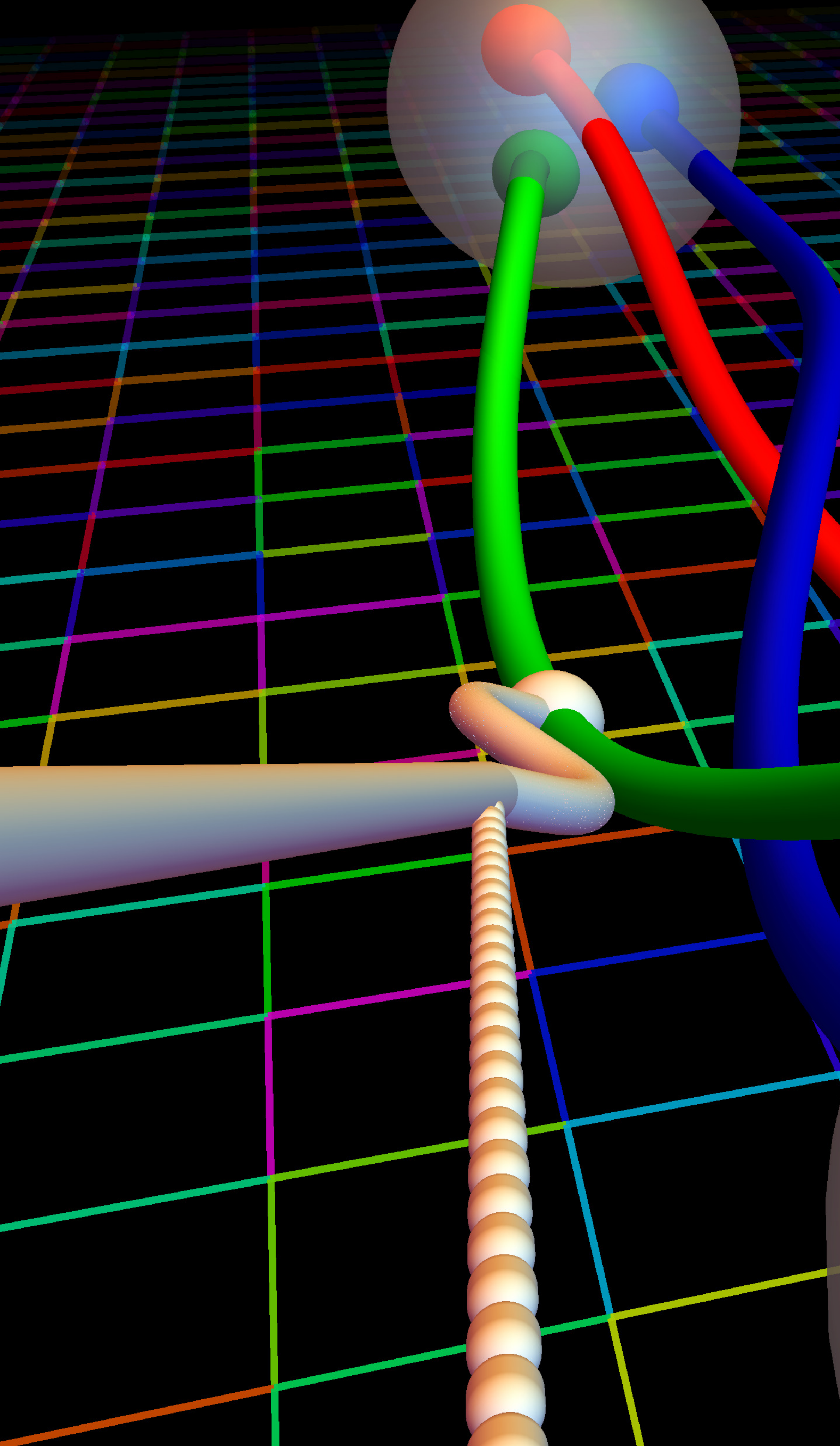


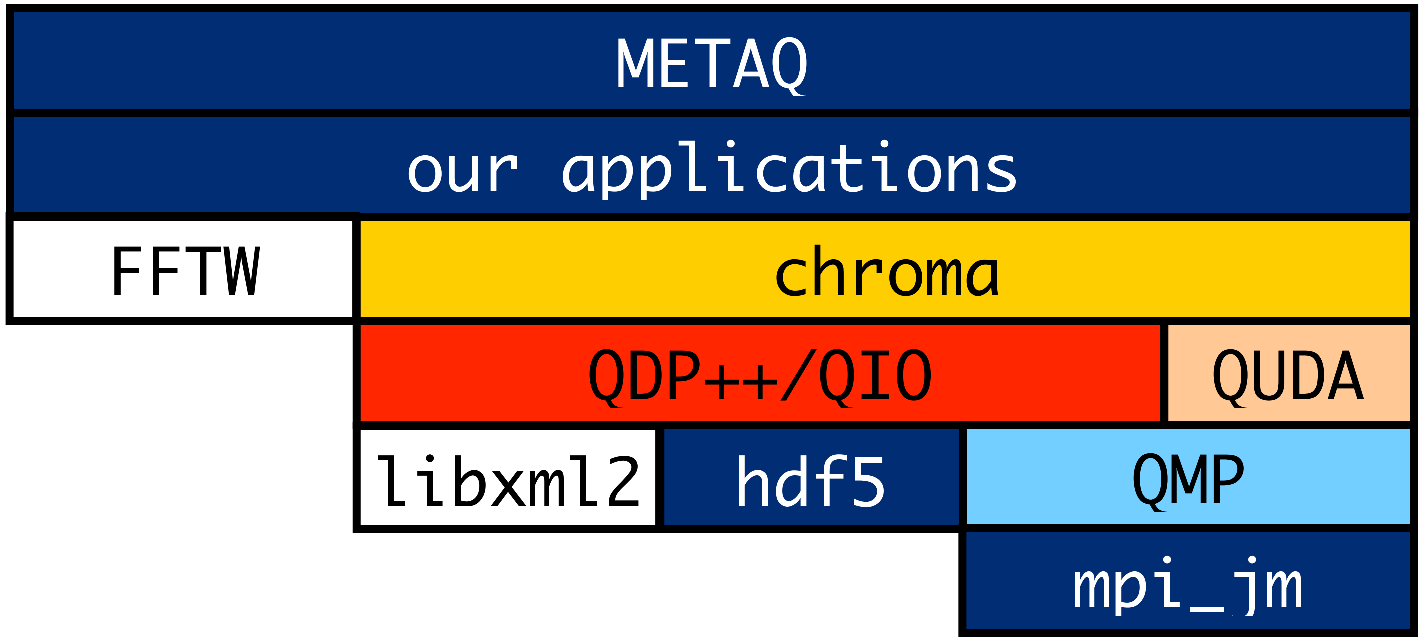
The Nucleon Axial Coupling from QCD

PRD 96 054513 1701.07559
1704.01114
Nature 558 91-94 (2018) 1805.12130

Evan Berkowitz
Institut für Kernphysik
Institute for Advanced Simulation
Forschungszentrum Jülich

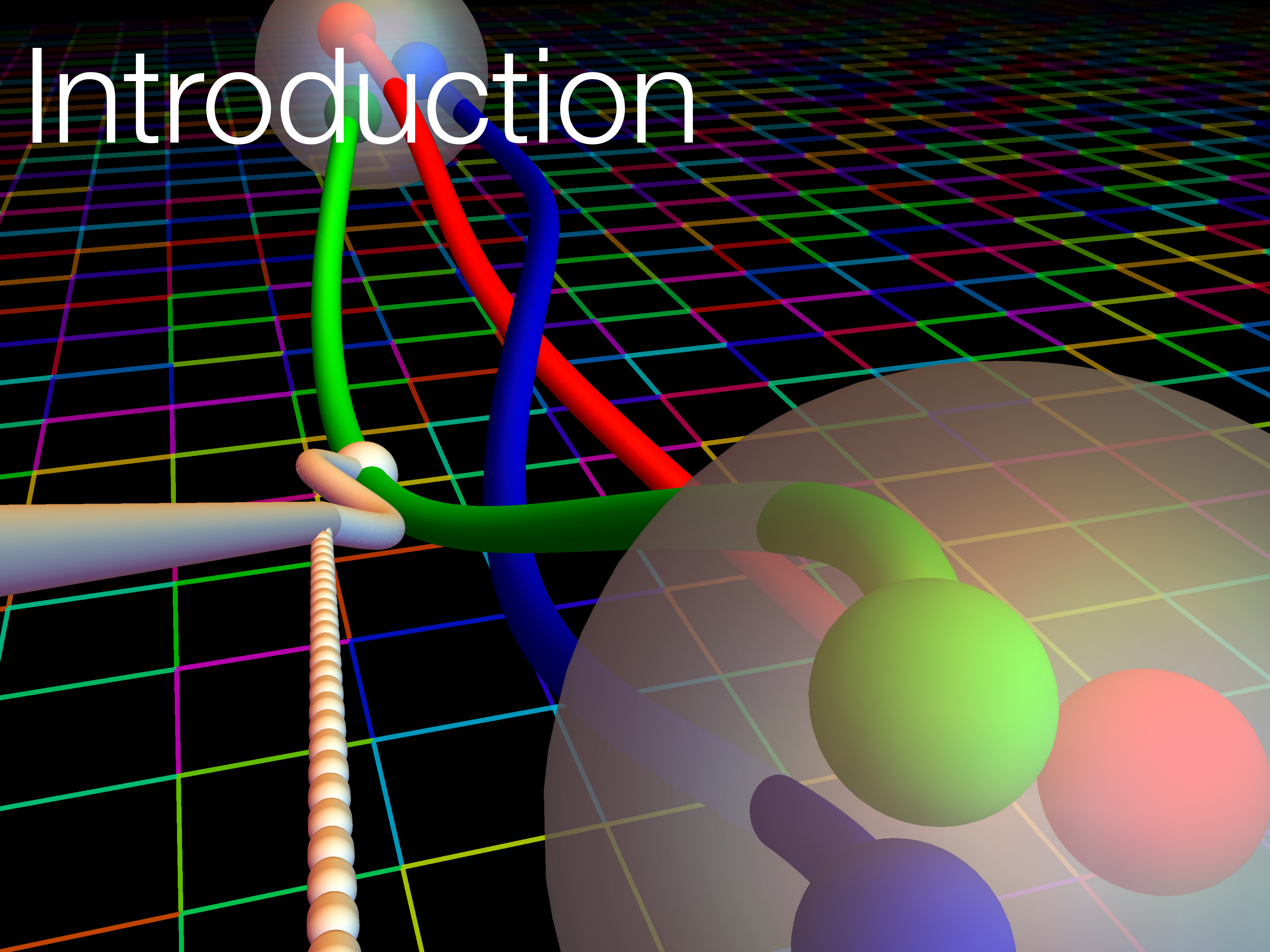
20 November 2018
Dr. Klaus Erkelenz Kolloquium

Berkeley LBL	Chia Cheng (Jason) Chang, Ken McElvain, André Walker-Loud
RBRC	Enrico Rinaldi
FZJ	EB
JLab	Bálint Joó
Liverpool Plymouth	Nicolas Garron
LLNL	Pavlos Vranas, David Brantley
NERSC	Thorsten Kurth
UNC	Amy Nicholson, Henry Monge Camacho
nVidia	Kate Clark
Glasgow	Chris Bouchard
INT	Chris Monahan
William & Mary	Kostas Orginos



Software	References
METAQ	Berkowitz arXiv:1702.06122 github.com/evanberkowitz/metaq Berkowitz et al. EPJ (LATTICE2017) 175 09007 (2018)
chroma QDP++	Edwards and Joo (SciDAC, LHPC and UKQCD Collaborations) Nucl. Phys. Proc. Suppl 140, 832 (2005)
QUDA	Clark et al. Comput. Phys. Commun. 181 1517 (2010) Babich et al. Supercomputing 11, 70
hdf5 in QDP++	Kurth et al PoS LATTICE2014 045 (2015)
qmp	Chen, Edwards, and Watson et al. https://github.com/usqcd-software/qmp
mpi_jm	Berkowitz et al. EPJ (LATTICE2017) 175 09007 (2018) McElvain et al. https://github.com/kenmcelvain/mpi_jm/

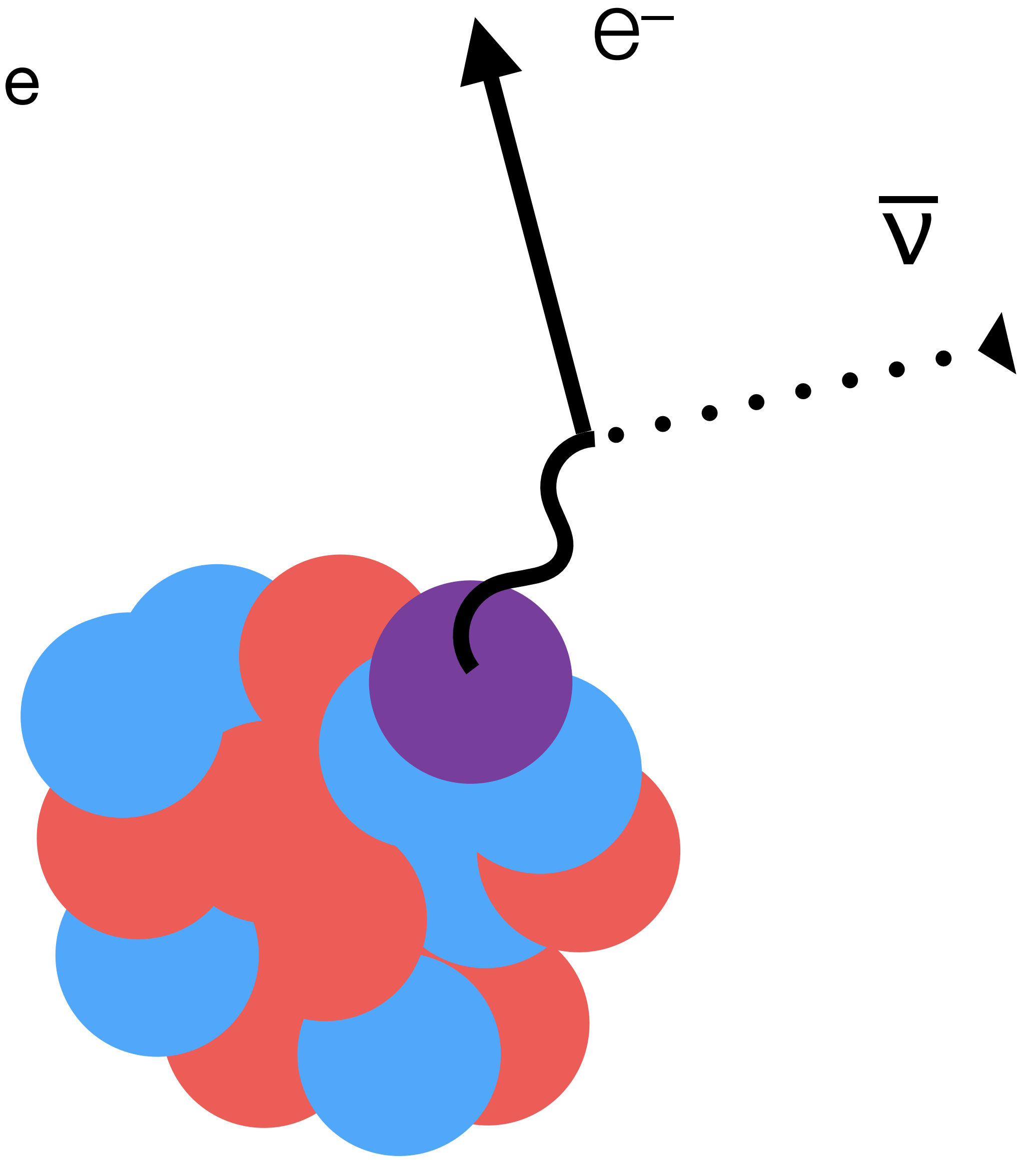
Introduction

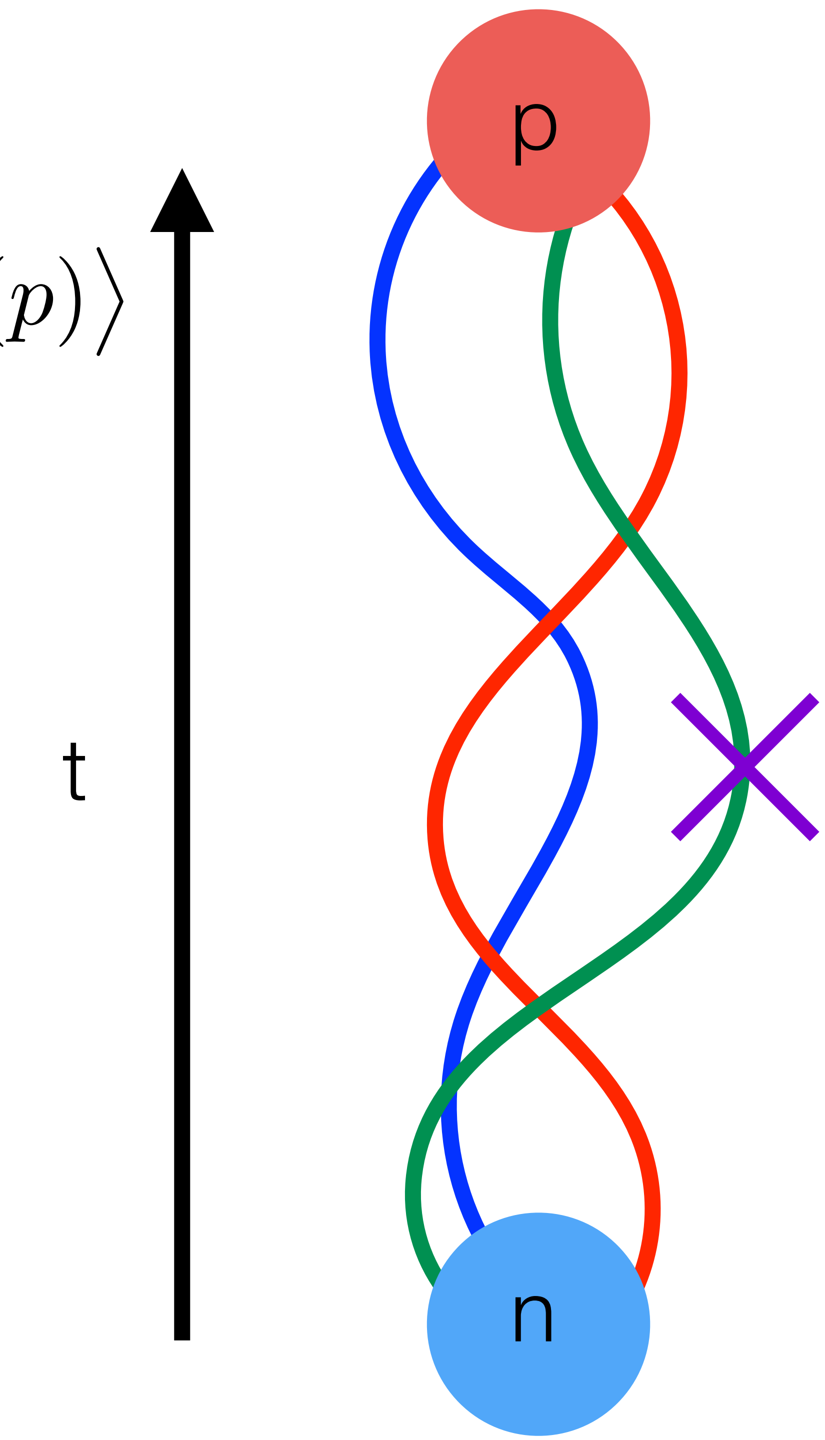


The Nucleon Axial Coupling

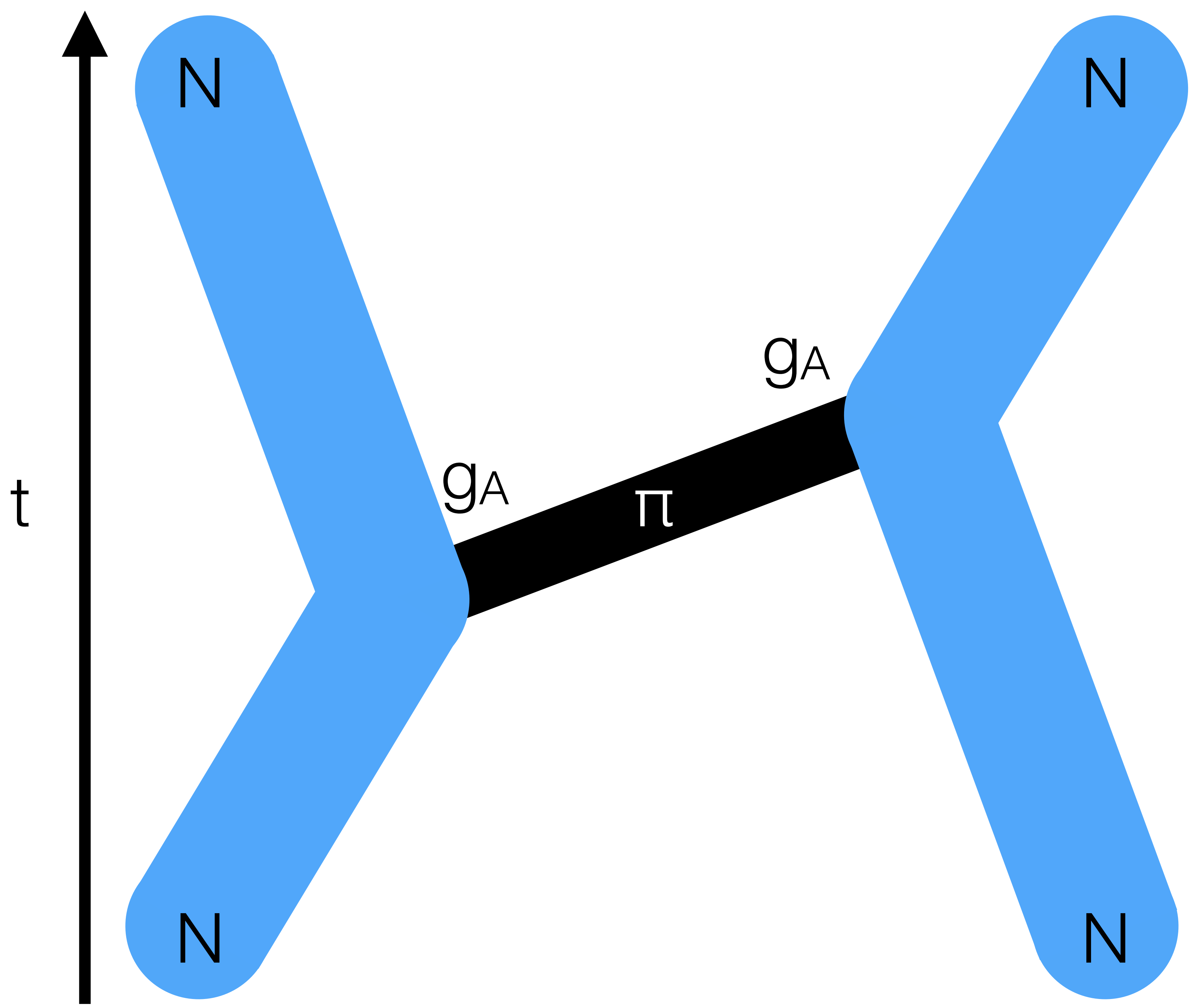
$$\langle N(p) \mid A^a_\mu \mid N(p) \rangle = \langle N(p) \mid \bar{\psi}\gamma_\mu\gamma_5\tau^a\psi \mid N(p) \rangle$$
$$= g_A \, \bar{n}(p)\gamma_\mu\gamma_5\tau^a n(p)$$

- Free neutron lifetime
- Nuclear β decay
- Nuclear force





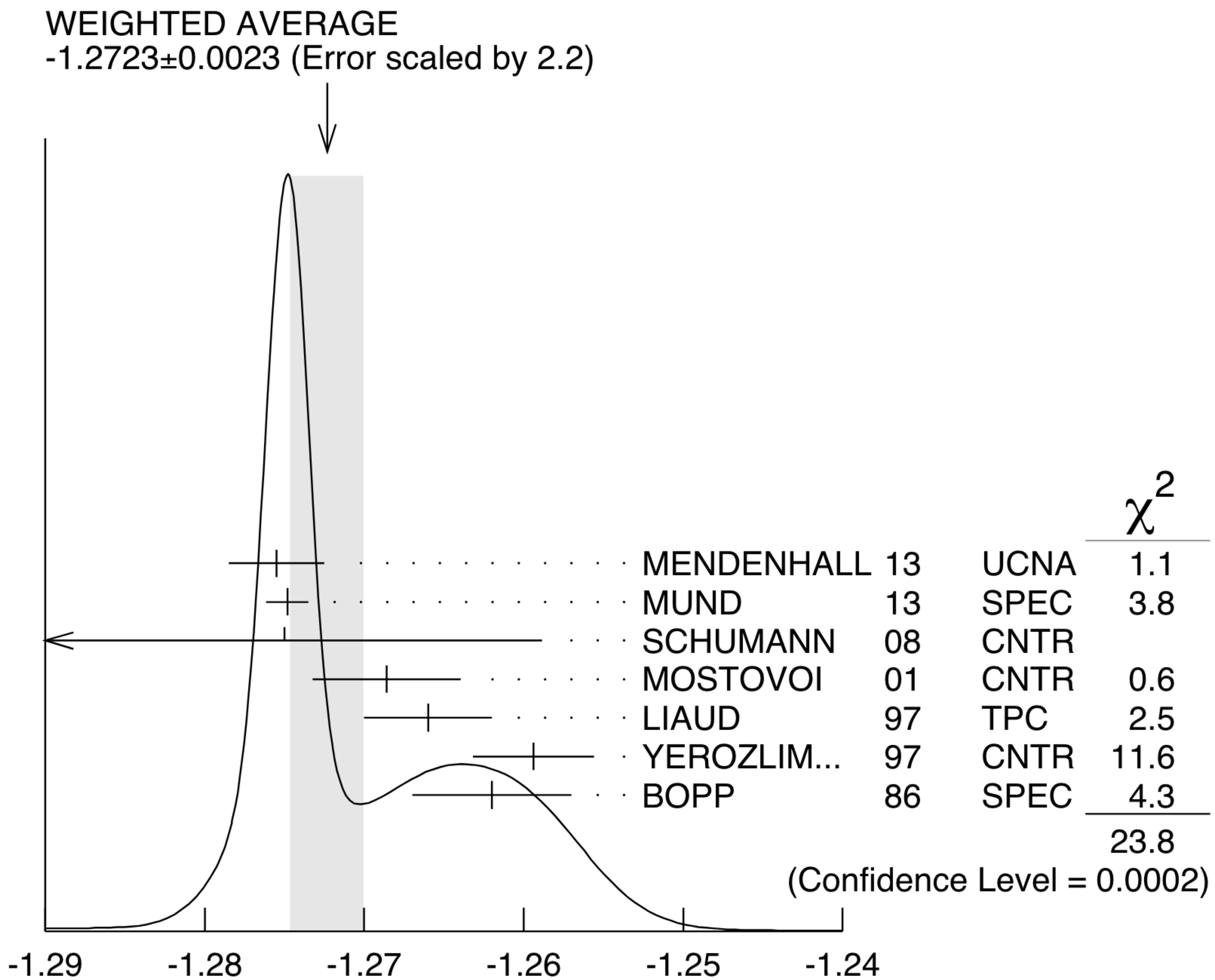
The Nucleon Axial Coupling



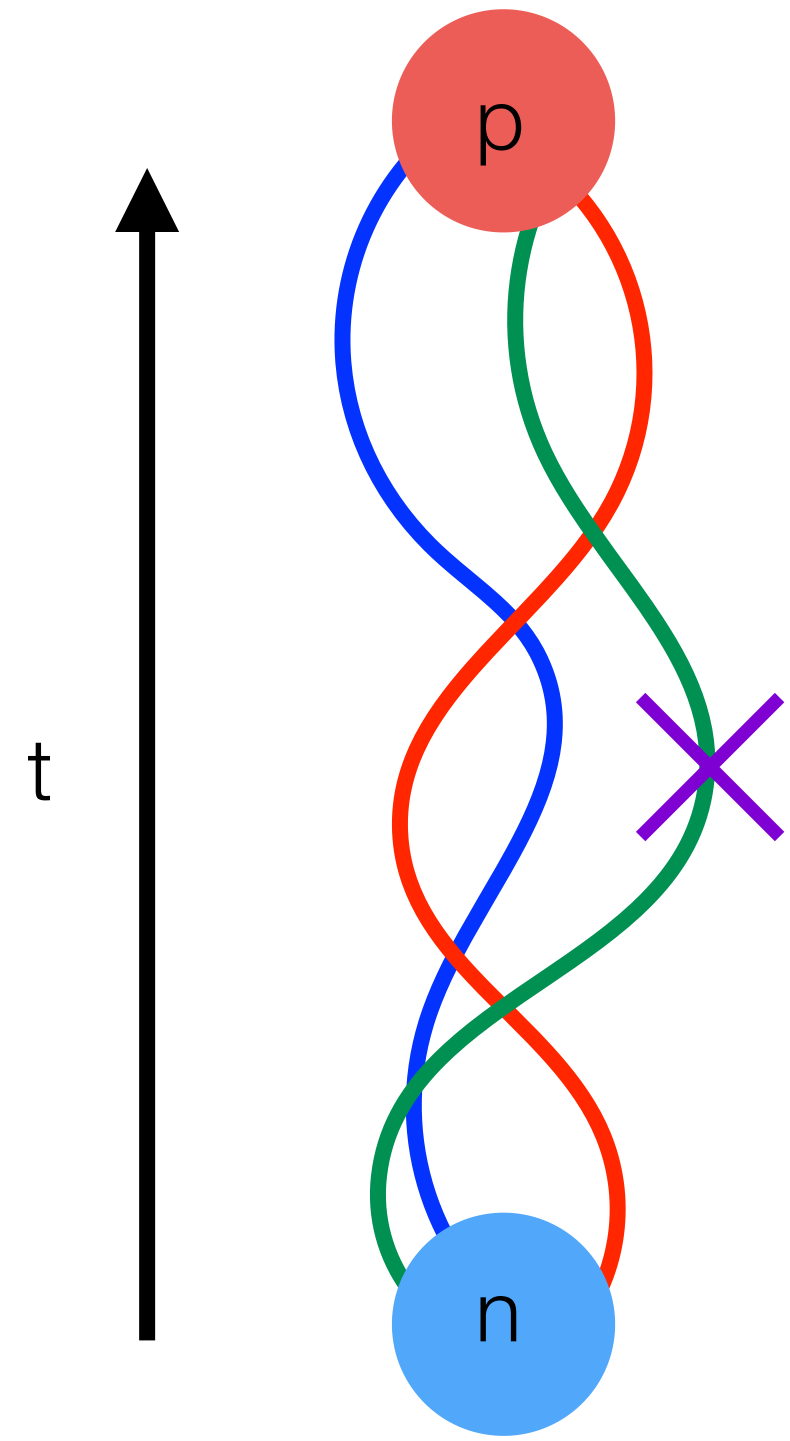
- Essential in modern nuclear interactions and chiral EFT forces
  Epelbaum, Hammer, Meißner
  Rev. Mod. Phys 81 (2009) 1773-1825
- Appears in all meson exchange models
  K. Erkelenz, K. Holinde, K. Bleuler
  Nucl. Phys. A139 (1969) 308-328
  Nucl. Phys. A161 (1971) 155-176
  Nucl. Phys. A194 (1972) 161-176
  K. Holinde, **K. Erkelenz**, R. Alzetta
  Nucl. Phys. A198 (1972) 598-608
  K. Bleuler, **K. Erkelenz**, K. Holinde, R. Machleidt
  Nucl. Phys. A205 (1973) 292-298
  R. Machleidt, **K. Erkelenz**, K. Holinde
  Nucl. Phys. A232 (1974) 398-416
  PLB 49 (1974) 209-212
  K. Erkelenz, Phys. Rept. 13 (1974) 191
- Notably, the pioneering **Bonn Potential**

The Nucleon Axial Coupling

PDG 2016

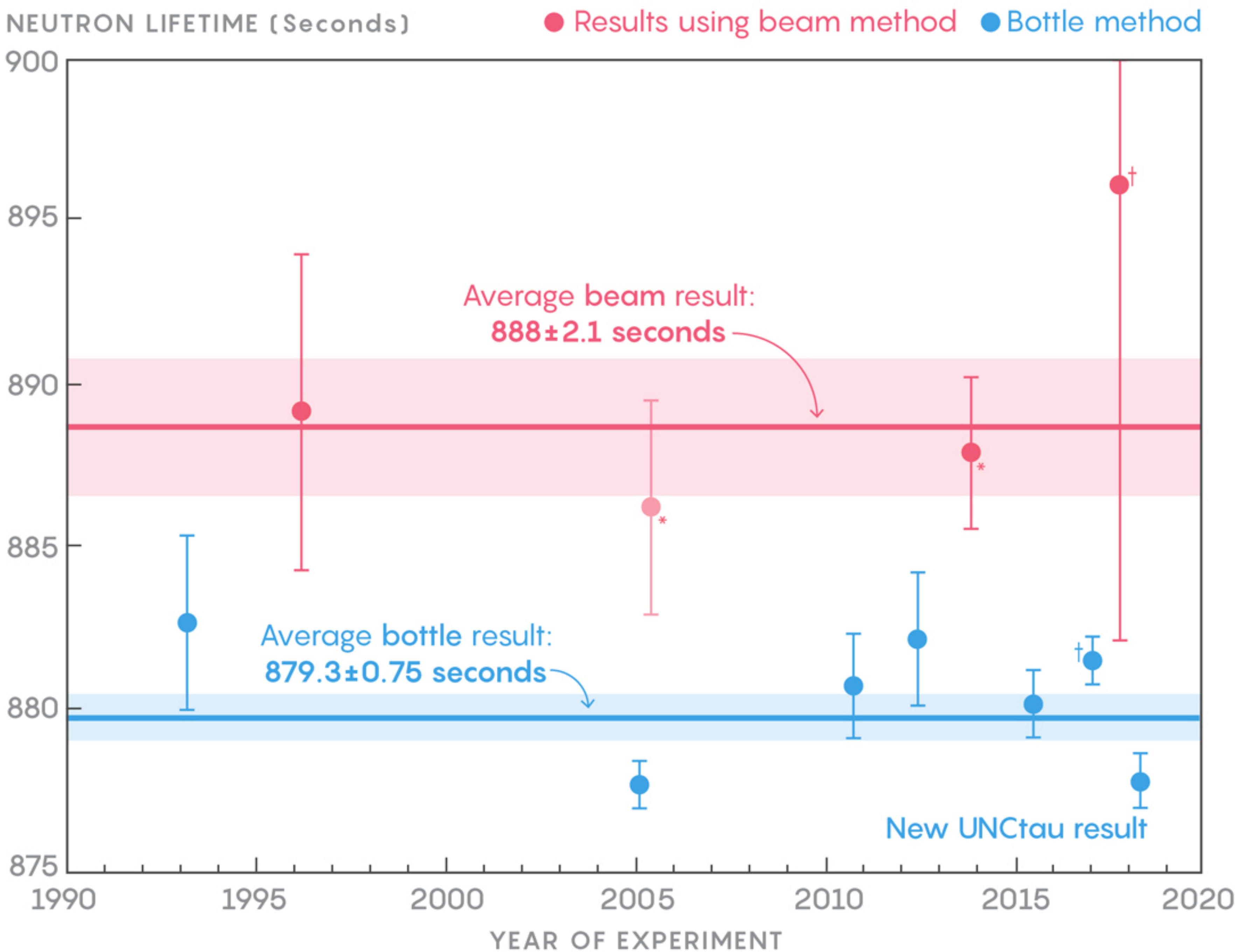


$\lambda \equiv g_A \,/\, g_V$

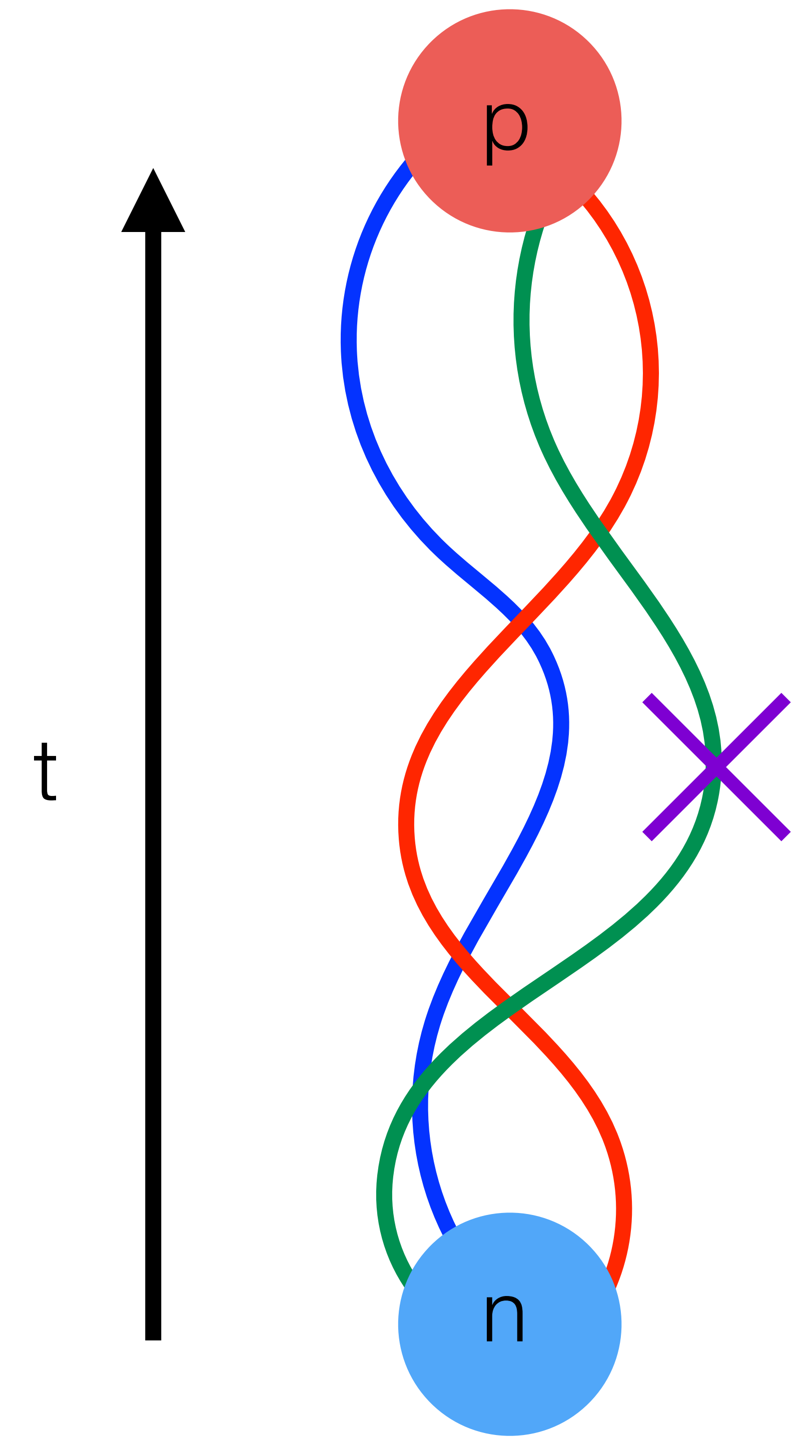


The Nucleon Axial Coupling

PDG 2016

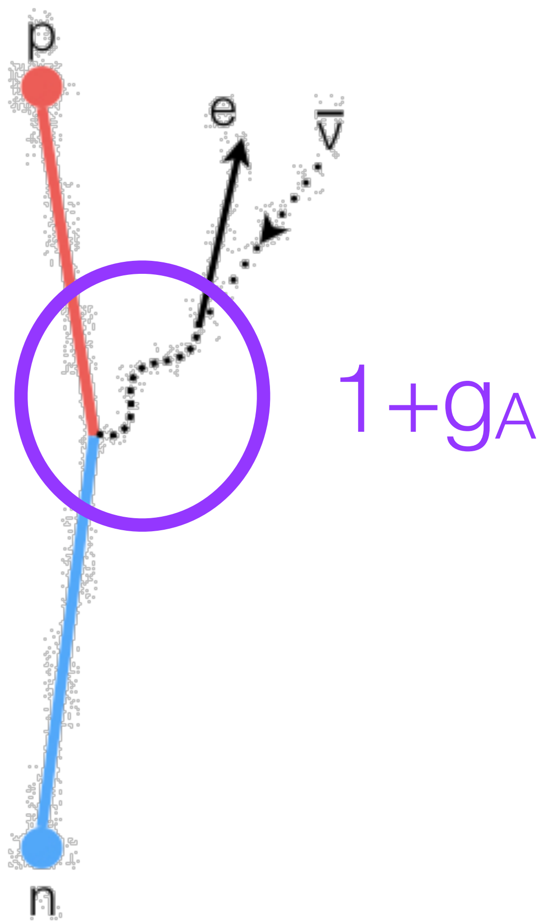


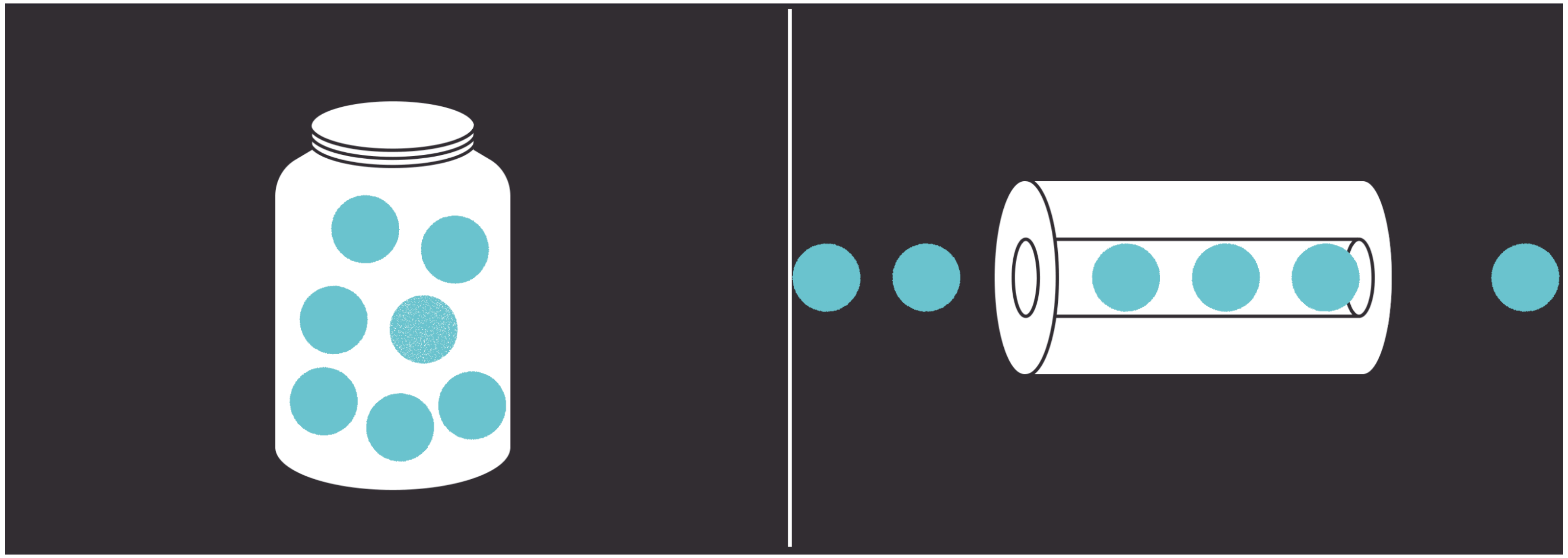
*Nico result (2005) was superseded by an updated and improved result, Yue (2013);
†Preliminary results



Lucy Reading-Ikkanda/Quanta Magazine - Neutron Lifetime Puzzle Deepens, but No Dark Matter Seen

Simple Problems Remain Outstanding





BOTTLE and BEAM

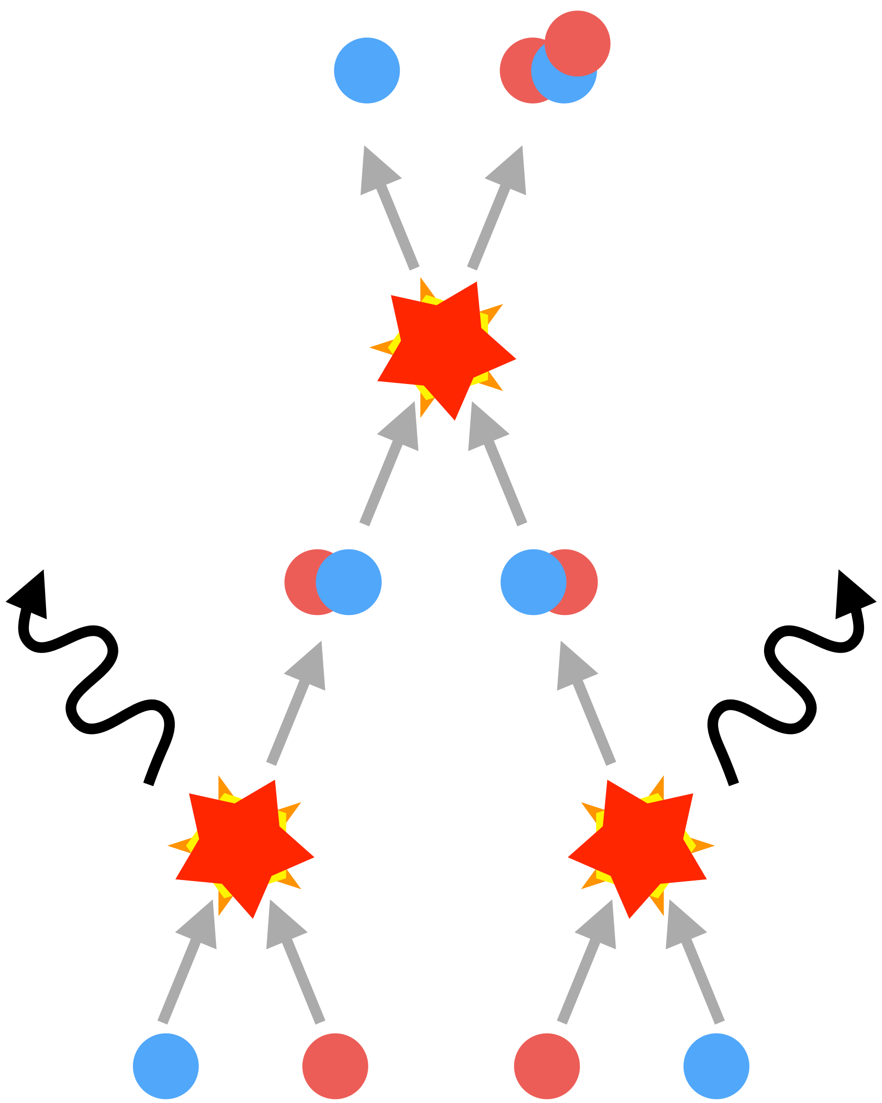
methods of measuring the neutron lifetime disagree at the 99% level

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

Can we calculate g_A?

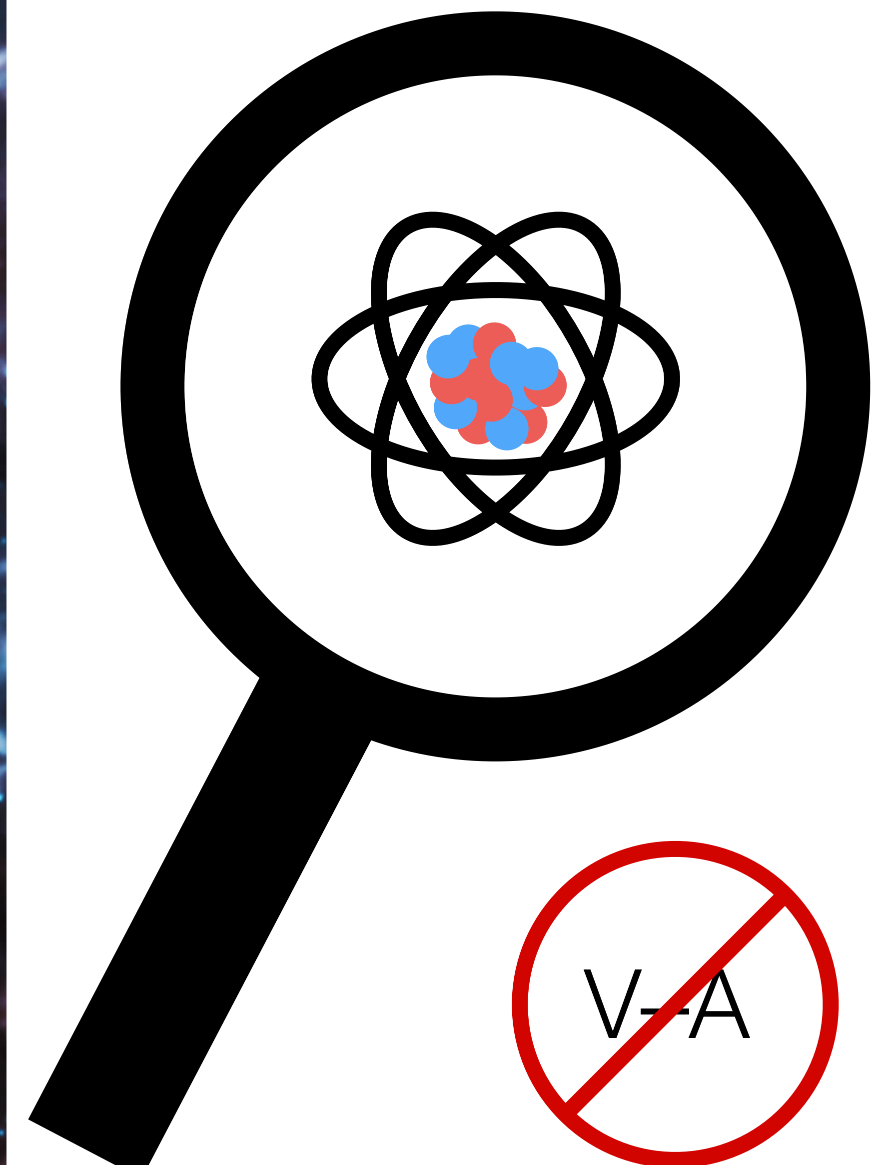
Bottle and Beam: Daniel Savage for Quanta Magazine

Applications

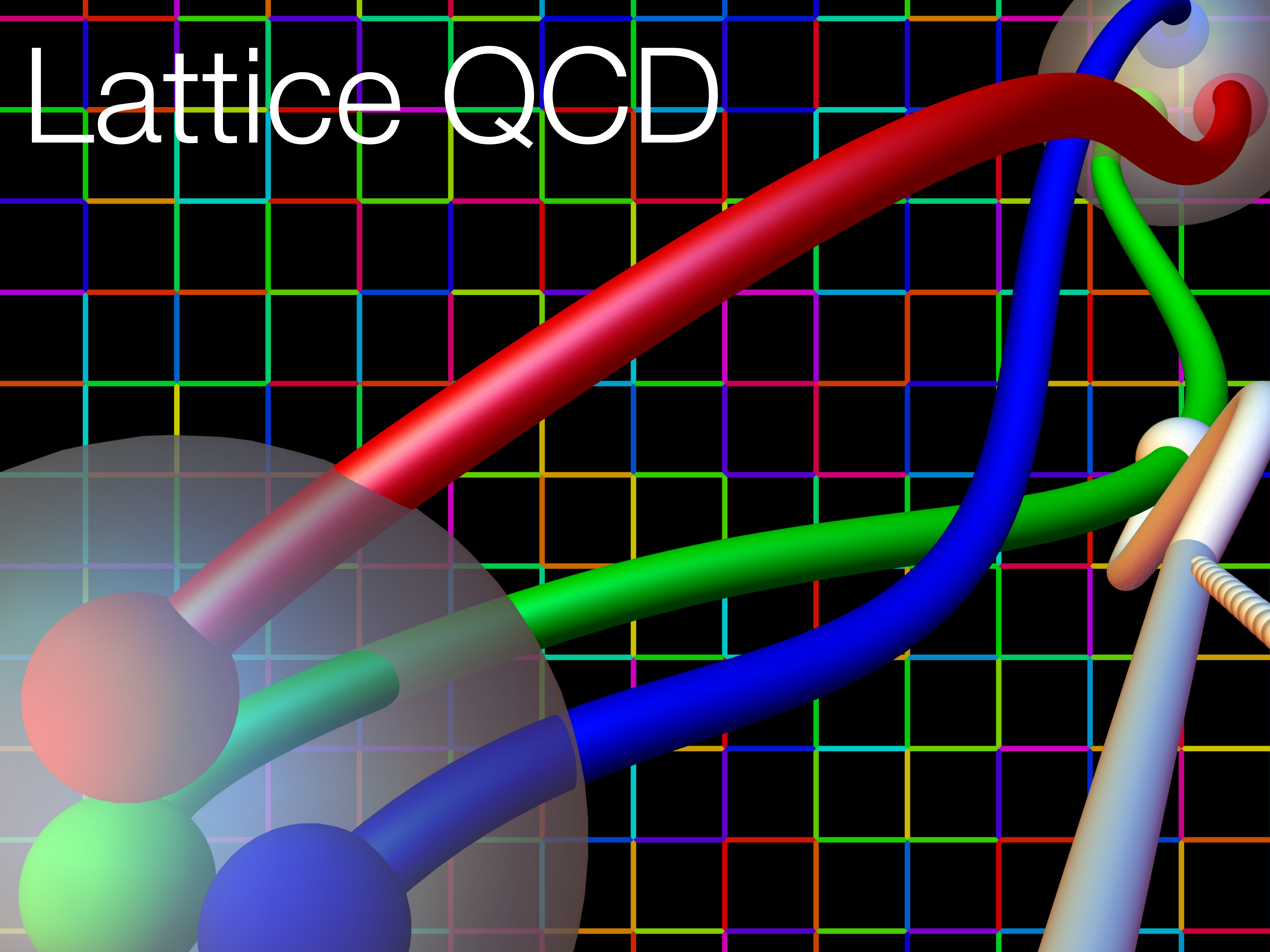


Big Bang
Nucleosynthesis

Astrophysics



New Physics
Searches

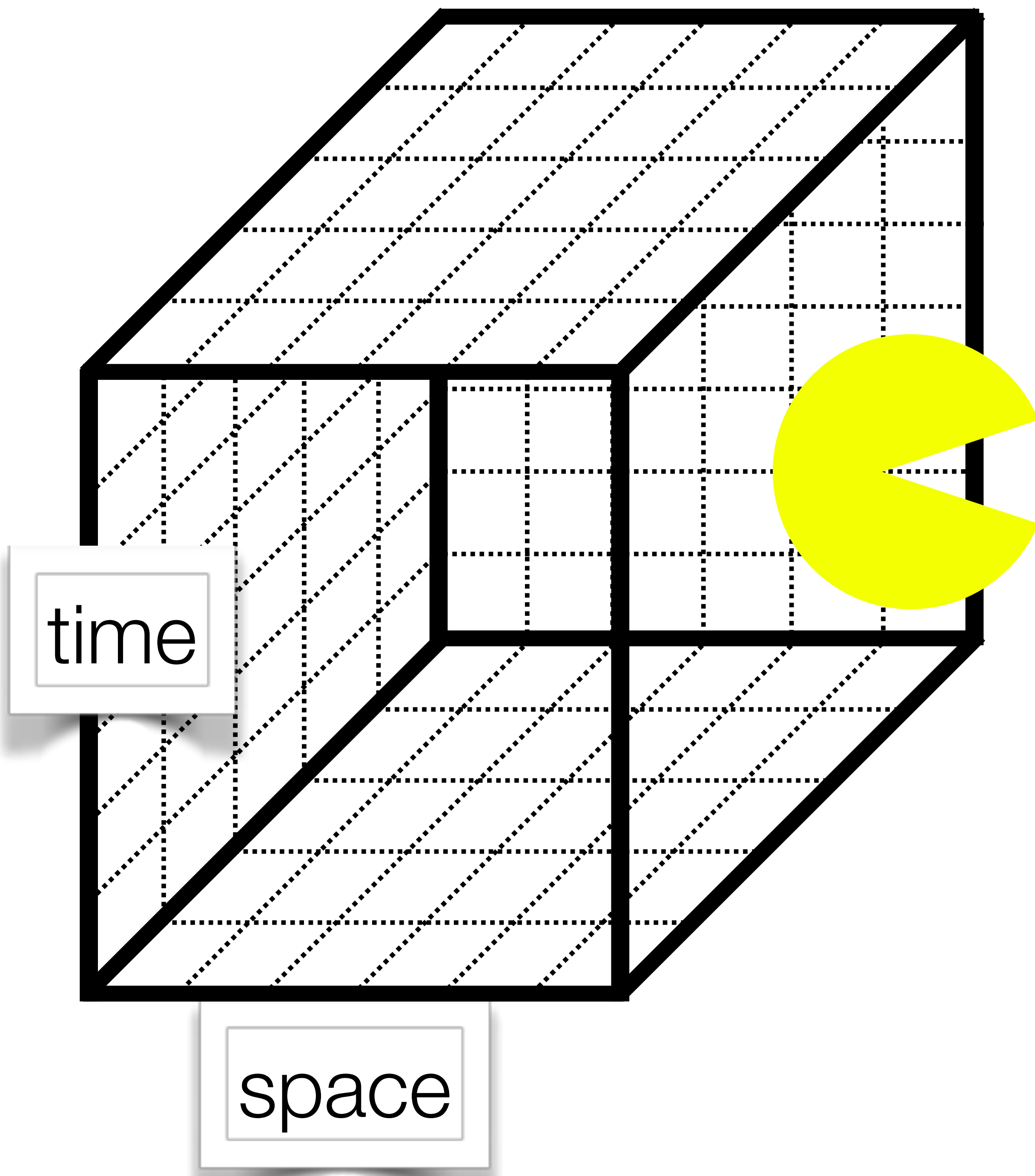

Lattice QCD

Introduction to LQCD

$$\mathcal{L}_{QCD} = -\frac{1}{4}F^2 + \bar{\psi}(i\not{D} + m)\psi$$

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0) \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}\psi\, \mathcal{D}\bar{\psi}\, \mathcal{D}U\; \mathcal{O}(t)\mathcal{O}^\dagger(0) e^{-S[\bar{\psi},\psi,U]}$$

$$= \frac{1}{\mathcal{Z}} \int \mathcal{D}U \det\left(\not{D} + M\right) e^{-S[U]}\; \mathcal{O}(t)\mathcal{O}^\dagger(0)$$

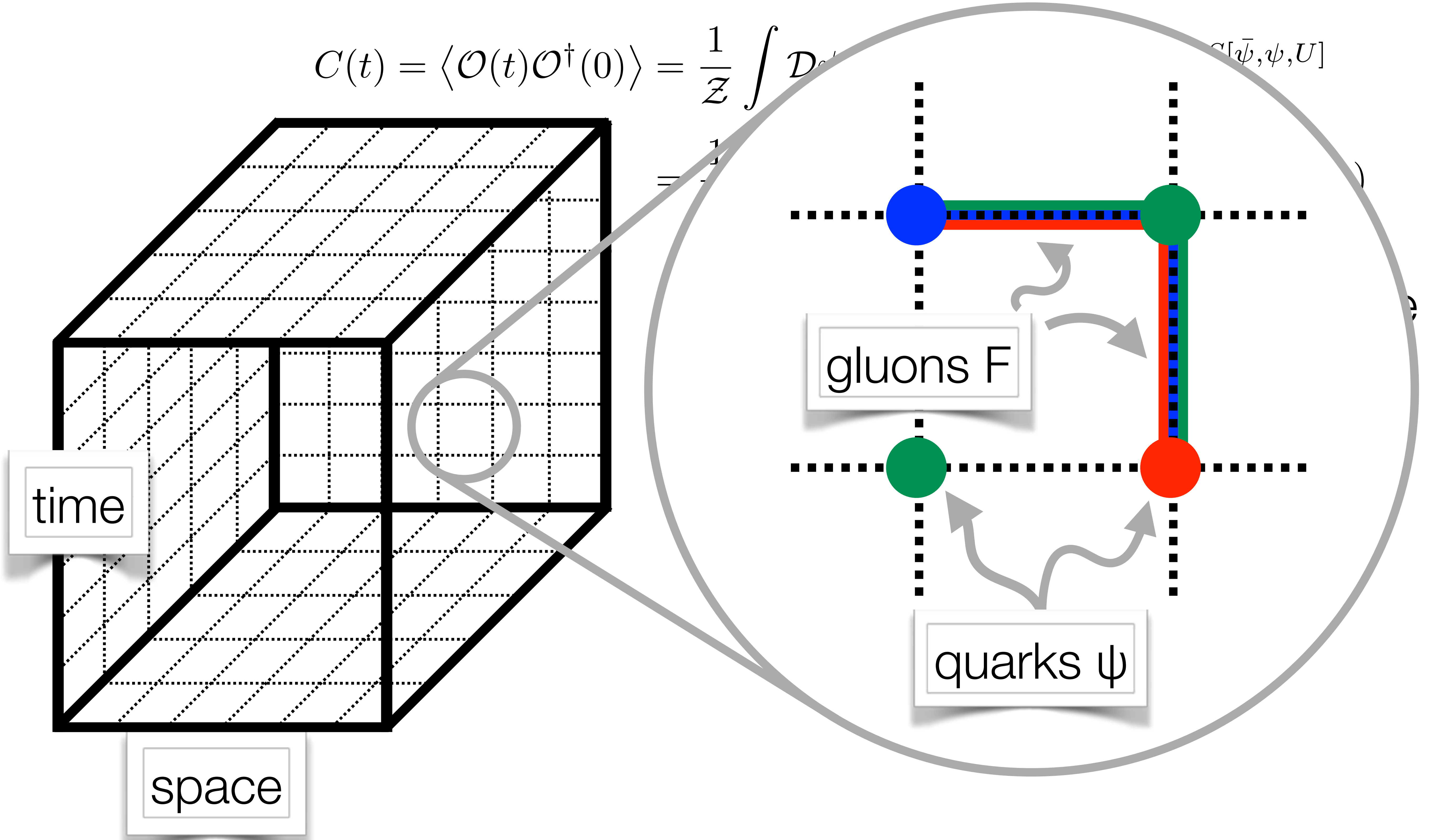


lattice

finite volume

Introduction to LQCD

$$\mathcal{L}_{QCD} = -\frac{1}{4}F^2 + \bar{\psi}(i\not{D} + m)\psi$$

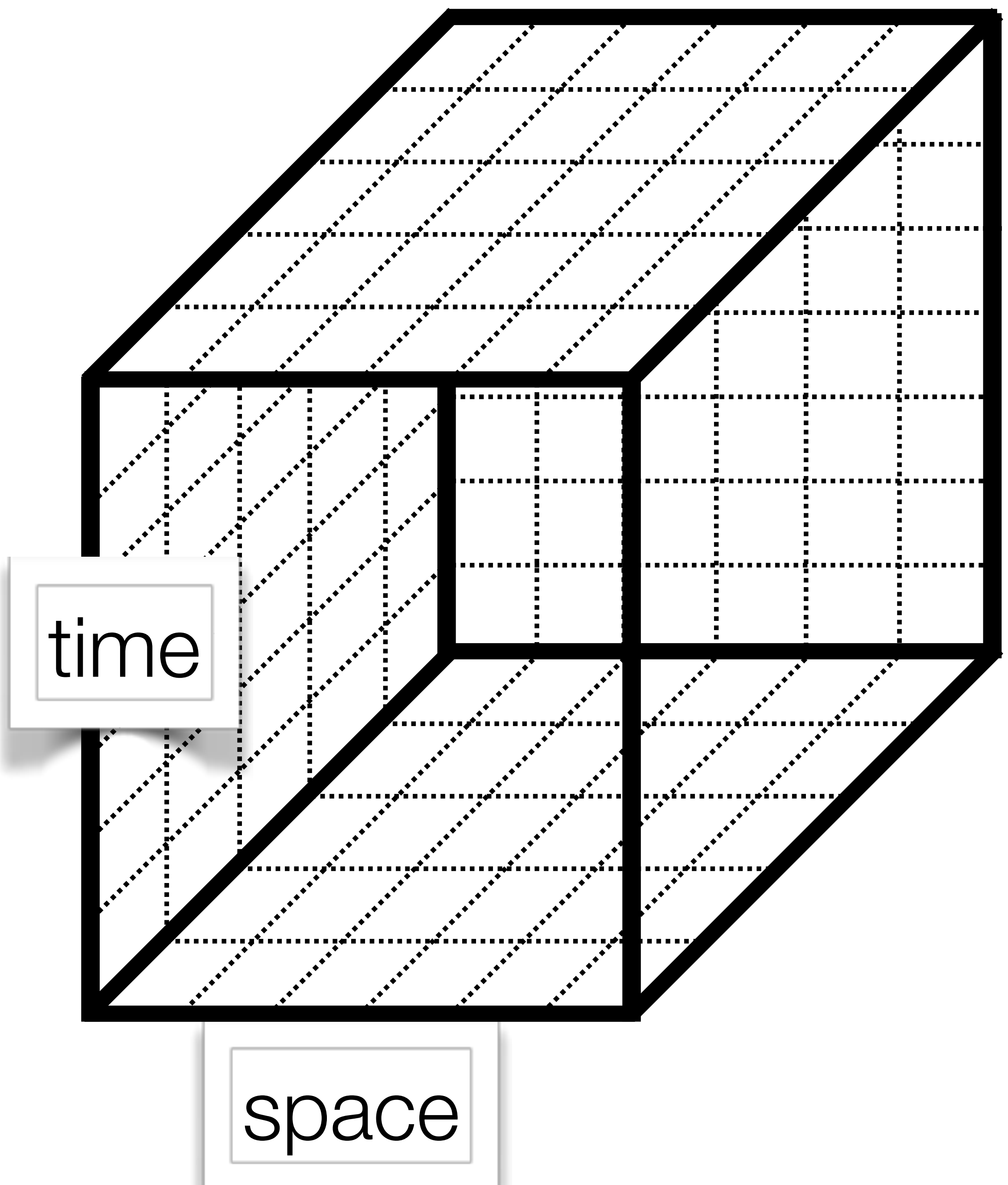


Introduction to LQCD

$$\mathcal{L}_{QCD} = -\frac{1}{4}F^2 + \bar{\psi}(i\not{D} + m)\psi$$

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \frac{1}{\mathcal{Z}}\int \mathcal{D}\psi\,\mathcal{D}\bar{\psi}\,\mathcal{D}U\;\mathcal{O}(t)\mathcal{O}^\dagger(0)e^{-S[\bar{\psi},\psi,U]}$$

$$= \frac{1}{\mathcal{Z}}\int \mathcal{D}U \,\underbrace{\det\left(\not{D}+M\right)e^{-S[U]}}_{\text{Probability}}\;\mathcal{O}(t)\mathcal{O}^\dagger(0)$$



$$\{U_1, U_2, U_3, \ldots, U_N\}$$

Markov Chain Monte Carlo

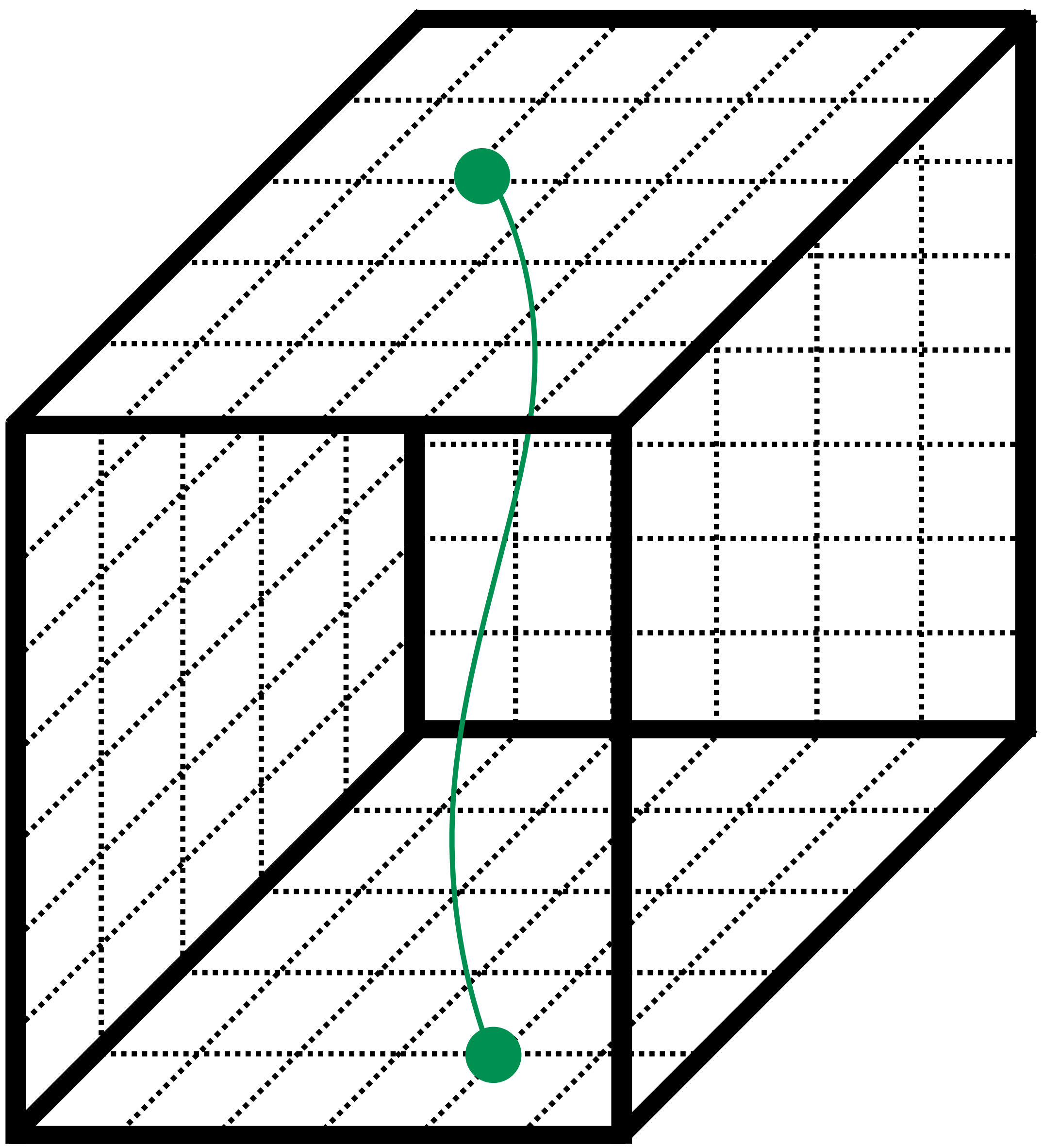
$$\approx \frac{1}{N}\sum_{i=1}^{N}\mathcal{O}(t)\mathcal{O}^\dagger(0)[U_i] + O\left(\frac{1}{\sqrt{N}}\right)$$

Introduction to LQCD

$$\mathcal{L}_{QCD} = -\frac{1}{4}F^2 + \bar{\psi}(i\not{D} + m)\psi$$

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0) \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}\psi\, \mathcal{D}\bar{\psi}\, \mathcal{D}U\;\mathcal{O}(t)\mathcal{O}^\dagger(0) e^{-S[\bar{\psi},\psi,U]}$$

$$= \frac{1}{\mathcal{Z}} \int \mathcal{D}U \det\left(\not{D} + M\right) e^{-S[U]}\; \mathcal{O}(t)\mathcal{O}^\dagger(0)$$



D is a sparse matrix

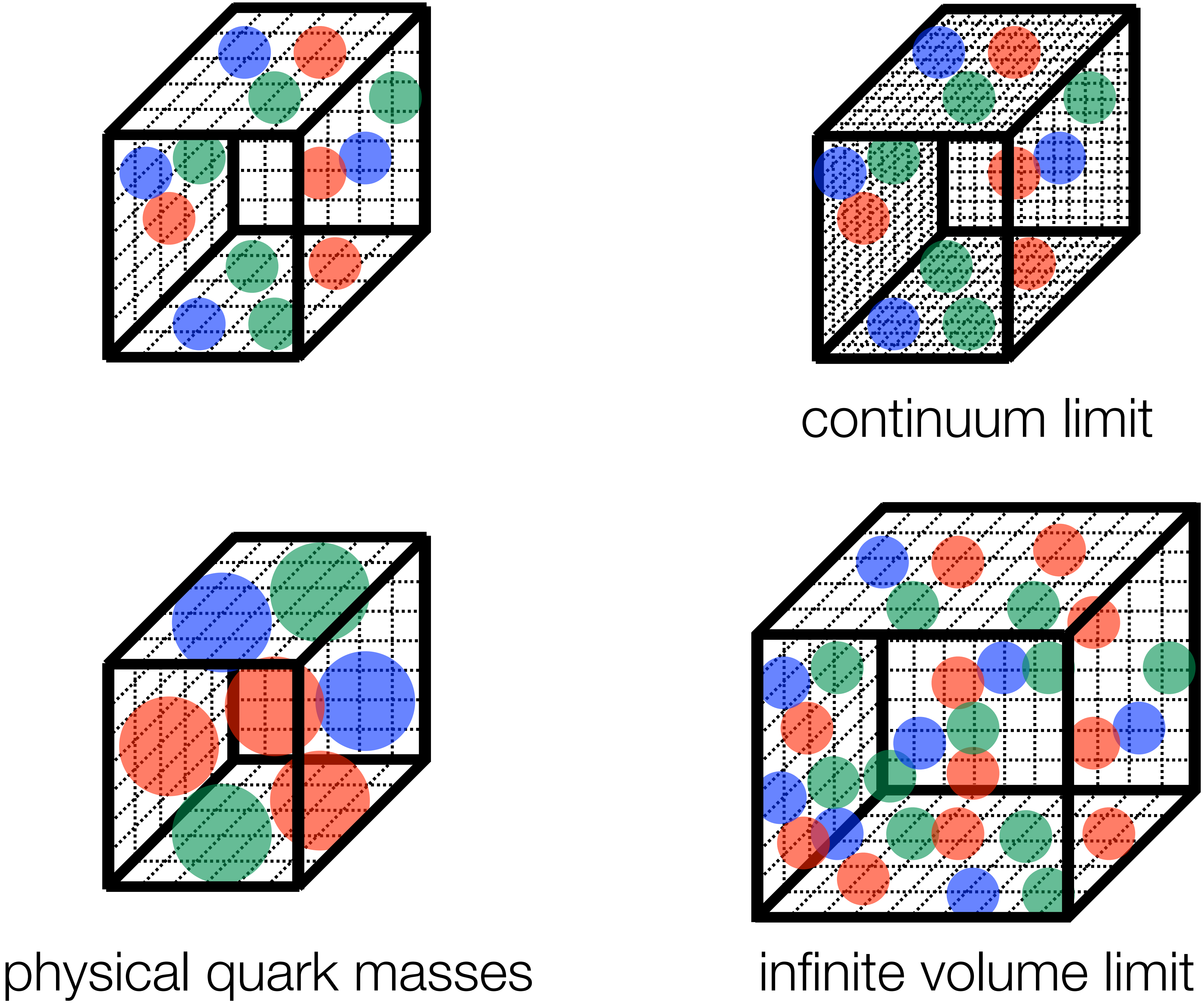
U-dependent

(N_x N_t N_c N_s) on a side

($48^3 \times 64 \times 3 \times 4$)=127 401 984

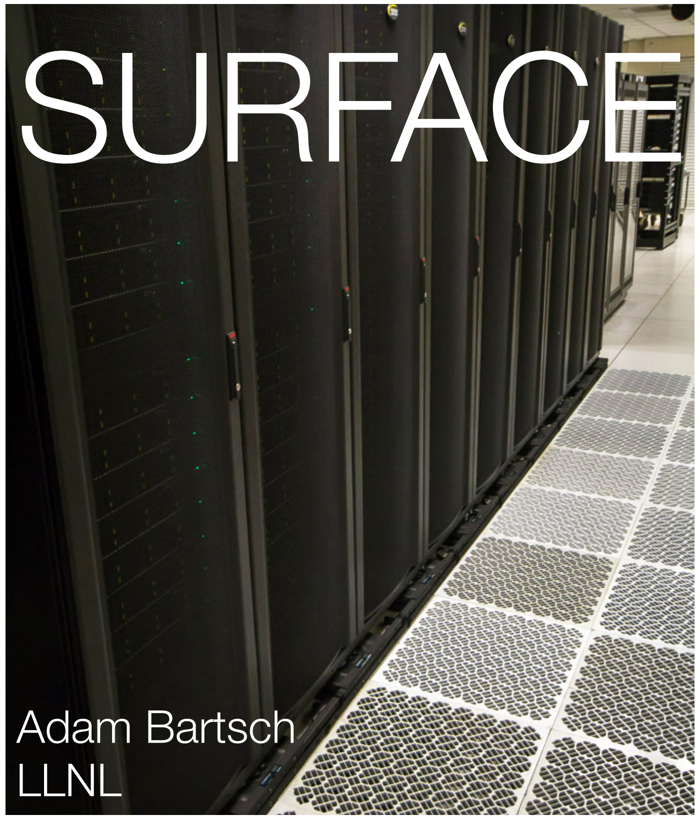
$$(\not{D}[U] + M)S_F(x \leftarrow y) = i\delta(x - y)$$

LQCD Systematics



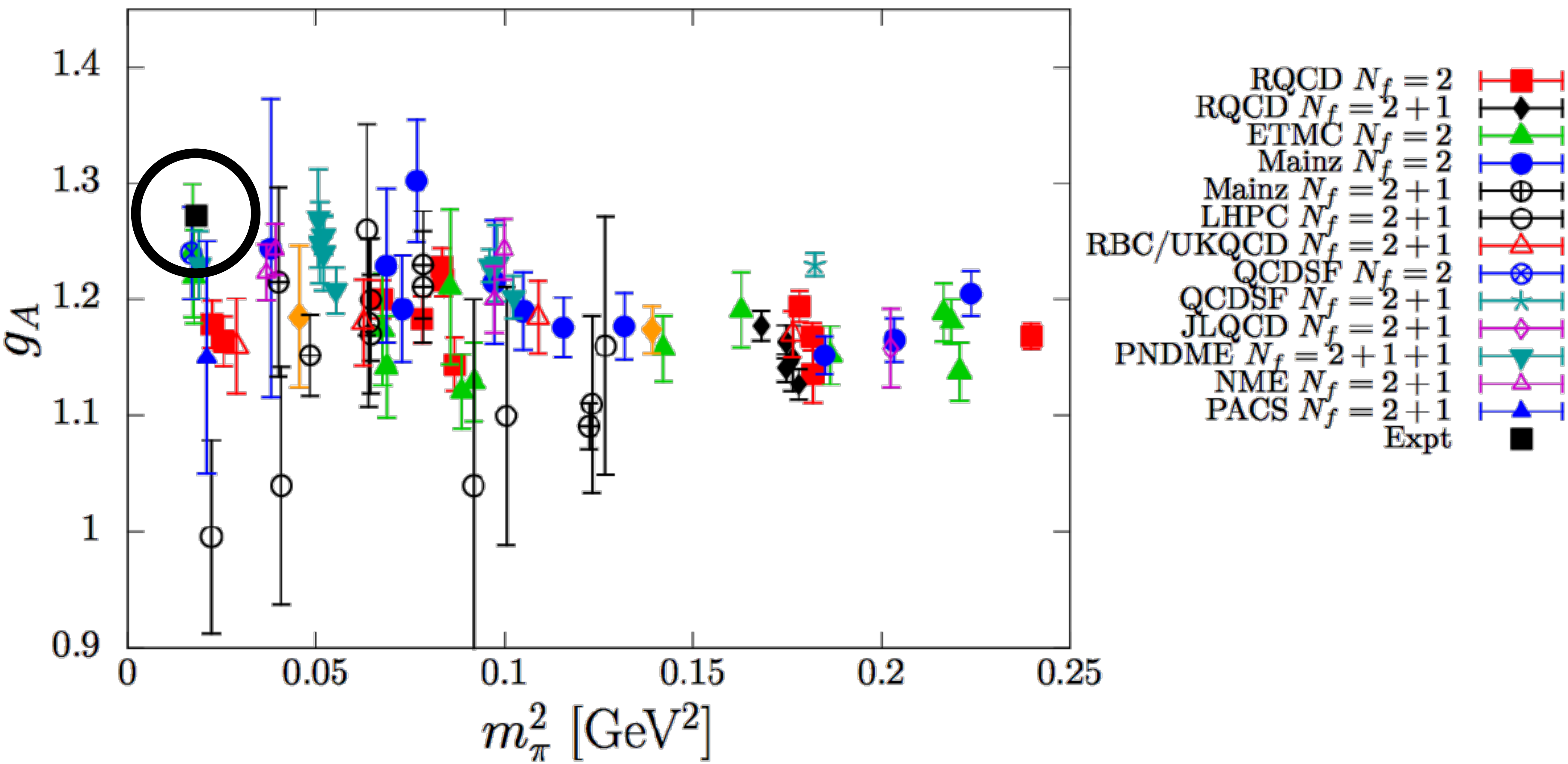

TITAN
OLCF


Edison
NERSC


SURFACE
Adam Bartsch
LLNL

A long-outstanding problem for LQCD

S. Collins, LATTICE2016 plenary



MILC Ensembles

MILC Collaboration Phys. Rev. D87 (2013) 054505 + additional HISQ ensembles generated at LLNL

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

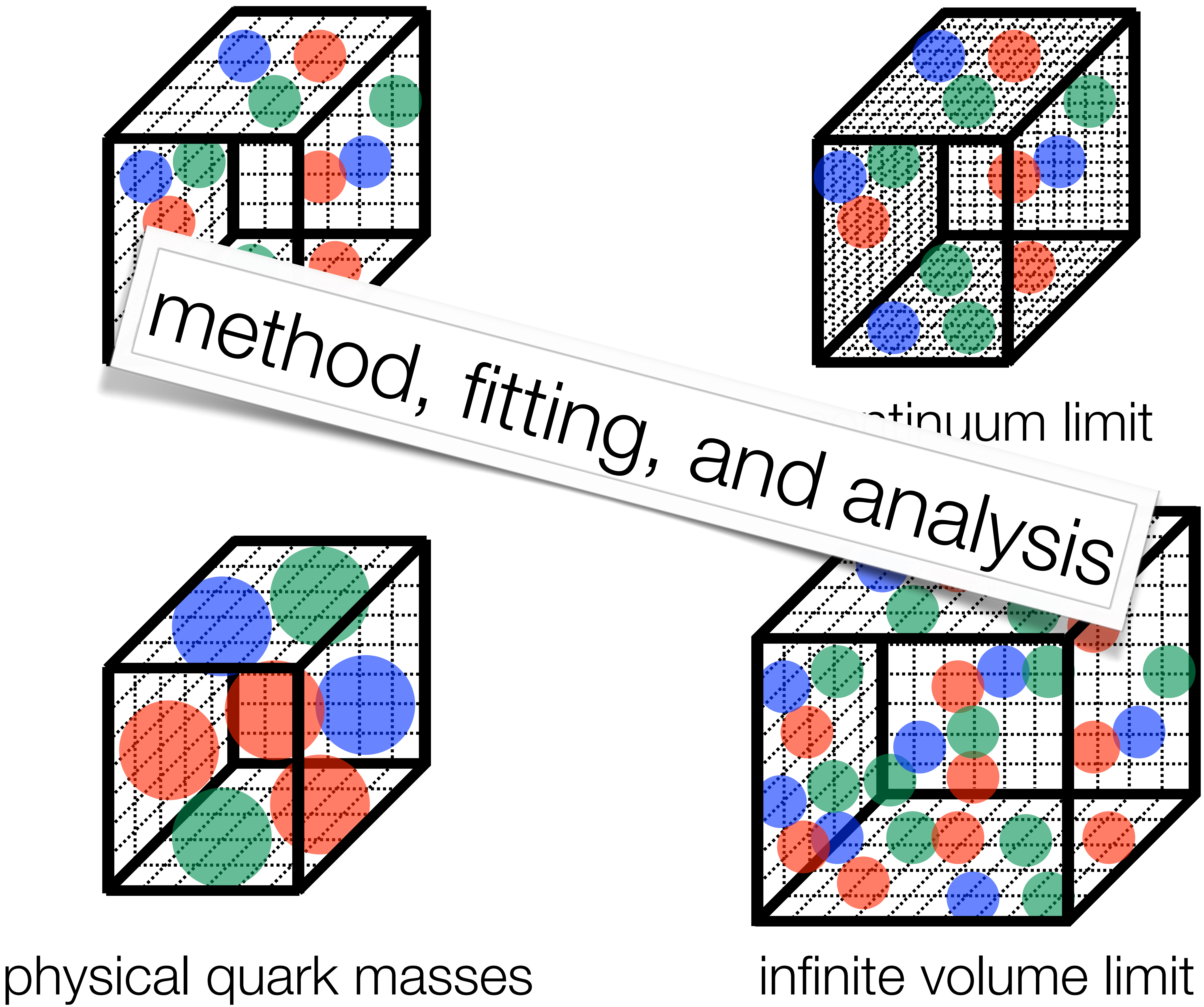
MDWF pion mass tuned to taste-5 HISQ pion mass within 1-2% - ensuring the unitary limit is recovered in the continuum

Free to use; large statistics available

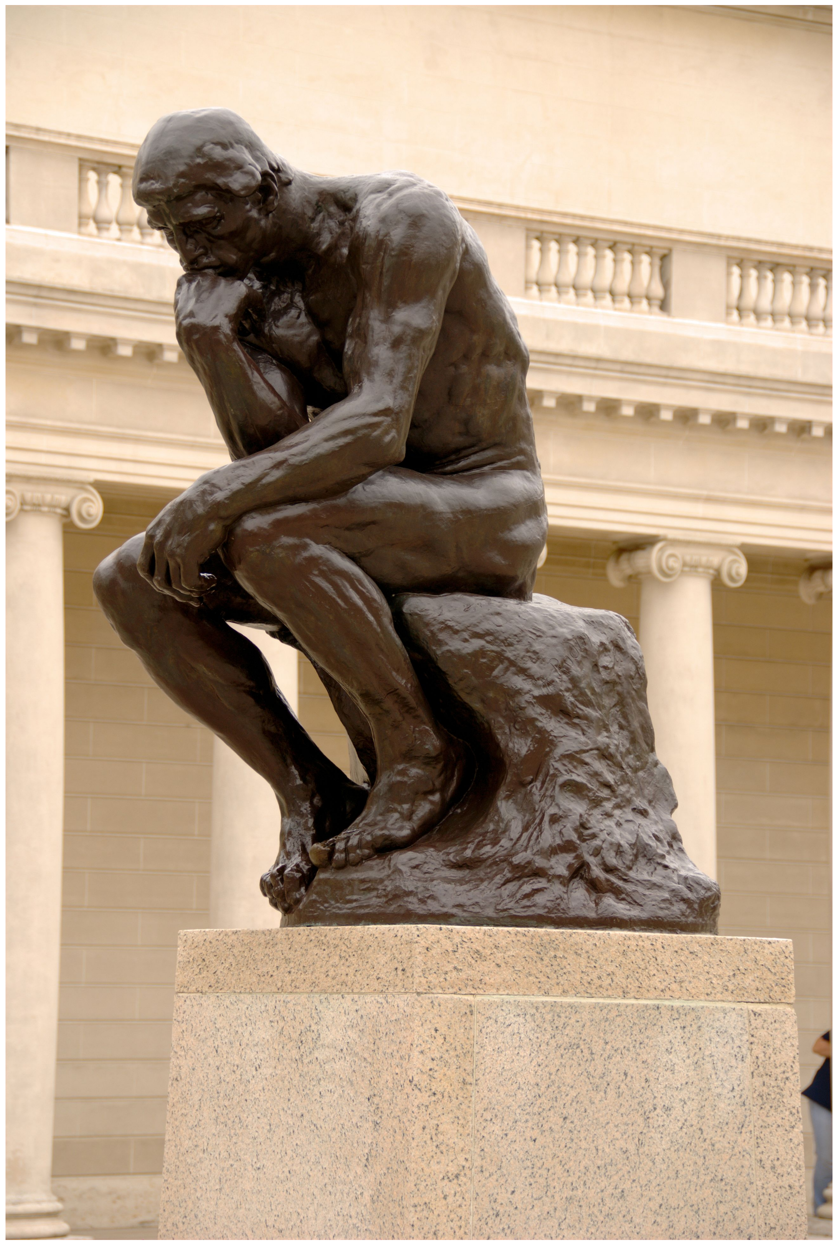
Capable of controlling all systematics

We use domain wall valence on the HISQ sea, $\mathcal{O}(a^2)$ errors [1701.07559].

LQCD Systematics



New Methods

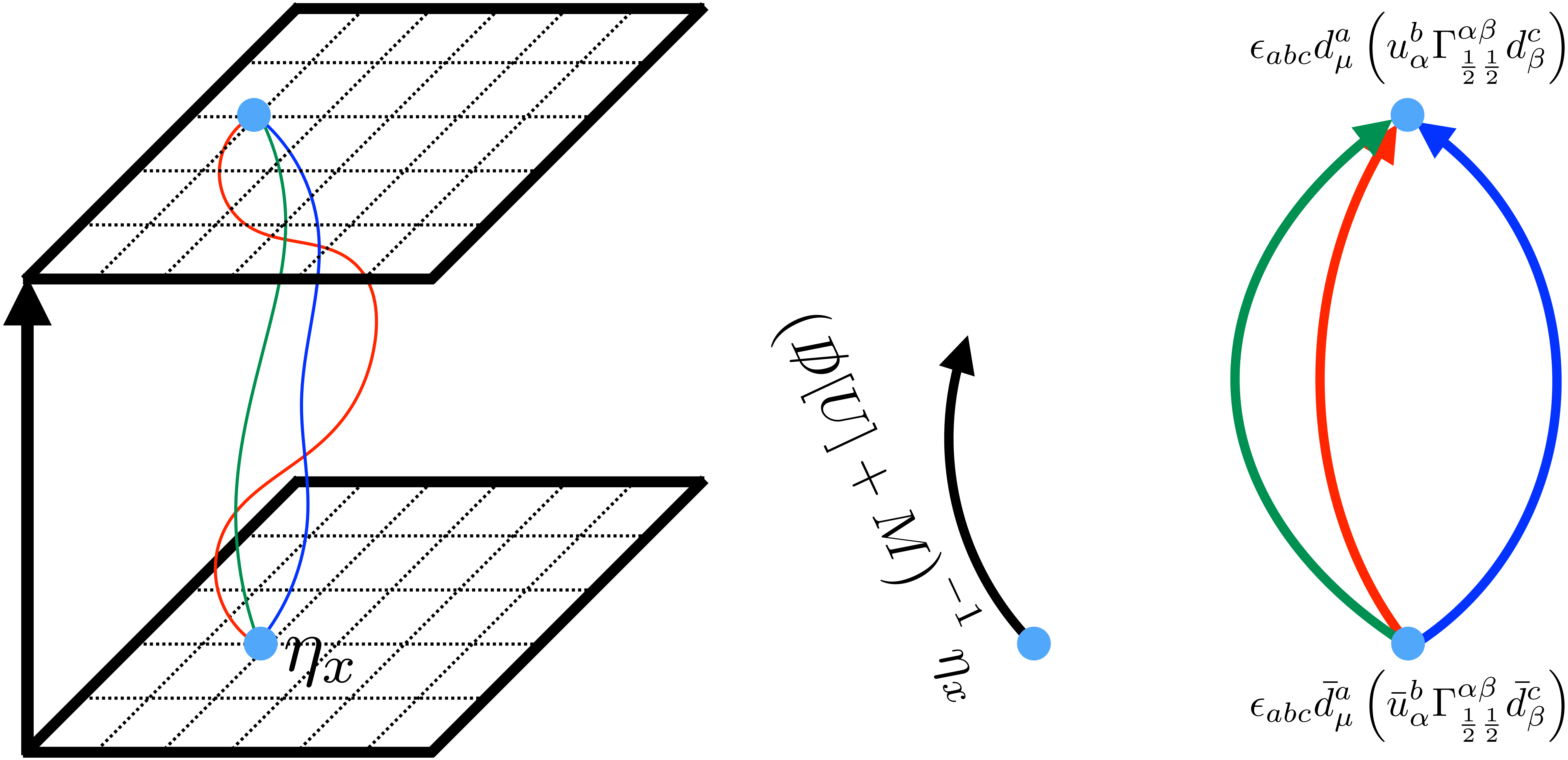


New Analytic Tools

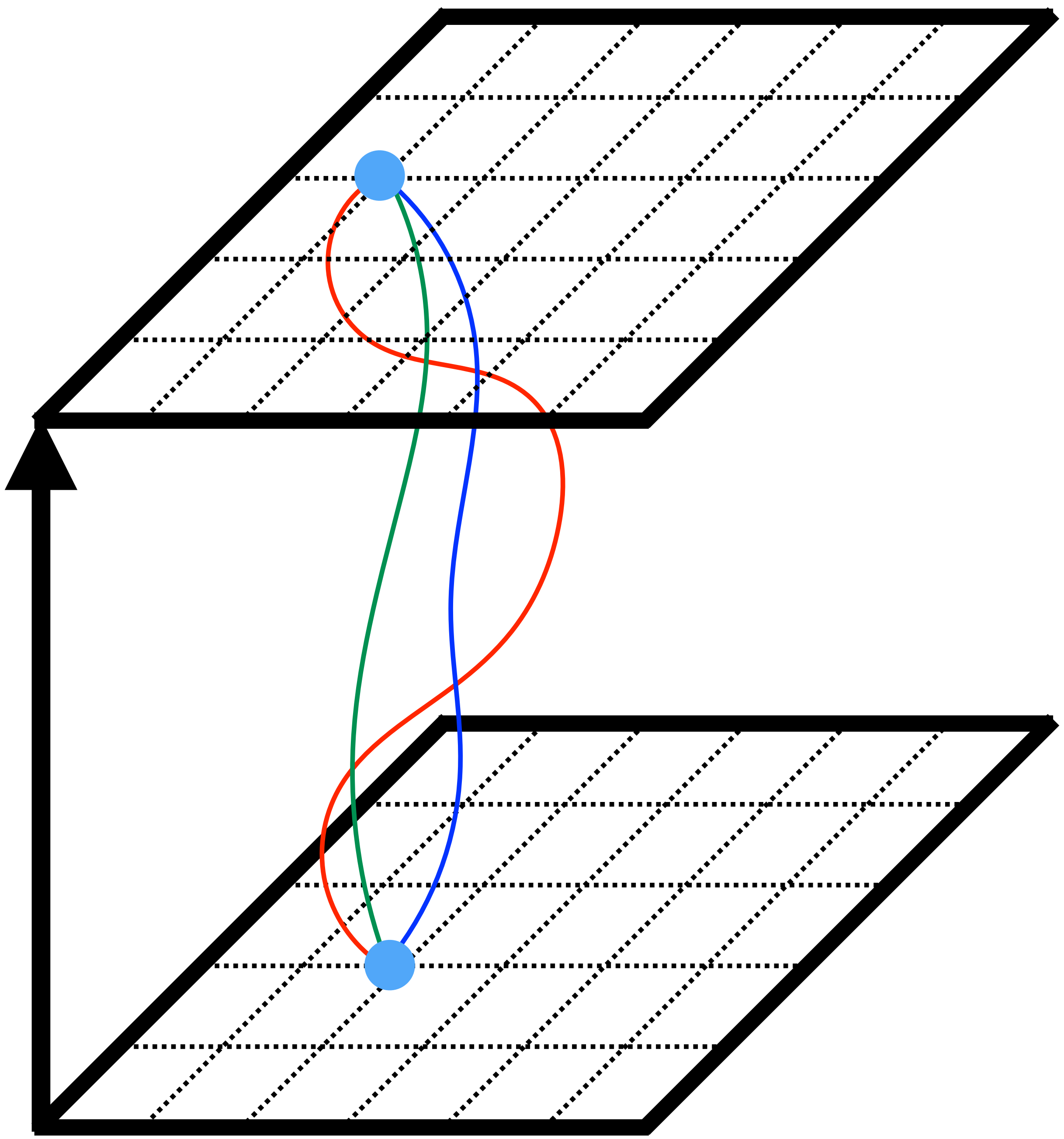
Improved Systematics

Computationally Affordable

2-Point Standard Method



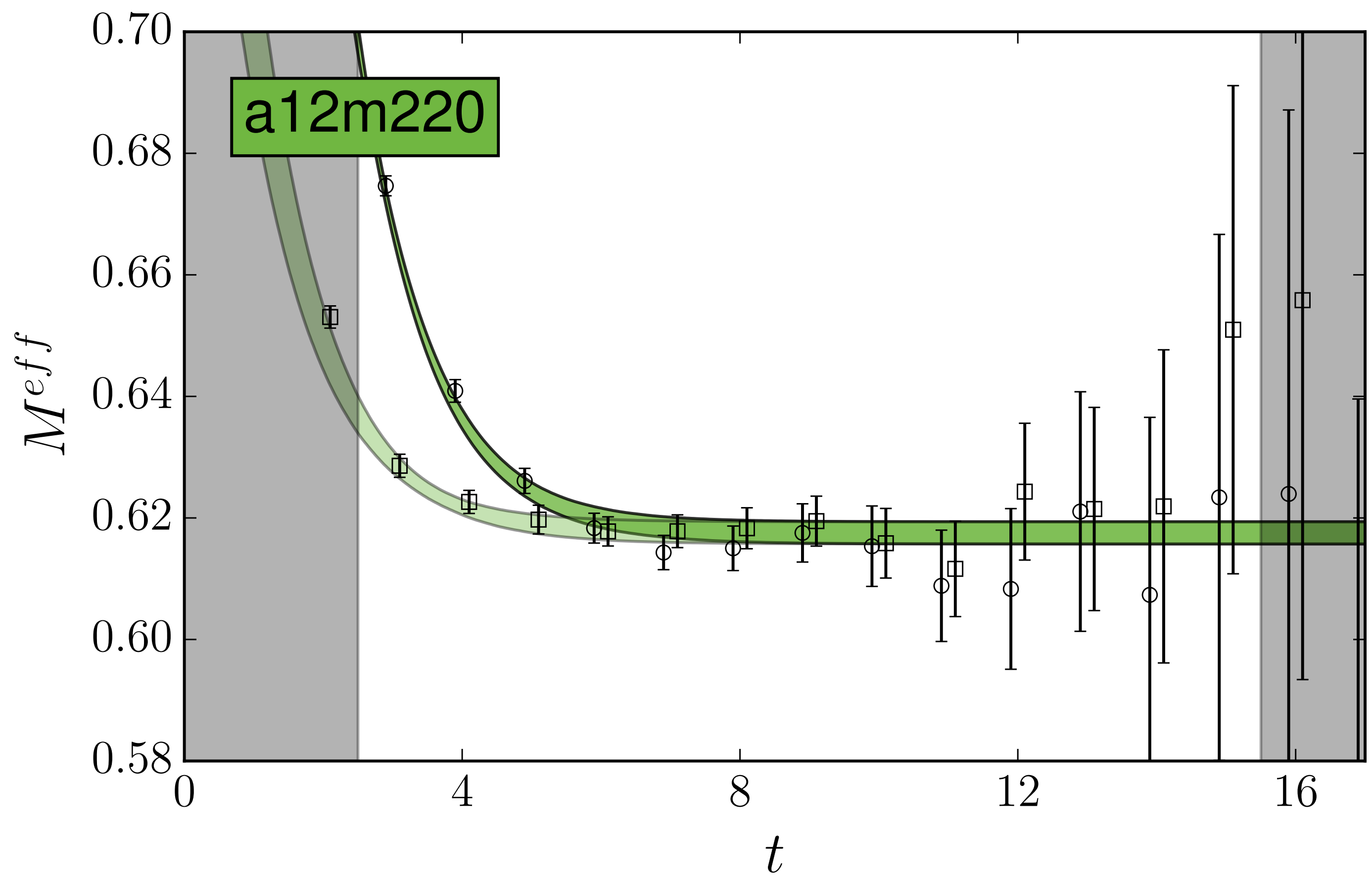
Effective Mass



$$C(t) = \langle \Omega | \mathcal{O}(t) \mathcal{O}^\dagger(0) | \Omega \rangle$$
$$= \sum_n \langle \Omega | e^{\hat{H}t} \mathcal{O}(0) e^{-\hat{H}t} \frac{|n\rangle\langle n|}{2E_n} \mathcal{O}^\dagger(0) | \Omega \rangle$$
$$= \sum_n Z_n Z_n^\dagger \frac{e^{-E_n t}}{2E_n}$$

$$M^{eff}(t) = -\partial_t \ln\left(C(t)\right)$$

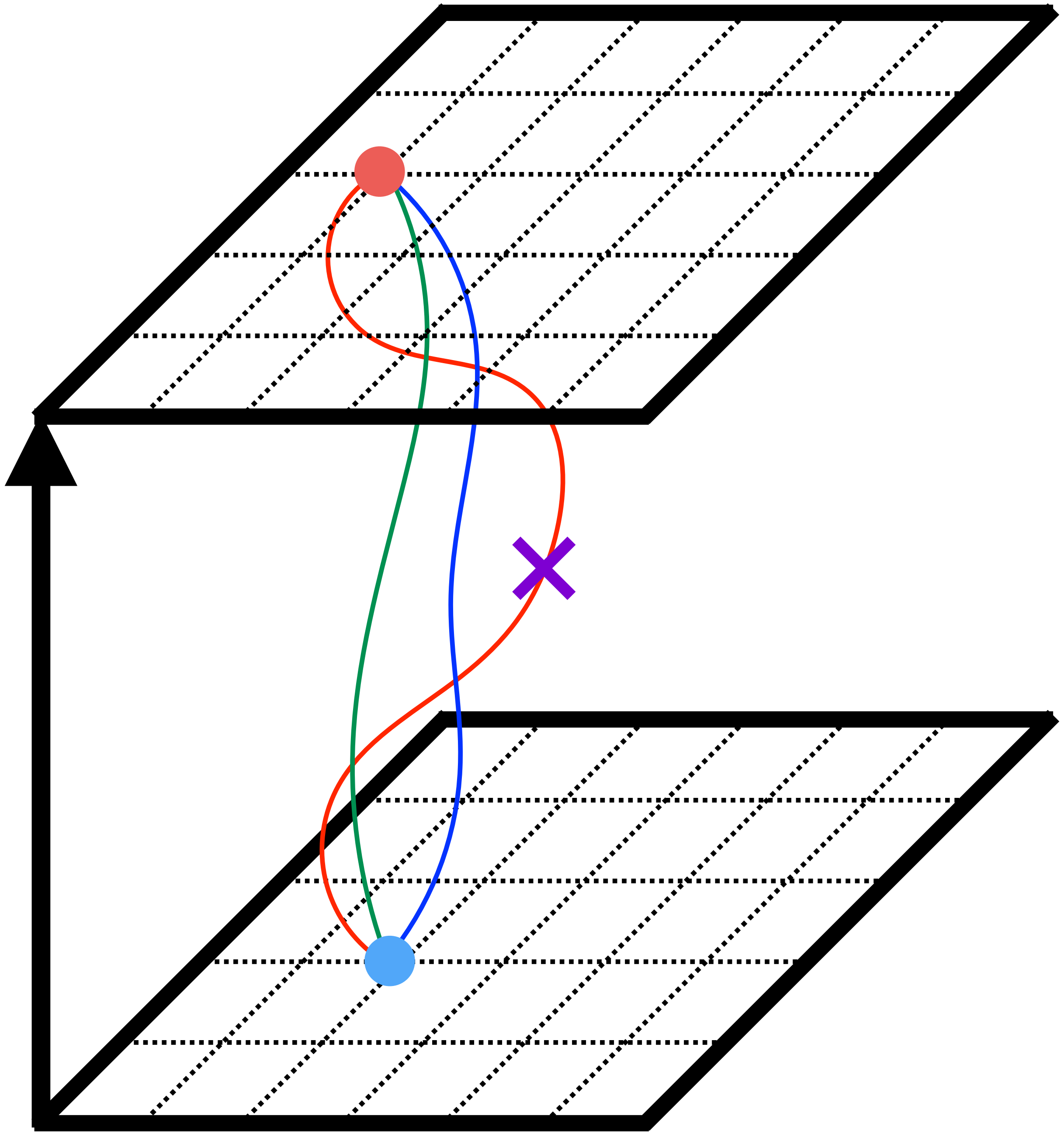
$$\lim_{t\to\infty} M^{eff}(t) = E_0$$



Matrix Elements

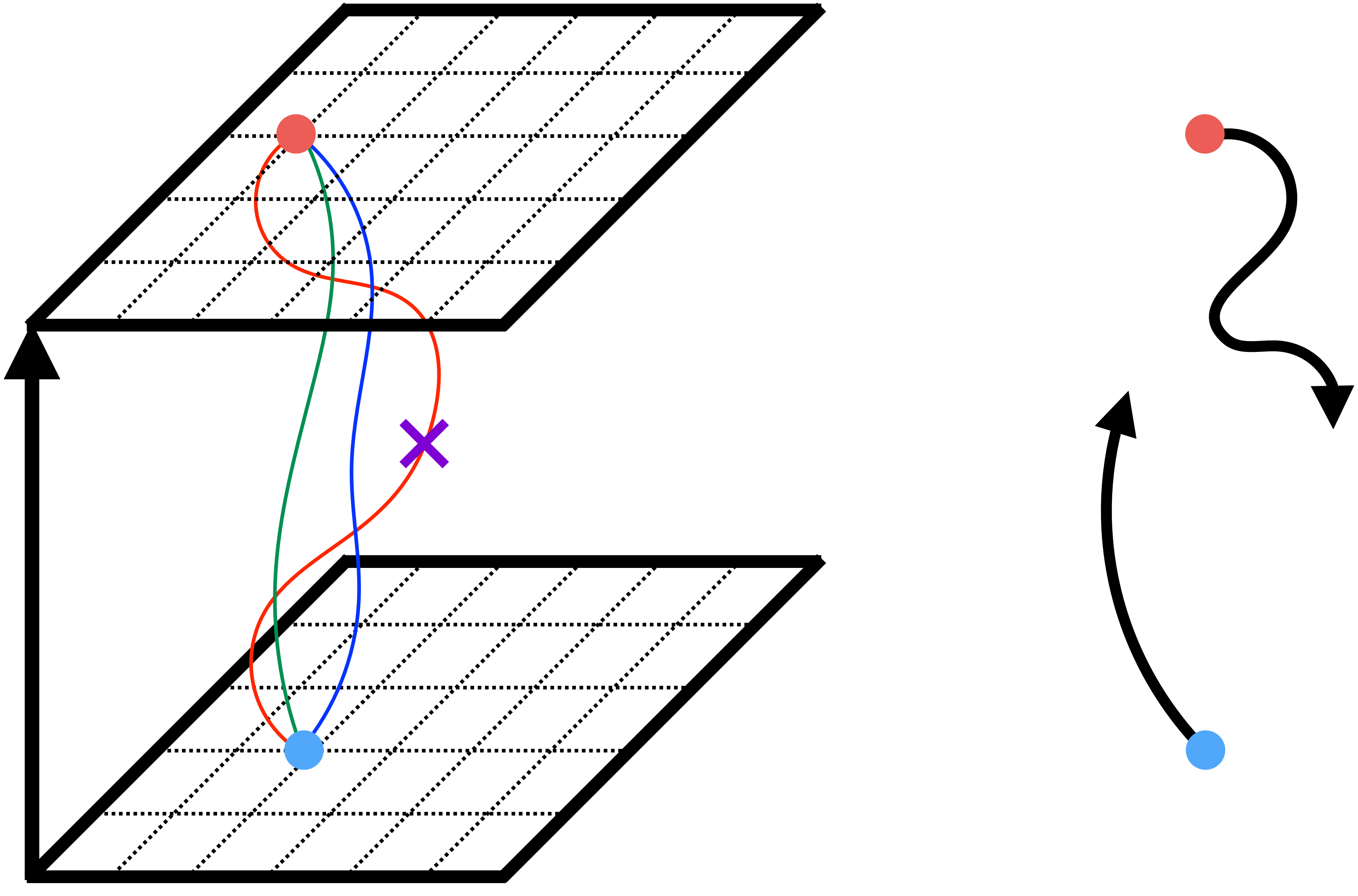
$$\langle \Omega | \mathcal{O}(t)\ \bar{q}\Gamma q(\tau)\ \mathcal{O}^\dagger(0) | \Omega \rangle$$

$$g_A: \quad \bar{q}\gamma_\mu\gamma_5\tau^a q$$

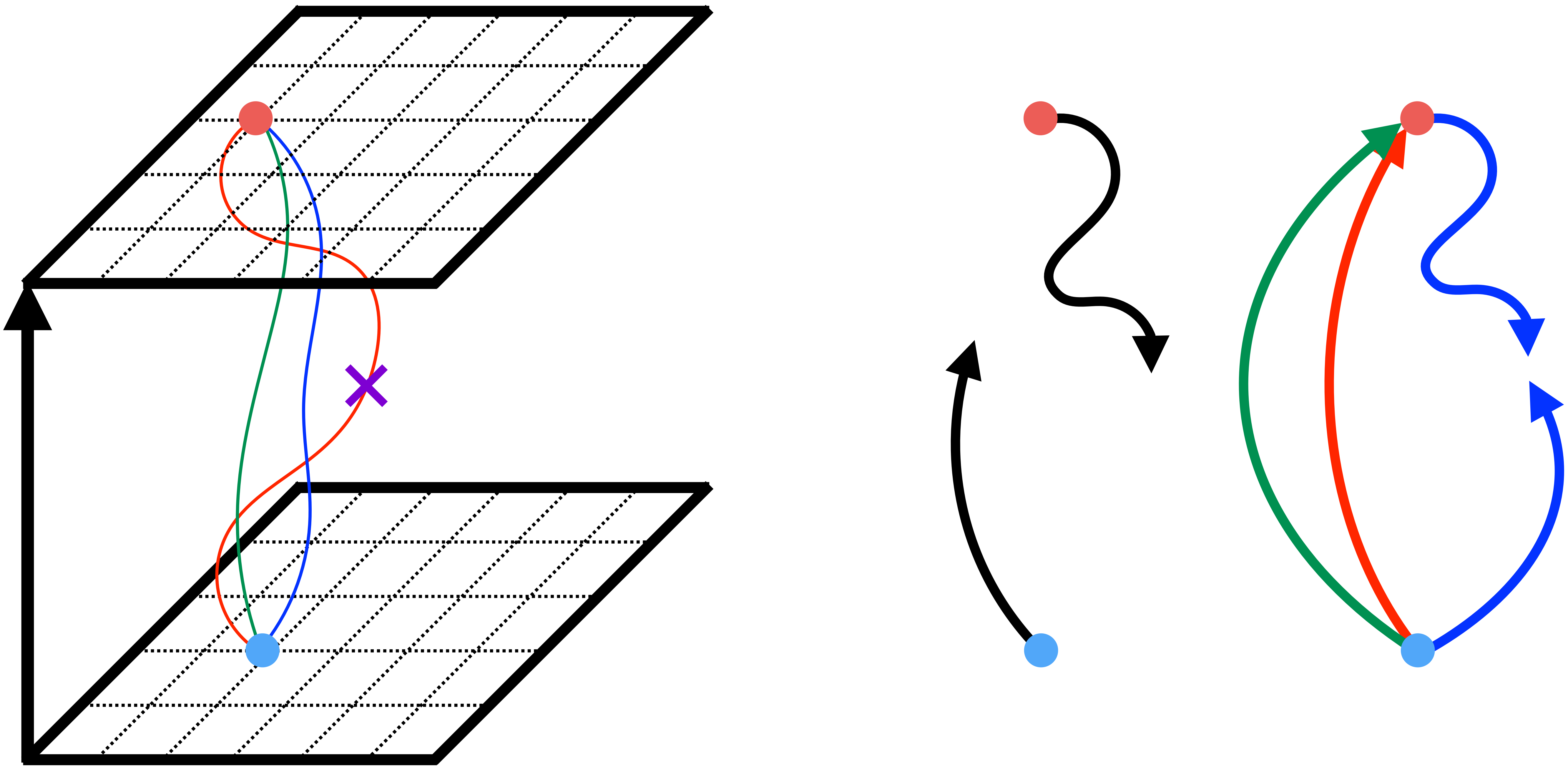


Widely separate
sink, current insertion, and source

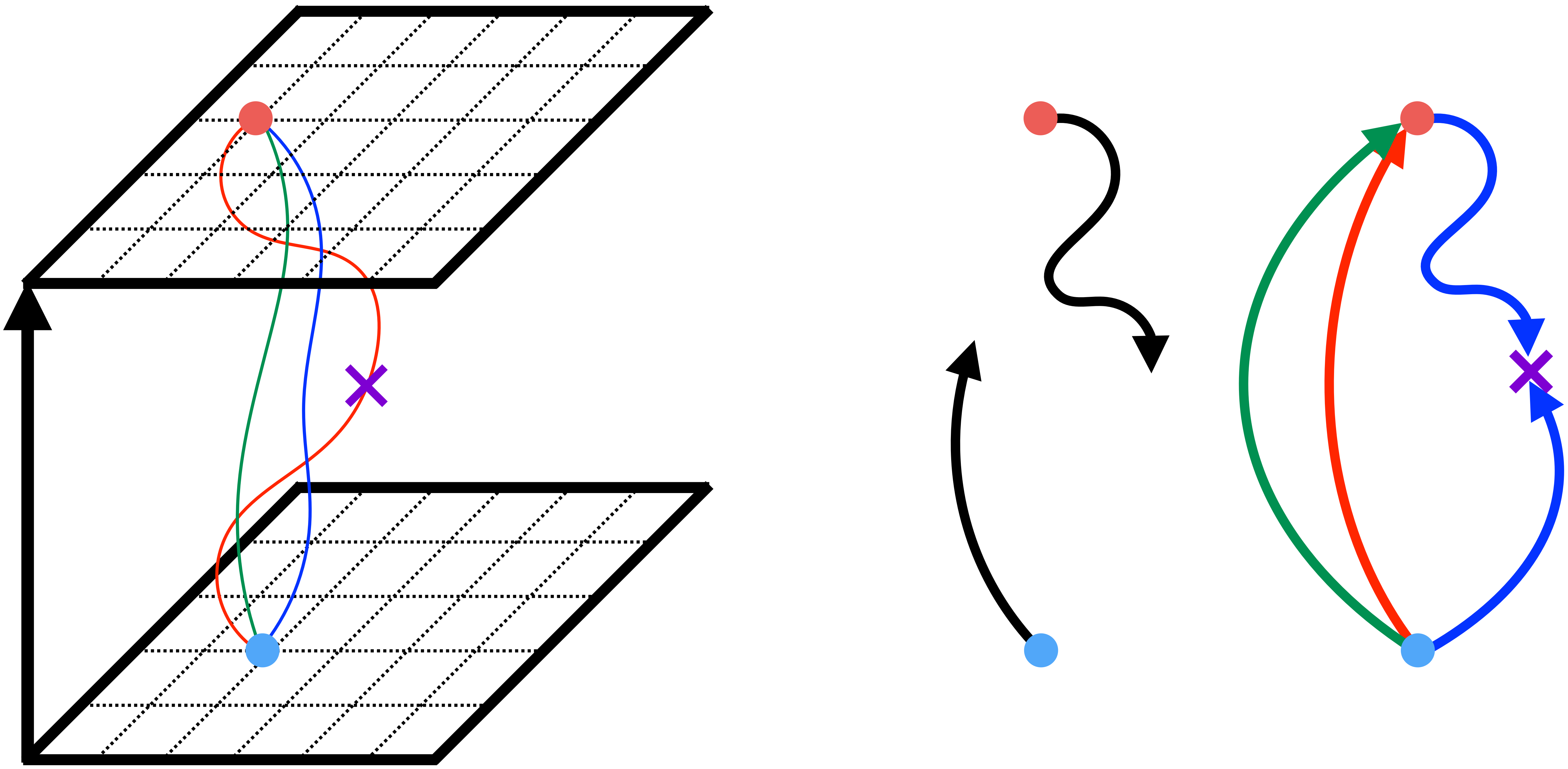
3-Point Standard Method



3-Point Standard Method



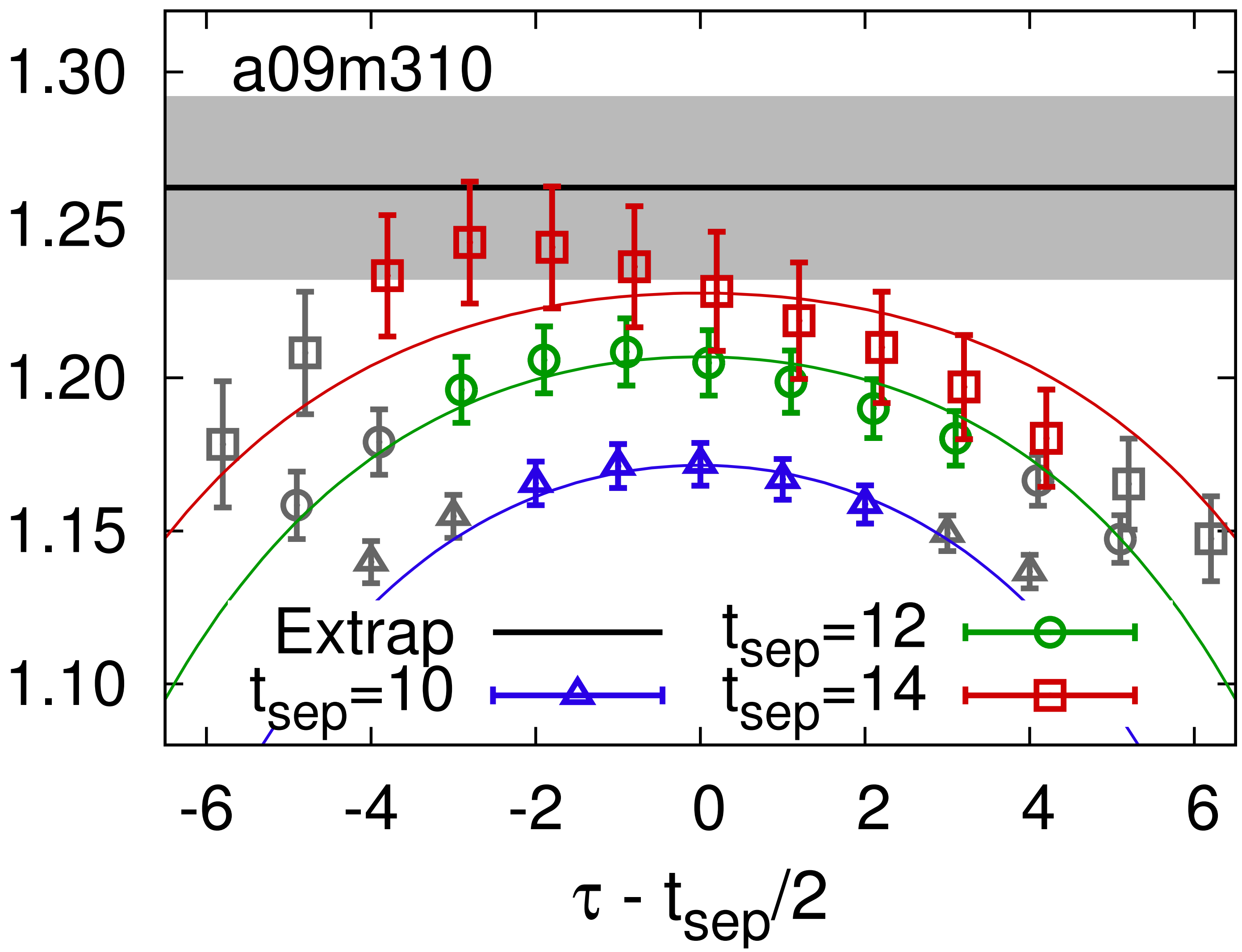
3-Point Standard Method

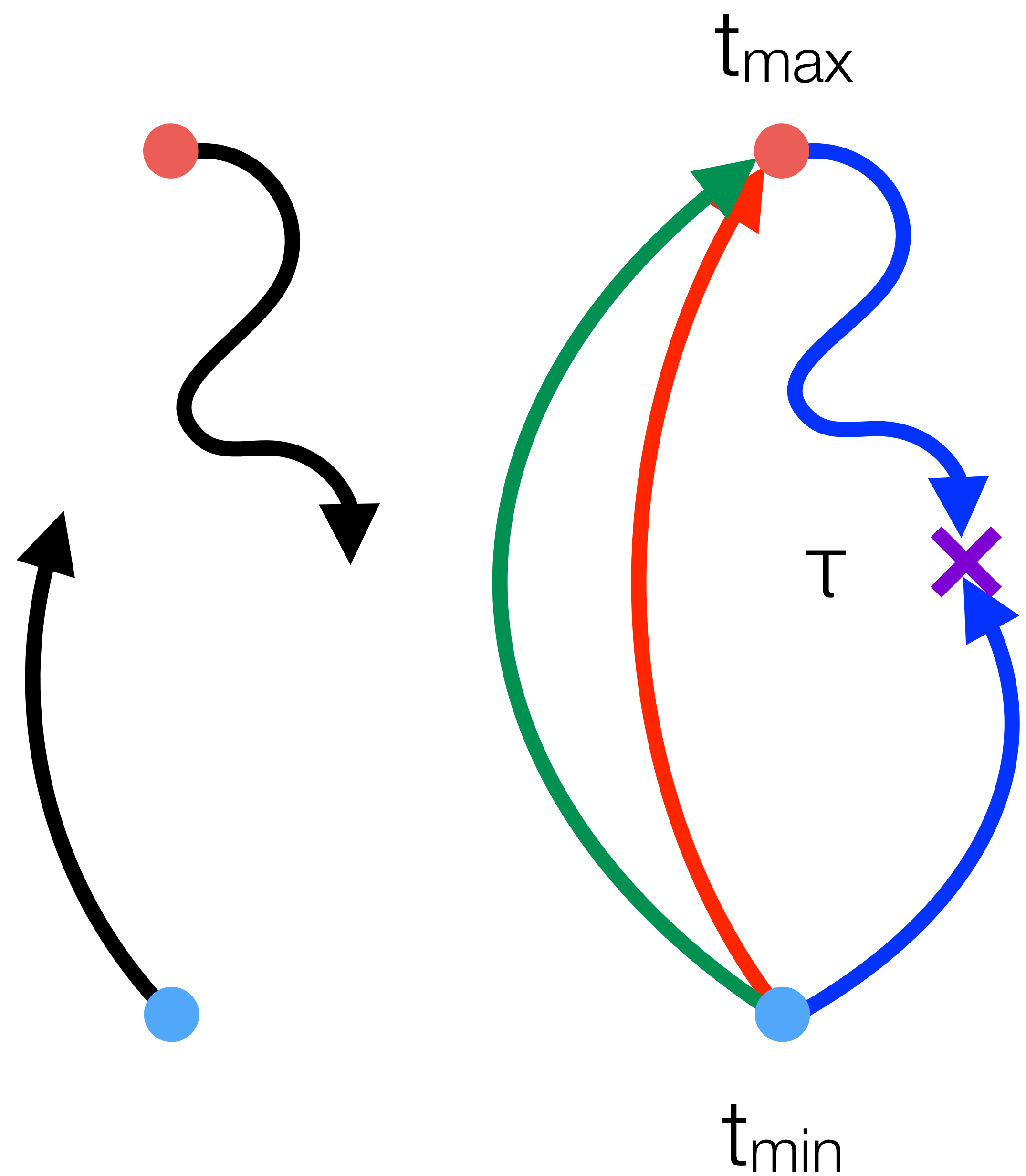


Two solves: one time separation but all bilinears

Standard Method

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



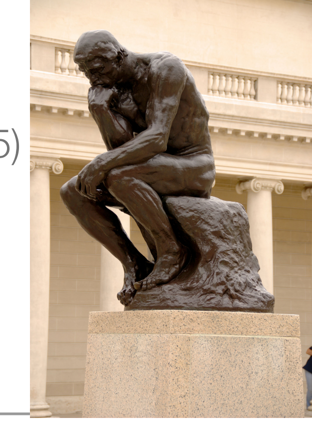


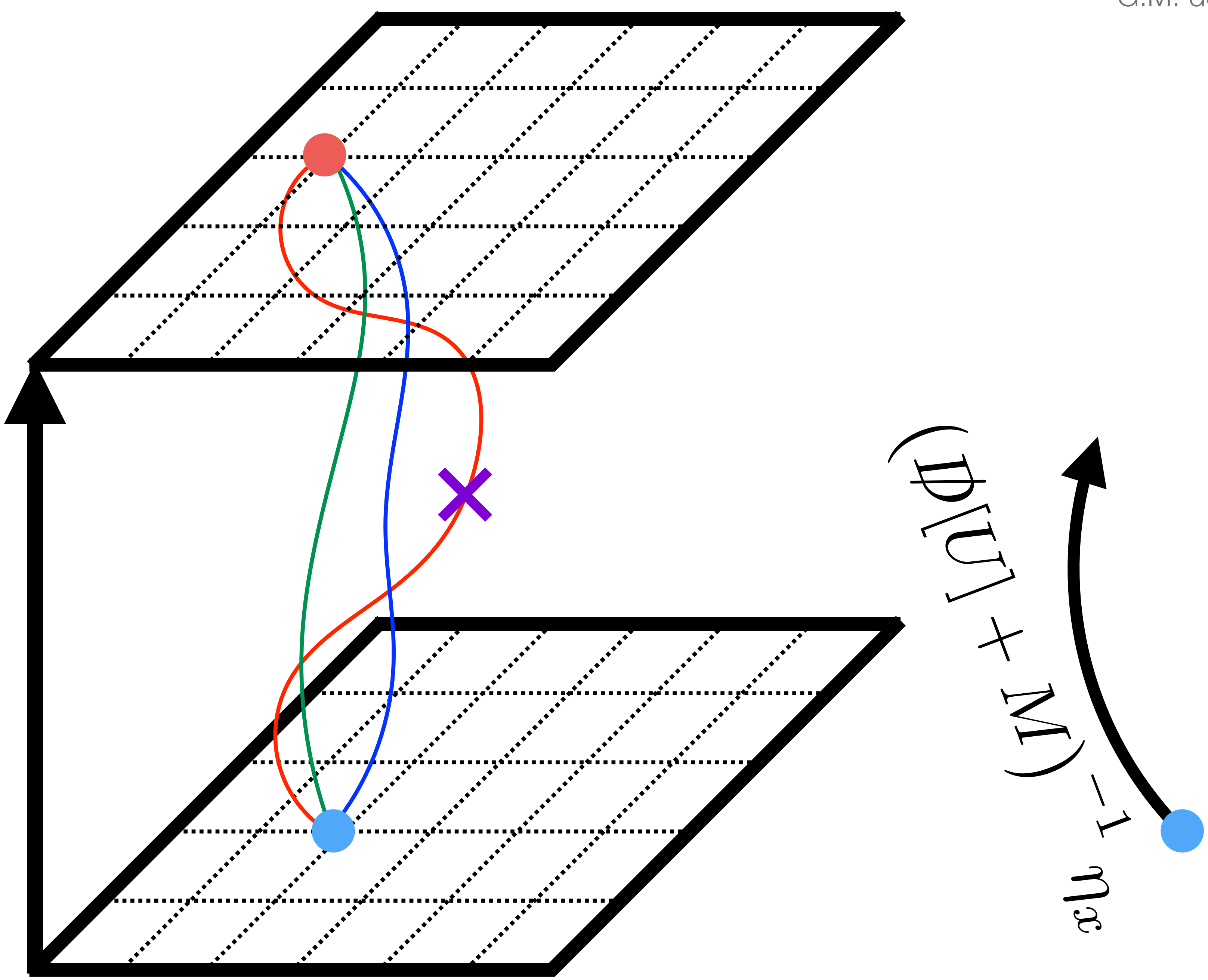
Feynman-Hellmann Method

Bouchard, Chang, Kurth, Orginos, and Walker-Loud arXiv:1612.06963

See also Maiani, Martinelli, Paciello and Taglienti Nucl. Phys. B293 (1987)
NPLQCD 1610.04545, 1611.00344, 1701.03456, 1702.02929

similar methods (other FH / GEVP):
J. Bulava et. al. JHEP 01,140 (2012)
F. Bernardoni et. al. Phys. Lett. B740, 278-284 (2015)
A.J. Chambers et. al. Phys. Rev. D 90, 014510
A.J. Chambers et. al. Phys. Rev. D 92, 114517
M.J. Savage et. al. Phys. Rev. Lett. 119, 062002
similar fit function:
S. Capitani et. al. Phys. Rev. D 86, 074502
propagator construction:
L. Maiani et. al. Nucl. Phys. B293 (1987)
G.M. de Divitiis et. al. Phys. Lett. B718 (2012))





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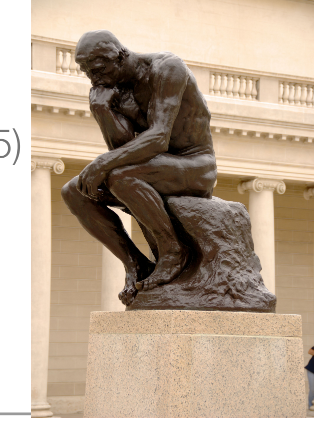

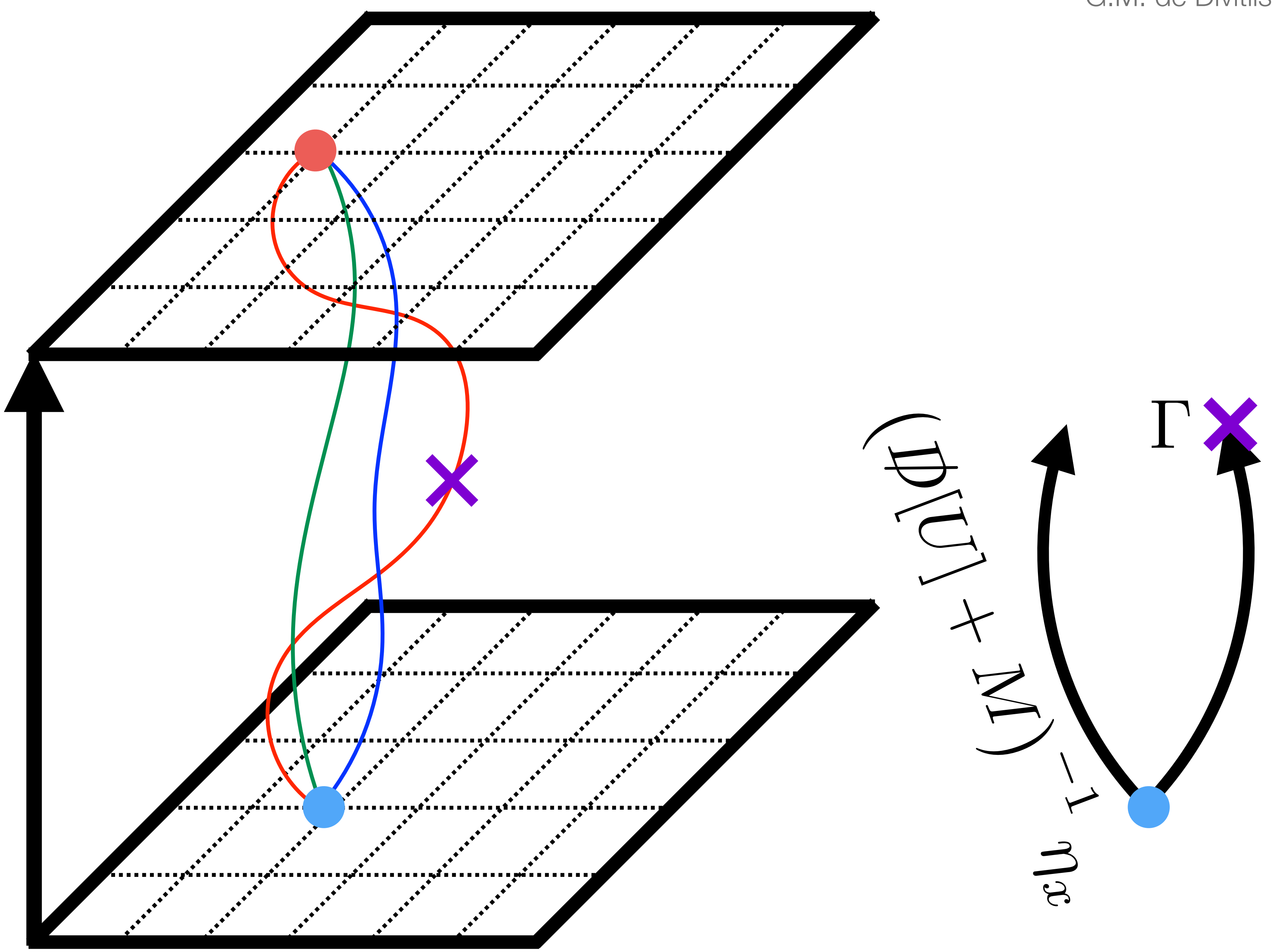

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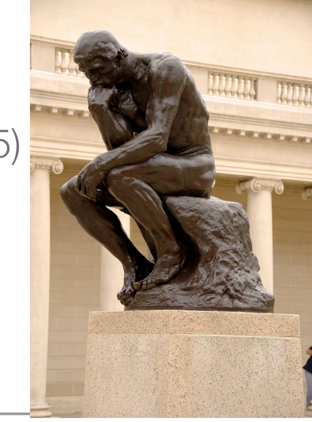
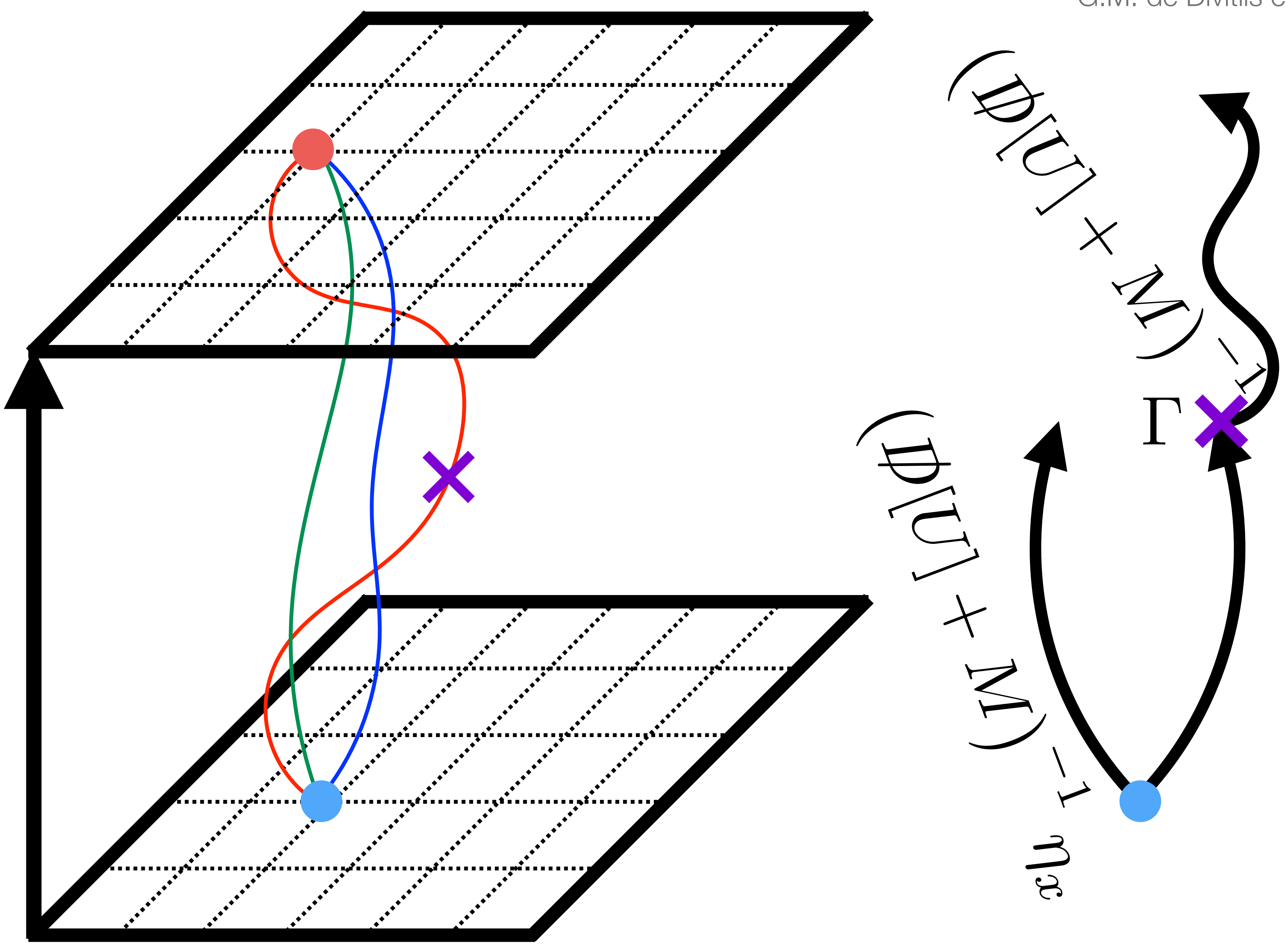
L. Maiani et. al. Nucl. Phys. B293 (1987)
G.M. de Divitiis et. al. Phys. Lett. B718 (2012))





Feynman-Hellmann Method

Bouchard, Chang, Kurth, Orginos, and Walker-Loud arXiv:1612.06963

See also Maiani, Martinelli, Paciello and Taglienti Nucl. Phys. B293 (1987)
NPLQCD 1610.04545, 1611.00344, 1701.03456, 1702.02929

similar methods (other FH / GEVP):
J. Bulava et. al. JHEP 01,140 (2012)
F. Bernardoni et. al. Phys. Lett. B740, 278-284 (2015)
A.J. Chambers et. al. Phys. Rev. D 90, 014510
A.J. Chambers et. al. Phys. Rev. D 92, 114517
M.J. Savage et. al. Phys. Rev. Lett. 119, 062002

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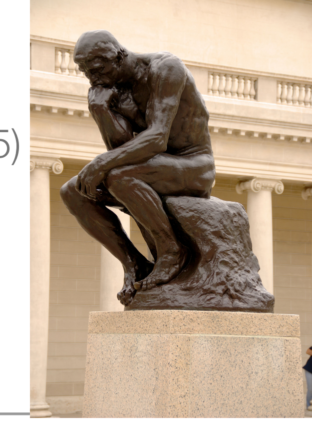

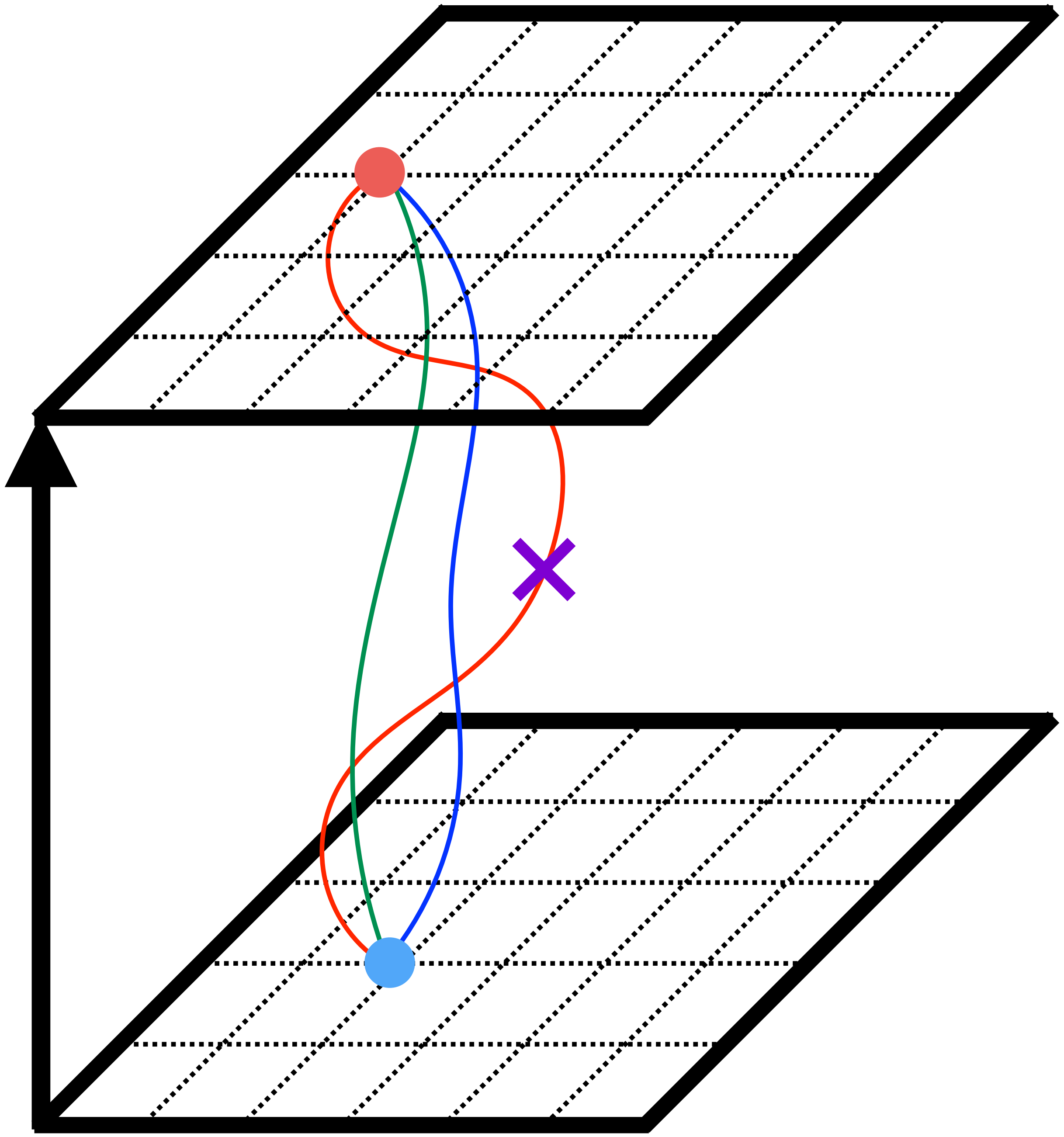

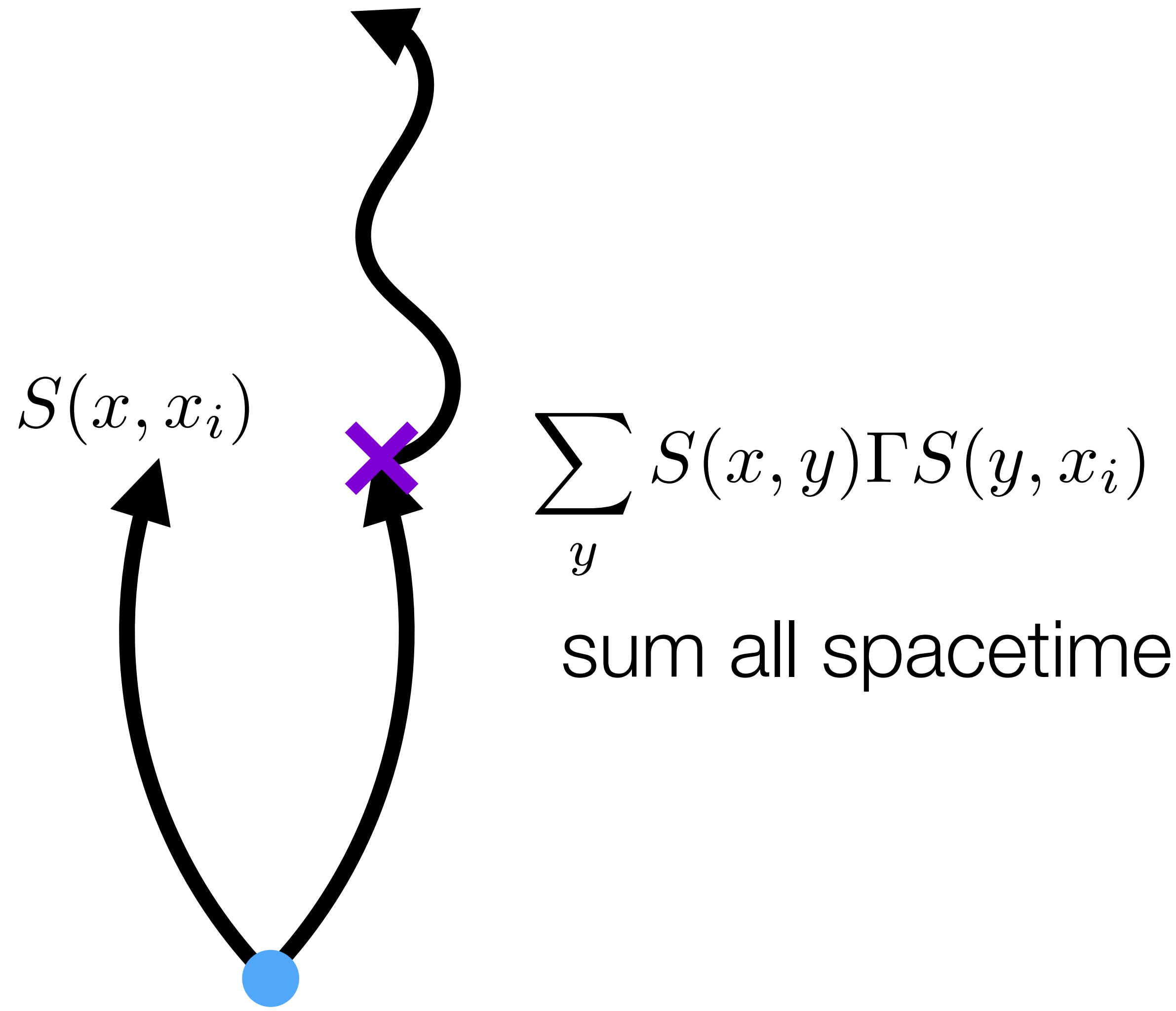

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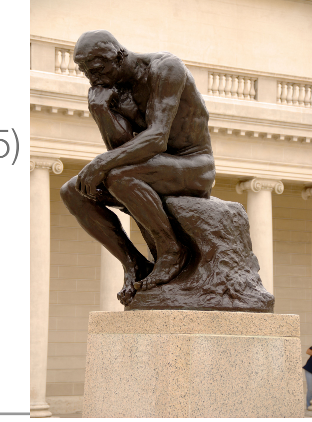
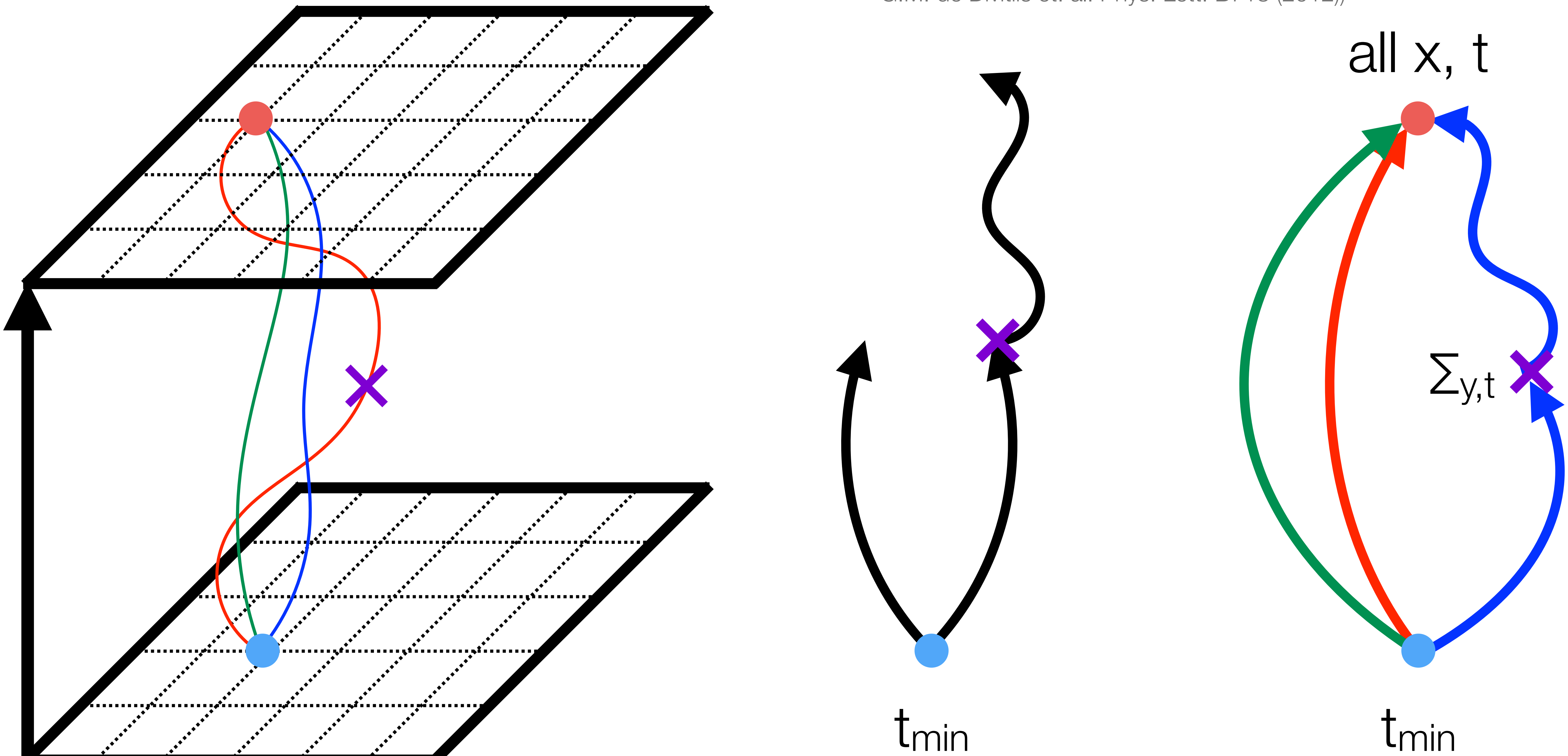
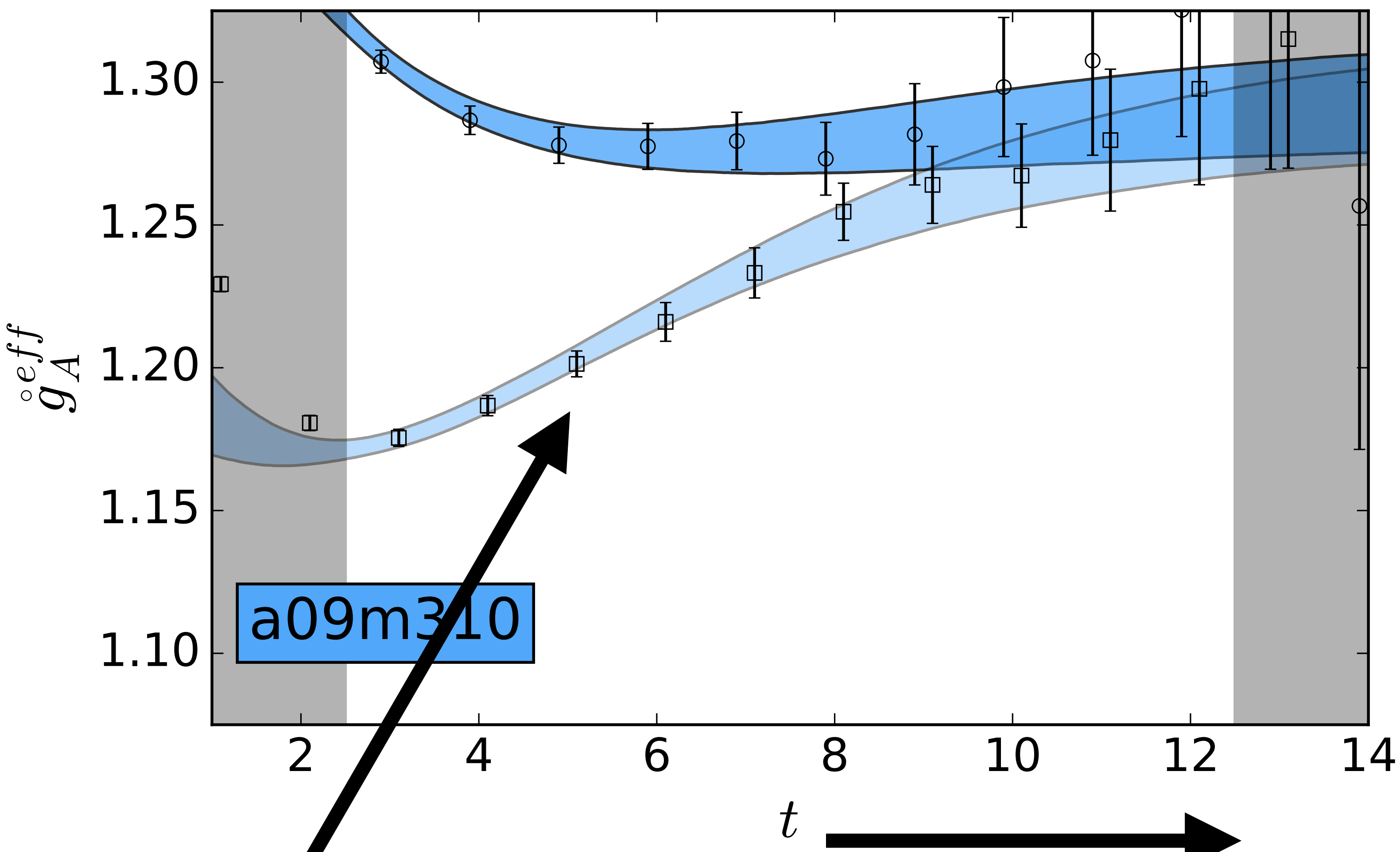




Two solves: all time separations but one bilinear

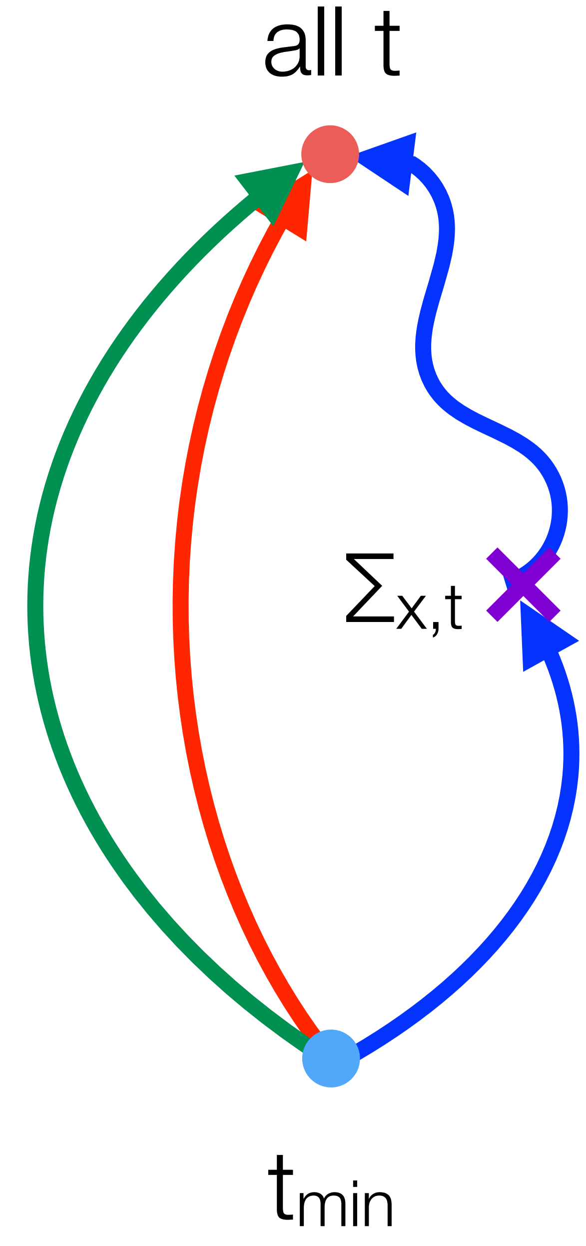
Example Effective Matrix Element

arXiv:1704.01114



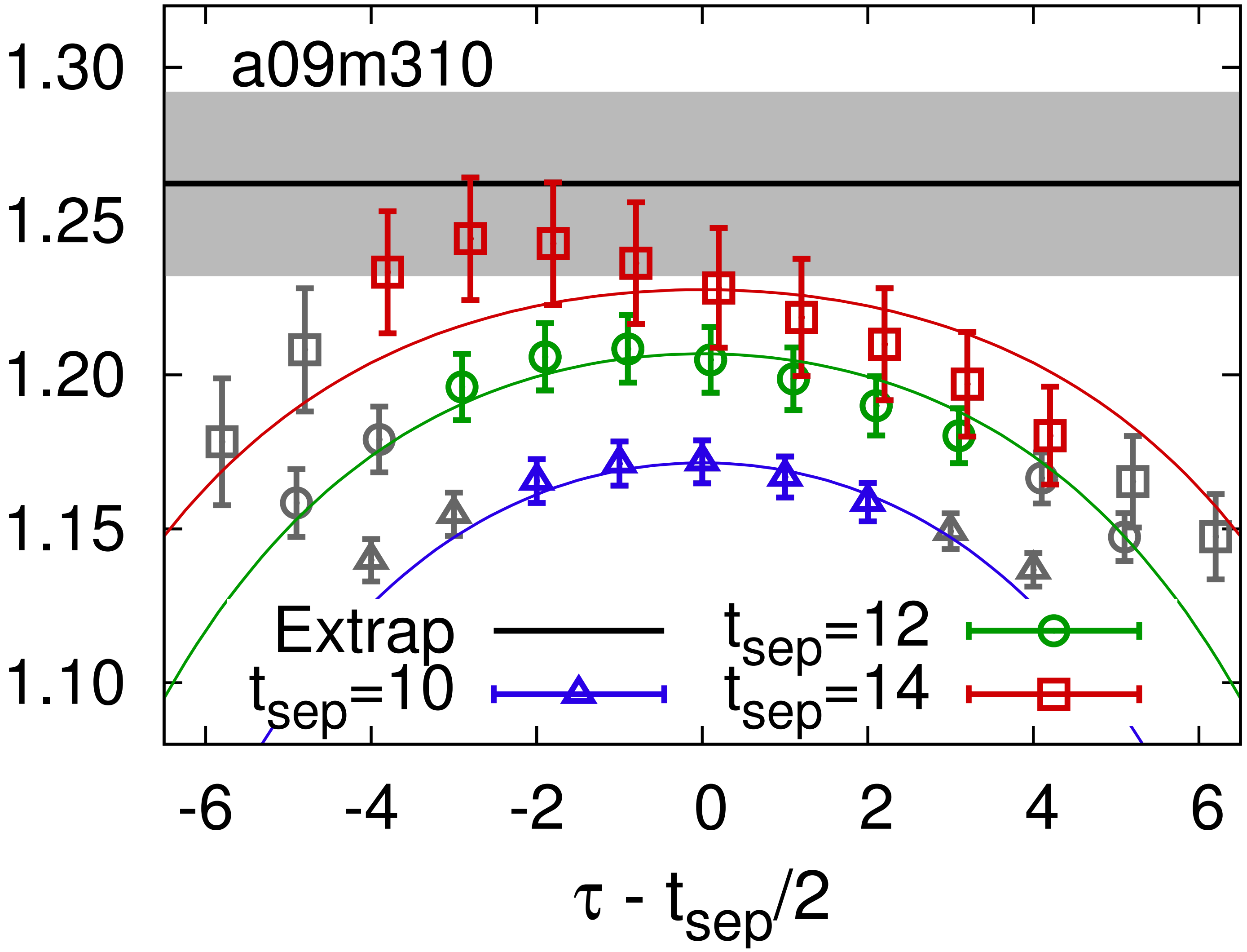
known functional form (spectral decomposition)

asymptotes in just one time variable



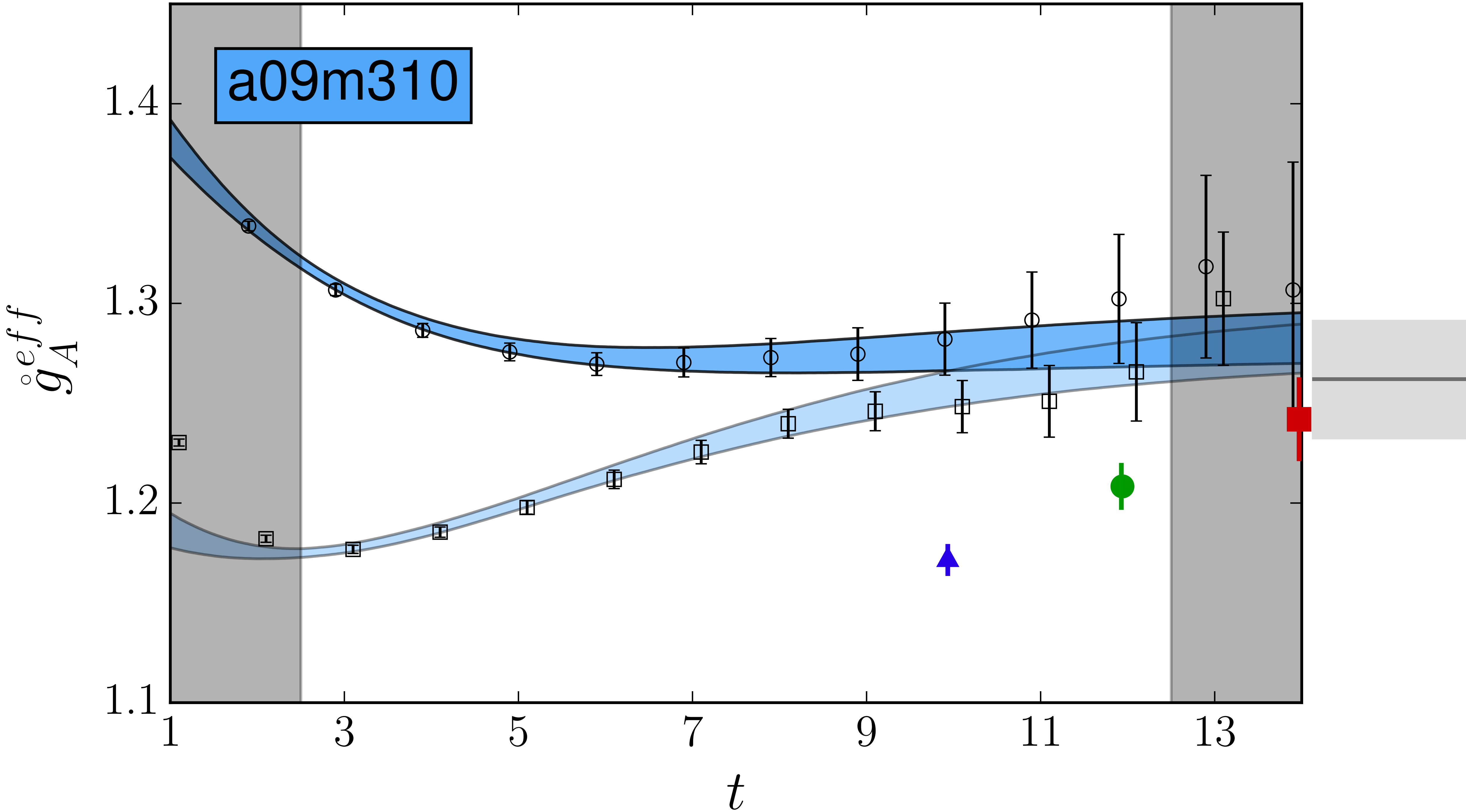
Improved Systematics

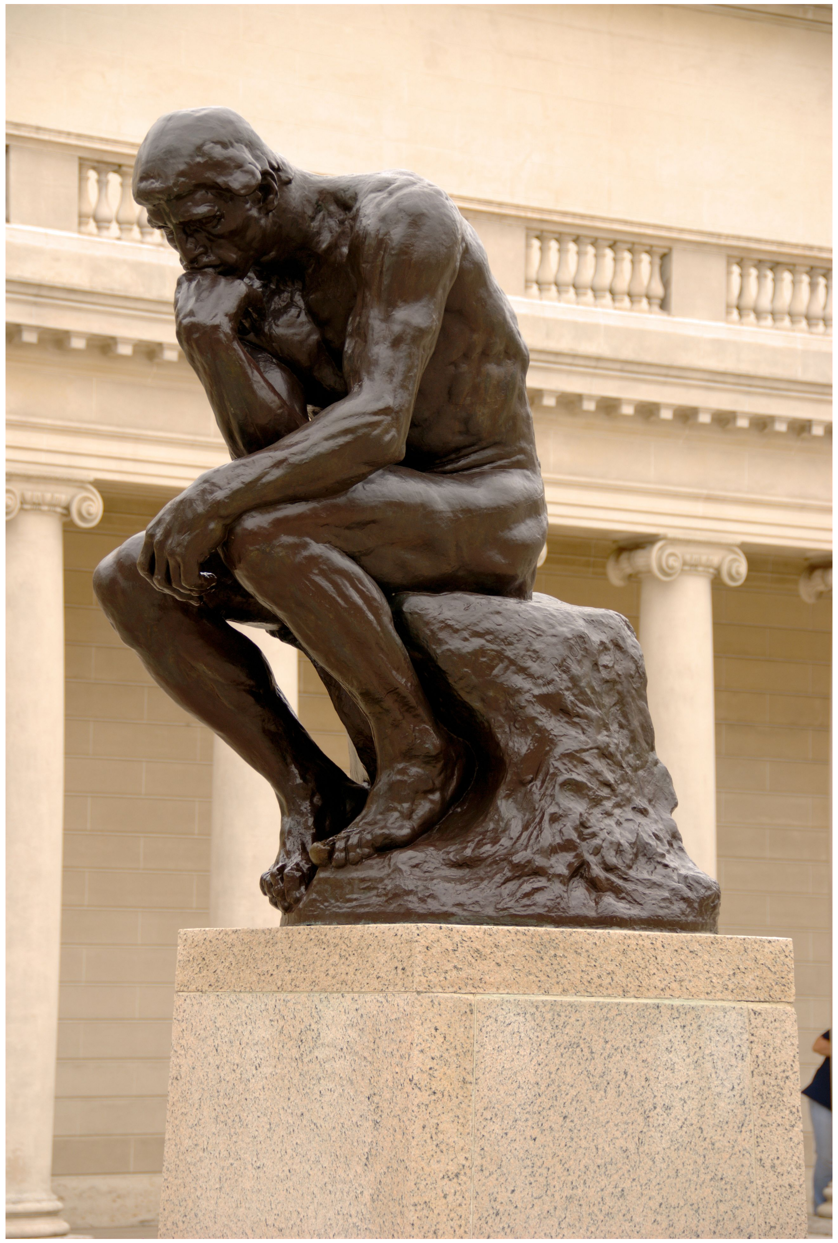
PNDME Phys. Rev. D94 (2016) arXiv:1606.07049

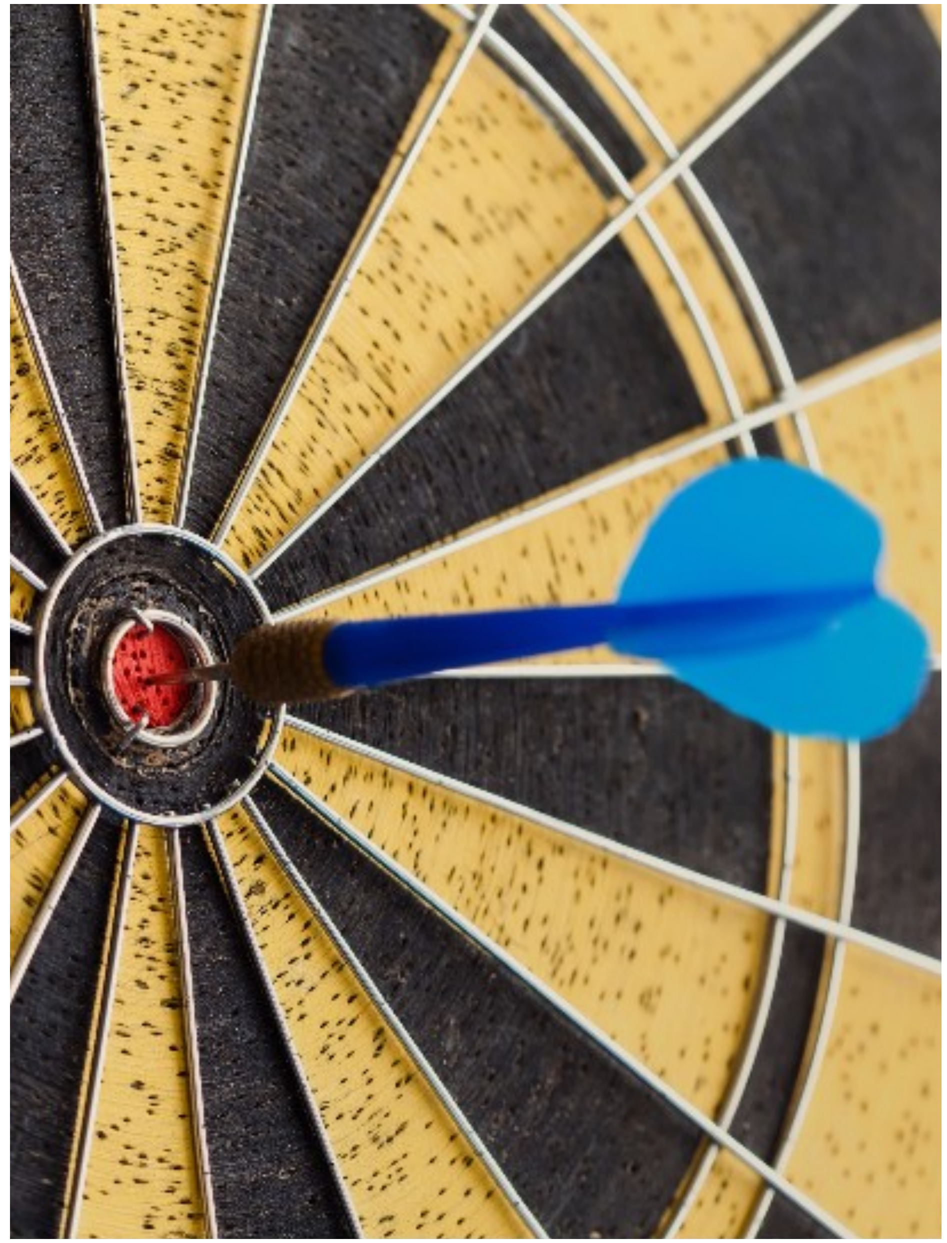


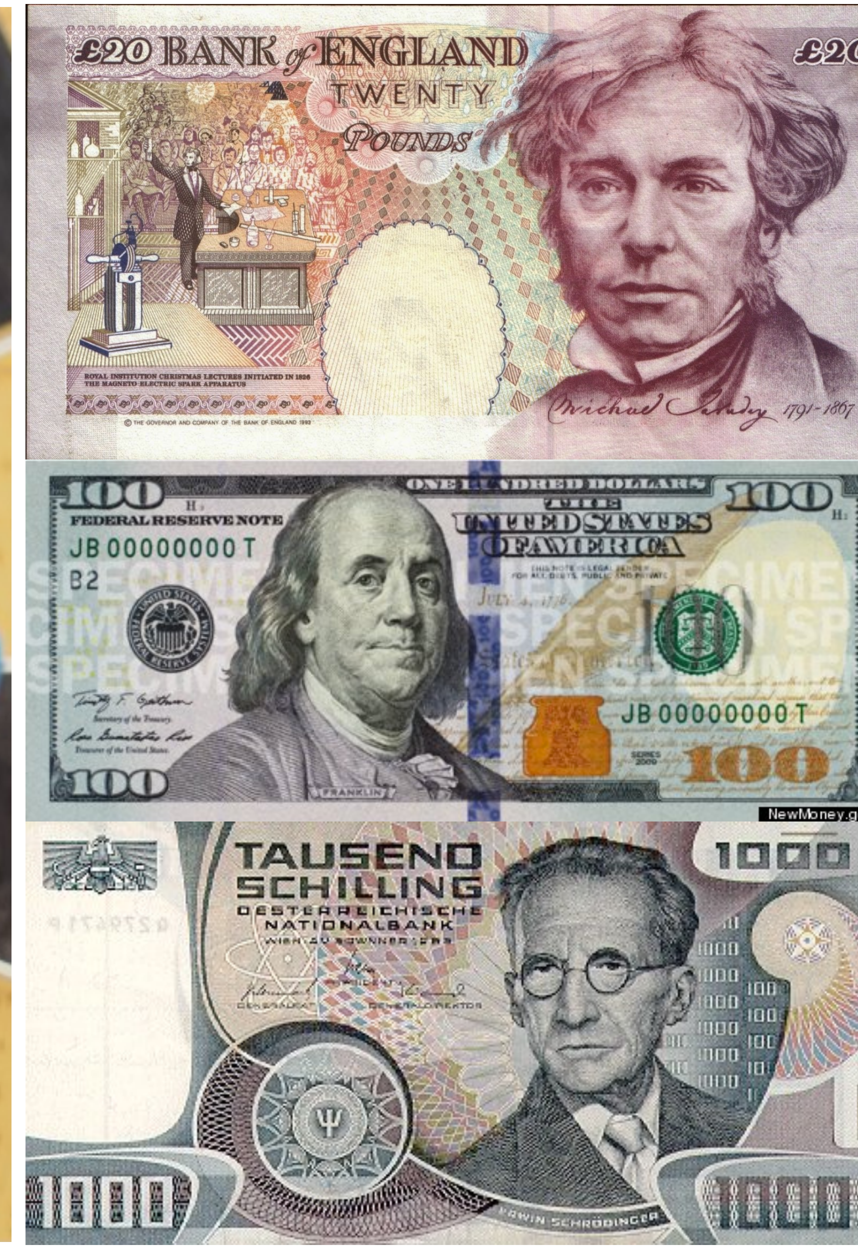
Improved Systematics

arXiv:1704.01114







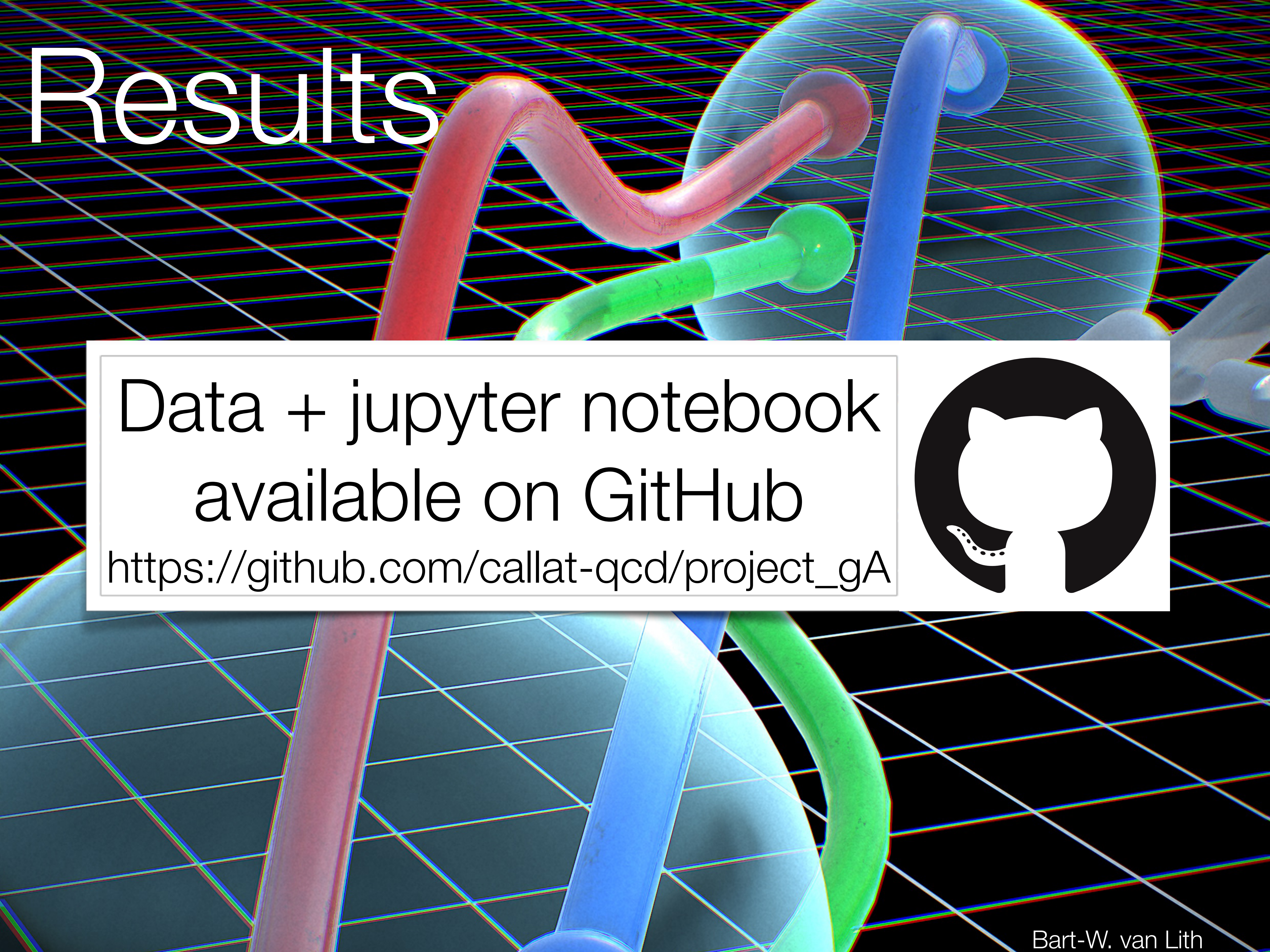


- Not QCD Specific
- Any fermion bilinear matrix element

- 3-point → 2-point function: easier fits
- Known spectral decomposition

- Stochastic enhancement
- 3/2 the cost of one temporal separation

Results



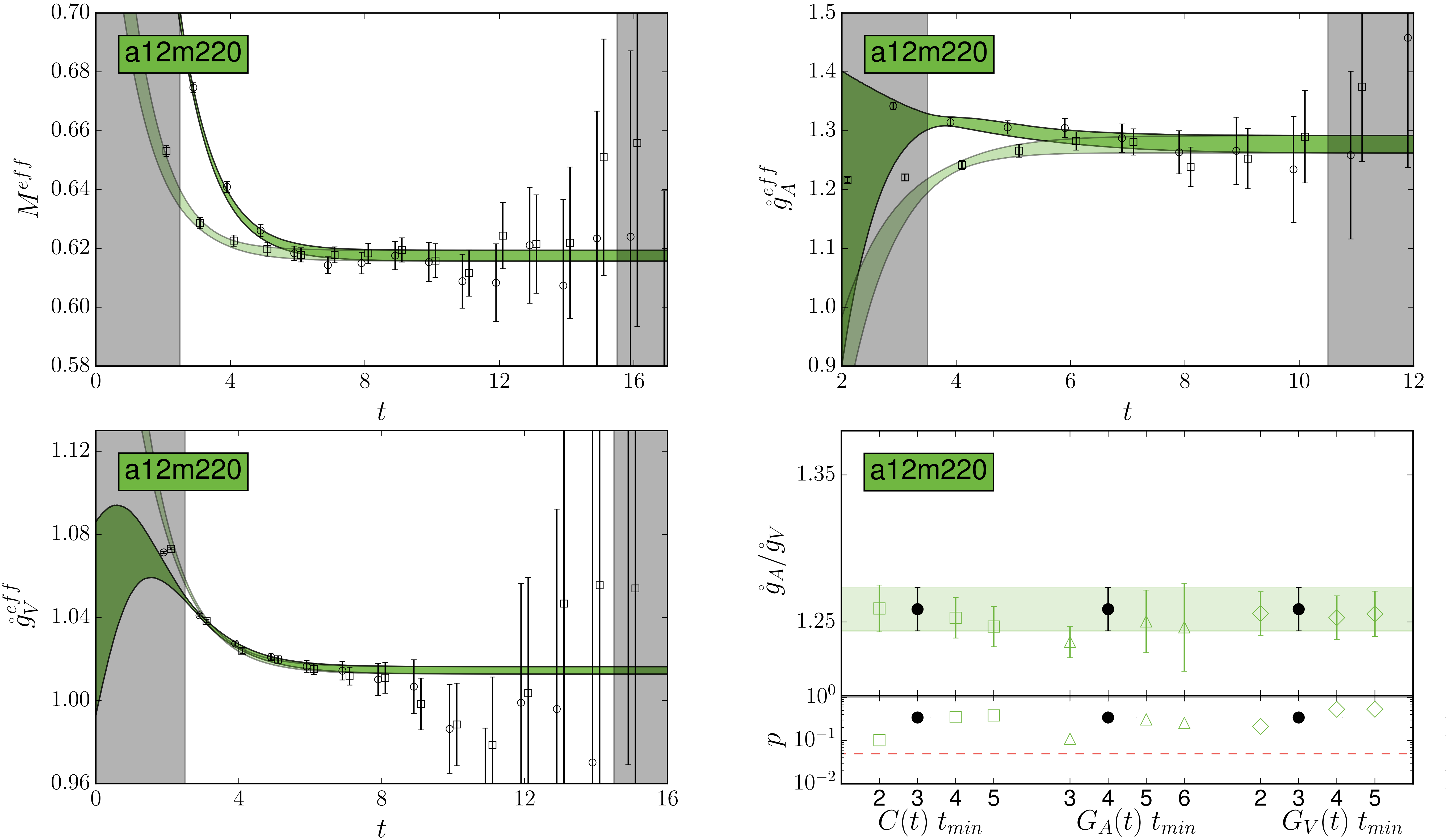
Data + jupyter notebook available on GitHub

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

Bart-W. van Lith

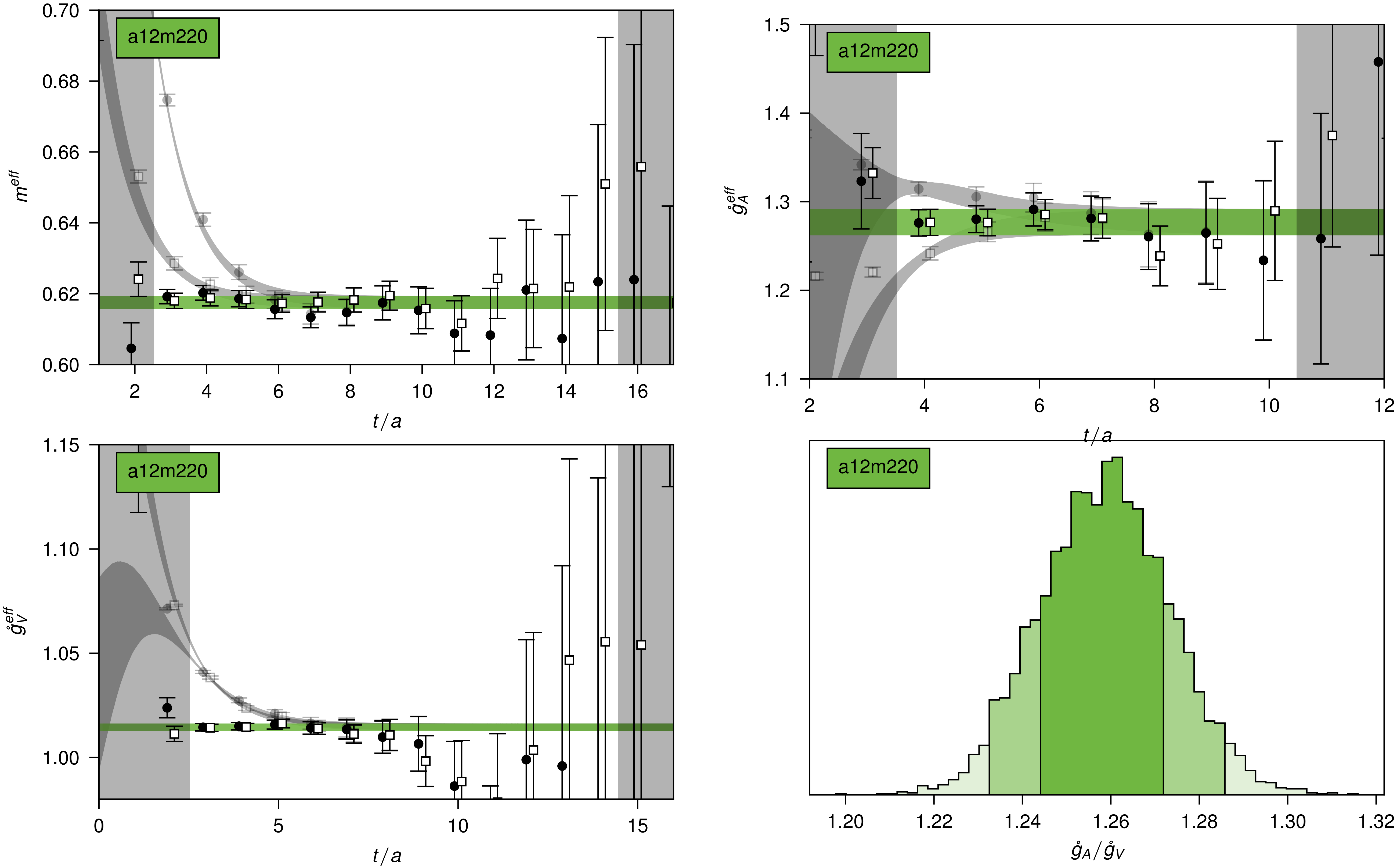
Systematics for an example point

Nature 558 (2018) 91



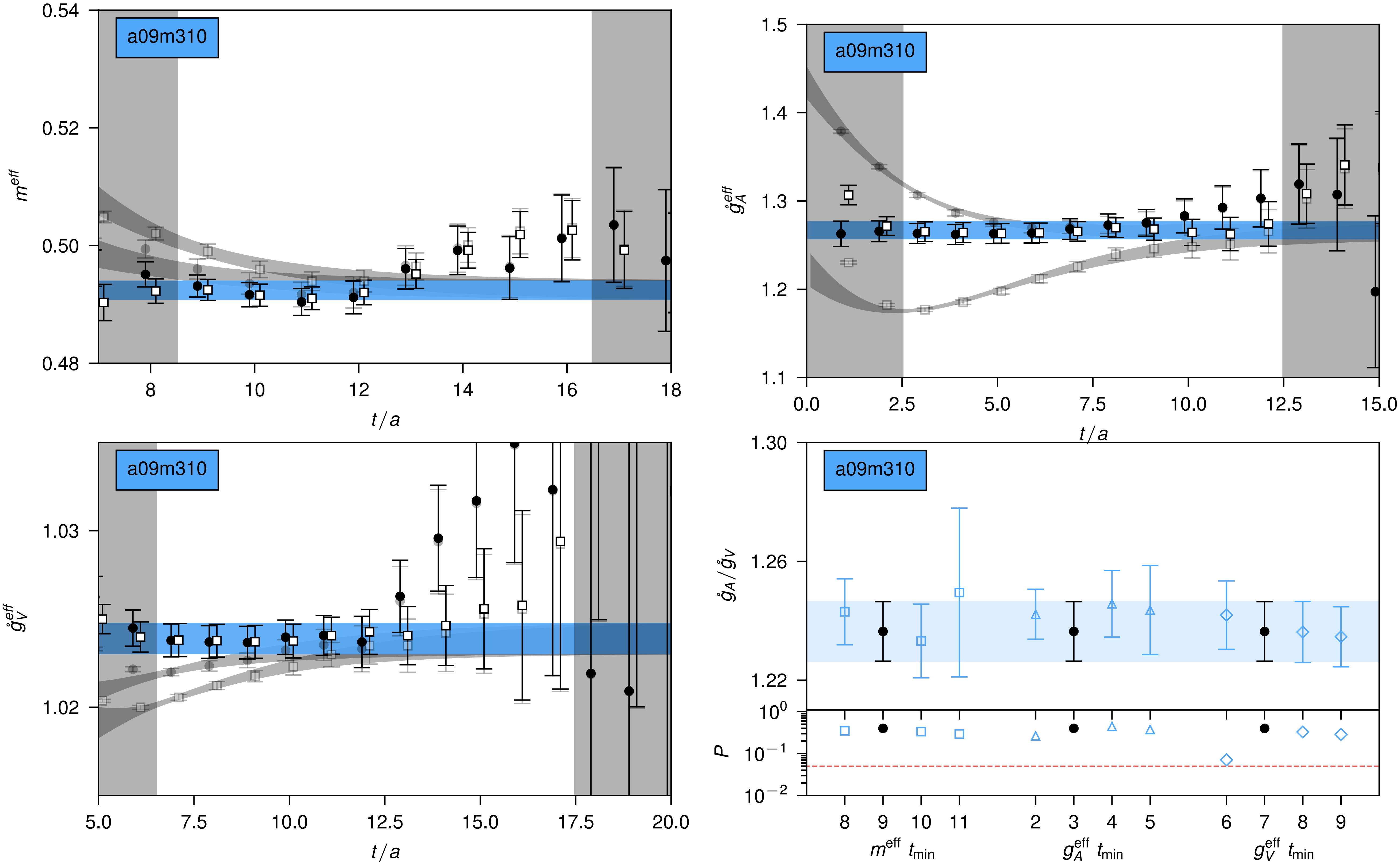
Systematics for an example point

Nature 558 (2018) 91



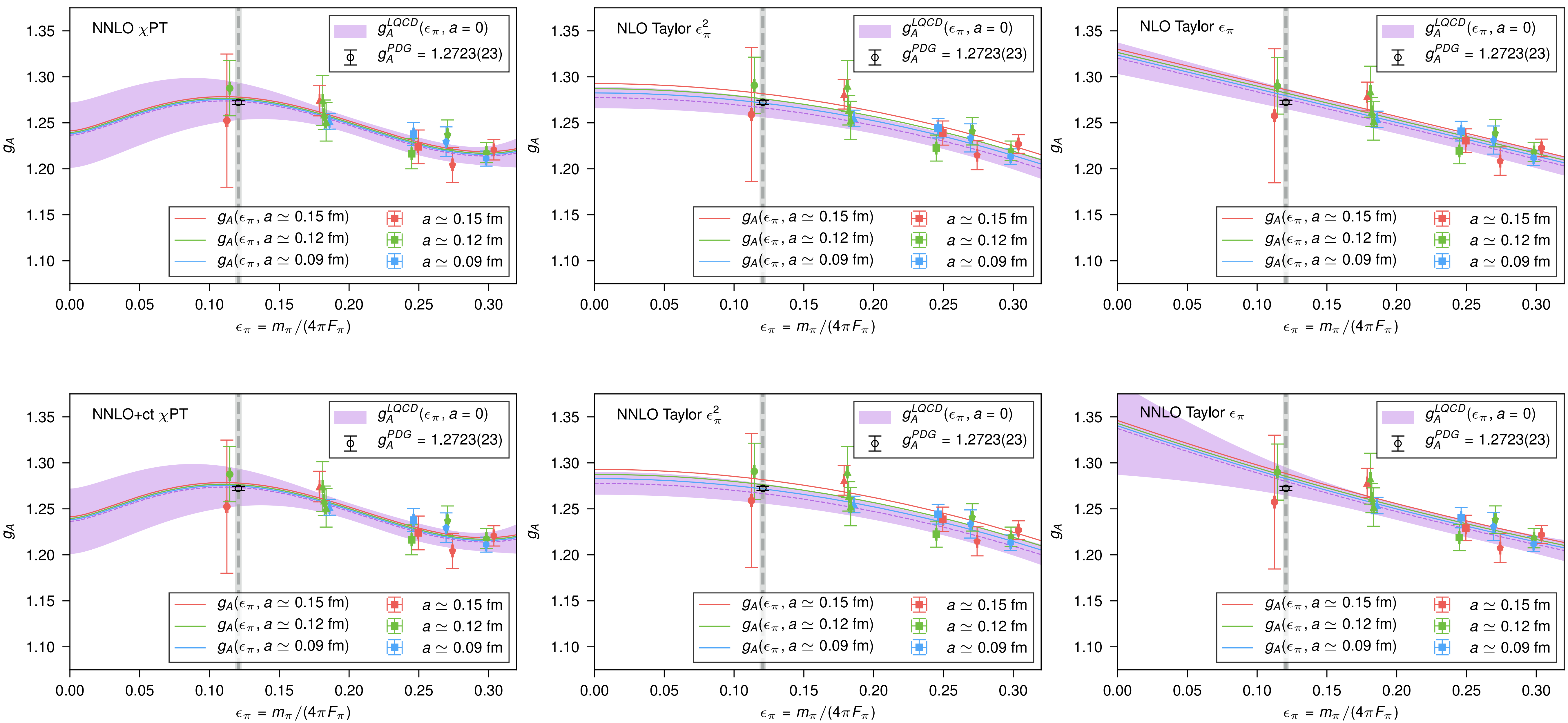
Another example point

Nature 558 (2018) 91



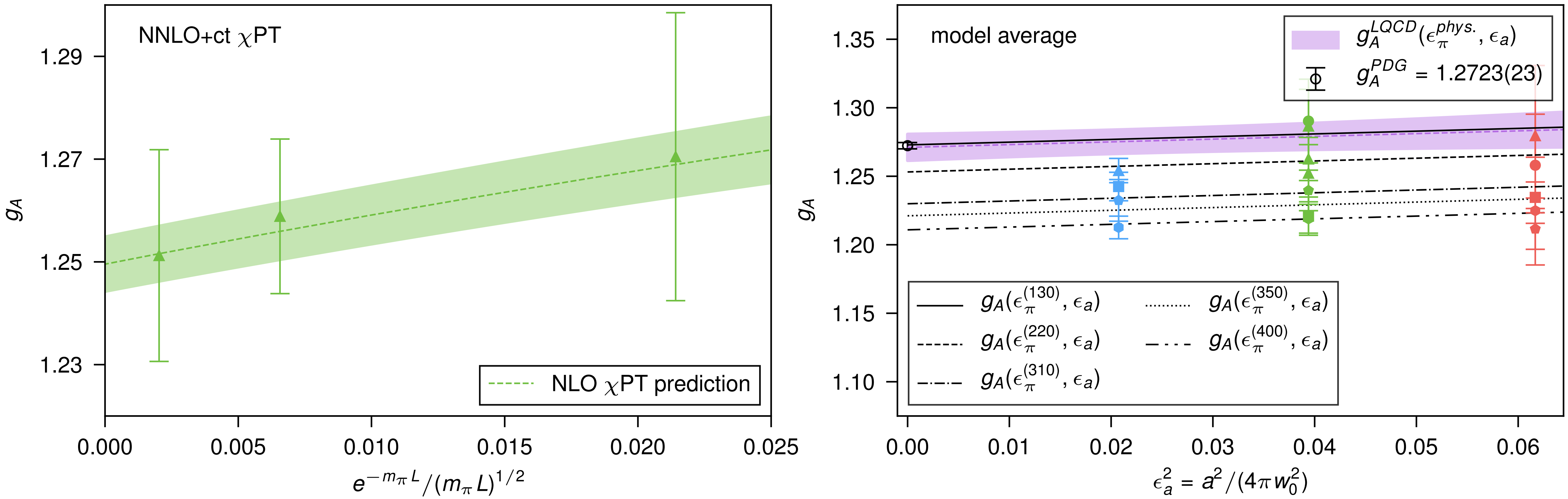
Systematics: m_π

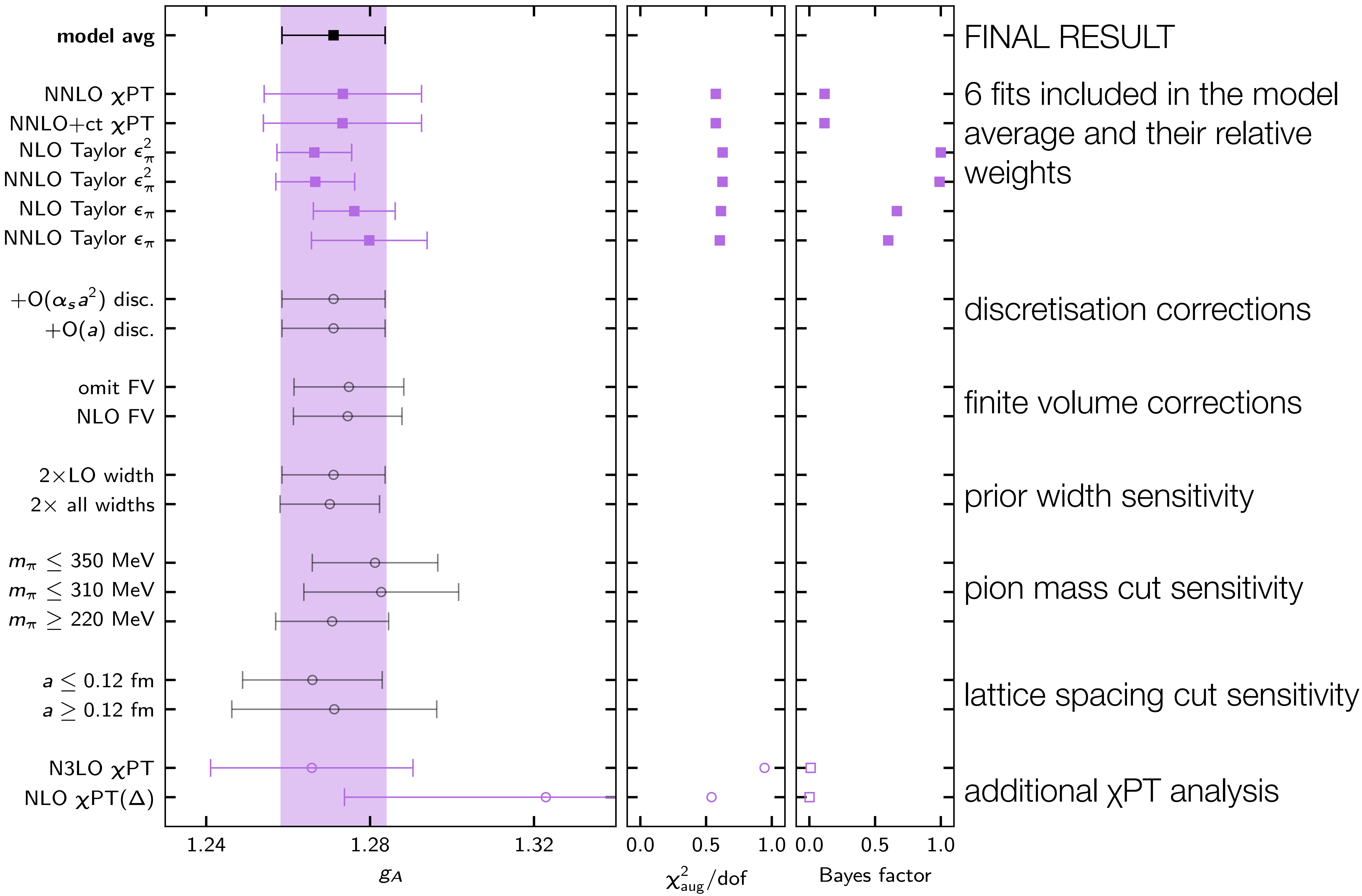
Nature 558 (2018) 91



Systematics: infinite volume, continuum

Nature 558 (2018) 91

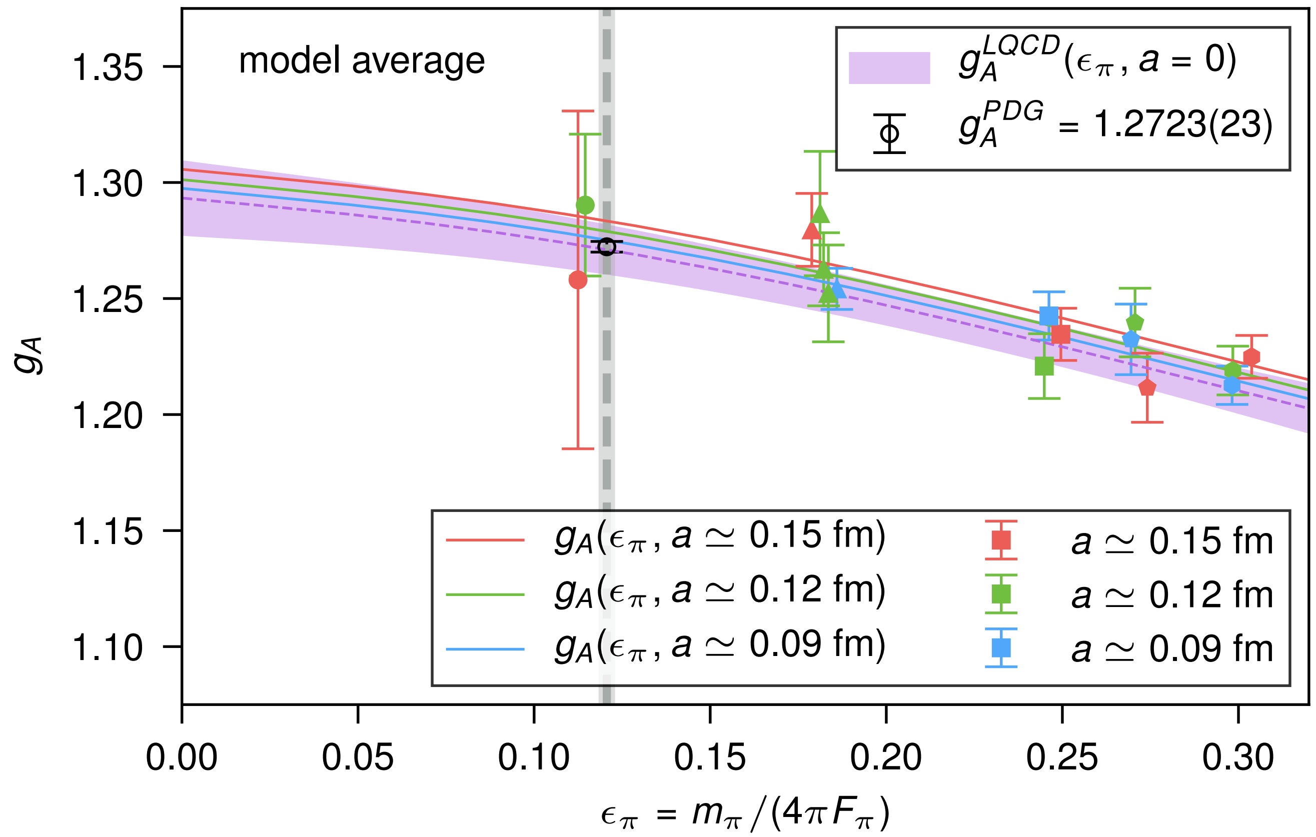


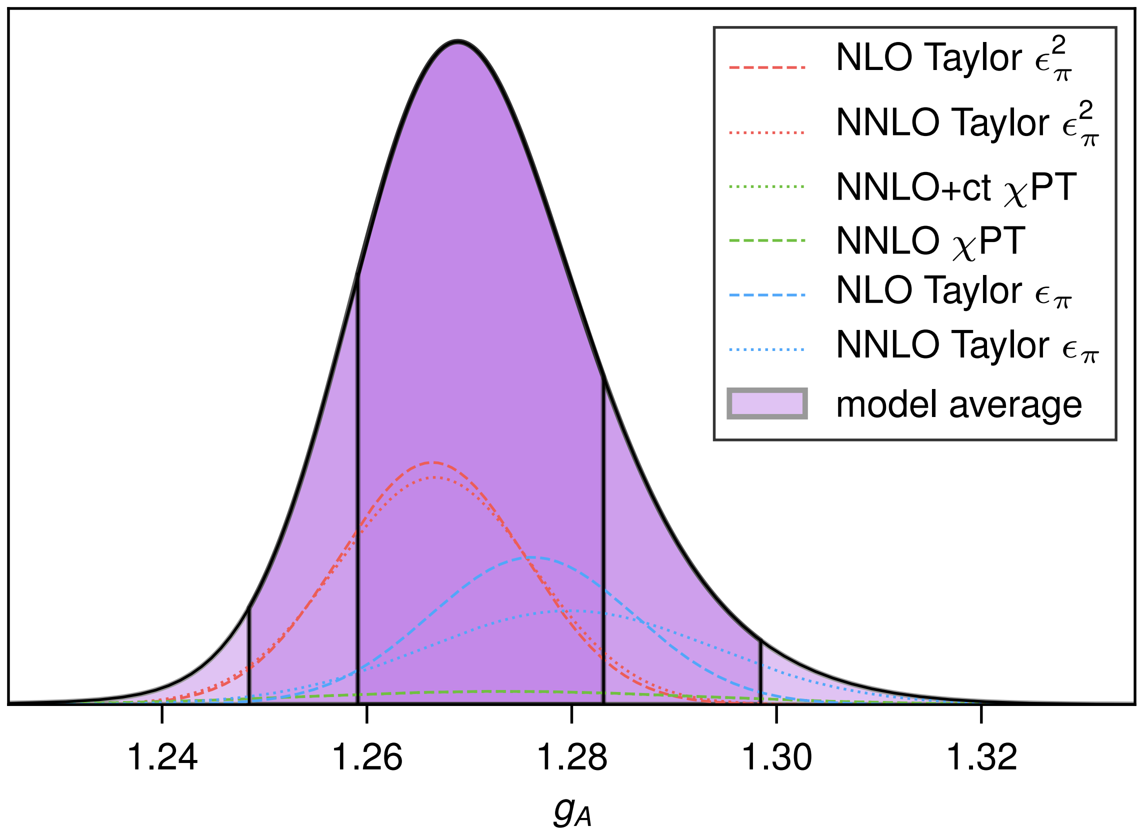


model avg
NNLO χPT
NNLO+ct χPT
NLO Taylor ϵ_π^2
NNLO Taylor ϵ_π^2
NLO Taylor ϵ_π
NNLO Taylor ϵ_π
+O($\alpha_s a^2$) disc.
+O(a) disc.
omit FV
NLO FV
2×LO width
2× all widths
$m_\pi \leq$ 350 MeV
$m_\pi \leq$ 310 MeV
$m_\pi \geq$ 220 MeV
$a \leq$ 0.12 fm
$a \geq$ 0.12 fm
N3LO χPT
NLO χPT(Δ)
1.24
1.28
1.32
g_A
0.0
0.5
1.0
χ^2_{aug}/dof
0.0
0.5
1.0
Bayes factor
FINAL RESULT
6 fits included in the model average and their relative weights
discretisation corrections
finite volume corrections
prior width sensitivity
pion mass cut sensitivity
lattice spacing cut sensitivity
additional χPT analysis

Model Average $gA = 1.2711(103)^{s}(39)^{\chi}(15)^{a}(19)^{V}(04)^{I}(55)^{M}$

Nature 558 (2018) 91





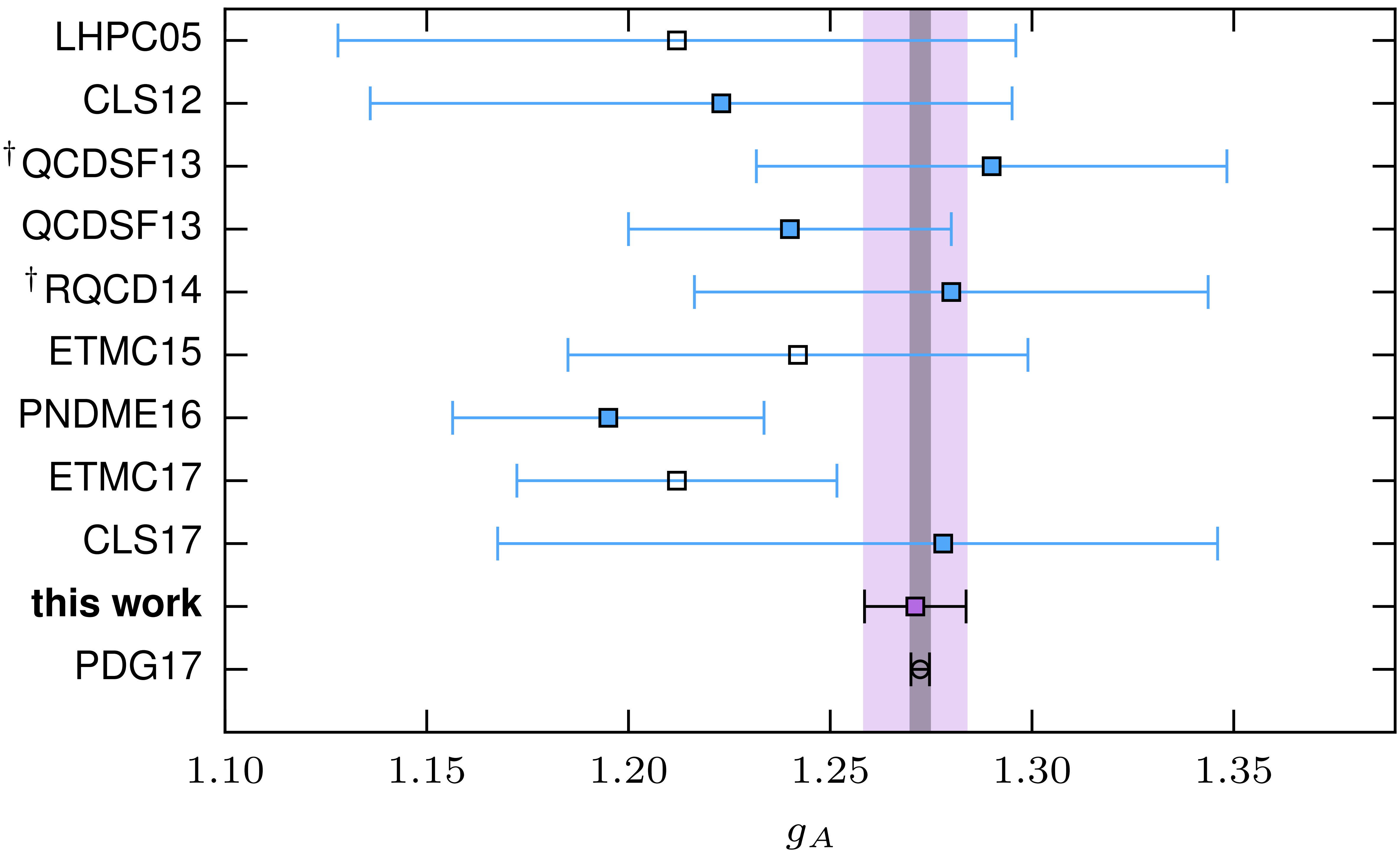
statistical	0.81%
chiral	0.30%
continuum	0.12%
infinite volume	0.15%
isospin breaking	0.03%
model selection	0.43%
total (added in quadrature)	**0.98%**

Final uncertainty is dominated by statistics, model selection, and chiral extrapolation.

Better control over the $m_\pi \sim 130$ MeV points will improve all three.

Comparison with previous LQCD results

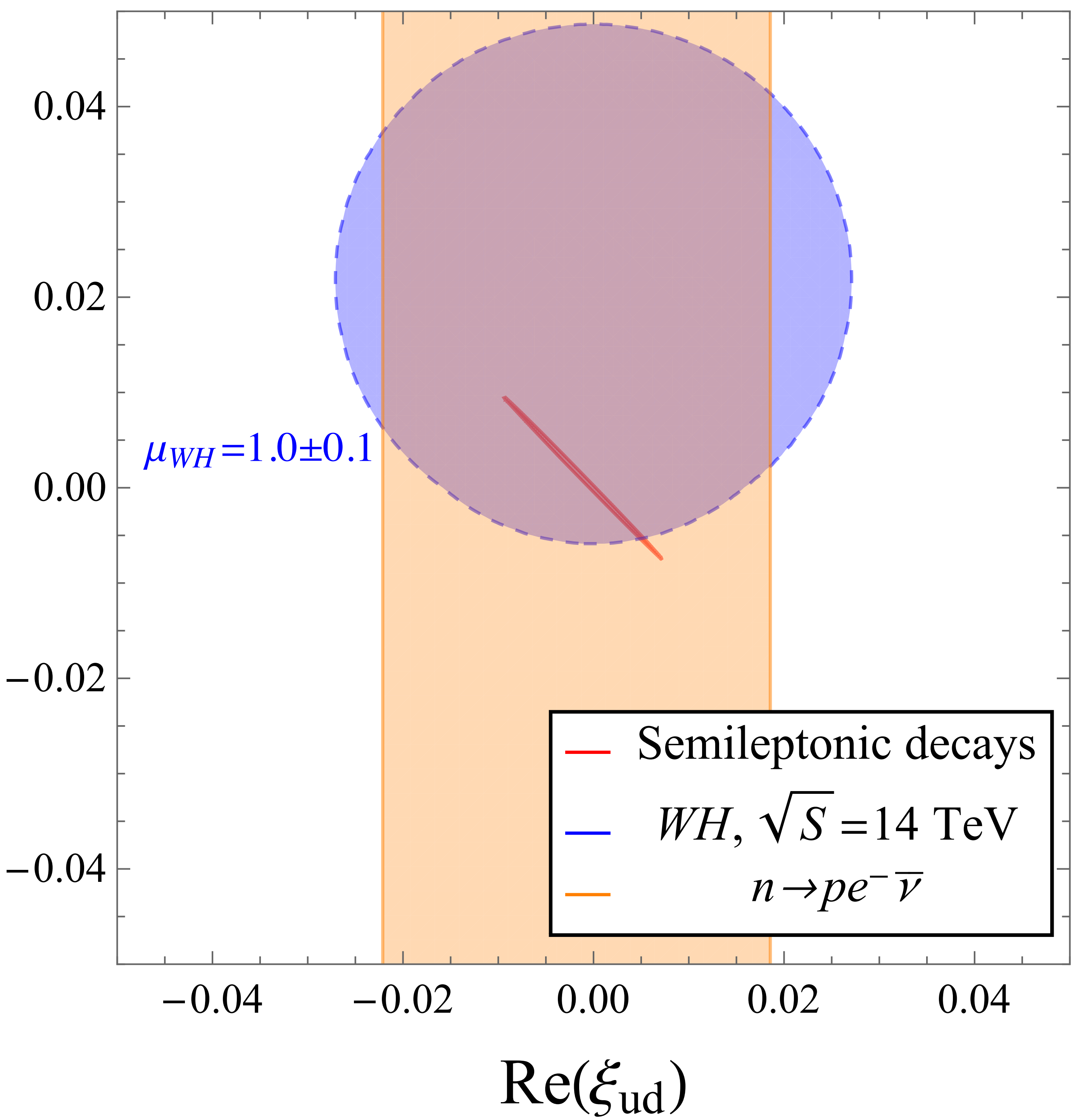
Nature 558 (2018) 91



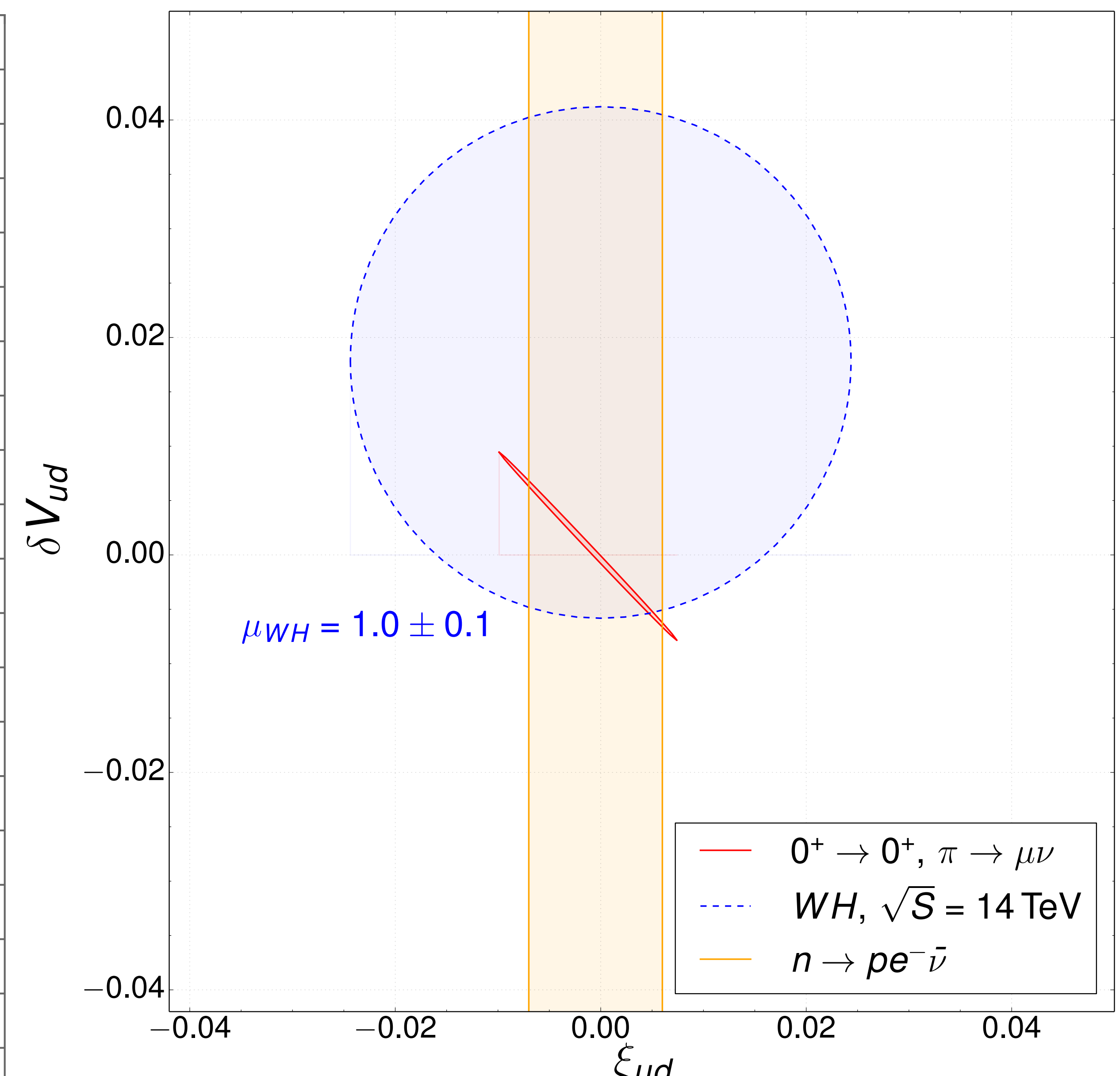
Searches for violations of V–A

Alioli, Cirigliano, Dekens, de Vries, Mereghetti JHEP 1705 (2017) 086 arXiv:1703.04751

g_A^{QCD}=1.27±0.05



g_A^{QCD}=1.271(13)



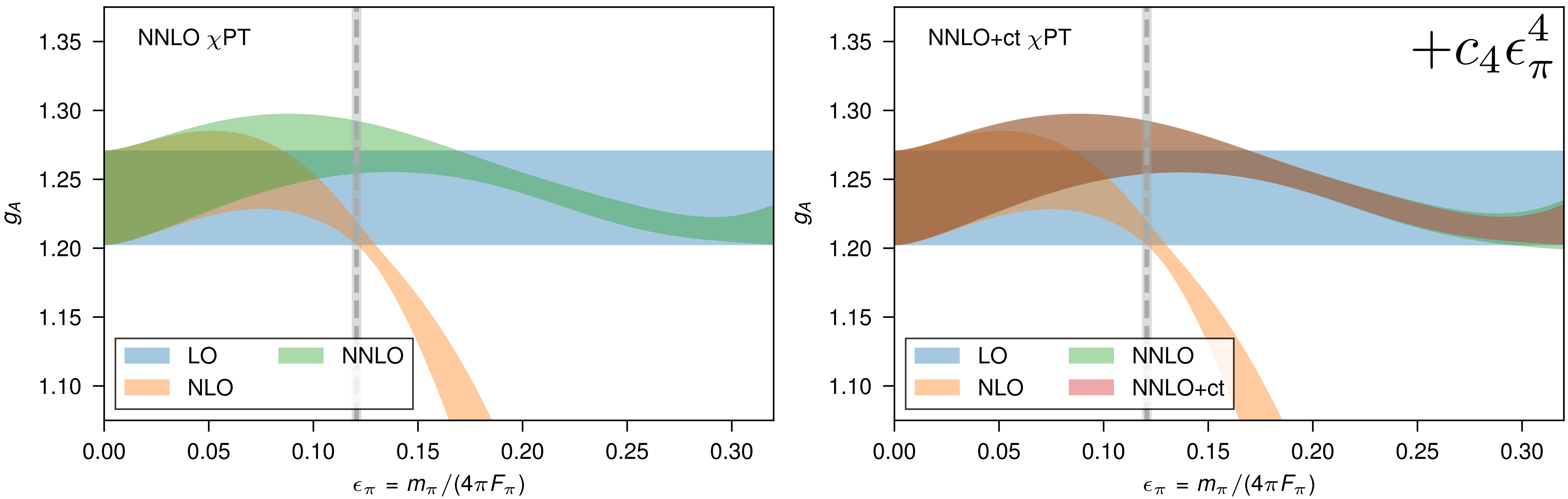
NNLO[+ct] χPT

Nature 558 (2018) 91

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

Bernard and Meißner, PLB 639 (2006) 279-282

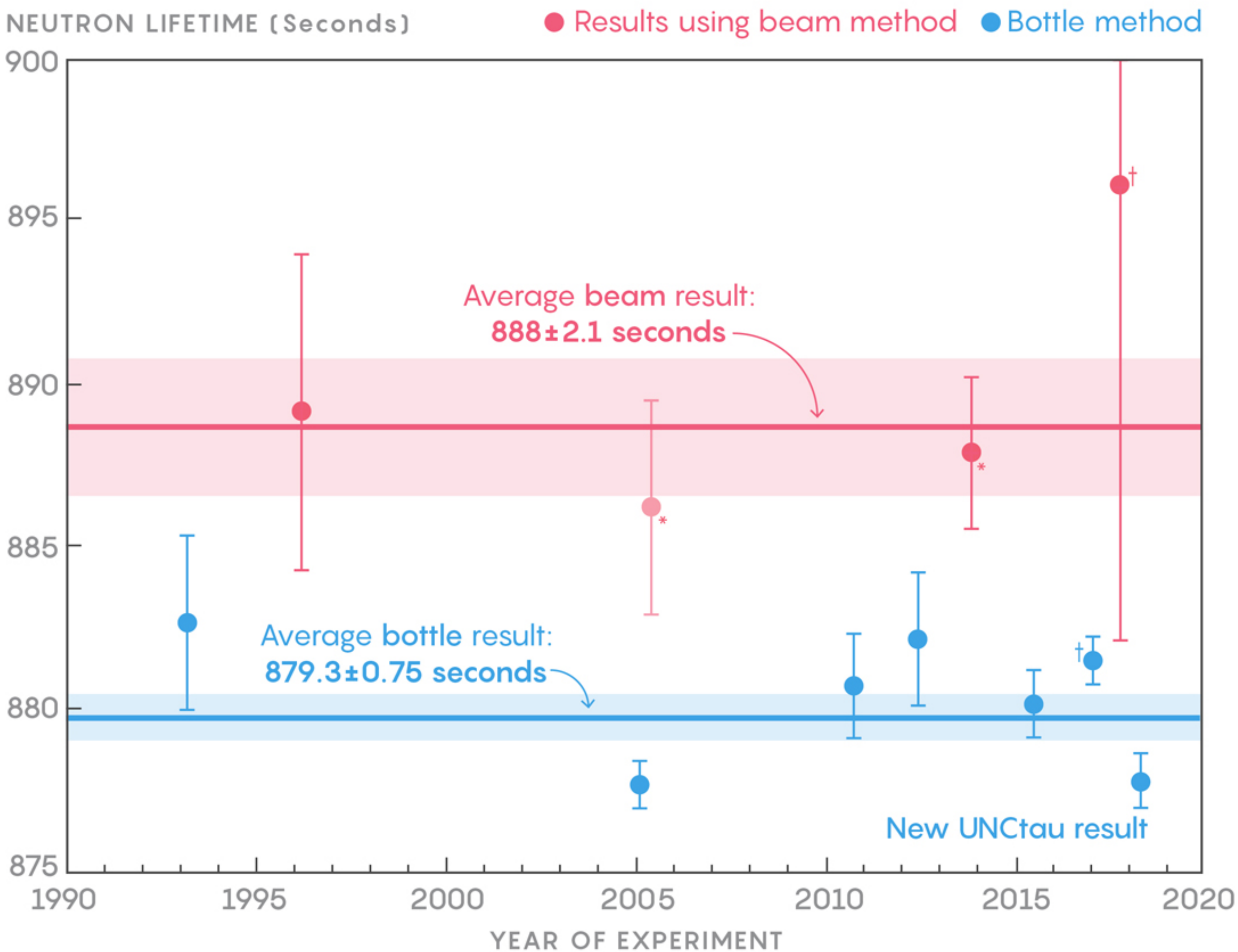
$$\epsilon_\pi = \frac{m_\pi}{4\pi F_\pi} \quad (F_\pi \sim 92\ \text{MeV})$$



$$gA = 1.2711(103)^{s}(39)^{X}(15)^{a}(19)^{V}(04)^{I}(55)^{M}$$

Nature 558 (2018) 91

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



*Nico result (2005) was superseded by an updated and improved result, Yue (2013);
†Preliminary results

According to the Standard Model 885(14) s

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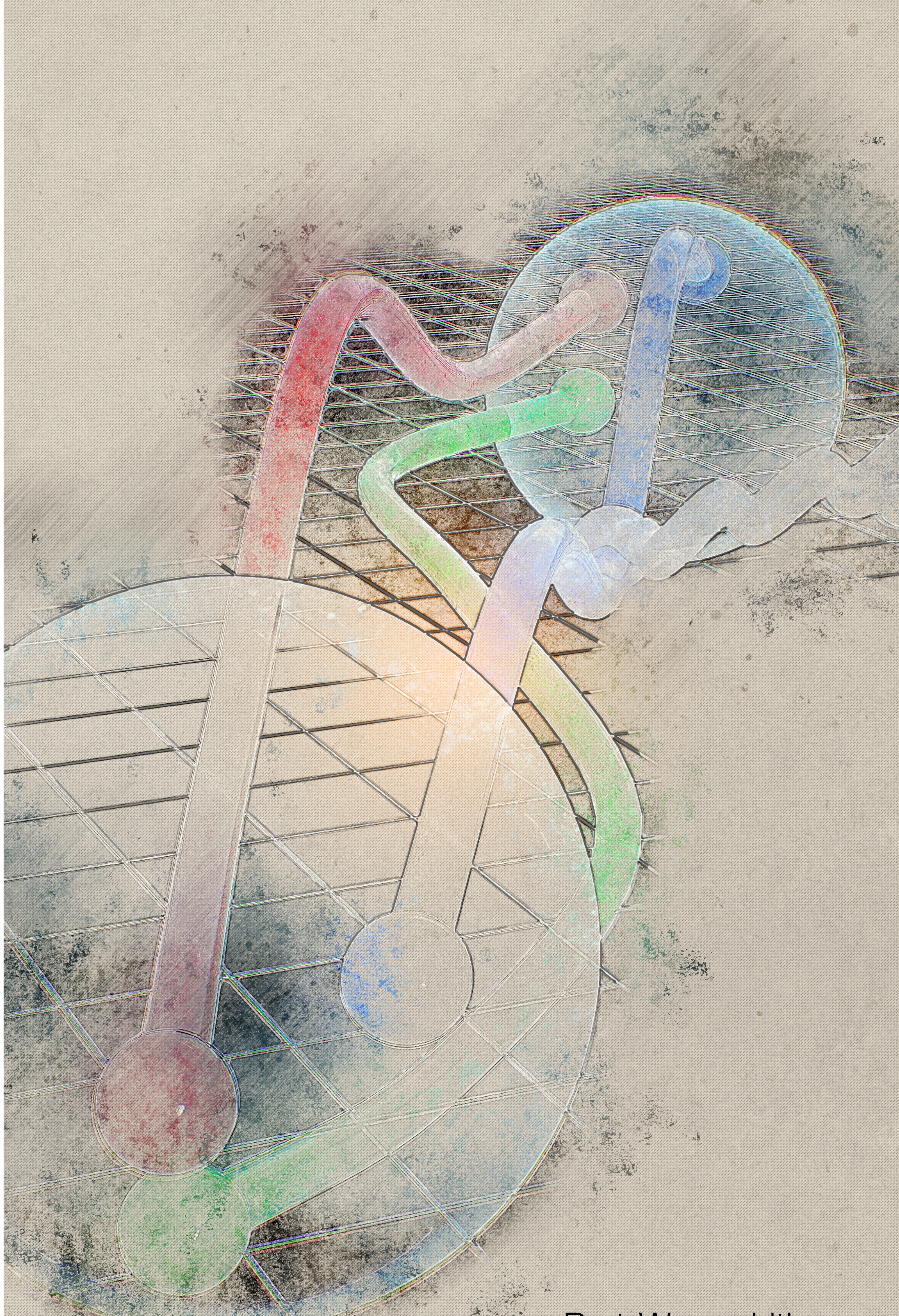
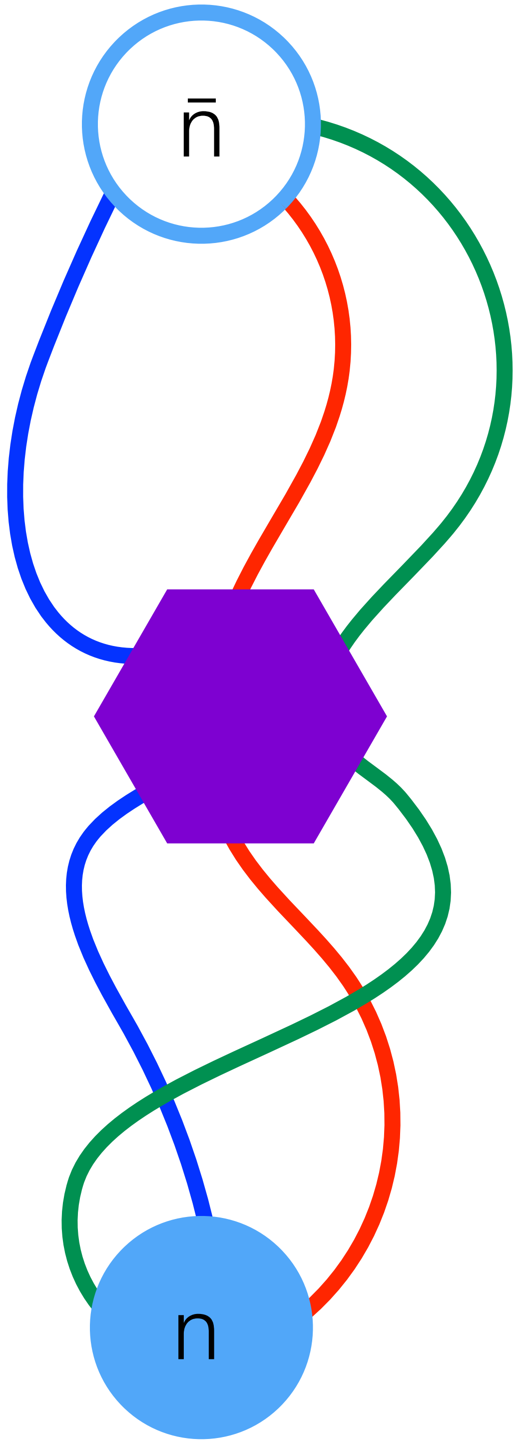
Outlook



Bart-W. van Lith

n̄n Oscillations

Rinaldi, Syritsyn, Wagman, Buchoff, Schroeder, and Wasem 1809.00246



✔ Physical point, continuum, infinite volume

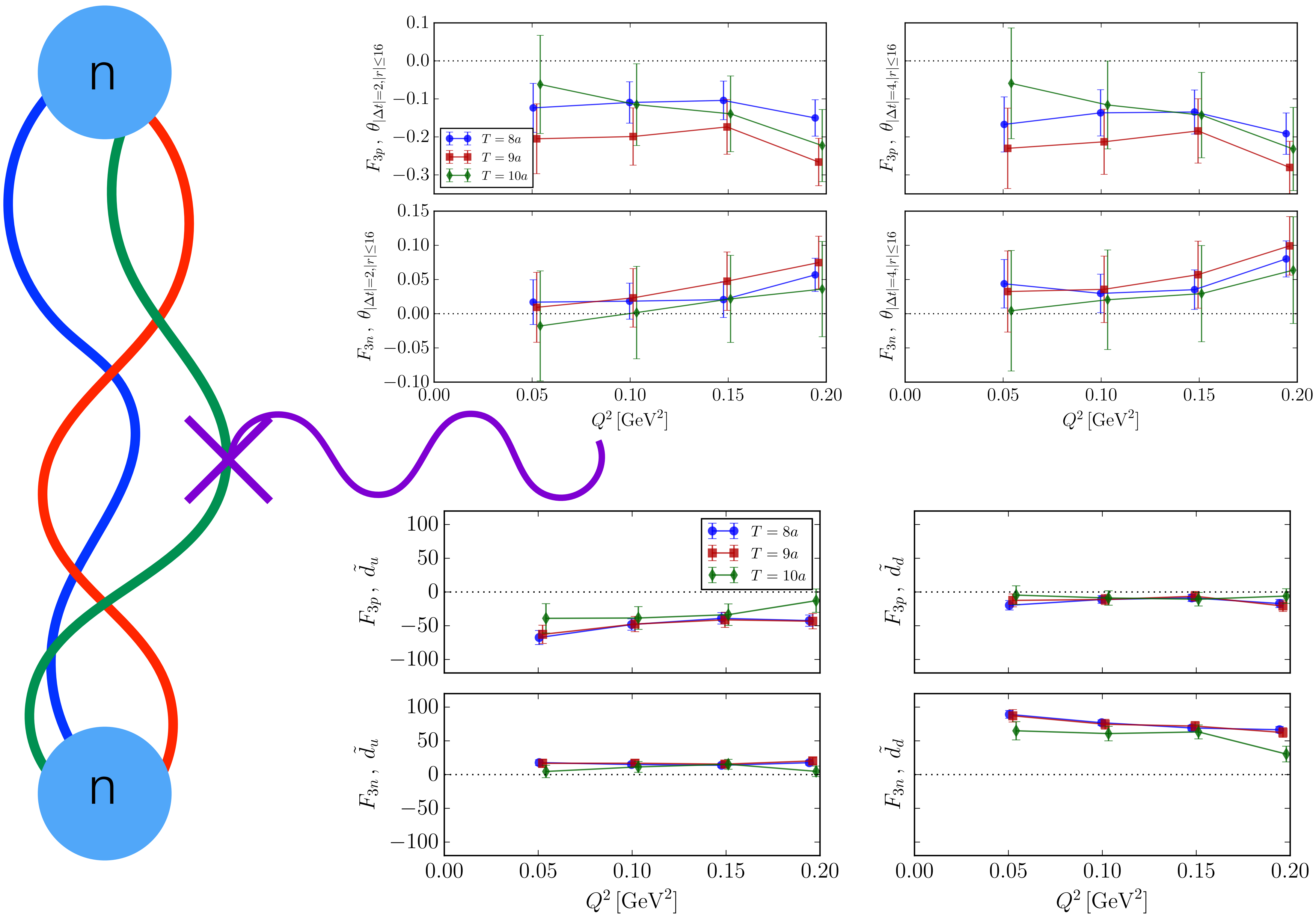
Operator	$\overline{\text{MS}}$(2 GeV), 10^{-5} GeV^6	$\frac{\overline{\text{MS}}\text{(2 GeV)}}{\text{MIT bag B}}$	Bare, 10^{-5} l.u.	χ^2/dof
Q_1	-44(19)	5.0	-3.7(1.6)	0.75
Q_2	140(40)	12.8	11.8(3.2)	0.69
Q_3	-79(23)	9.7	-6.6(1.9)	0.72
Q_5	-1.43(64)	2.1	-0.096(42)	0.73

enhancement
means experiments
have greater reach

n EDM

Syritsyn, Ohki, Izubuchi CIPANP 2018 1810.03721

$V = 48^3 \times 96$ ($\times$ 24 DWF)
$a = 0.114$ fm
$m_\pi = 139.2$ MeV

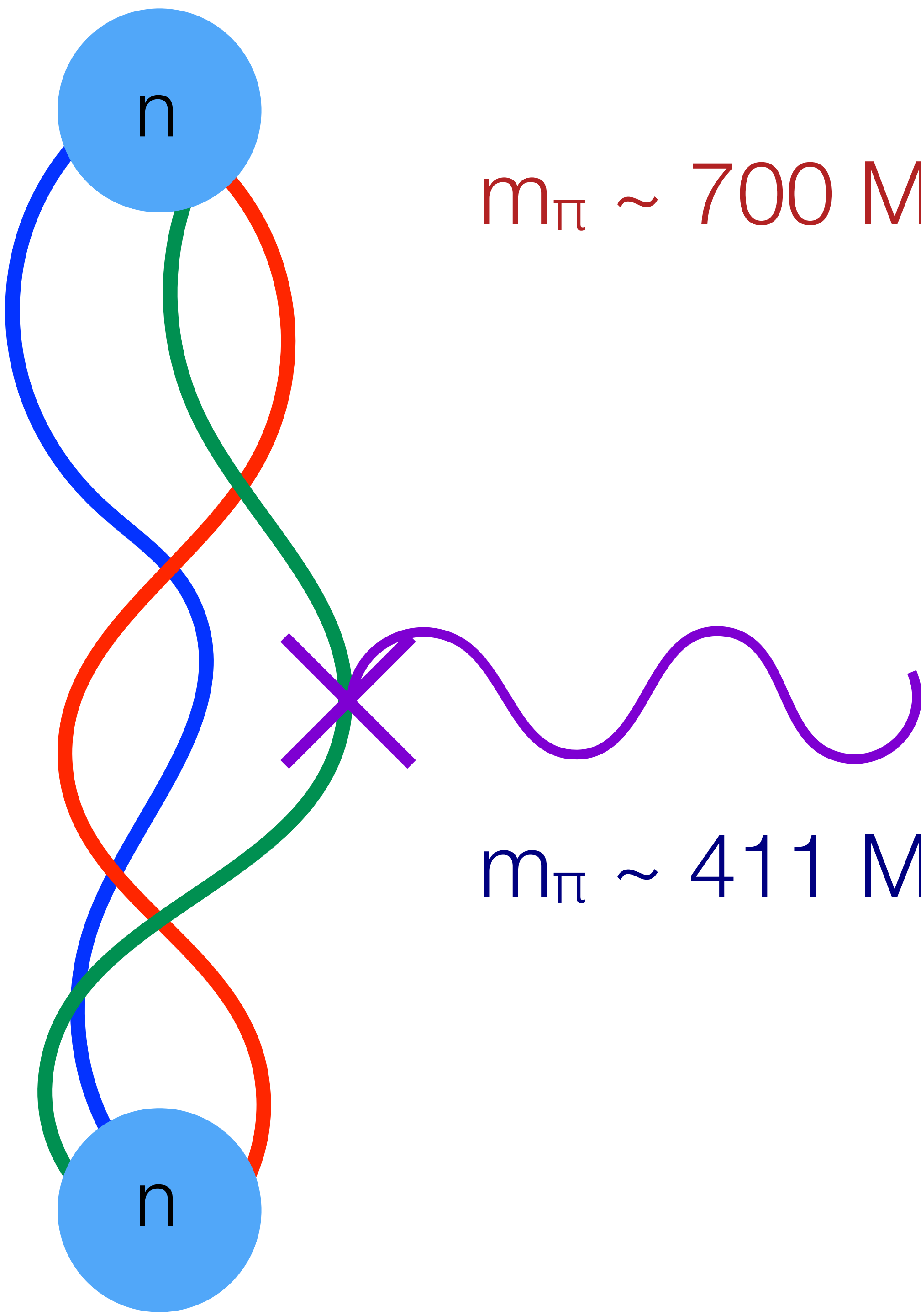


θQCD

cEDM

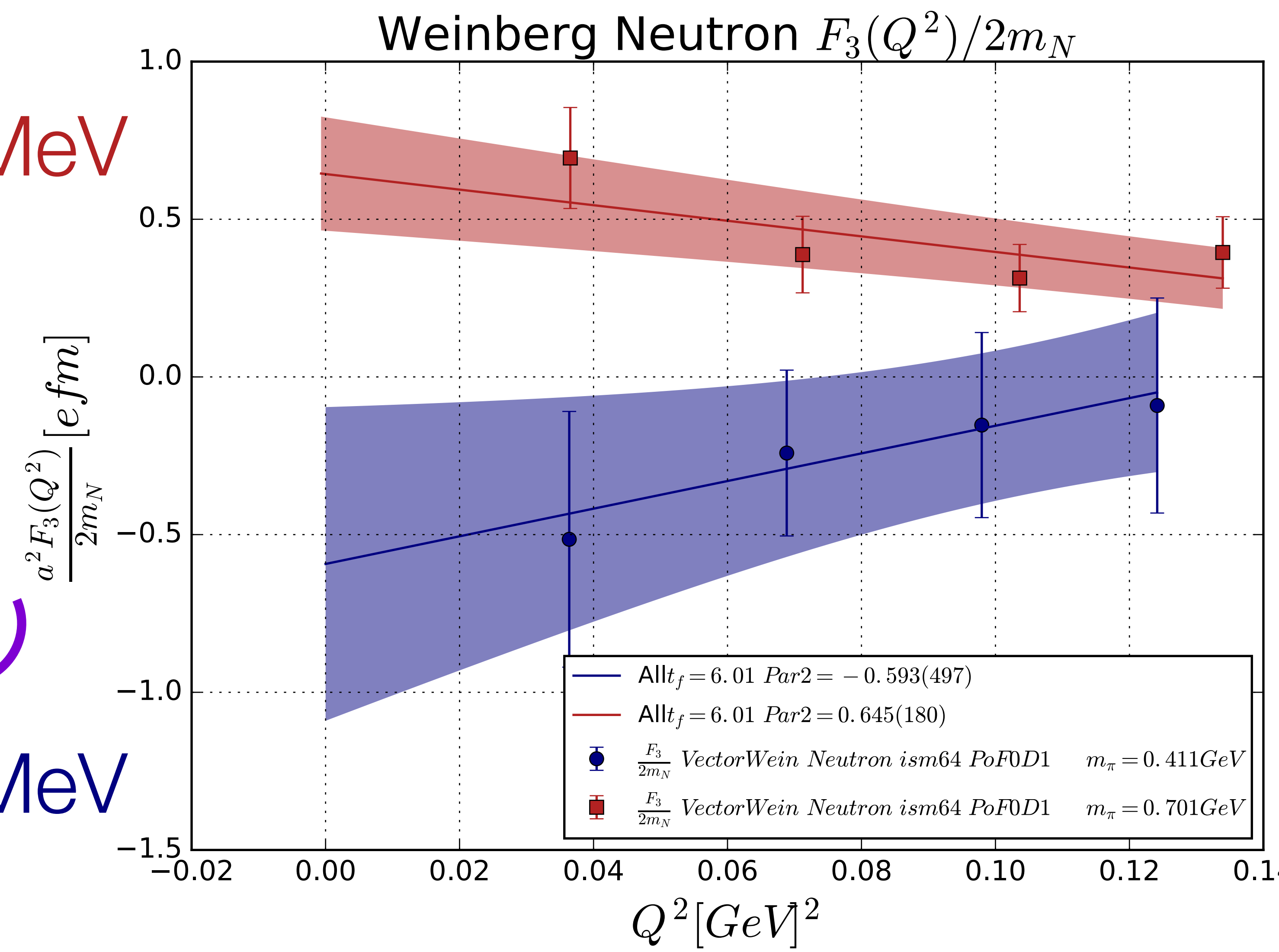
n EDM

Dragos, Luu, Shindler, de Vries LATTICE 2017 EPJ Web Conf 175 (2018) 06018 arXiv:1711.04730



m_π ~ 700 MeV

m_π ~ 411 MeV

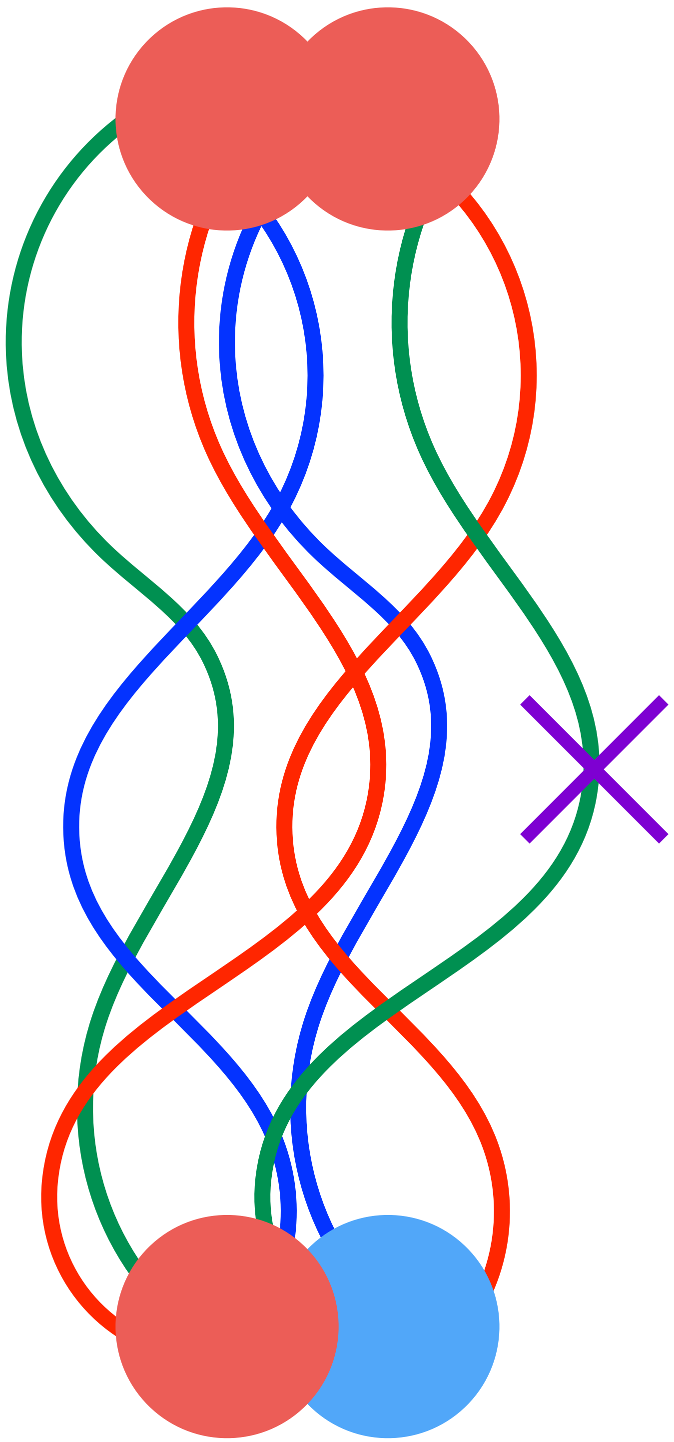


$$-i\frac{\alpha_{\tilde{G}}}{\Lambda^2}\ \frac{1}{3}f^{ABC}\tilde{G}^A_{\mu\nu}G^B_{\mu\rho}G^C_{\nu\rho}$$

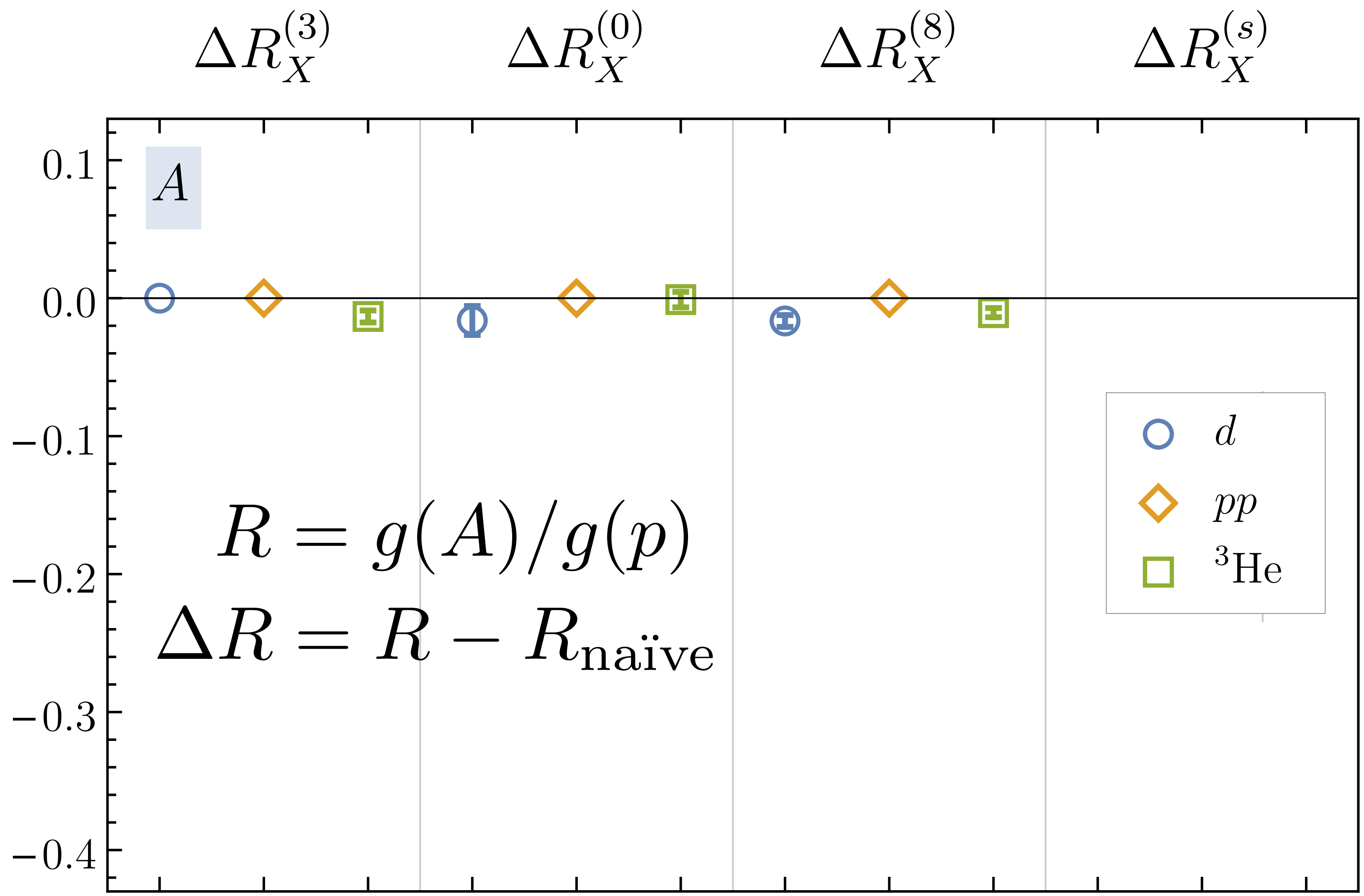
g_A Quenching

NPLQCD PRL 120 (2018) 15 152002 arXiv:1712.03221

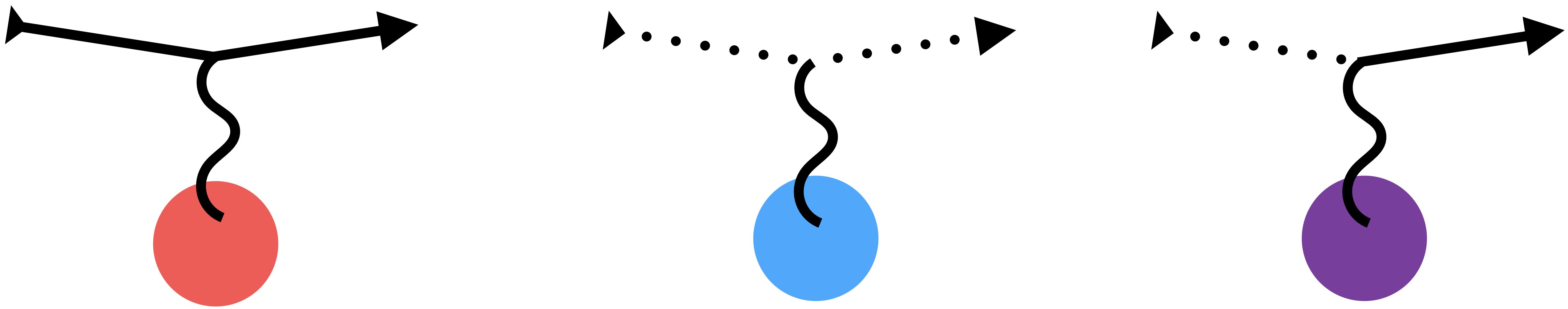
$m_\pi \sim 800$ MeV; a~0.12 fm



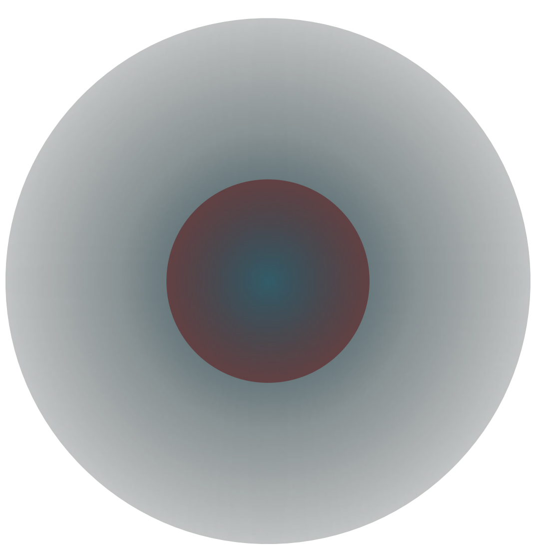
different flavor structures



Other Bilinear Matrix Elements



r_E | r_A | ve conversion



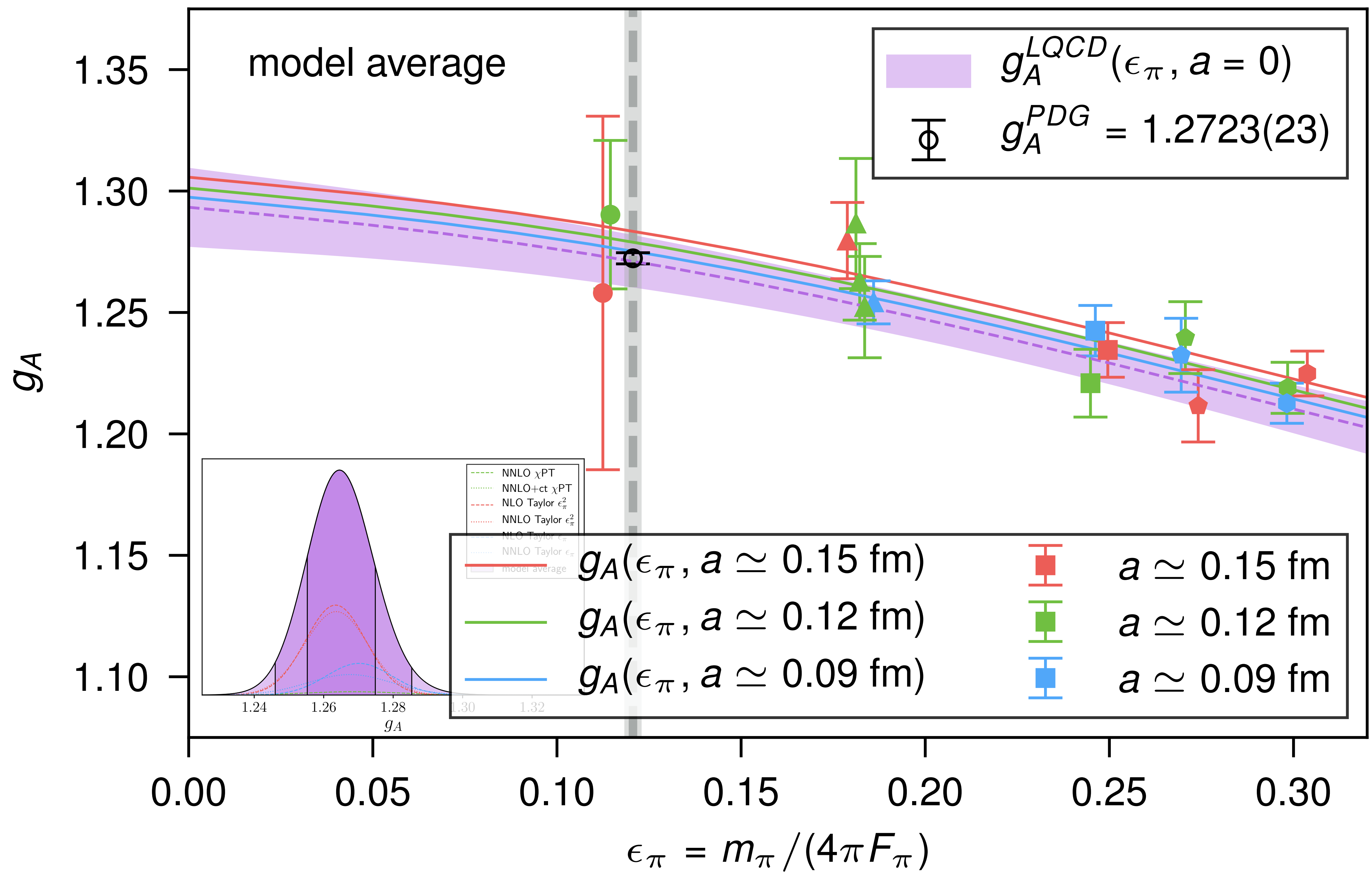
Form Factors
Radii
σ term
Polarizabilities
...


SIERRA
LLNL


summit
OLCF


LASSEN
LLNL

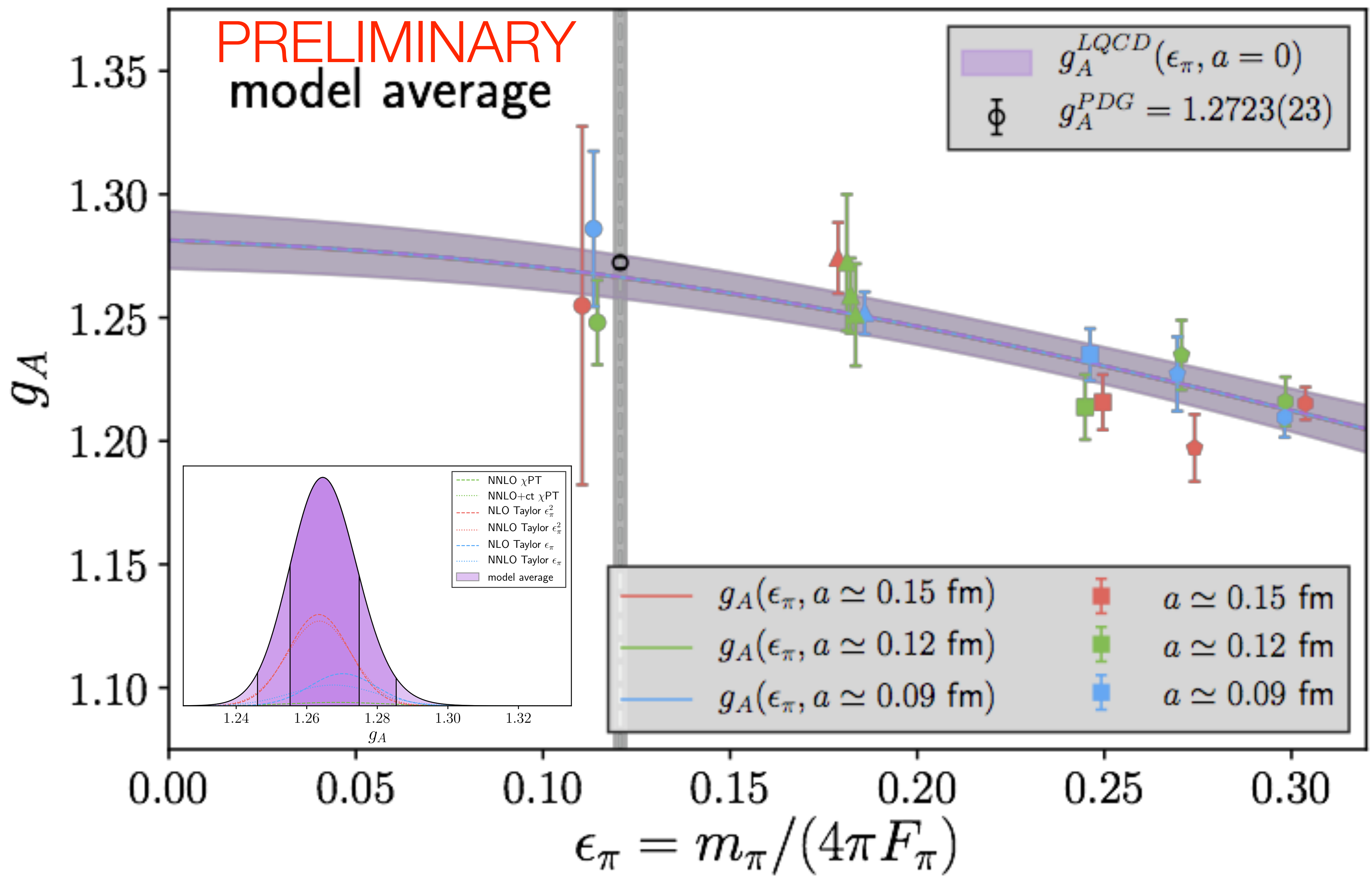
Published $g_A^{QCD} = 1.271(13)$



Published $g_A^{QCD} = 1.271(13)$

UPDATE $g_A^{QCD} = 1.2670(97)$ [0.76%]

PRELIMINARY!!!!!

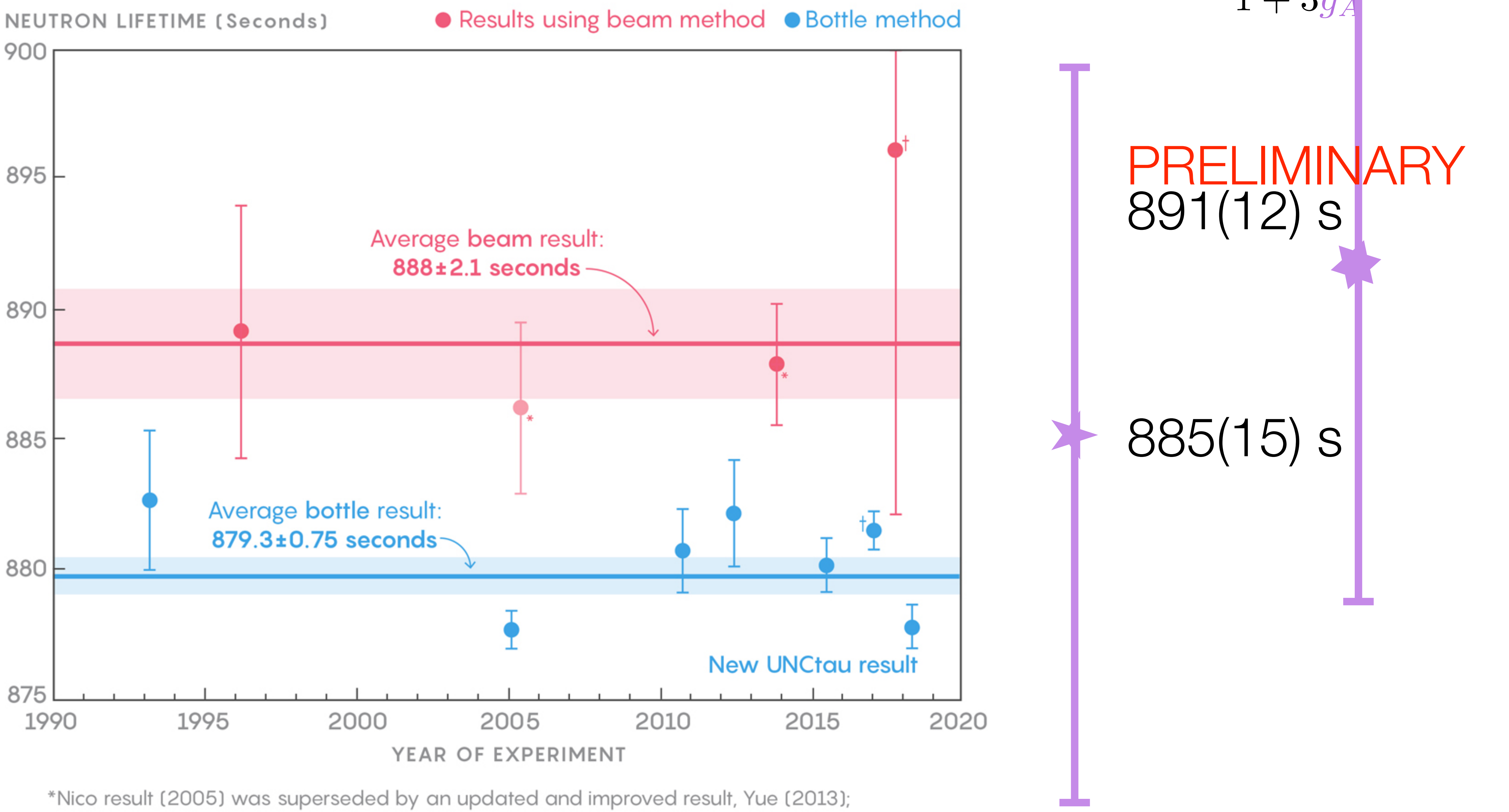


Published $g_A^{QCD} = 1.271(13)$ [1%]

UPDATE $g_A^{QCD} = 1.2670(97)$ [0.76%]

Nature 558 (2018) 91

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



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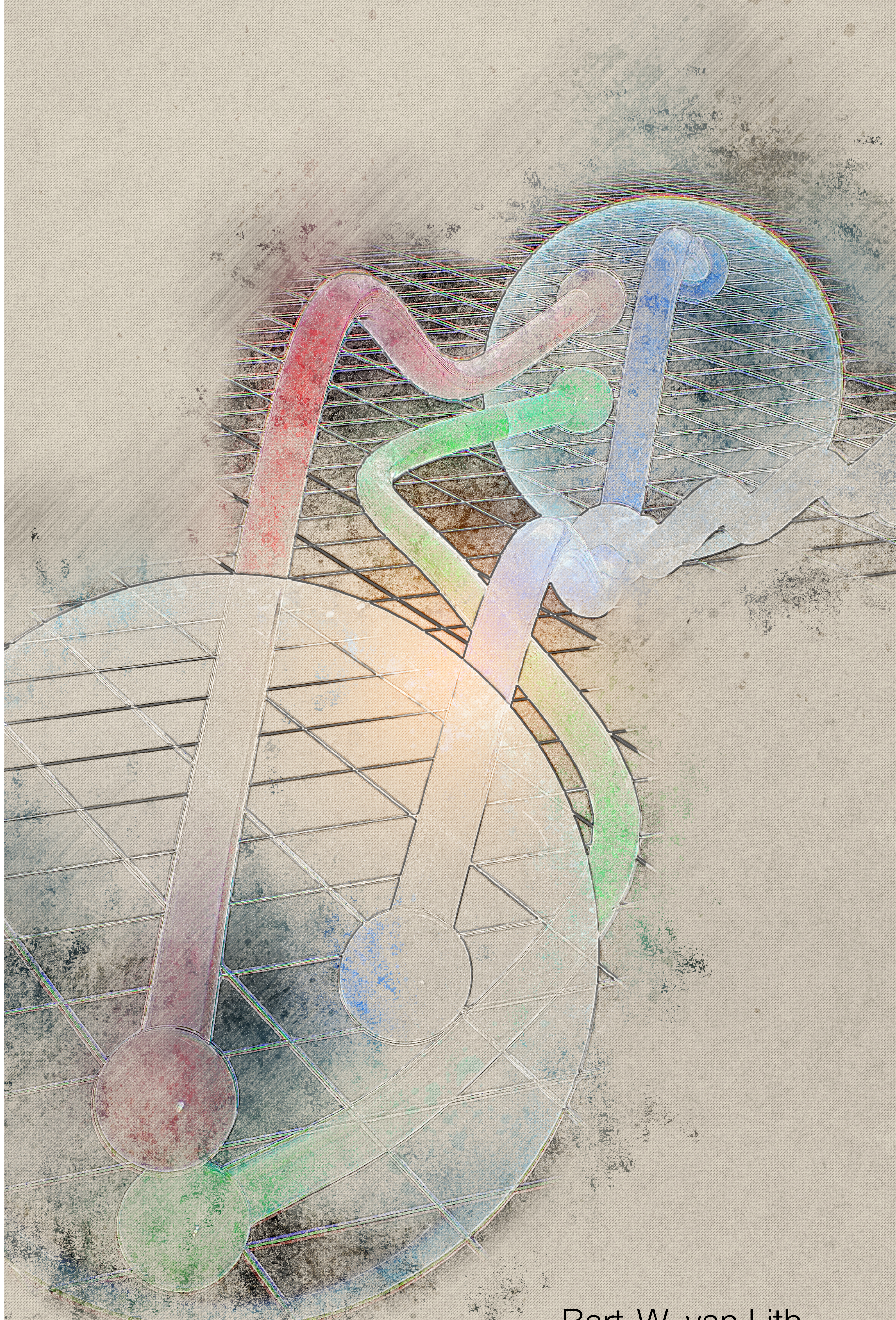
†Preliminary results

Lucy Reading-Ikkanda/Quanta Magazine - Neutron Lifetime Puzzle Deepens, but No Dark Matter Seen

Backup Slides


Bart-W. van Lith

Improved systematics

Bouchard, Chang, Kurth, Orginos, and Walker-Loud arXiv:1612.06963

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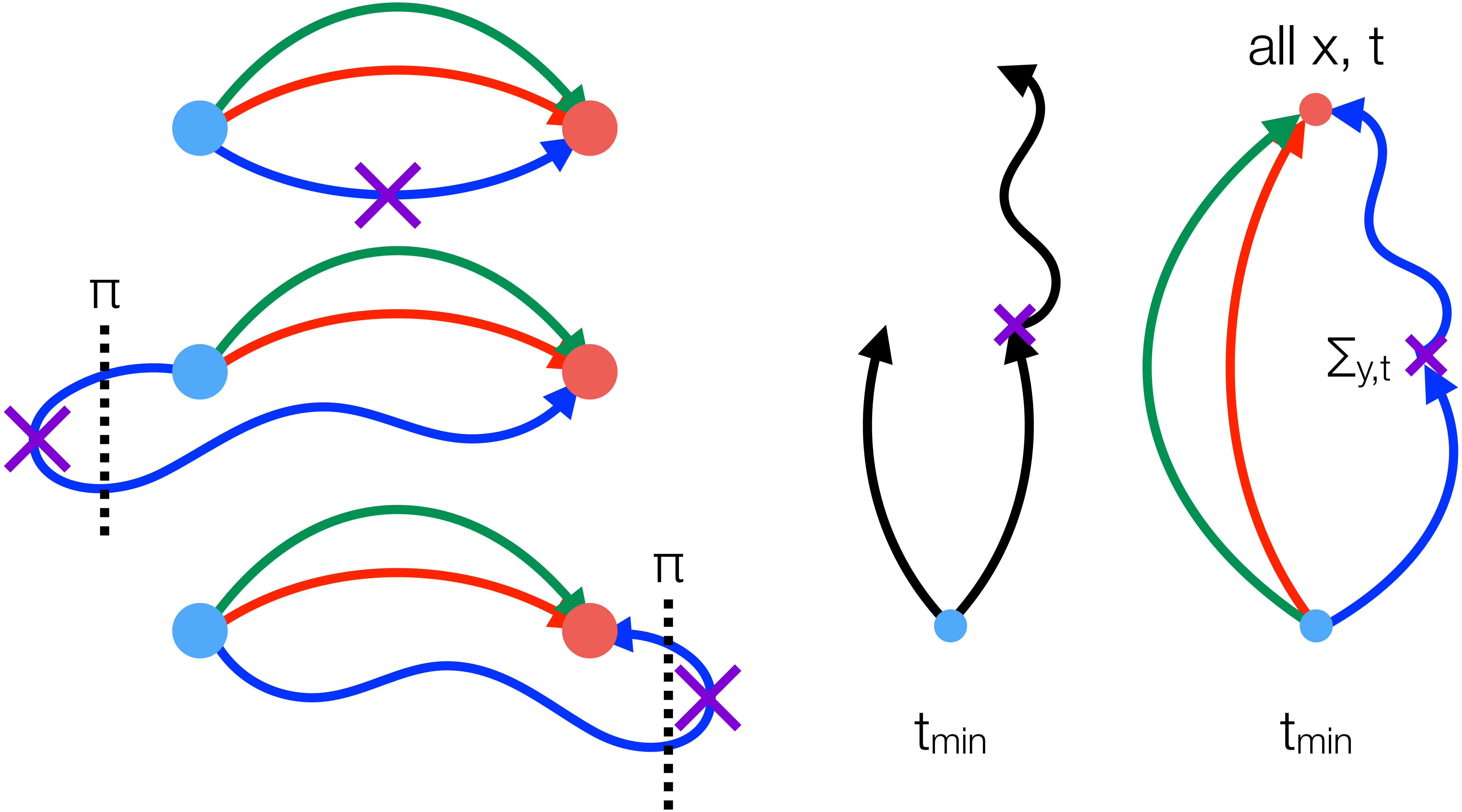
NPLQCD 1610.04545, 1611.00344, 1701.03456, 1702.02929



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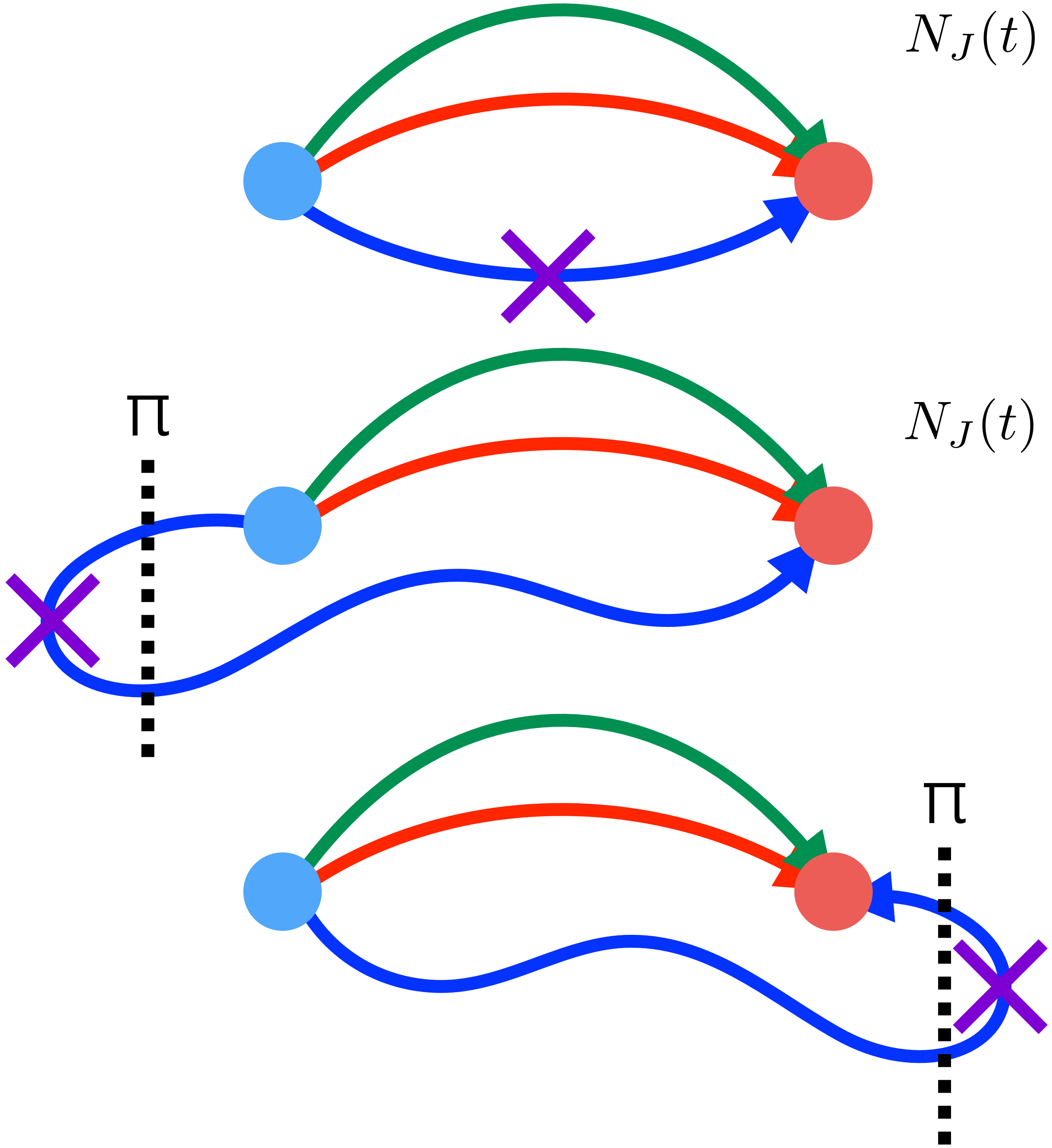


$$N_J(t) = \sum_{t'} \langle \Omega | T\{O(t) J(t') O^\dagger(0)\} | \Omega \rangle$$

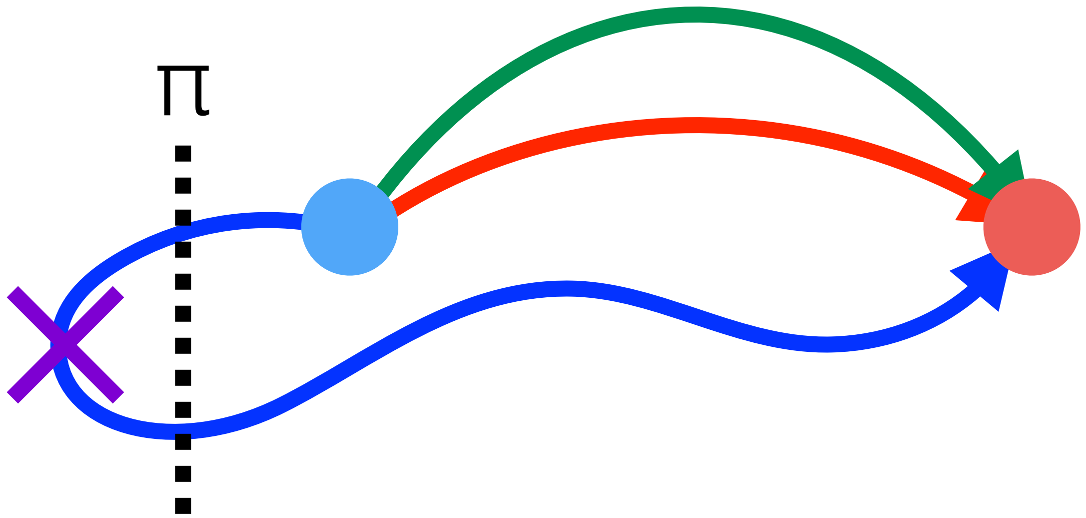
time dependence of
what you want

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

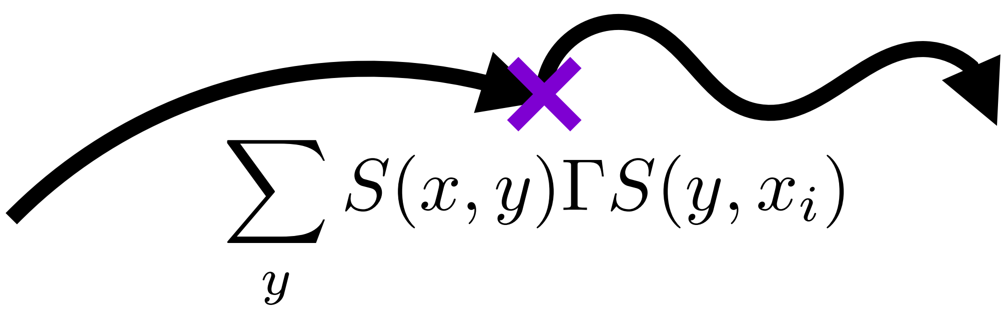
$$+ \sum_{\substack{n \\ m \neq n}} z_n g^J_{nm} z^\dagger_m \frac{e^{-E_n t + \frac{\Delta_{nm}}{2}} - e^{-E_m t + \frac{\Delta_{mn}}{2}}}{e^{\frac{\Delta_{nm}}{2}} - e^{\frac{\Delta_{mn}}{2}}}$$

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

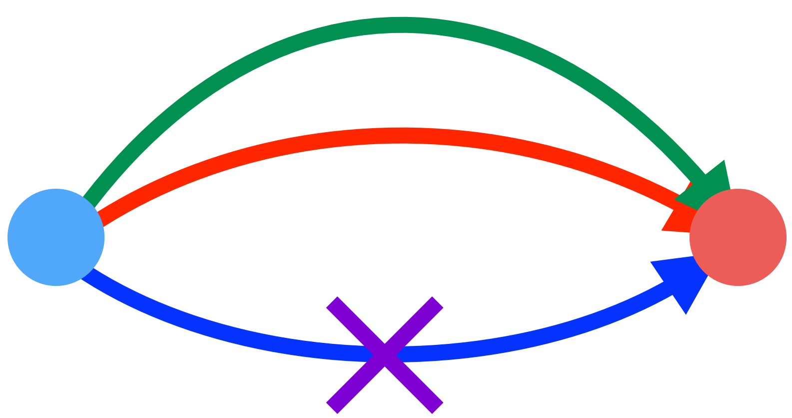
Comparison with the summation method



Summation method doesn't have this contamination

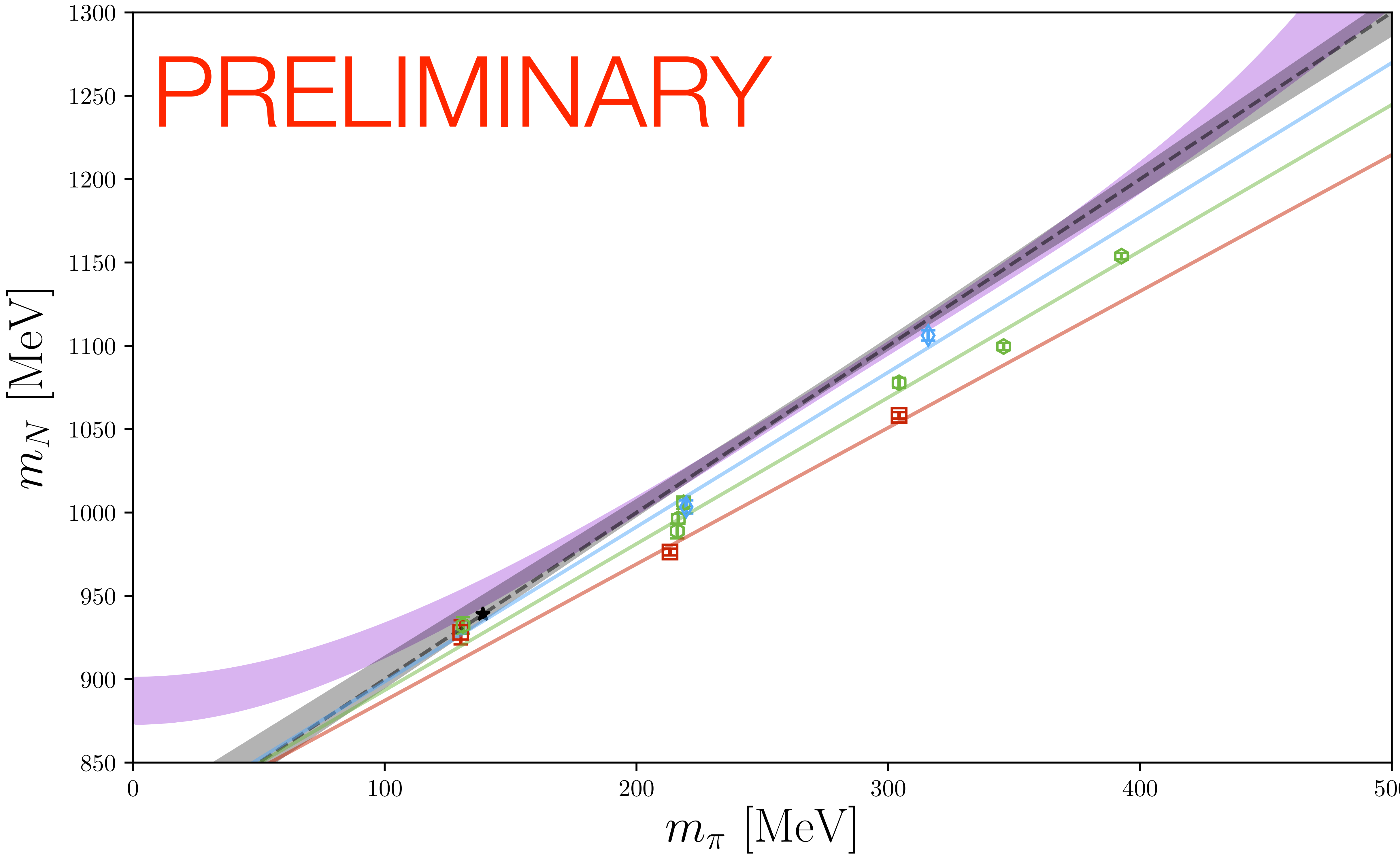


FH method requires new solves to study different insertions

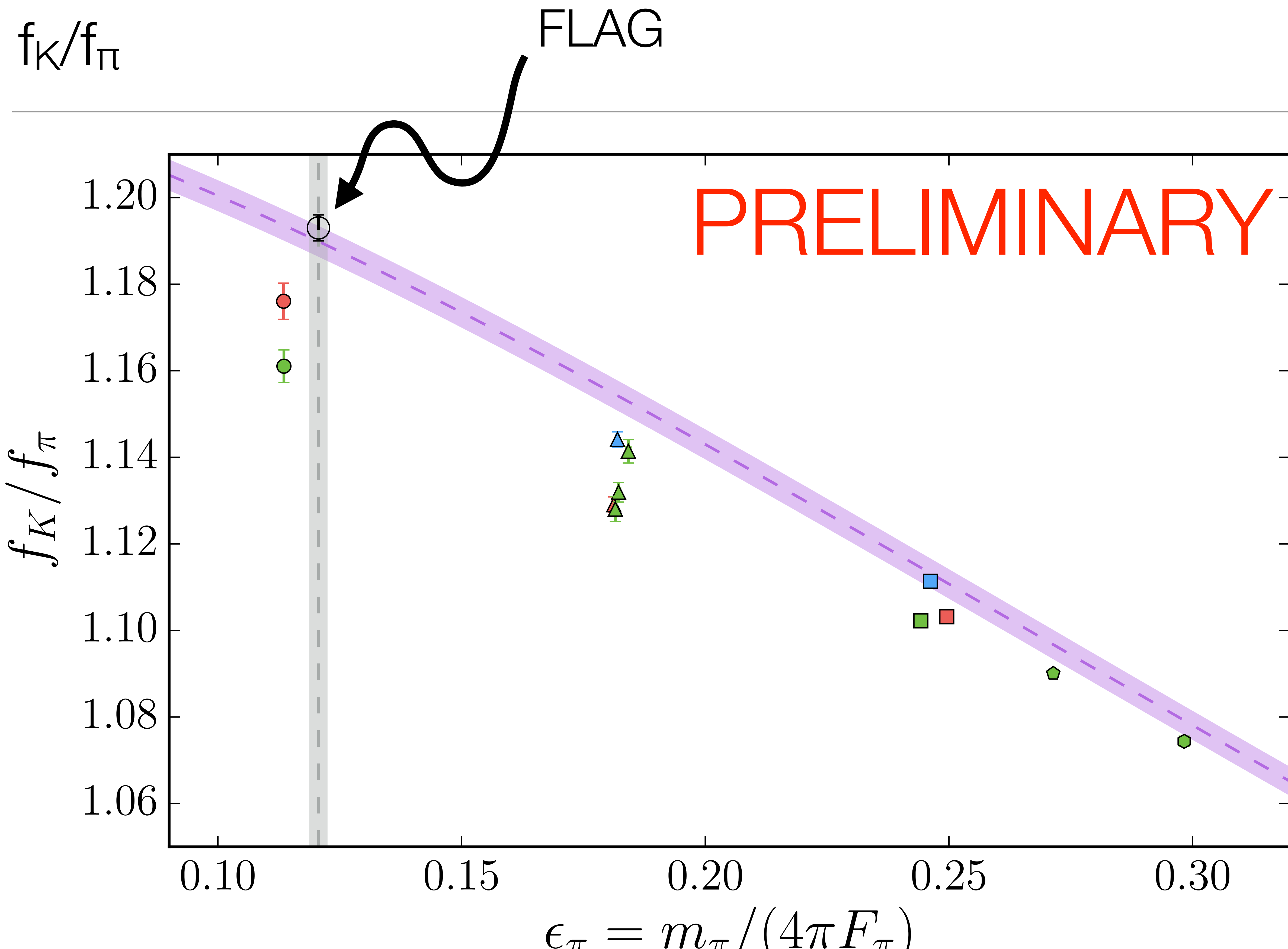


Summation method needs new solves for different source-sink separations

The Ruler still rules: $m_N(m_\pi) \approx 800$ MeV + m_π

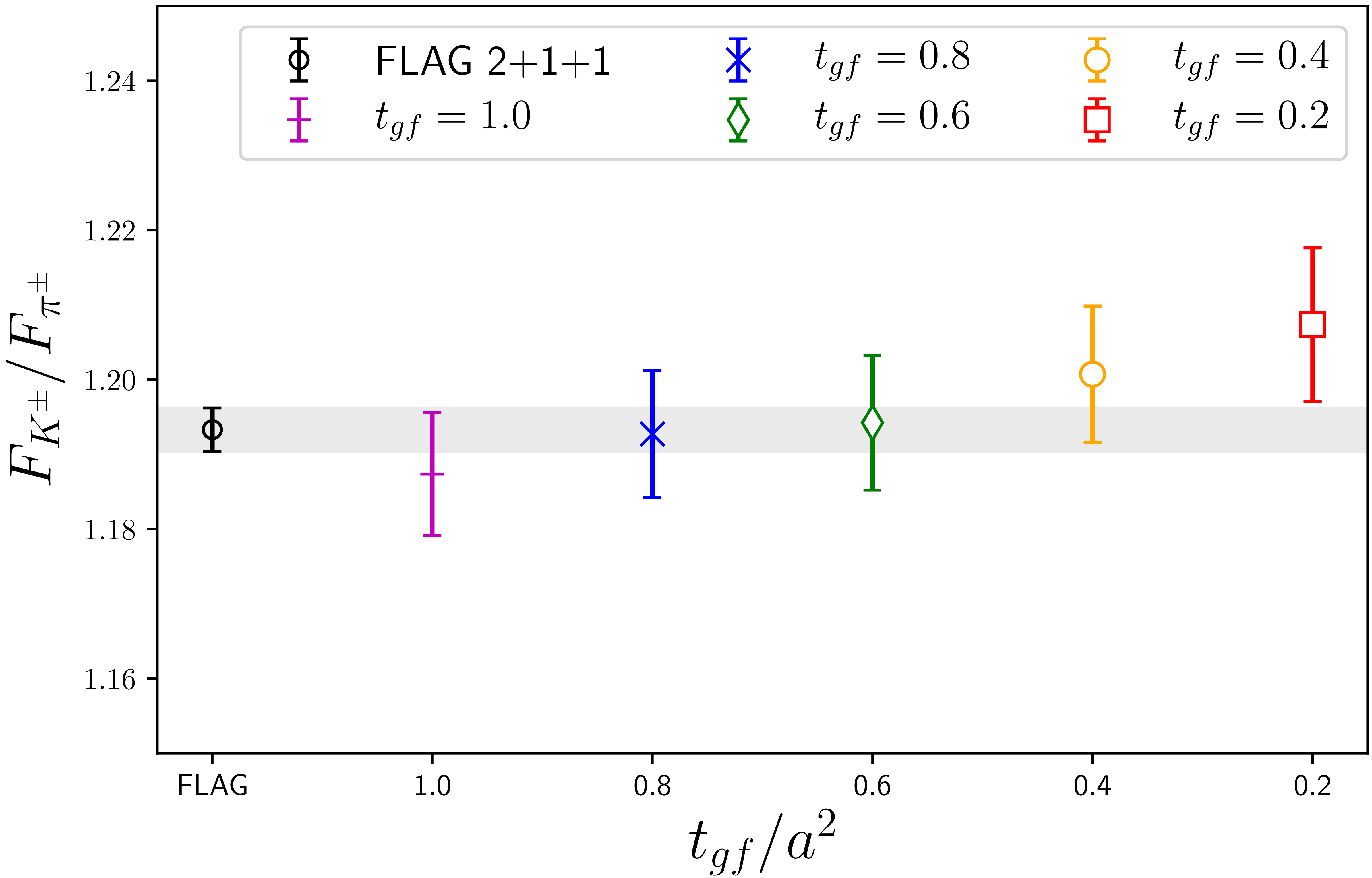


f_K/f_π

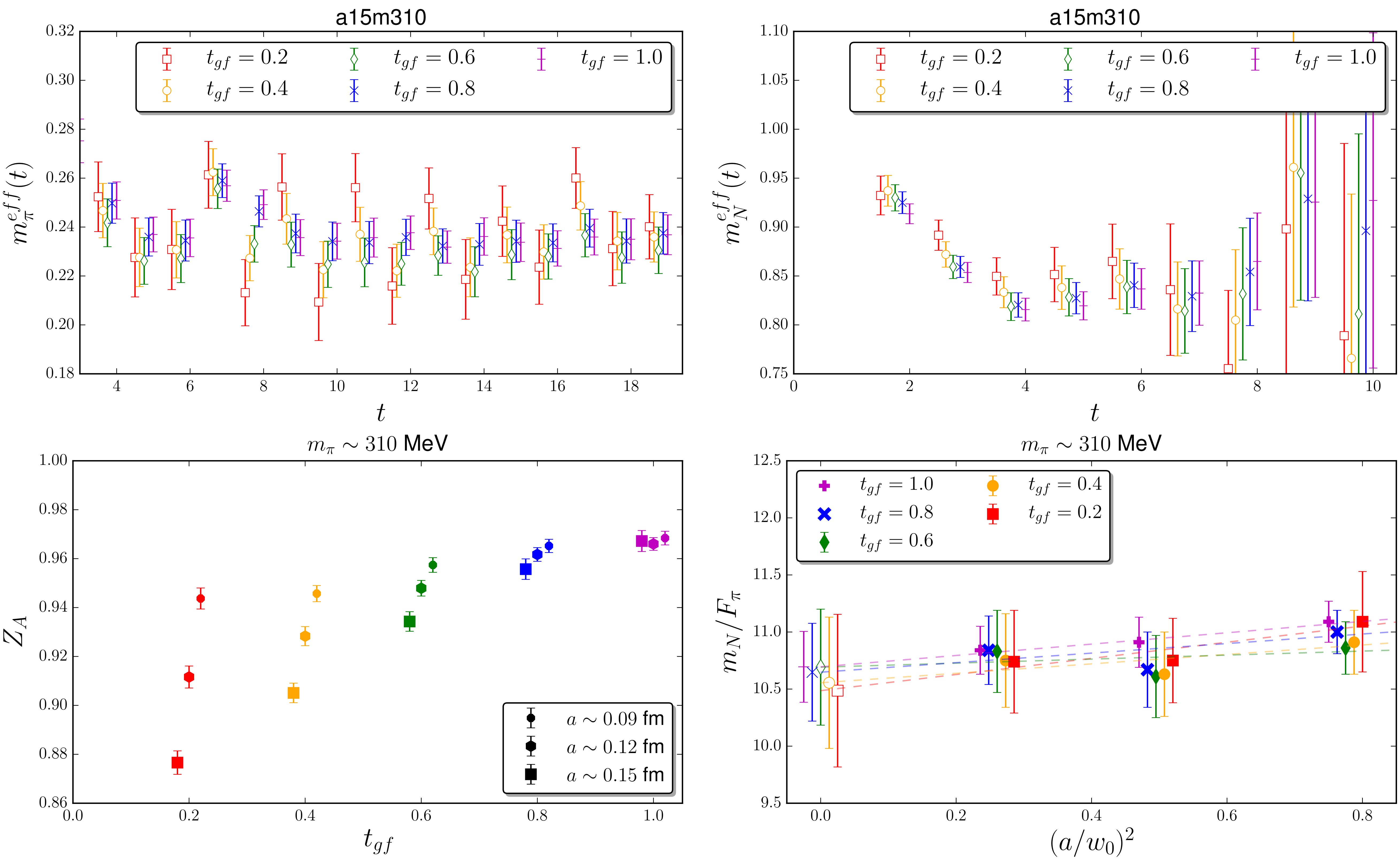


FLAG
PRELIMINARY
1.20
1.18
1.16
1.14
1.12
1.10
1.08
1.06
f_K / f_π
0.10
0.15
0.20
0.25
0.30
$\epsilon_\pi = m_\pi/(4\pi F_\pi)$

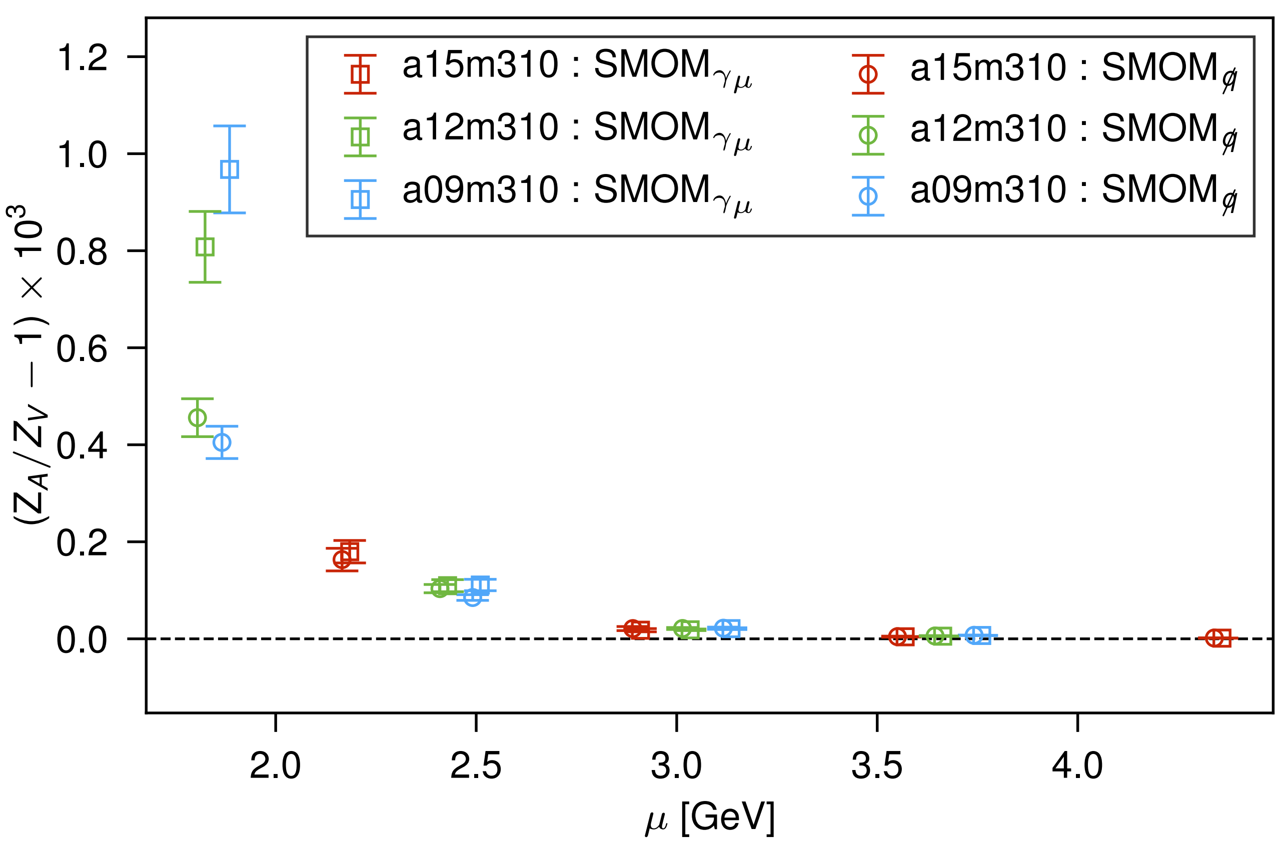
F_K/F_π smearing study (m_π = 135 MeV)

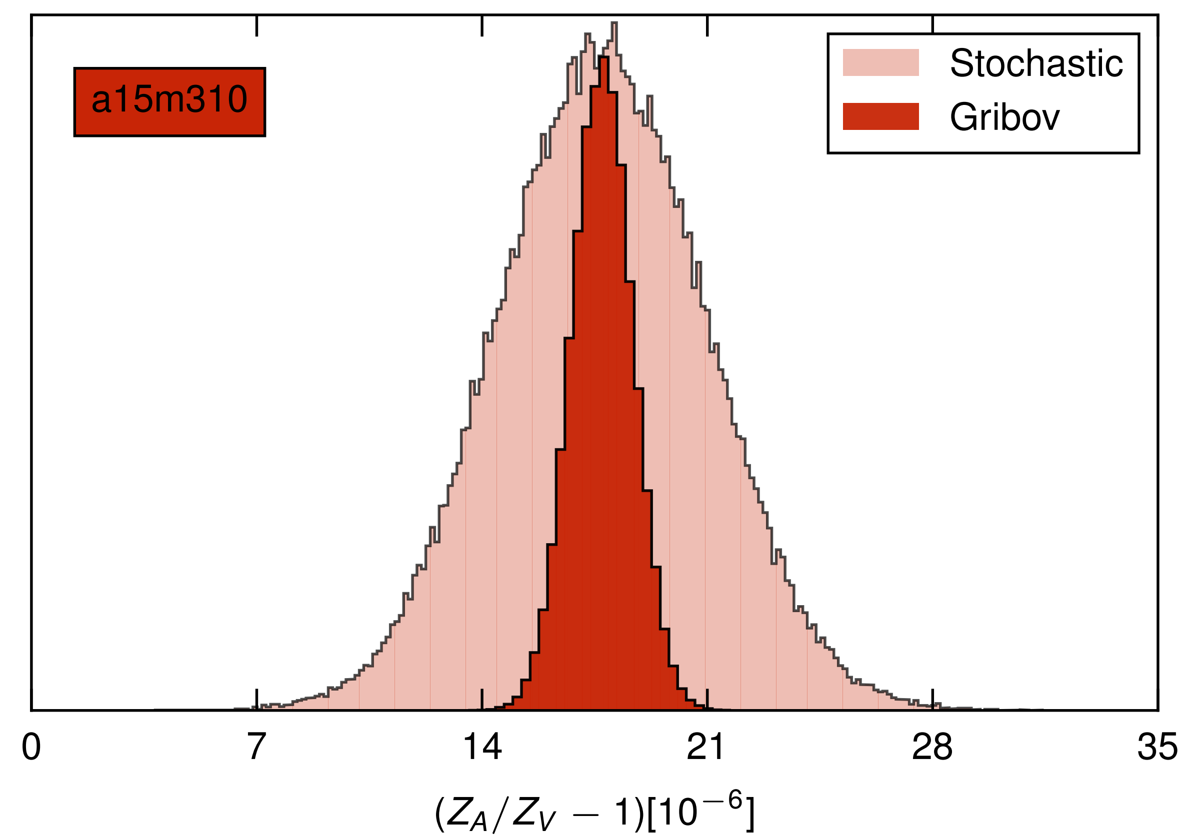


Smearing Study



Nonperturbative Renormalization





What does this have to do with Feynman-Hellmann?

Bouchard, Chang, Kurt, Orginos, Walker-Loud arXiv:1612.06963

NPLQCD 1610.04545, 1611.00344, 1701.03456, 1702.02929

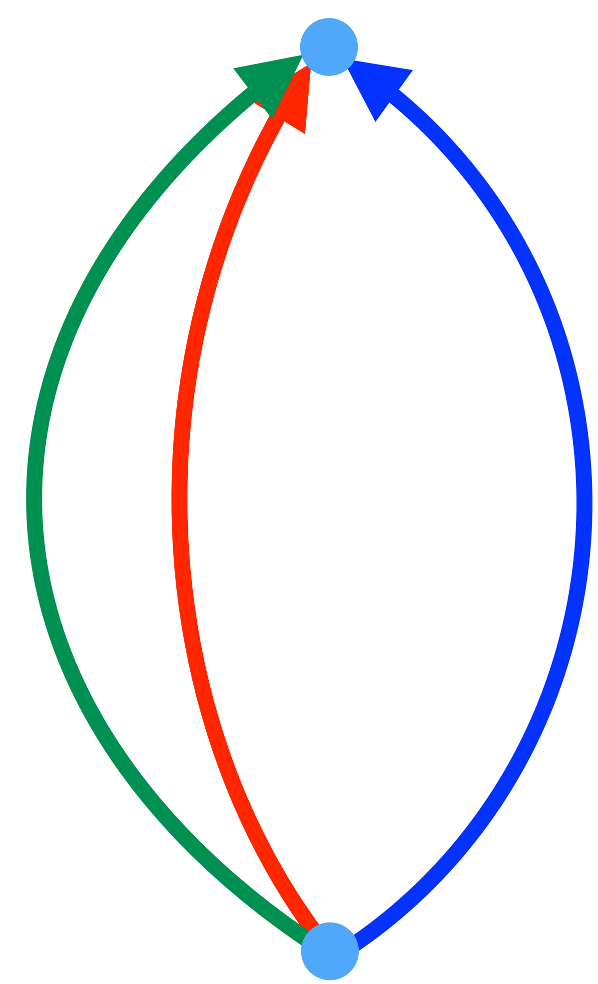
$$C(t) = \langle \mathcal{N}(t)\bar{\mathcal{N}}(0)\rangle = \frac{1}{\mathcal{Z}}\int \mathcal{D}U\ \mathcal{N}(t)\bar{\mathcal{N}}(0)\ e^{-S[U]} = \frac{\mathrm{tr}\left[\mathcal{N}(t)\bar{\mathcal{N}}(0)e^{-\beta H}\right]}{\mathrm{tr}\left[e^{-\beta H}\right]}$$

$$m_{\mathrm{eff}} = \frac{1}{\tau}\ln\left(\frac{C(t)}{C(t+\tau)}\right) \xrightarrow{t\to\infty} E_0$$

FH: $$\frac{\partial E_\lambda}{\partial \lambda} = \left\langle \psi_\lambda \left| \frac{\partial \hat{H}_\lambda}{\partial \lambda} \right| \psi_\lambda \right\rangle$$

$$\partial_\lambda E_0 = \text{a matrix element of interest}$$

C(t)



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$$S[U] \to S[U] + \lambda \int_x \mathcal{J}(x)\mathcal{O}(x)$$

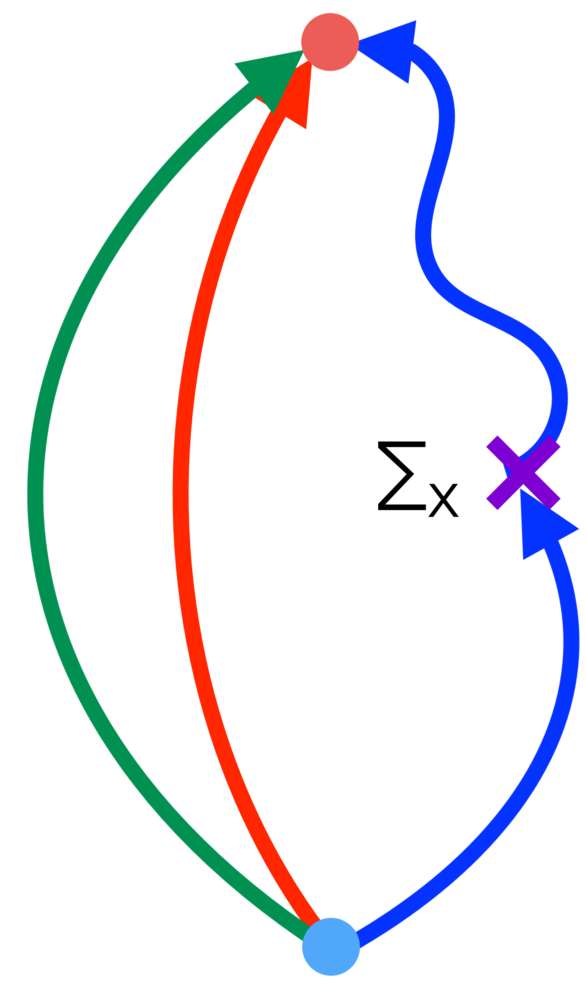
$$\partial_\lambda C(t) = -\left\langle \mathcal{N}(t) \left(\int_x \mathcal{J}(x)\mathcal{O}(x) \right) \bar{\mathcal{N}}(0) \right\rangle$$

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

$$\mathcal{J}_\mu(x) = 1$$

$$\mathcal{O}^\mu(x) = \bar{q}\gamma^\mu\gamma^5\tau^+ q$$

$$\xrightarrow{t\to\infty} g_A + O\left(e^{-E_n t}\right)$$



Improved systematics

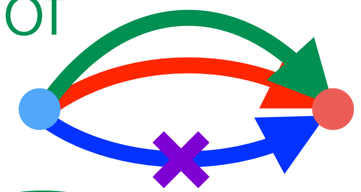
Bouchard, Chang, Kurth, Orginos, and Walker-Loud arXiv:1612.06963

See also Maiani, Martinelli, Paciello and Taglienti Nucl. Phys. B293 (1987)
NPLQCD 1610.04545, 1611.00344, 1701.03456, 1702.02929

$$N_J(t) = \sum_{t'} \langle \Omega | T\{O(t) J(t') O^\dagger(0)\} | \Omega \rangle$$

$$g^J_{nn} \equiv \frac{J_{nn}}{2E_n} \qquad J_{nn} = \langle n | J | n \rangle$$

time dependence of what you want



$$g^J_{nm} \equiv \frac{J_{nm}}{\sqrt{4E_n E_m}}$$

$$J_{nm} = \langle n | J | m \rangle$$

$$\Delta_{nm} \equiv E_n - E_m$$

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

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

$$d^J_n \equiv Z_n Z^\dagger_{J:n} + Z_{J:n} Z^\dagger_n + Z_n Z^\dagger_n \langle \Omega \mid J \mid \Omega \rangle + \sum_j \frac{Z_n Z^\dagger_{nj} J^\dagger_j + J_j Z_{jn} Z^\dagger_n}{2E_j (e^{E_j} - 1)}$$