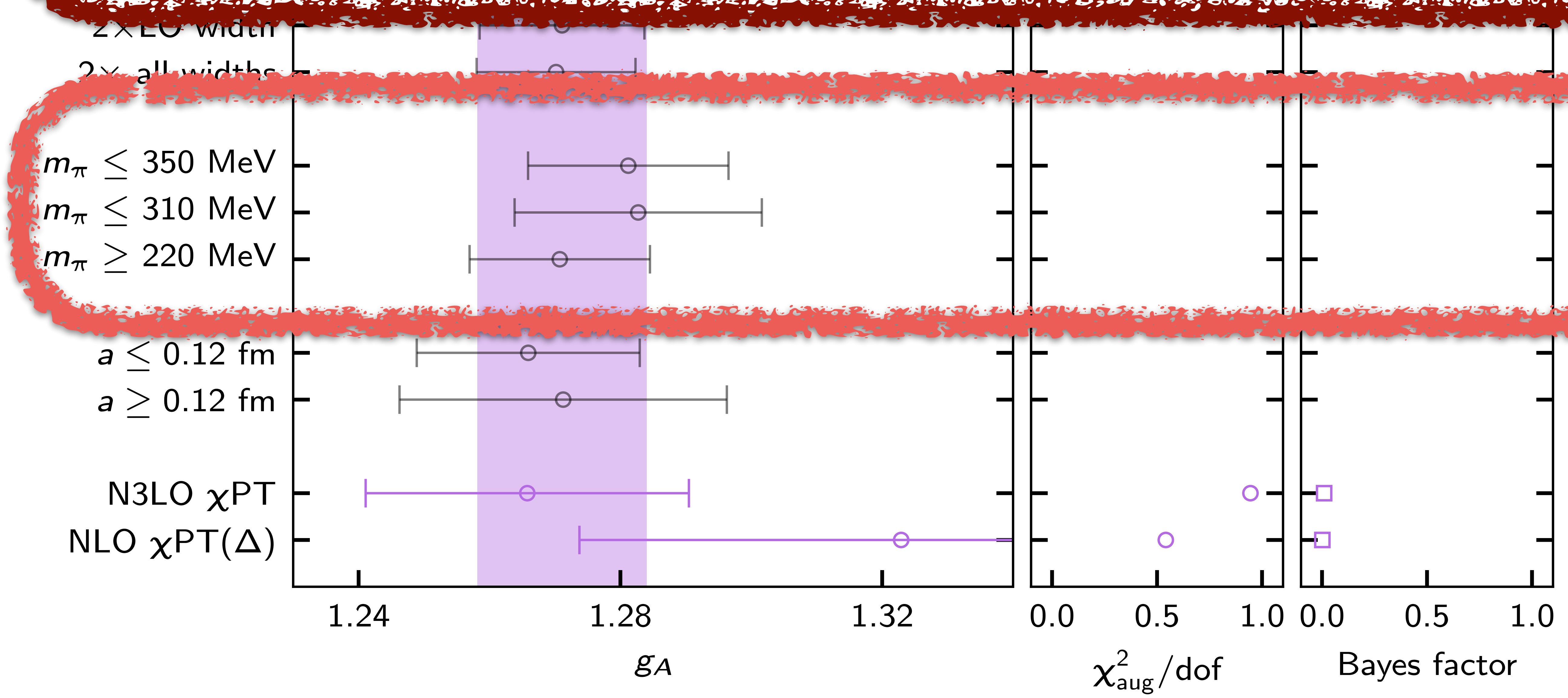
additional XPT analysis

Analysis Details

Stability of Extrapolation Analysis

$m_\pi \leq 400$ MeV | $m_\pi \leq 350$ MeV | $m_\pi \leq 310$ MeV





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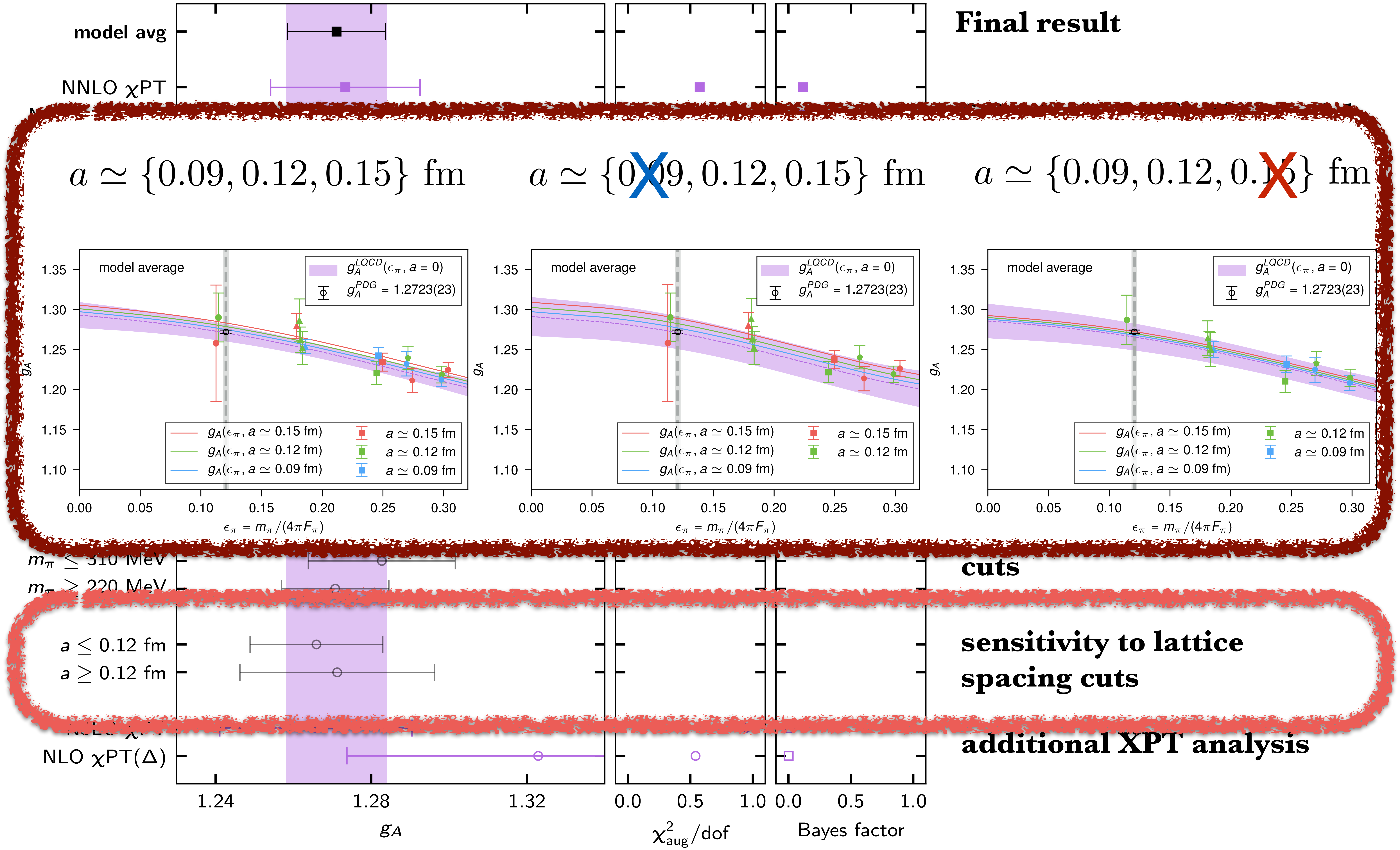
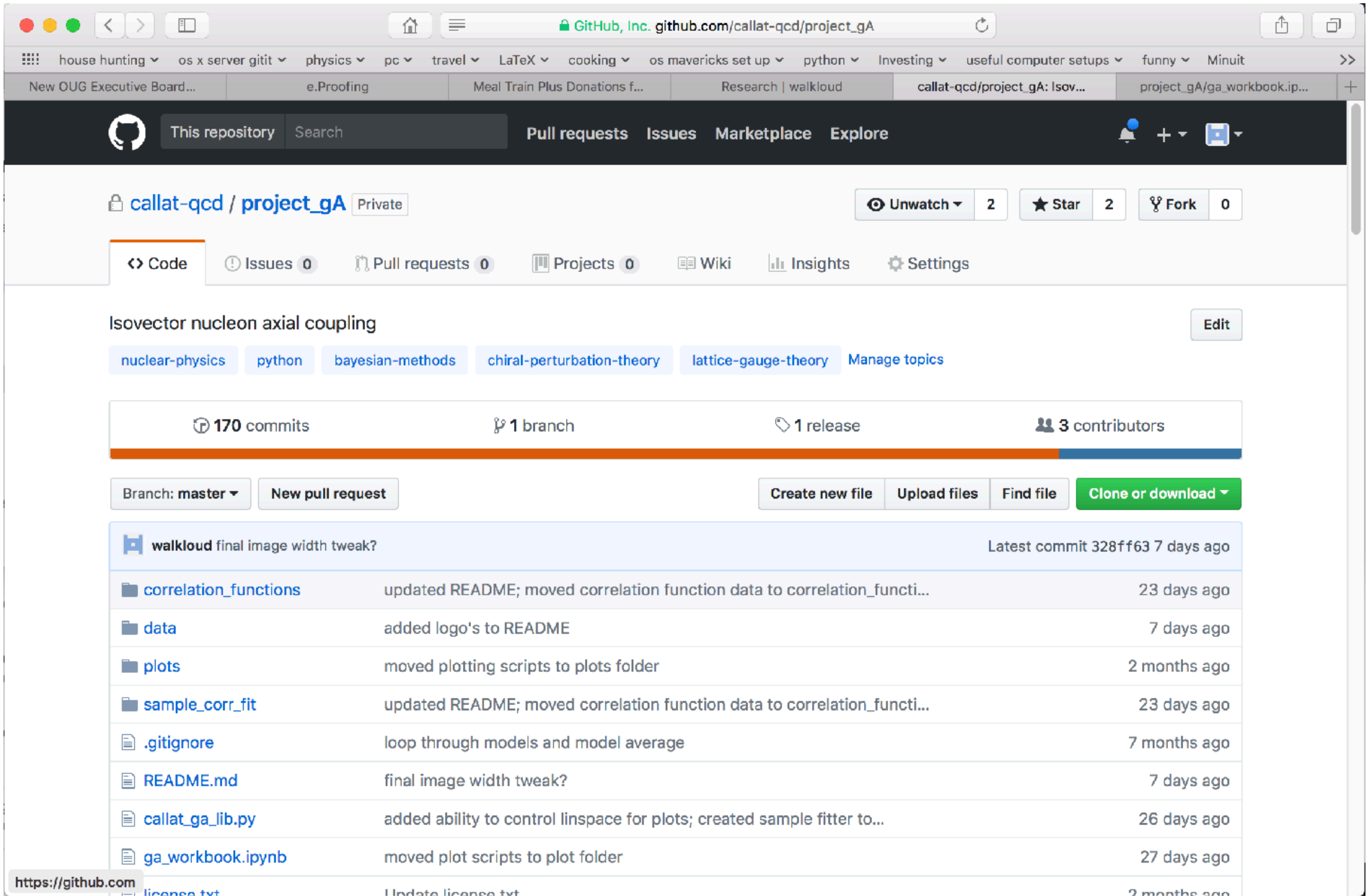


https://github.com/callat-qcd/project_gA

raw correlation functions, correlation function analysis results, extrapolation analysis



What are the implications now?

Final result

statistical	0.81%
chiral extrapolation	0.31%
$a \to 0$	0.12%
$L \to \infty$	0.15%
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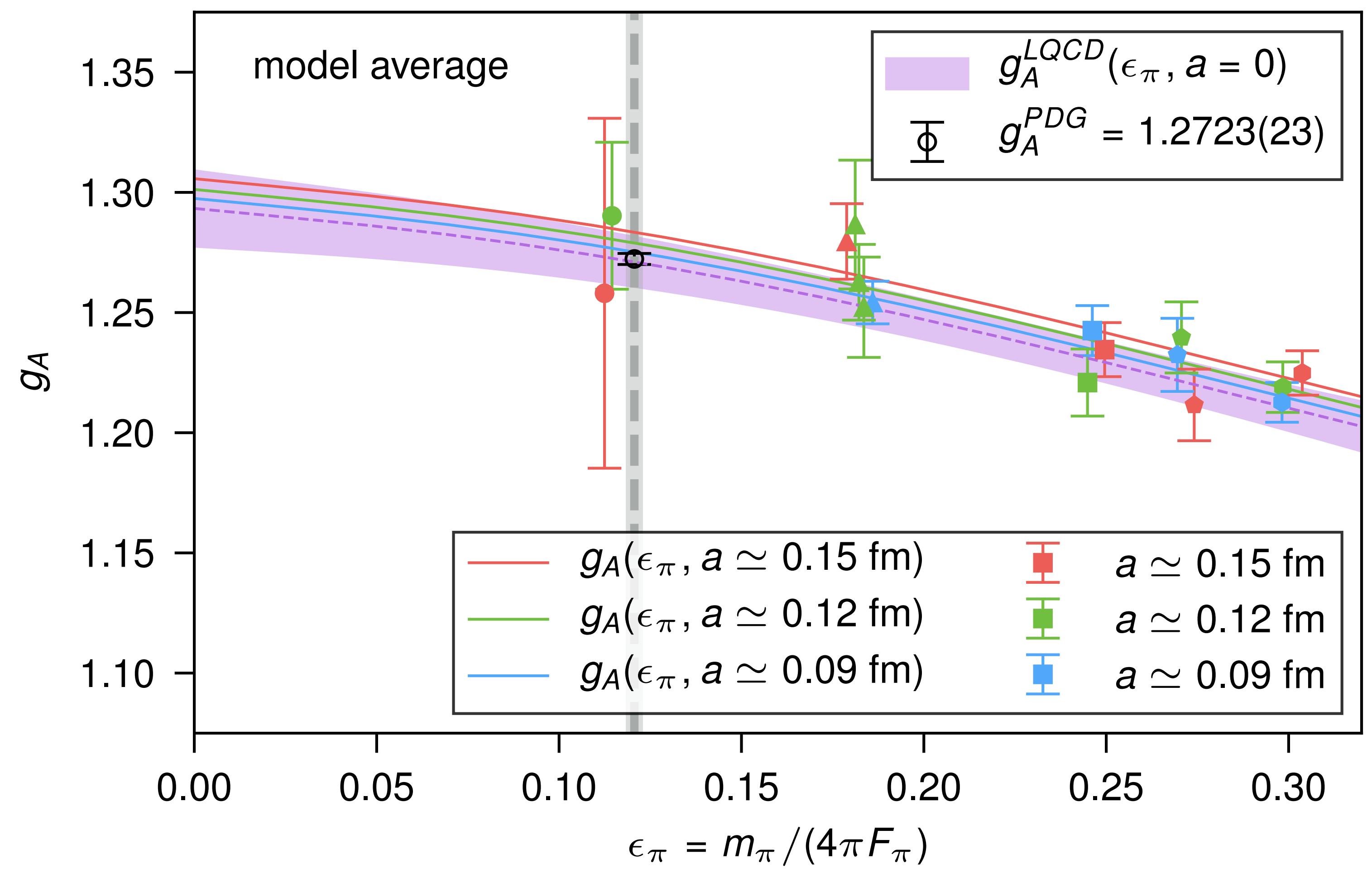
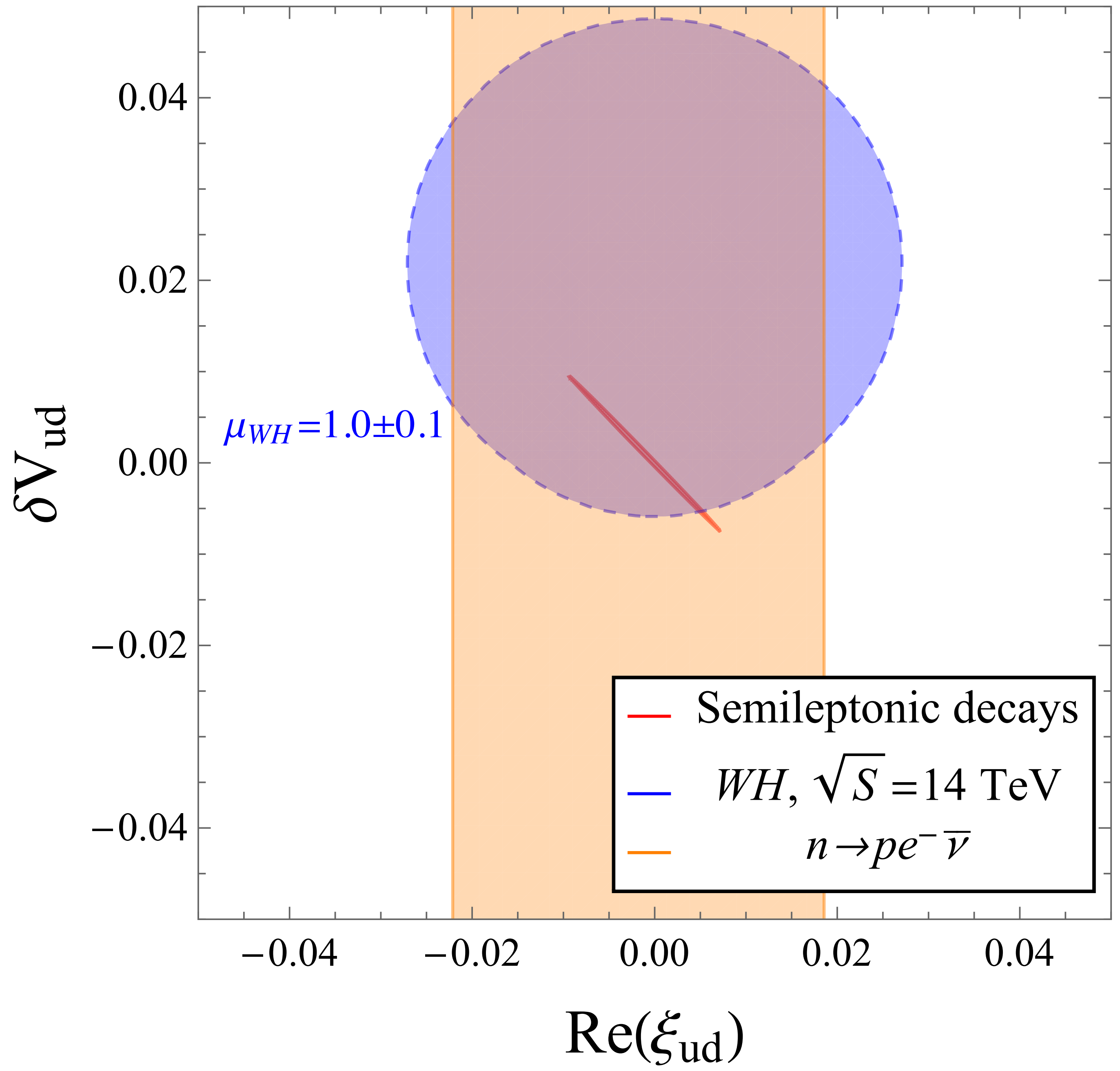
model selection	0.43%
total	0.99%

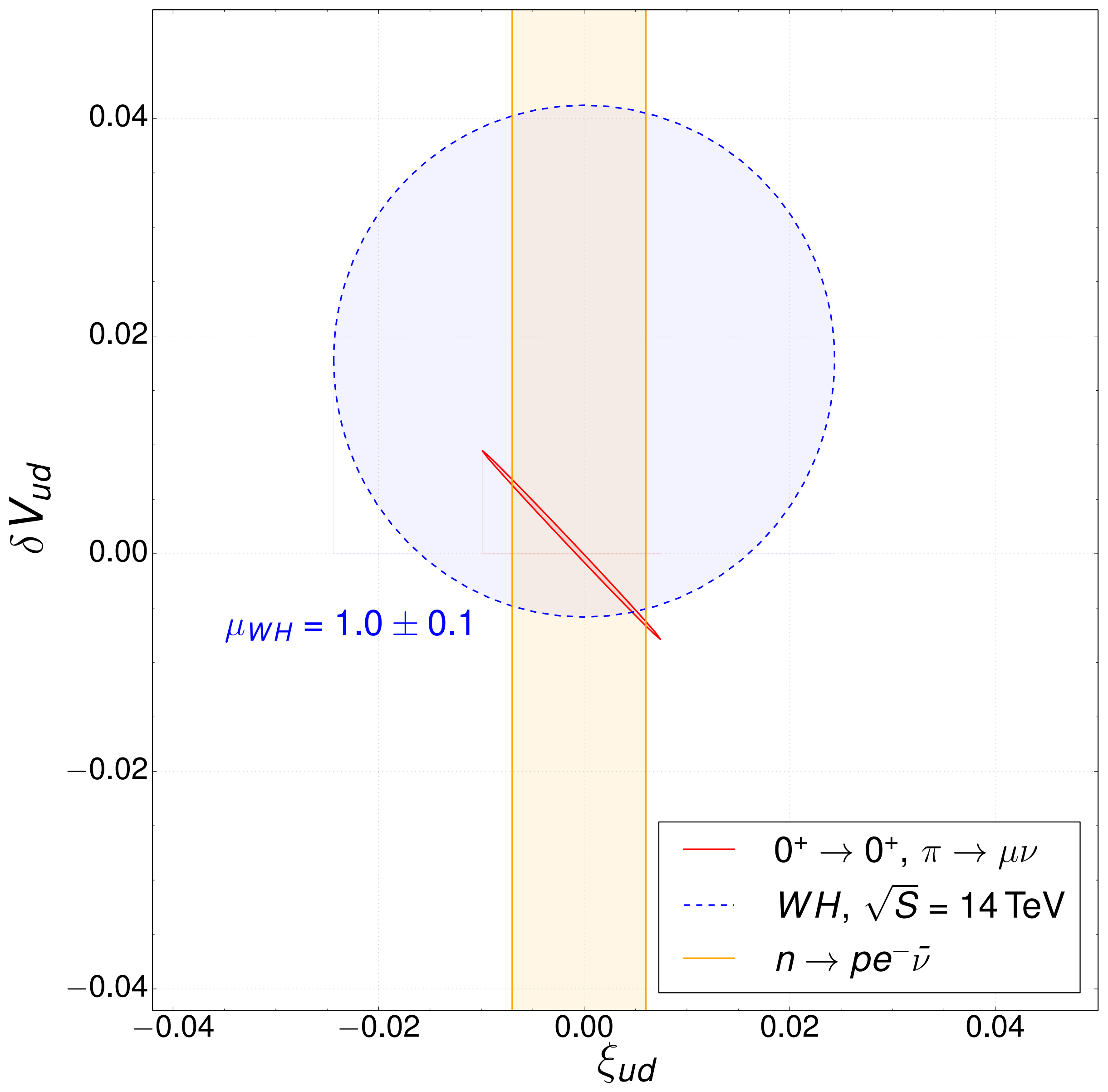


$$g_A^{\mathrm{QCD}} = 1.2711(103)^s(39)^\chi(15)^a(19)^V(04)^I(55)^M$$



Most stringent constraint on BSM right handed coupling

Alioli, Cirigliano, Dekens, de Vries, Mereghetti JHEP 1705 (2017) [arXiv:1703.04751]



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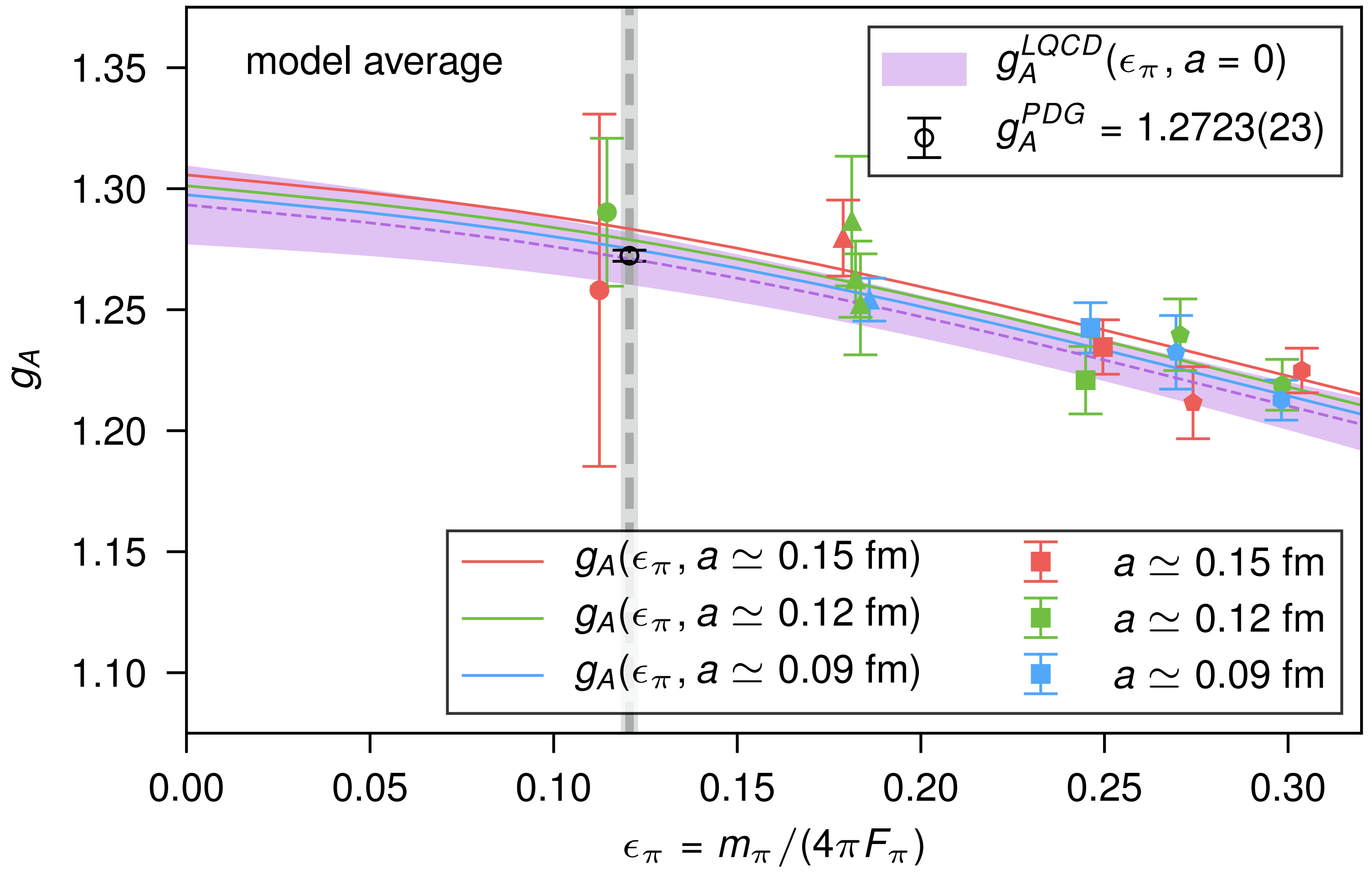


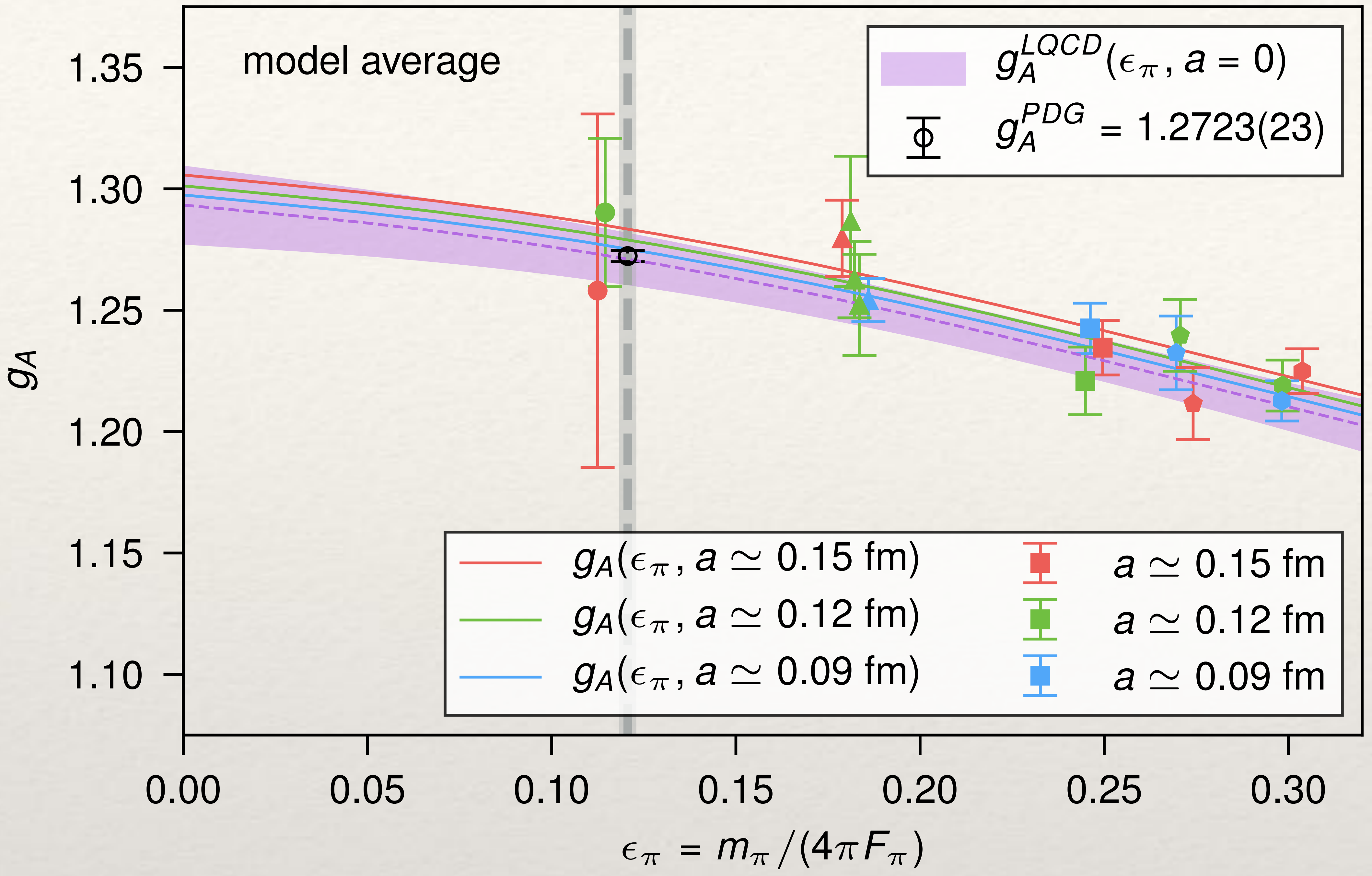
$$g_A^{\mathrm{QCD}} = 1.2711(103)^s(39)^\chi(15)^a(19)^V(04)^I(55)^M$$

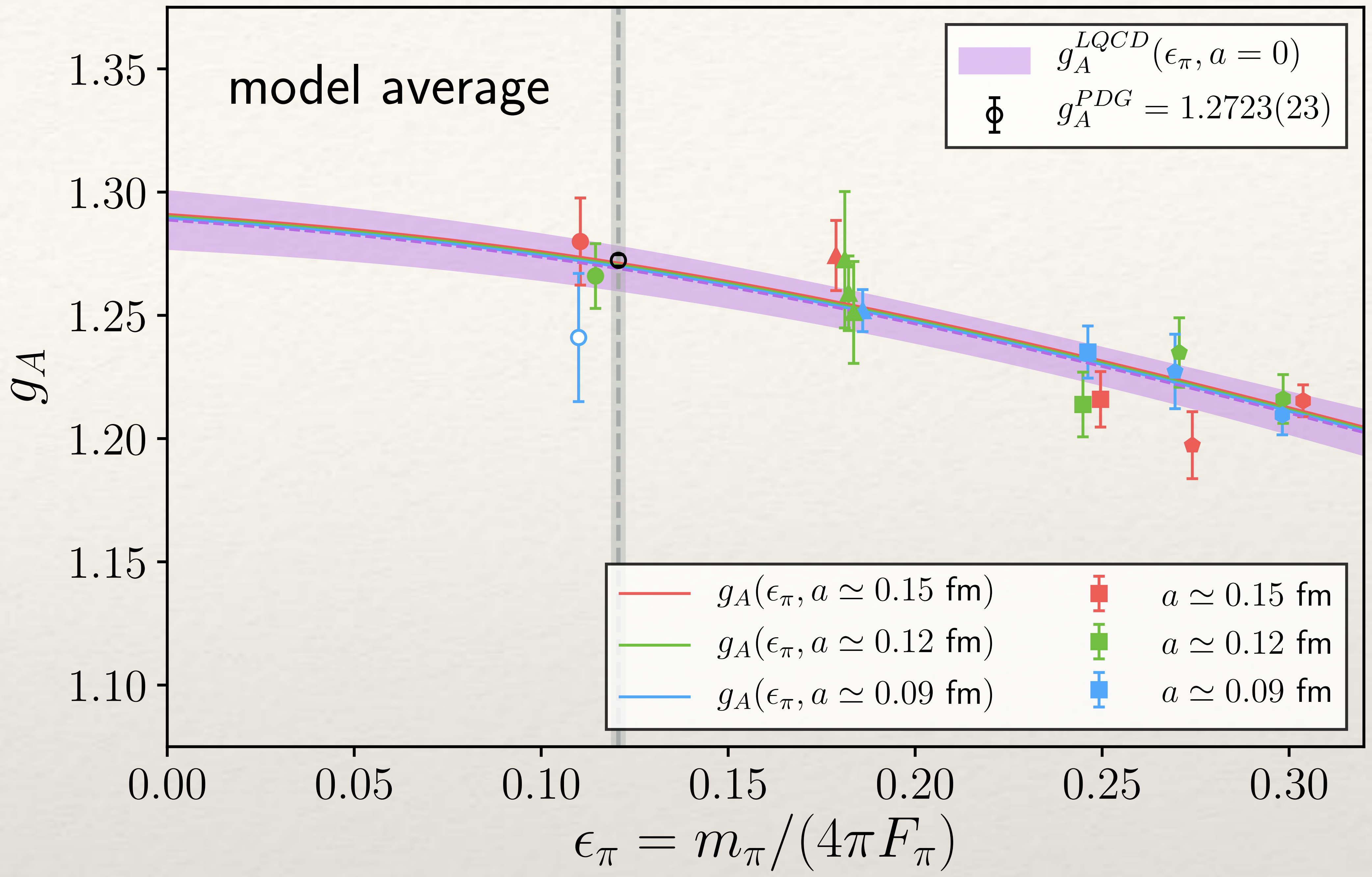
Isospin corrections

- The leading radiative corrections are subtracted from the experimental measurement leaving corrections of $\mathcal{O}\left(\frac{\alpha_{EM}^2}{\pi^2}\right) \sim 0.0005\%$
- There are $(m_d\text{-}m_u)^2$ corrections $\mathcal{O}\left(\frac{(m_d-m_u)^2}{(m_d+m_u)^2}\epsilon_\pi^4\right) \sim 0.002\%$
- There are mixed corrections of $\mathcal{O}\left(\alpha_{EM}\frac{m_d-m_u}{m_d+m_u}\epsilon_\pi^2\right) \sim 0.004\%$
- The largest isospin correction comes from the extrapolation to $\epsilon_{\pi^-} = \dfrac{m_{\pi^-}}{4\pi F_{\pi^-}}$ $\epsilon_{\pi^0} = \dfrac{m_{\pi^0}}{4\pi F_{\pi^0}}$
- There are non-universal structure corrections which have not been determined but are expected to be O(10^{-3}) - Ando et al. Phys. Lett. B595 (2004) [nucl-th/0402100]

The Neutron Lifetime on Sierra Early Science

1 year on Titan (ORNL) + 2 years on GPU machines at LLNL





Nature 558 (2018) no. 7708, 91-94

Sierra Early Science

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- The green point in our publication cost as much computing time as all the other points combined
- The green point from Sierra has **10x** more statistics than our publication
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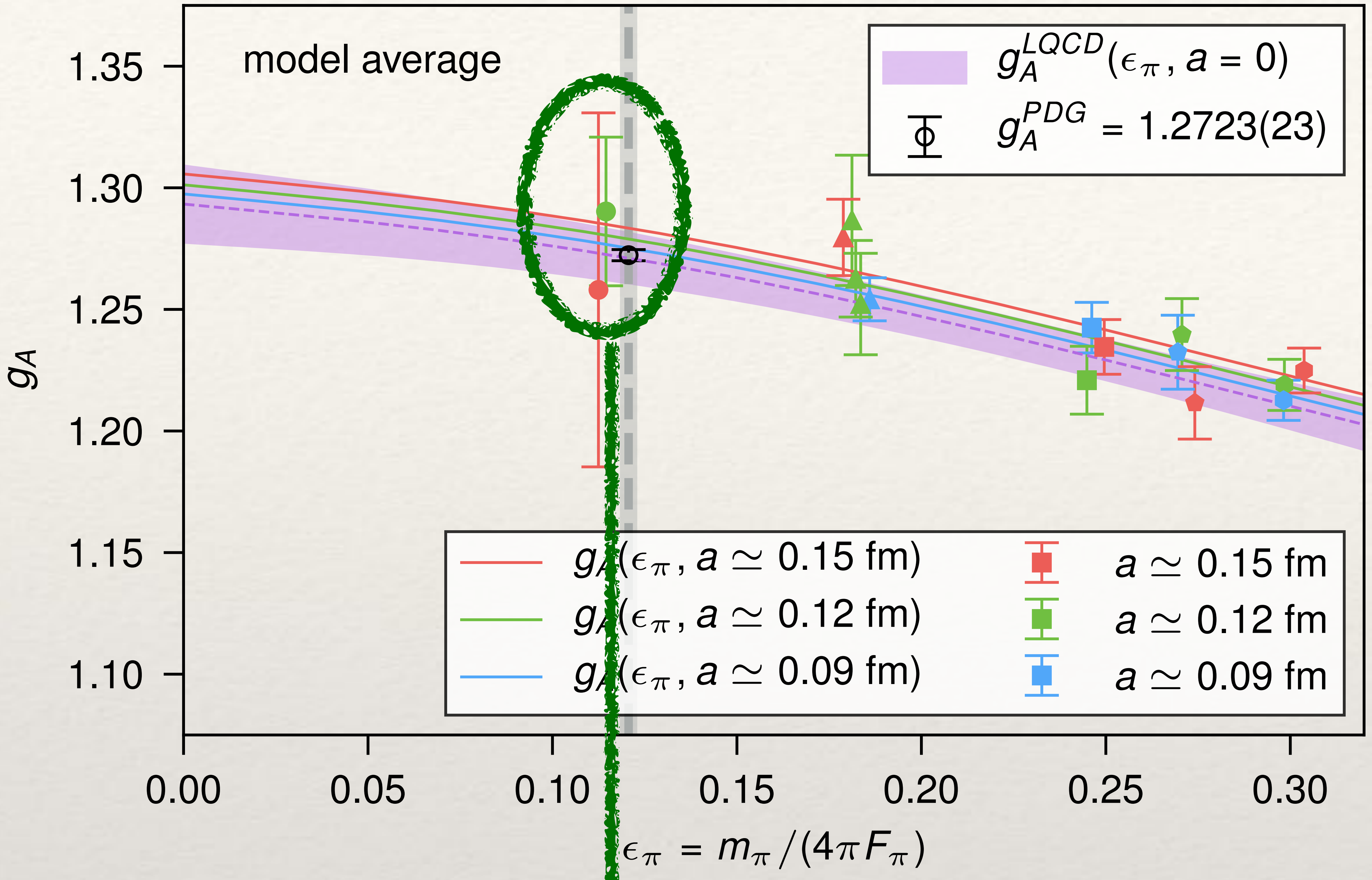

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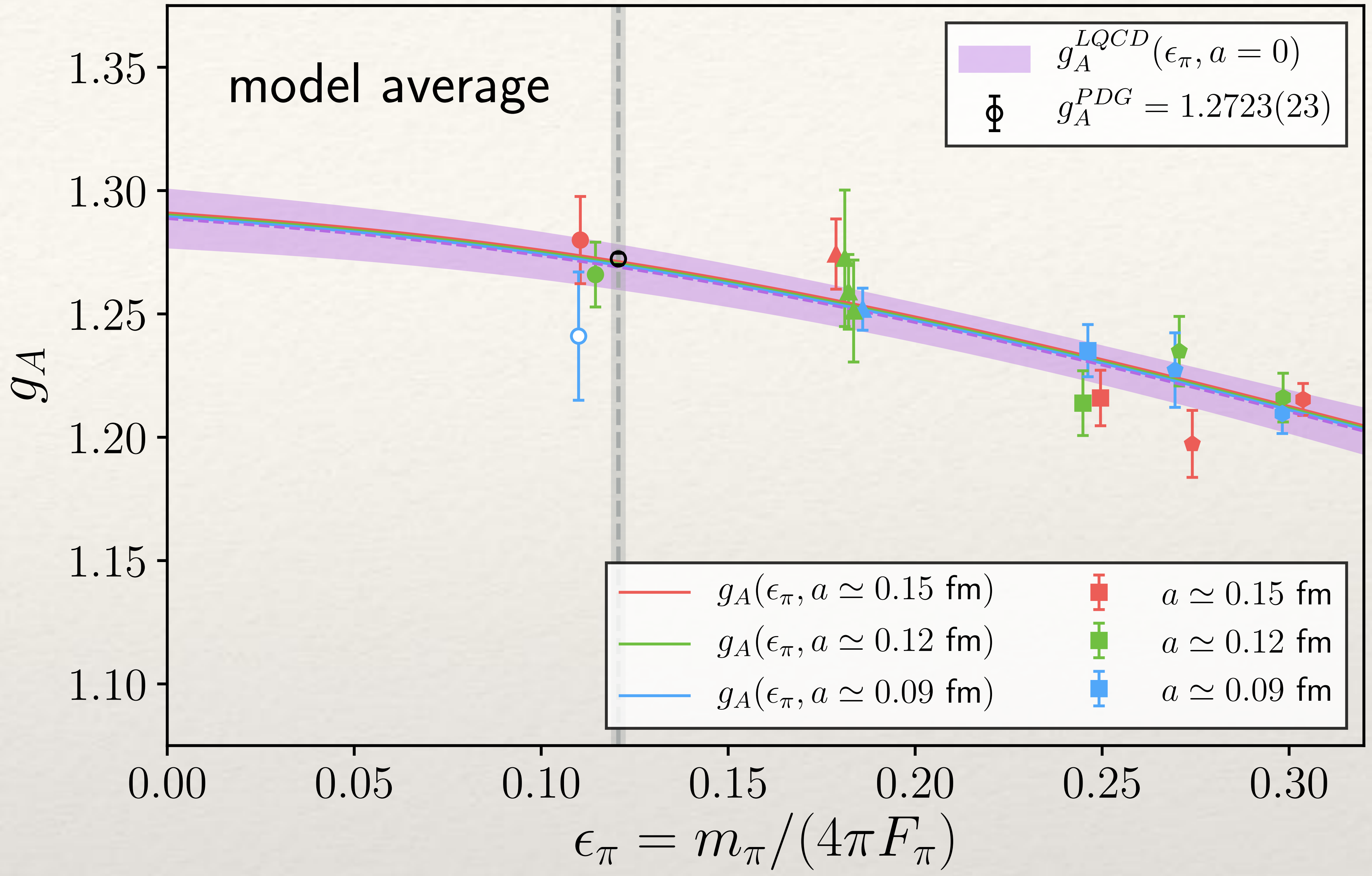

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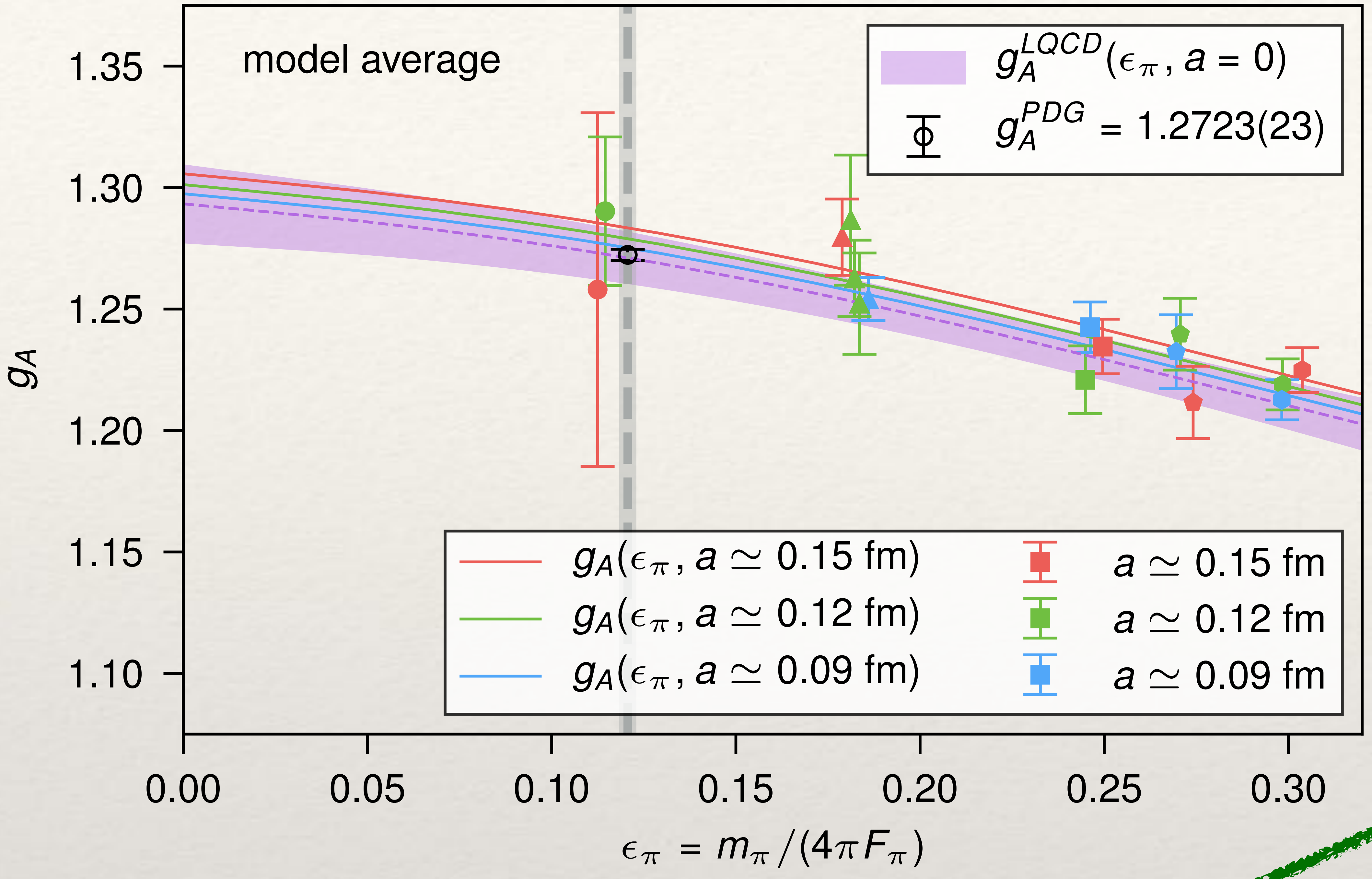

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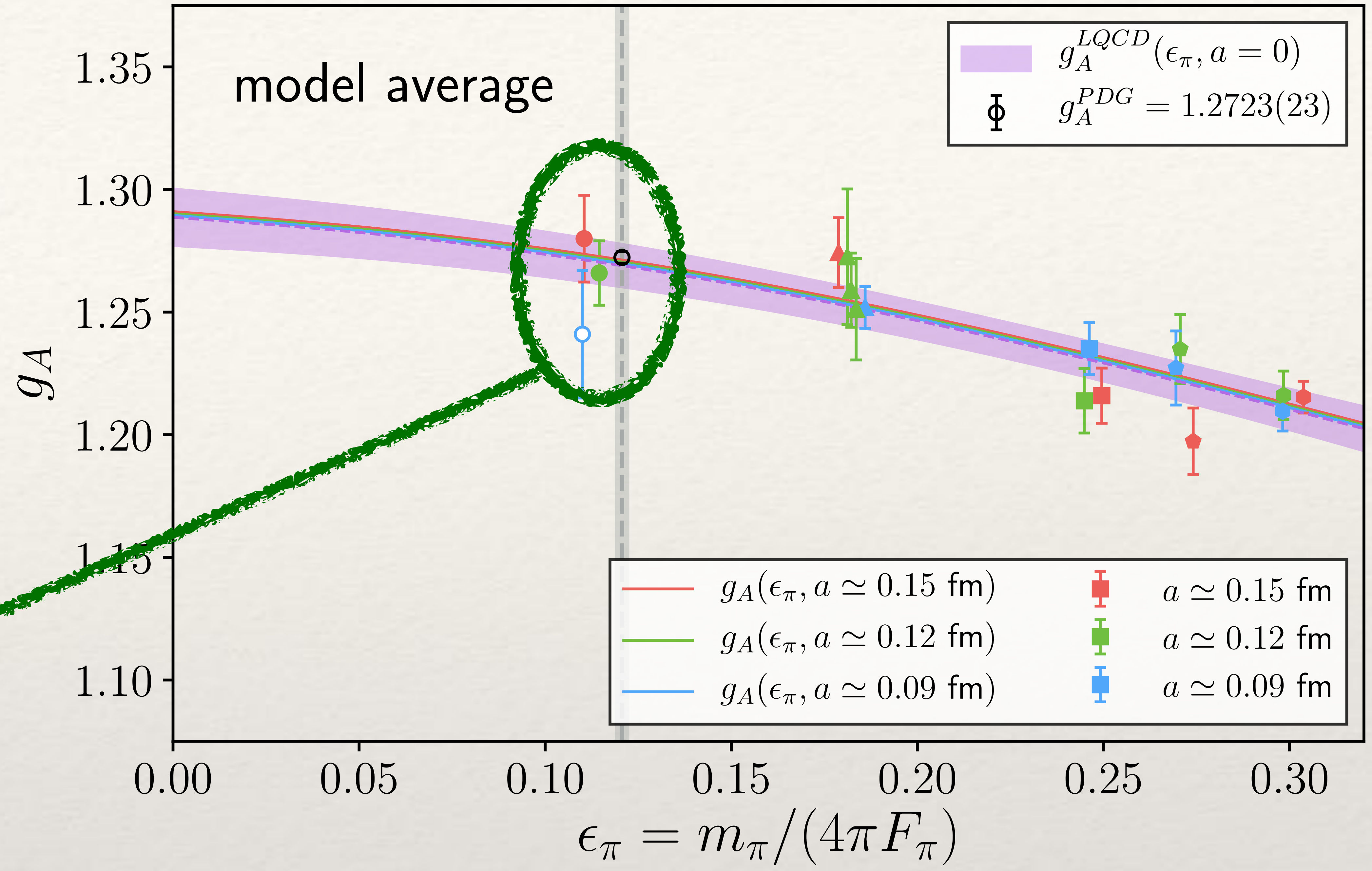

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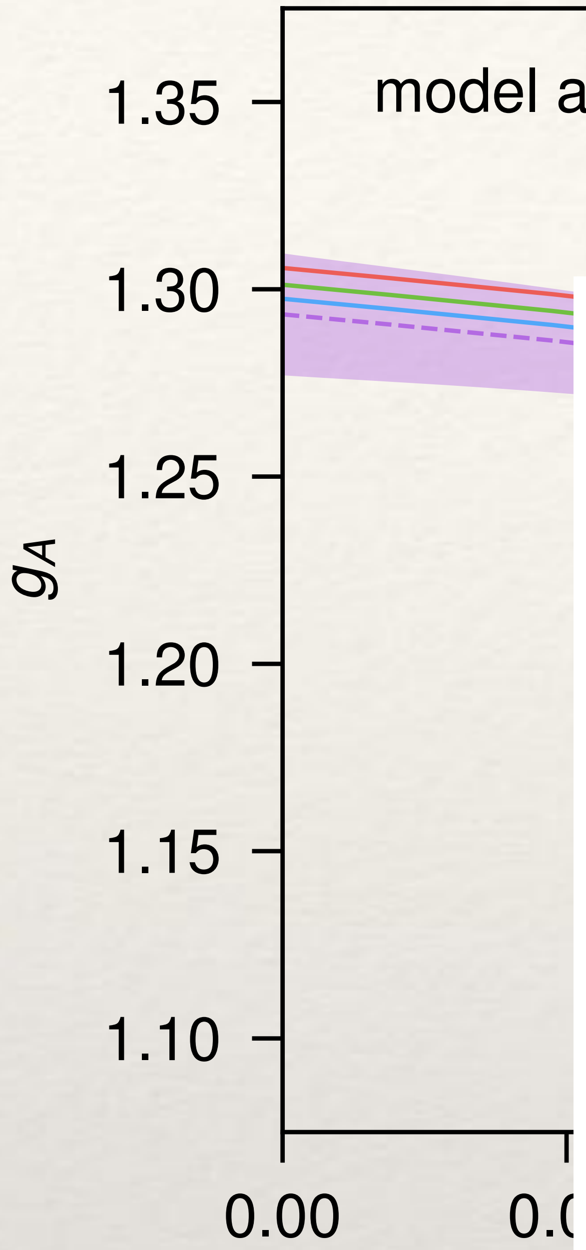

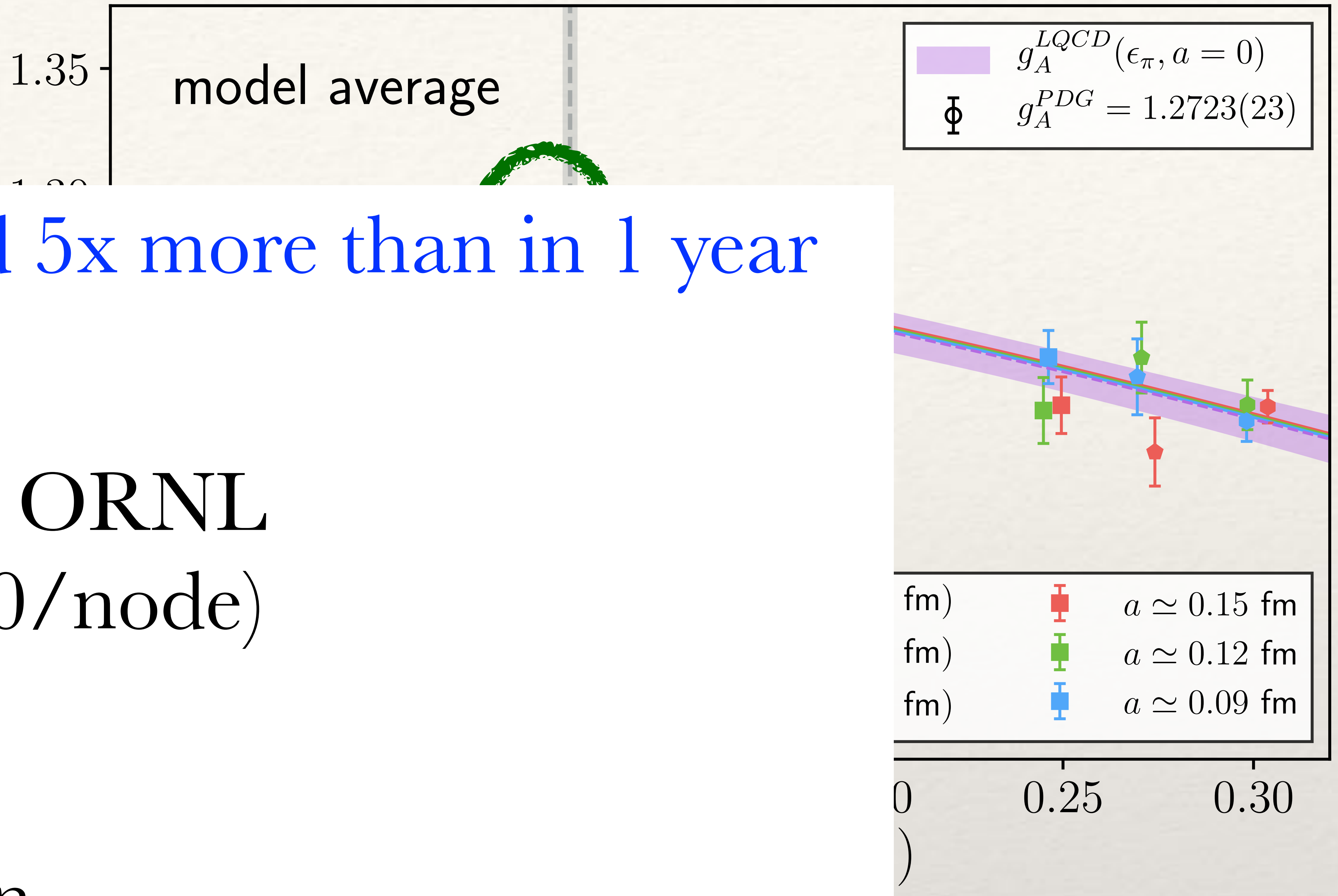

- In 2.5 weekends on Sierra - we accomplished 5x more than in 1 year on Titan

- Machine-to-machine, compared to Titan @ ORNL (Titan is 18,688 nodes 16-core AMD + 1 K20/node)

  For our research
  Sierra (~4300) is **~10 times** faster than Titan
  Summit (~4600) is **~15 times** faster than Titan

- These machines are **disruptively** faster than previous computers

Natu

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- The gree
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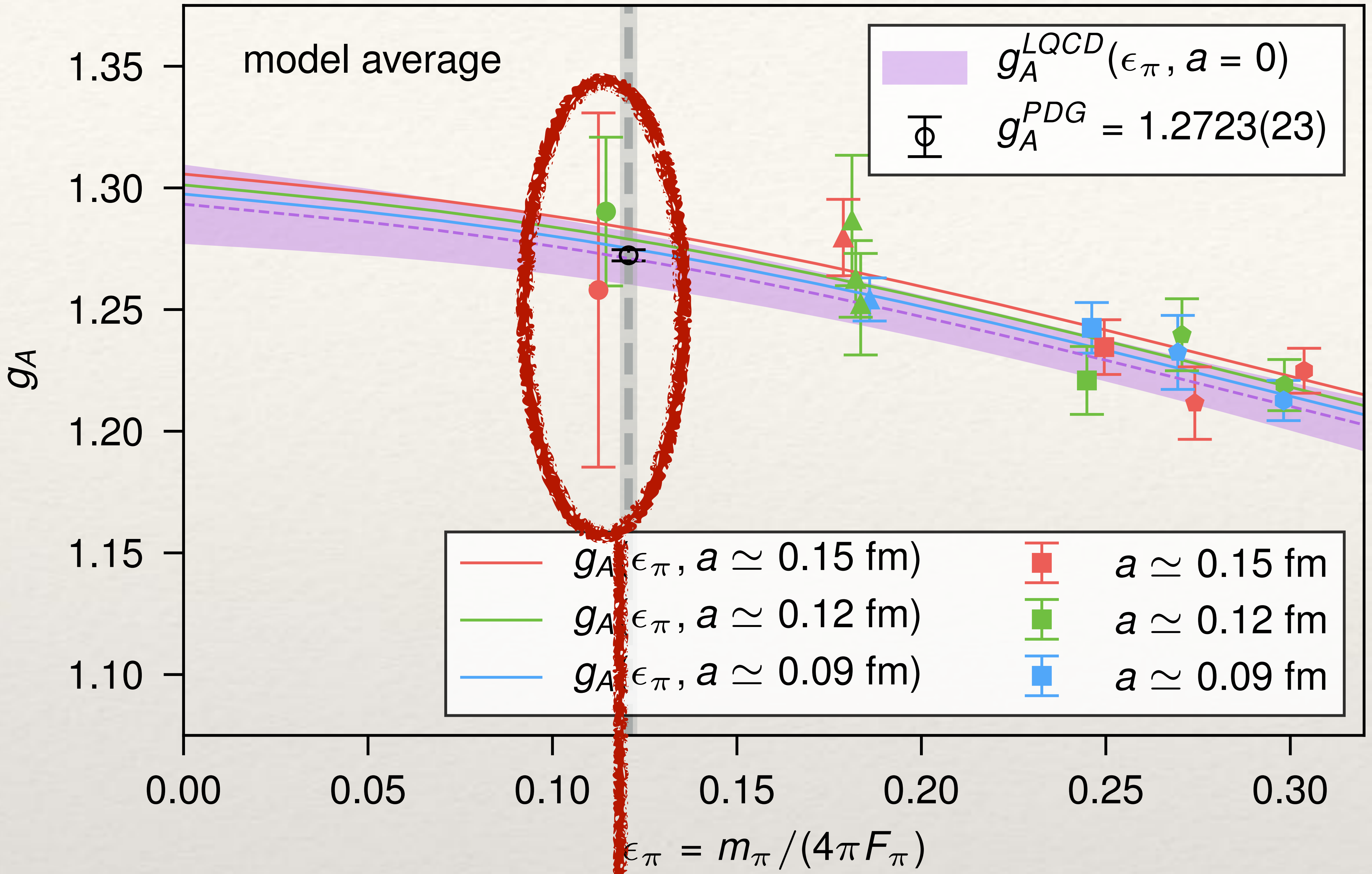

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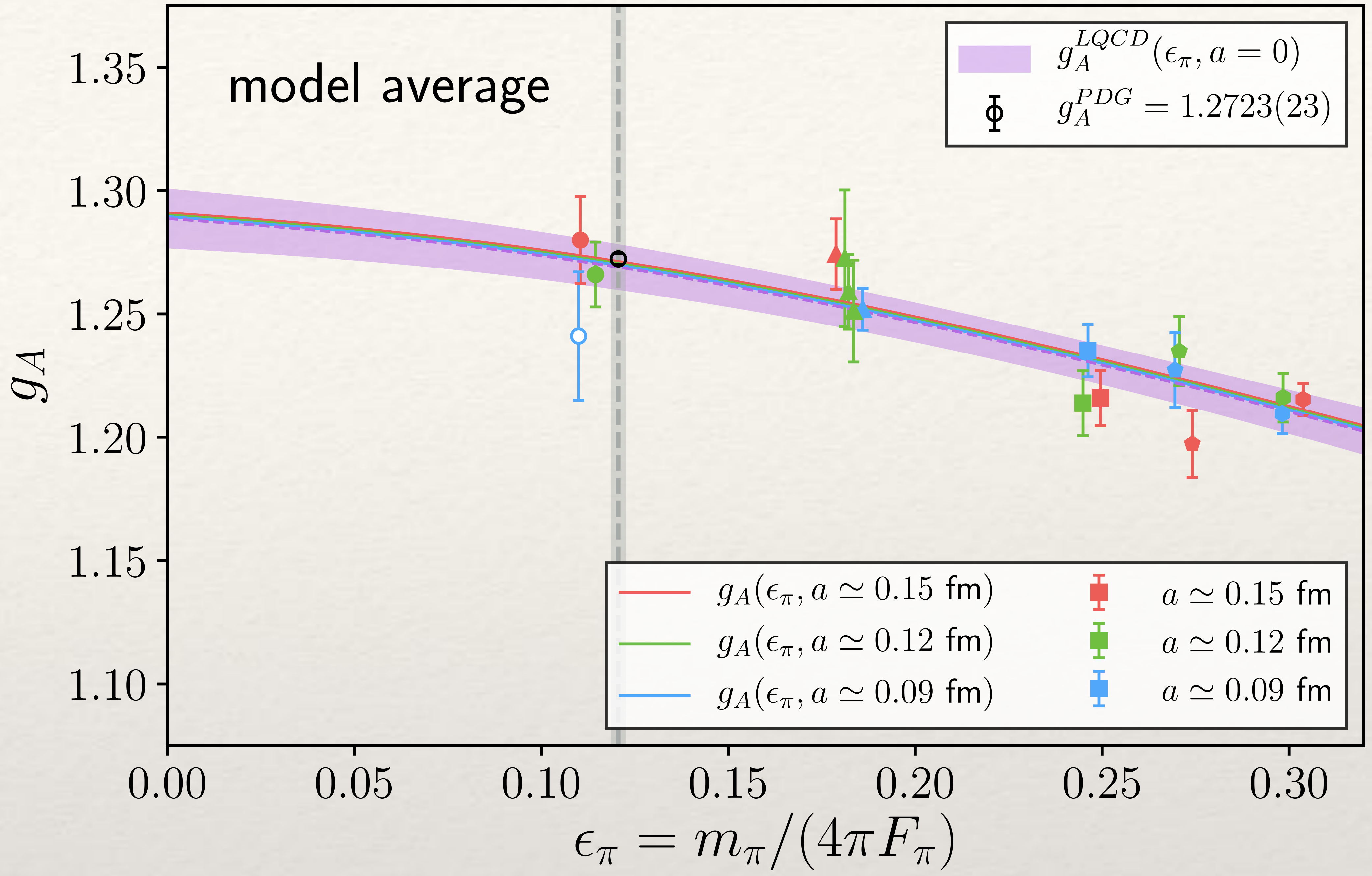

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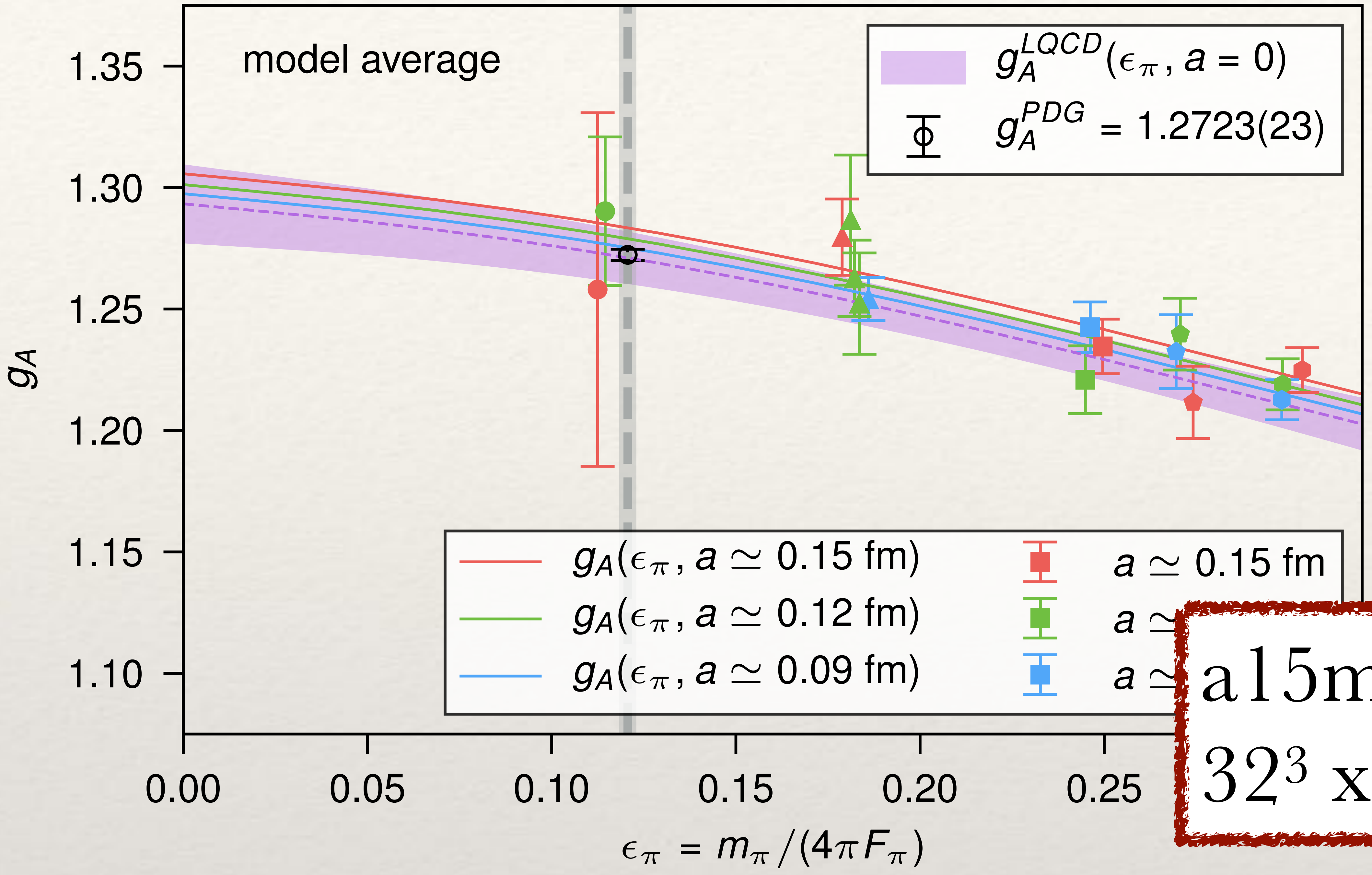

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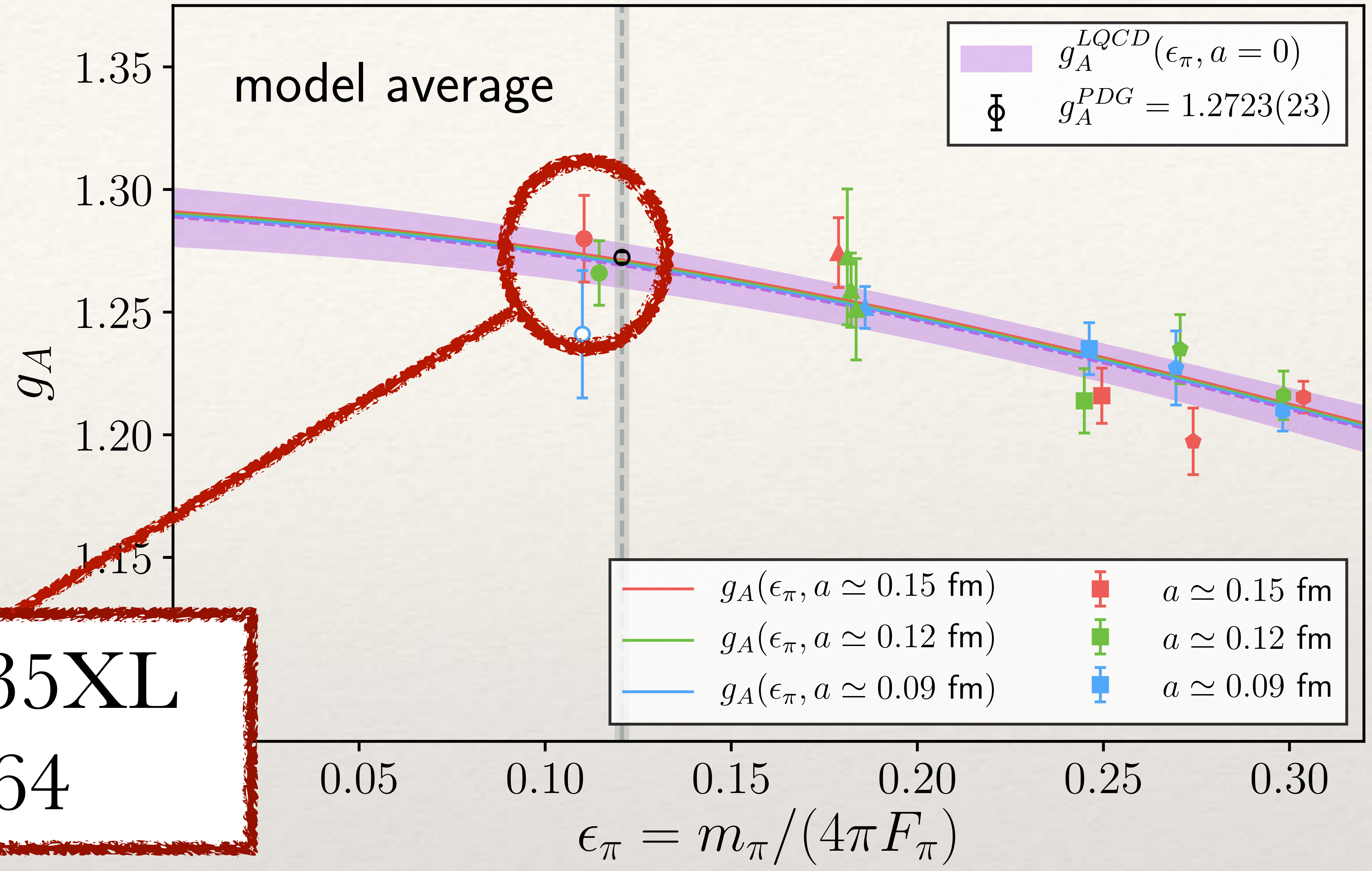

Sierra Early Science

a15m130 → a15m135XL

32^3 x 48 → 48^3 x 64

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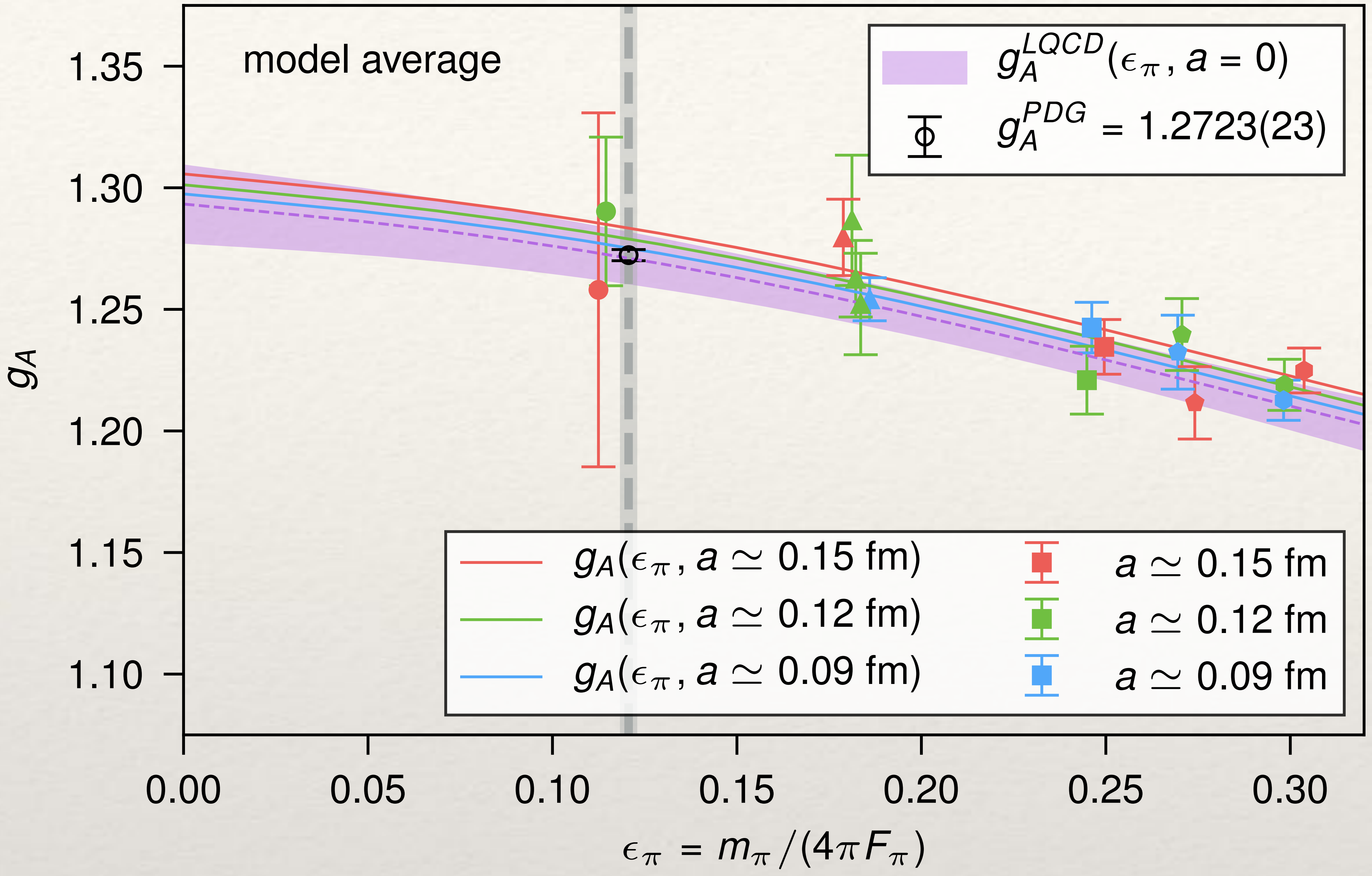

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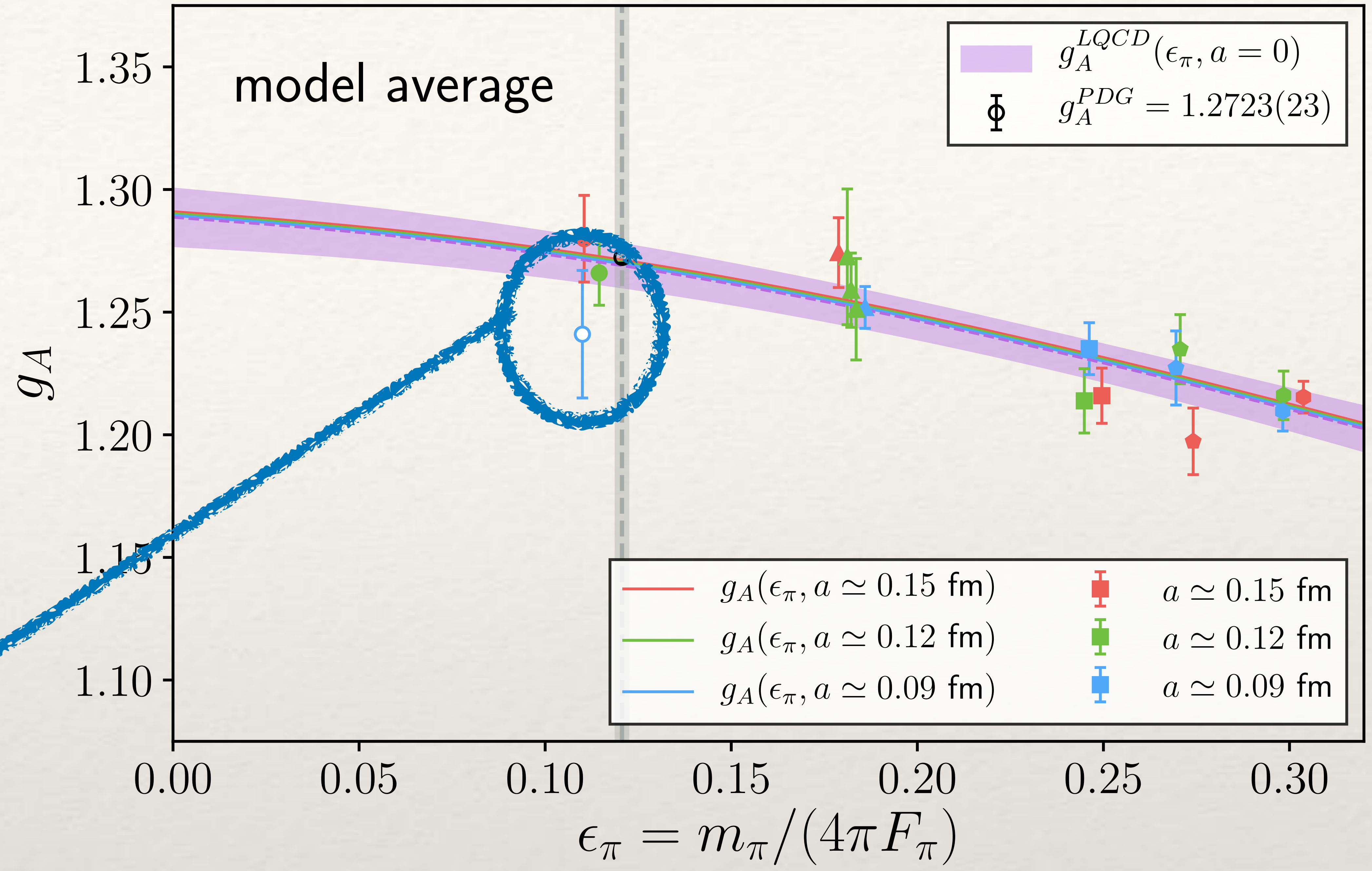

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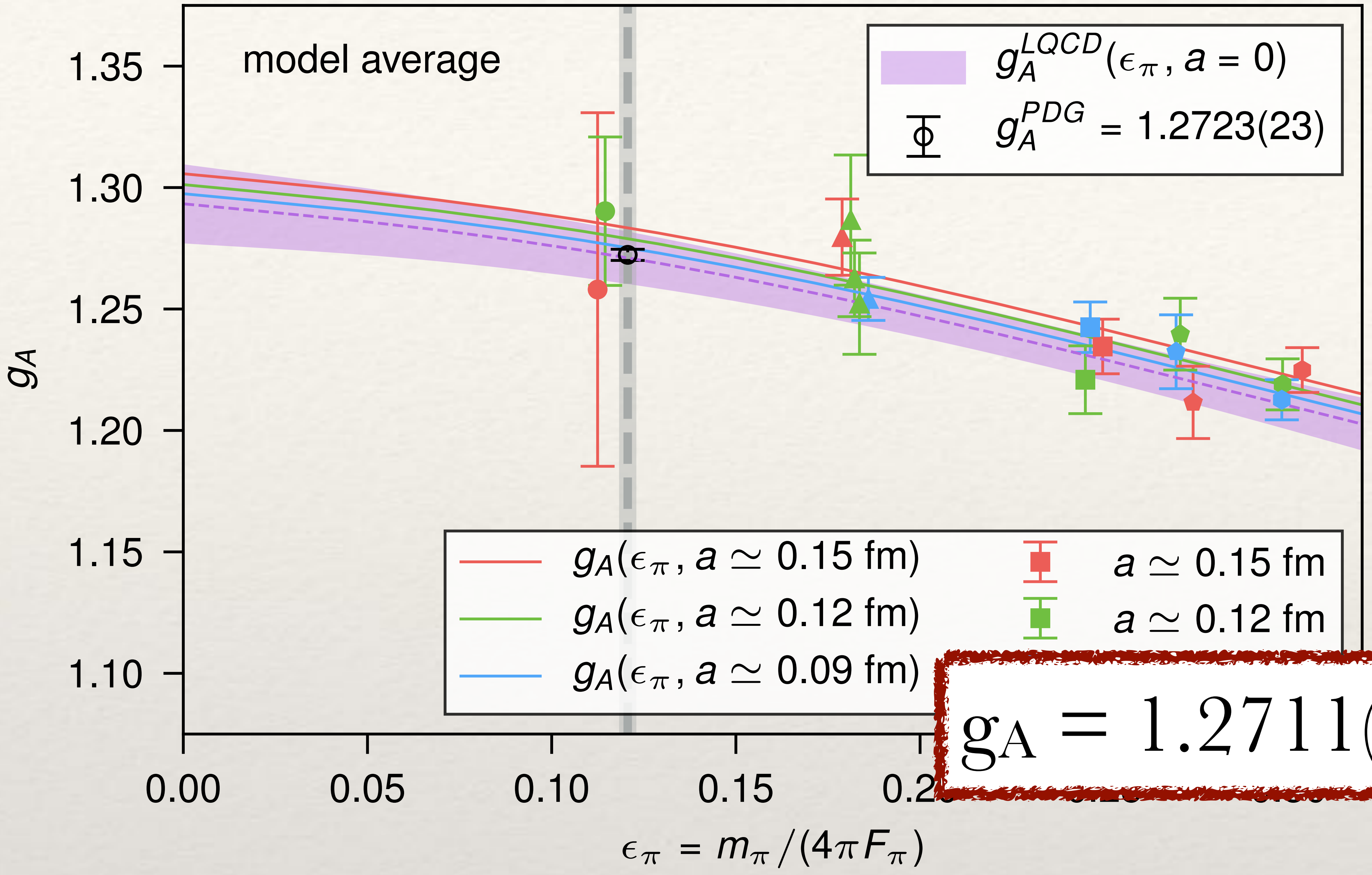

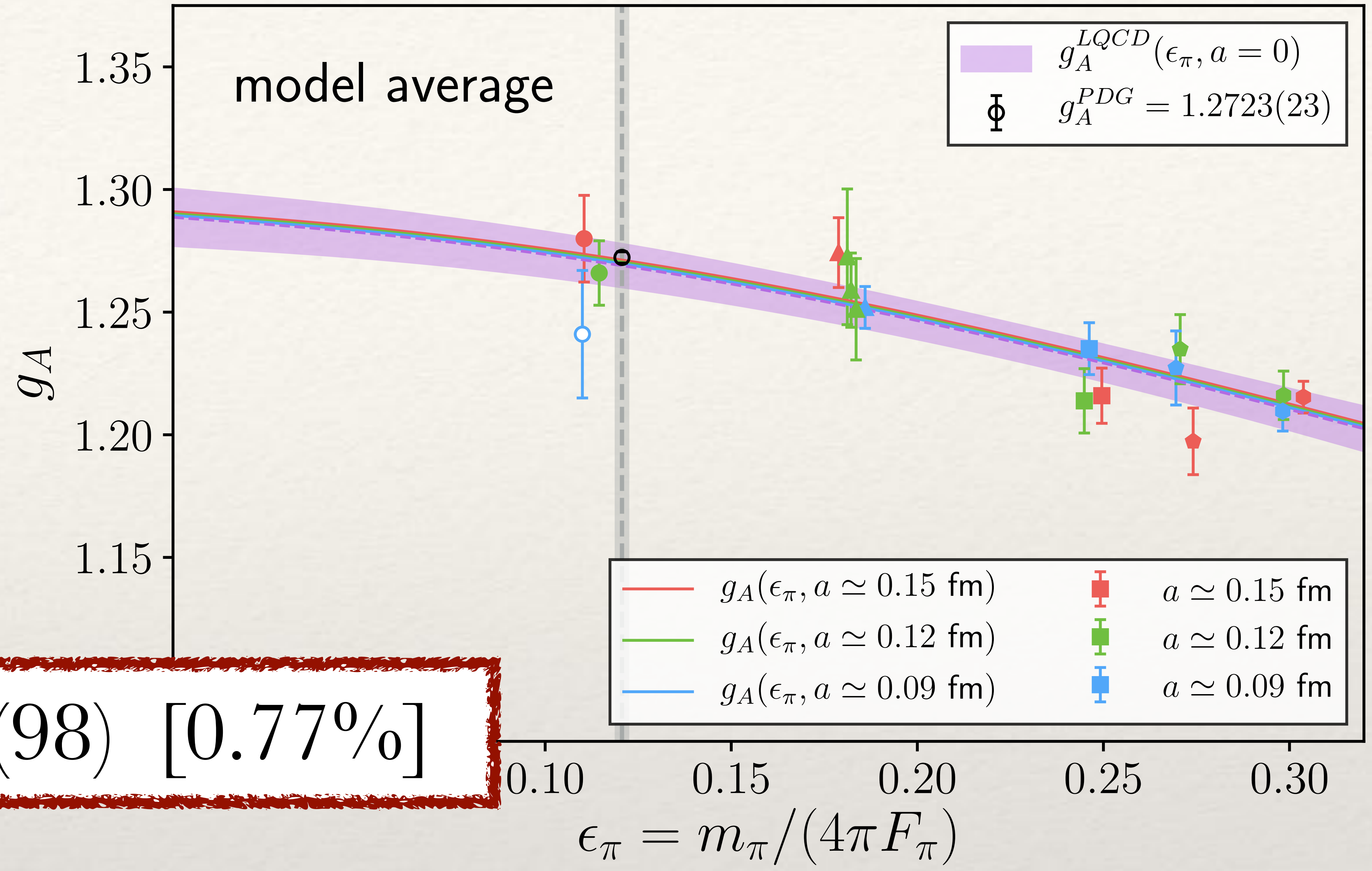

$g_A = 1.2711(125) \rightarrow 1.2690(98)$ [0.77%]

Nature 558 (2018) no. 7708, 91-94 **Sierra Early Science**

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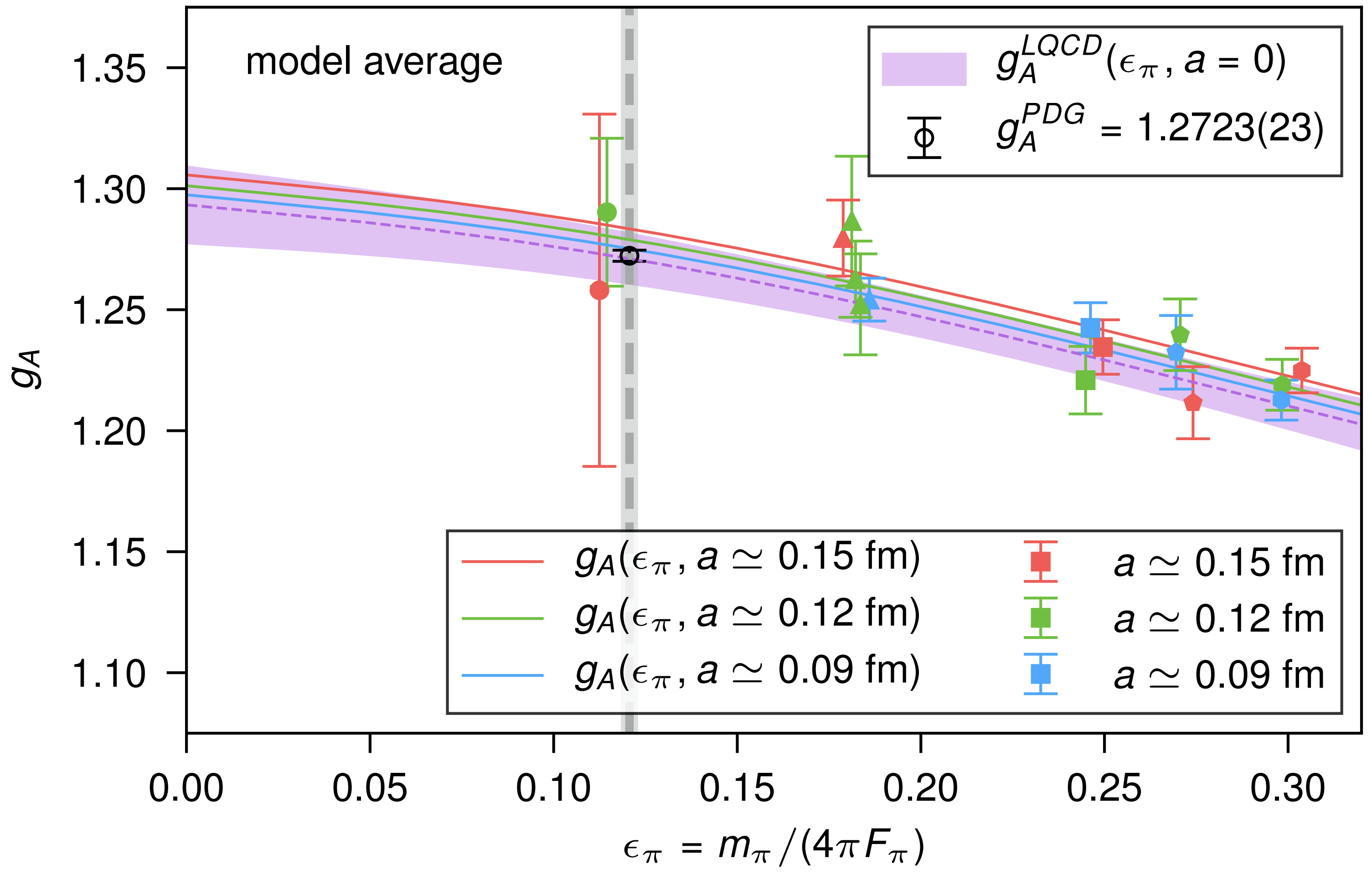
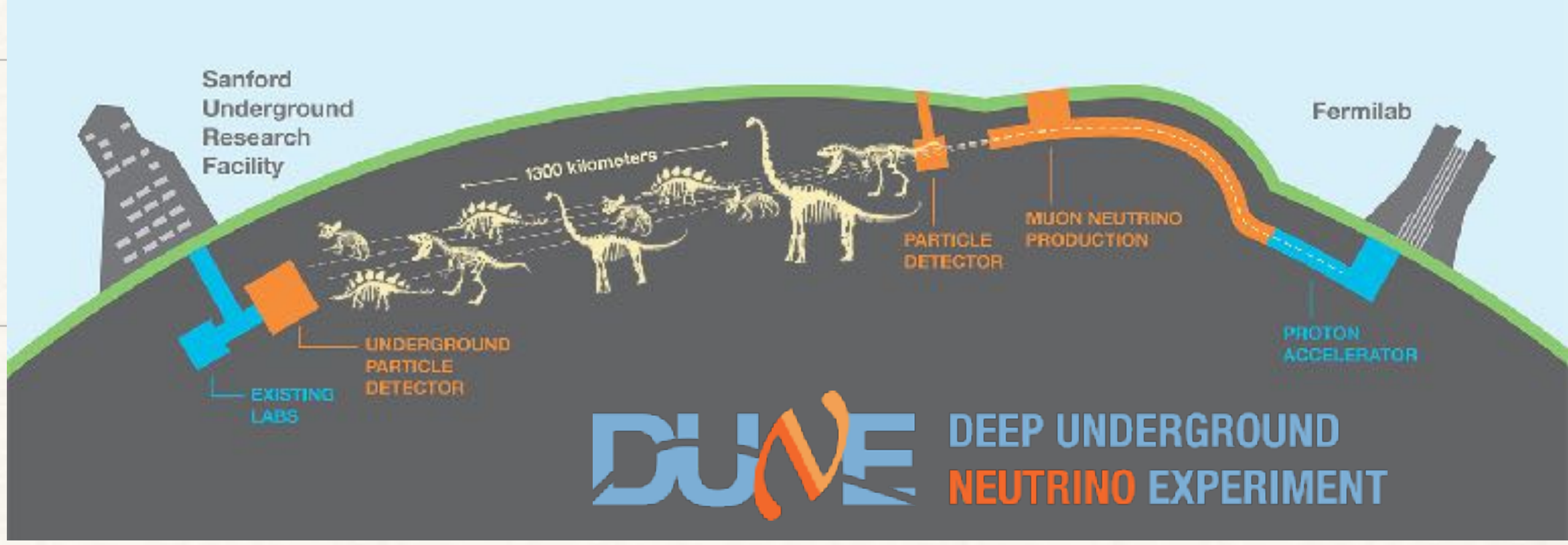


$$g_A^{\mathrm{QCD}} = 1.2711(103)^s(39)^\chi(15)^a(19)^V(04)^I(55)^M$$

How precise can we get g_A?

- Without changing strategy (just 3 lattice spacings), we should be able to get 0.5% by improving the three physical pion mass points - likely this year with our INCITE allocation on Summit at OLCF
- To achieve 0.2% precision, at least a 4th lattice spacing will be required, ideally at two or more pion masses. This can still be achieved with Summit (6 Volta GPUs/IBM Power9 node)
- To convince the broad community of a 0.2% or better uncertainty, we will have to incorporate isospin violating corrections to ensure they behave as expected theoretically - particularly if the neutron lifetime puzzle is still a puzzle (i.e. it is being used to search for new physics)

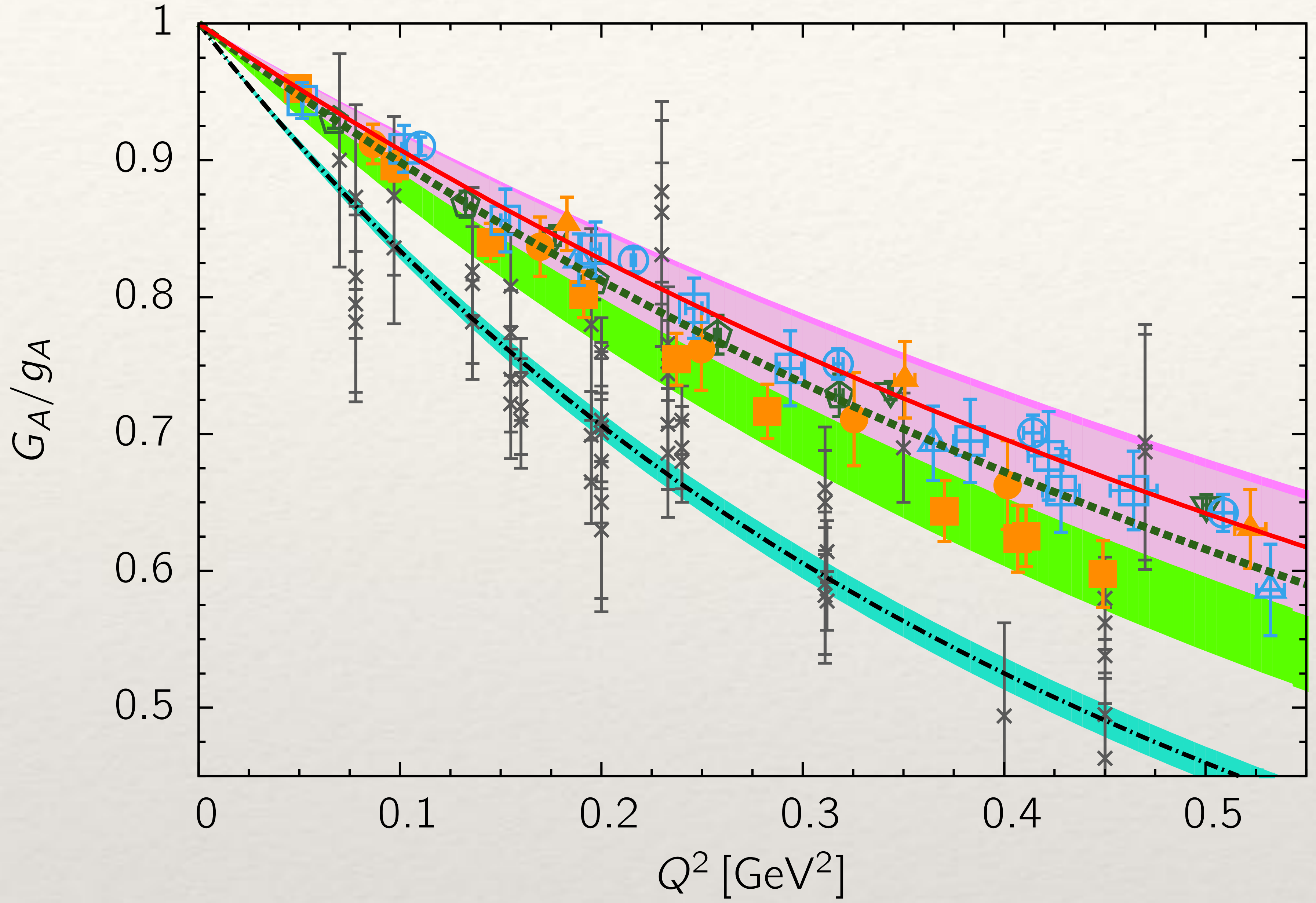
Nucleon Axial FormFactor



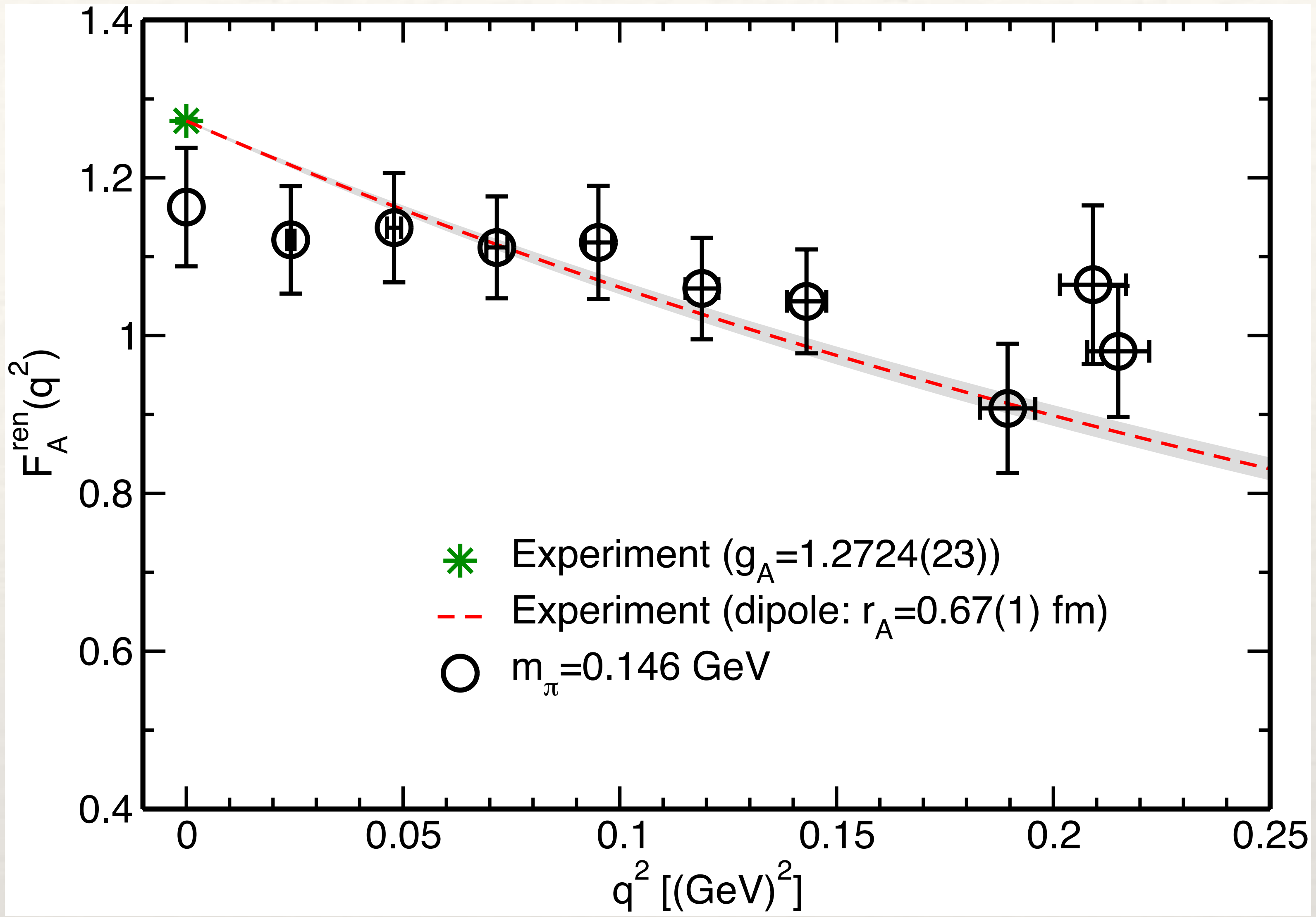
- DUNE is a future neutrino oscillation experiment that will fire a beam of neutrinos from FNAL into an Argonne target in South Dakota.
  - A determination of the CP-violating phase in the neutrino-mixing (PMNS) matrix is one of the goals
  - enough CP violation could explain the matter/anti-matter asymmetry of the universe through Leptogenesis
- The T2K and NOVA experiments are also conducting oscillation experiments
  - "A determination of the nucleon axial form factor at the 5% level would be very helpful, possibly allowing for the isolation of nuclear effects" [private communications with T2K members, Y. Hayato and K. Mcfarland]
- Ultimately, we need to understand neutrino-NUCLEUS cross sections which begins with neutrino-nucleon cross sections
  - The experimental data on $g_A(Q^2)$ is sufficiently limited that a simple dipole-formfactor is assumed
  - The dipole model is too simplistic and overly constraining (the quoted uncertainties do not reflect the true uncertainty of our understanding)

Nucleon Axial FormFactor

Gupta et al. PRD96 (2017) [1705.06834]



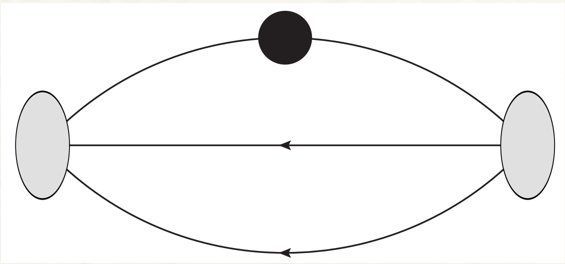
Ishikawa et al. PRD98 (2018) [1807.03974]

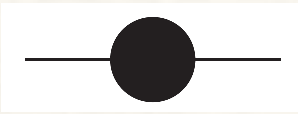


- All lattice QCD results determine an axial form factor with a significantly different slope (30%) than that determined from the phenomenological determination - two recent examples here
- Examining the LQCD results, it is difficult to understand/guess where this discrepancy is coming from
- A few years ago - this was the same situation with g_A (no one understood why gA results were consistently low compared to the experimental value)
- For g_A, we made progress by pushing to the extreme the LQCD calculations - a similar strategy here seems warranted

Nucleon Axial FormFactor

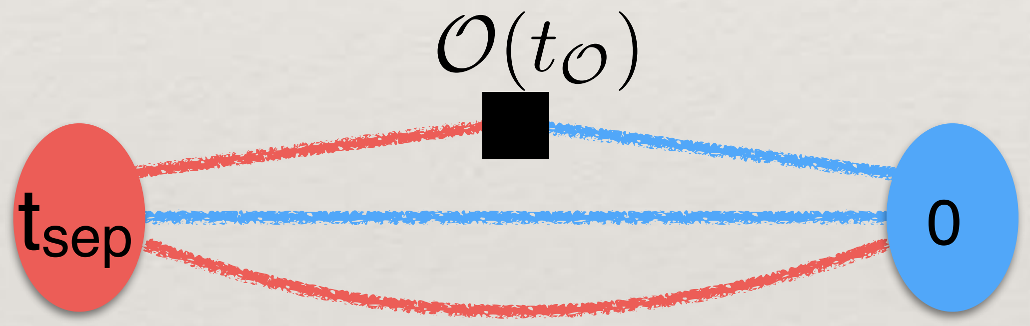
- Inherent to our gA calculation was the "Feynman-Hellmann" Propagator





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

- For each choice of current and momentum, a new FH propagator is required
- We have tried several variants of stochastic methods to relax this constraint, but the noise is too large
- We have resorted to the standard fixed source-sink separation method (with our tail between our legs a little)



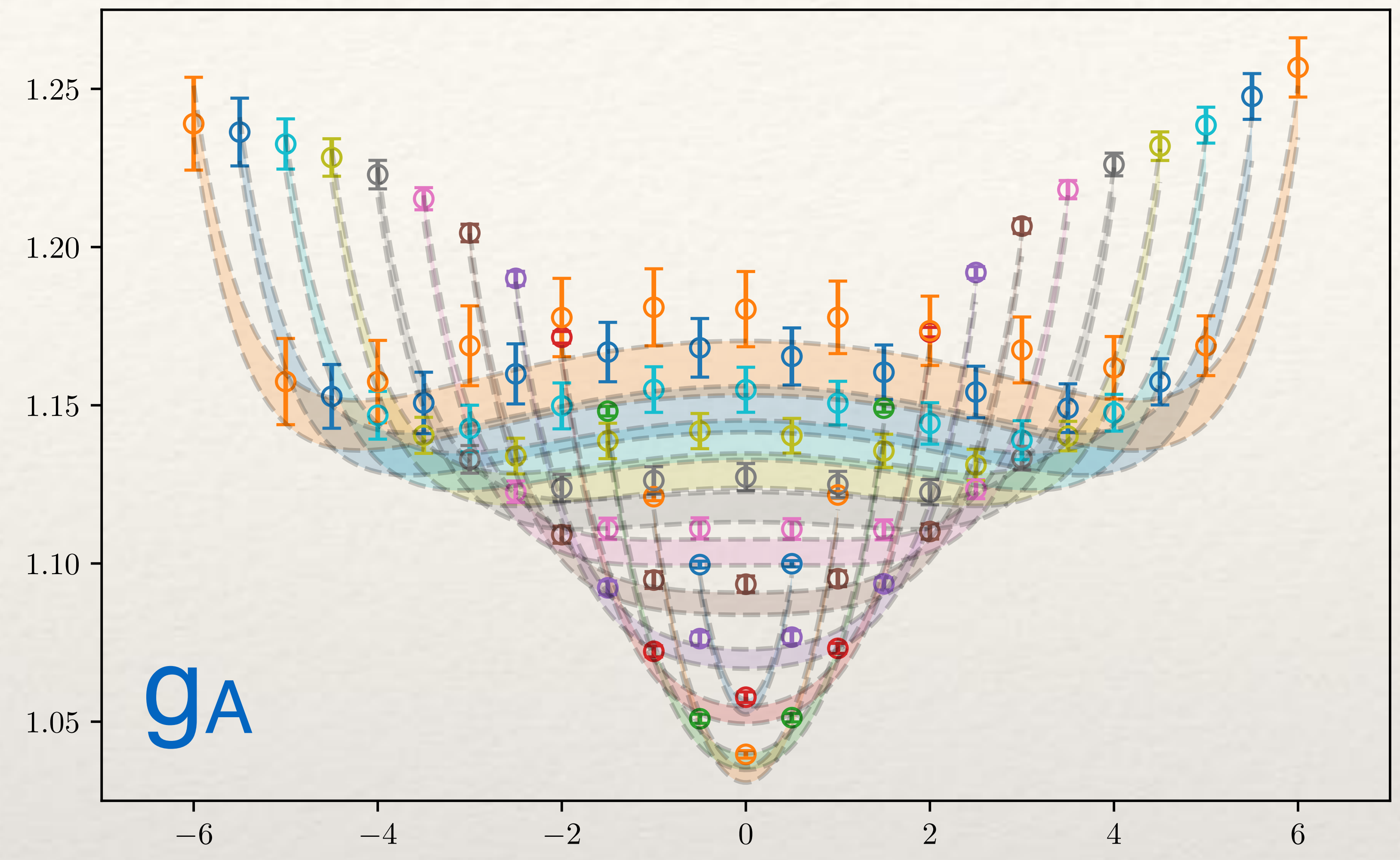
repeat for multiple values of $\mathbf{t_{sep}}$

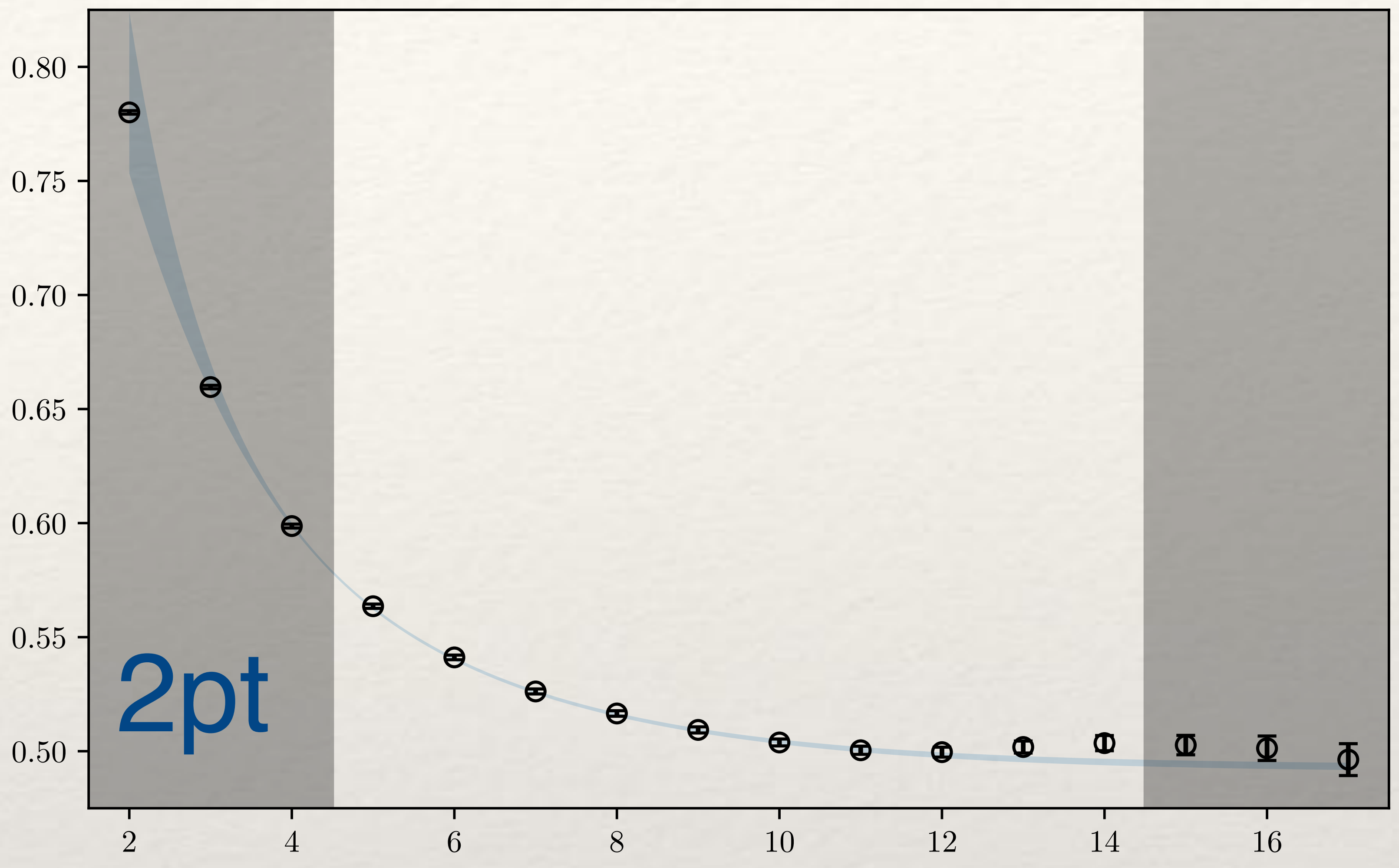
- However, if there was a lesson to be learned from our g_A calculation when applying the fixed source-sink separation method - it is imperative to use many values of $\mathbf{t_{sep}}$ and also small values
  - See also S. Meinel, Chiral Dynamics 2012 and Hasan et al. (LHPC) 1903.06487

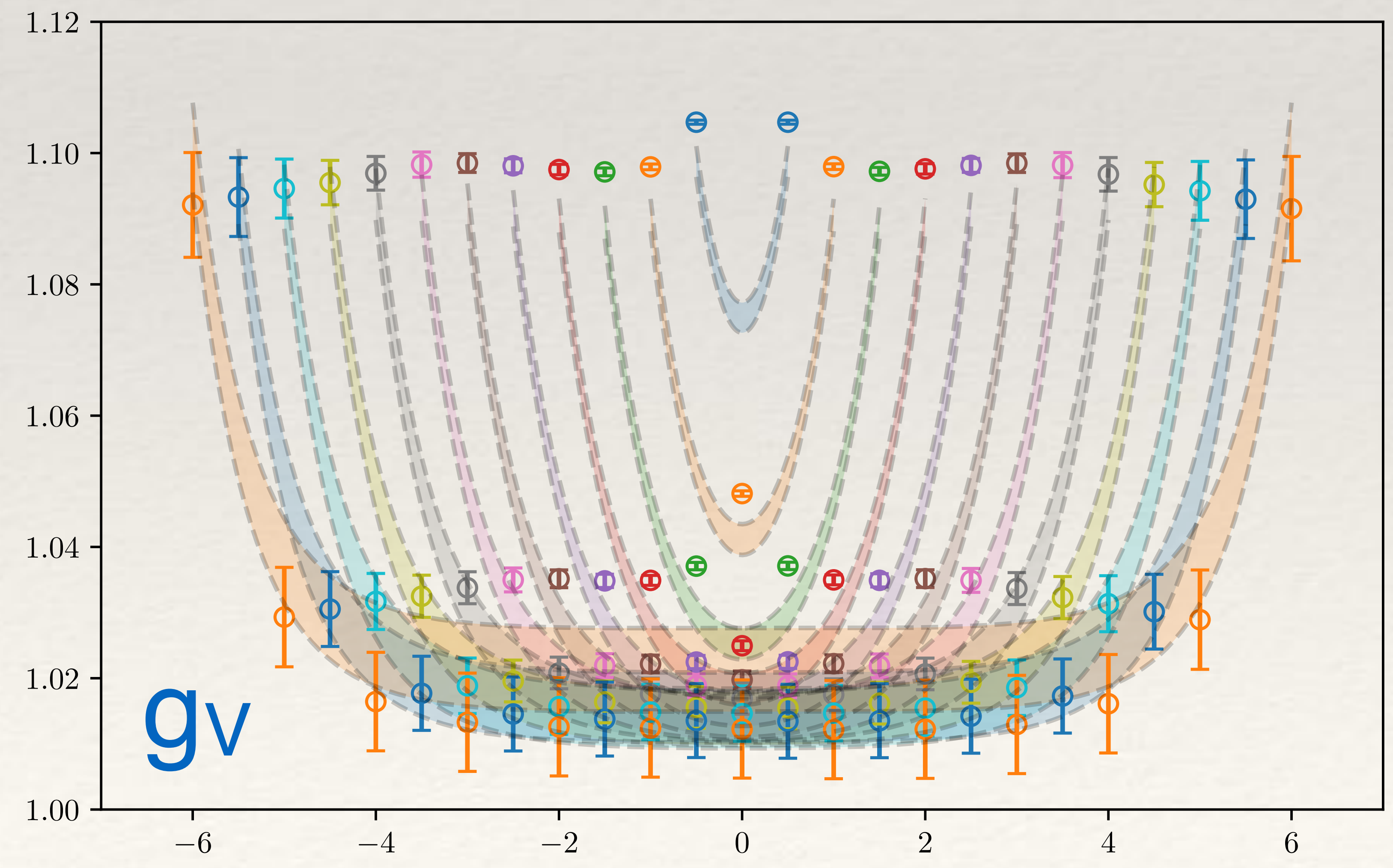
Nucleon Axial FormFactor PRELIMINARY

a09m310

t_{sep} = [3,4,5,6,7,8,9,10,11,12,13,14]







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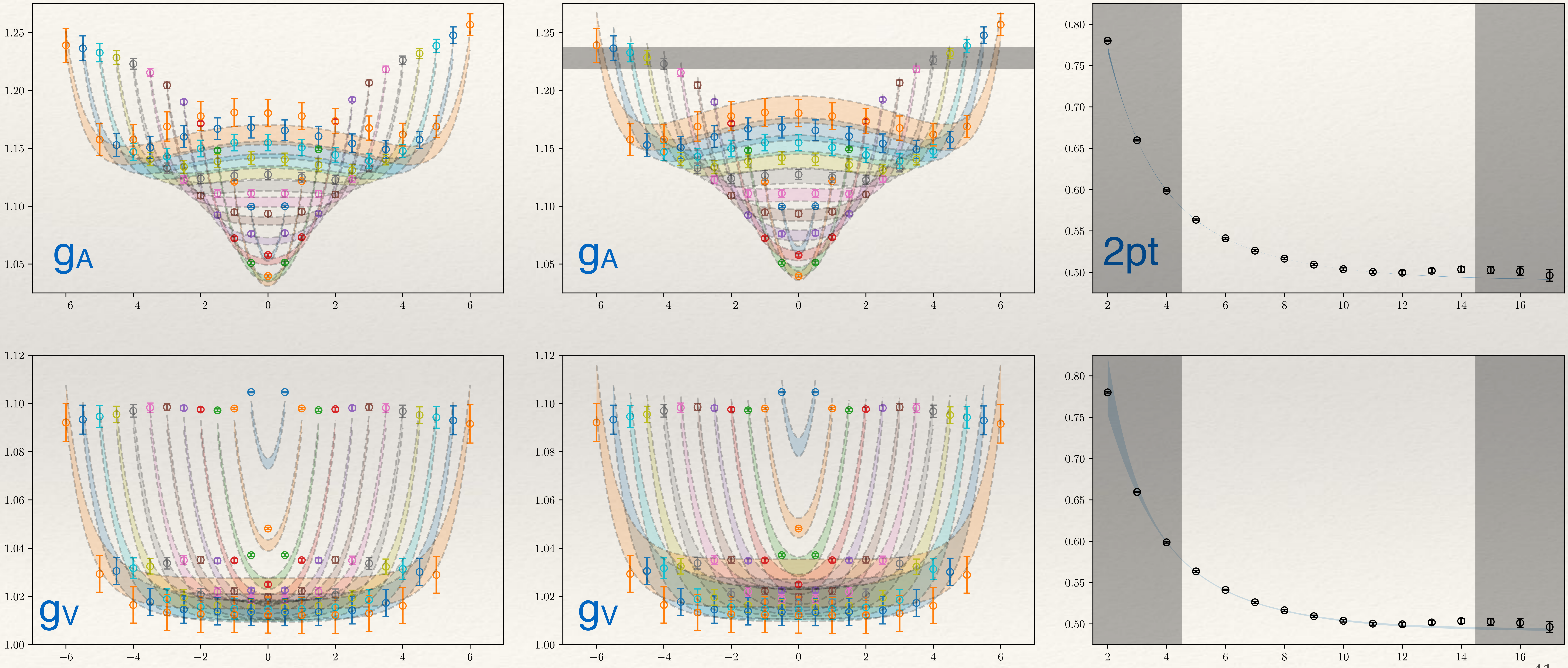

LETTER
https://doi.org/10.1038/s41586-018-0161-8
arXiv:1805.12130
Nature 558 (2018) no.7708, 91-94
https://github.com/callat-qcd/project_gA

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

- The success of this result was enabled through several key features:
  - an unconventional strategy that can exploit **exponentially more precise data** at early time and has **demonstrable control of excited state** contributions
  - access to a set of ensembles (HISQ 2+1+1 from **MILC**) that allowed for control over all standard lattice systematics,
  - ***ludicrously fast*** GPU code - QUDA
  - an action with **improved stochastic behavior** and a **mild continuum** extrapolation $m_\pi \to m_\pi^{phys}, a \to 0, L \to \infty$
  - access to Leadership Computing

- Making progress in understanding $g_A(Q^2)$ - it seems essential to have enough $\mathbf{t_{sep}}$ values to control the infinite separation extrapolation - more than is common

LETTER

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Lattice QCD Team

(postdoc, grad student)

plus a few friends

Chia Cheng (Jason) Chang	LBNL, RIKEN-iTHEMS
Amy Nicholson	Berkeley —> UNC, Chapel Hill
Enrico Rinaldi	RIKEN-BNL
Evan Berkowitz	Forschungszentrum Jülich
Nicolas Garron	Liverpool
David Brantley	W&M, LBNL —> LLNL
Henry Monge-Camacho	W&M, LBNL —> UNC
Chris Monahan	INT —> W&M
Chris Bouchard	Glasgow
Kate Clark	NVIDIA
Bálint Joó	JLab
Thorsten Kurth	NERSC, LBNL
Kostas Orginos	W&M, JLab
Pavlos Vranas	LLNL
André Walker-Loud	LBNL

New characters

Chris Koerber

Ben Hörz

Arjun Gambhir

Ken McElvain

Bart van Lith
E. Berkowitz

DOE Topical Collaboration
Double Beta Decay

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Kate Clark	NVIDIA
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Thank You

Bart van Lith
E. Berkowitz

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