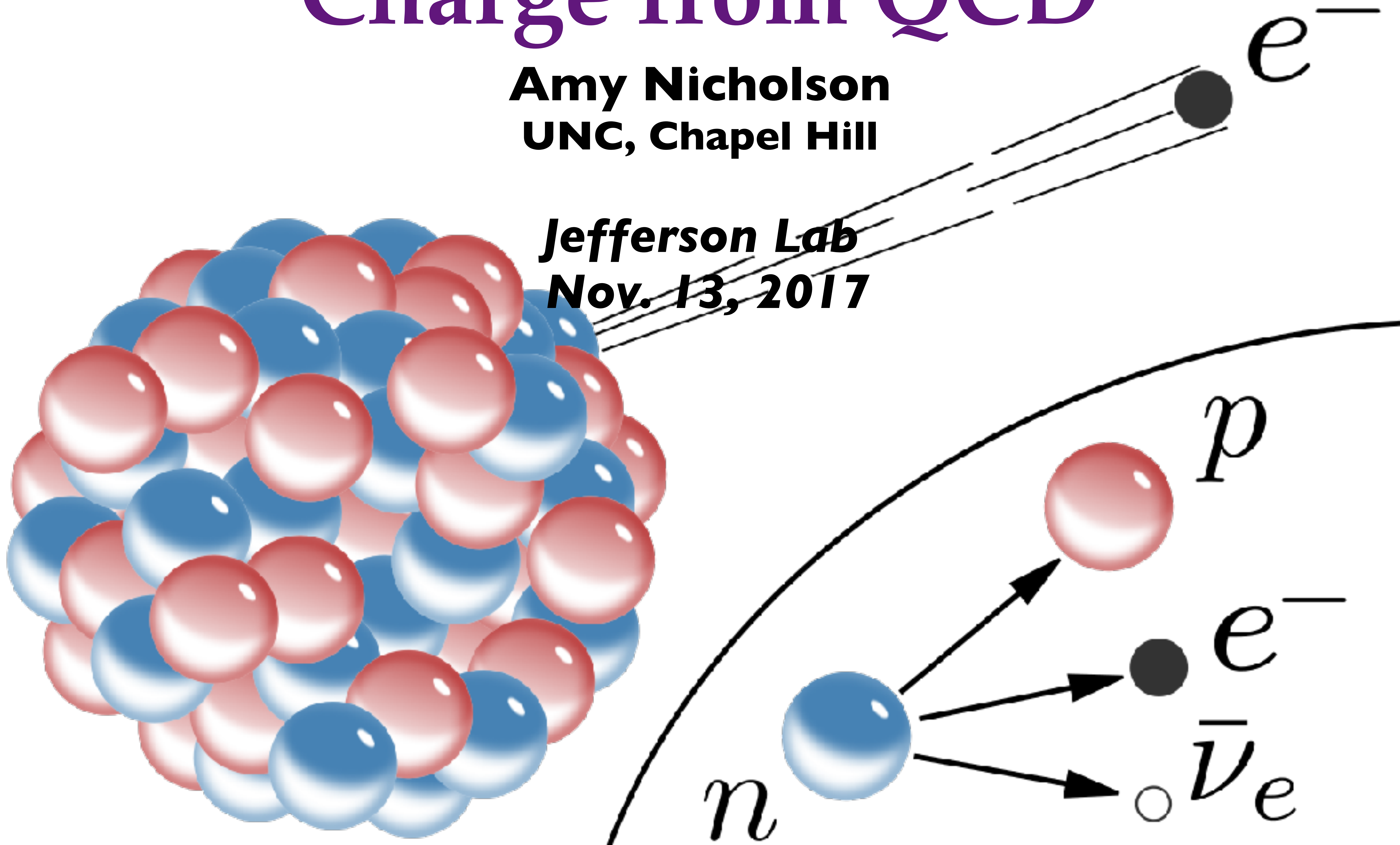
The Nucleon Axial Charge from QCD

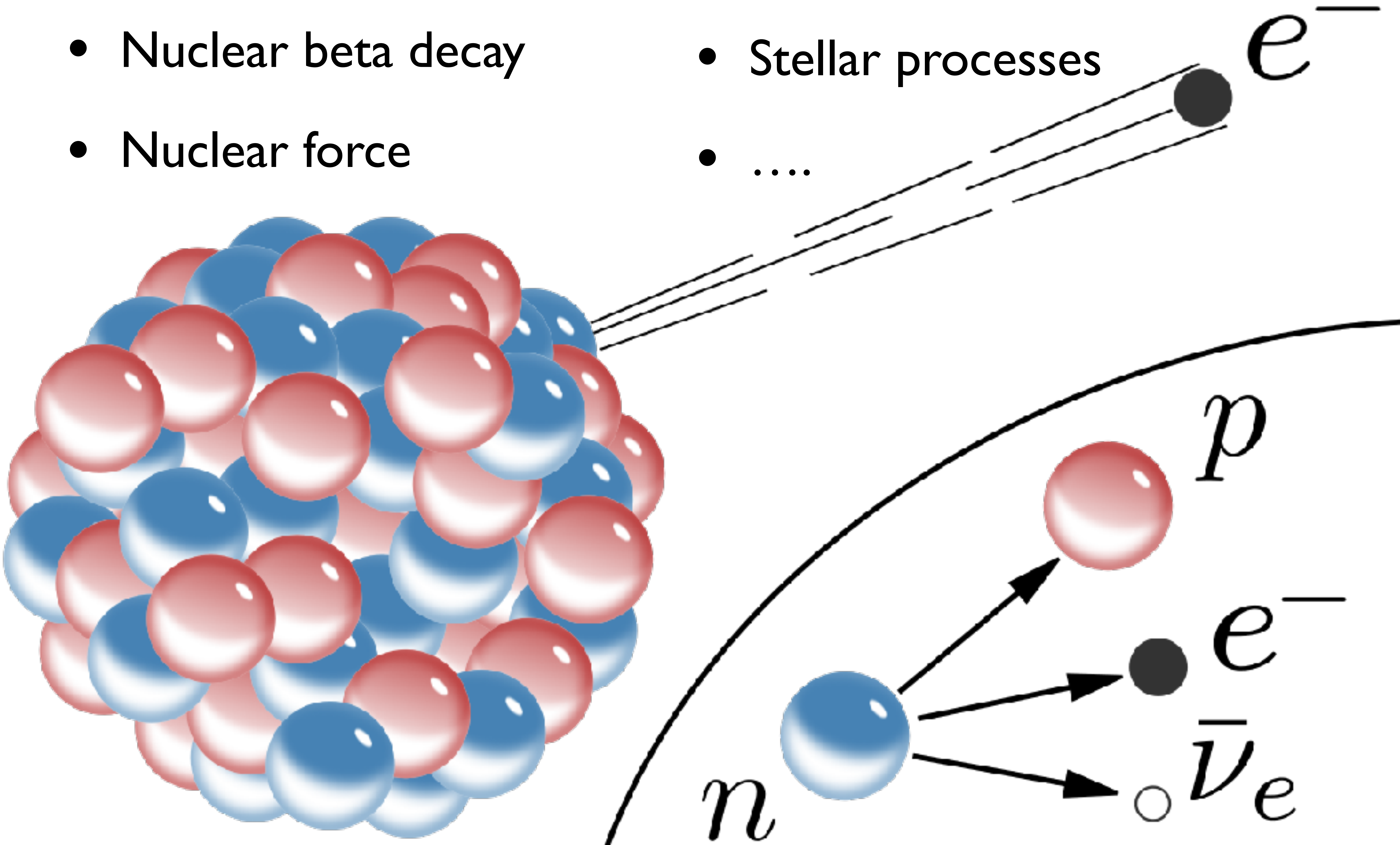
Amy Nicholson
UNC, Chapel Hill

Jefferson Lab
Nov. 13, 2017



What depends on g_A?

- Free neutron lifetime
- Nuclear beta decay
- Nuclear force
- Big Bang nucleosynthesis
- Stellar processes
- ....



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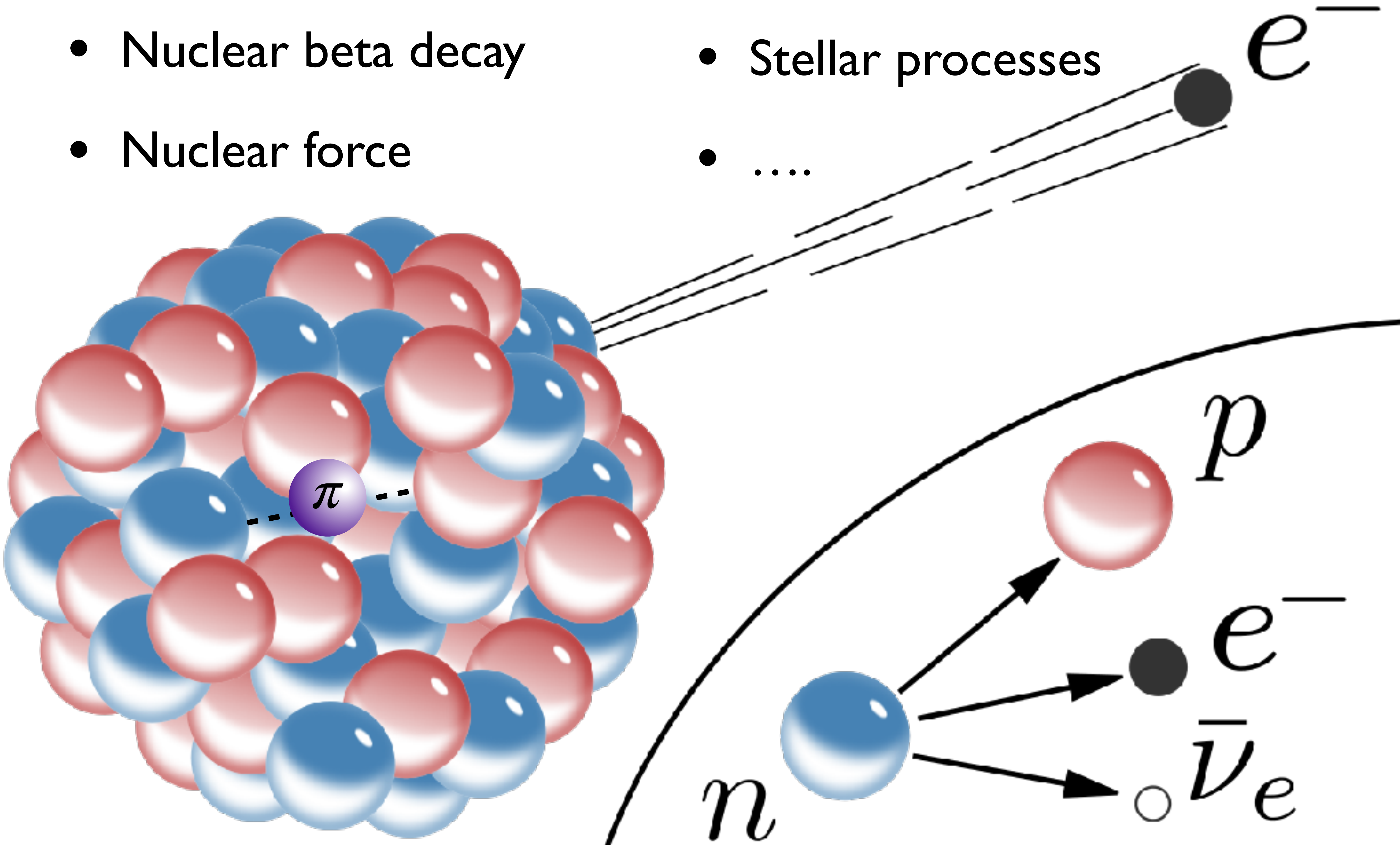

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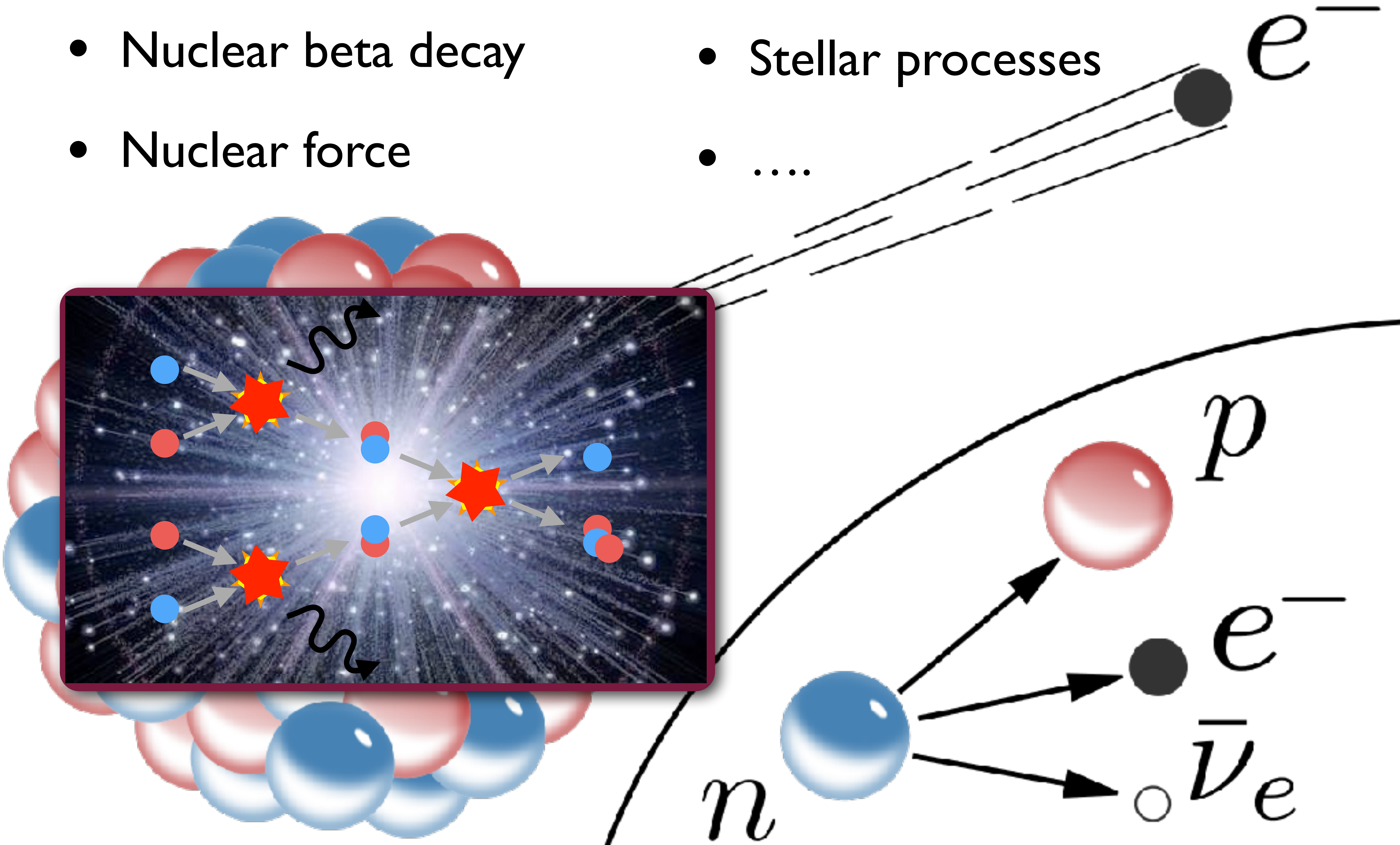

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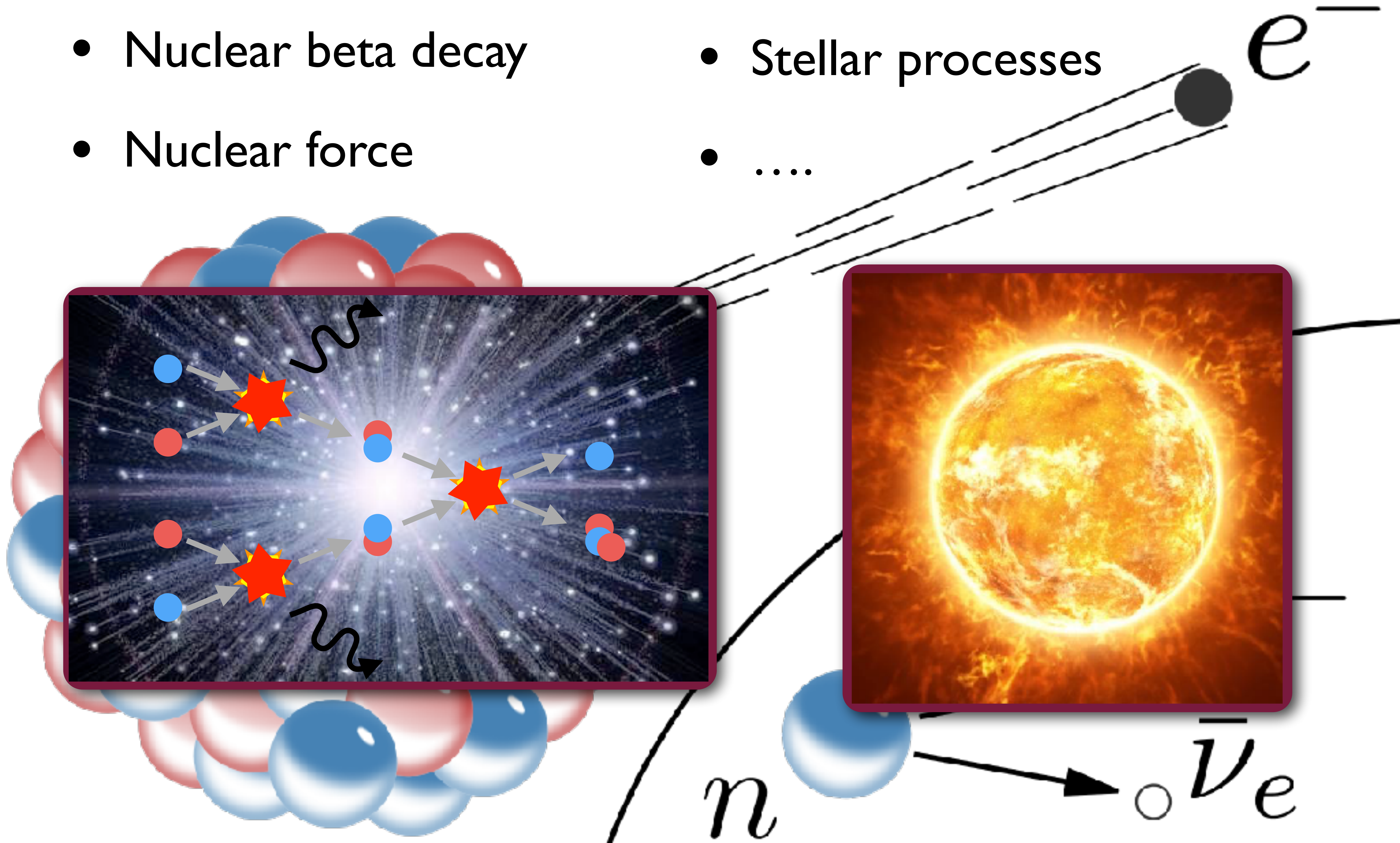
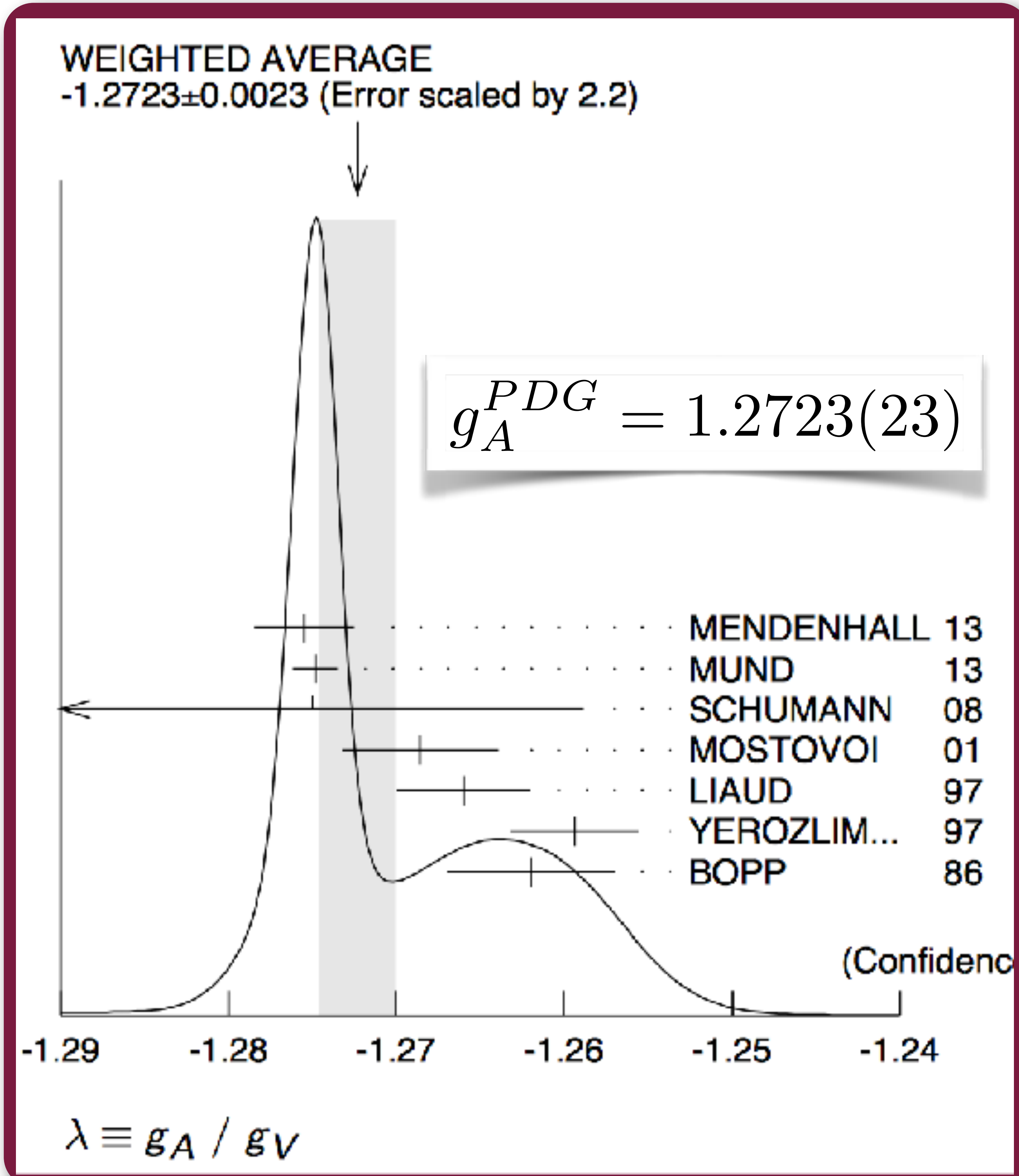
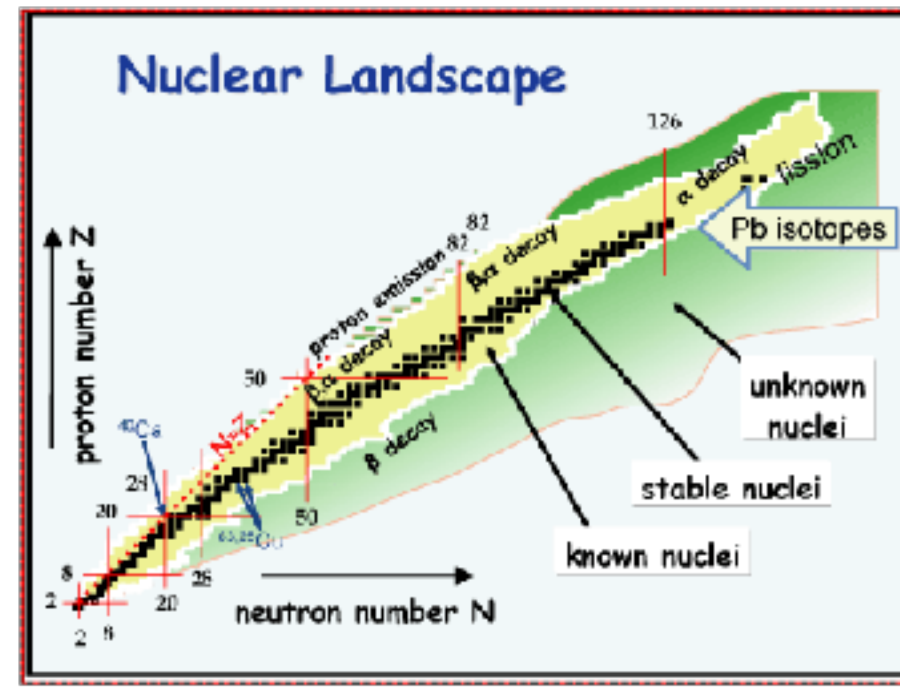


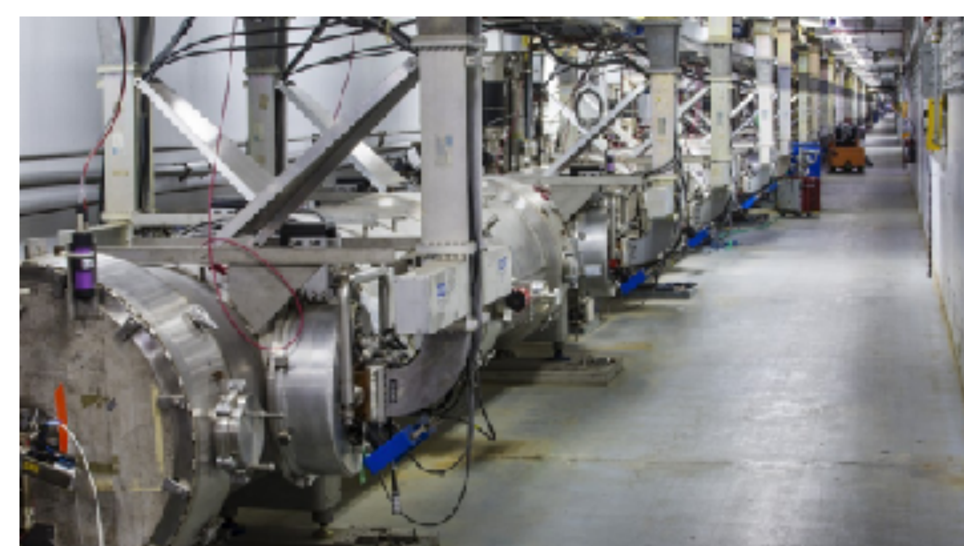
Very well measured experimentally



Why calculate g_A from LQCD?

- Look for new physics
- g_A quenching/axial form factors
  - neutrinoless double beta decay, long baseline neutrino exps
- Build quantitative connection between QCD & nuclear physics
  - requires interplay between LQCD & many-body approaches
  - some quantities difficult to measure experimentally: NNN, YN, ….
  - g_A should be a benchmark
    - one of the simplest hadron structure matrix elements





Why calcul

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    - one of
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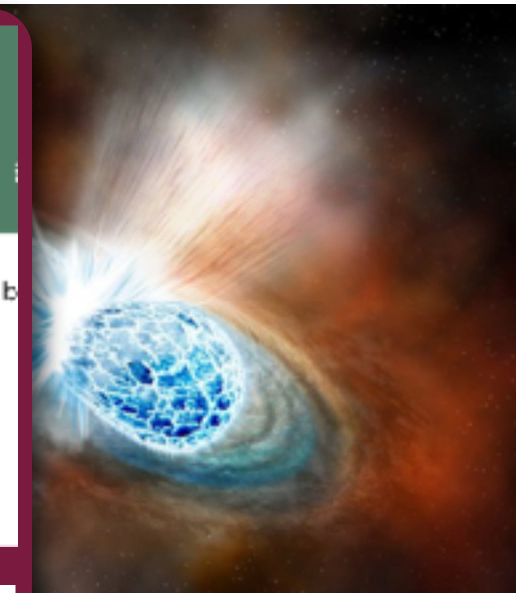
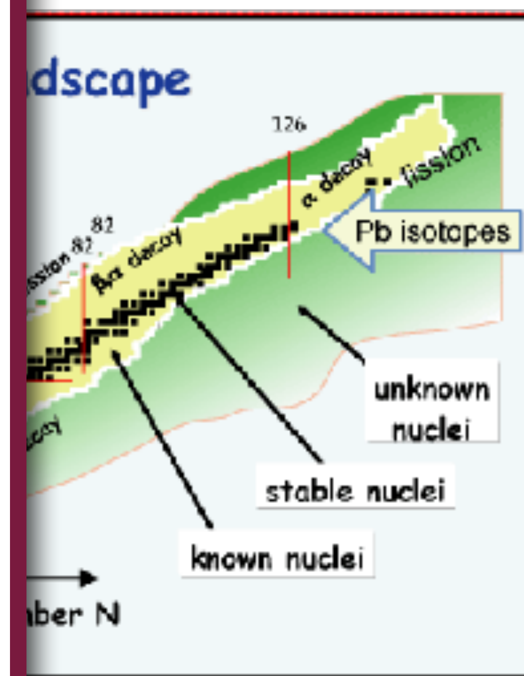
Nucleon Axial Charge in Full Lattice QCD

R. G. Edwards, G. T. Fleming, Ph. Hägler, J. W. Negele, K. Orginos, A. V. Pochinsky, D. B. Renner, D. G. Richards, and W. Schroers (LHPC Collaboration)

Phys. Rev. Lett. **96**, 052001 – Published 7 February 2006

The axial charge is the ideal starting point in the quest for precision lattice calculation of hadron structure for several reasons. It is accurately measured experimentally and the isovector combination $\langle 1 \rangle_{\Delta u} - \langle 1 \rangle_{\Delta d}$ has no contributions from disconnected diagrams, which are much more computationally demanding than the connected diagrams considered in this work. The functional dependence on both m_π^2 and volume is known at small masses from chiral perturbation theory (χPT) [5,6] and renormalization of the lattice axial vector current can be performed accurately nonperturbatively using the five-dimensional conserved current for domain wall fermions. Thus, conceptually, it is a "gold plated" test of our ability to calculate hadron observables from first principles on the lattice. In addition, since it is known to be particularly sensitive to finite lattice volume effects that reduce the contributions of the pion cloud [7,8], it is also a stringent test of our control of finite volume artifacts.





Precision era for LQCD

Neutron-proton mass difference: accurate to 300 KeV (BMW Collaboration 2015)

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REPORT

Ab initio calculation of the neutron-proton mass difference

Sz. Borsanyi[1], S. Durr[1,2], Z. Fodor[1,2,3,*], C. Hoelbling[1], S. D. Katz[3,4], S. Krieg[1,2], L. Lellouch[5], T. Lippert[1,2], A. Portelli[5,6], K. K. Szabo[1,2], B. C. Toth[1]

[1]Department of Physics, University of Wuppertal, D-42119 Wuppertal, Germany.
[2]Jülich Supercomputing Centre, Forschungszentrum Jülich, D-52428 Jülich, Germany.
[3]Institute for Theoretical Physics, Eötvös University, H-1117 Budapest, Hungary.
[4]Lendület Lattice Gauge Theory Research Group, Magyar Tudományos Akadémia–Eötvös Loránd University, H-1117 Budapest, Hungary.
[5]CNRS, Aix Marseille Université, Université de Toulon, CPT UMR 7332, F-13288, Marseille, France.
[6]School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK.
*Corresponding author. E-mail: fodor@bodri.elte.hu

Science 27 Mar 2015:
Vol. 347, Issue 6229, pp. 1452-1455
DOI: 10.1126/science.1257050

Precision era for Nuclear Physics from LQCD?

g_A^{exp} = 1.2723(23)
g_A^{lat} = 1.195(33)(20)

PHYSICAL REVIEW D

PNDME, Nov. 2016

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Axial, scalar, and tensor charges of the nucleon from 2 + 1 + 1-flavor Lattice QCD

Tanmoy Bhattacharya, Vincenzo Cirigliano, Saul D. Cohen, Rajan Gupta, Huey-Wen Lin, and Boram Yoon
(Precision Neutron Decay Matrix Elements (PNDME) Collaboration)
Phys. Rev. D **94**, 054508 – Published 19 September 2016

rors contribute and to reduce the overall uncertainty to $O(2\%)$ will require at least $O(200,000)$ measurements on the seven ensembles at different a and M_π used in this study and the analysis of one additional ensemble at $a = 0.06$ fm and $M_\pi = 135$ MeV. Increasing the statistics by a factor of four will reduce the errors in the data with the largest t_{sep} we have analyzed and thus improve the $t_{sep} \to \infty$ estimates. Adding the point at the physical quark mass and the smallest lattice spacing $a = 0.06$ fm, will further constrain the chiral fit. This level of precision is achievable with the next generation of leadership-class computing resources.

Challenges

- Matrix elements are more difficult
- Nucleon noise/sign problem
  signal/noise ~ $e^{-A(m_N - 3/2 m_\pi)t}$
- Need to carefully control systematics:
  - Pion mass extrapolation
  - Discretization
  - Finite volume
  - Excited state contamination
  - All can be masked by noise!

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  Most calculations done at unphysically heavy quark (pion) masses - need theory to extrapolate in m_π

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Need new theoretical tools

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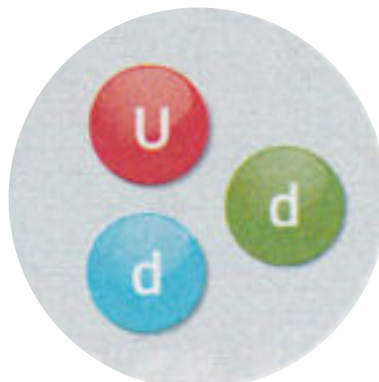
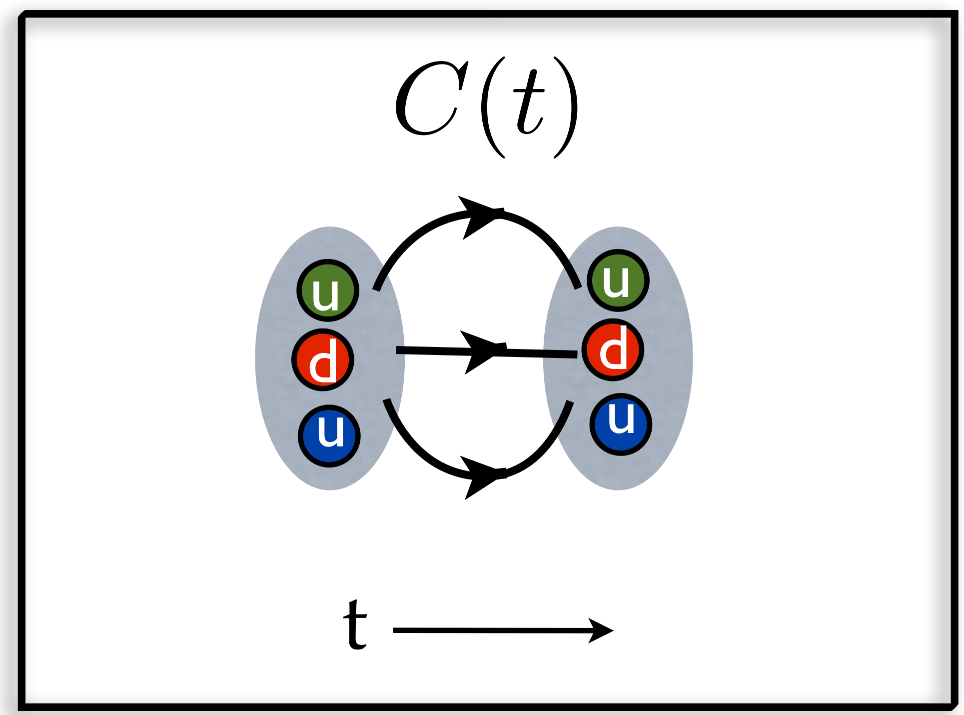
Improvements

- New calculation technique based on Feynman-Hellman theorem
  - easier to analyze (improved systematics)
  - lower computational cost
  - can be reused for matrix elements between different states (g_A quenching)
- New mixed action: DWF on HISQ
  - smaller discretization effects, better chiral symmetry
  - gradient flow: improved statistics

Calculating Observables

$\mathcal{O}$:





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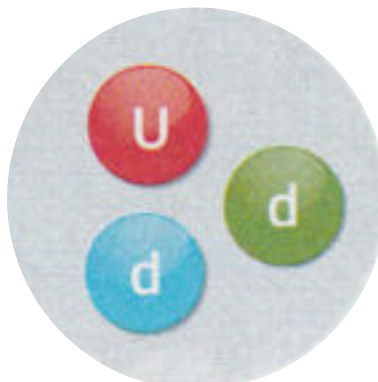
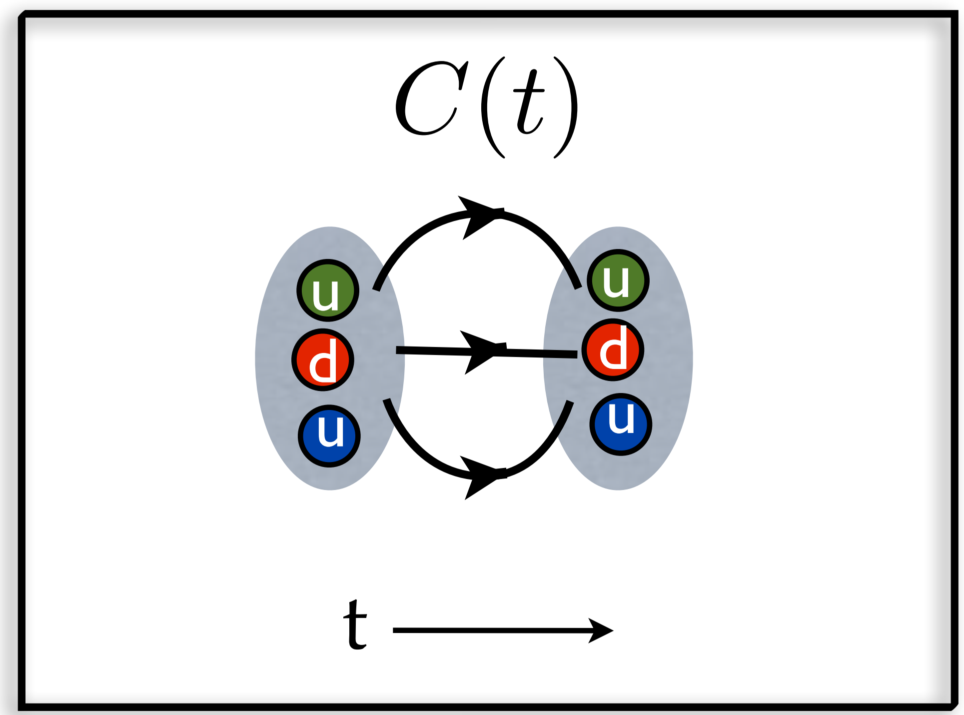


$\langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle$



Calculating Observables

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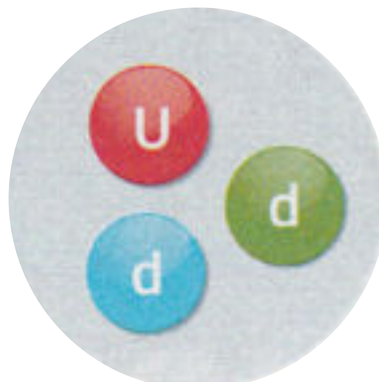
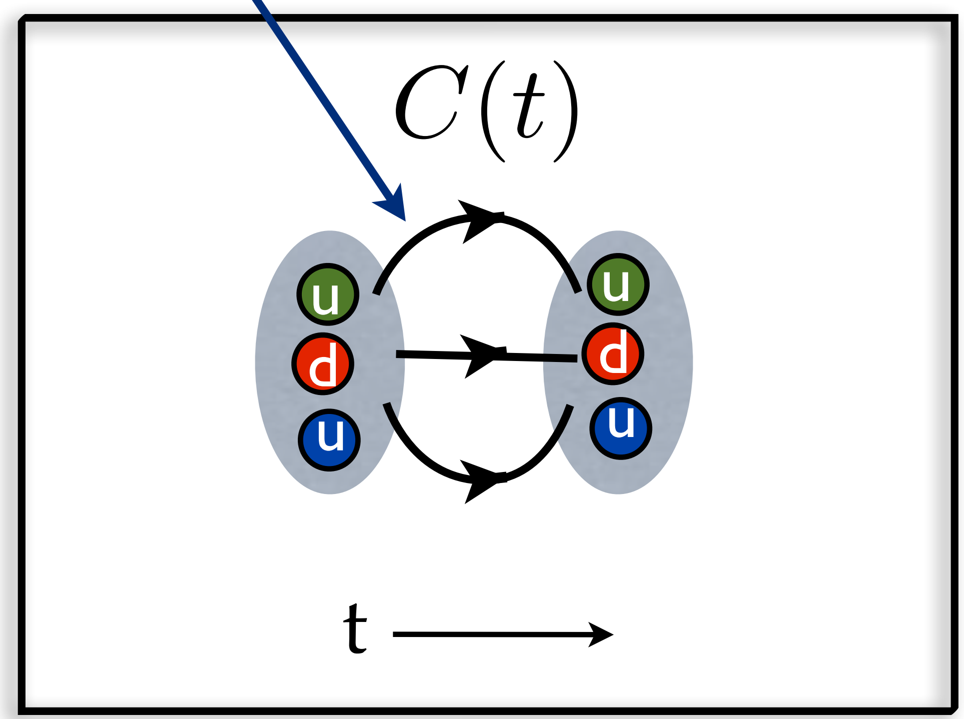


$$\langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \langle \mathcal{O}(0)e^{-Ht}\mathcal{O}(0)\rangle$$

(Euclidean) Time evolution



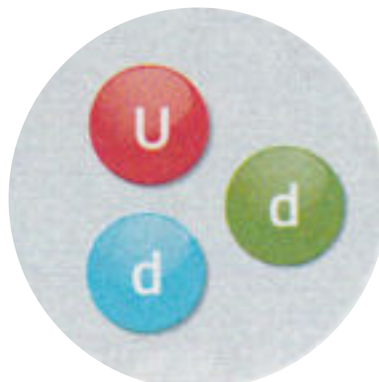
Calculating Observables

$$\langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \langle \mathcal{O}(0)e^{-Ht}\mathcal{O}(0)\rangle = \sum_n |\langle 0|\mathcal{O}|n\rangle|^2 e^{-E_n t}$$

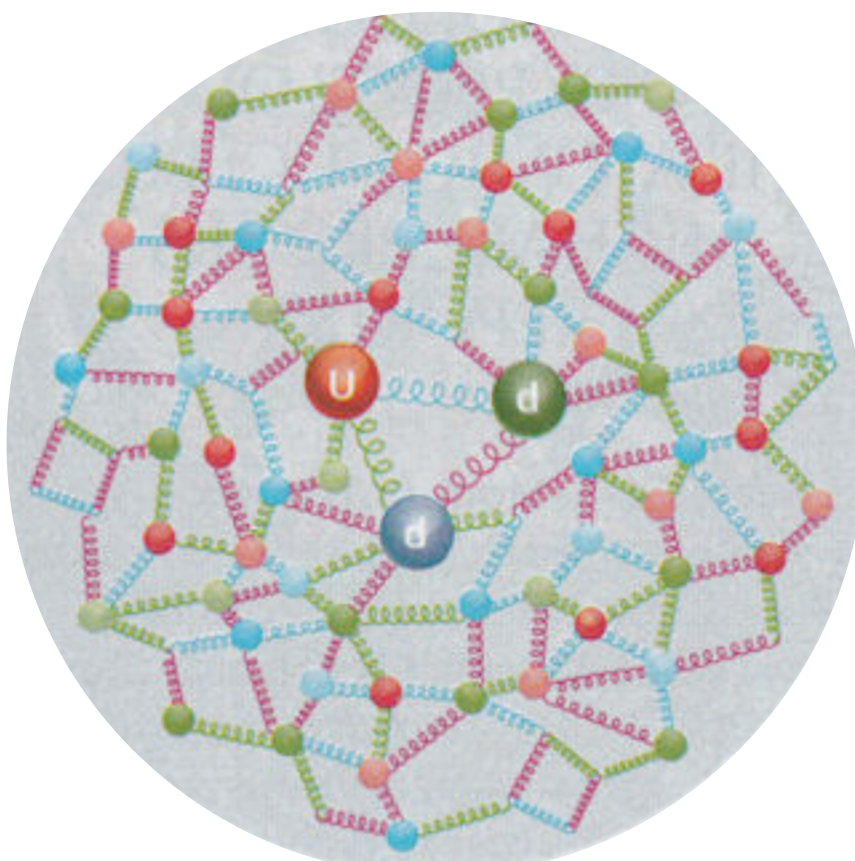
(Euclidean) Time evolution

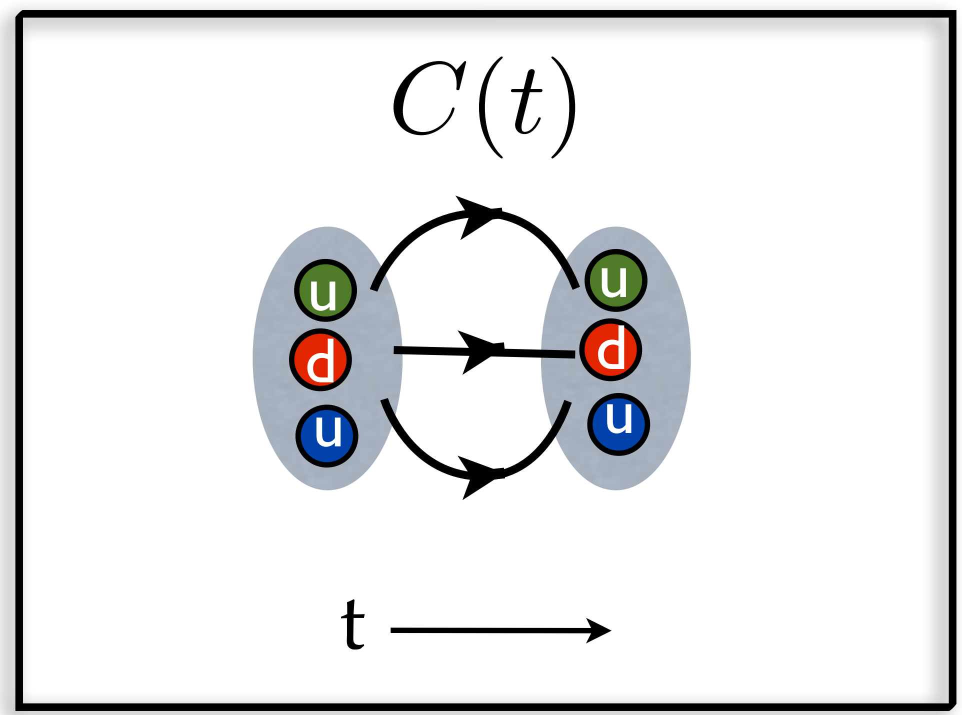
Complete set of states

$\mathcal{O}$:



ψ_n :





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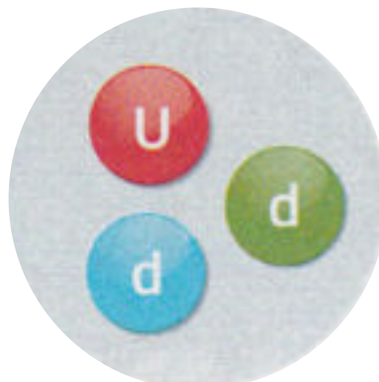
Like a Boltzmann factor

$\mathcal{O}$:



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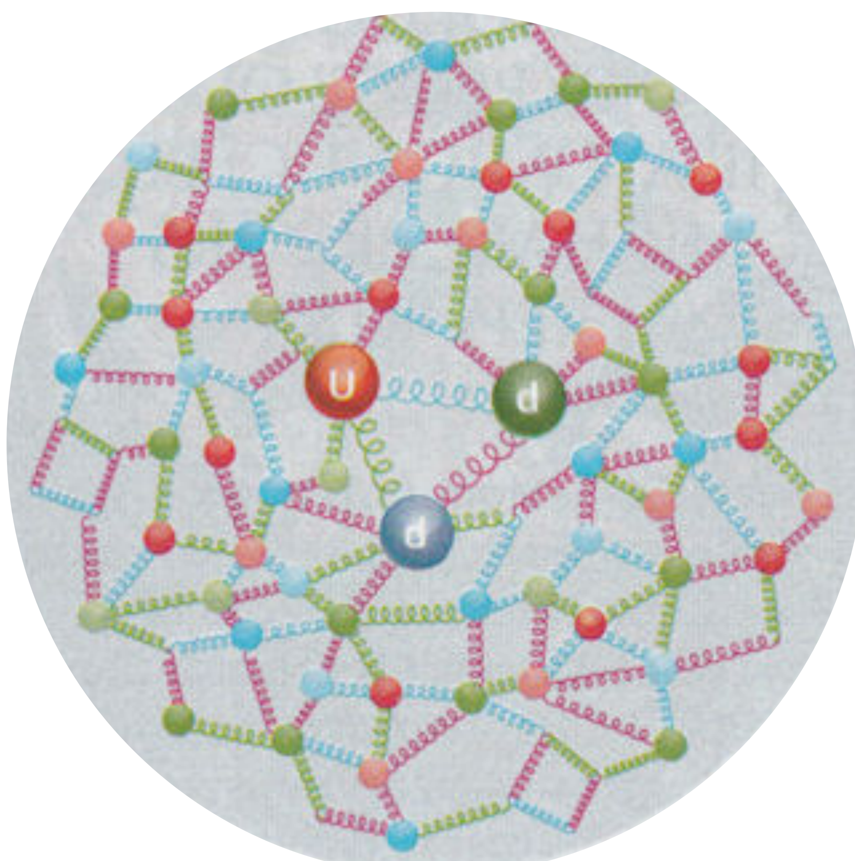

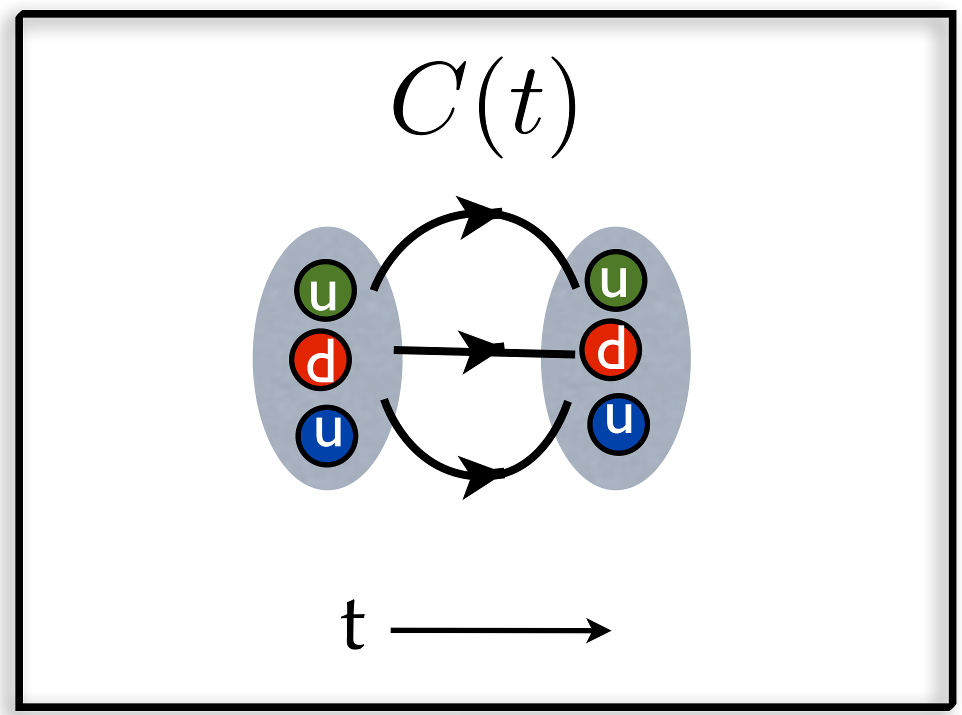

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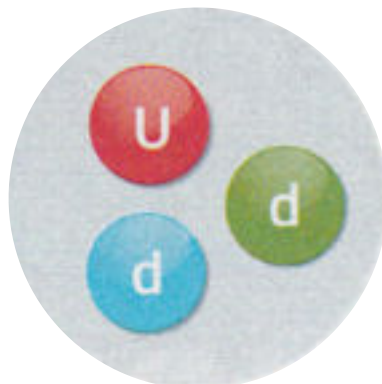

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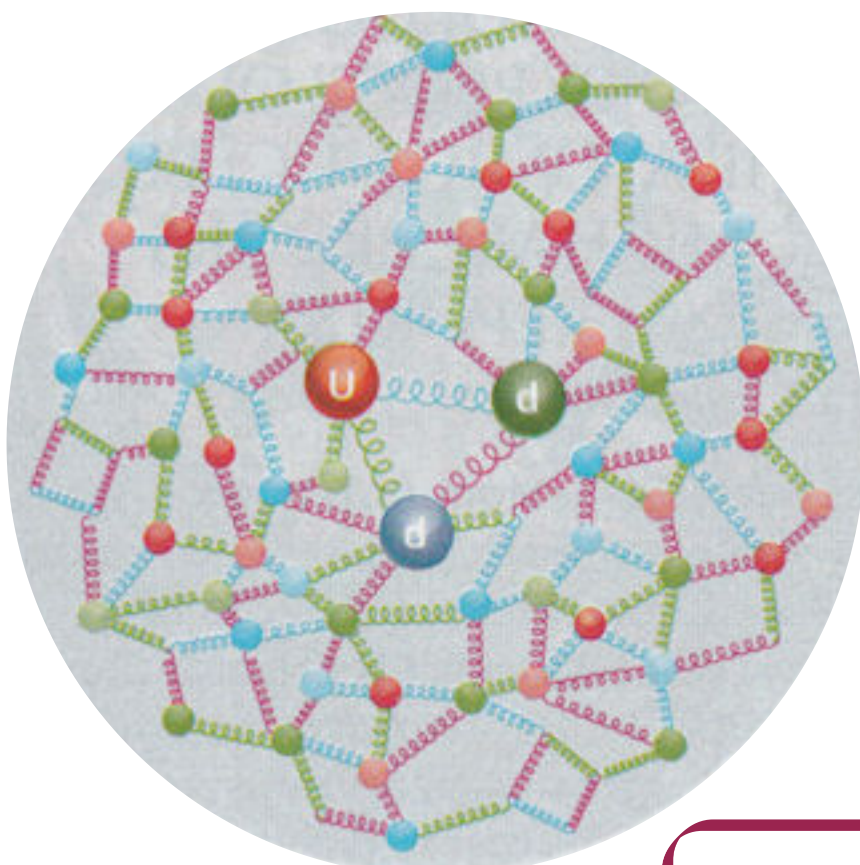

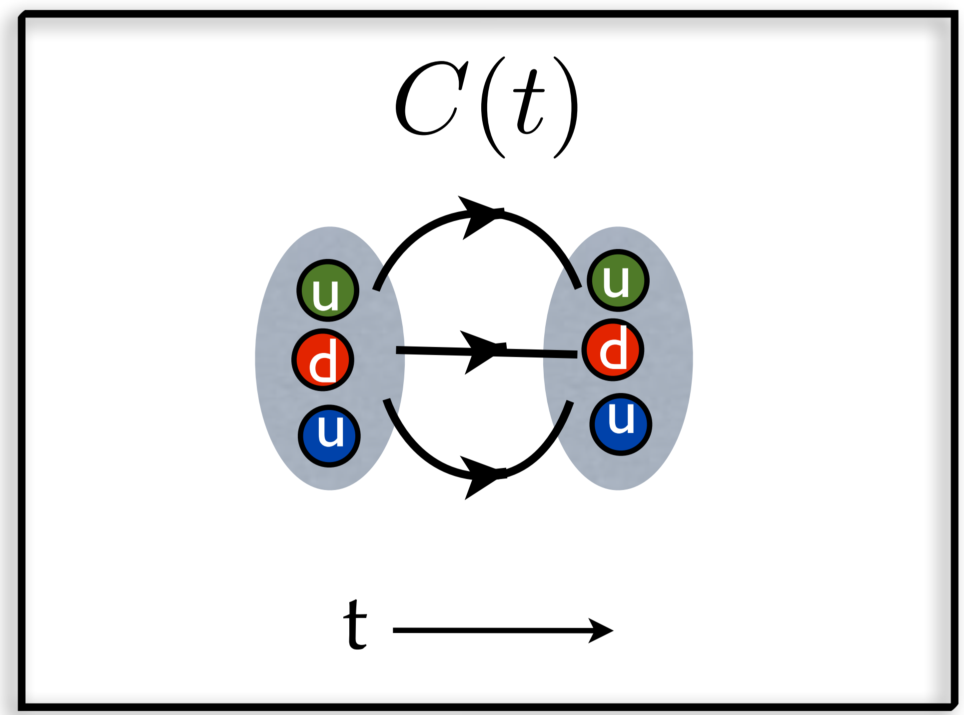

$$C(t) = A_0 e^{-E_0 t} + A_1 e^{-E_1 t} + A_2 e^{-E_2 t} + A_3 e^{-E_3 t} + \cdots$$

Calculating Observables

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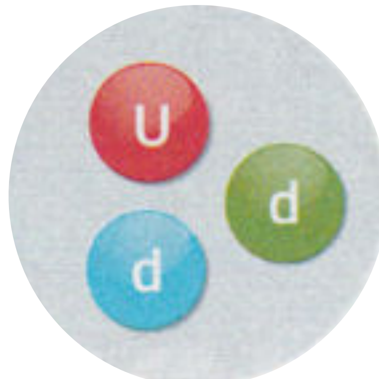

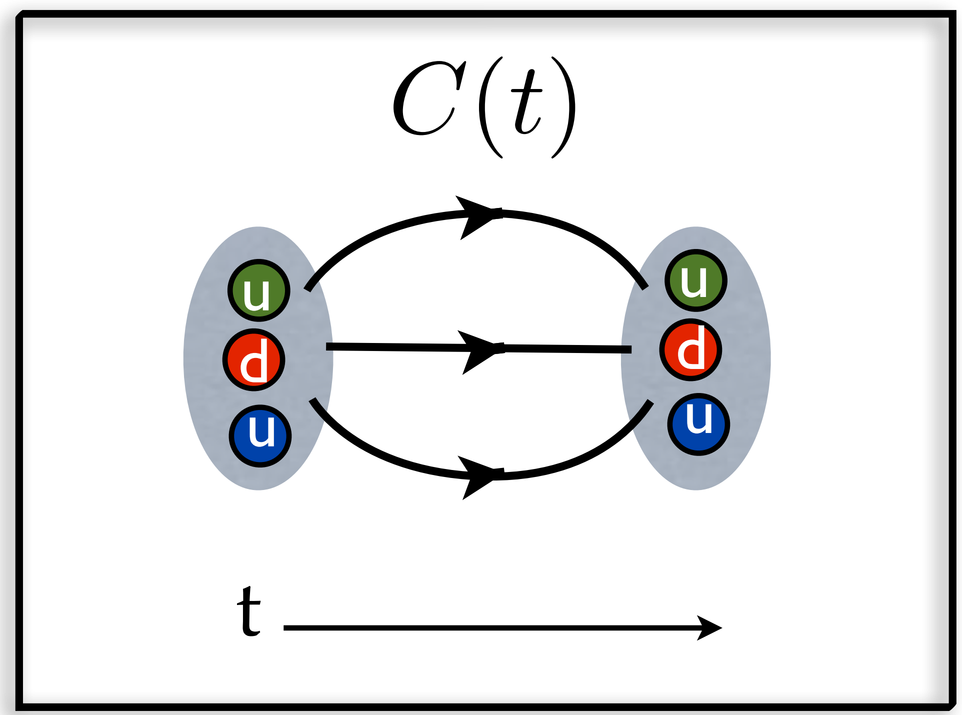

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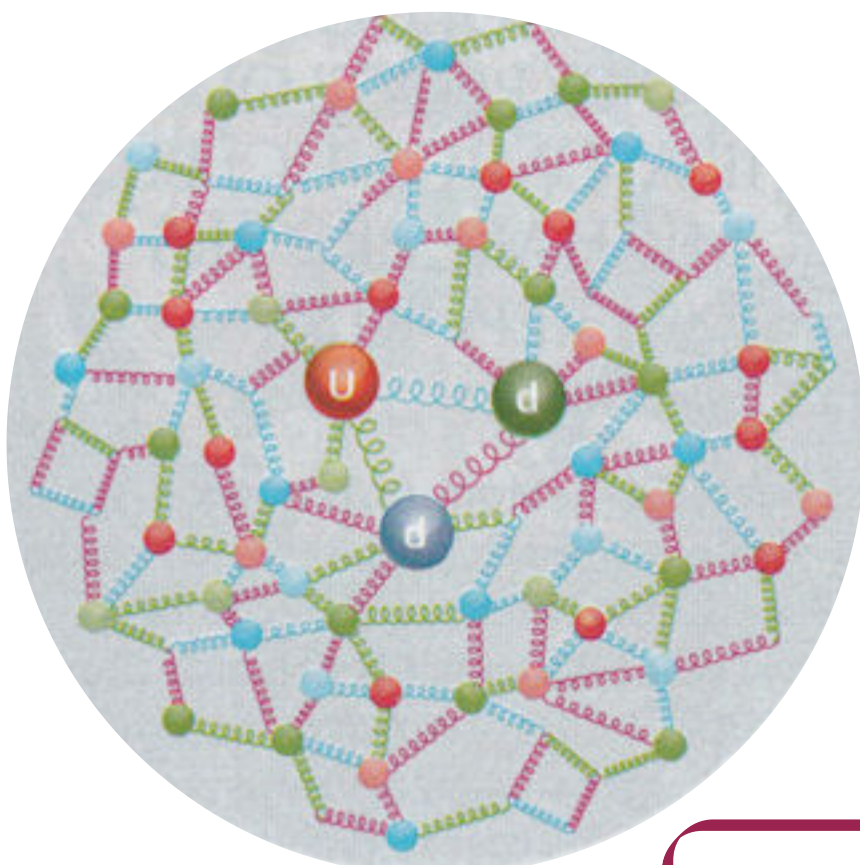

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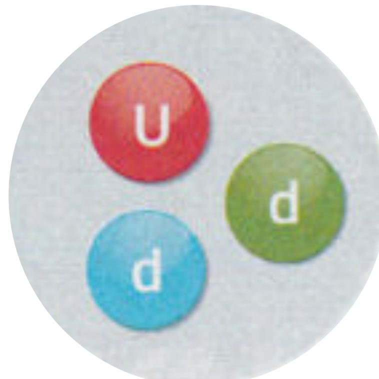

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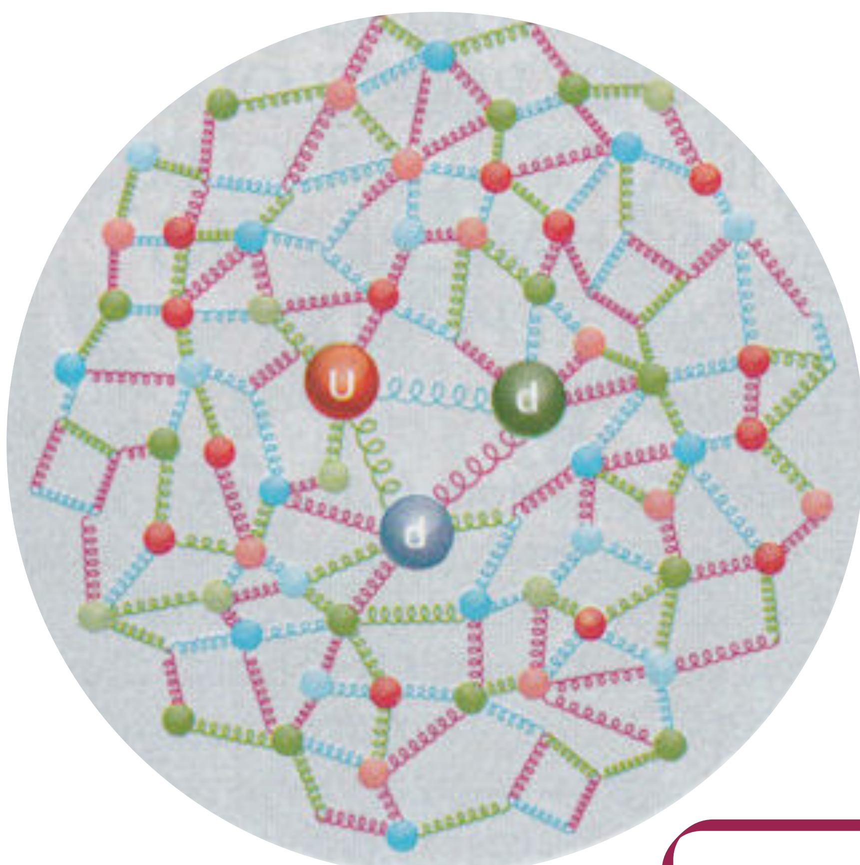

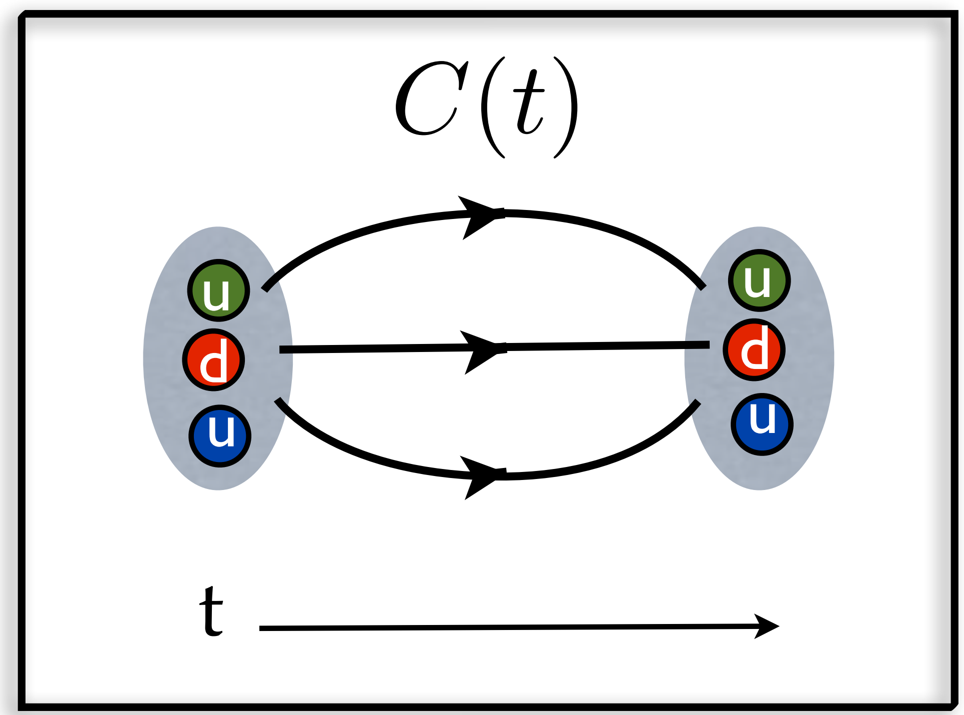

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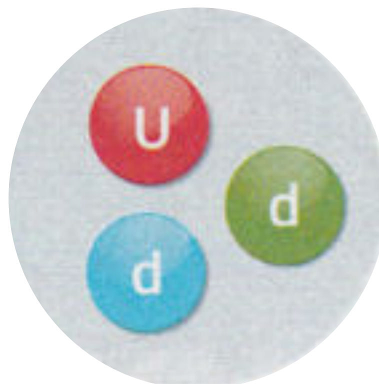

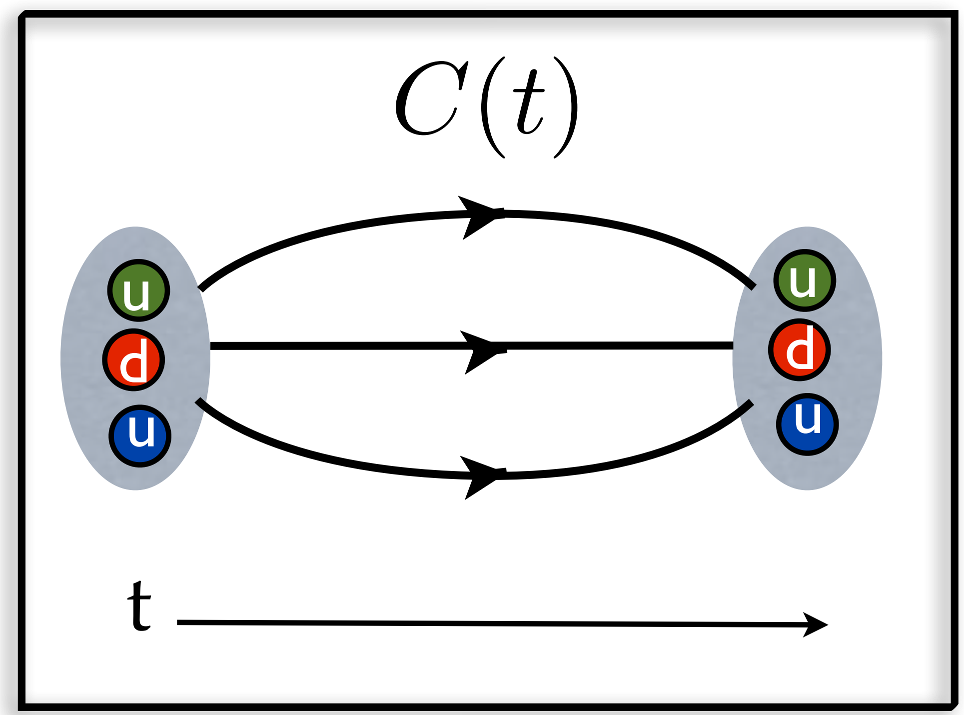

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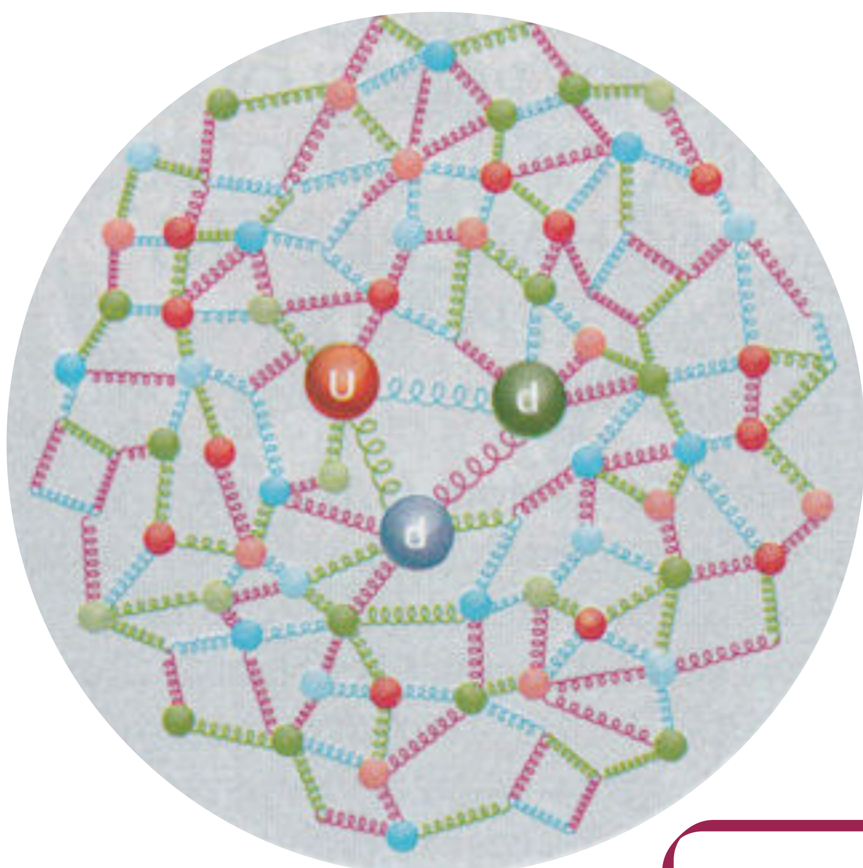

$$C(t) = A_0 e^{-E_0 t} + \cancel{A_1 e^{-E_1 t}} + \cancel{A_2 e^{-E_2 t}} + \cancel{A_3 e^{-E_3 t}} + \cdots$$

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$$\langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \langle \mathcal{O}(0)e^{-Ht}\mathcal{O}(0)\rangle = \sum_n |\langle 0|\mathcal{O}|n\rangle|^2 e^{-E_n t}$$

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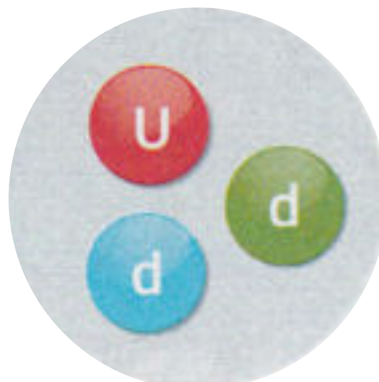

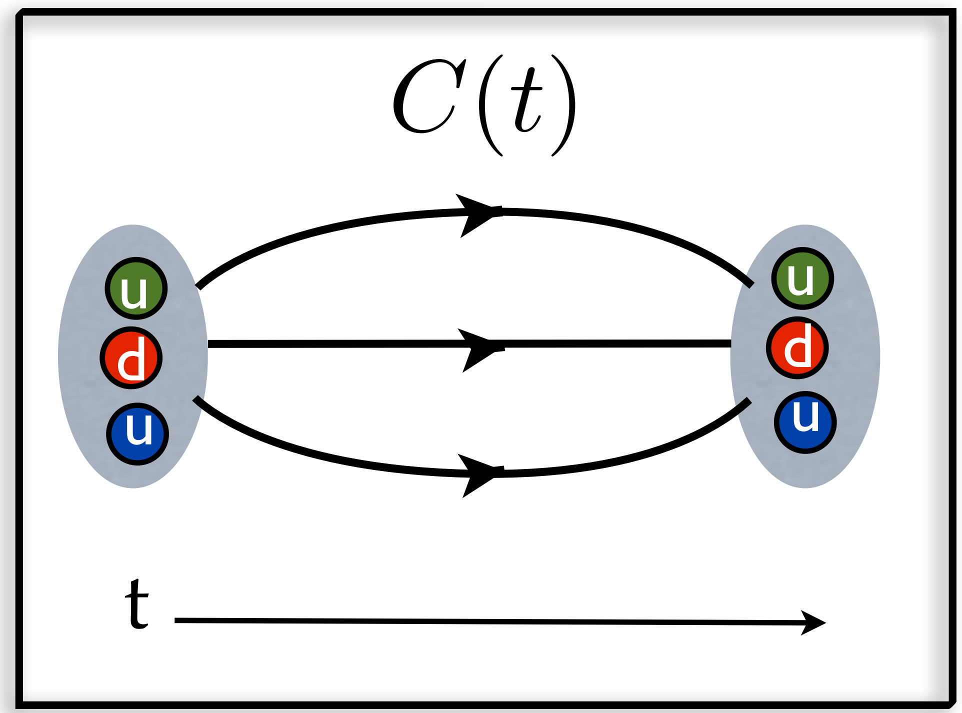

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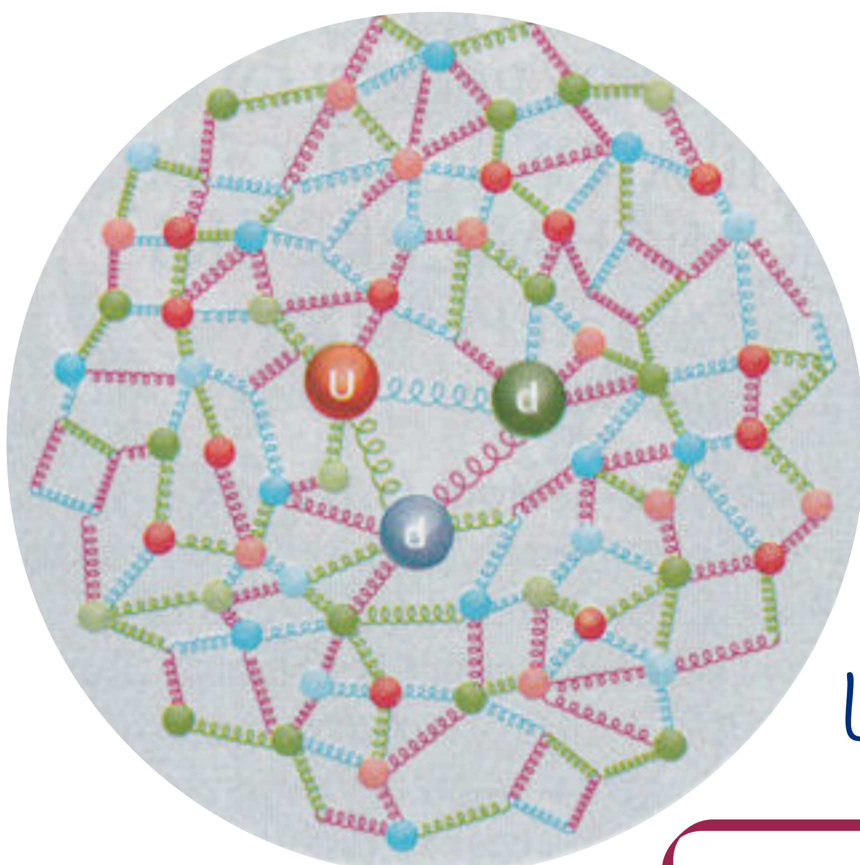

Long time limit = zero temperature

$$C(t) = A_0 e^{-E_0 t} + A_1 e^{-E_1 t} + A_2 e^{-E_2 t} + A_3 e^{-E_3 t} + \cdots$$

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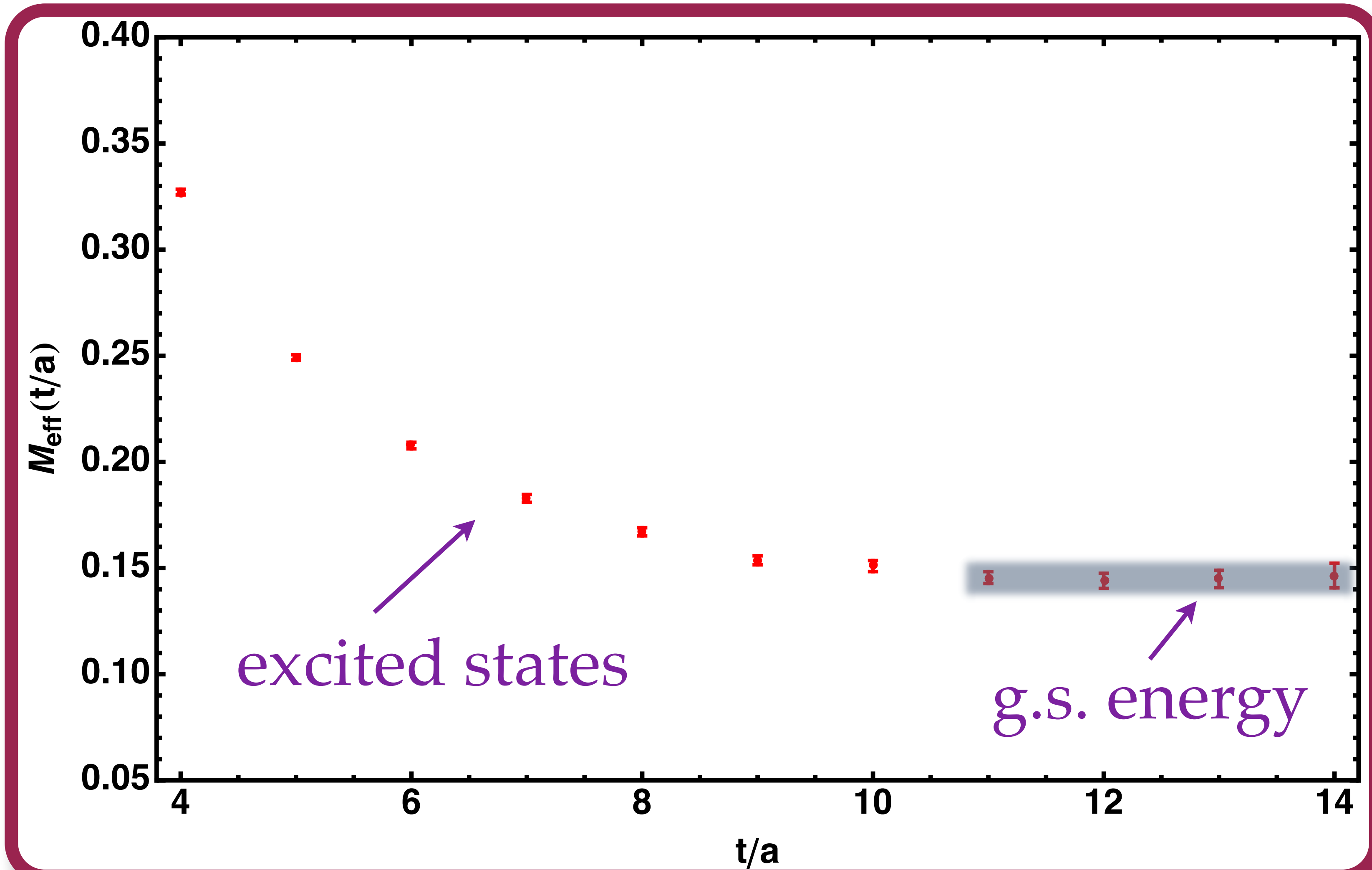

Effective mass plot:

$$M_{\rm eff} \equiv \ln \frac{C(t)}{C(t+1)}$$

$$\xrightarrow[t\to\infty]{} E_0$$

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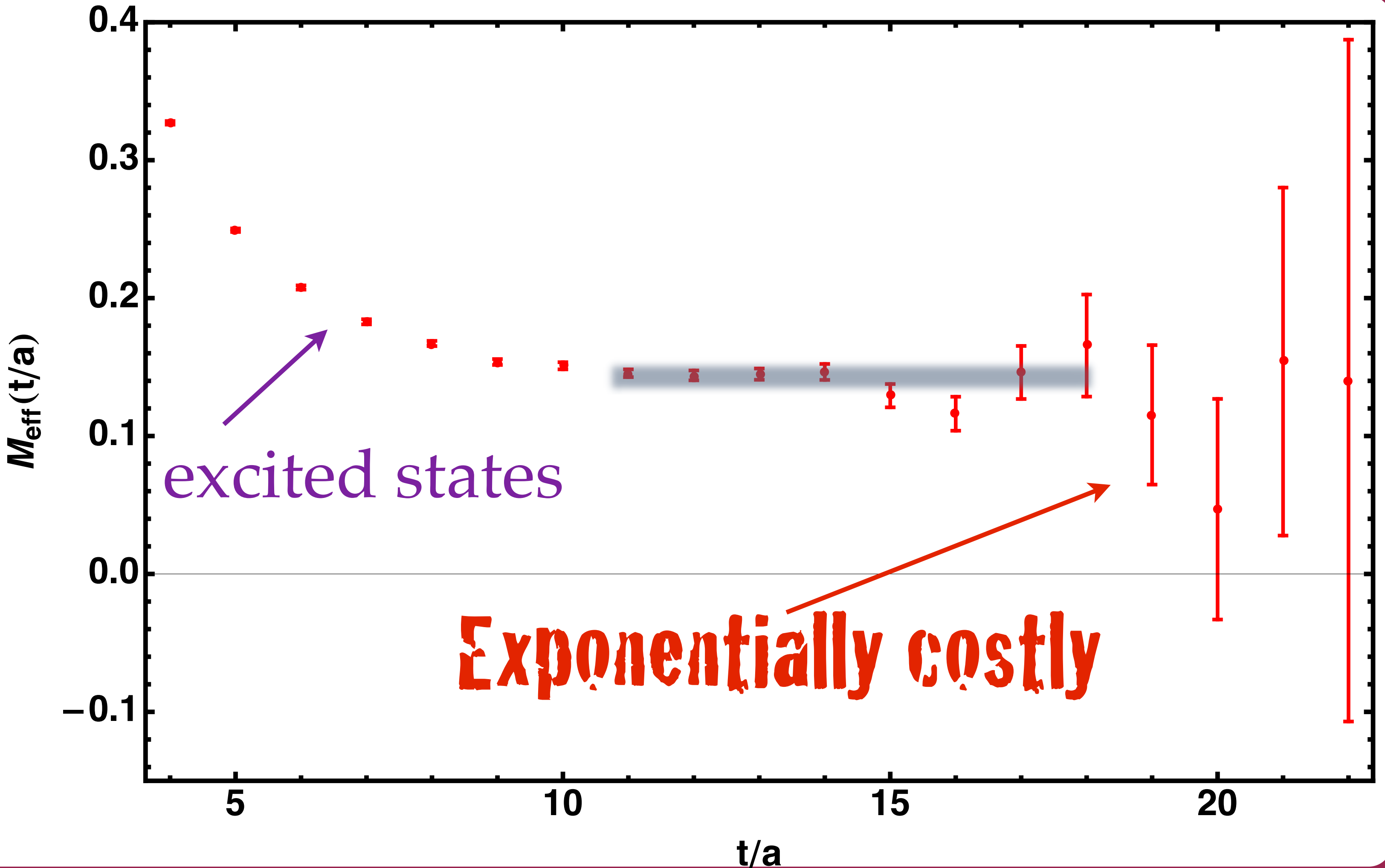

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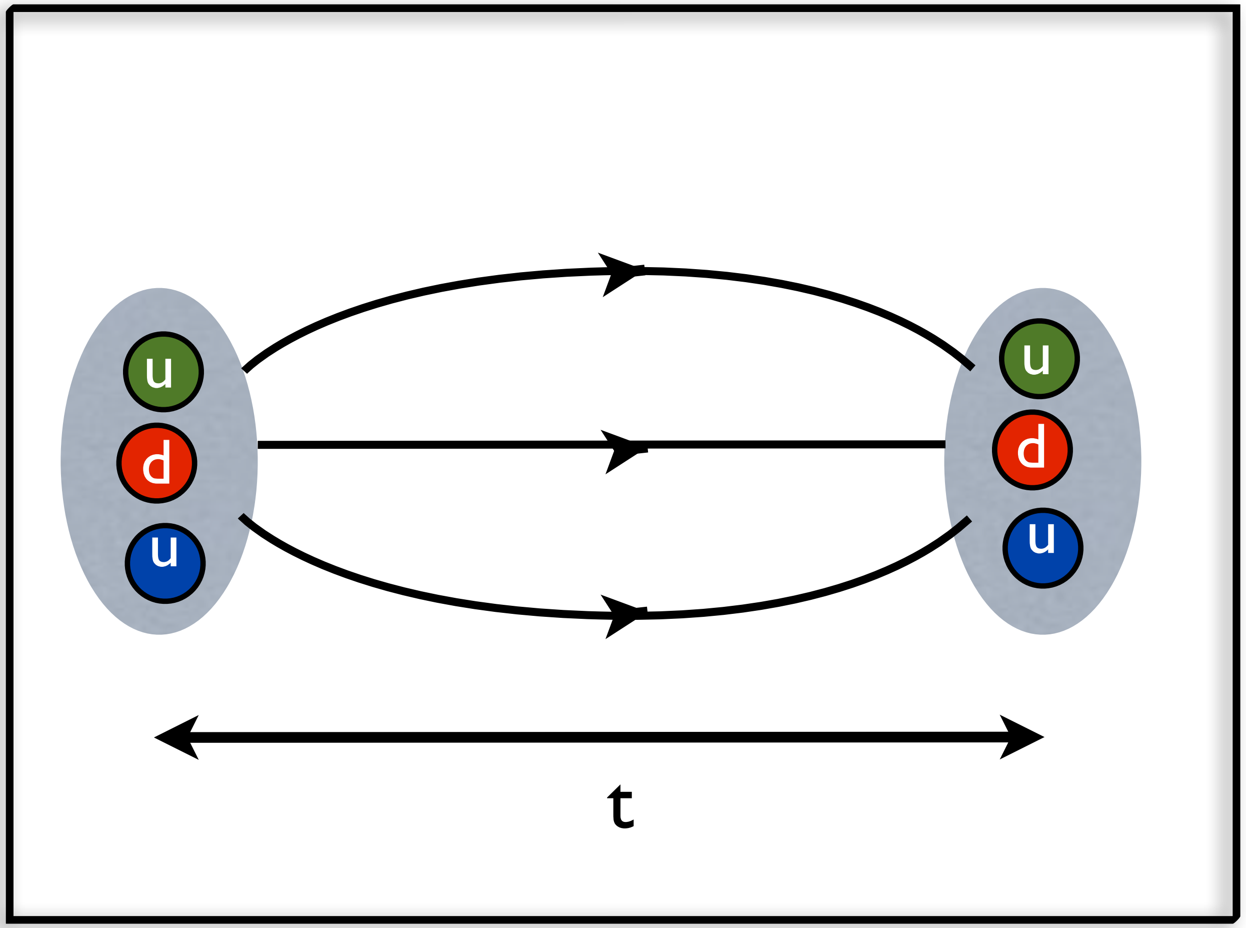
Matrix Elements

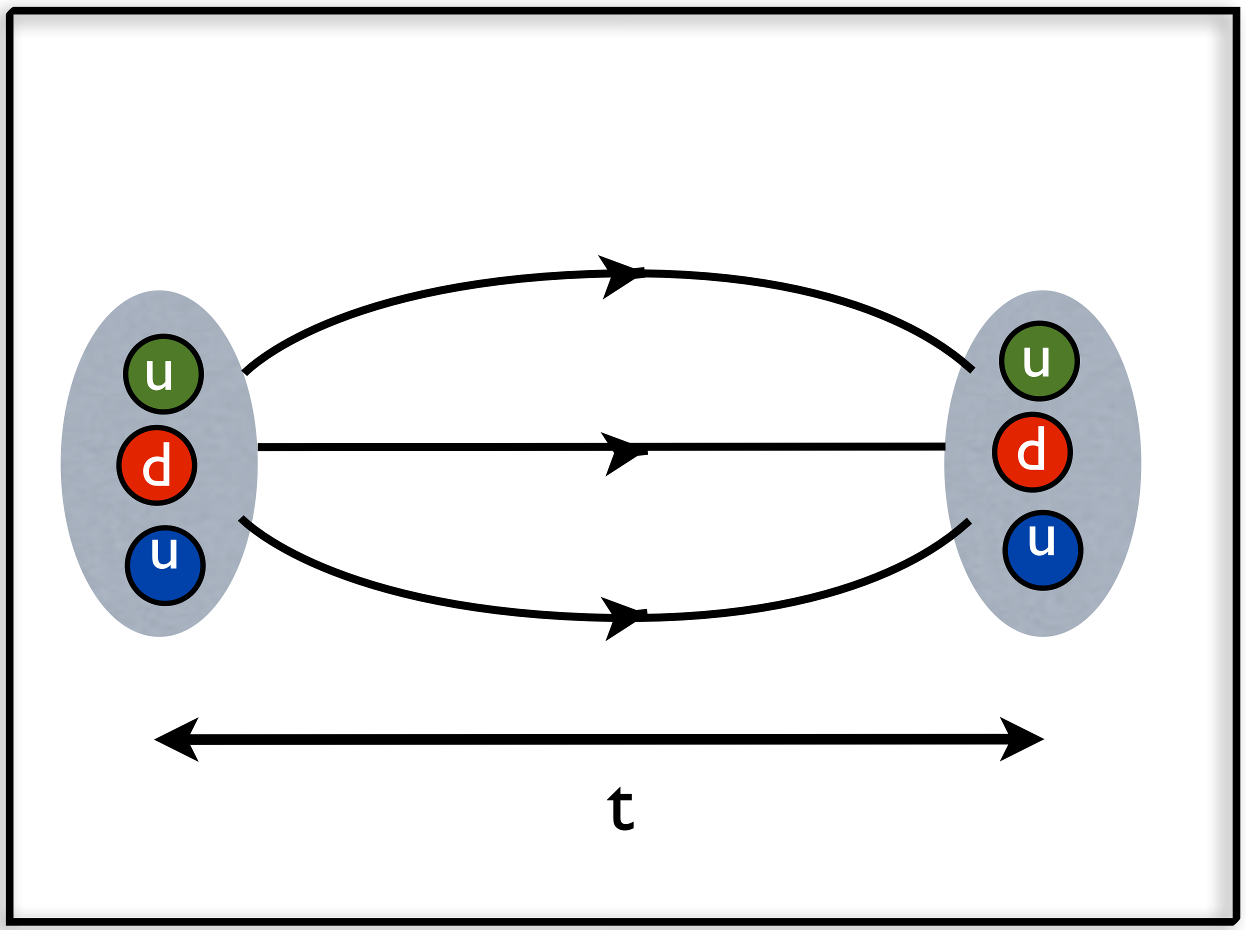
2-point function

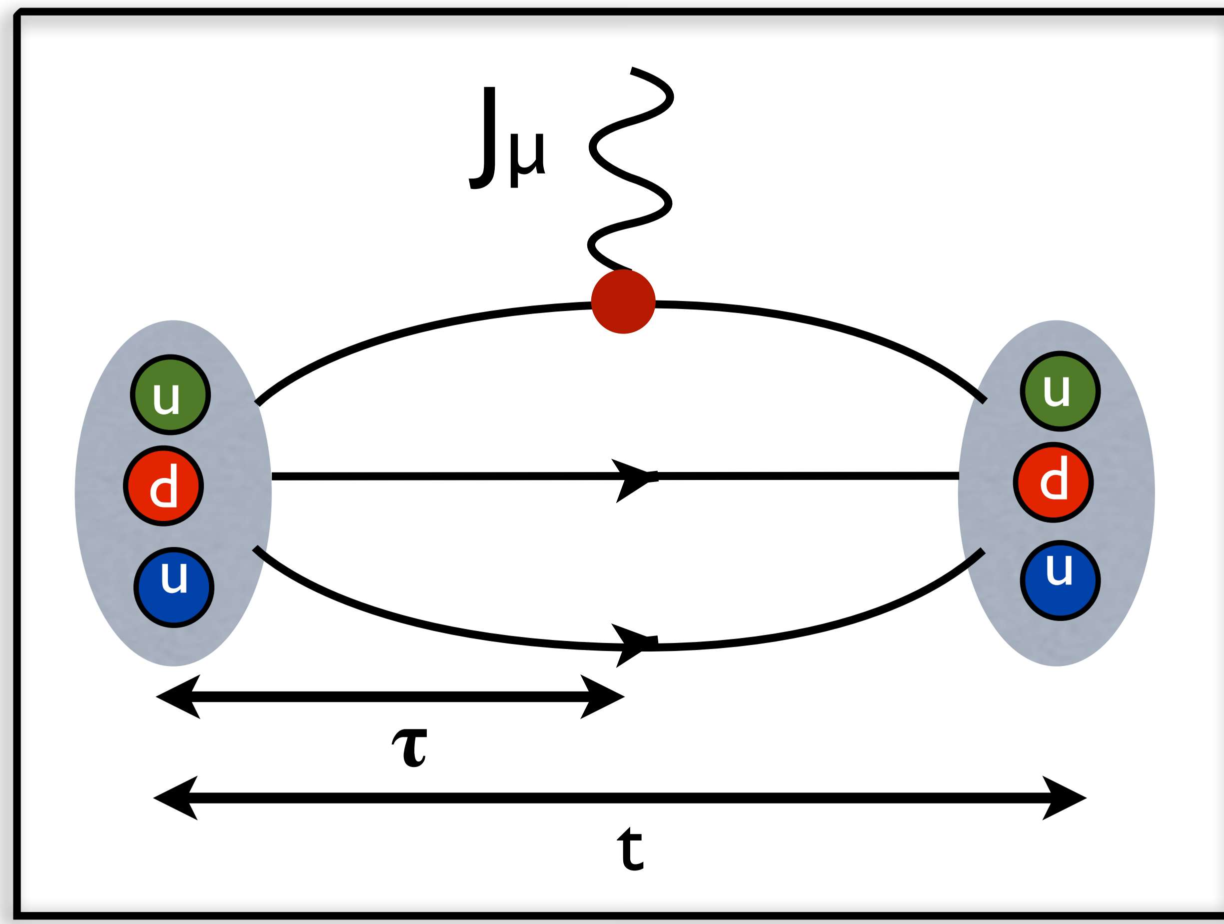


Matrix Elements

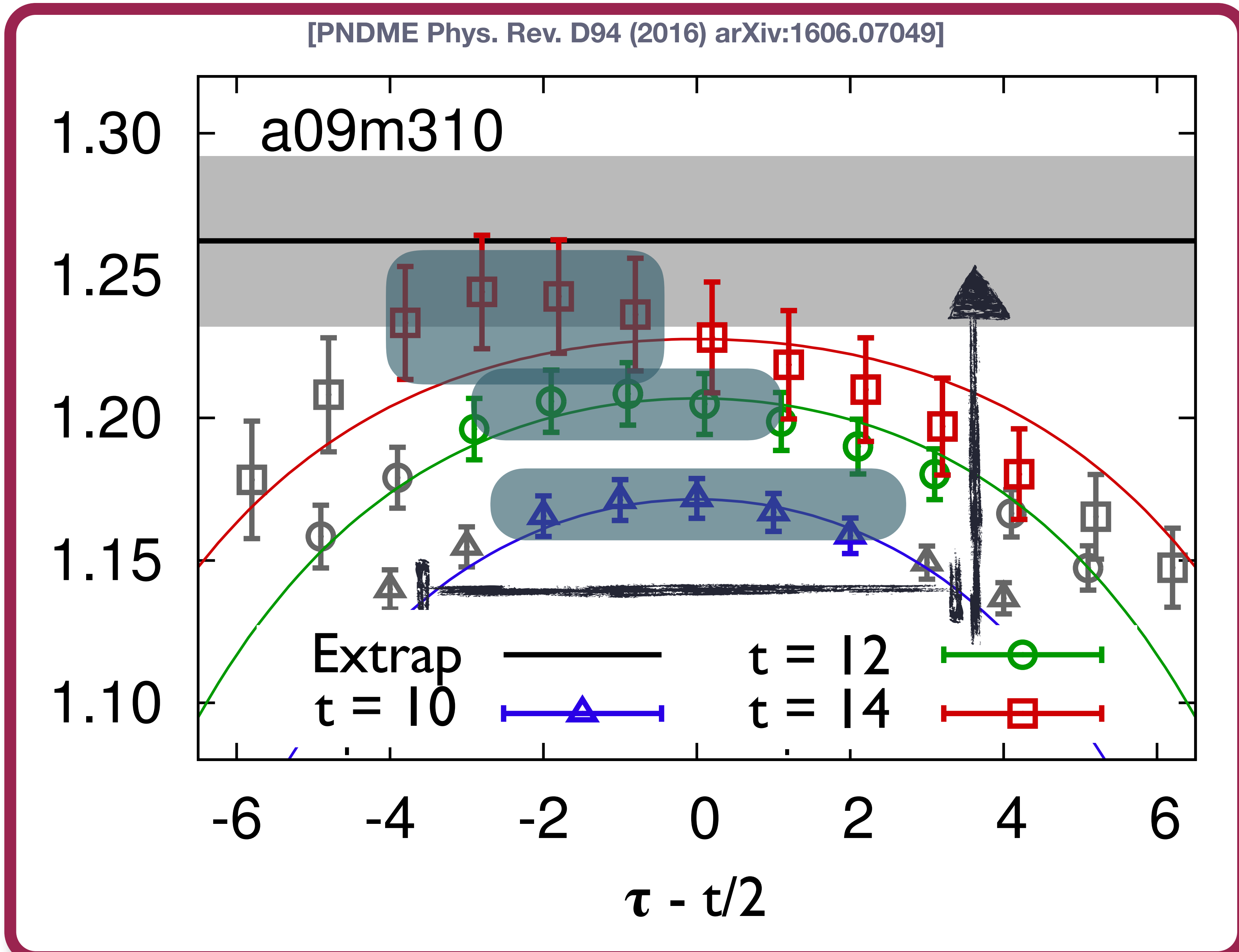
2-point function

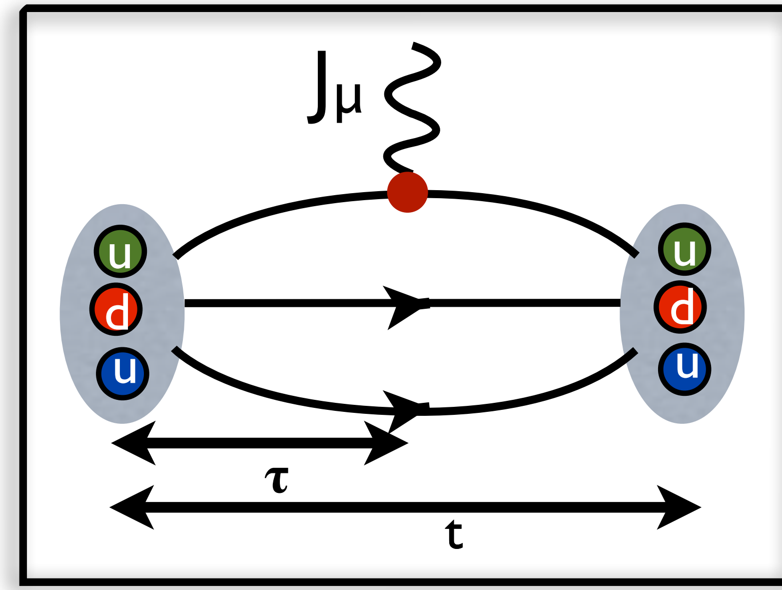
3-point function



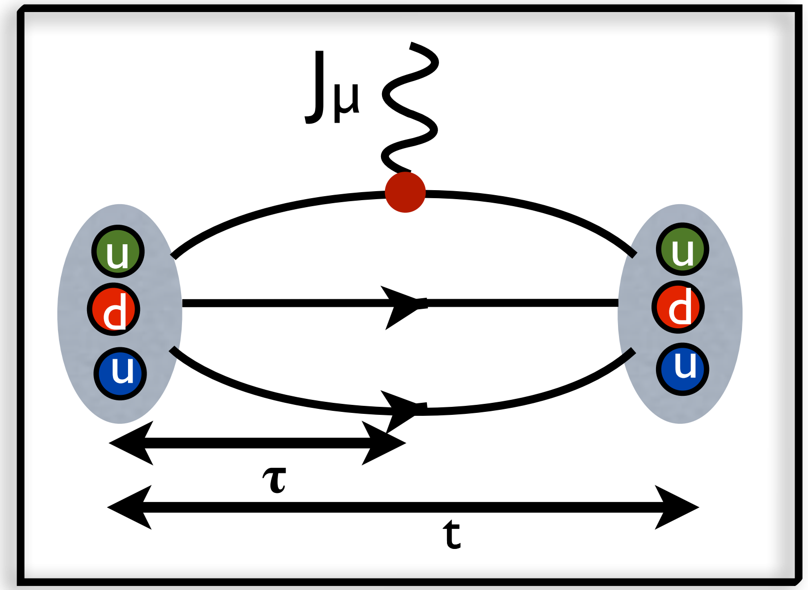


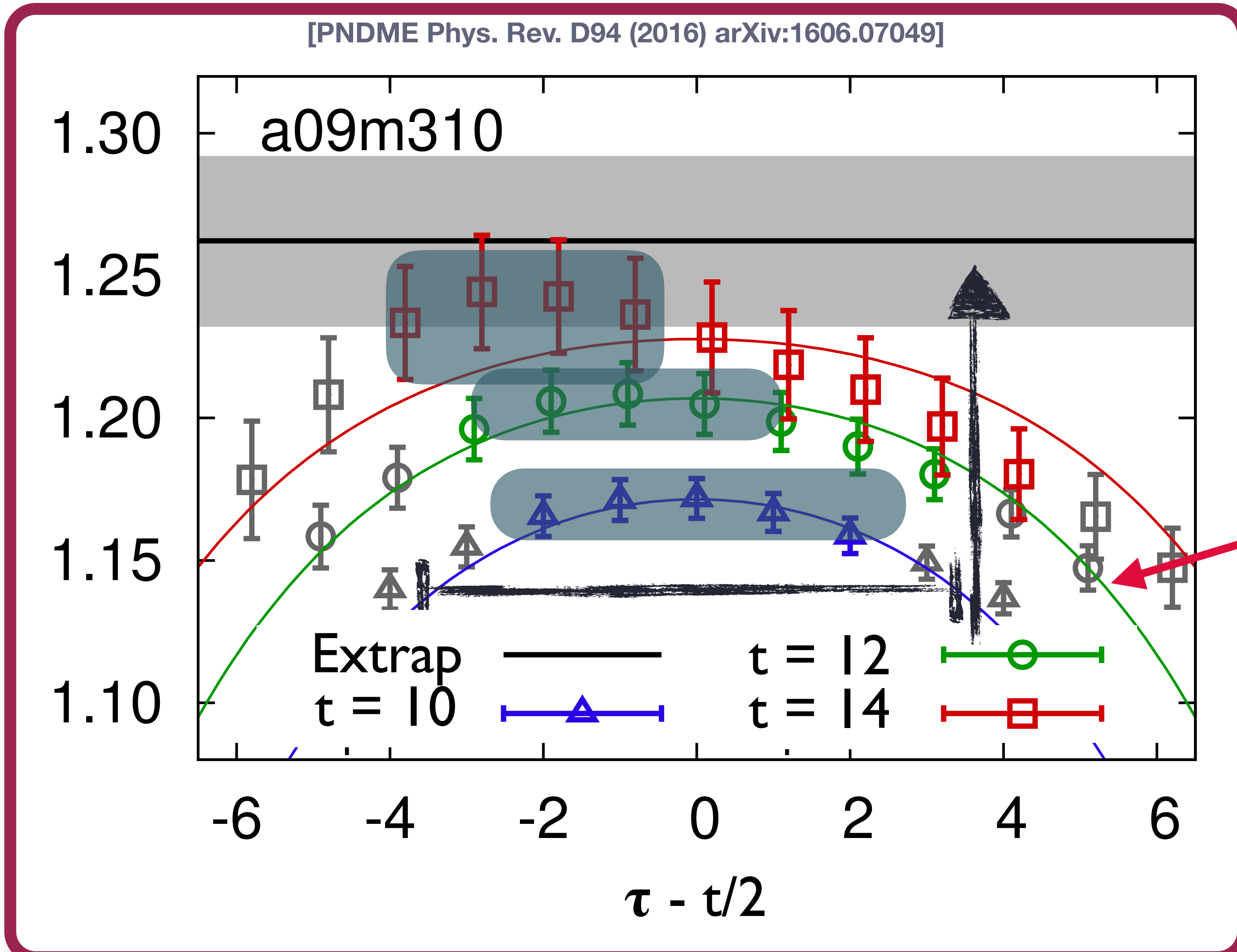
3-point function





3-point function



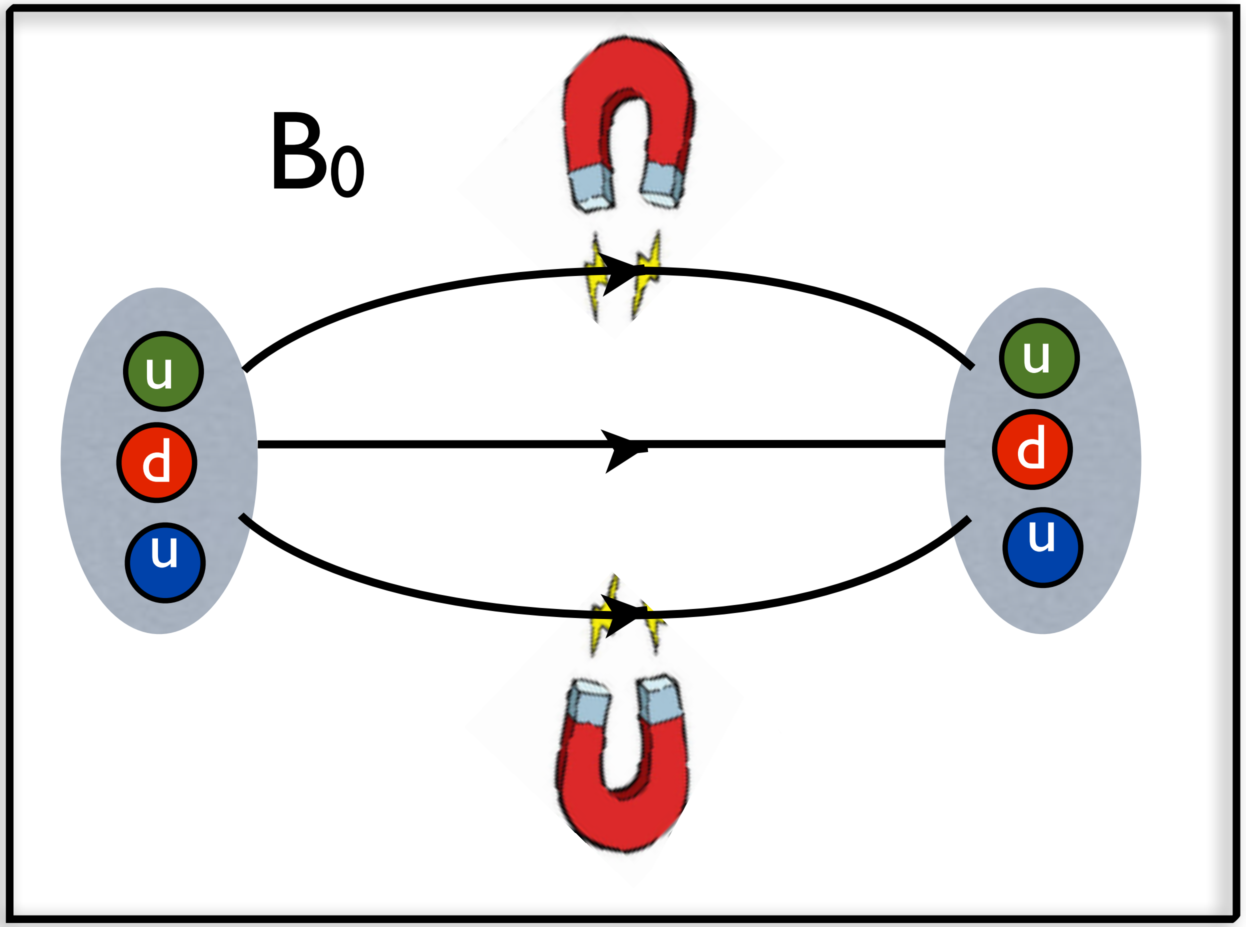


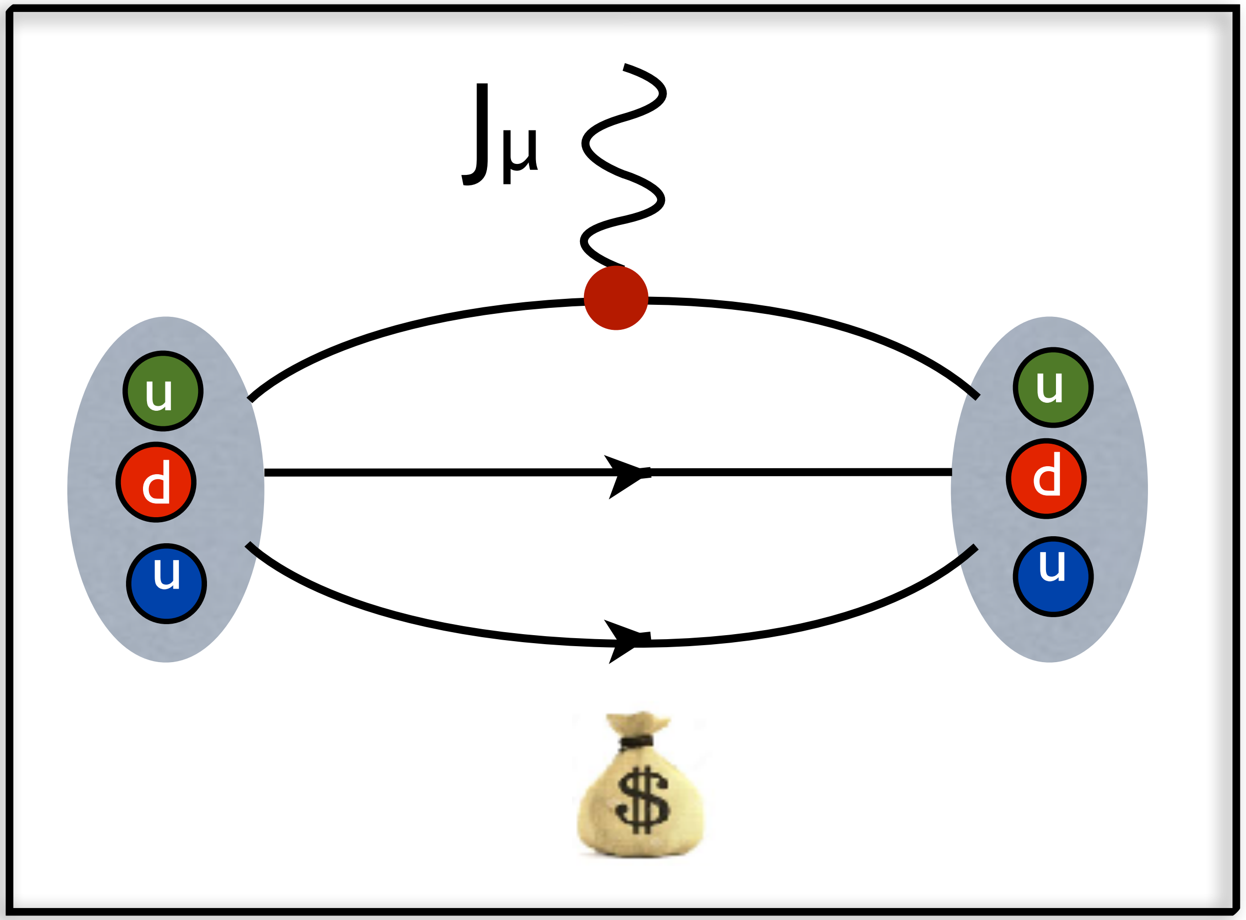
Each t_{sep} can cost exponentially more than the last: must perform difficult extrapolations in two variables!

Matrix Elements

Background field

3-point function





FH Theorem: $H = H_0 + \lambda J$

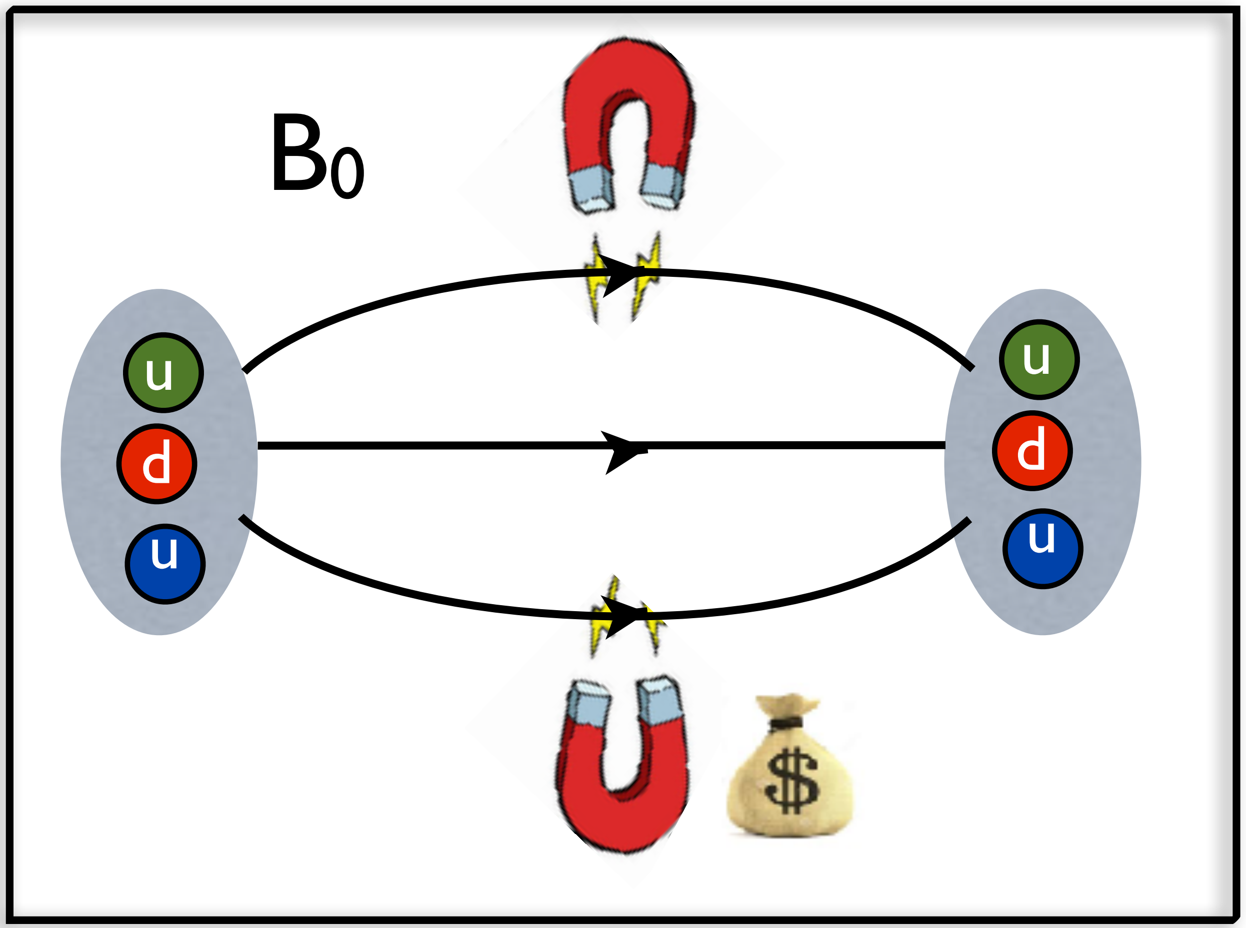
$$\frac{dE}{d\lambda} = \langle\psi|J|\psi\rangle$$

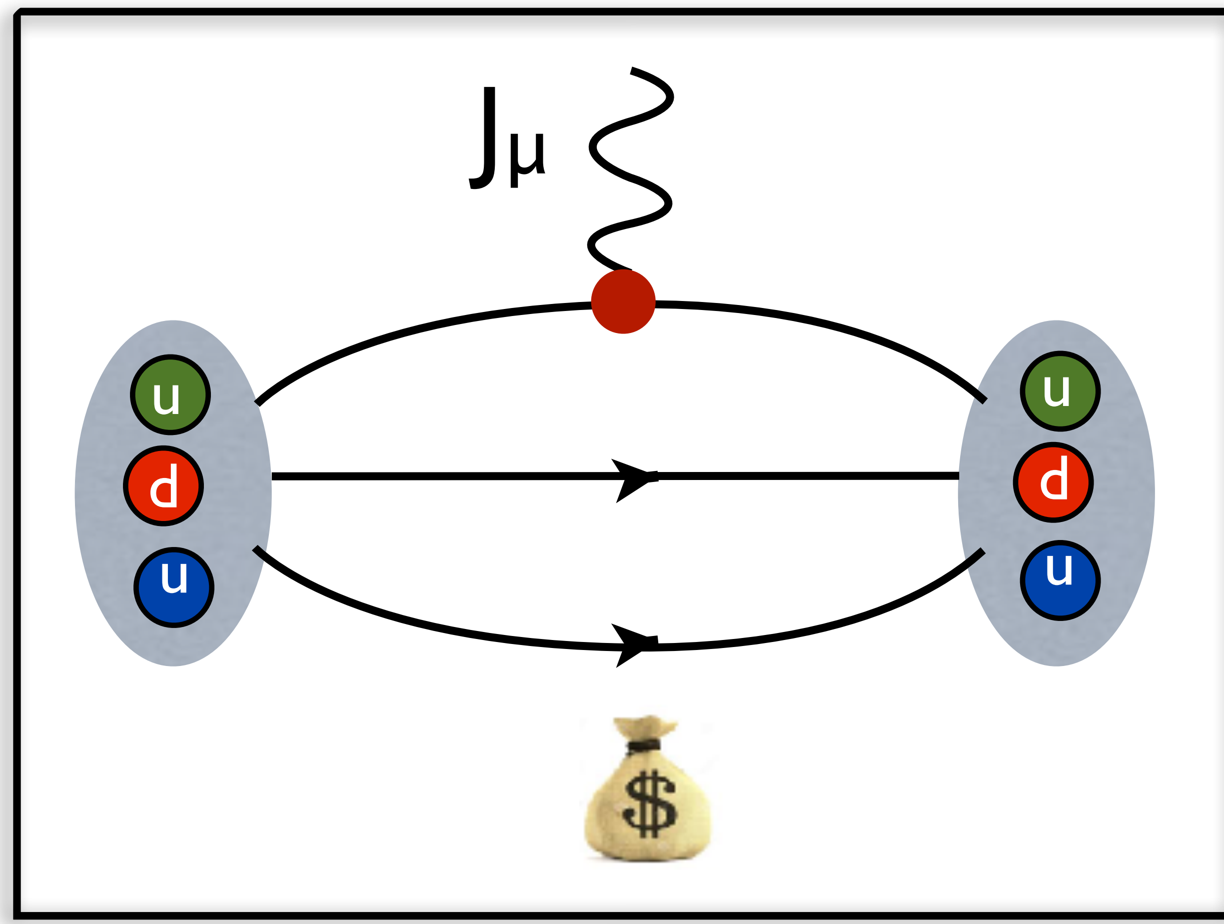
FH turns a 3-pt calc into a 2-pt calc - much easier to analyze

Matrix Elements

Background field

3-point function





FH Theorem: $H = H_0 + \lambda J$

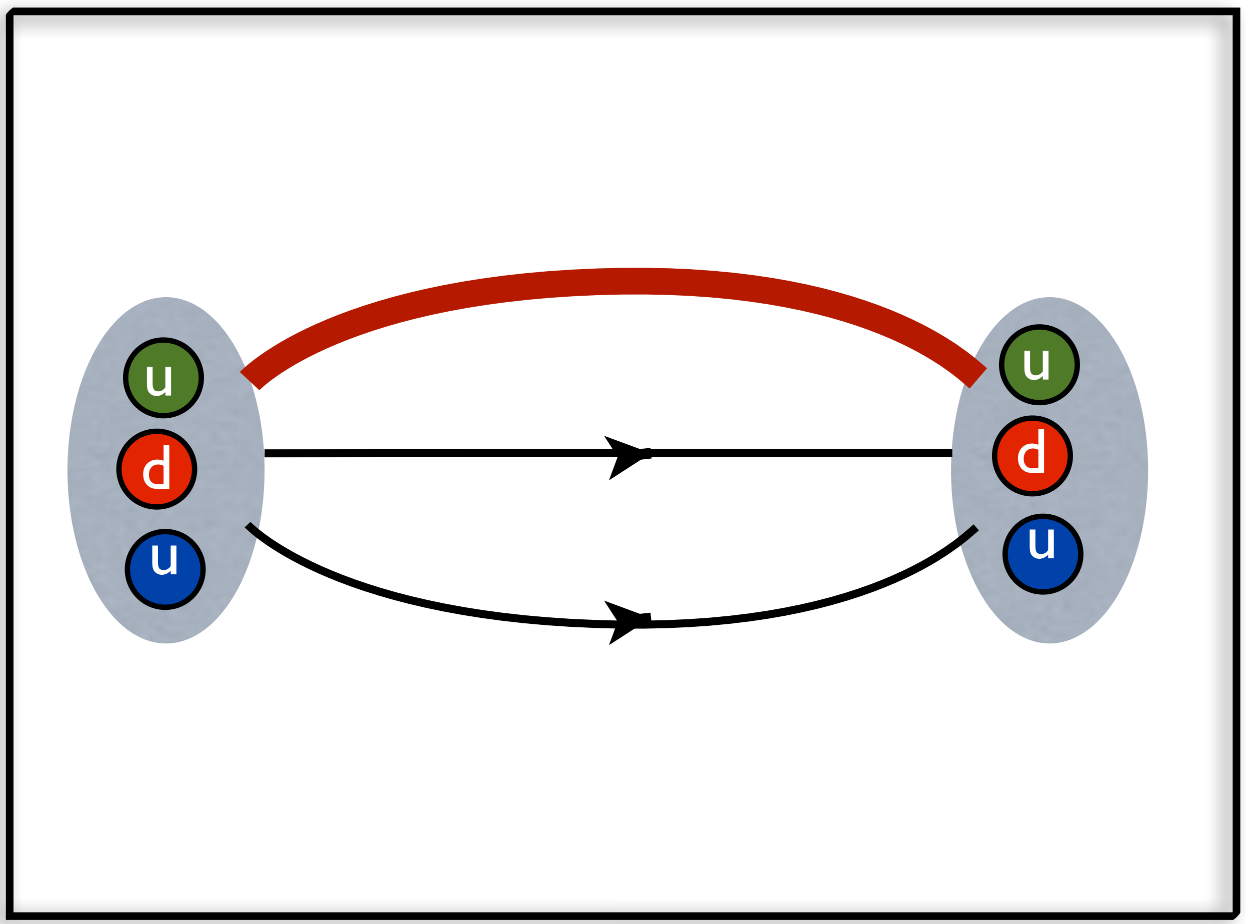
$$\frac{dE}{d\lambda} = \langle \psi | J | \psi \rangle$$

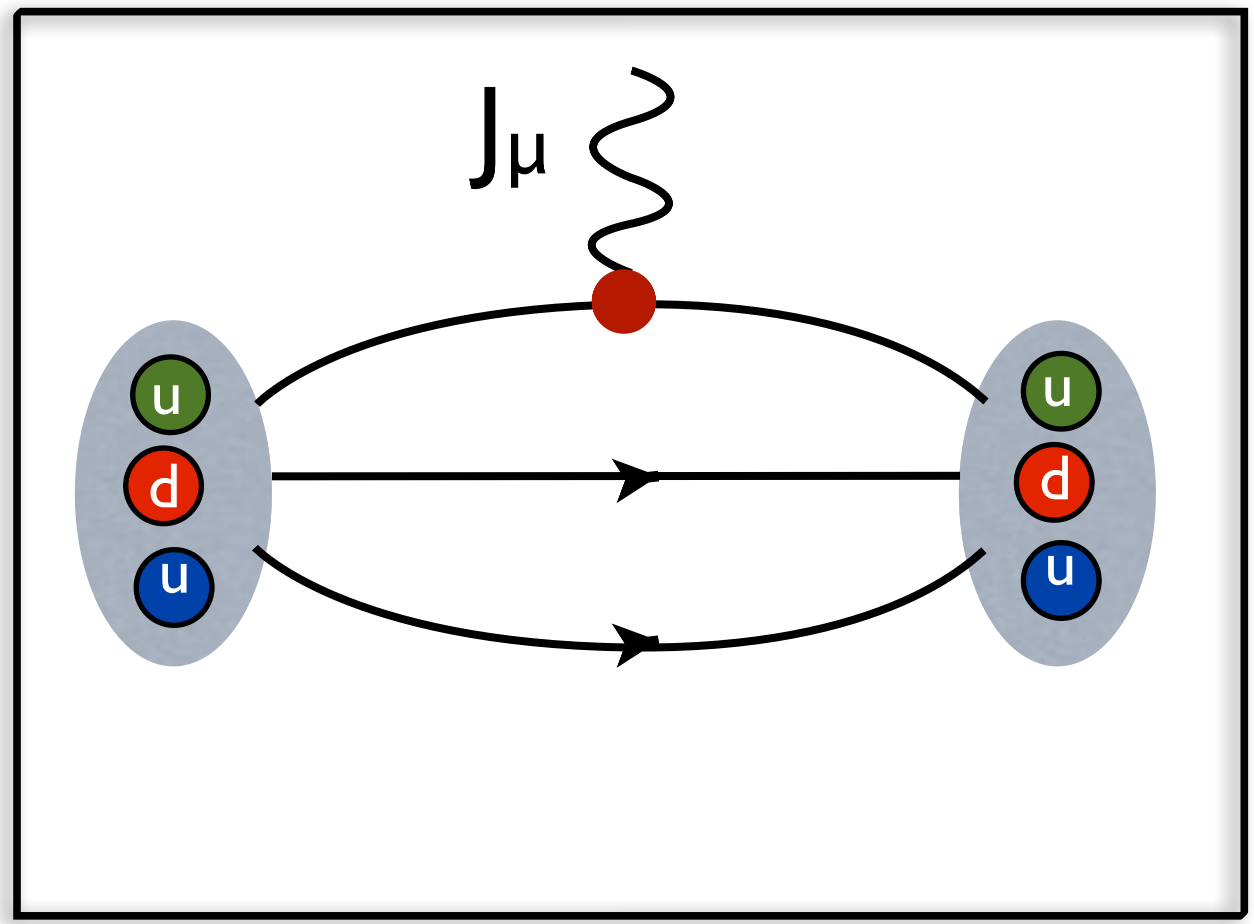
Must calculate field configurations at several λ to extract linear response

Matrix Elements

Feynman-Hellmann

3-point function





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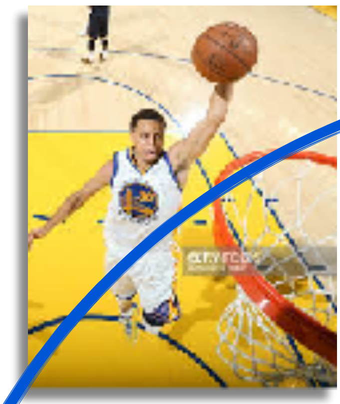
Chris Bouchard, Chia Cheng Chang, Thorsten Kurth, Kostas Orginos, Andre Walker-Loud arXiv:1612.06963

Matrix Elements



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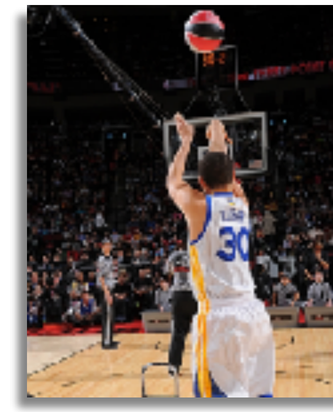

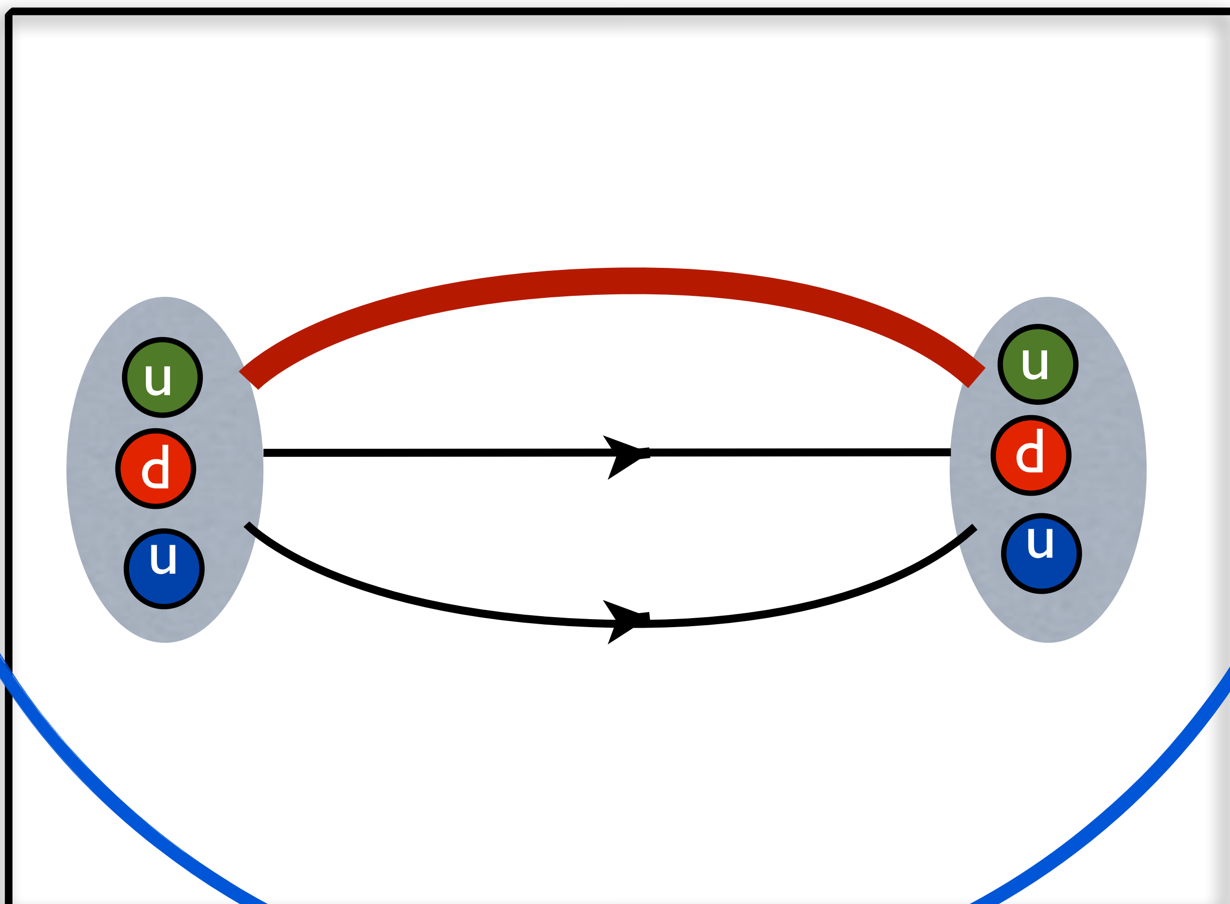

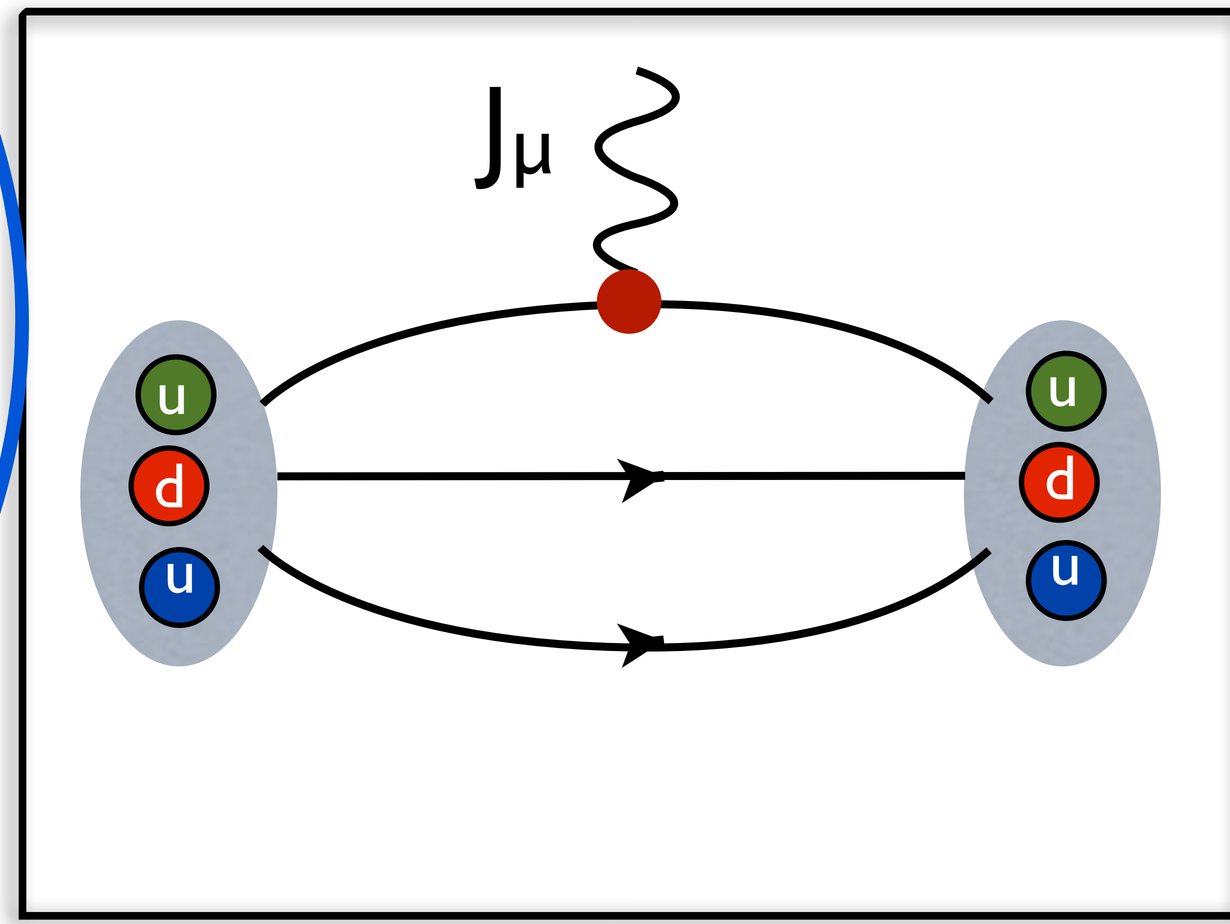

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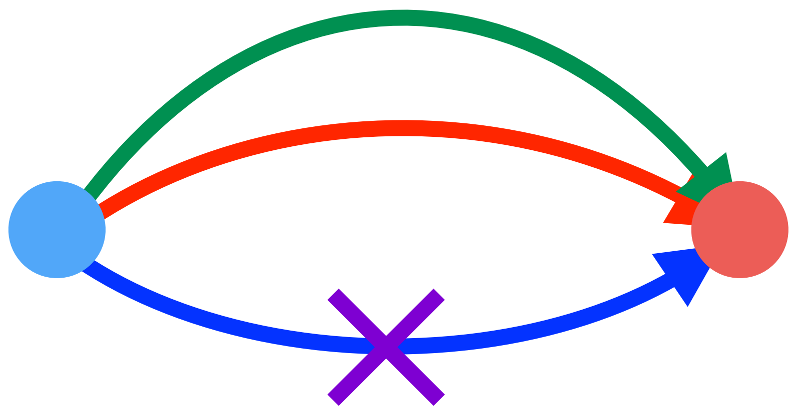
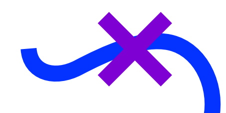
NPLQCD 1610.04545, 1611.00344, 1701.03456, 1702.02929



$$S_\lambda = \lambda \sum_t \mathcal{J}(t)$$

$$\mathcal{J}(t) = \int d^3x \bar{\psi}(x,t)\Gamma\psi(x,t)$$

$$\partial_\lambda C(t) = -\sum_{t'} \langle \mathcal{N}(t)\mathcal{J}(t')\mathcal{N}^\dagger(0)\rangle$$



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

Slides adapted from E. Berkowitz

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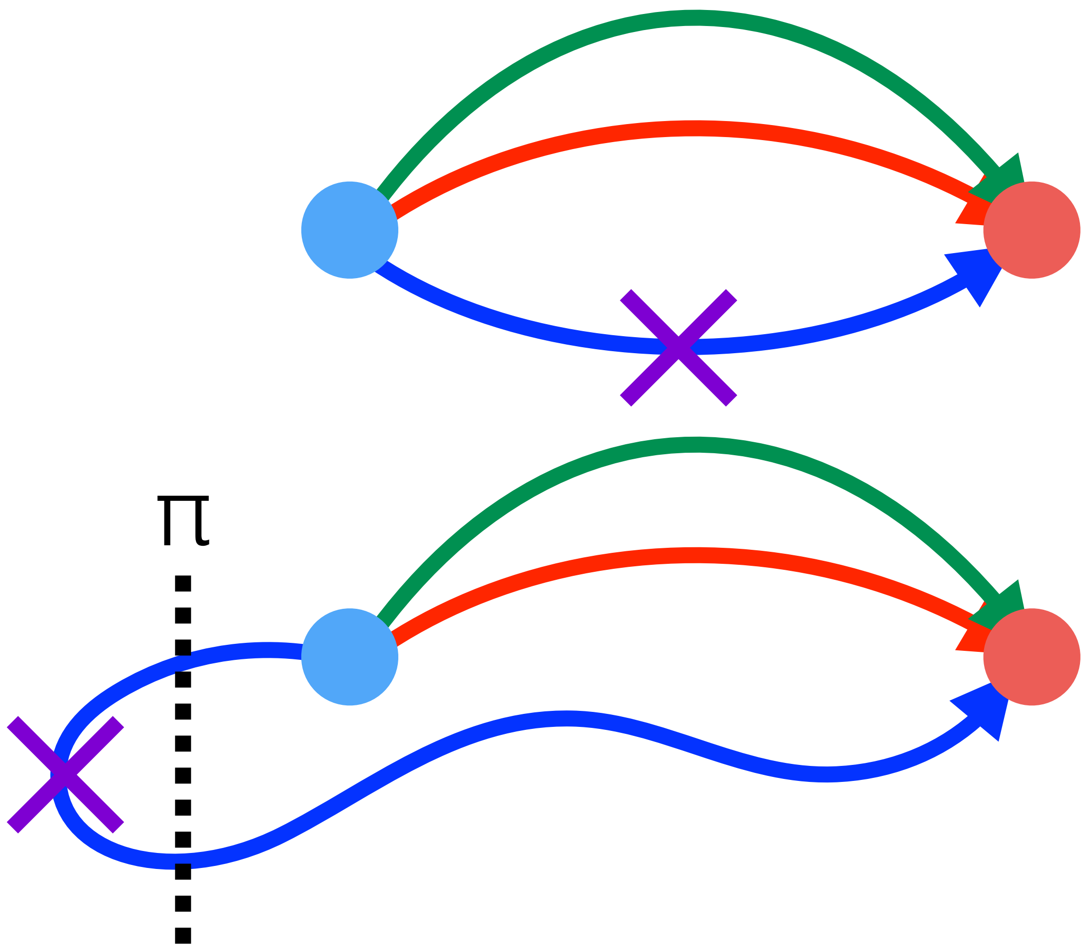

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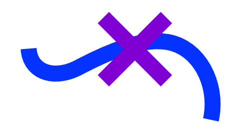

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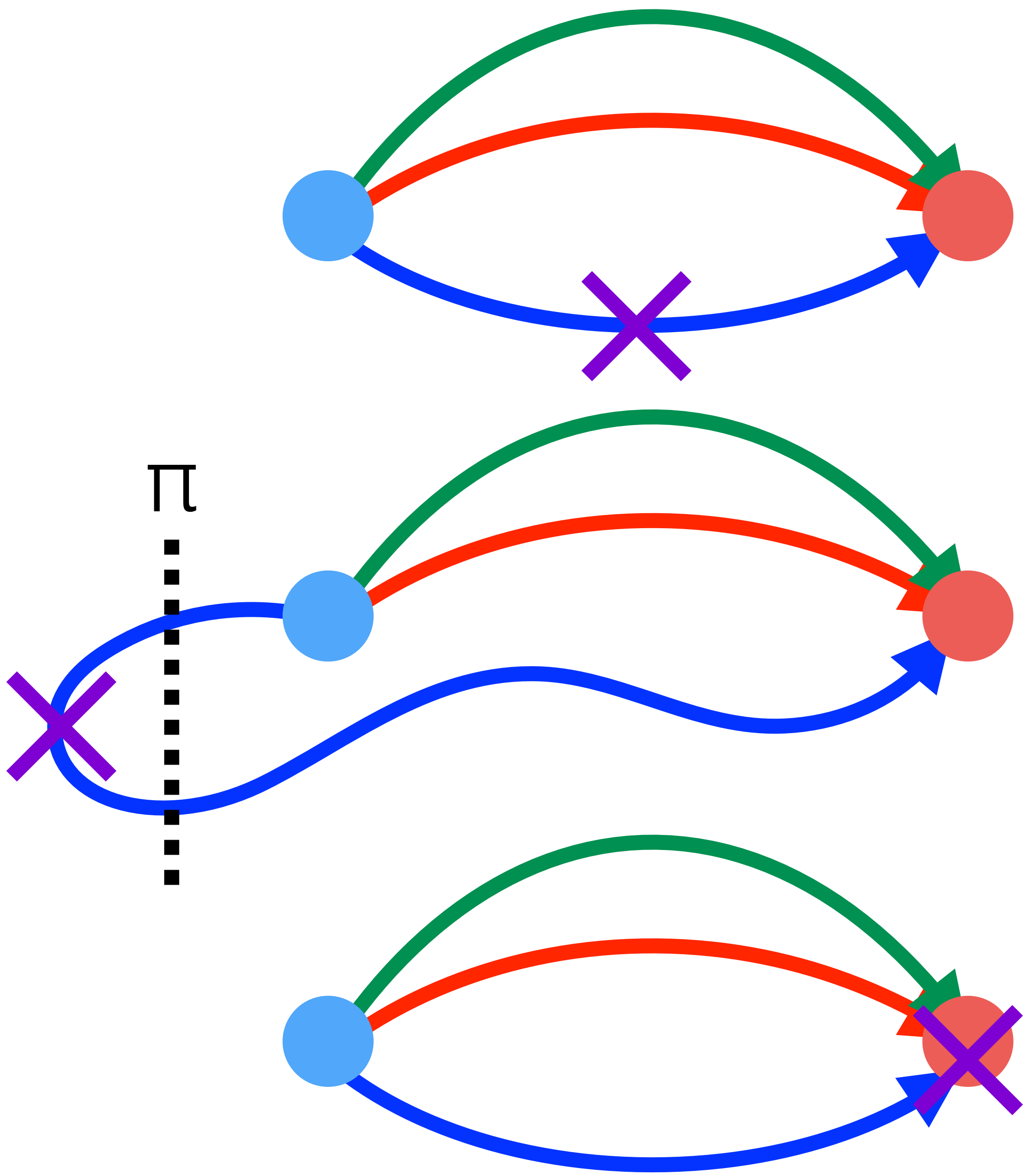

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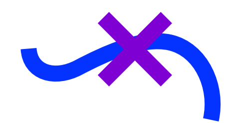

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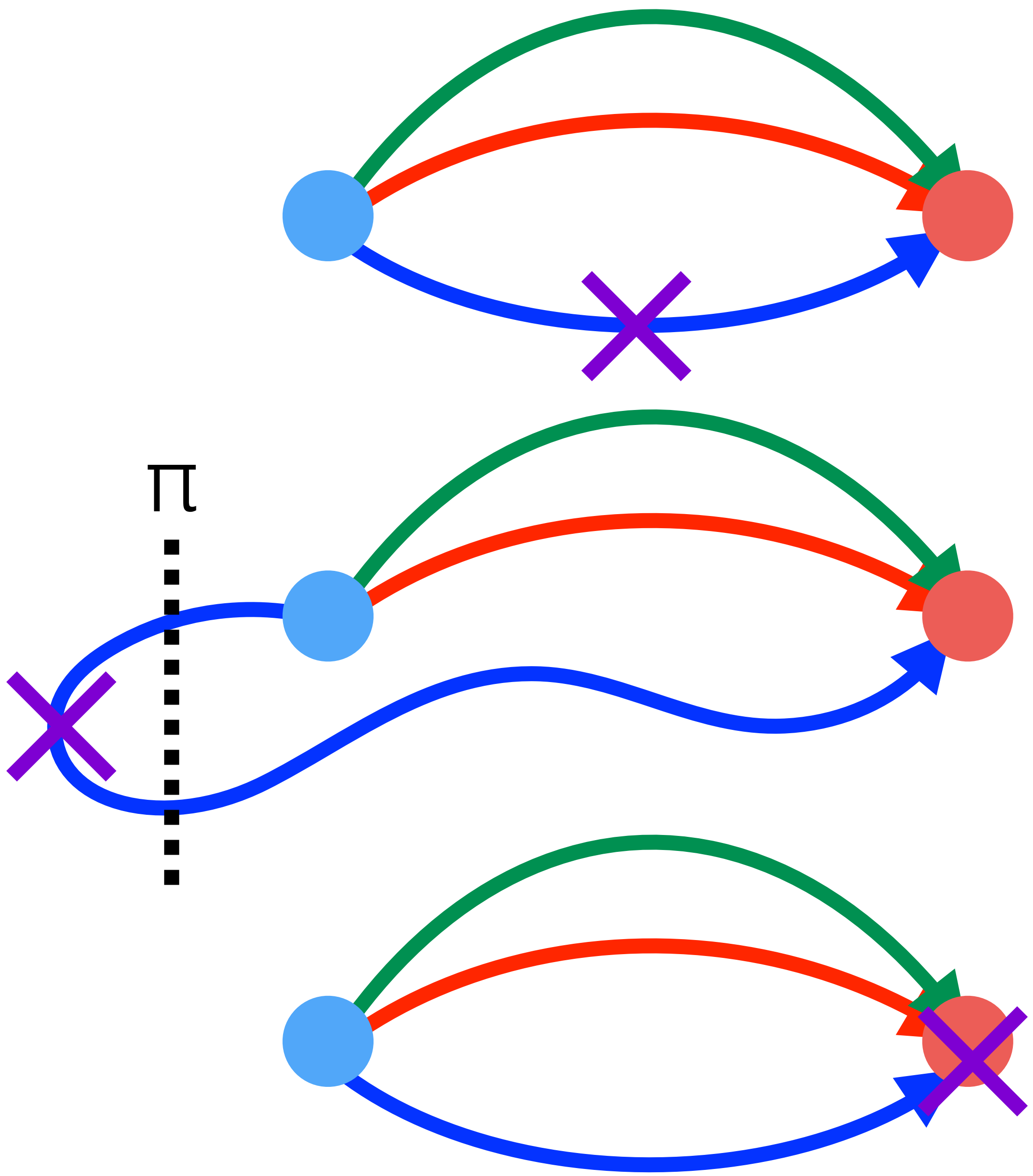

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$$C_{\mathcal{J}}(t) = \sum_n \left[(t-1) z_n g^J_{nn} z^\dagger_n + d^J_n\right] e^{-E_n t} + \sum_{\substack{n \\ m\neq n}} z_n g^J_{nm} z^\dagger_m \frac{e^{-E_n t + \frac{\Delta_{nm}}{2}} - e^{-E_m t + \frac{\Delta_{mn}}{2}}}{e^{\frac{\Delta_{nm}}{2}} - e^{\frac{\Delta_{mn}}{2}}}$$

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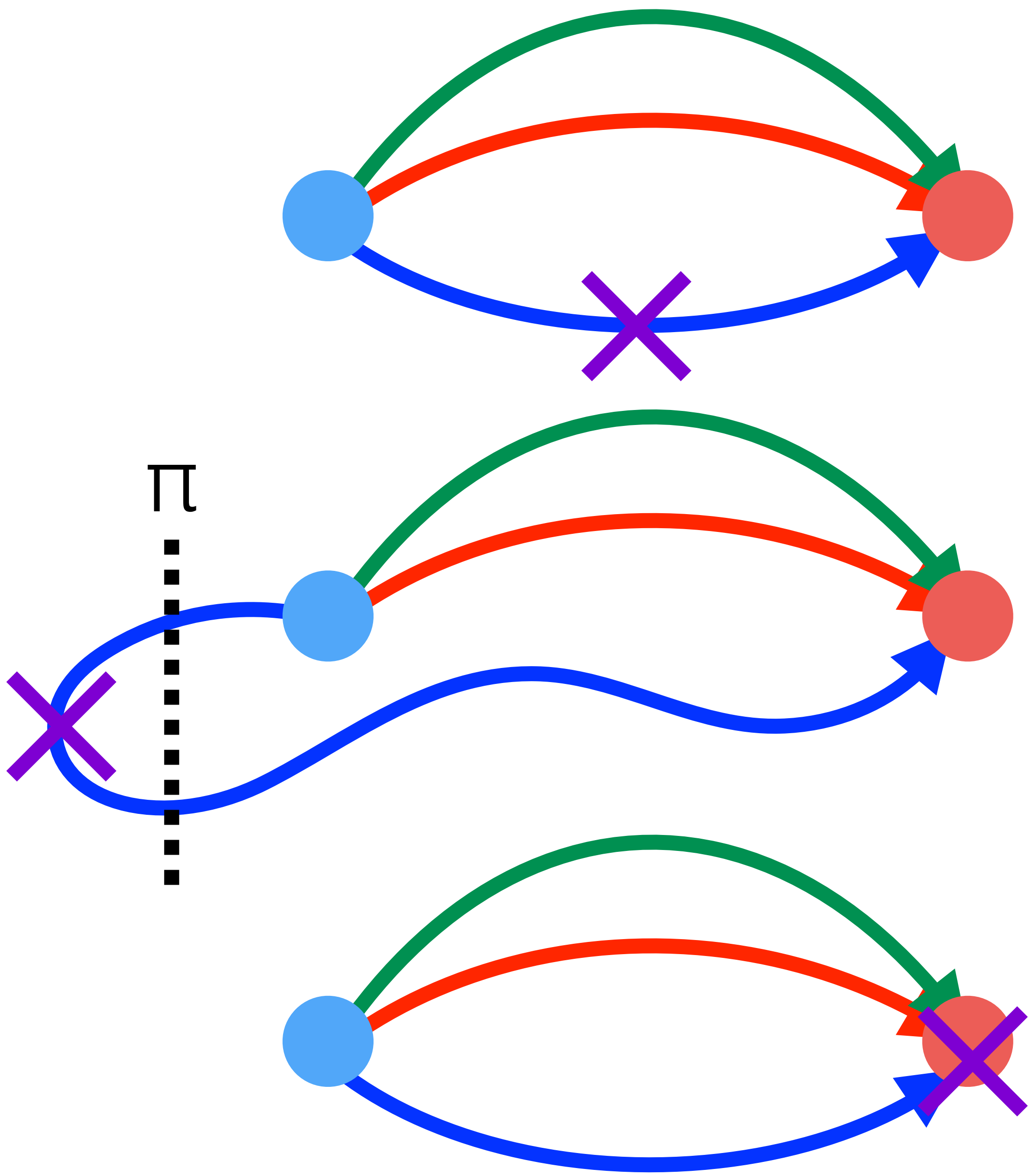

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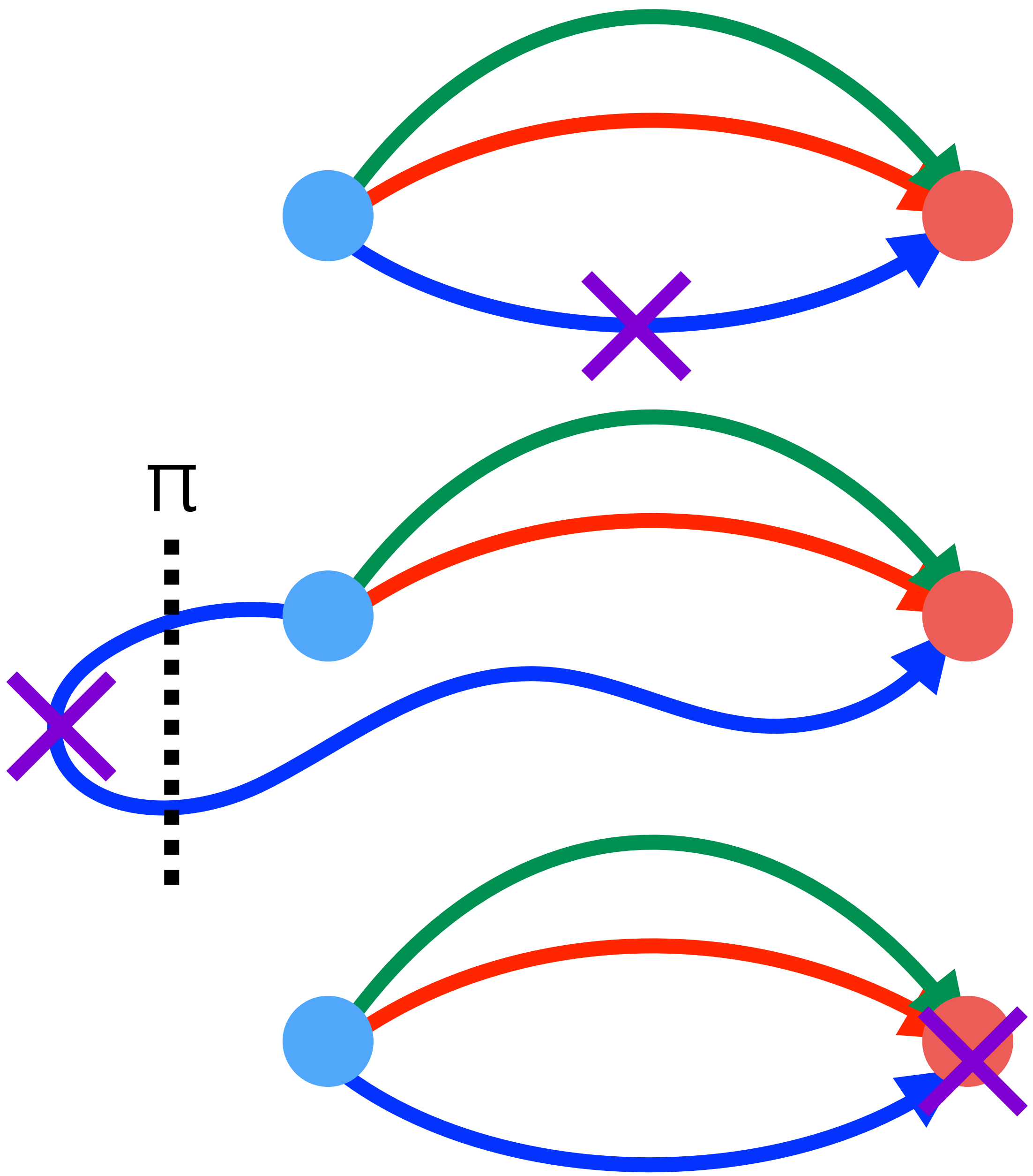

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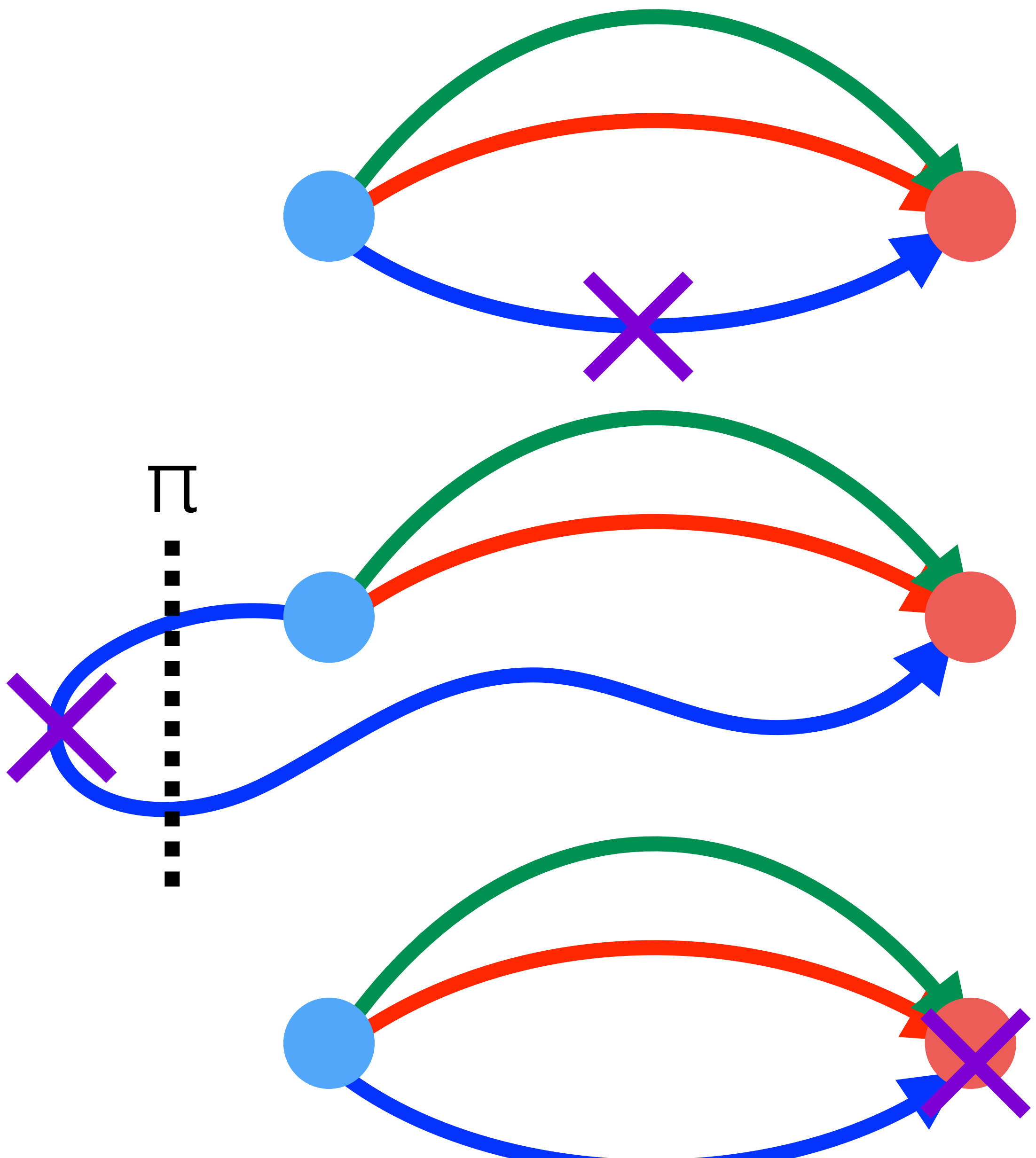

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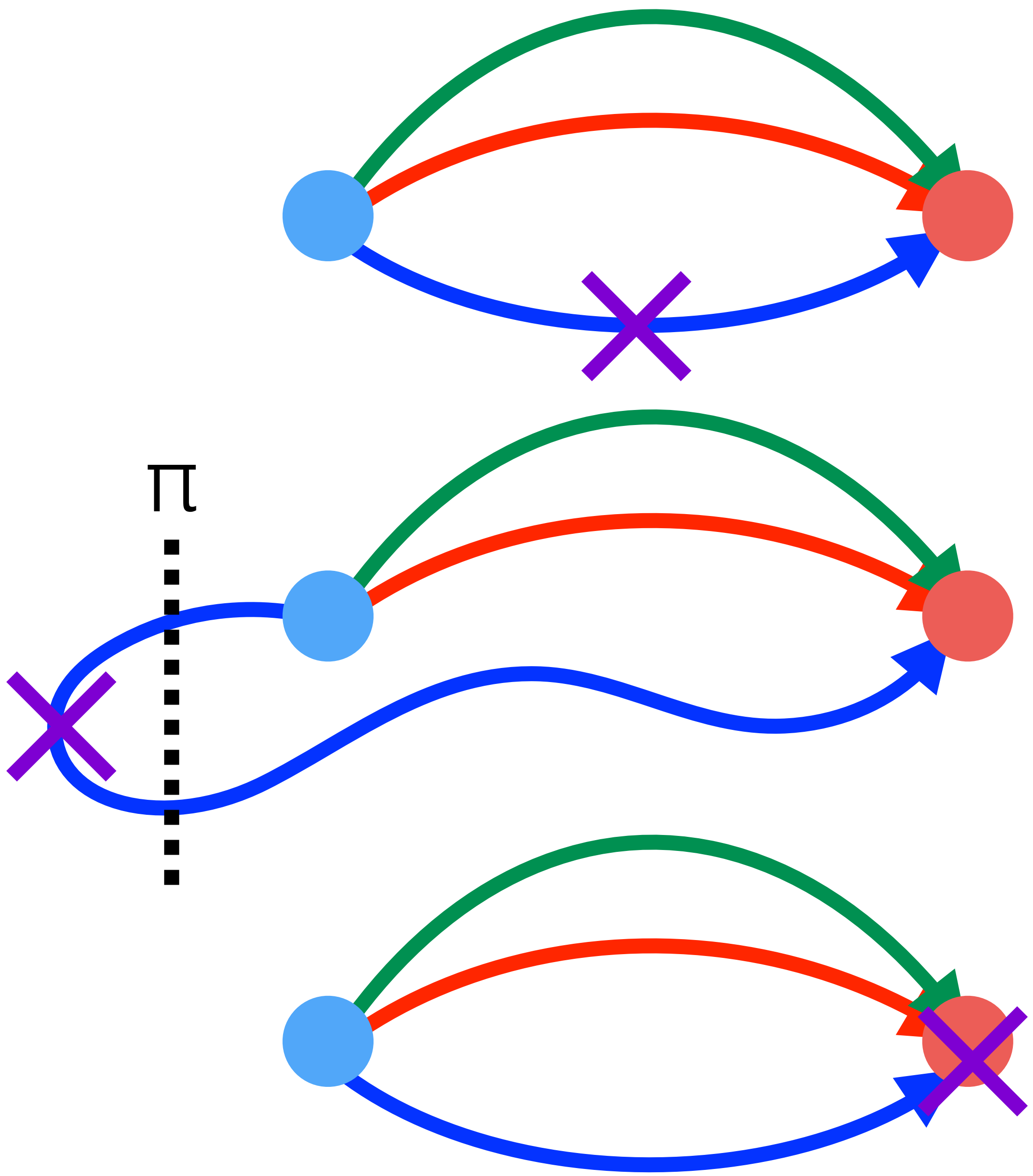

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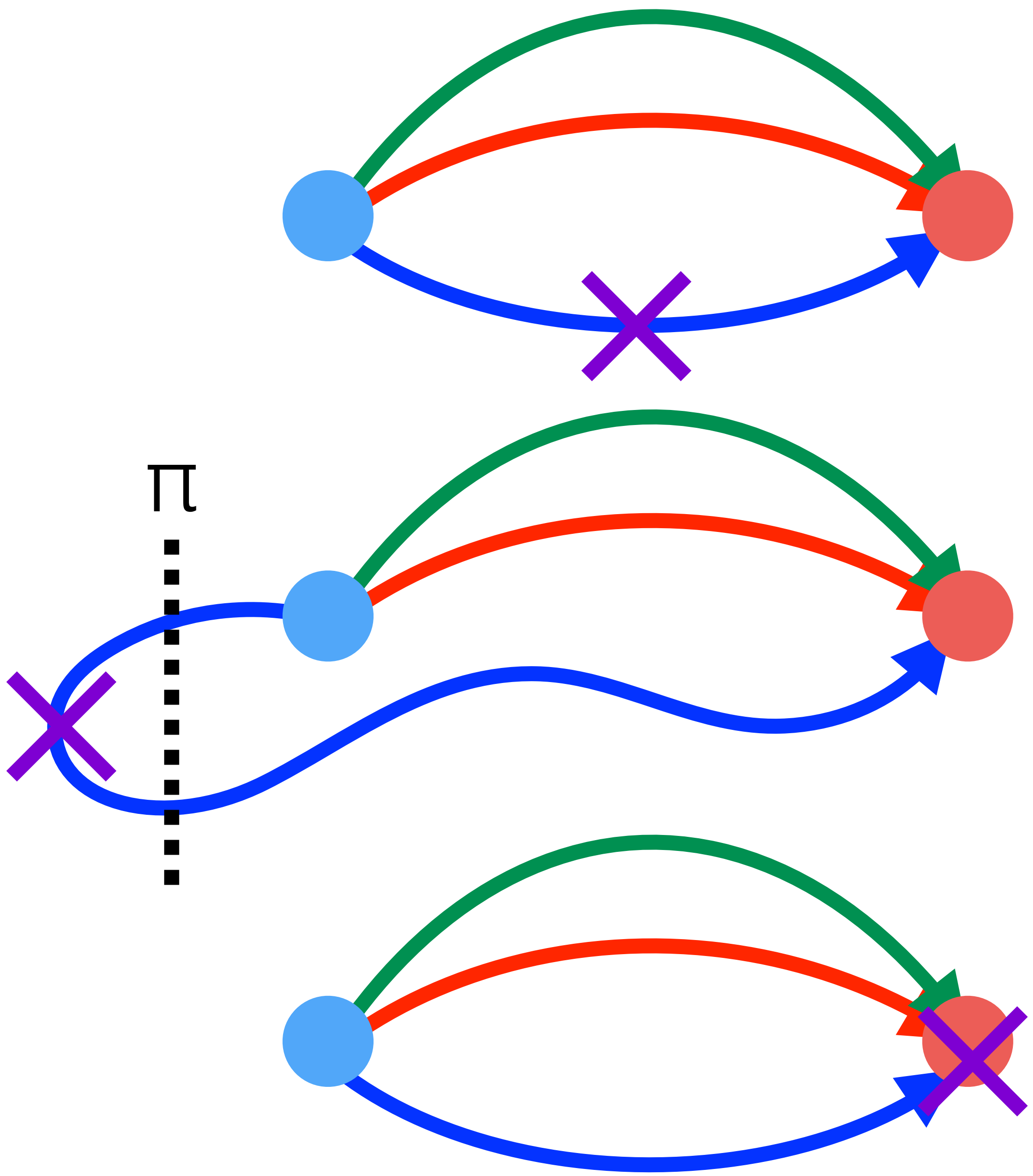

Time dependence:

linearly enhanced

$$C_{\mathcal{J}}(t) = \sum_n \left[(t-1)\, z_n g^J_{nn} z^\dagger_n + d^J_n \right] e^{-E_n t}$$

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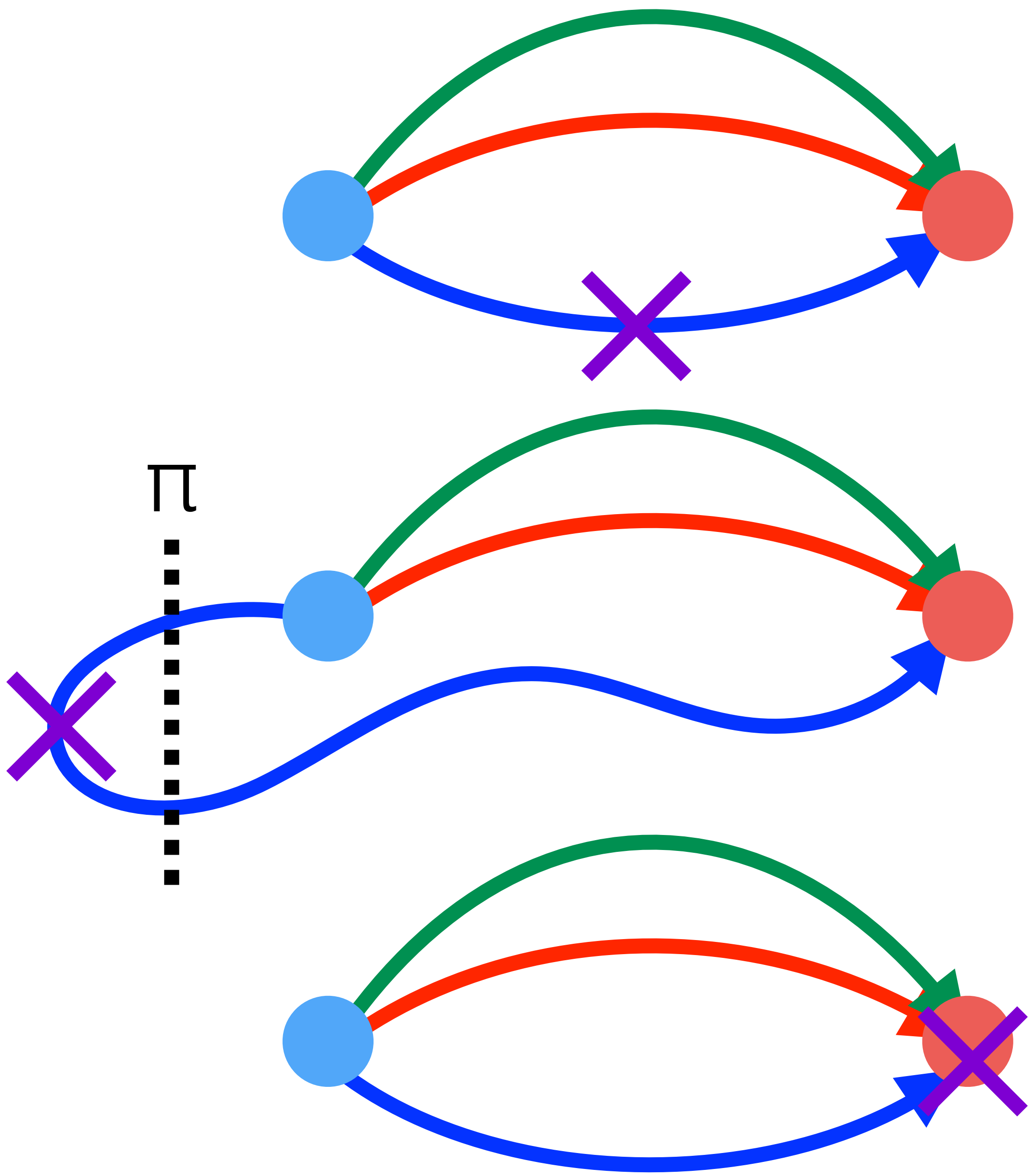

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time dependence of what you want differs from the time dependence of pieces you don't care about

Slides adapted from E. Berkowitz

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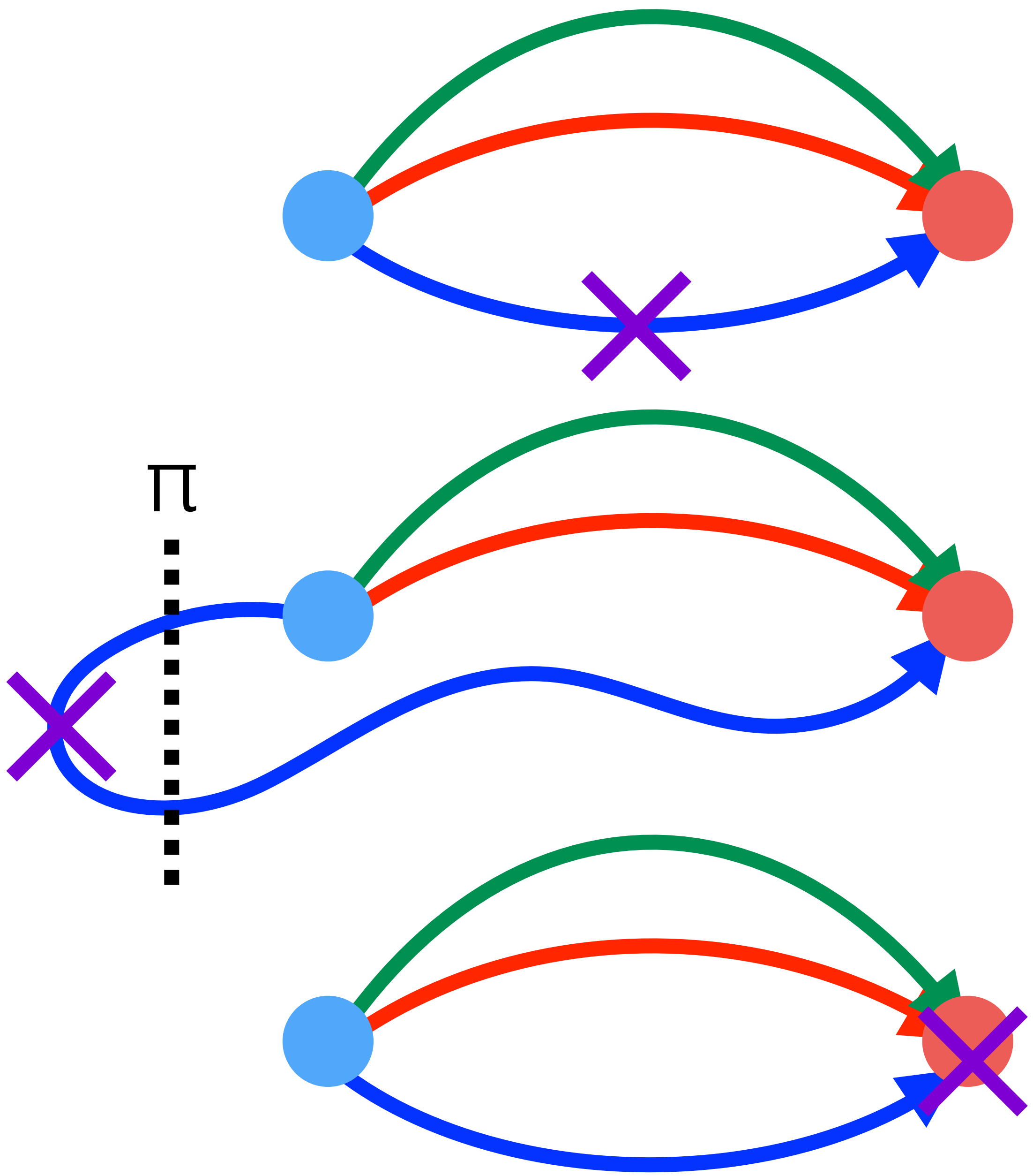

Time dependence:

at the cost of one new (tower of) coefficients

$$C_{\mathcal{J}}(t) = \sum_n \left[(t-1) z_n g^J_{nn} z^\dagger_n + d^J_n\right] e^{-E_n t} + \sum_{\substack{n \\ m\neq n}} z_n g^J_{nm} z^\dagger_m \frac{e^{-E_n t + \frac{\Delta_{nm}}{2}} - e^{-E_m t + \frac{\Delta_{mn}}{2}}}{e^{\frac{\Delta_{nm}}{2}} - e^{\frac{\Delta_{mn}}{2}}}$$

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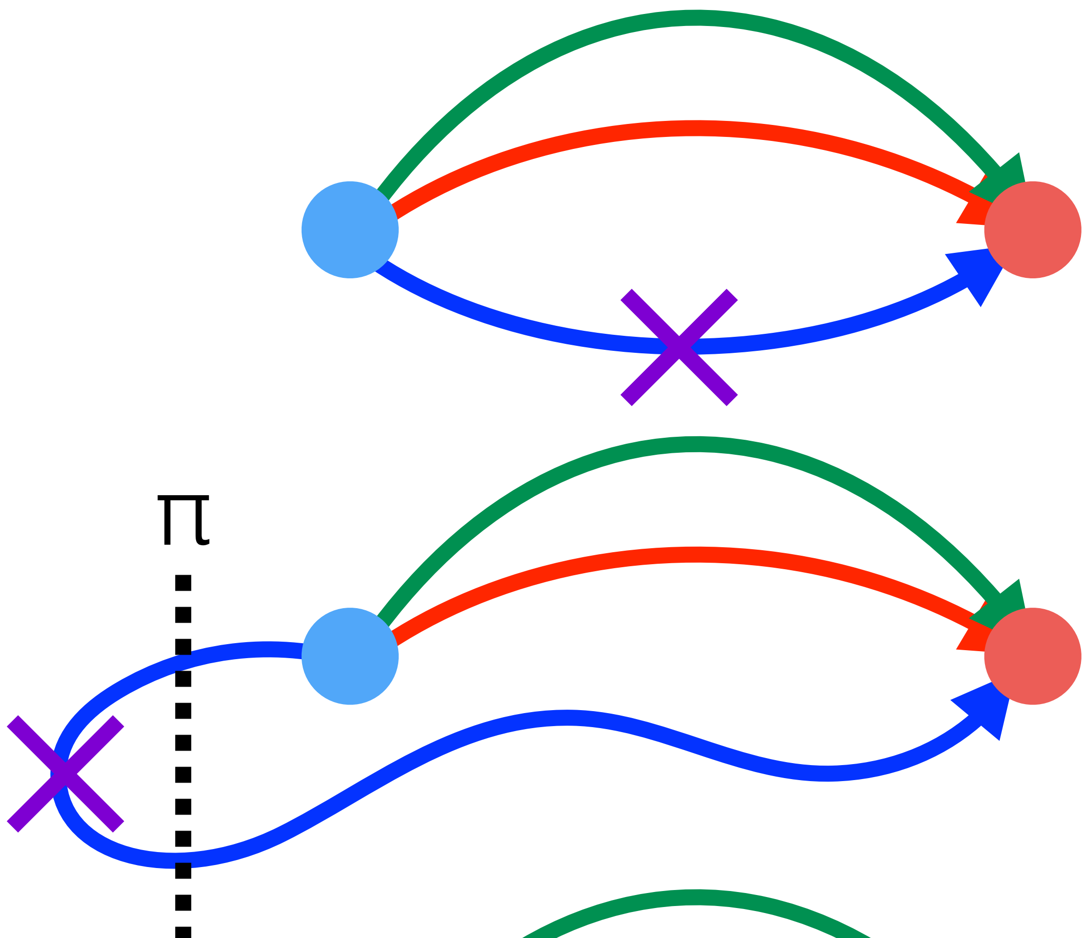

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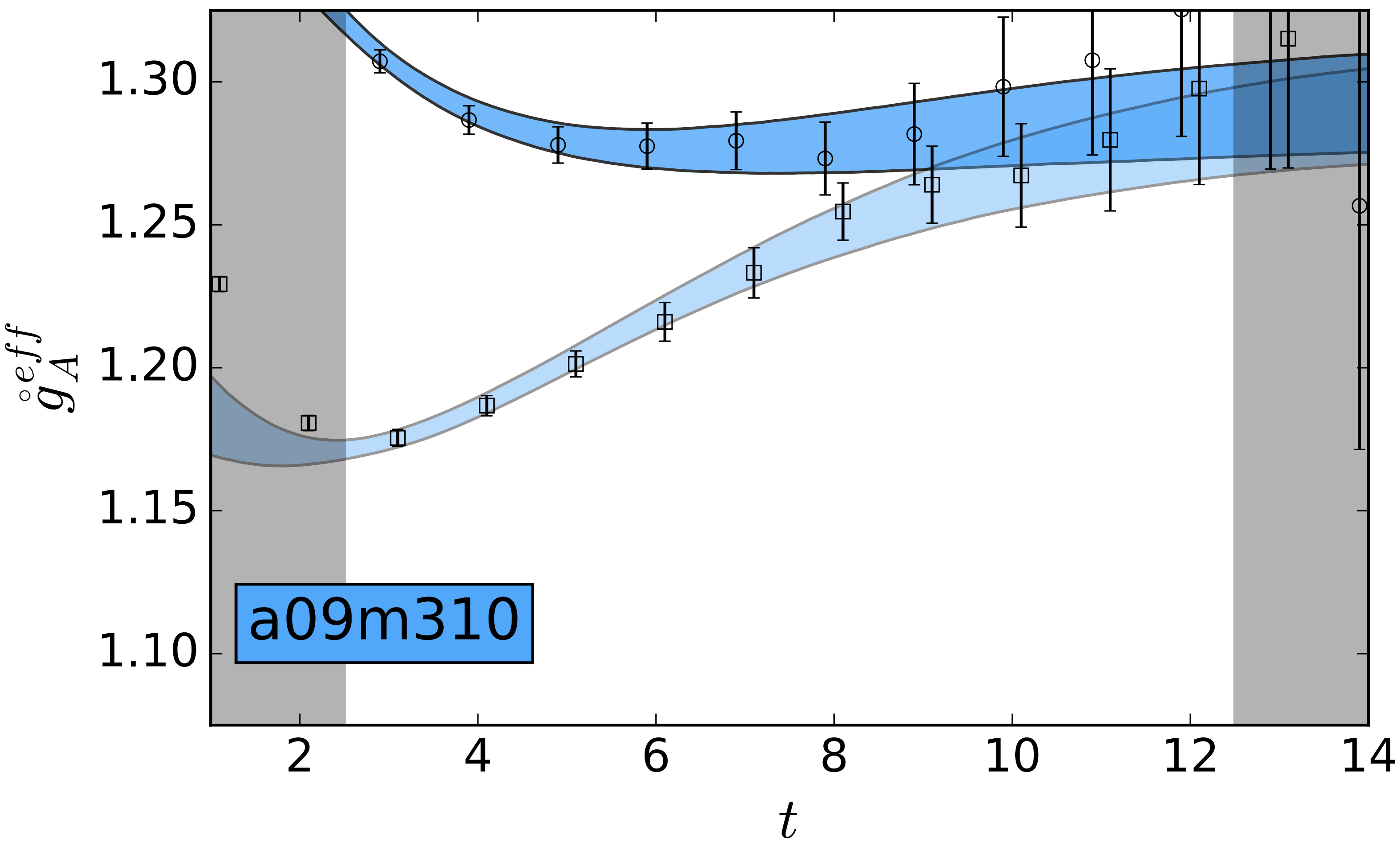
But:

1. Their size can be estimated at t=1
2. We have lots of data points to fit!

Slides adapted from E. Berkowitz

Example Effective Matrix Element

arXiv:1704.01114



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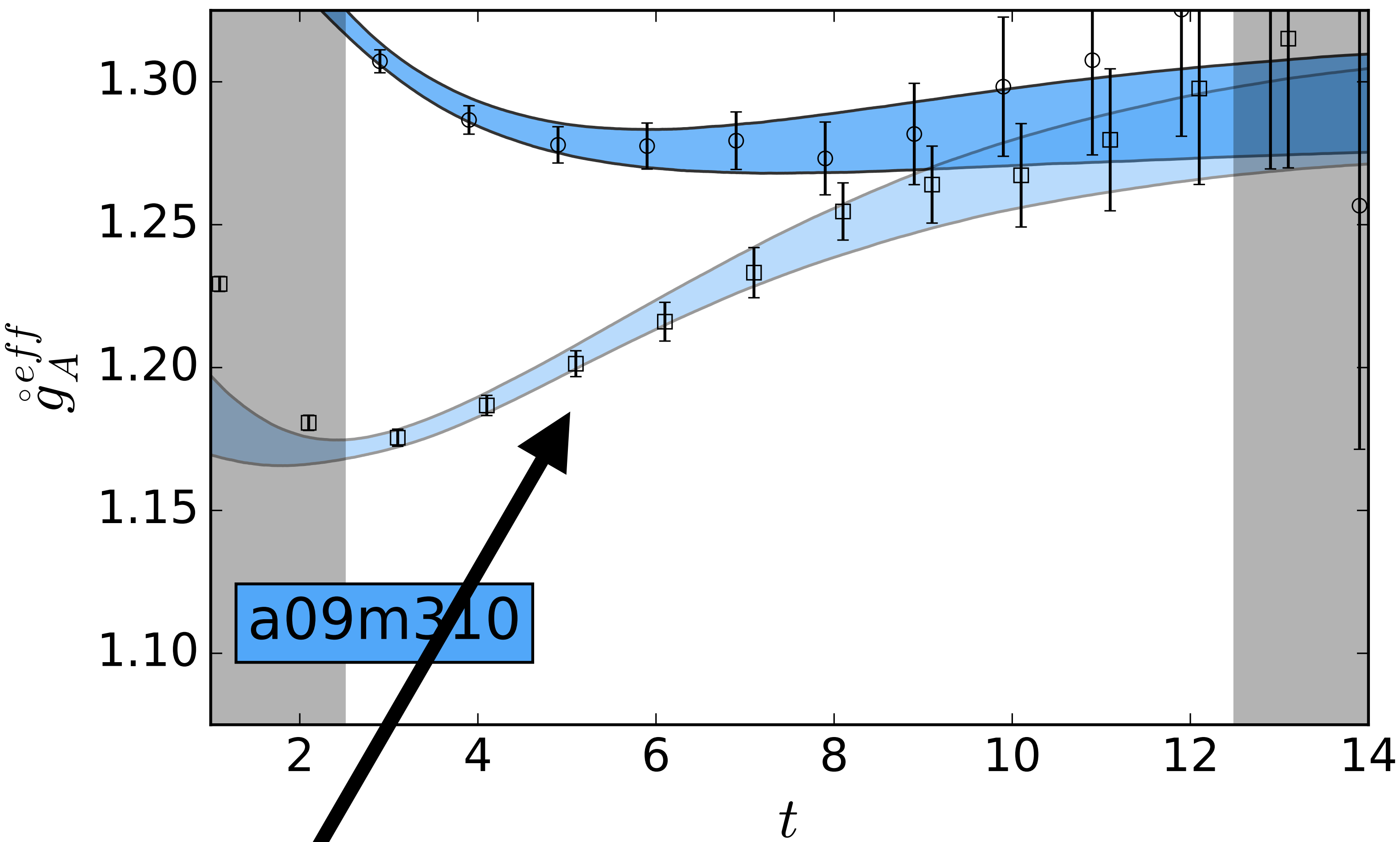

known functional form

Slides adapted from E. Berkowitz

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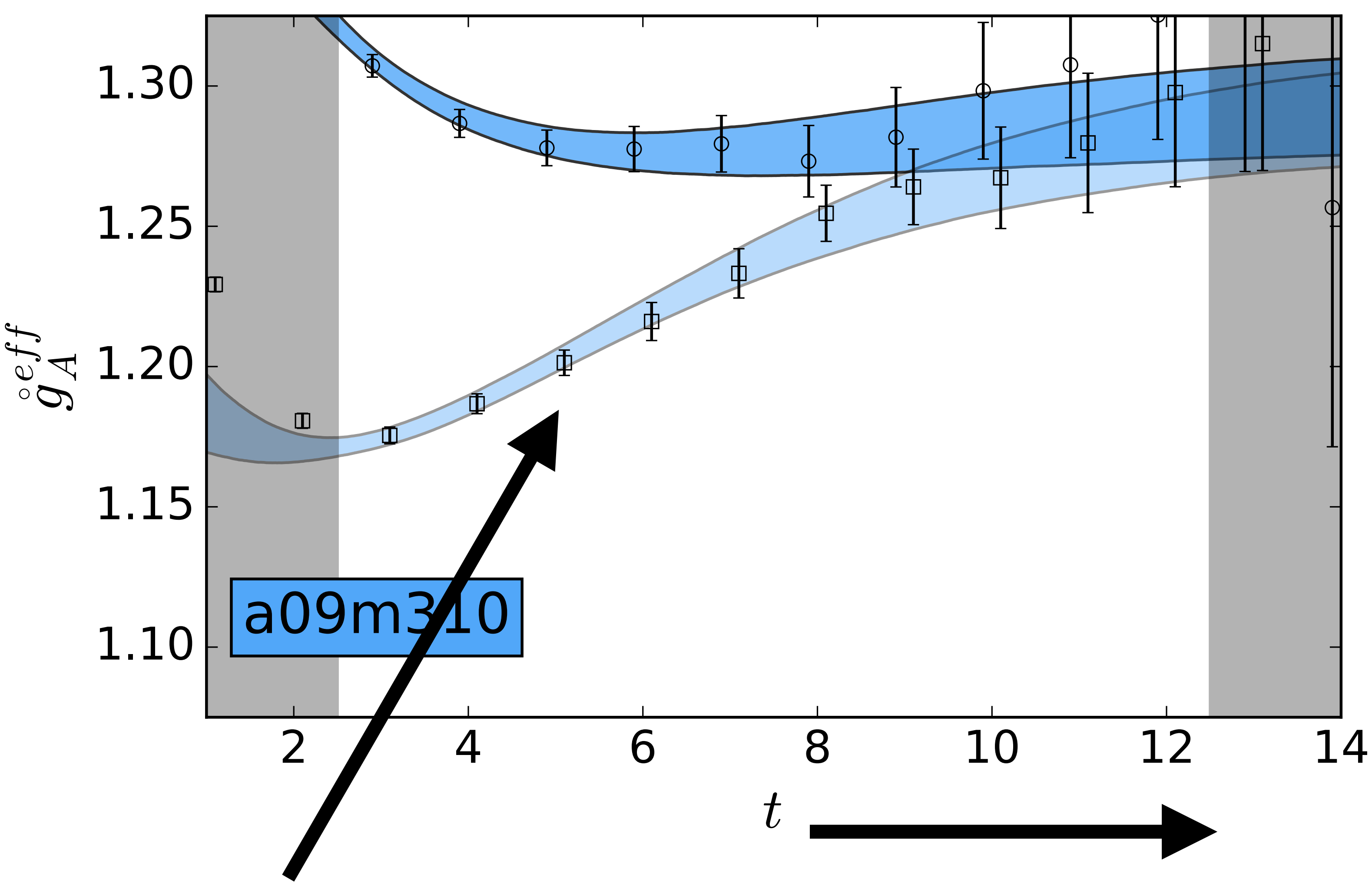

known functional form

asymptotes in just one time variable

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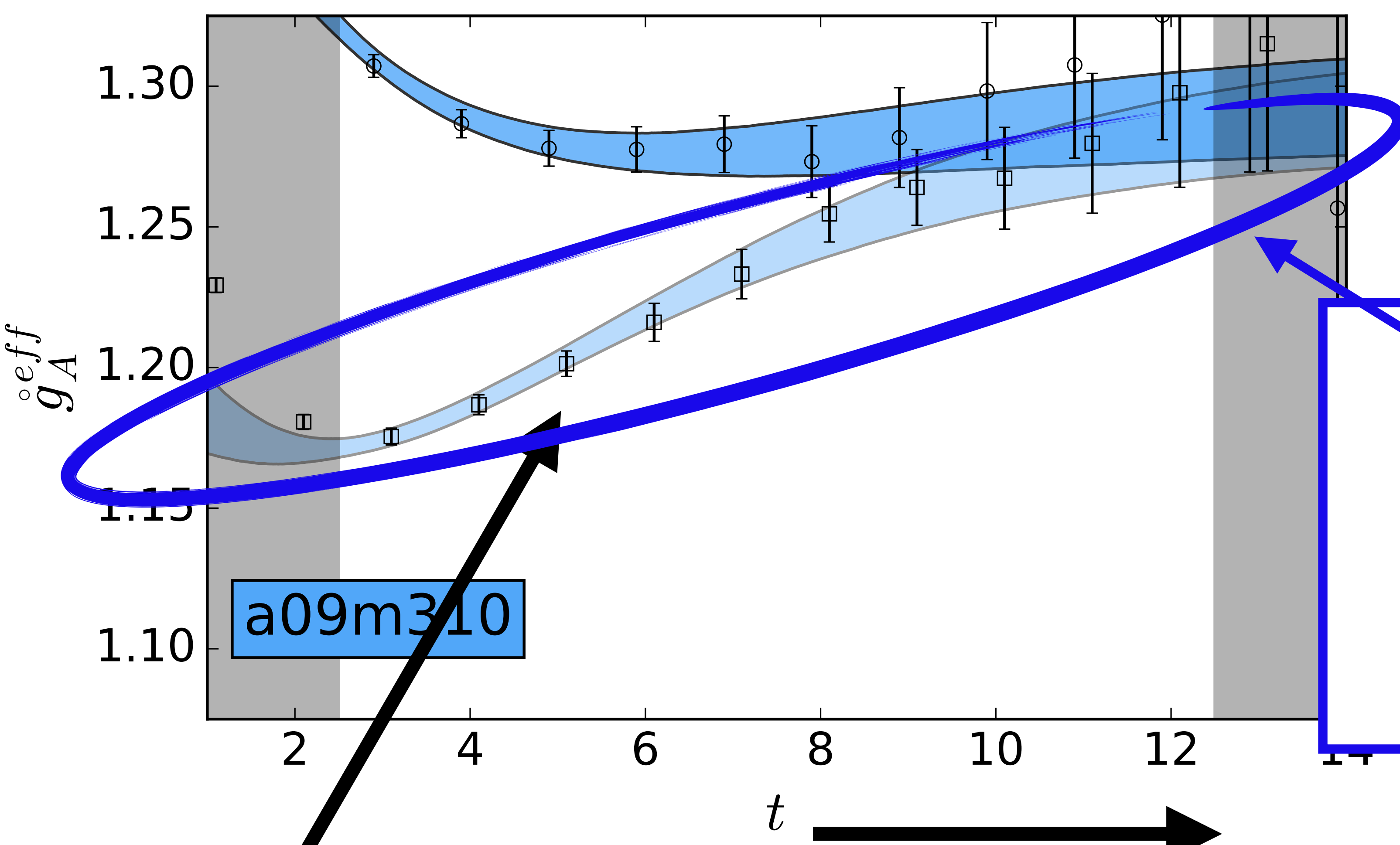

Two different nucleon interpolators: asymptote to same ground state value (g_A), different overlap onto excited states

known functional form

asymptotes in just one time variable

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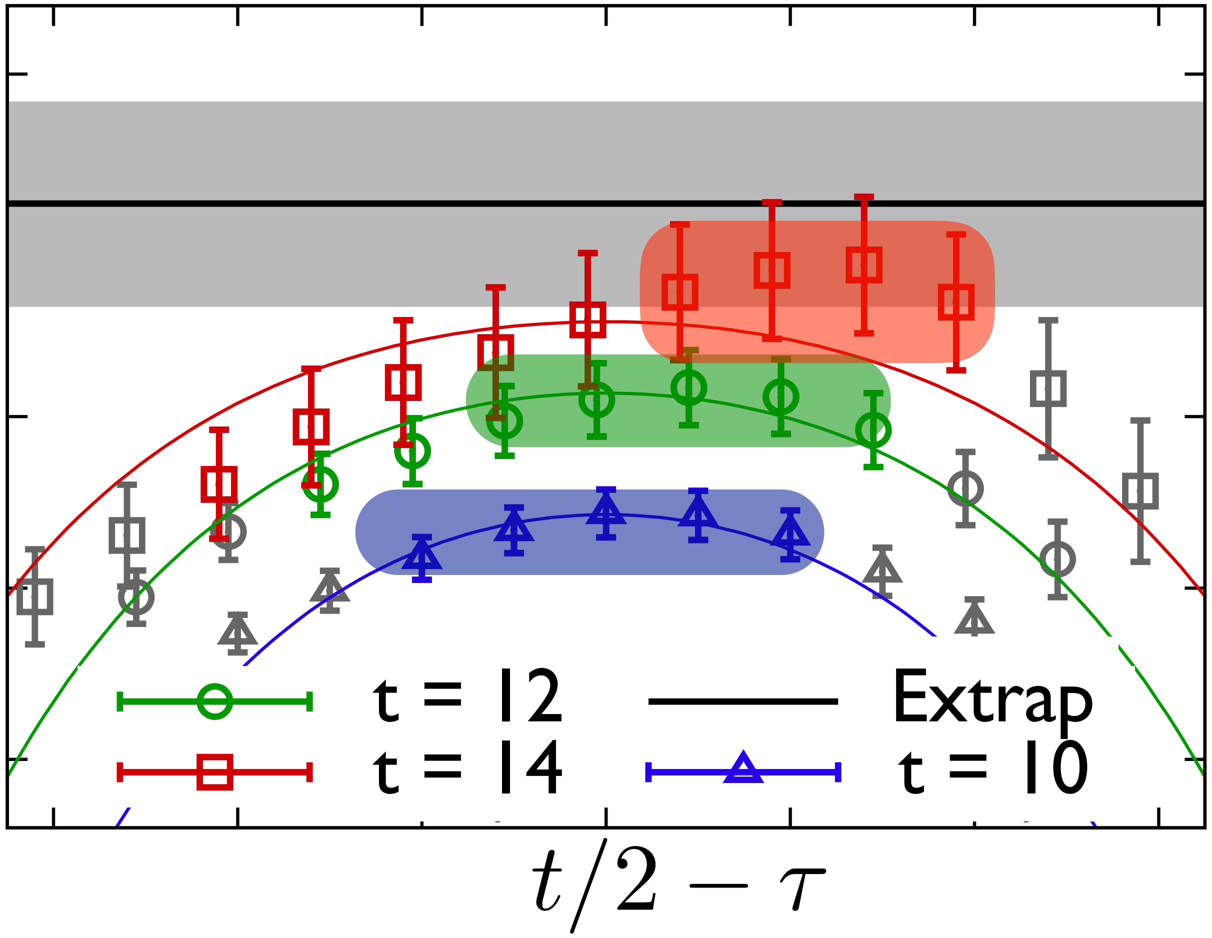
Improved Systematics

PNDME Phys. Rev. D94 (2016) arXiv:1606.07049



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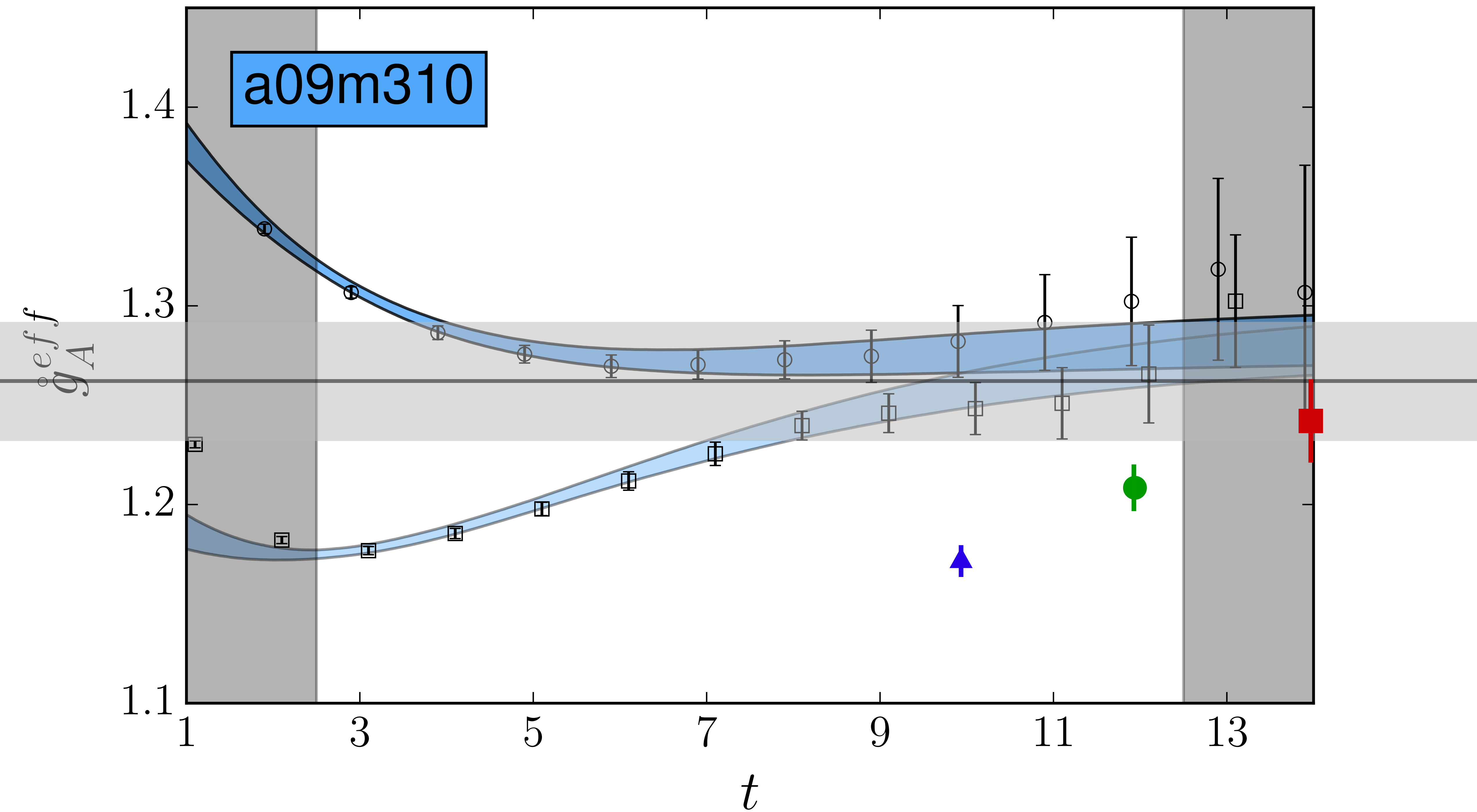

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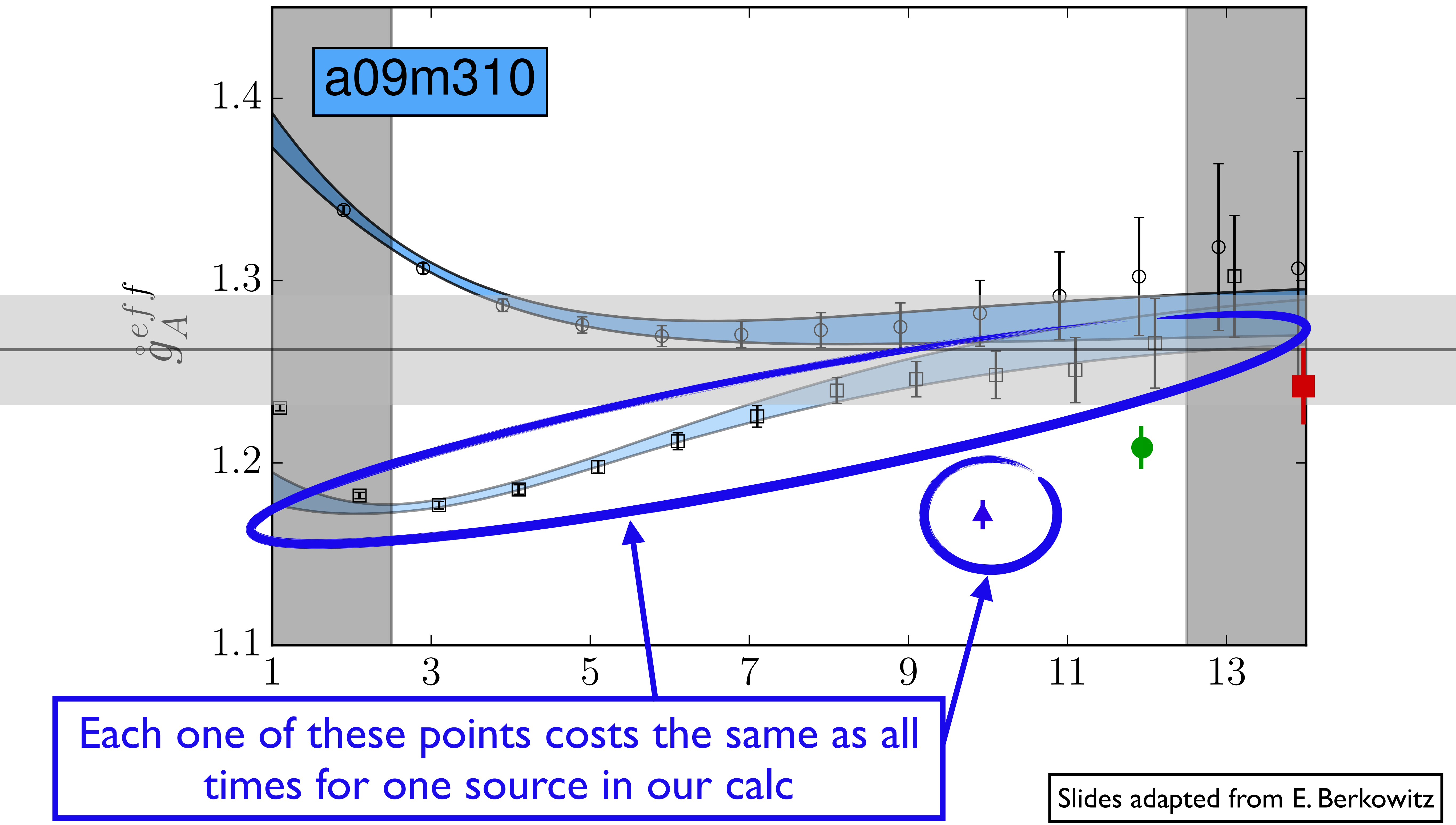

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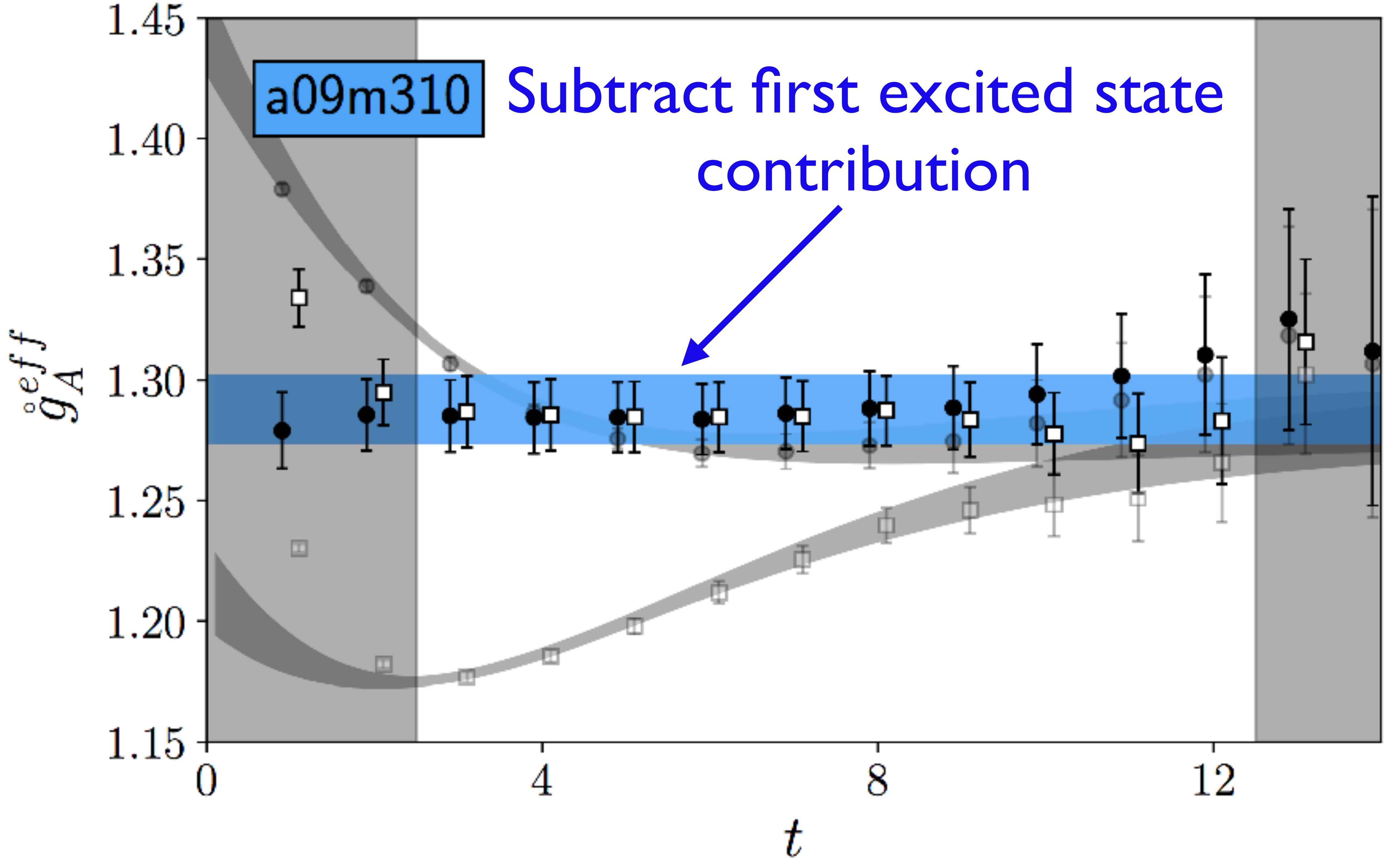

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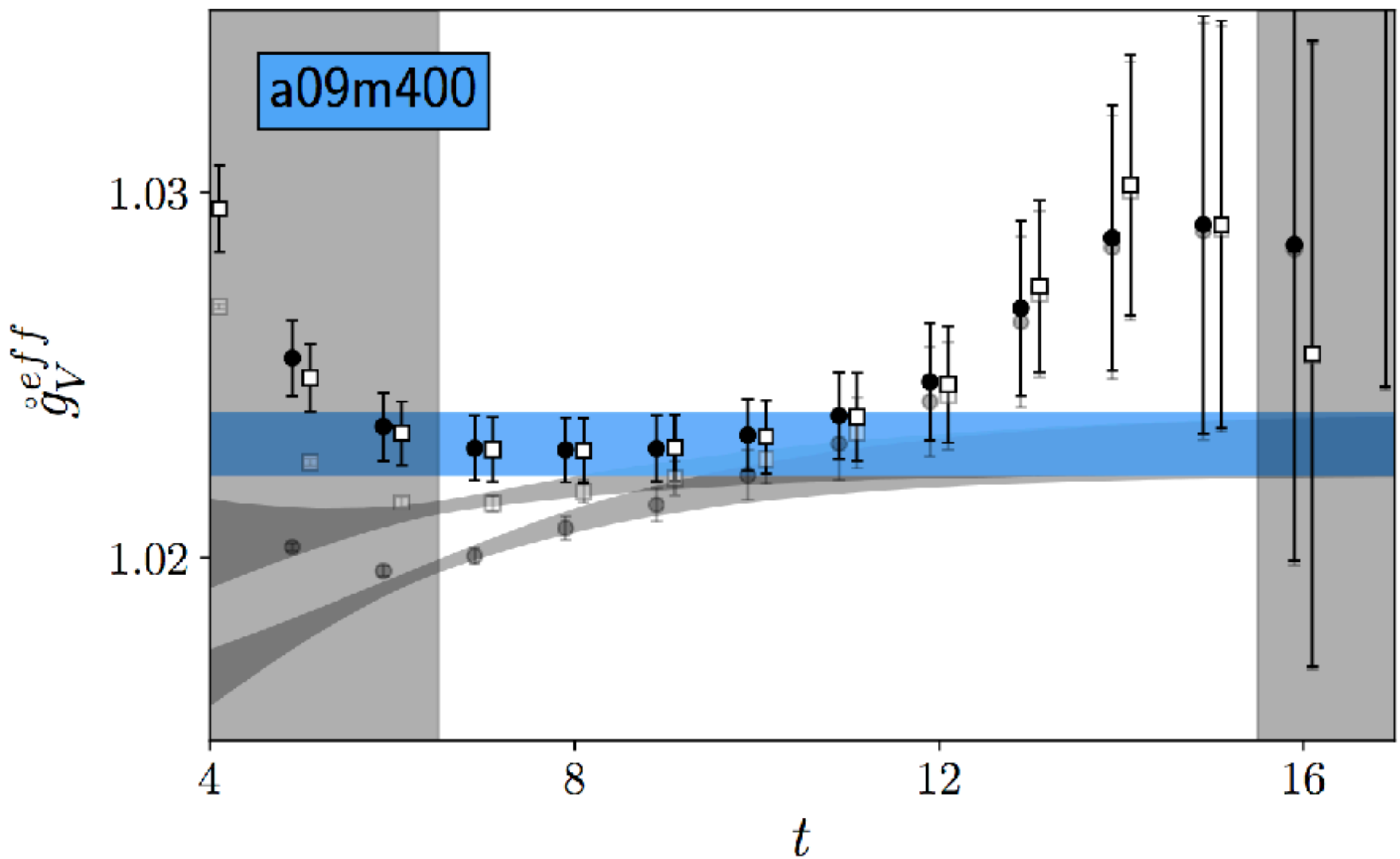

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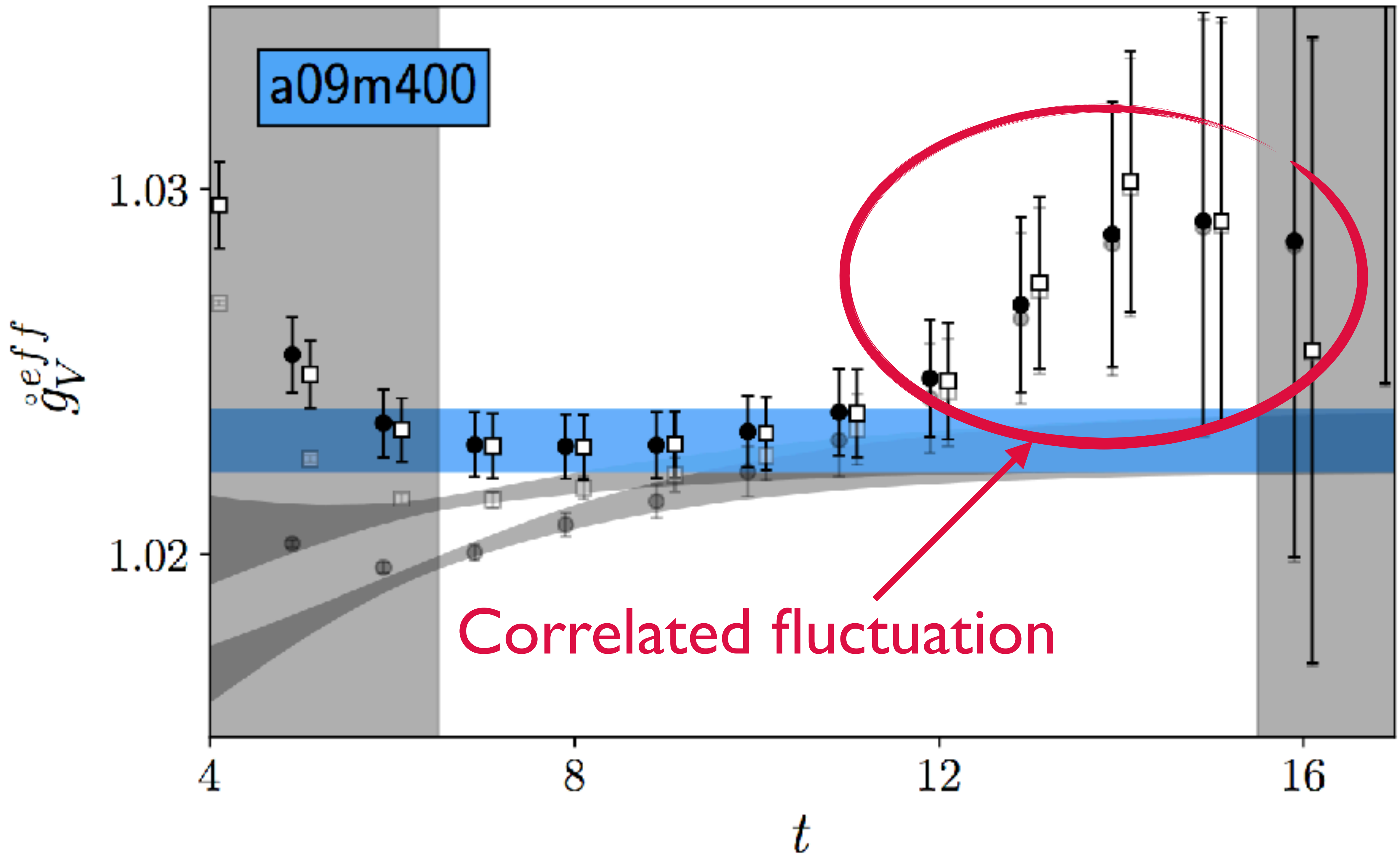

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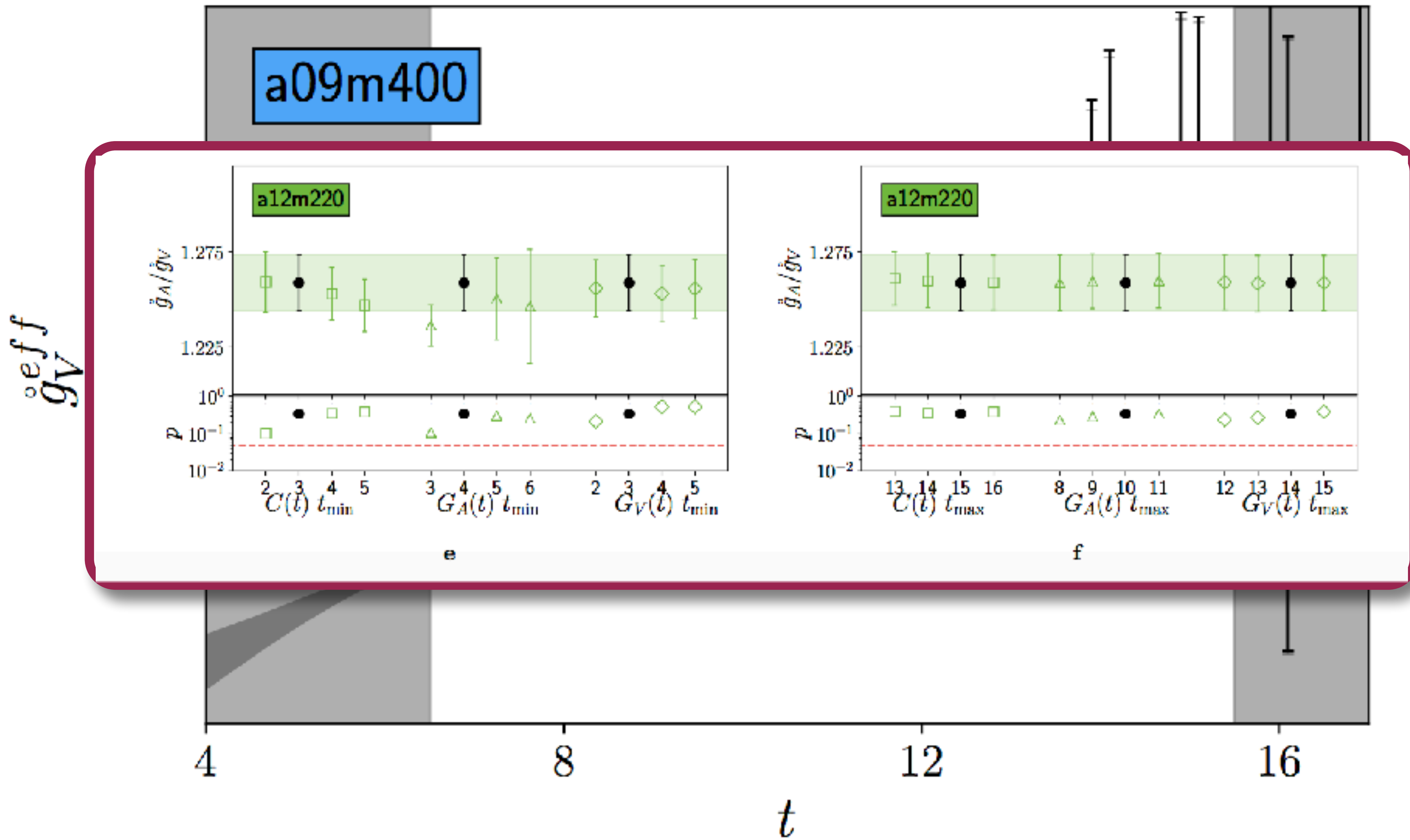
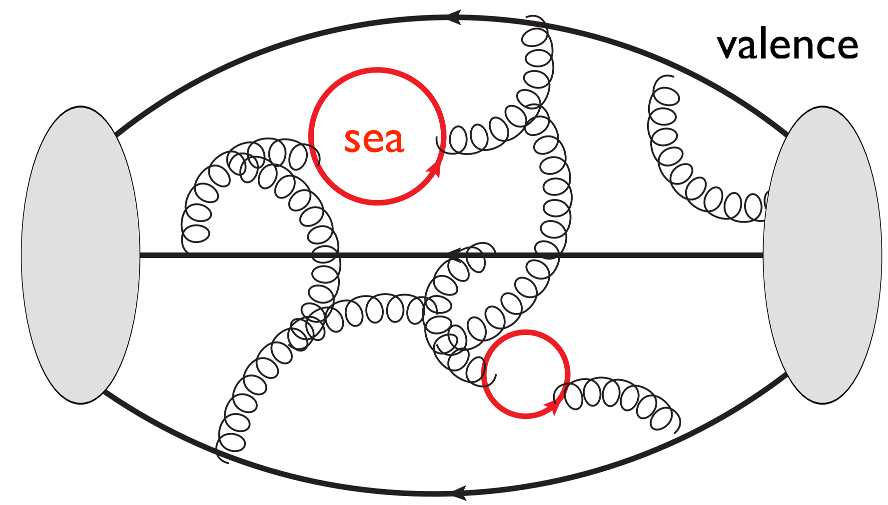


Mixed Action LQCD

- Discretization (action) used to calculate sea (gauge field configurations) and valence (propagators) don't need to be the same



- Mixed action balances computation time and systematics

- We use:

    - HISQ sea (fast, coarse)

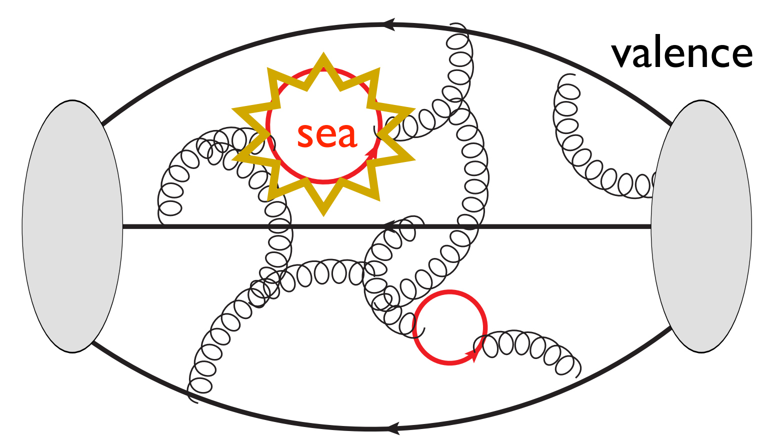
    - DWF valence (slow, precise)

- Consequences of mixed action can be parameterized using mixed action EFT

HISQ Ensembles

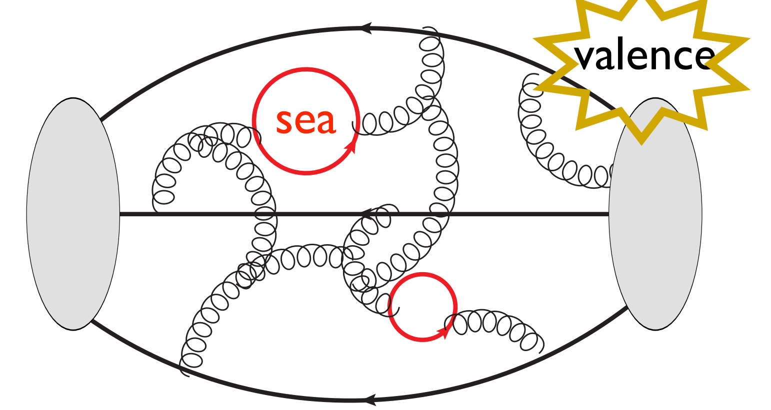
$a[\text{fm}]$: $m_\pi[\text{MeV}]$	400	350	310	220	130
0.15	$m_\pi L \sim 4.8$	$m_\pi L \sim 4.2$	$m_\pi L \sim 3.78$	$m_\pi L \sim 3.99$	$m_\pi L \sim 3.25$
				$m_\pi L \sim 3.22$	
0.12	$m_\pi L \sim 5.8$	$m_\pi L \sim 5.1$	$m_\pi L \sim 4.54$	$m_\pi L \sim 4.29$	$m_\pi L \sim 3.91$
				$m_\pi L \sim 5.36$	
0.09	$m_\pi L \sim 5.8$	$m_\pi L \sim 5.1$	$m_\pi L \sim 4.50$	$m_\pi L \sim 4.73$	

- Nf = 2+1+1 Highly Improved Staggered Quarks (HISQ)
- Chiral symmetry only partially preserved
- Fast!
- Publicly available!
- Added ensembles at heavier pion mass to improve chiral/continuum extrapolations

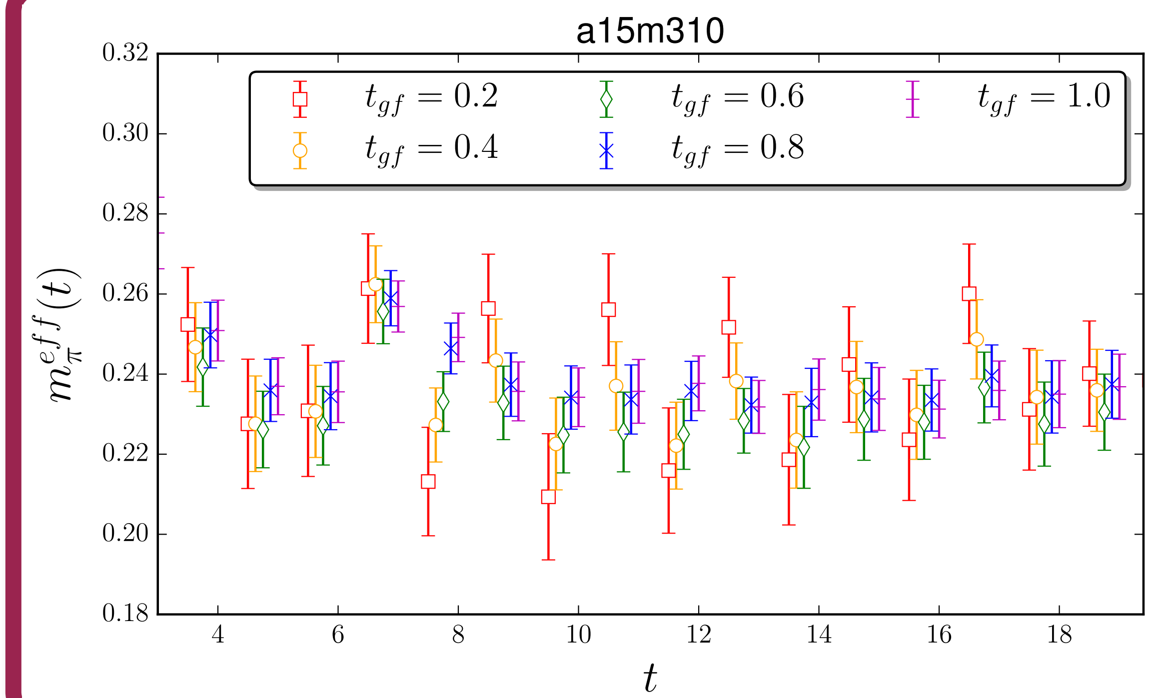


MILC Collaboration
Phys. Rev. D87 (2013) 054505

Möbius DWF propagators



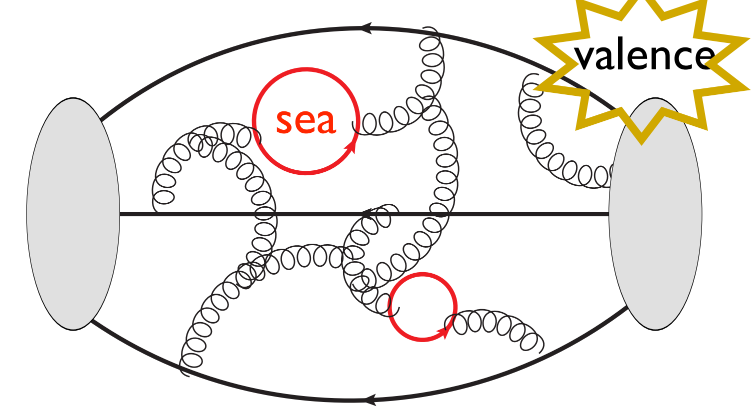
- Improved Domain-Wall Fermions
  - Chiral symmetry breaking exponentially suppressed
  - g_A/g_V is a quantitative measure of chiral symmetry breaking
  - Discretization effects come in at $O(a^2)$
- Gradient flow method for smearing configs
  - $m_{res} < 0.1\ m_\ell$ for moderate L_5
  - $M_5 < 1.3$
  - improved statistics



Narayanan, Neuberger (2006), Luscher (2010)

Callat arXiv:1701.07559

Möbius DWF propagators



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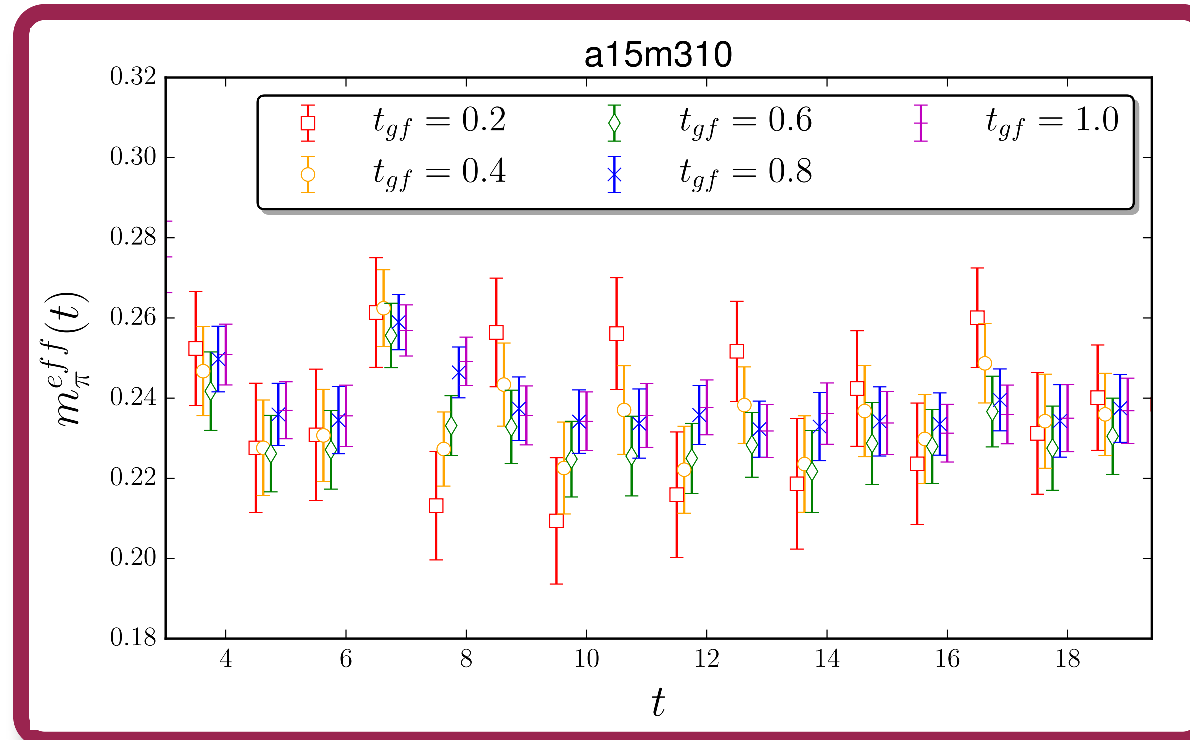

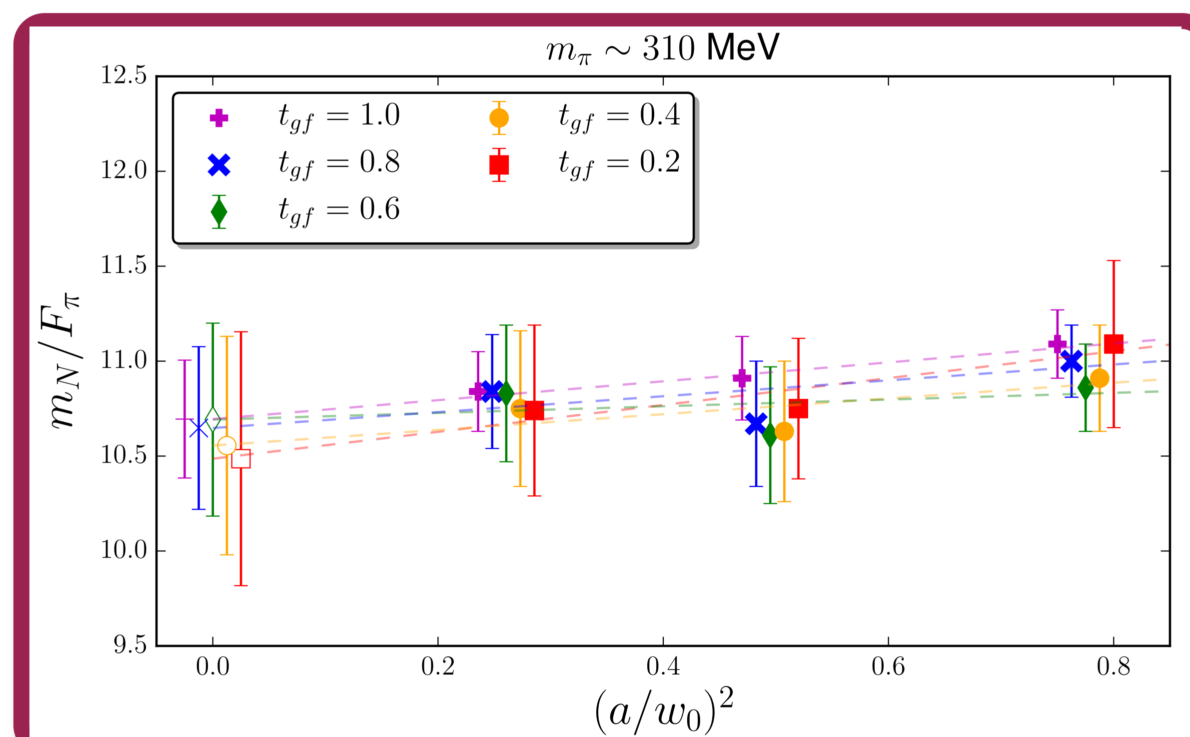

Narayanan, Neuberger (2006), Luscher (2010)

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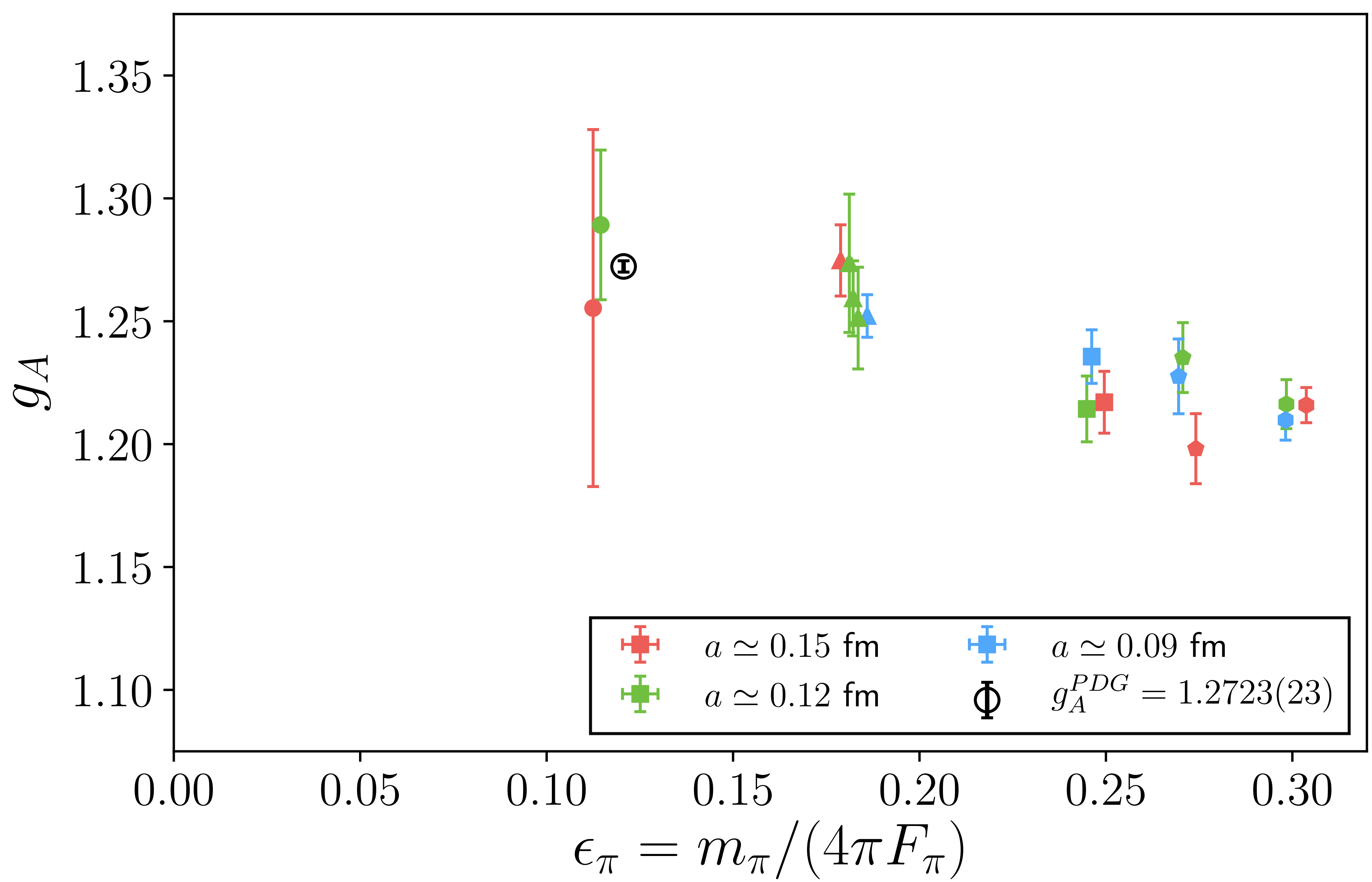
Results



1.35
1.30
1.25
1.20
1.15
1.10
g_A
0.00
0.05
0.10
0.15
0.20
0.25
0.30
$\epsilon_\pi = m_\pi/(4\pi F_\pi)$
$a \simeq 0.15$ fm
$a \simeq 0.12$ fm
$a \simeq 0.09$ fm
$g_A^{PDG} = 1.2723(23)$

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

Extrapolations

Dimensionless parameters:

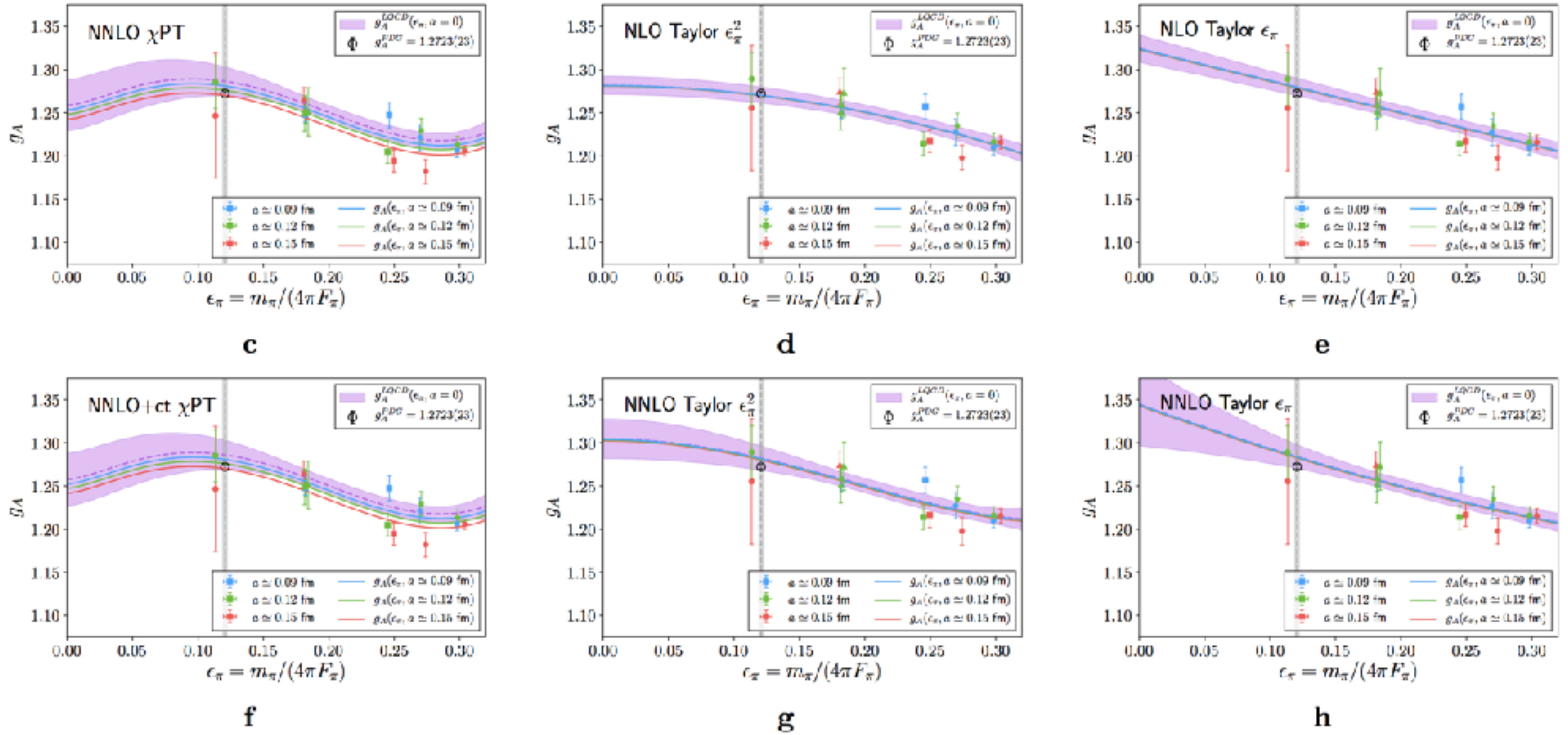
lattice spacing, volume, pion mass

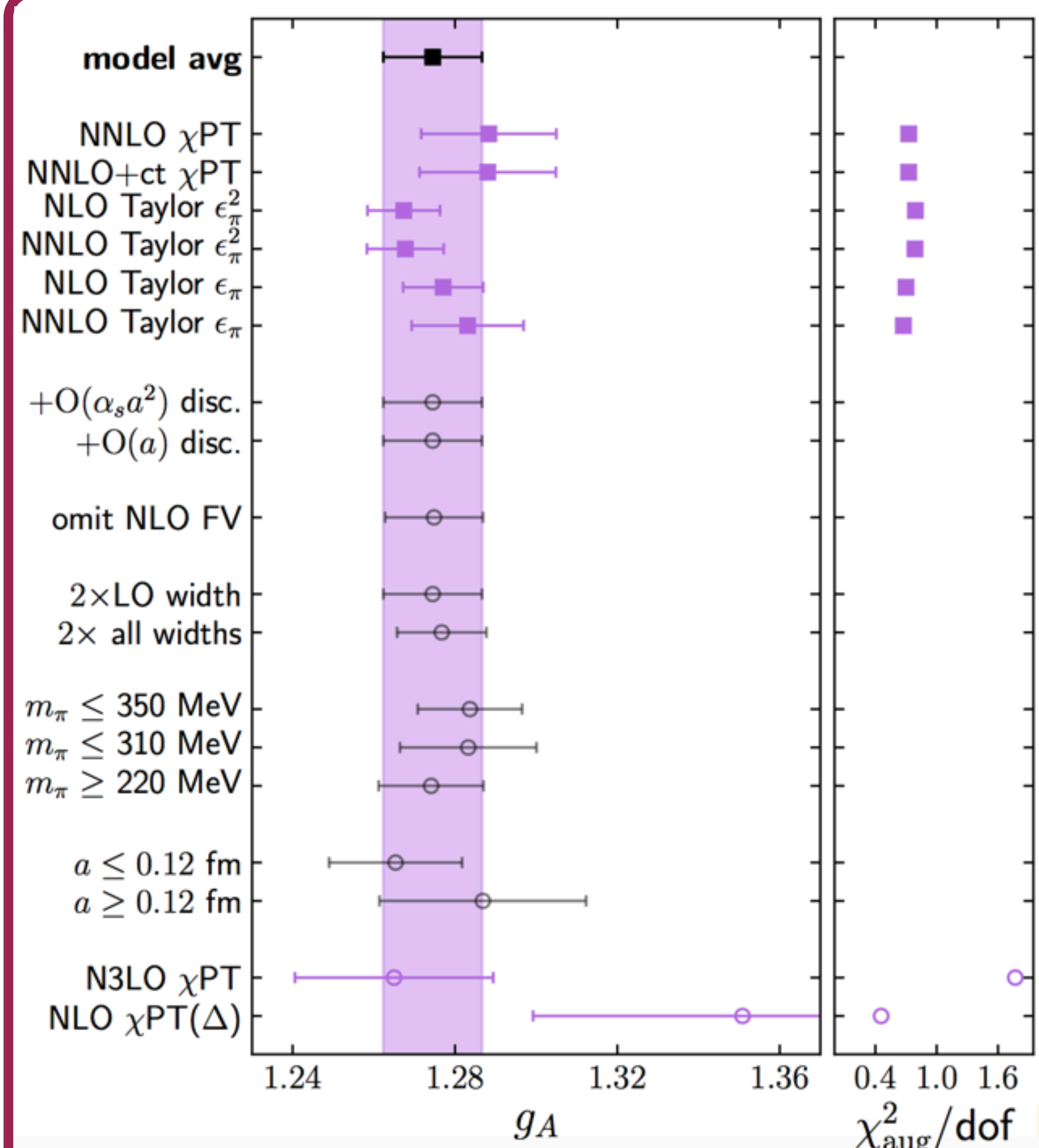
$$\epsilon_a^2 = \frac{1}{4\pi}\frac{a^2}{w_0^2} \qquad m_\pi L \qquad \epsilon_\pi = \frac{m_\pi}{4\pi F_\pi}$$

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

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

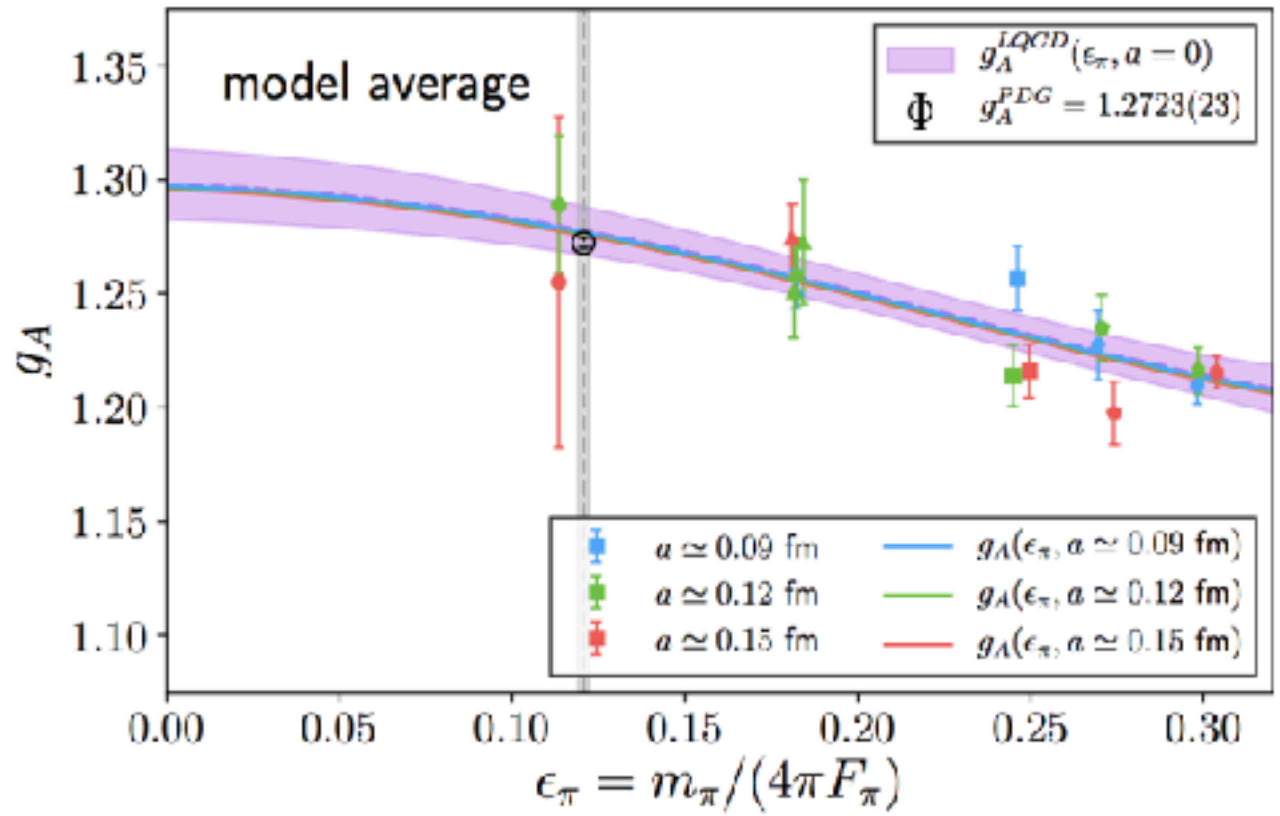
Extrapolations

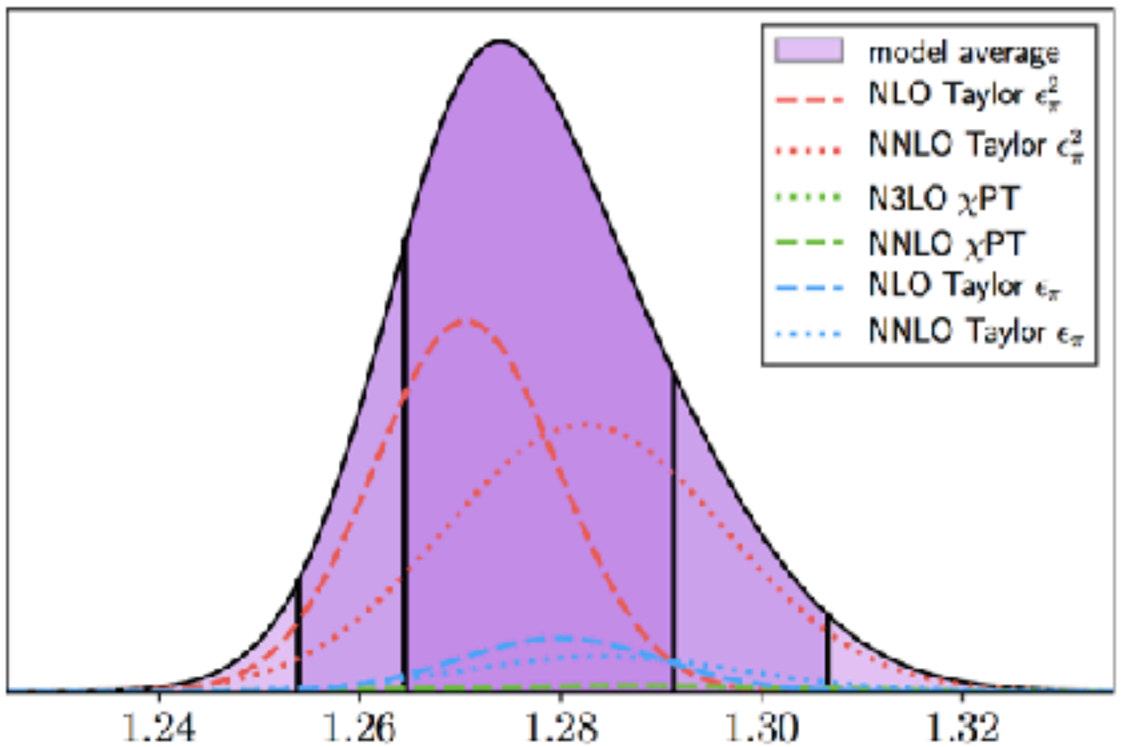




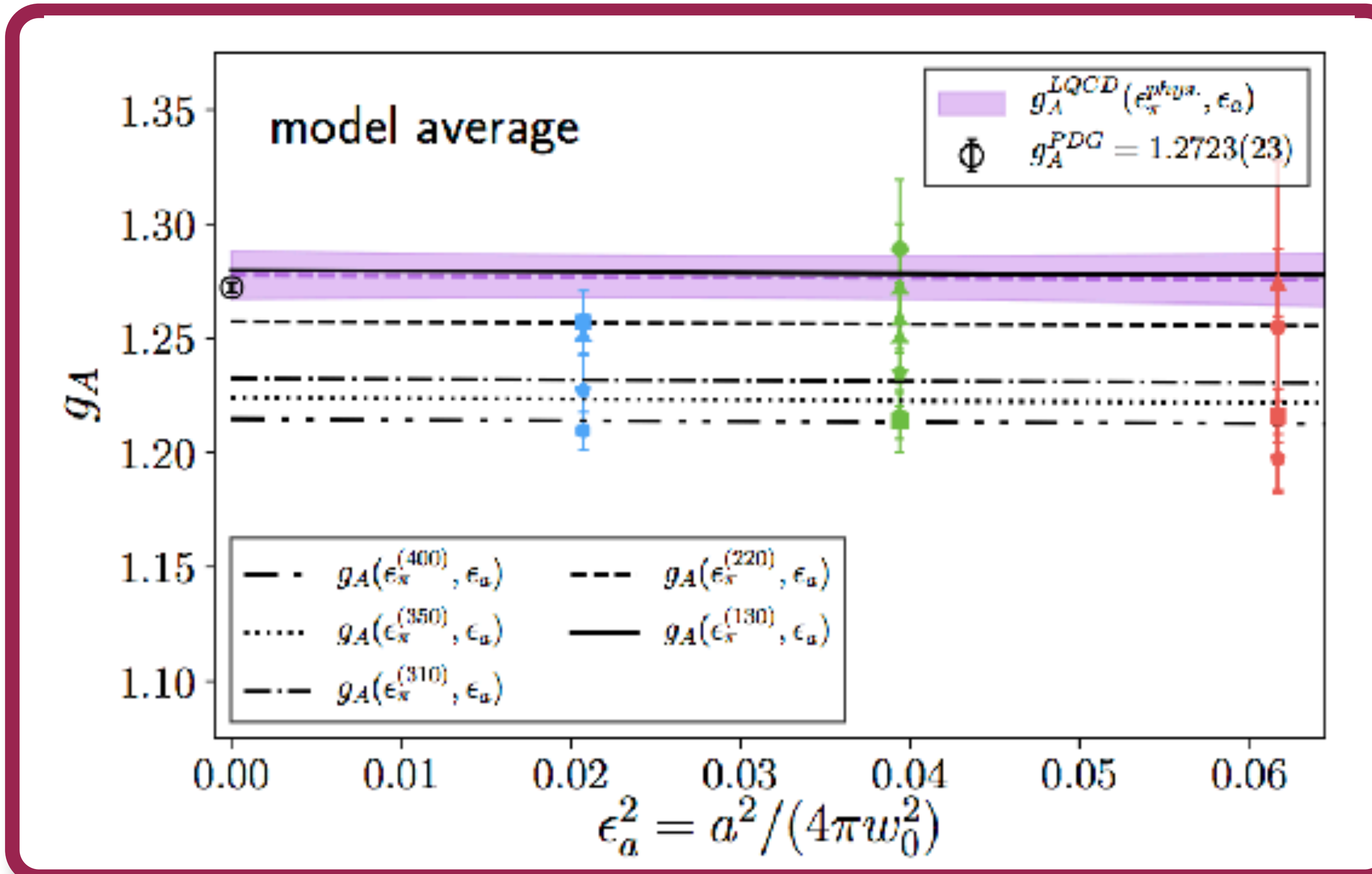
model avg
NNLO χPT
NNLO+ct χPT
NLO Taylor ϵ_π^2
NNLO Taylor ϵ_π^2
NLO Taylor ϵ_π
NNLO Taylor ϵ_π
$+\mathrm{O}(\alpha_s a^2)$ disc.
$+\mathrm{O}(a)$ disc.
omit NLO FV
2×LO width
2× all widths
$m_\pi \leq$ 350 MeV
$m_\pi \leq$ 310 MeV
$m_\pi \geq$ 220 MeV
$a \leq 0.12$ fm
$a \geq 0.12$ fm
N3LO χPT
NLO χPT(Δ)
1.24
1.28
1.32
1.36
g_A
0.4
1.0
1.6
χ^2_{aug}/dof

Model Average

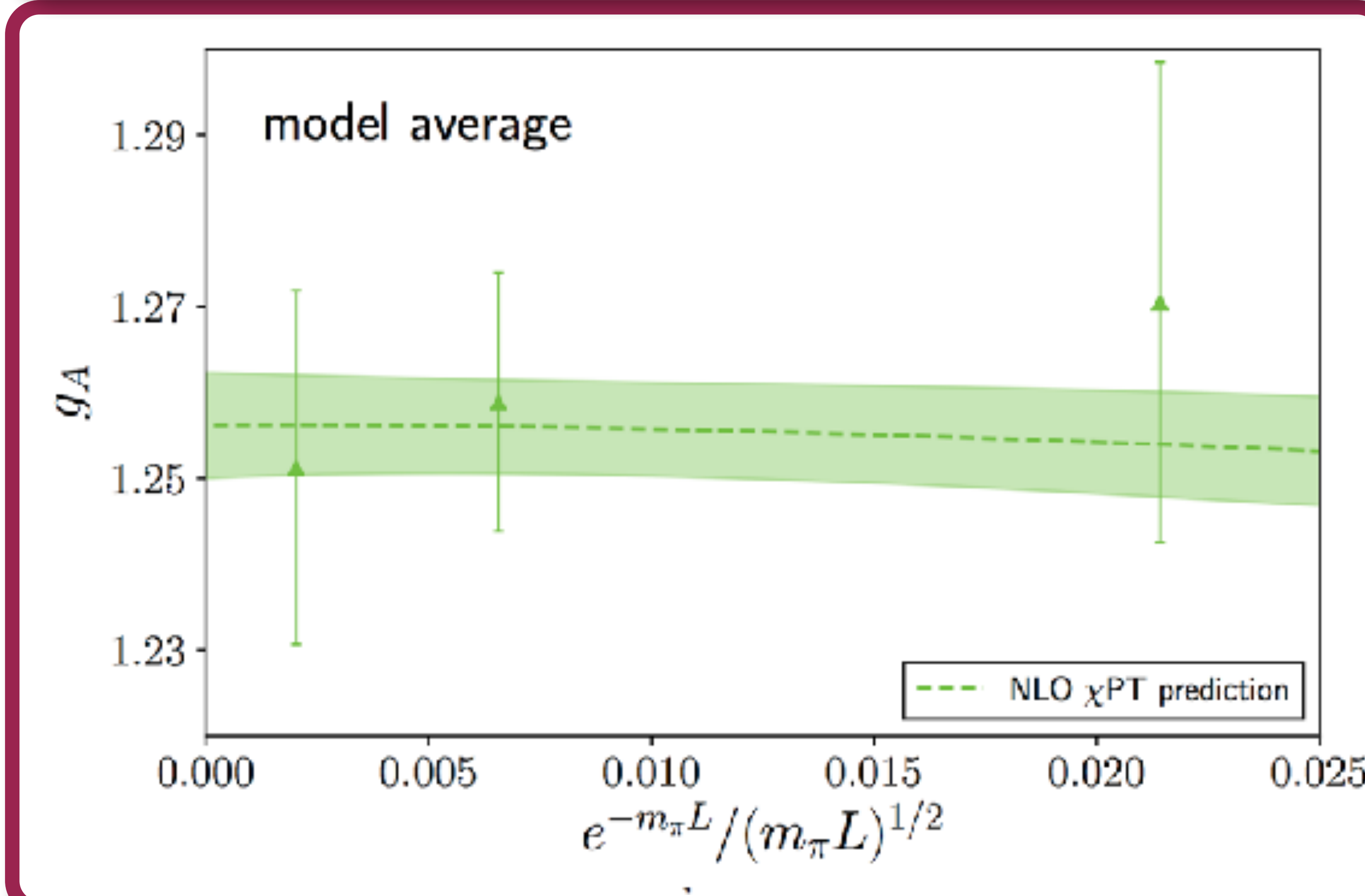




Discretization

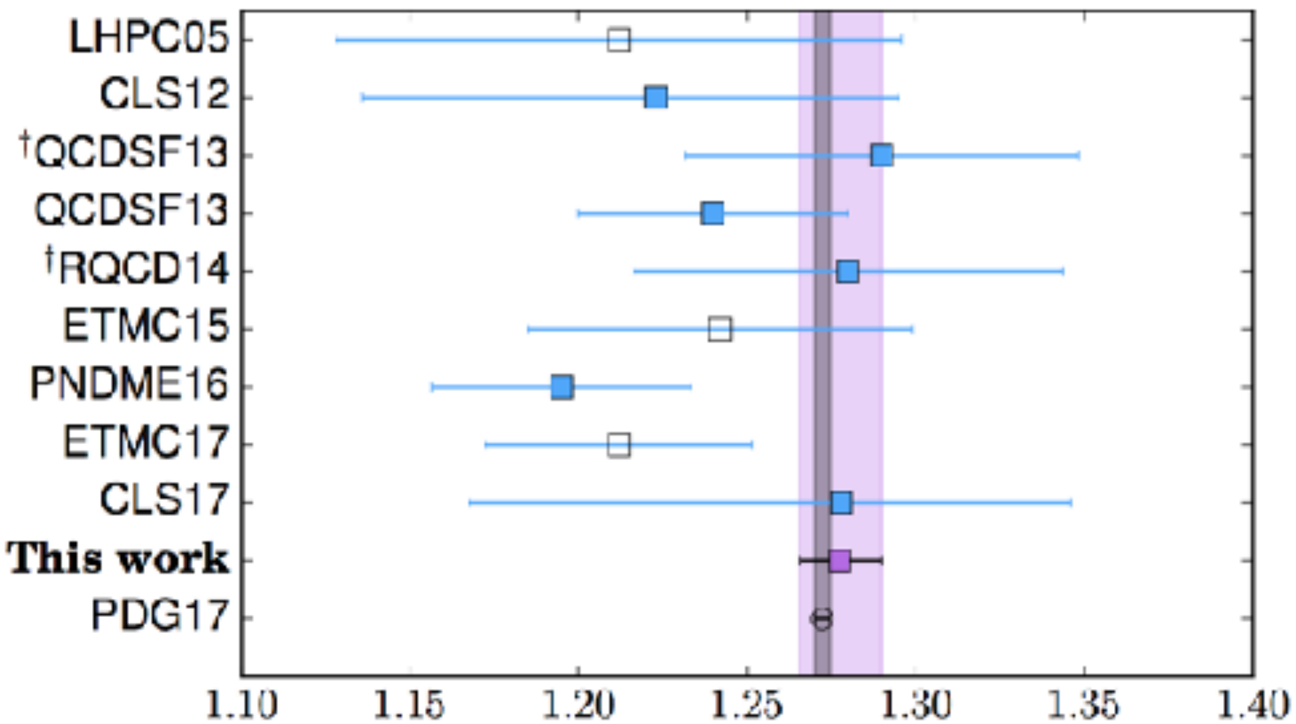


Finite Volume



Final result: $g_A = 1.275 \pm 0.12$

PRELIMINARY!

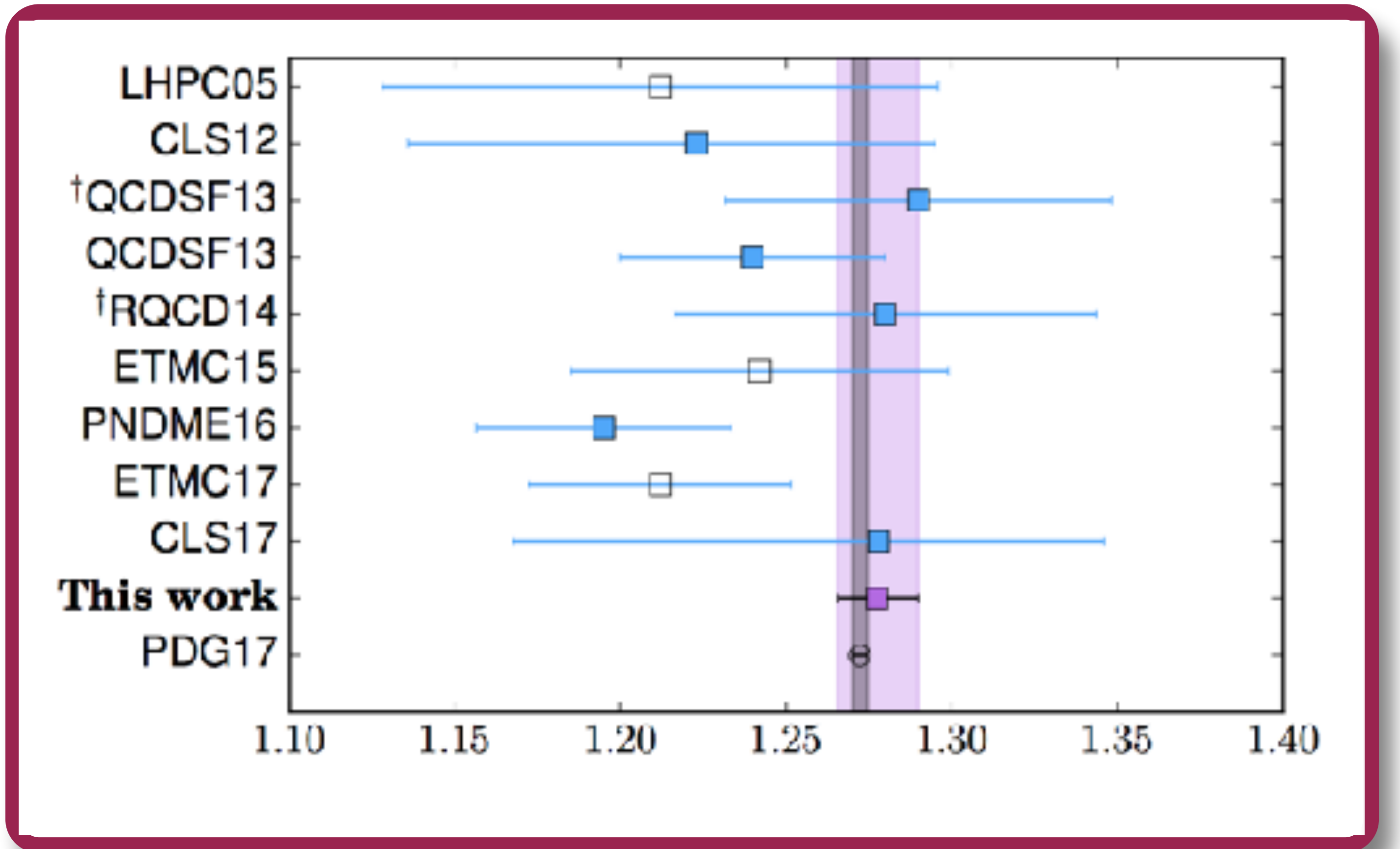


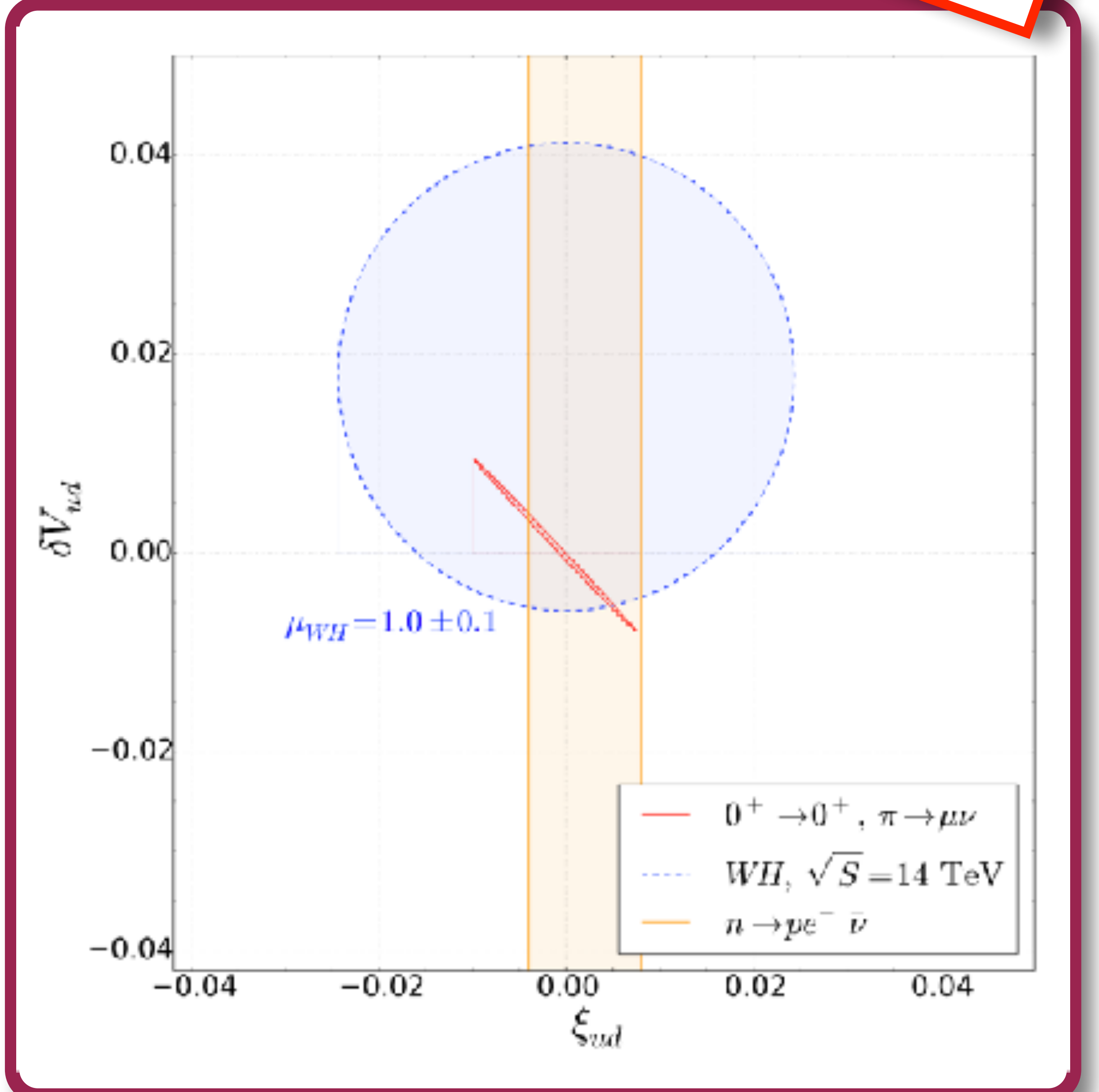
Error Budget:

statistical	0.75%
chiral extrapolation	0.15%
continuum extrapolation	0.04%
infinite volume	0.01%
isospin breaking	0.04%
model selection	0.57%
total (added in quadrature)	0.95%

Final result: g_A = 1.275±0.12

PRELIMINARY!

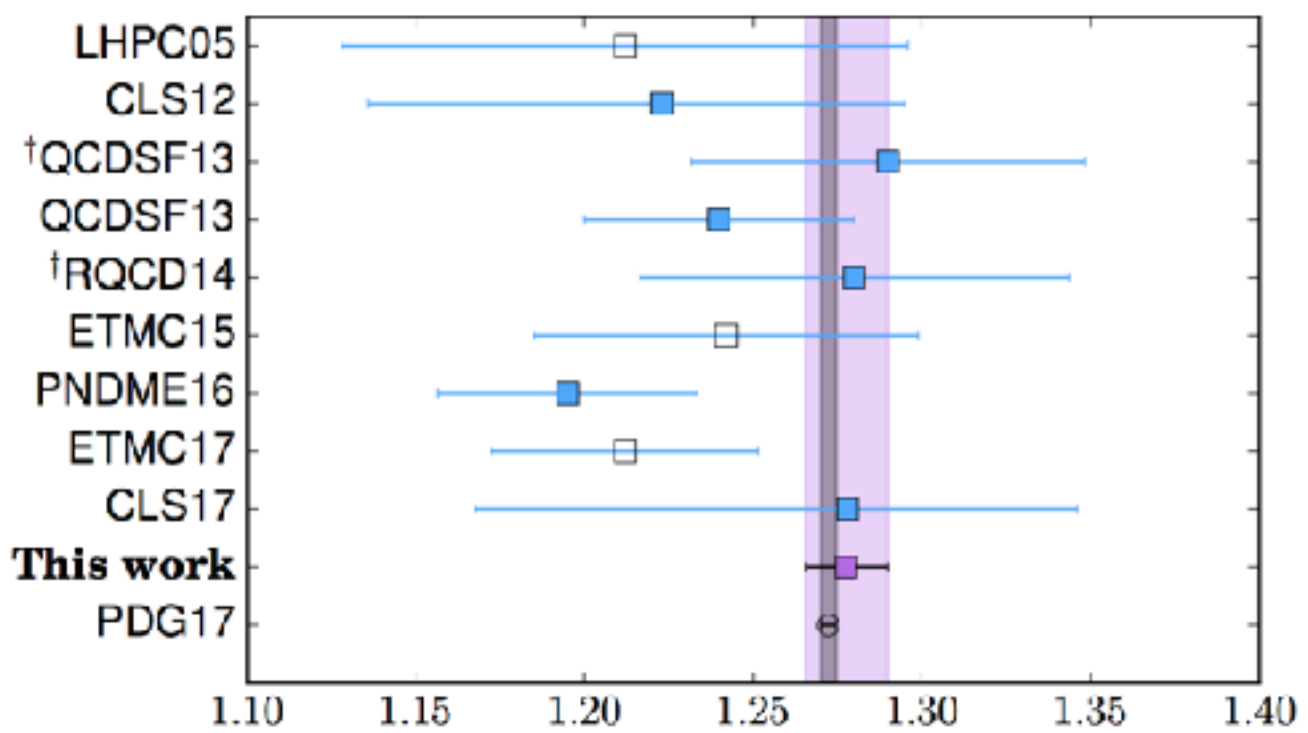


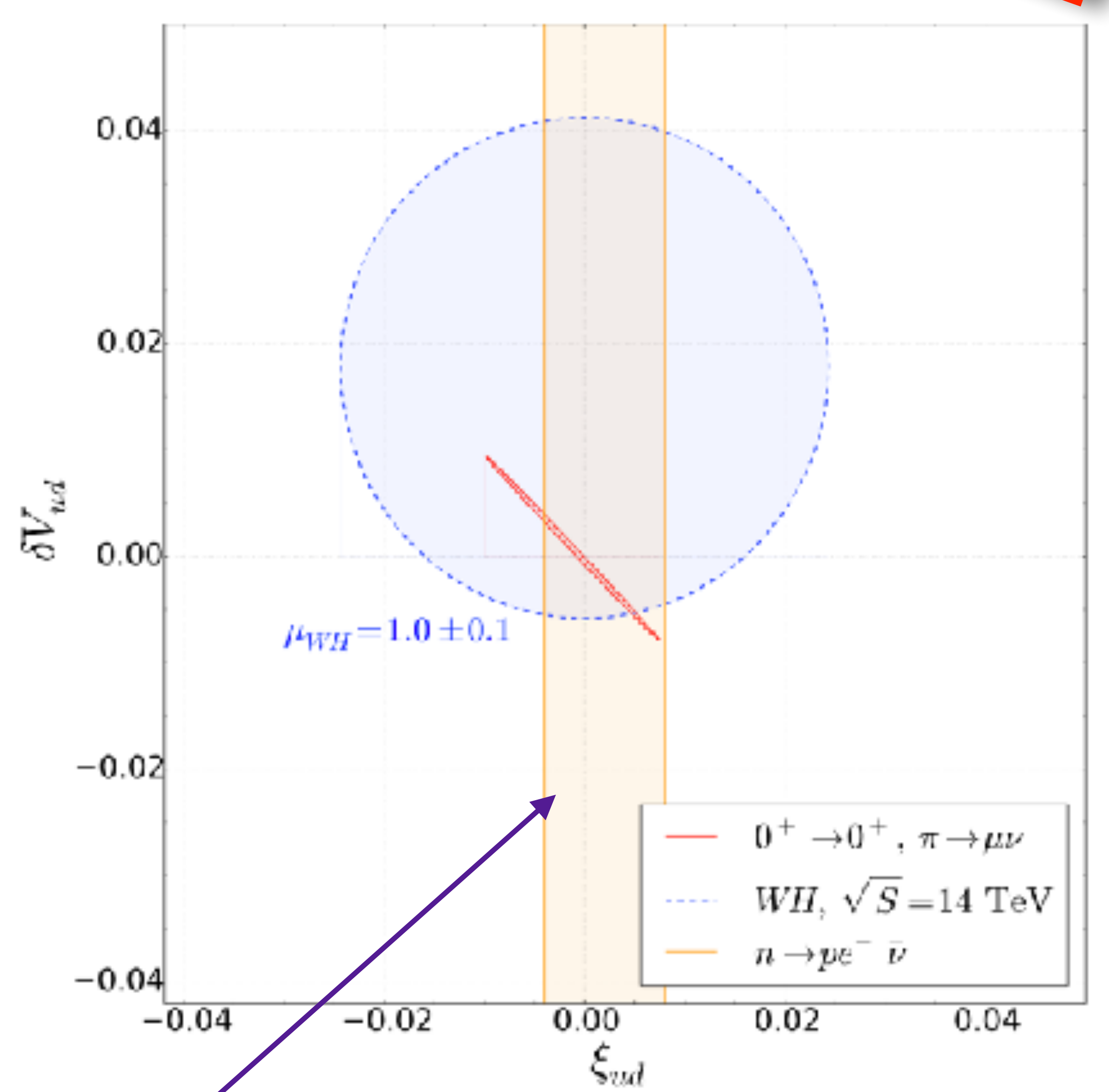


Alioli, Cirigliano, Dekens, de Vries, Mereghetti
arXiv:1703.04751

Final result: g_A = 1.275±0.12

PRELIMINARY!





Our result gives the strongest constraint on right-handed BSM currents!

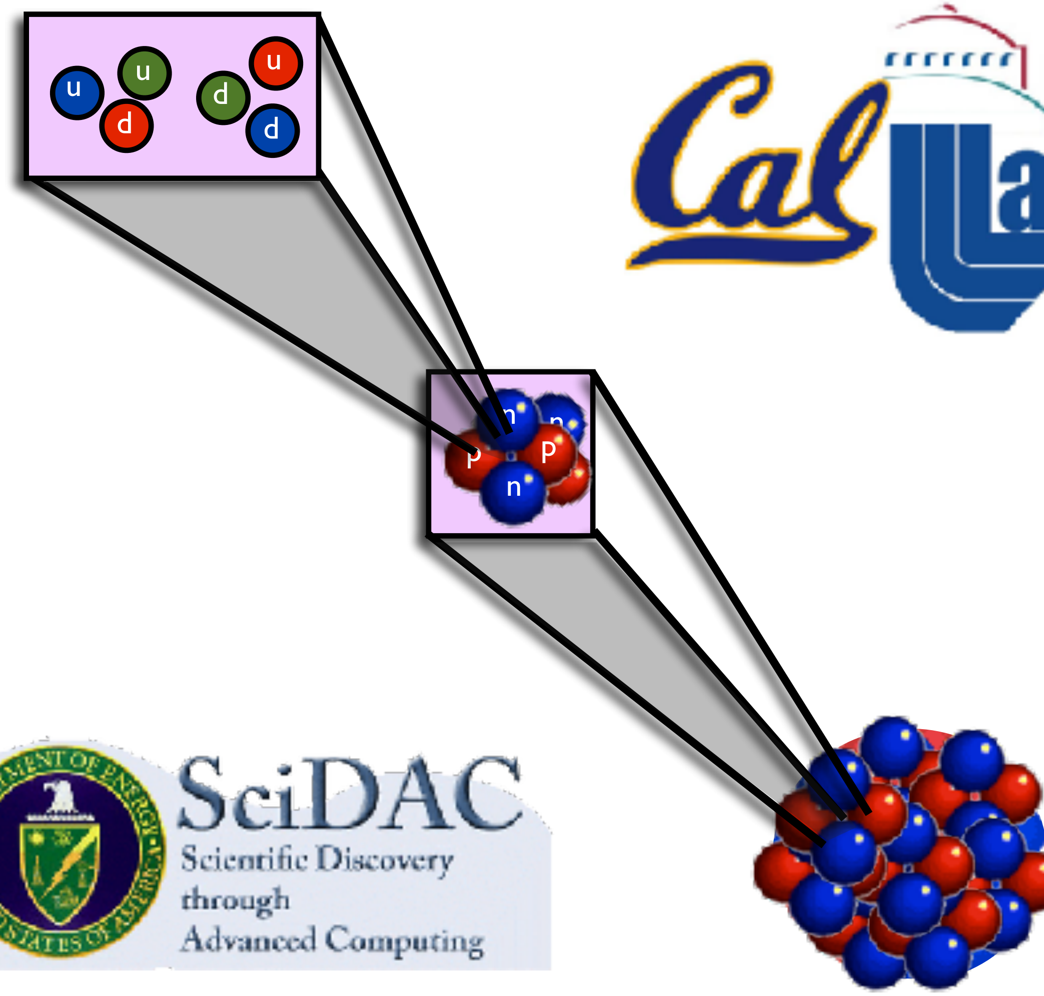
Alioli, Cirigliano, Dekens, de Vries, Mereghetti
arXiv:1703.04751

g_A: Conclusions

- We've finally calculated g_A on the lattice to 1%!
  - Required new technique based on FH theorem to perform on current computers
  - Error budget dominated by statistics: should be able to reduce errors to experimental level to look for new physics
  - At current precision we can help constrain right-handed BSM currents
- g_A proved to be a formidable adversary
  - Doesn't seem to be any one systematic responsible
  - Nuclear physics on the lattice will require precise control over all systematics
  - New theoretical techniques will be necessary for precision nuclear physics

red = postdoc
blue = grad student

Jülich	Evan Berkowitz
LBL/UCB	David Brantley Chia Cheng Chang Thorsten Kurth Henry Monge Camacho
Glasgow	Chris Bouchard
NVIDIA	Kate Clark
Liverpool/Plymouth	Nicolas Garron
JLab	Balint Jóo
UW/INT	Chris Monahan
W&M/JLab	Kostas Orginos
RIKEN/BNL	Enrico Rinaldi
LLNL	Pavlos Vranas



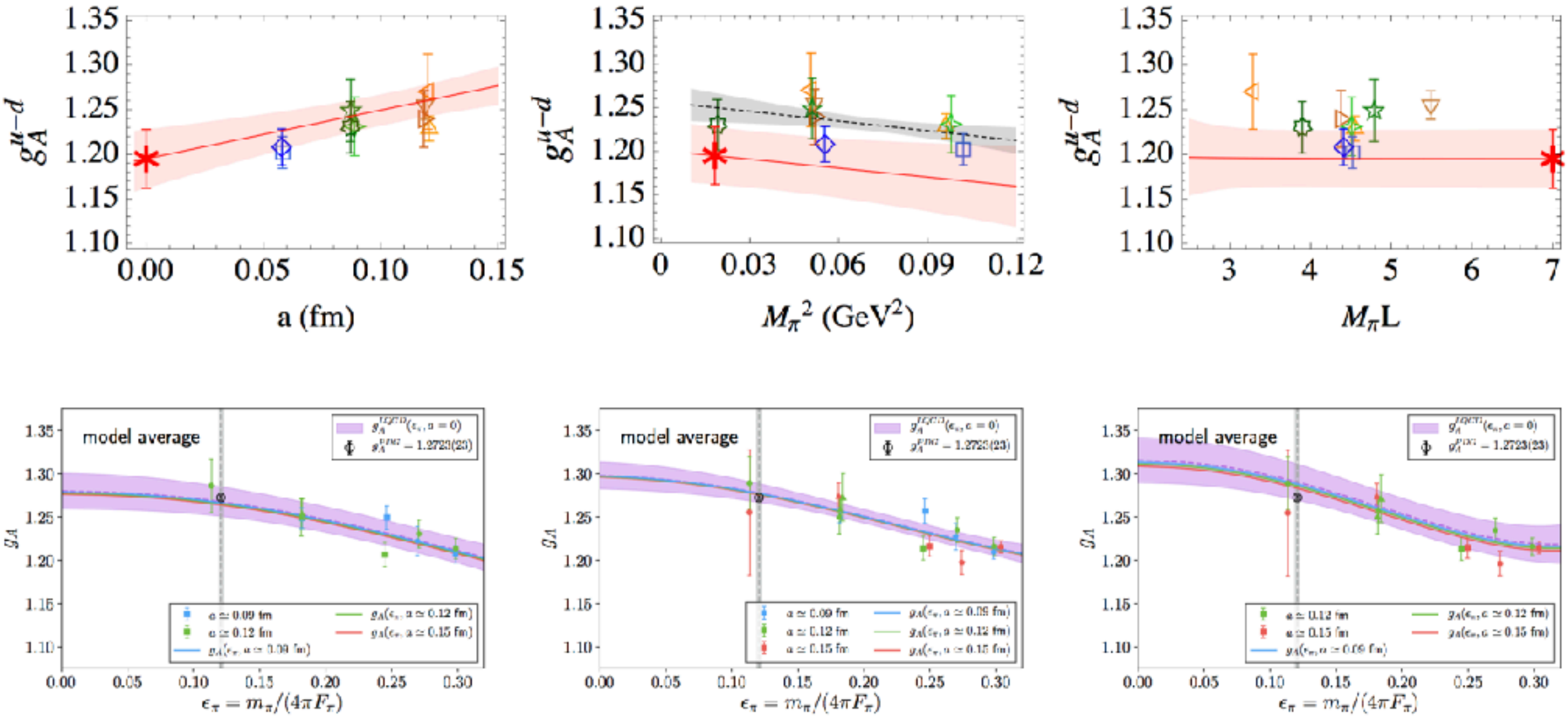
CalLat

SciDAC
Scientific Discovery through Advanced Computing

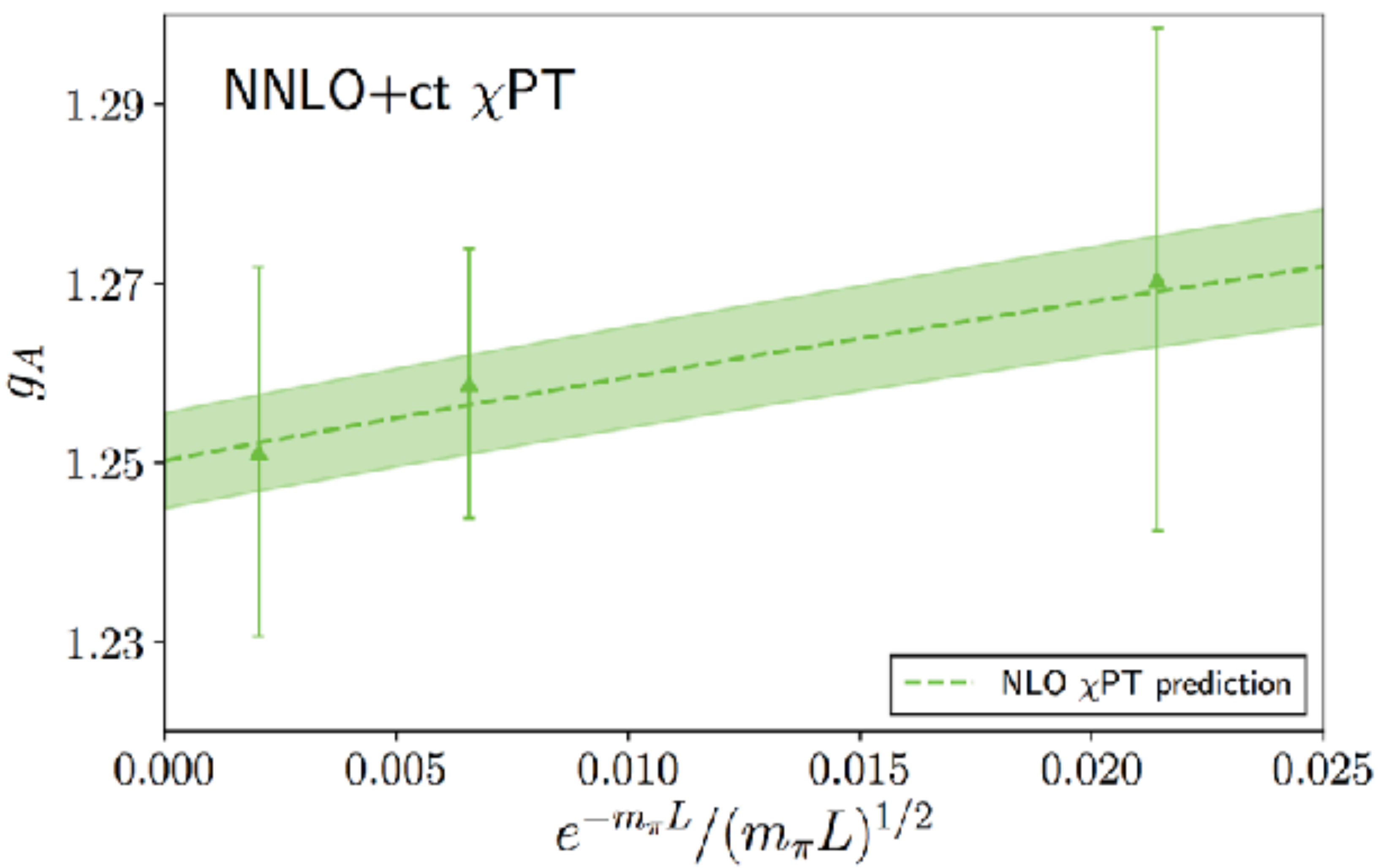
NERSC

U.S. DEPARTMENT OF ENERGY
INCITE
LEADERSHIP COMPUTING

OLCF
OAK RIDGE LEADERSHIP COMPUTING FACILITY

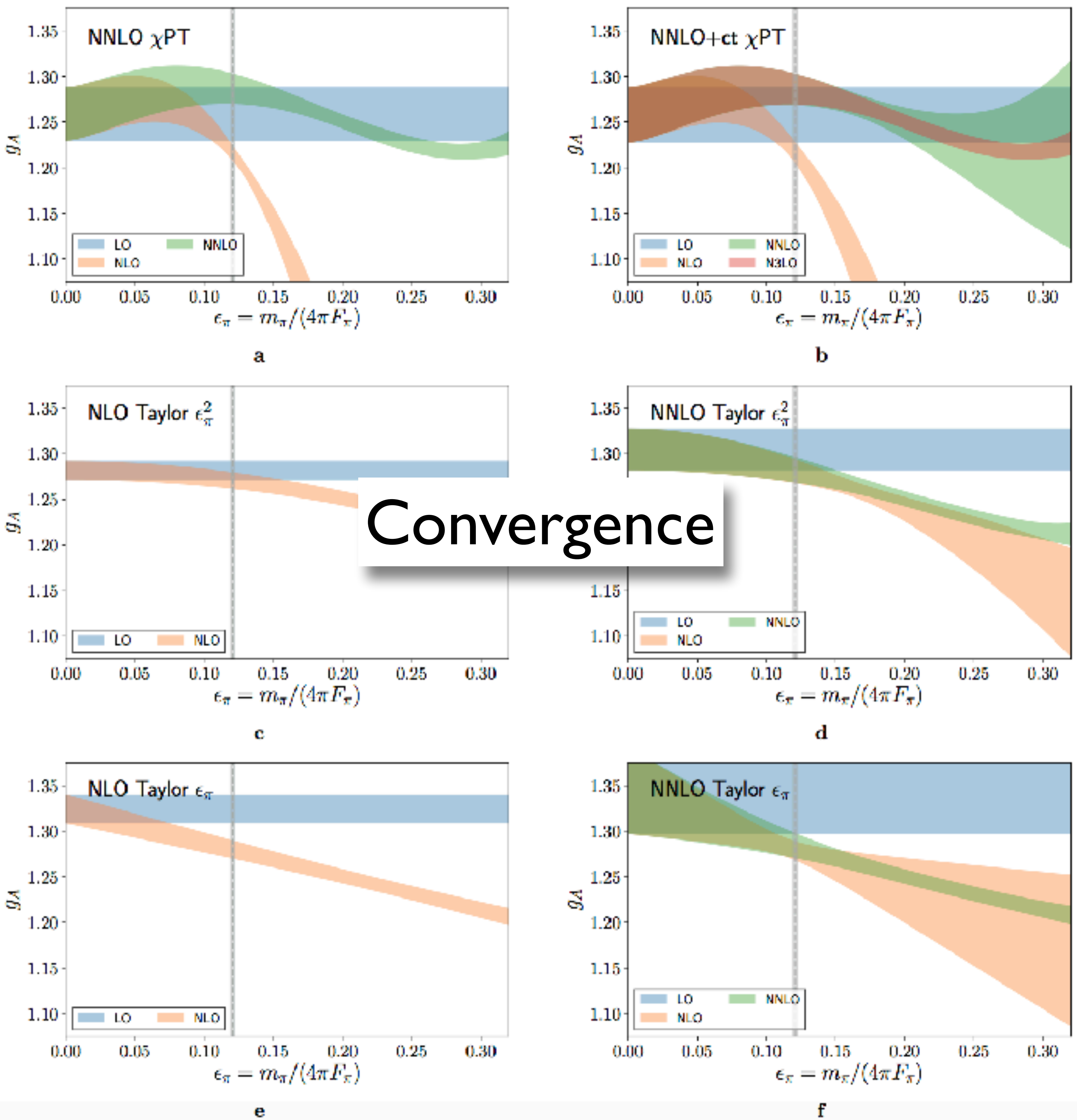


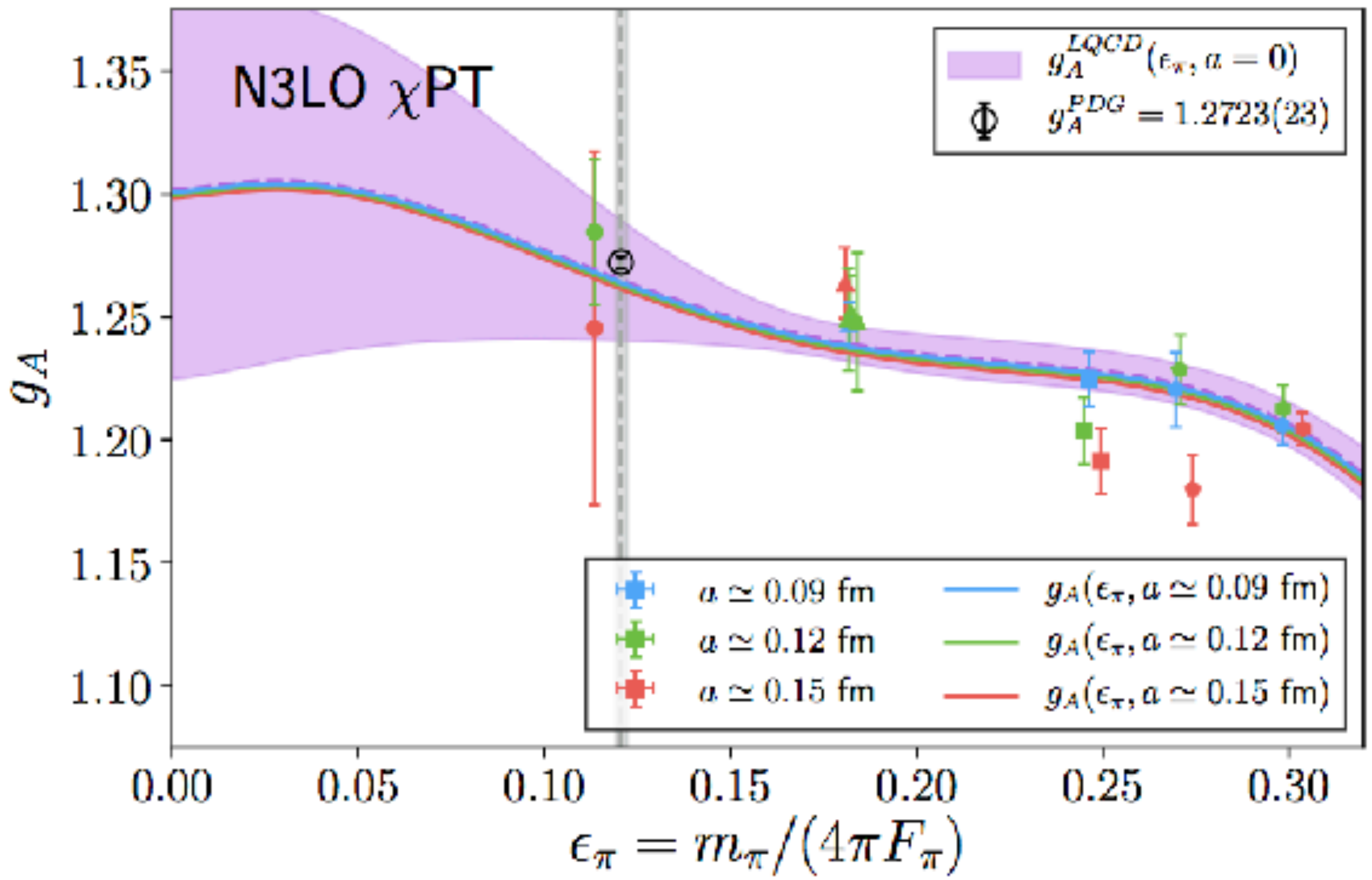
1.35
1.30
1.25
1.20
1.15
1.10
g_A^{u-d}
0.00
0.05
0.10
0.15
a (fm)
0
0.03
0.06
0.09
0.12
M_π^2 (GeV^2)
3
4
5
6
7
M_πL
model average
g_A
$\epsilon_\pi = m_\pi/(4\pi F_\pi)$

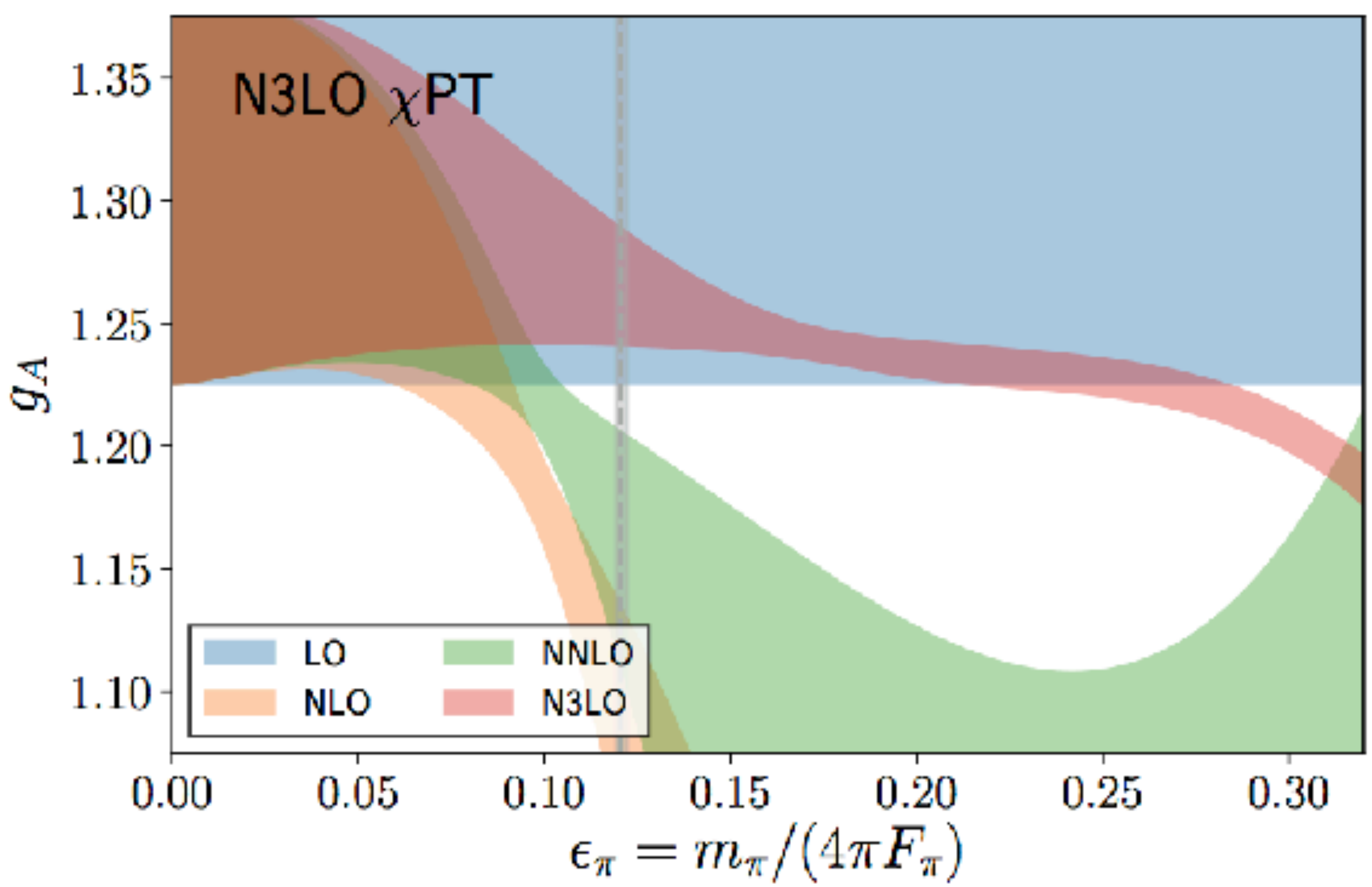


NNLO+ct χPT
1.29
1.27
1.25
1.23
g_A
NLO χPT prediction
0.000
0.005
0.010
0.015
0.020
0.025
$e^{-m_\pi L}/(m_\pi L)^{1/2}$

Convergence

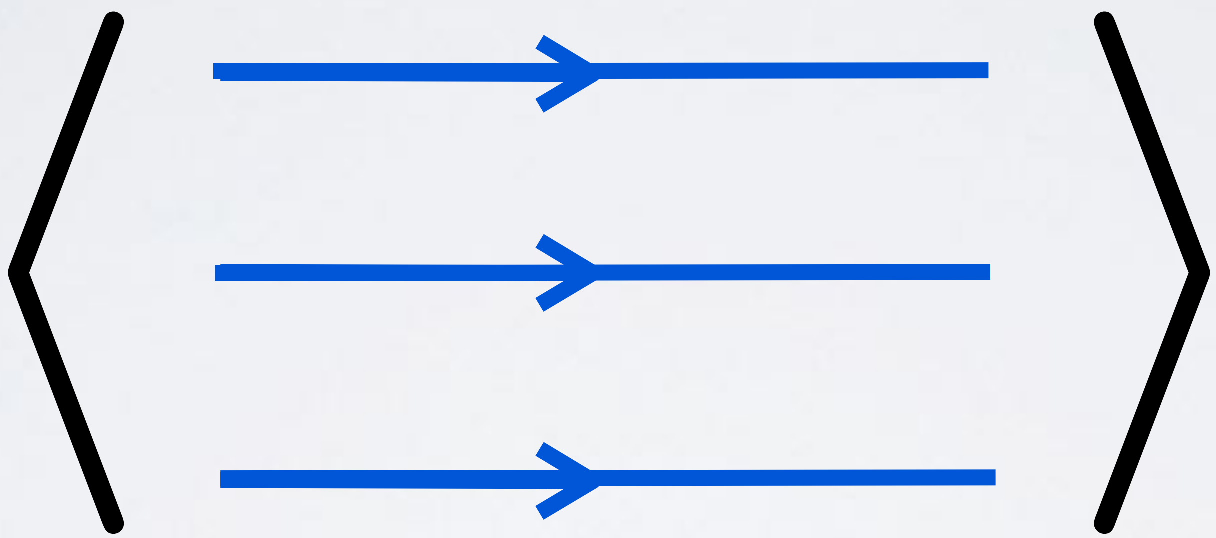



N3LO χPT
$g_A^{LQCD}(\epsilon_\pi, a=0)$
$g_A^{PDG} = 1.2723(23)$
$a \simeq 0.09$ fm
$a \simeq 0.12$ fm
$a \simeq 0.15$ fm
$g_A(\epsilon_\pi, a \simeq 0.09$ fm$)$
$g_A(\epsilon_\pi, a \simeq 0.12$ fm$)$
$g_A(\epsilon_\pi, a \simeq 0.15$ fm$)$
g_A
1.35
1.30
1.25
1.20
1.15
1.10
0.00
0.05
0.10
0.15
0.20
0.25
0.30
$\epsilon_\pi = m_\pi/(4\pi F_\pi)$


N3LO χPT
LO
NLO
NNLO
N3LO
g_A
1.35
1.30
1.25
1.20
1.15
1.10
0.00
0.05
0.10
0.15
0.20
0.25
0.30
$\epsilon_\pi = m_\pi/(4\pi F_\pi)$

BARYON SNR

$$C_N(\tau) =$$

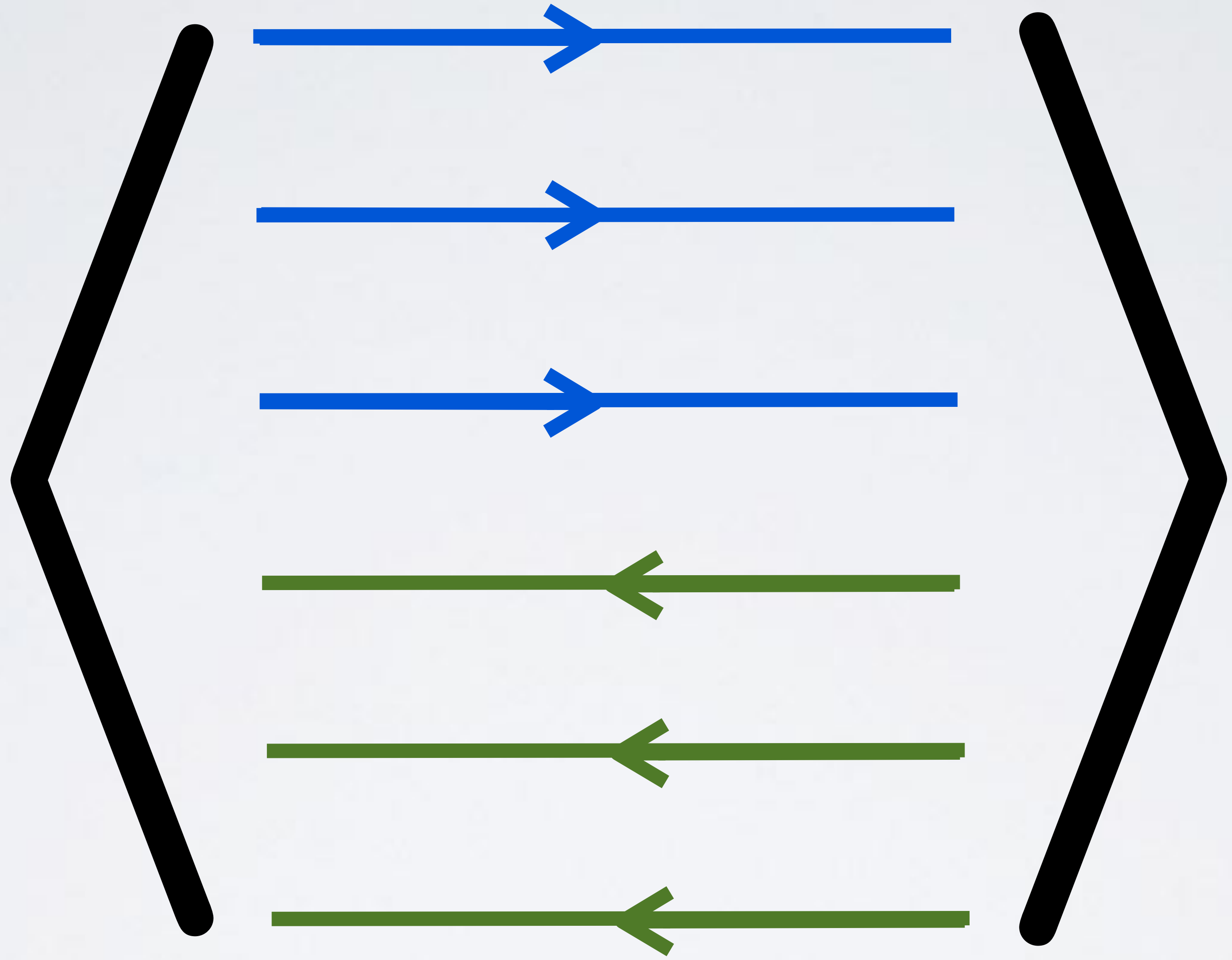


$$\xrightarrow[\tau\to\infty]{} e^{-M_N \tau}$$

Lepage (1989)

BARYON SNR

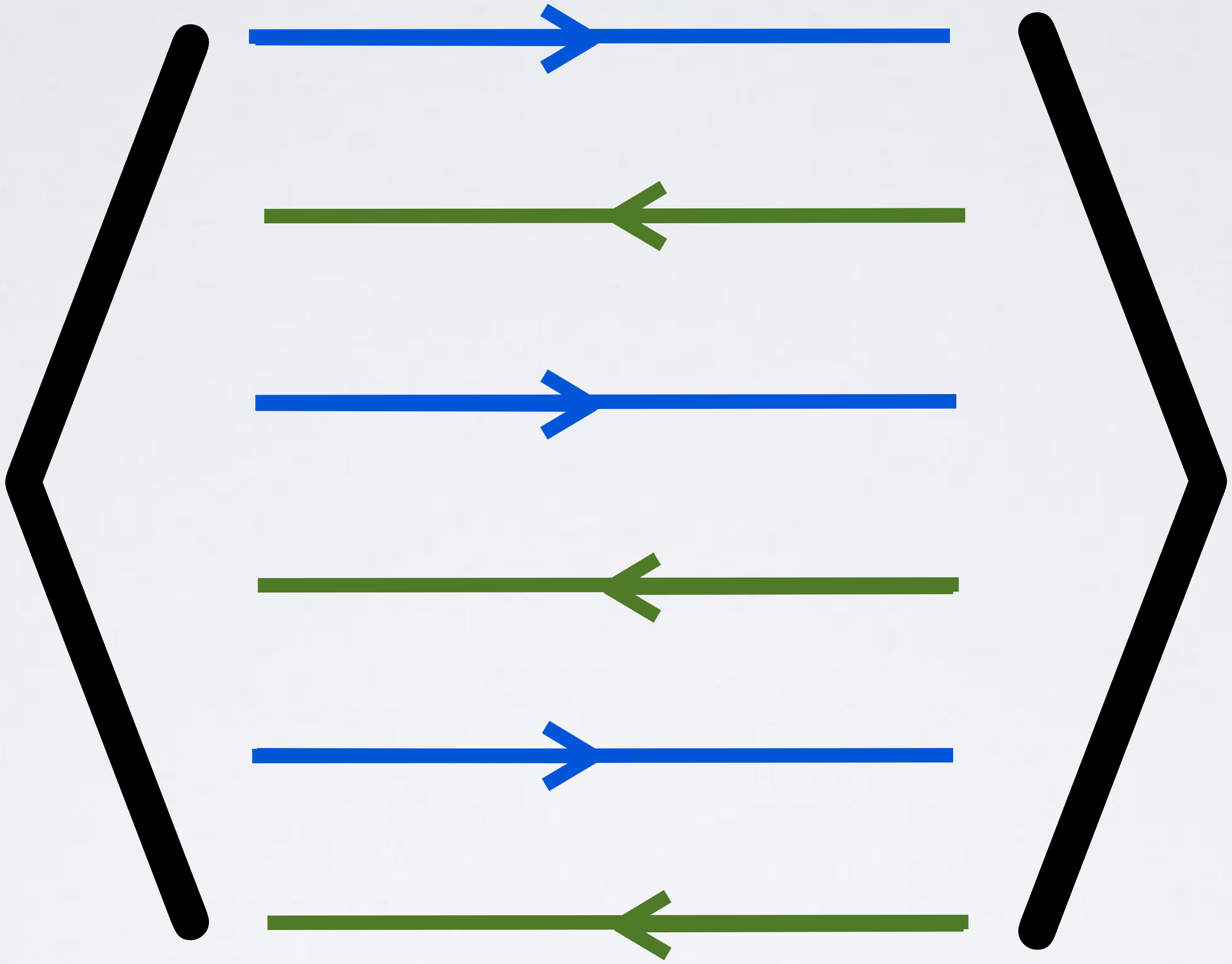
$$C_{N^\dagger N}(\tau) = $$



$$\xrightarrow[\tau \to \infty]{} e^{-2M_N \tau}$$

Lepage (1989)

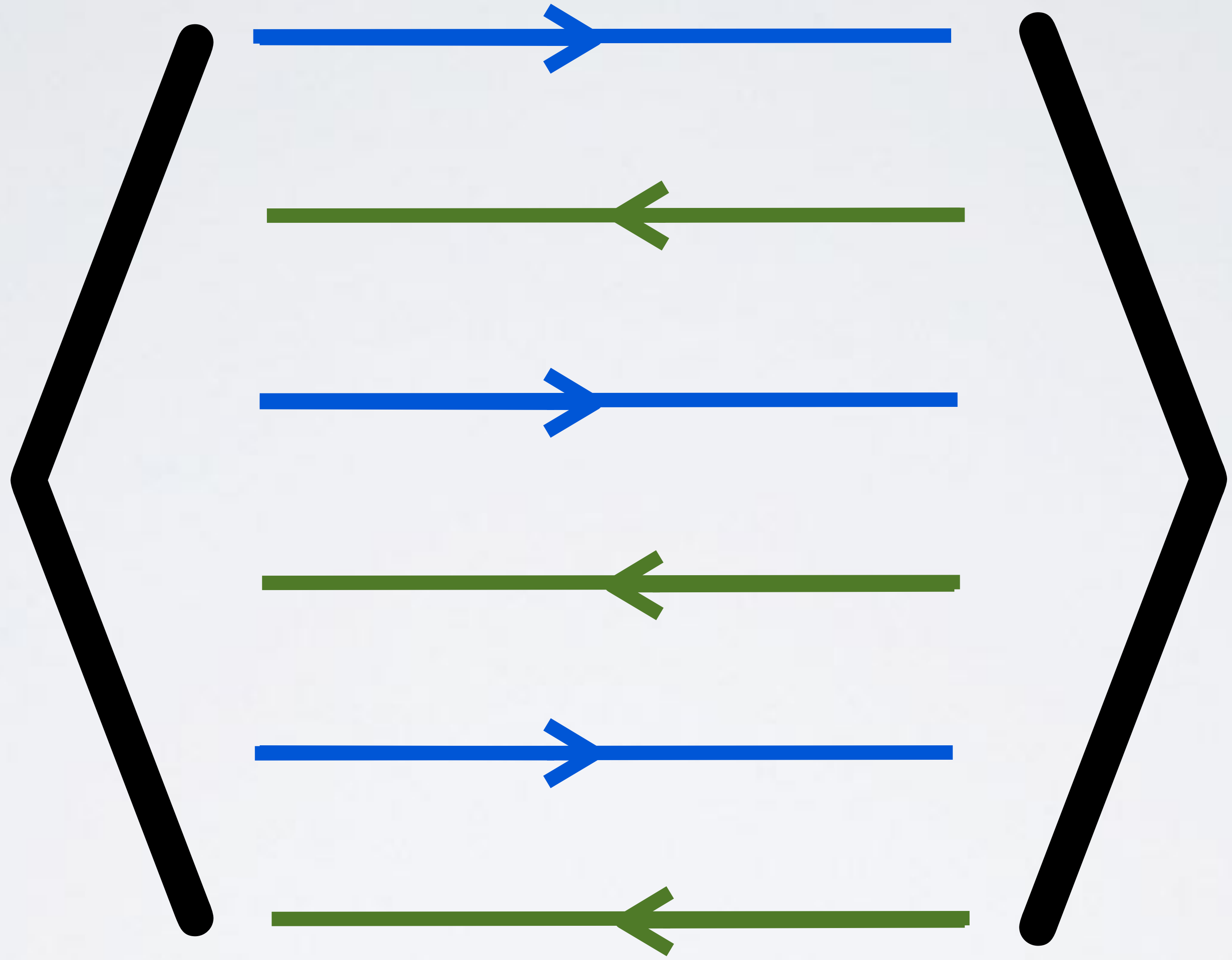
BARYON SNR

$C_{N^\dagger N}(\tau) =$  $\underset{\tau \to \infty}{\longrightarrow} e^{-2M_N \tau}$

Lepage (1989)

BARYON SNR

$C_{N^\dagger N}(\tau) =$



$\xrightarrow[\tau \to \infty]{} e^{-3 m_\pi \tau}$

Lepage (1989)

BARYON SNR

Signal-to-noise ratio:

$$\frac{C_N(\tau)}{\sigma(\tau)} \underset{\tau\to\infty}{\longrightarrow} \sqrt{N_{cfg}}e^{-(M_N-3/2m_\pi)\tau}$$

Exponentially poor signal-to-noise!