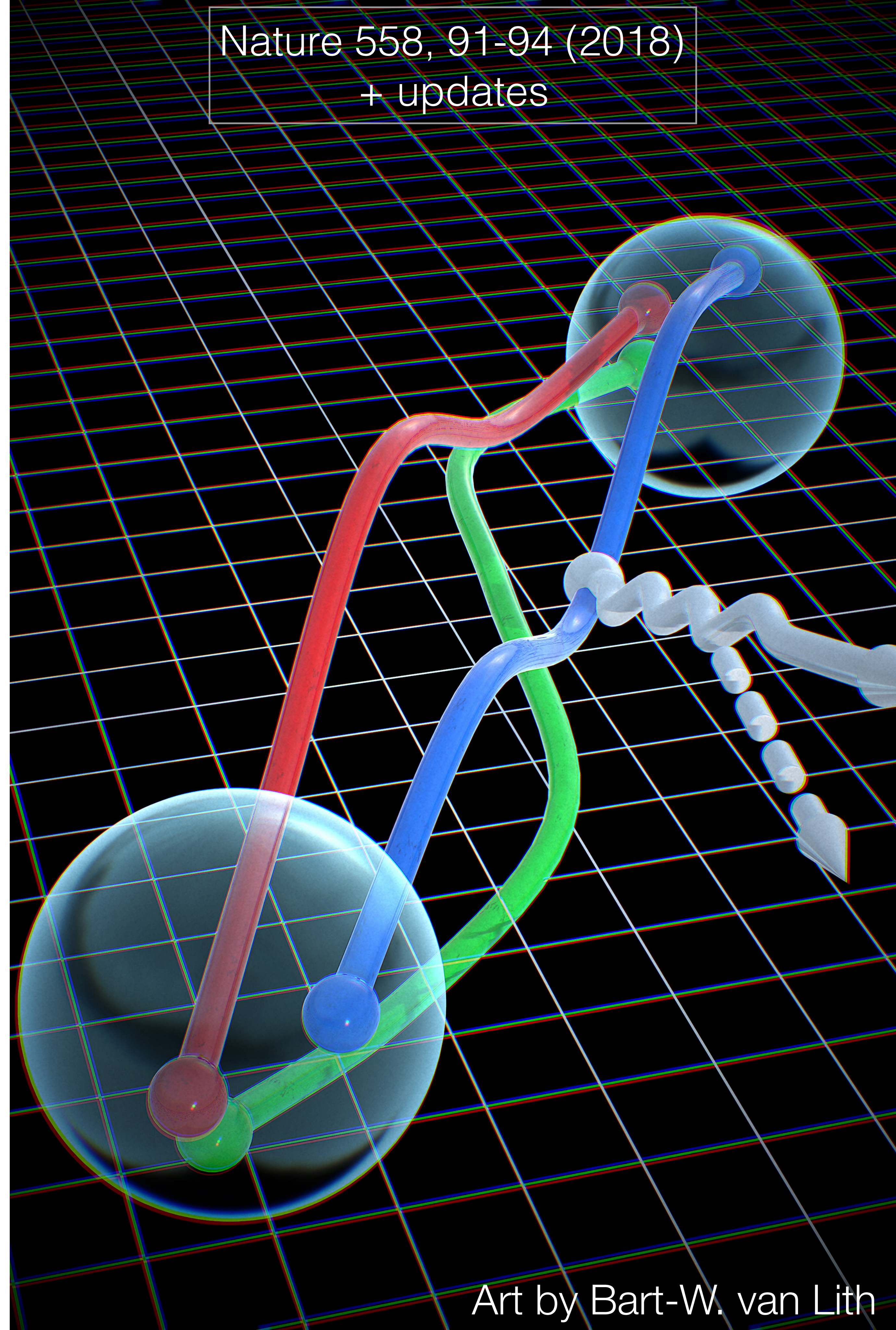
ACFI - Amherst 11/03/2018

First-principles QCD calculation of the neutron lifetime

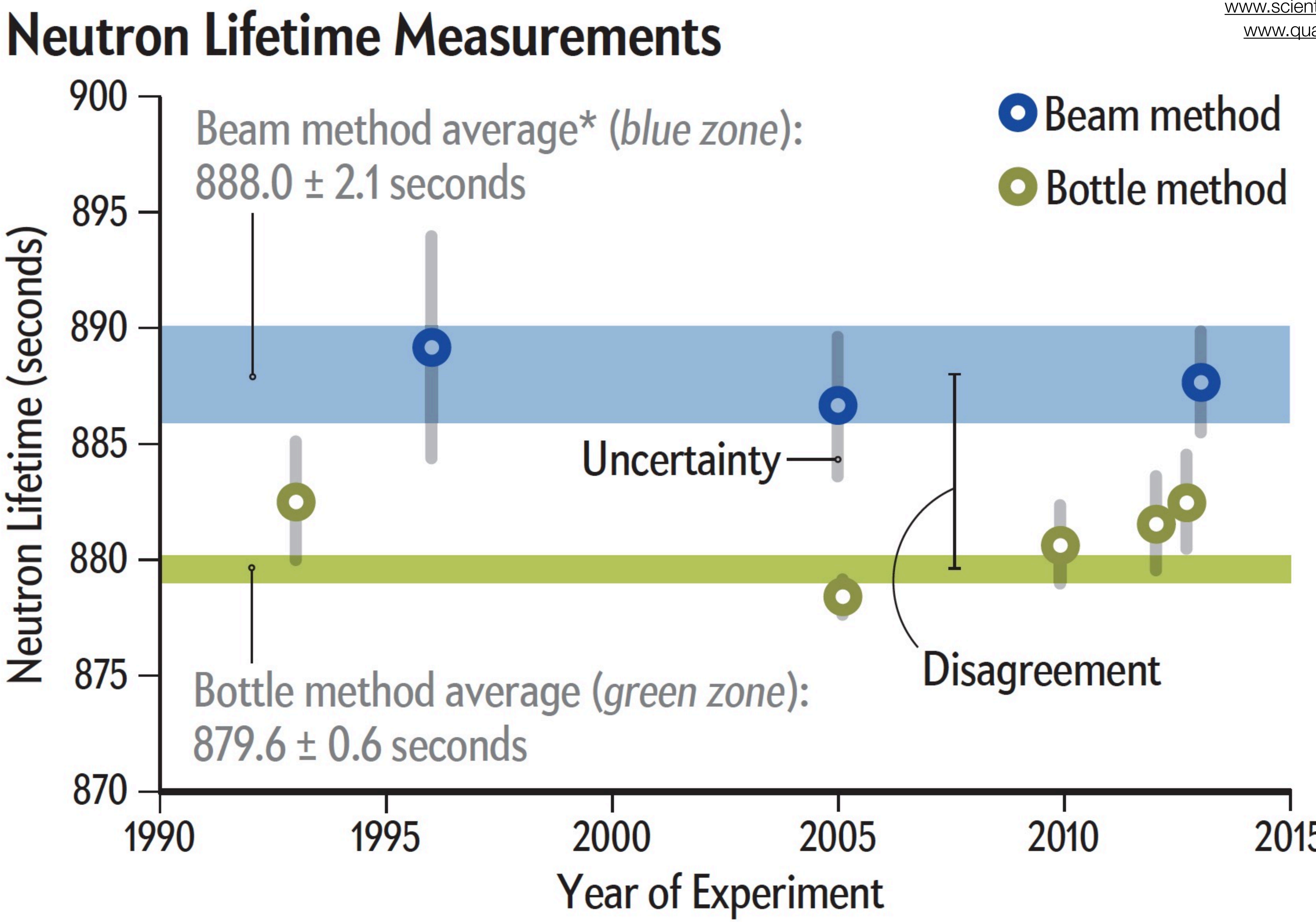
Enrico Rinaldi

RIKEN BNL Research Center



Berkeley LBL	David Brantley, Chia Cheng Chang, Ken McElvain, André Walker-Loud
RBRC	ER
FZJ	Evan Berkowitz
JLab	Bálint Jóo
Liverpool	Nicolas Garron
LLNL	Pavlos Vranas Arjun Gambhir
NERSC	Thorsten Kurth
UNC	Amy Nicholson Henry Monge Camacho
nVidia	Kate Clark
Glasgow	Chris Bouchard
INT	Chris Monahan
William & Mary	Kostas Orginos

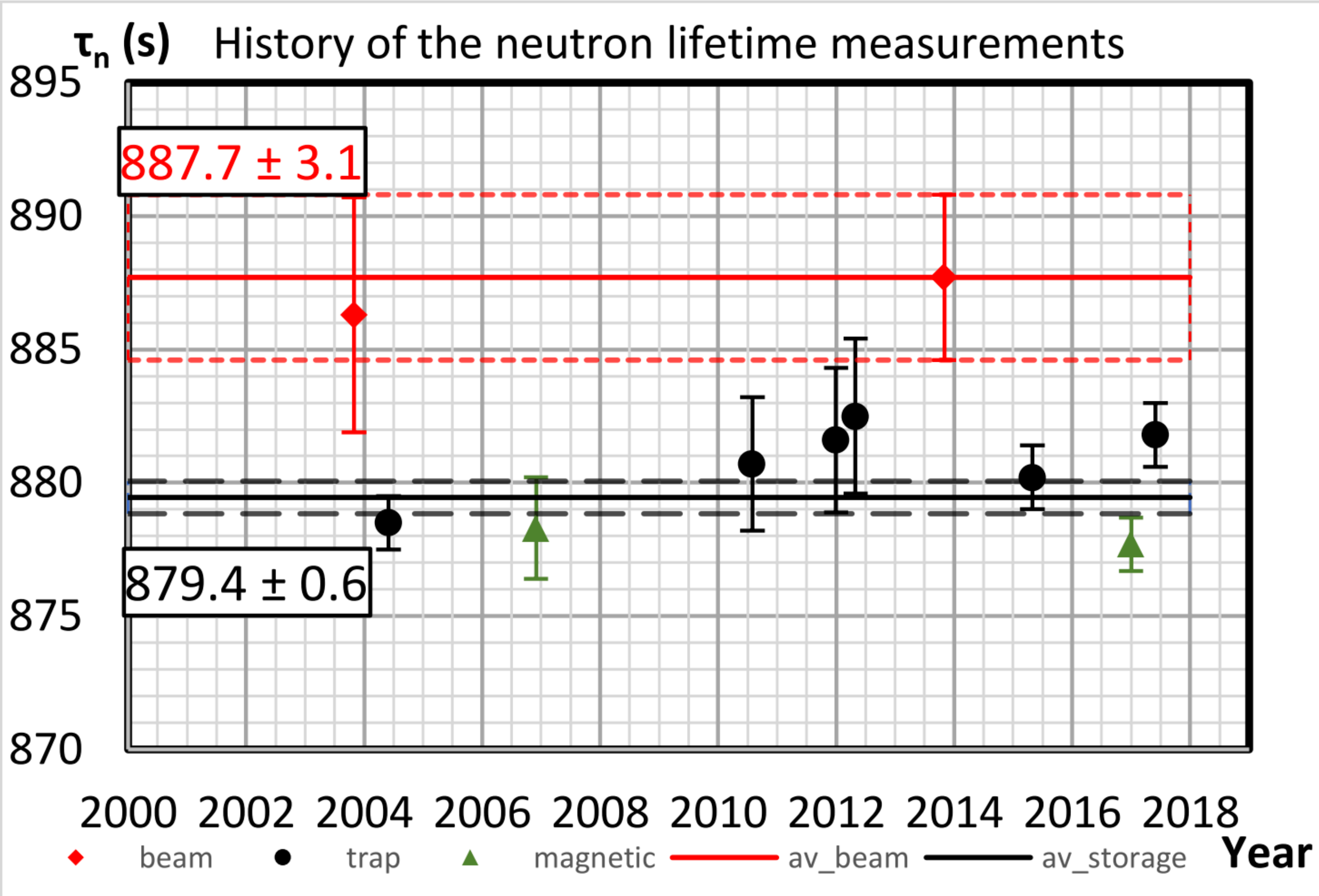
collaboration
(Cal-ifornia Lat-tice)



Neutron lifetime "puzzle"

$$\tau_n^{\text{beam}} = 888.0 \pm 2.0\ \text{s}$$

$$\tau_n^{\text{bottle}} = 879.6 \pm 0.6\ \text{s}$$

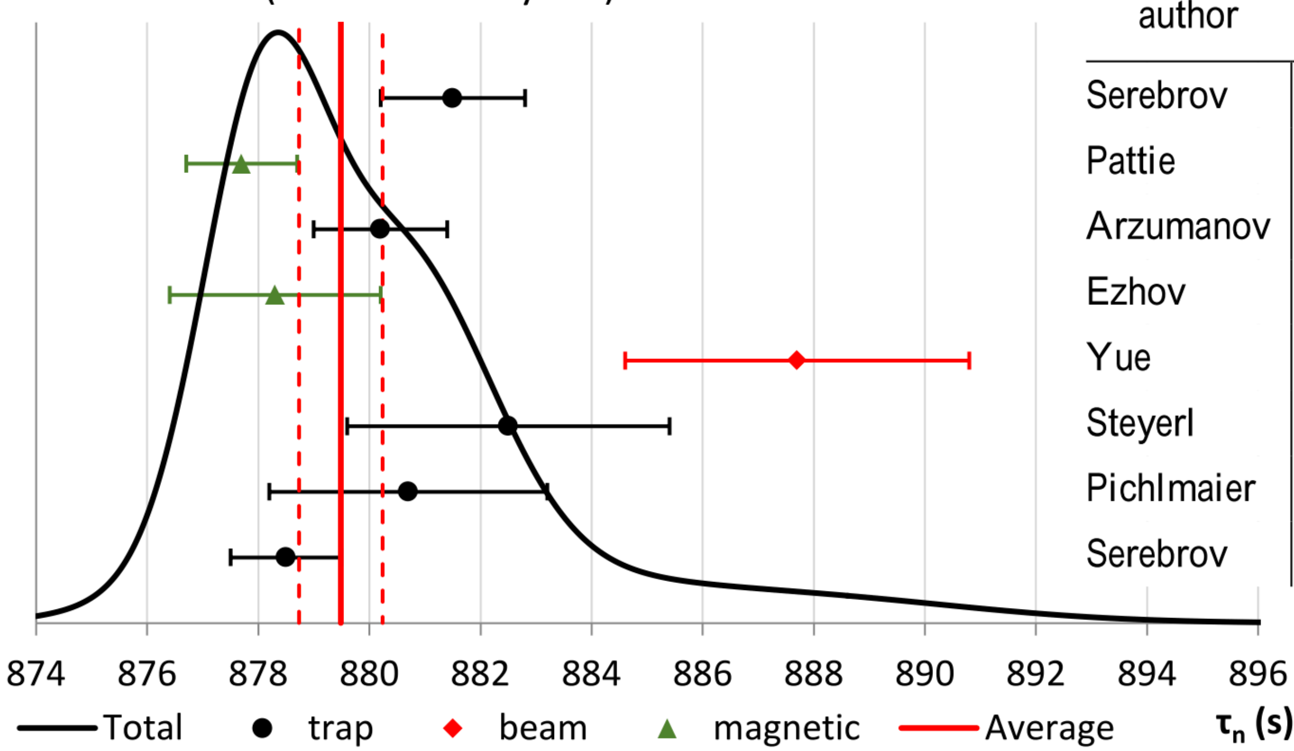


Serebrov et al. Phys. Rev. C 97 (055503) 2018

- The discrepancy of ~4σ between different methods is still unresolved.
- Experiments are trying to reduce all their systematics and provide robust estimates for their uncertainties
- Neutron decays to “dark” or “exotic” particles have been invoked to explain the discrepancy

[Fornal&Grinstein, PRL120(191801)2018]

Weighted average
879.5 ± 0.8 (error scaled by 1.5)



author	year	value	error stat	error sys	Σ	χ^2	Ref
Serebrov	2017	881.5	0.7	0.6	1.3	2.4	—
Pattie	2017	877.7	0.7	0.3	1.0	3.2	[21]
Arzumanov	2015	880.2	1.2		1.2	0.4	[22]
Ezhov	2014	878.3	1.9		1.9	0.4	[23]
Yue	2013	887.7	1.2	1.9	3.1	7.0	[24]
Steyerl	2012	882.5	1.4	1.5	2.9	1.1	[25]
Pichlmaier	2010	880.7	1.3	1.2	2.5	0.2	[26]
Serebrov	2004	878.5	0.7	0.3	1.0	1.0	[15, 16]

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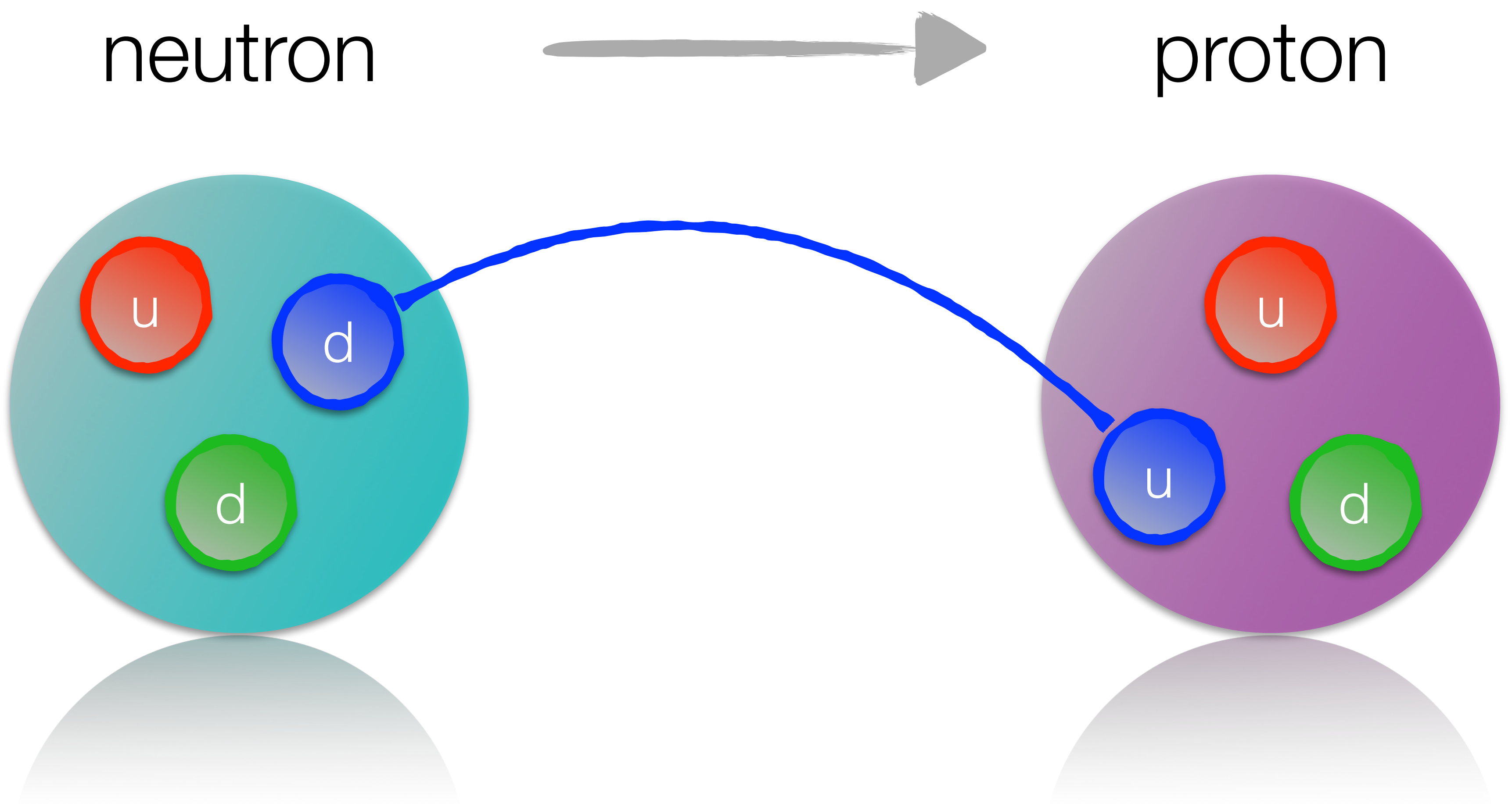
Vol. 360, Issue 6389, pp. 627-632

Exotic decays of the neutron



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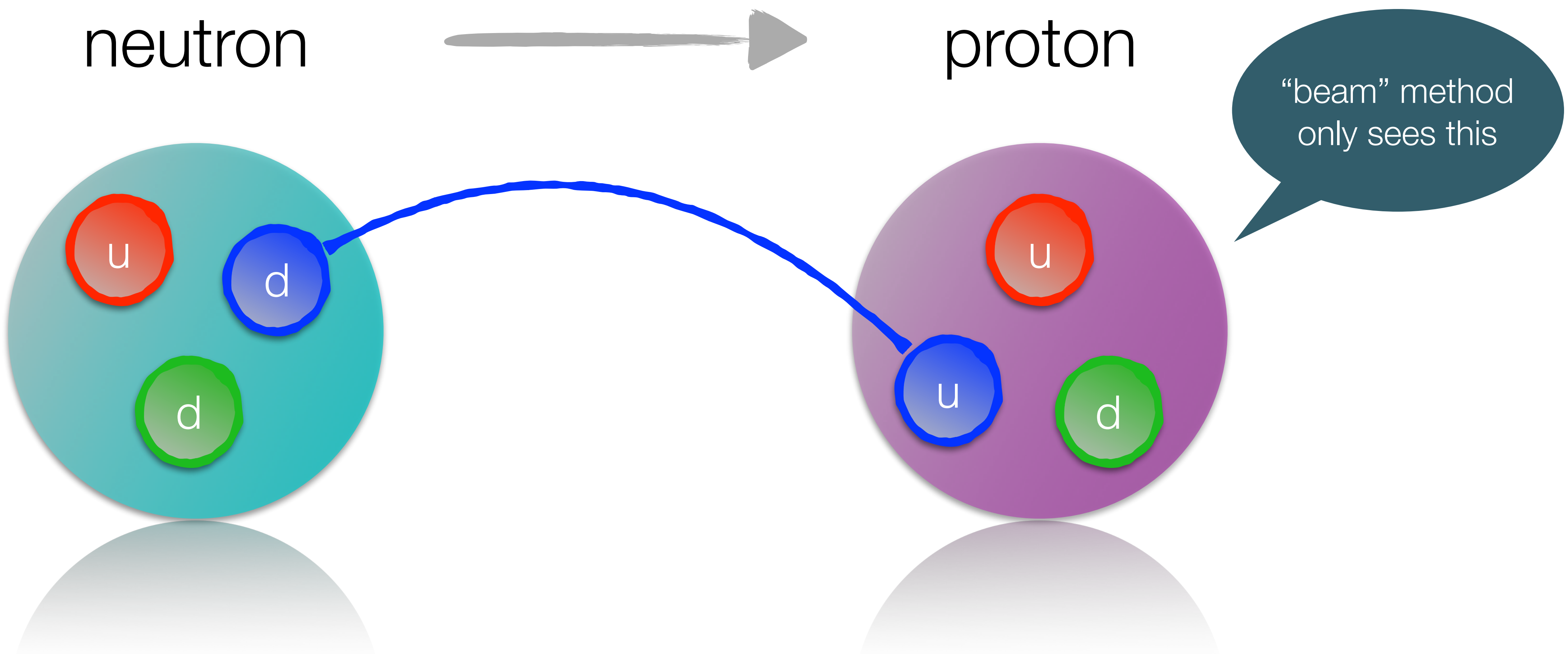

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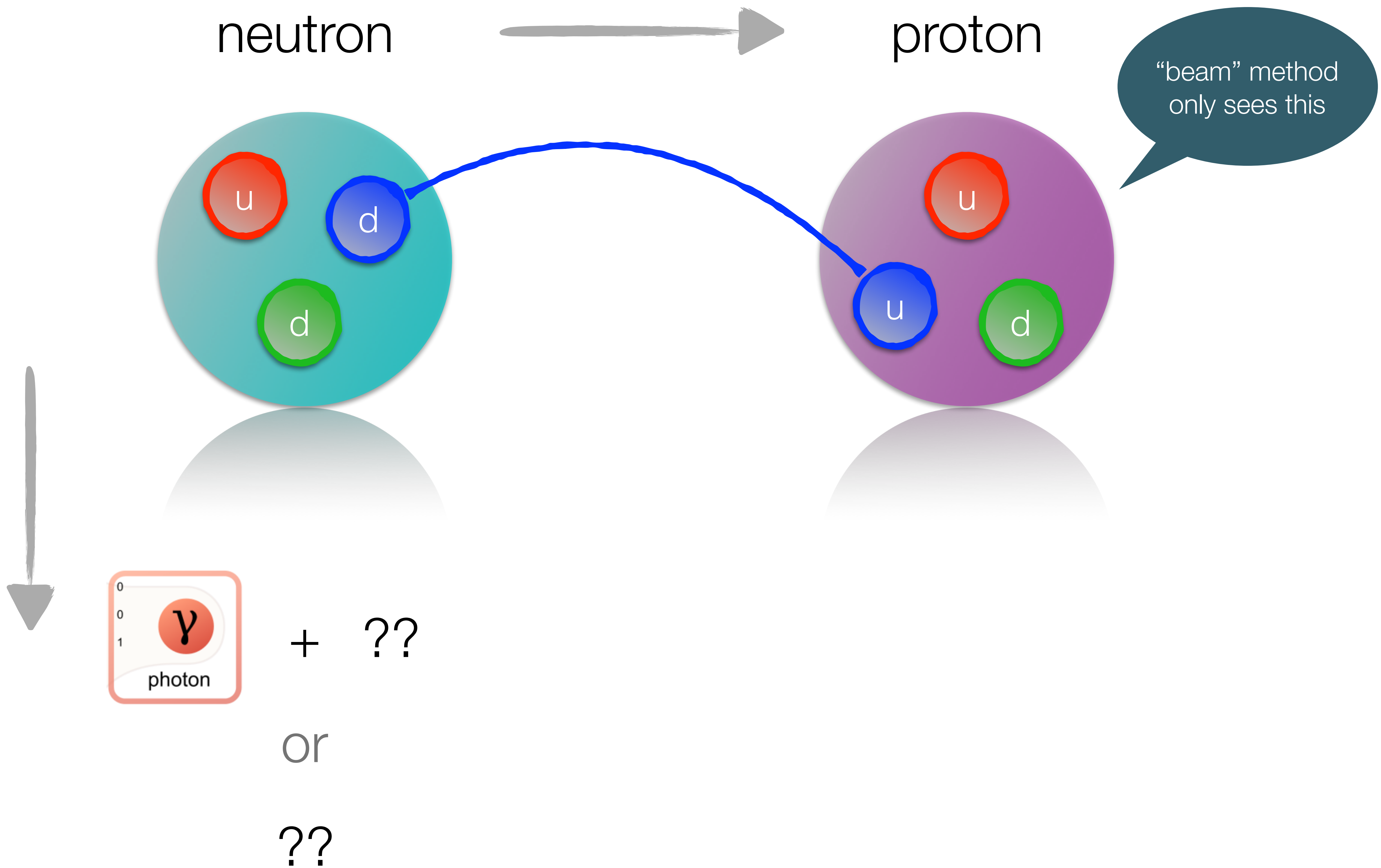

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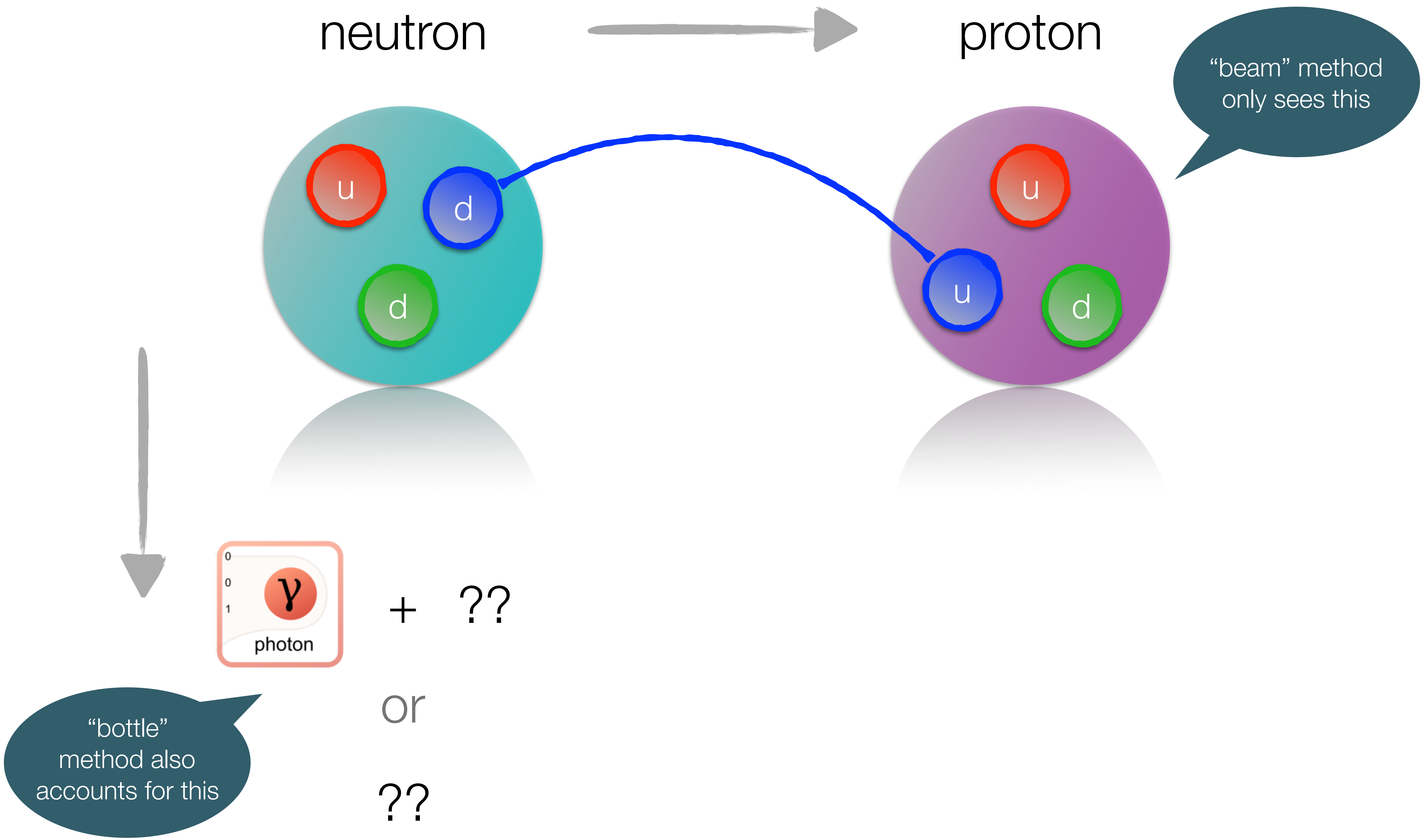

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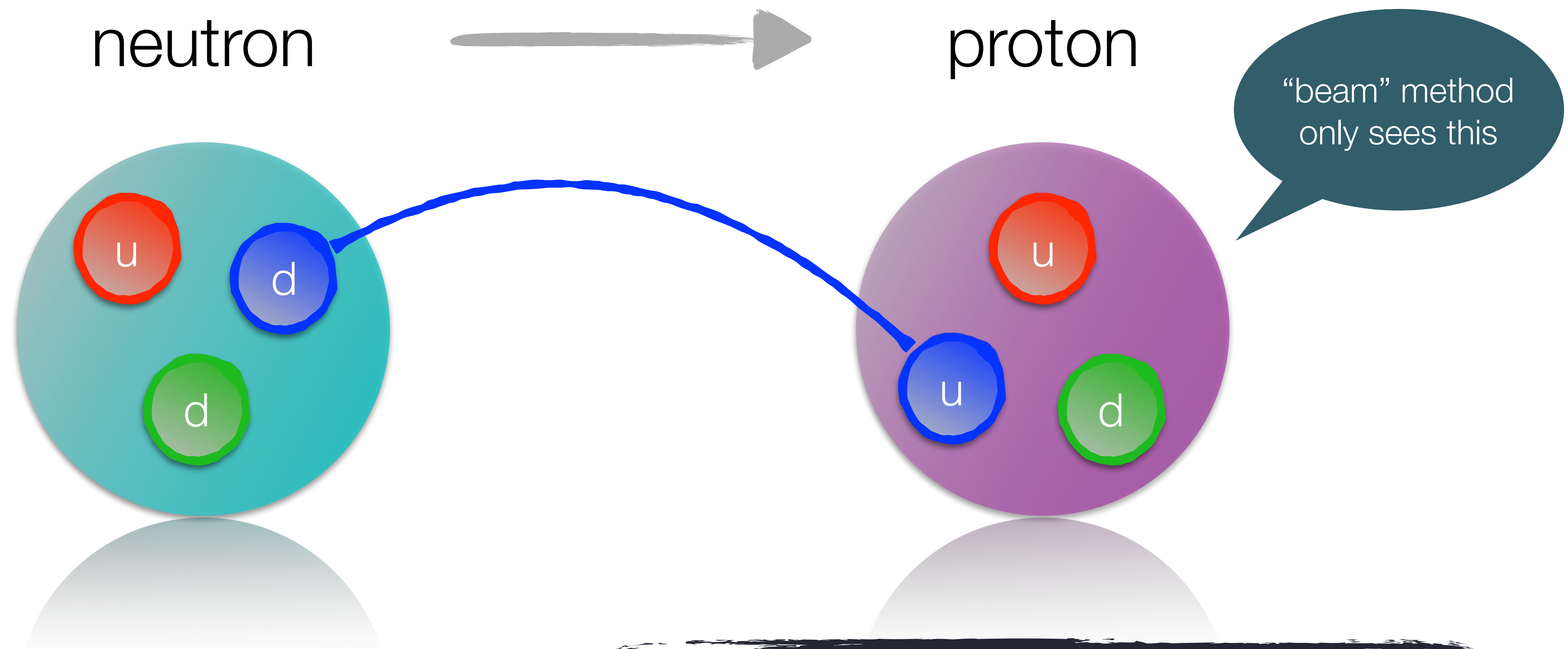
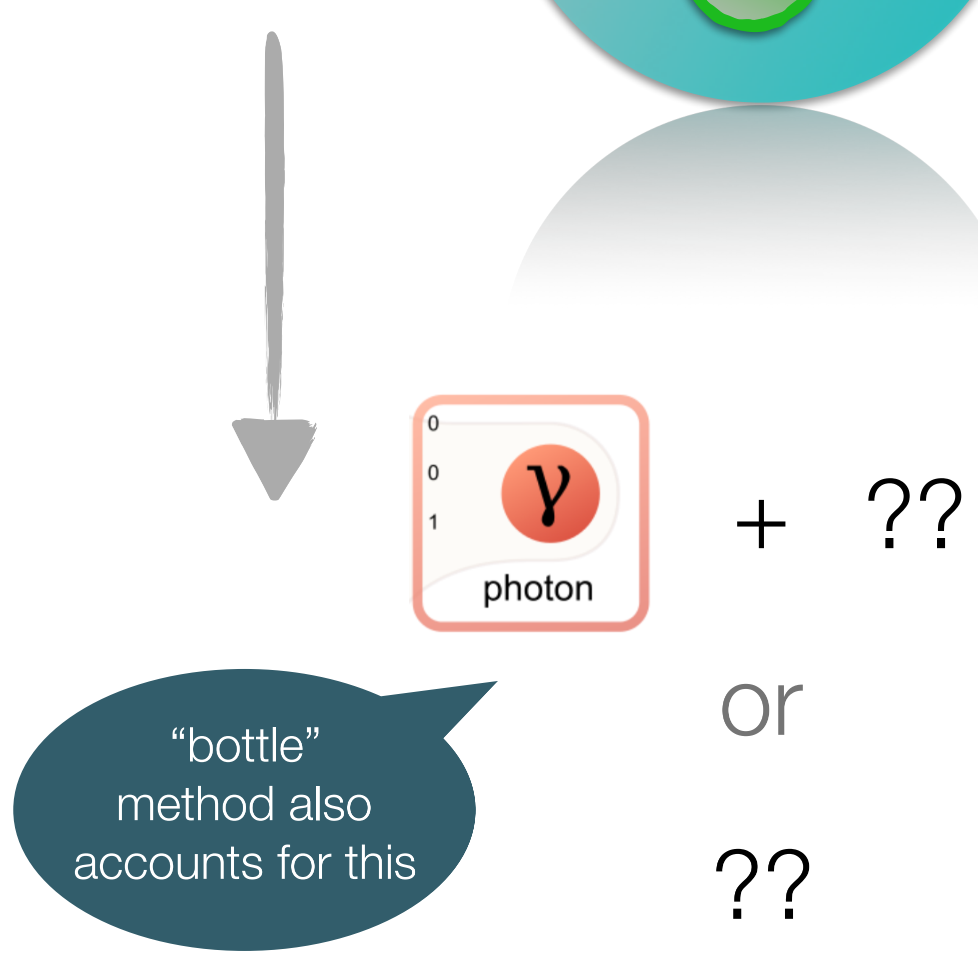




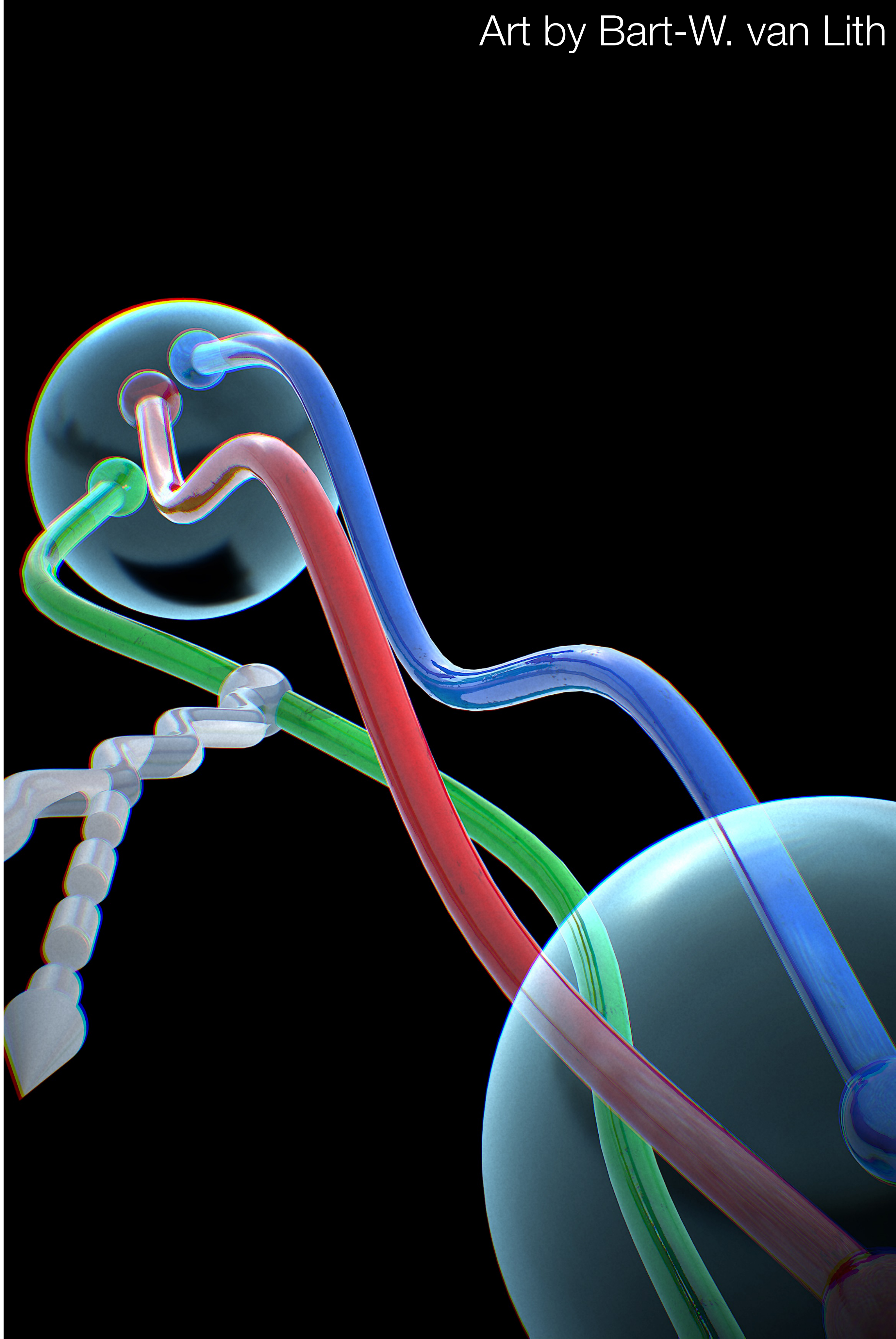
- Experiments are already putting constraints on decays including photons and invisible particles
- Theorists are putting bounds on exotic decays by using neutron stars observations
- What else can we do?

Neutron beta decay

- In the Standard Model, beta decay is driven by the electroweak sector
- The master formula includes the quark mixing matrix element, the neutron lifetime and the axial coupling:

$$|V_{ud}|^2 \tau_n (1 + 3 g_A{}^2) = 4908.6(1.9)s$$

[Czarnecki, Marciano and Sirlin, Phys. Rev. Lett. 120, 202002 (2018)]



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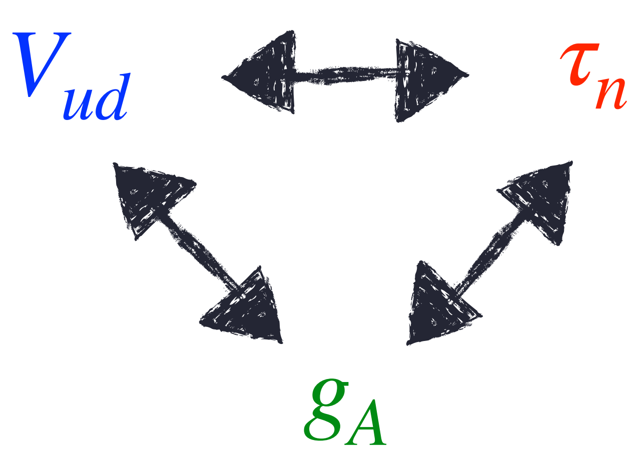

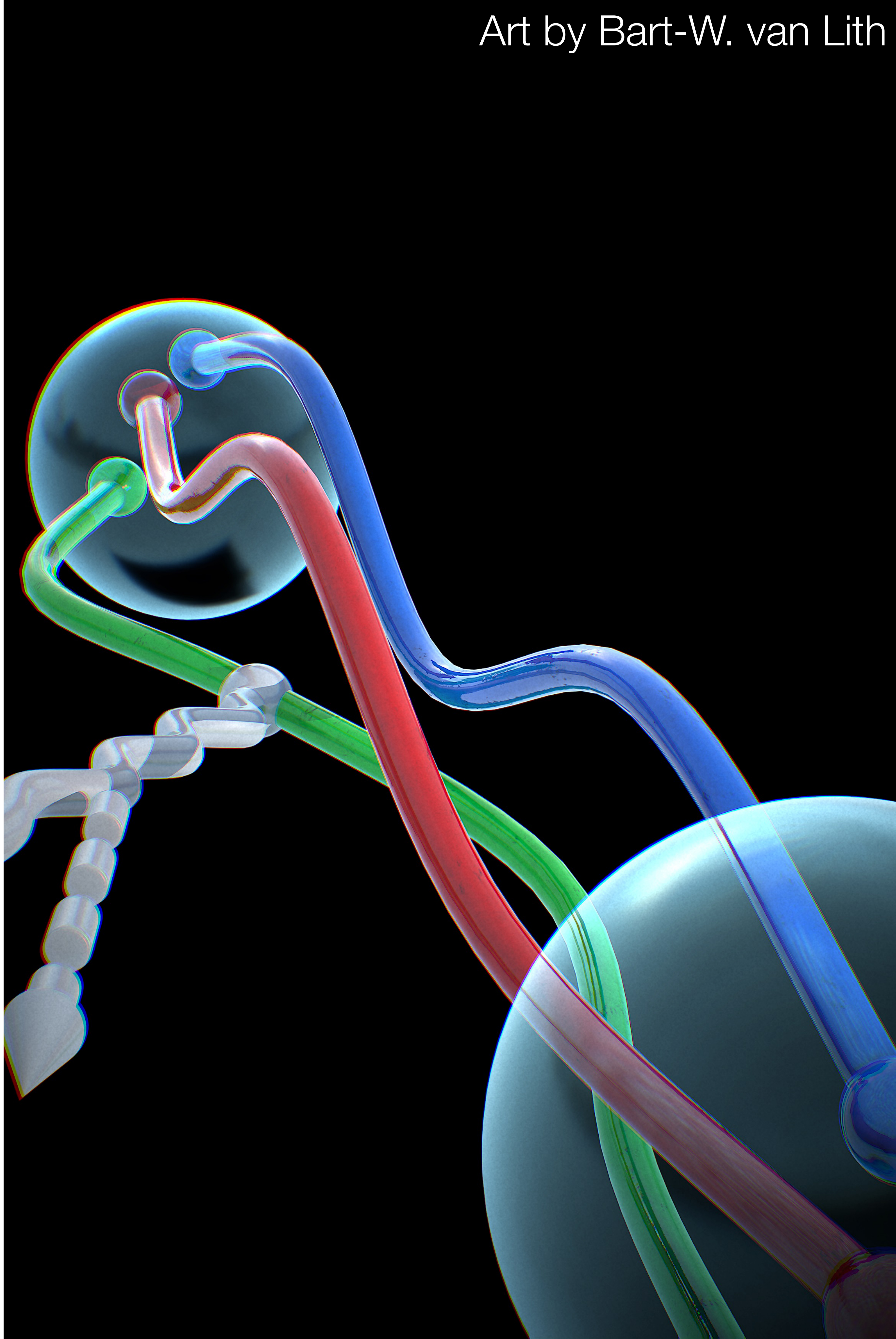

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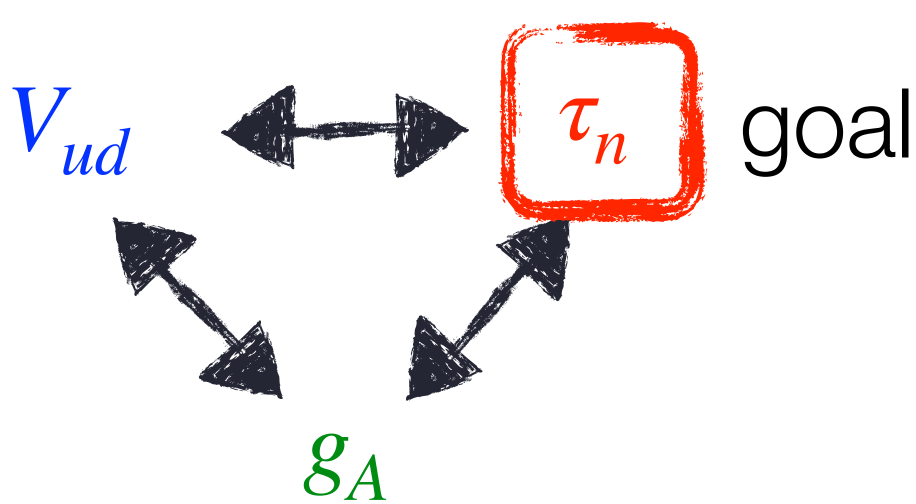

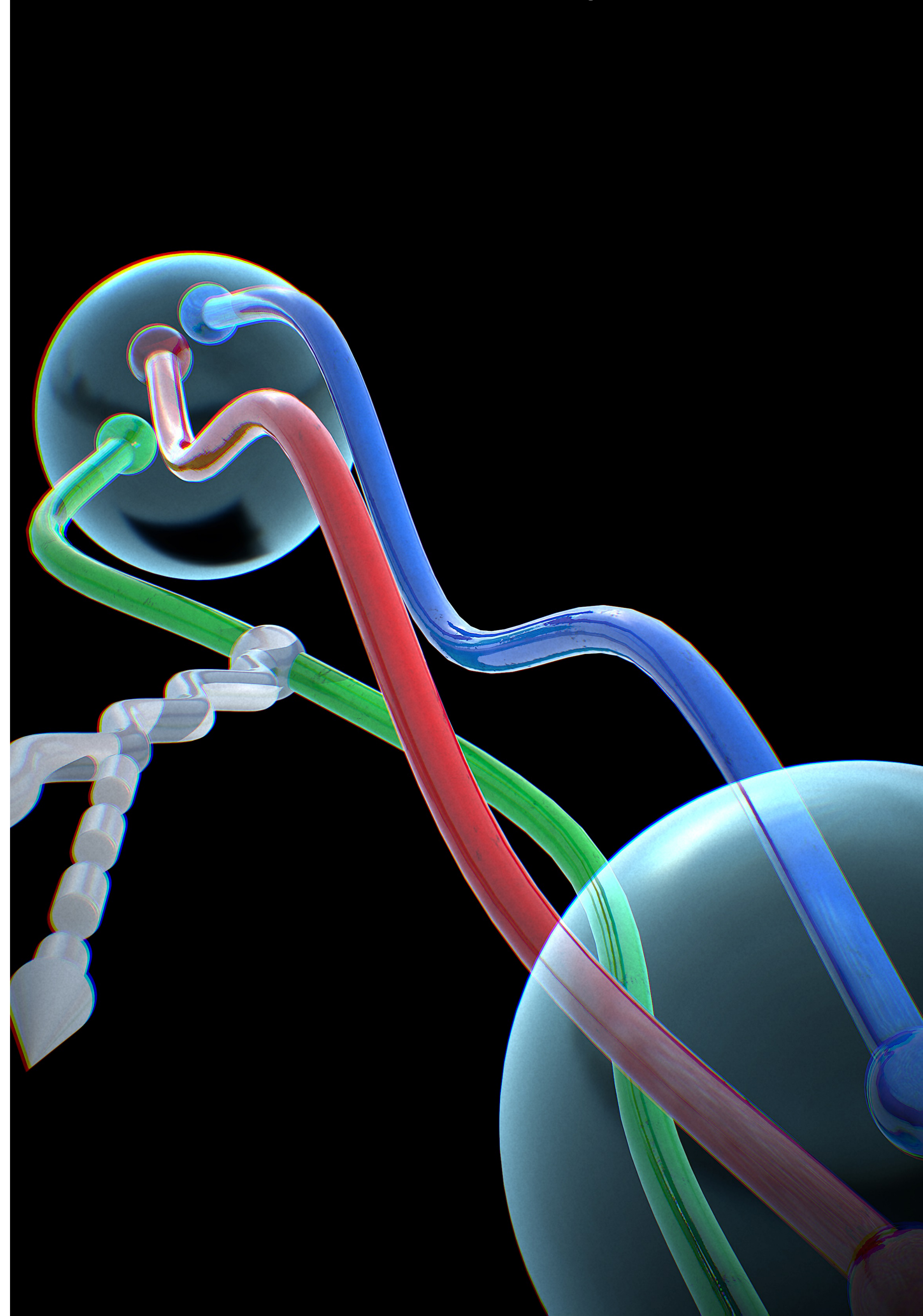
Art by Bart-W. van Lith

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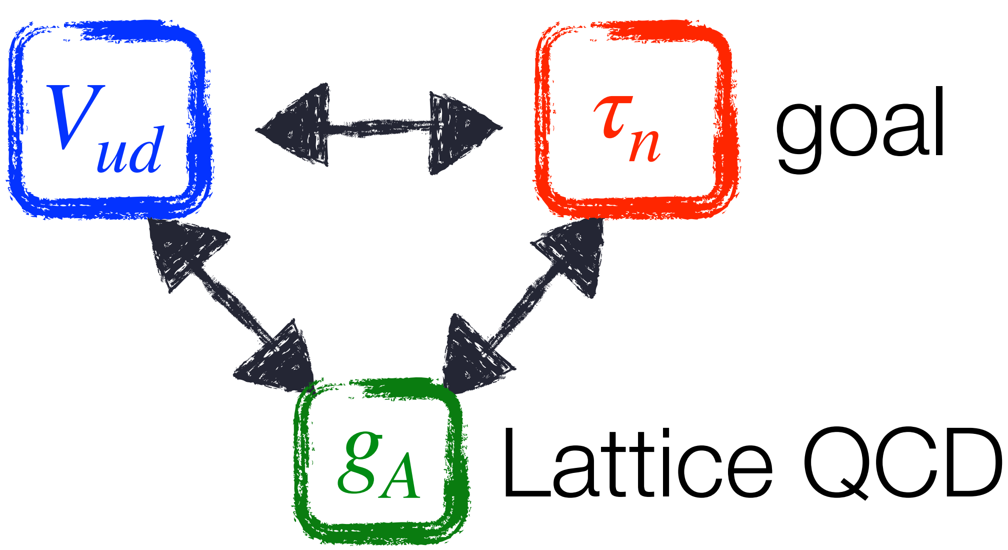

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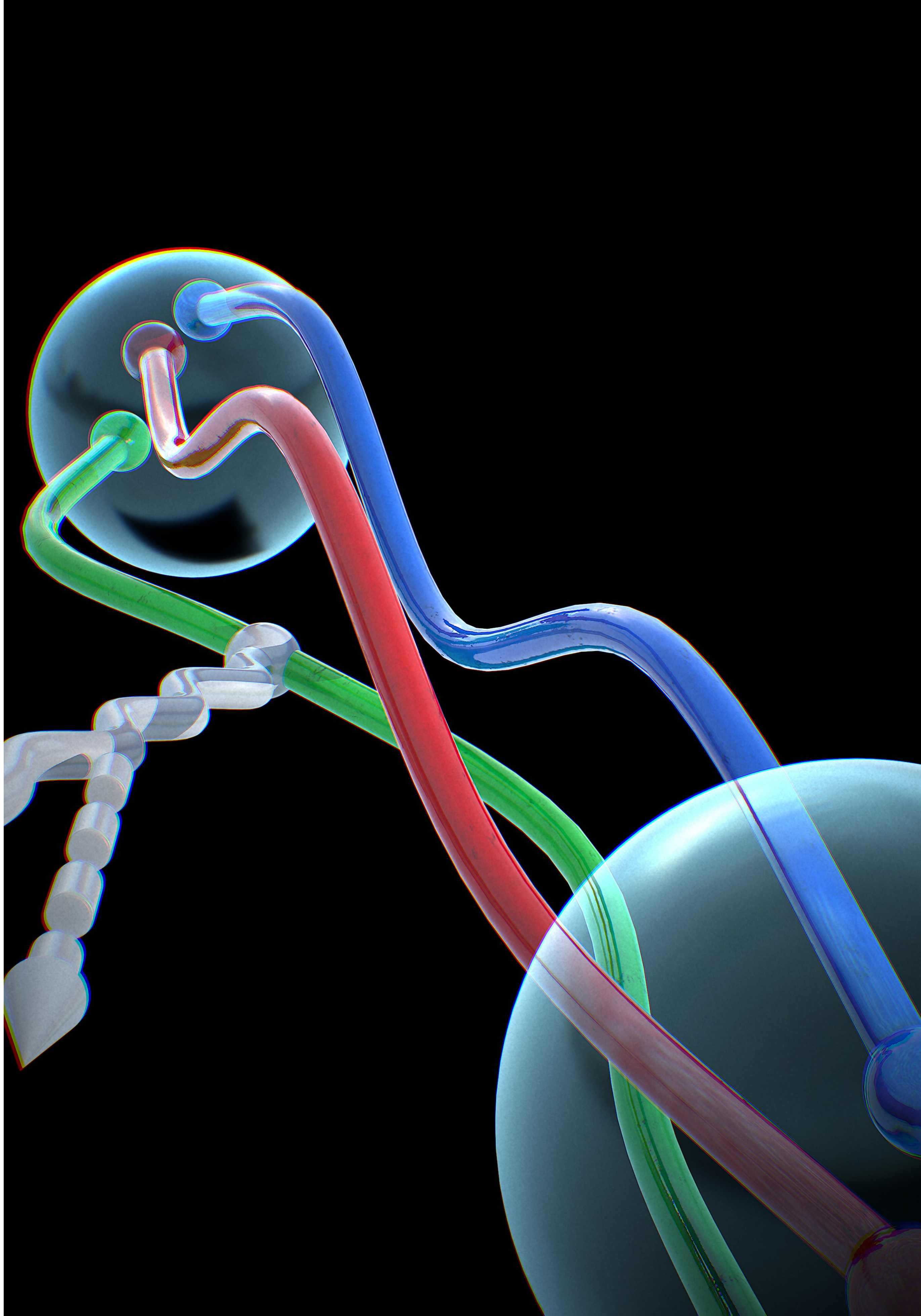

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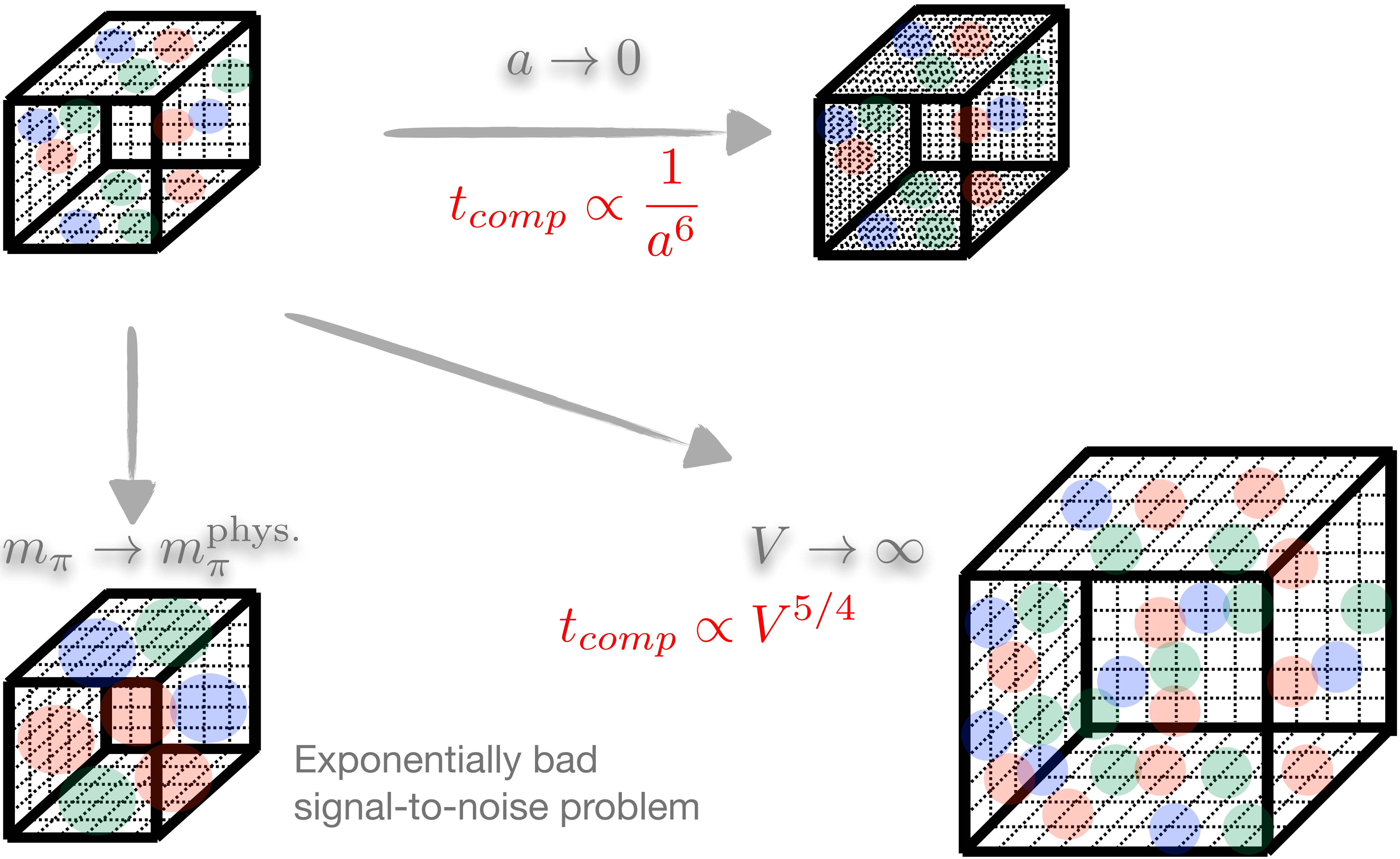
Challenging systematics



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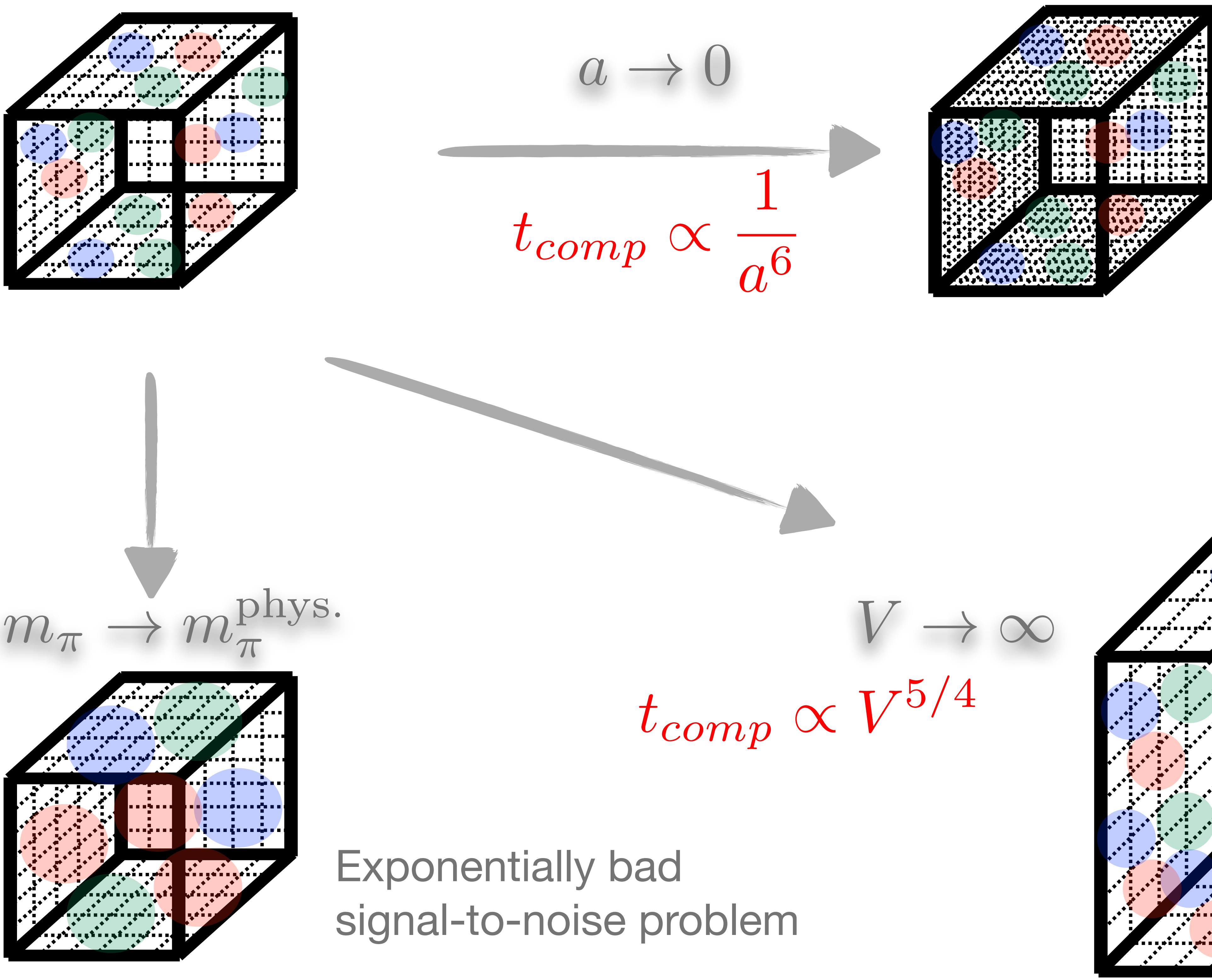

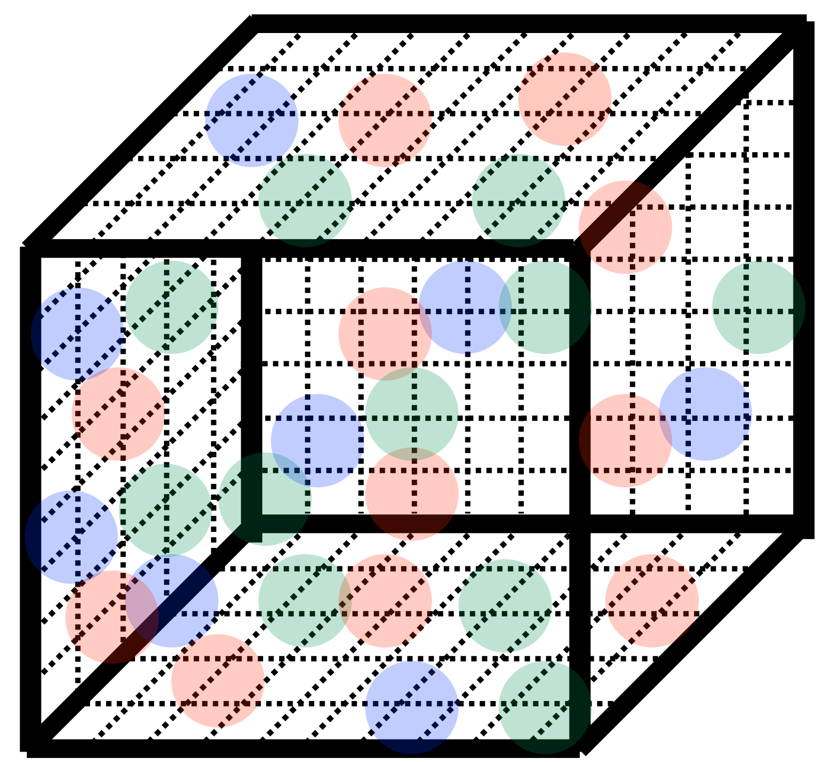

- Complete calculations require multiple “a”, “V” and “m_π”
- Increasing cost requires using “top500” supercomputers

Lattice QCD gauge configurations

HISQ gauge configuration parameters							**valence parameters**							
abbr.	N_{cfg}	volume	$\sim a$ [fm]	m_l/m_s	$\sim m_{\pi_5}$ [MeV]	$\sim m_{\pi_5} L$	N_{src}	L_5/a	aM_5	b_5	c_5	$am_l^{\text{val.}}$	σ_{smr}	N_{smr}
a15m400	1000	$16^3 \times 48$	0.15	0.334	400	4.8	8	12	1.3	1.5	0.5	0.0278	3.0	30
a15m350	1000	$16^3 \times 48$	0.15	0.255	350	4.2	16	12	1.3	1.5	0.5	0.0206	3.0	30
a15m310	1960	$16^3 \times 48$	0.15	0.2	310	3.8	24	12	1.3	1.5	0.5	0.01580	4.2	60
a15m220	1000	$24^3 \times 48$	0.15	0.1	220	4.0	12	16	1.3	1.75	0.75	0.00712	4.5	60
a15m130	1000	$32^3 \times 48$	0.15	0.036	130	3.2	5	24	1.3	2.25	1.25	0.00216	4.5	60
a12m400	1000	$24^3 \times 64$	0.12	0.334	400	5.8	8	8	1.2	1.25	0.25	0.02190	3.0	30
a12m350	1000	$24^3 \times 64$	0.12	0.255	350	5.1	8	8	1.2	1.25	0.25	0.01660	3.0	30
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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
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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
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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

[CalLat Nature 558, 91-94 (2018), arxiv:1805.12130]

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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

$$a \to 0 \qquad V \to \infty$$

$$m_\pi \to m_\pi^{\text{phys.}}$$

Lattice QCD gauge configurations

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	$am_l^{val.}$	σ_{smr}	N_{smr}
a15m400	1000	$16^3 \times 48$	0.15	0.334	400	4.8	8	12	1.3	1.5	0.5	0.0278	3.0	30
a15m350	1000	$16^3 \times 48$	0.15	0.255	350	4.2	16	12	1.3	1.5	0.5	0.0206	3.0	30
a15m310	1960	$16^3 \times 48$	0.15	0.2	310	3.8	24	12	1.3	1.5	0.5	0.01580	4.2	60
a15m220	1000	$24^3 \times 48$	0.15	0.1	220	4.0	12	16	1.3	1.75	0.75	0.00712	4.5	60
a15m130	1000	$32^3 \times 48$	0.15	0.036	130	3.2	5	24	1.3	2.25	1.25	0.00216	4.5	60
a12m400	1000	$24^3 \times 64$	0.12	0.334	400	5.8	8	8	1.2	1.25	0.25	0.02190	3.0	30
a12m350	1000	$24^3 \times 64$	0.12	0.255	350	5.1	8	8	1.2	1.25	0.25	0.01660	3.0	30
a12m310	1053	$24^3 \times 64$	0.12	0.2	310	4.5	8	8	1.2	1.25	0.25	0.01260	3.0	30
a12m220S	1000	$24^3 \times 64$	0.12	0.1	220	3.2	4	12	1.2	1.5	0.5	0.00600	6.0	90
a12m220	1000	$32^3 \times 64$	0.12	0.1	220	4.3	4	12	1.2	1.5	0.5	0.00600	6.0	90
a12m220L	1000	$40^3 \times 64$	0.12	0.1	220	5.4	4	12	1.2	1.5	0.5	0.00600	6.0	90
a12m130	1000	$48^3 \times 64$	0.12	0.036	130	3.9	3	20	1.2	2.0	1.0	0.00195	7.0	150
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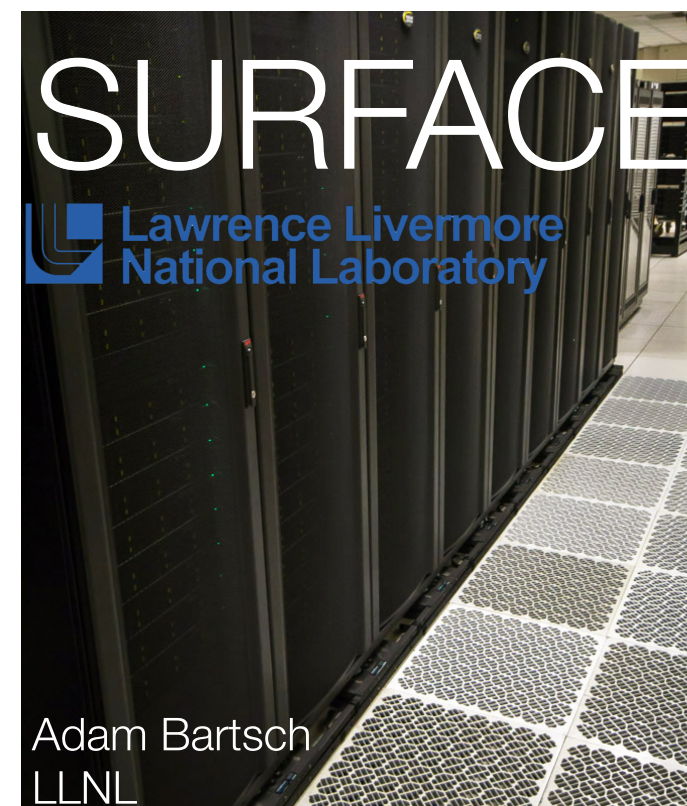
a09m220	1001	$48^3 \times 96$	0.09	0.1	220	4.7	6	8	1.1	1.25	0.25	0.00449	8.0	150

- ★ 16 ensembles with N_f=2+1+1 Highly Improved Staggered Quarks (HISQ)
- ★ 5 pion masses, 3 lattice spacings, multiple volumes
- ★ High statistics ensembles, publicly available



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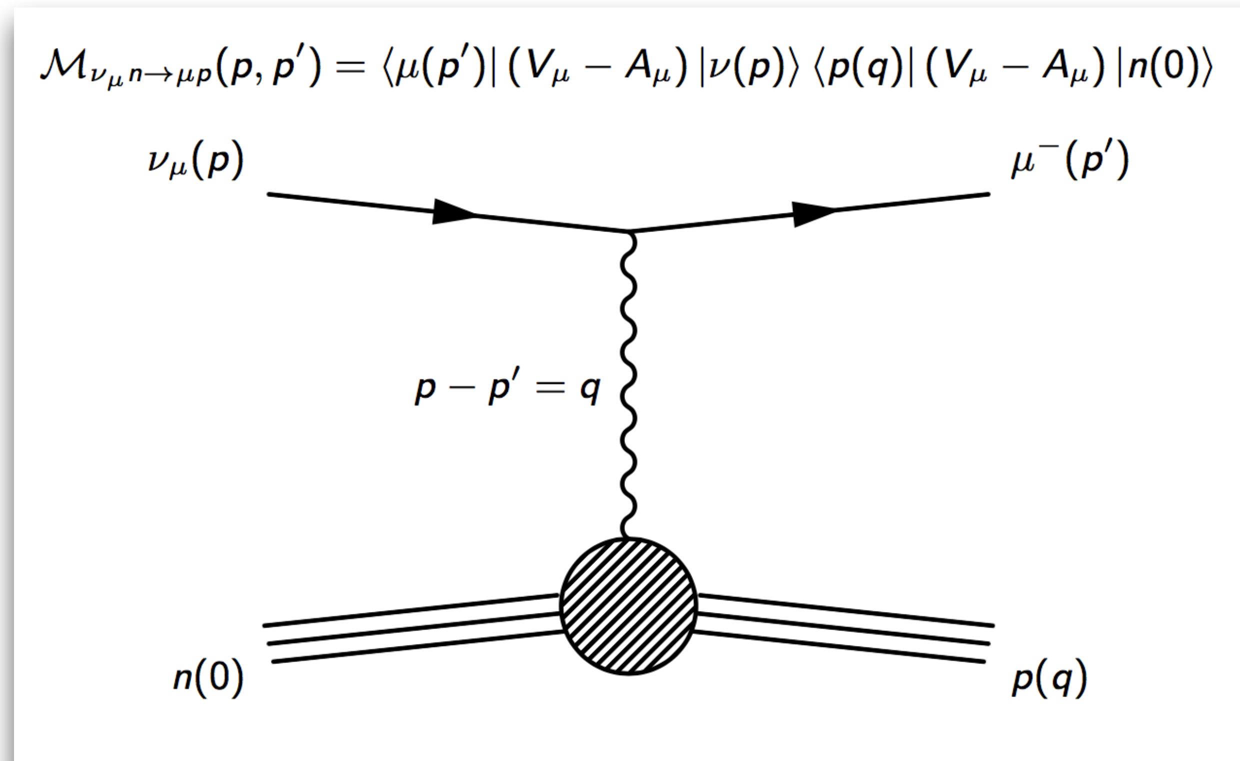
U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING

SciDAC Scientific Discovery through Advanced Computing

g_A from LQCD

g_A from LQCD

- **Matrix element** of the axial current between nucleon ground states



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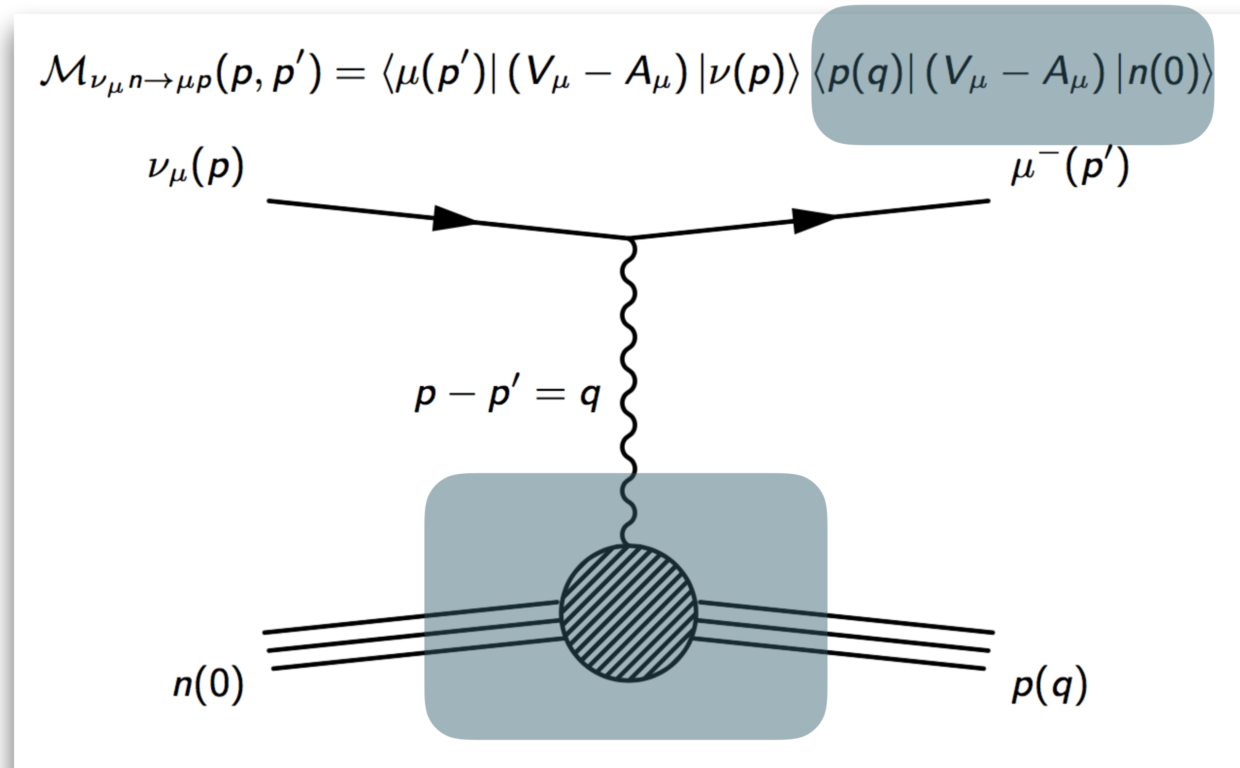

g_A from LQCD

$$\langle 0|N(t)A_\mu(\tau)N(t')|0\rangle$$

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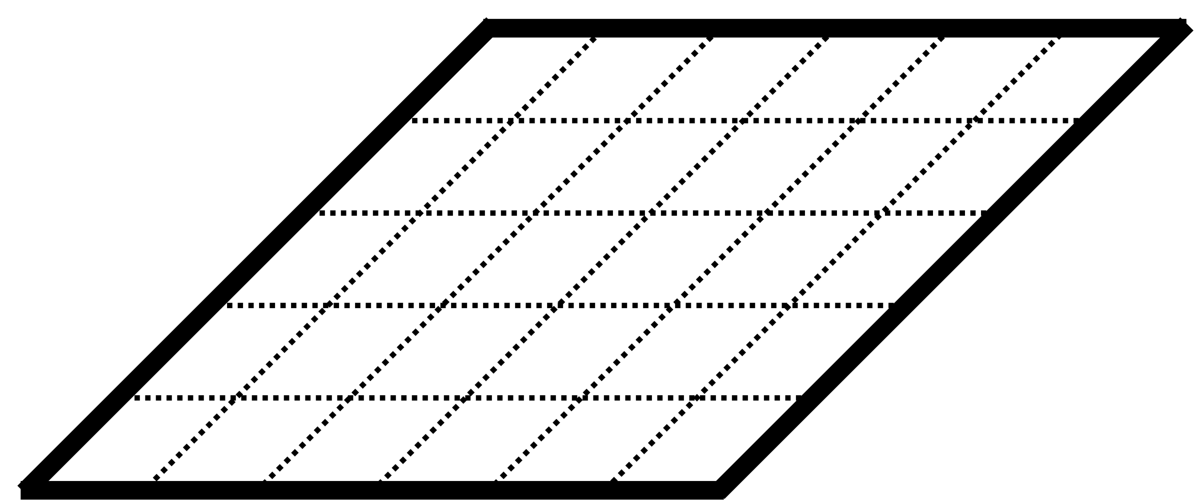
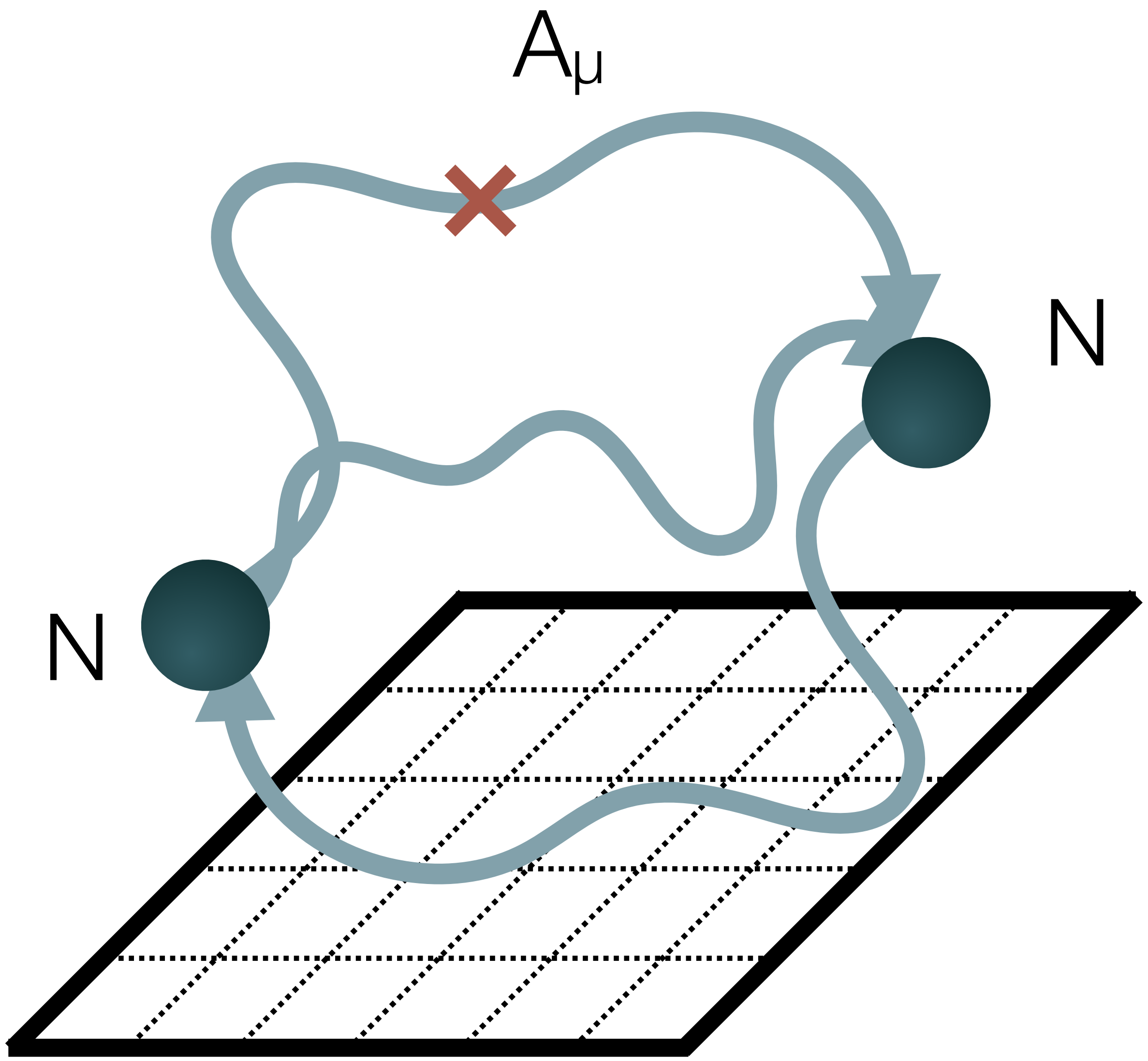


g_A from LQCD

$$\langle 0|N(t)A_\mu(\tau)N(t')|0\rangle$$

- Matrix element of the axial current between nucleon ground states
- Calculate a 3-point correlation function:

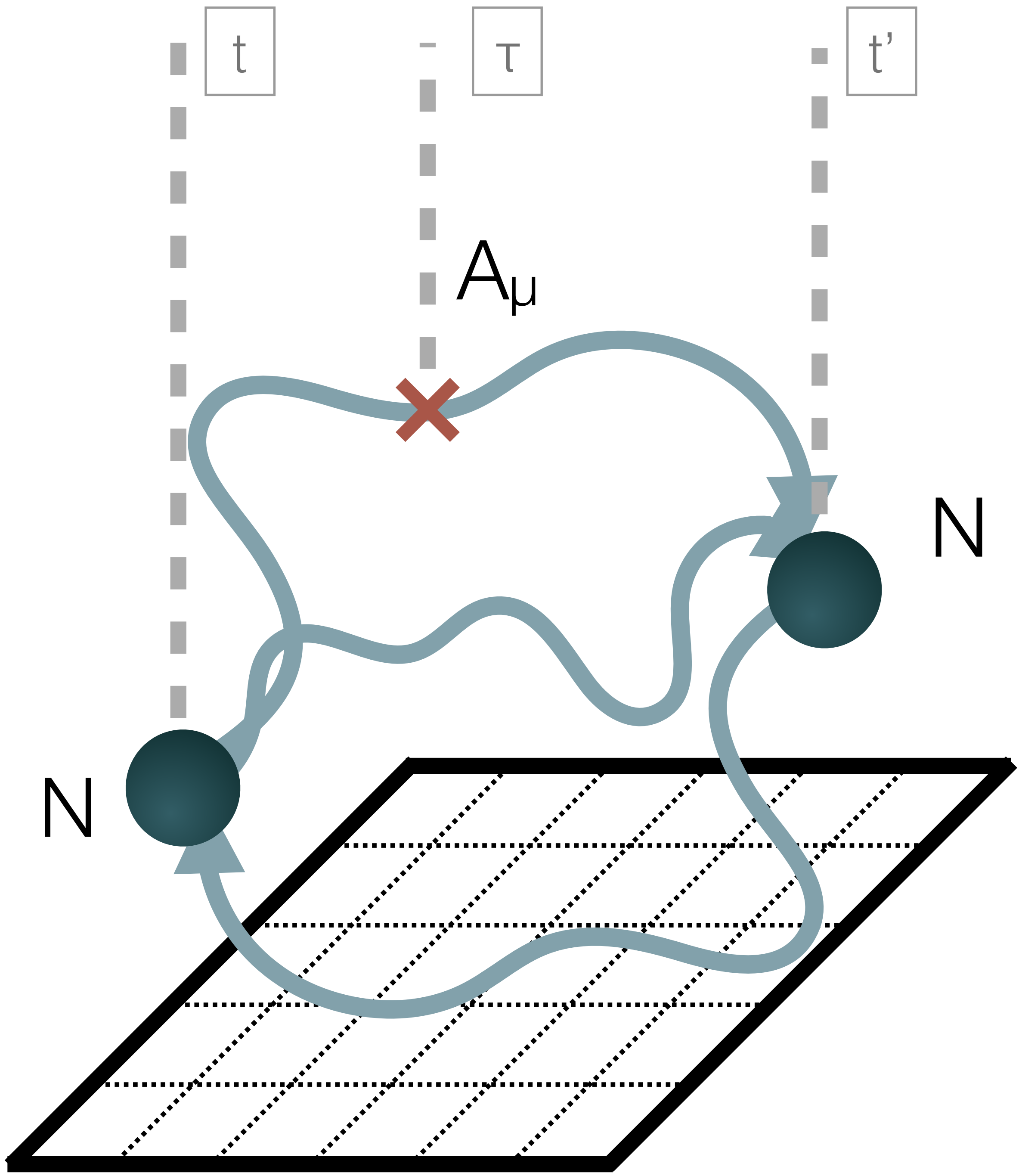


g_A from LQCD

- Matrix element of the axial current between nucleon ground states
- Calculate a 3-point correlation function:
  - 2 independent time variables

$$(t_{\text{sep}} = t' - t,\ \tau)$$

$$\langle 0 | N(t) A_\mu(\tau) N(t') | 0 \rangle$$



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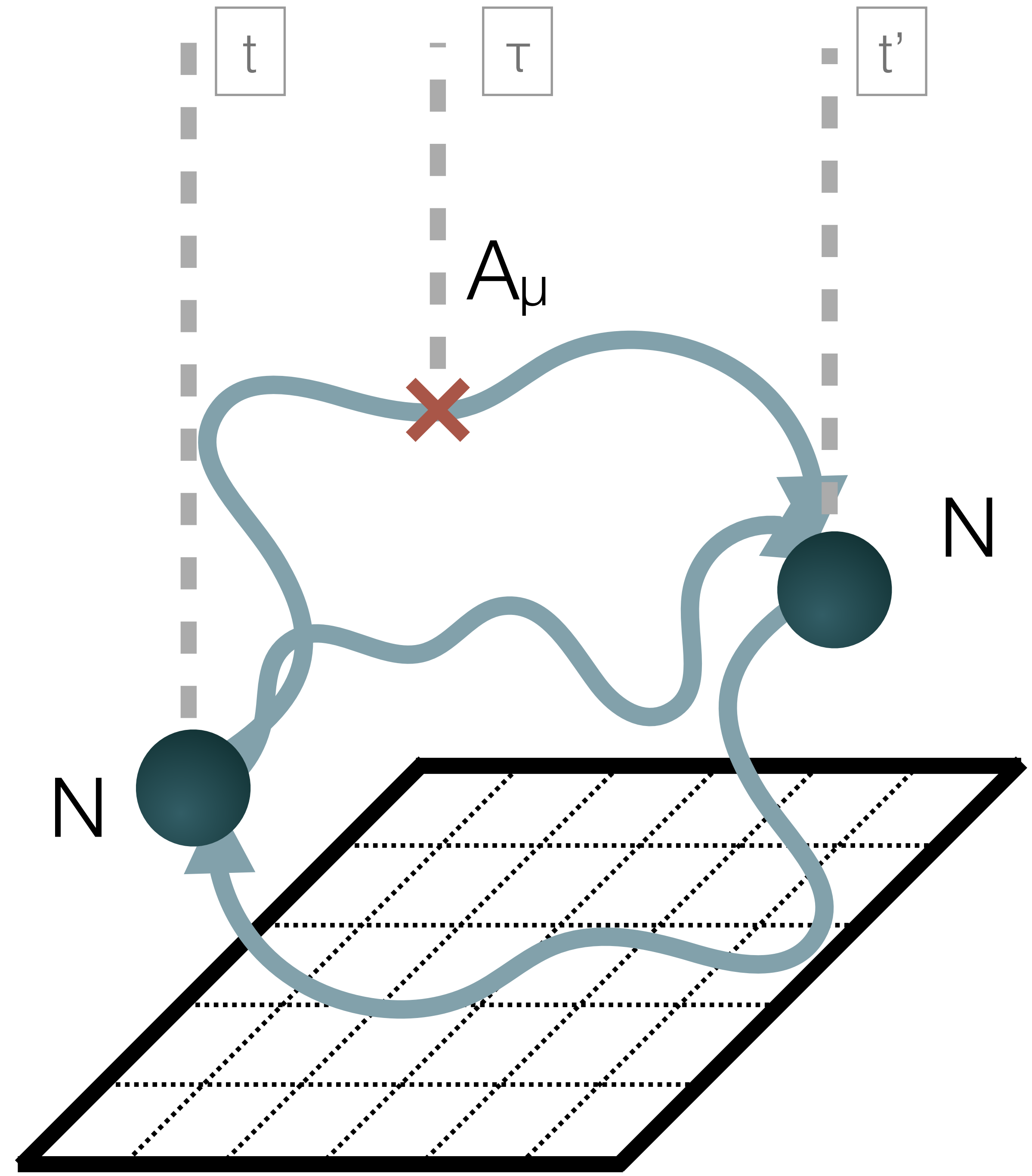
- **Matrix element** of the axial current between nucleon ground states
- Calculate a **3-point correlation function**:
  - 2 independent time variables
    $$(t_{\text{sep}} = t' - t,\ \tau)$$
  - Statistical noise increases *rapidly* with t_{sep}

$$\langle 0|N(t)A_\mu(\tau)N(t')|0\rangle$$



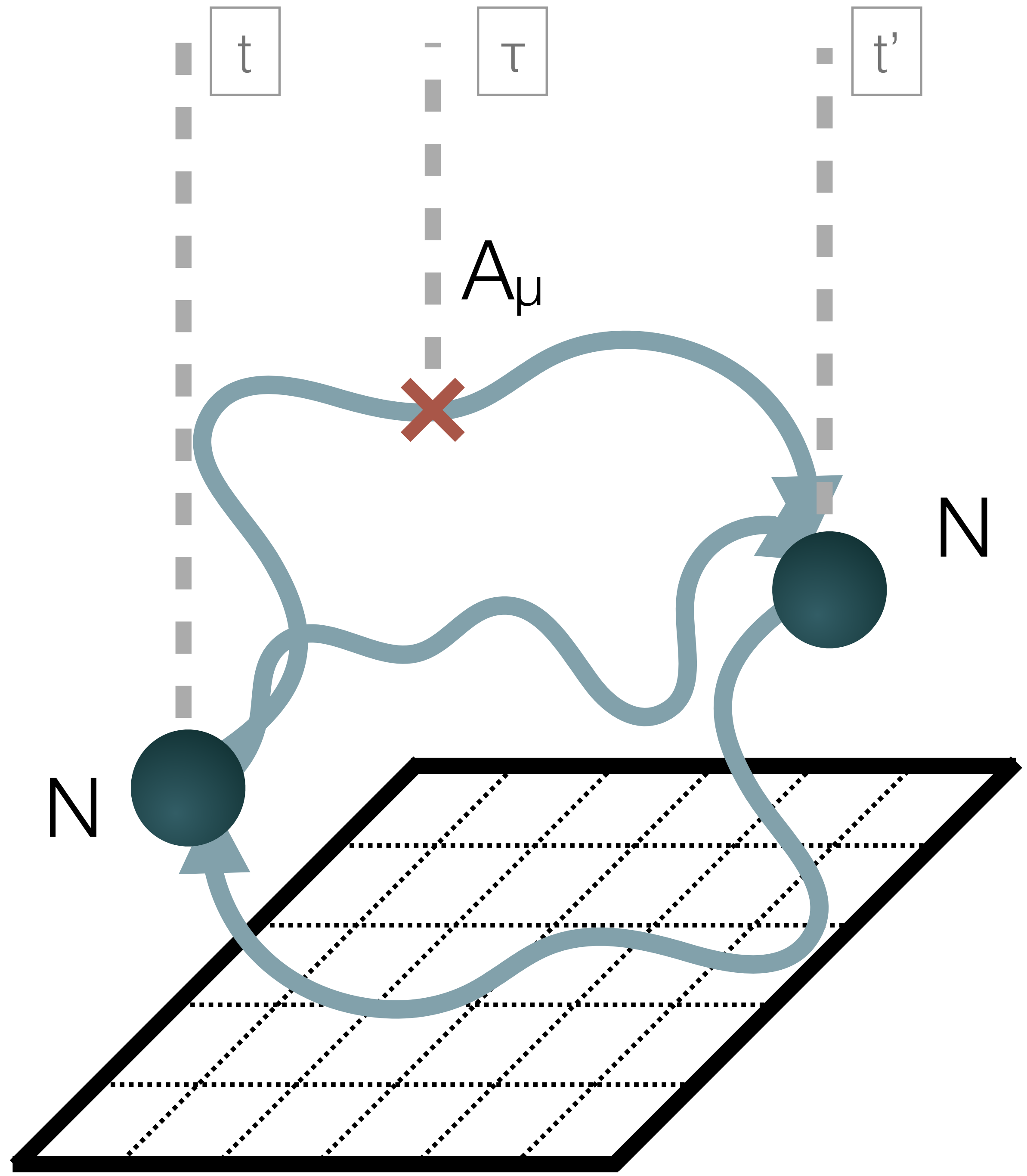
g_A from LQCD

- Matrix element of the axial current between nucleon ground states
- Calculate a 3-point correlation function:
  - 2 independent time variables

    $$(t_{\text{sep}} = t' - t,\ \tau)$$

  - Statistical noise increases *rapidly* with t_{sep}
- Excited states contributions disappear at large (t_{sep},τ)

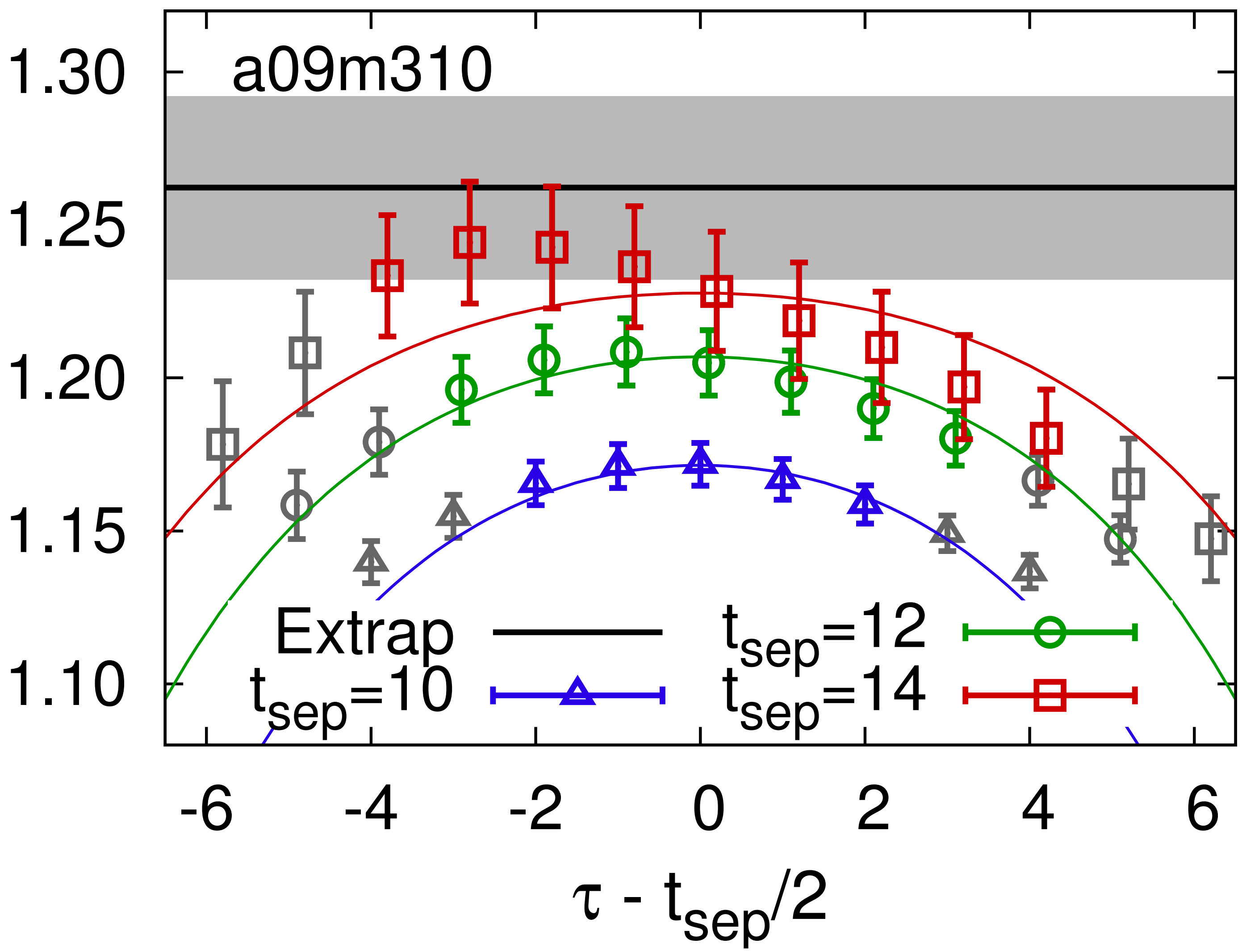
$$\langle 0 | N(t) A_\mu(\tau) N(t') | 0 \rangle$$



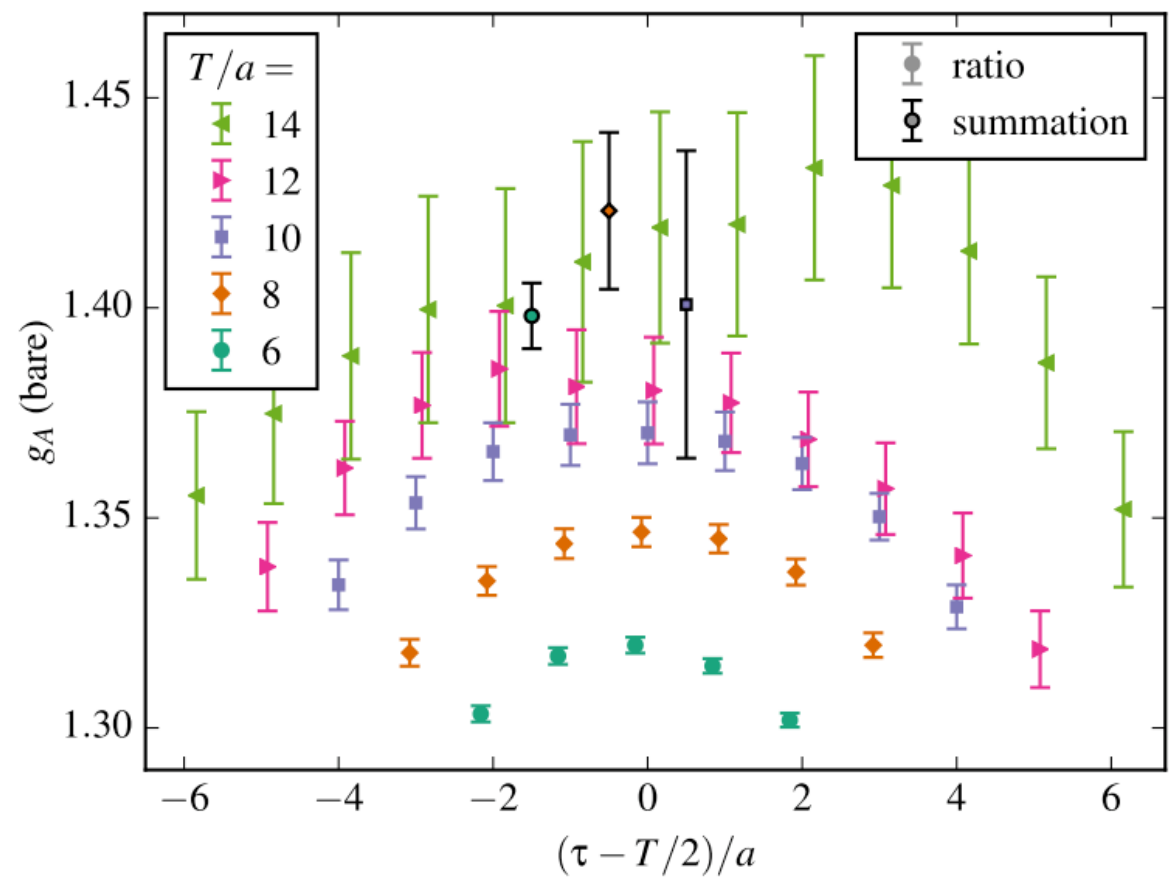
Example of excited states contaminations

Different lattice discretizations and gauge configurations

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



[LHPC arXiv:1703.06703]



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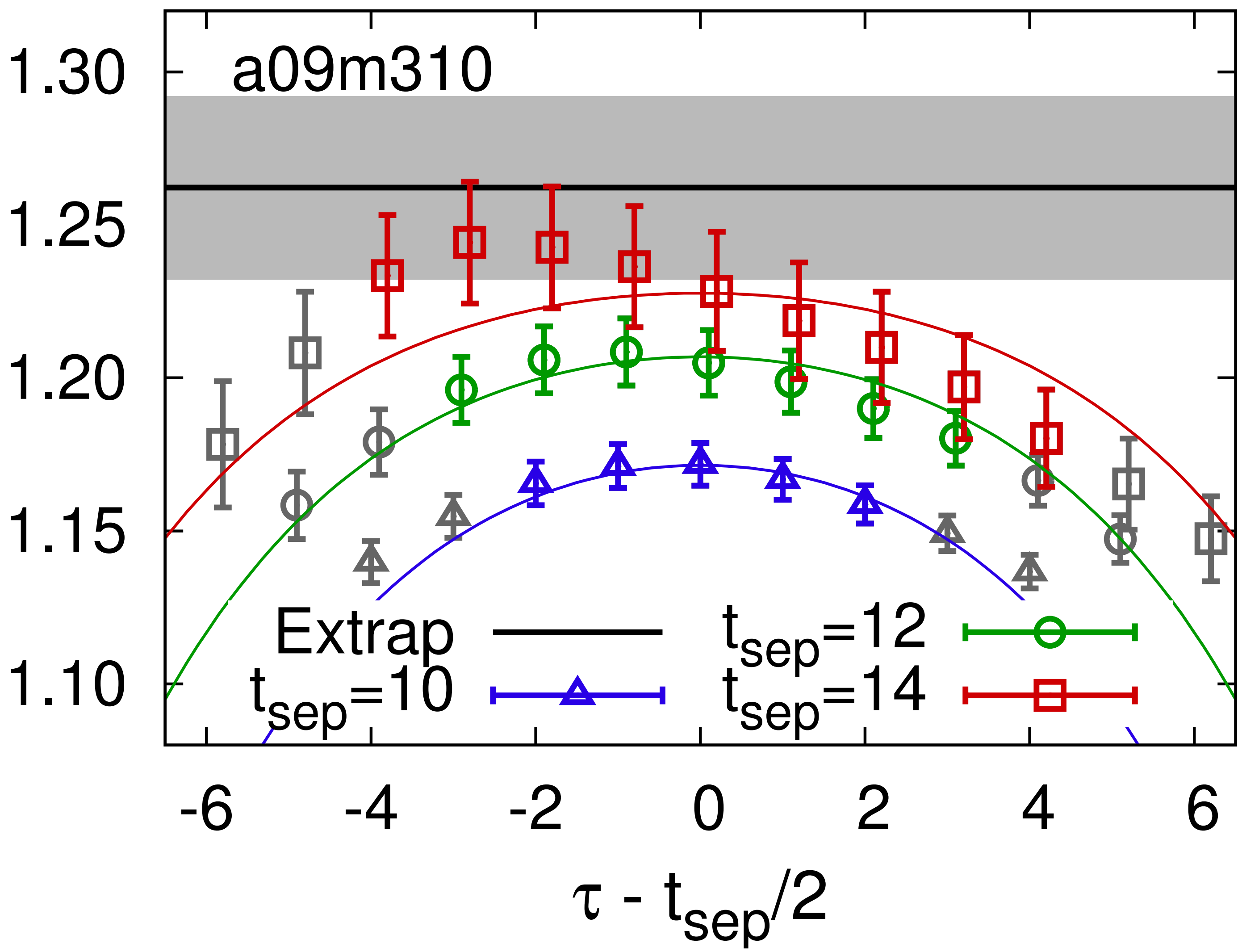

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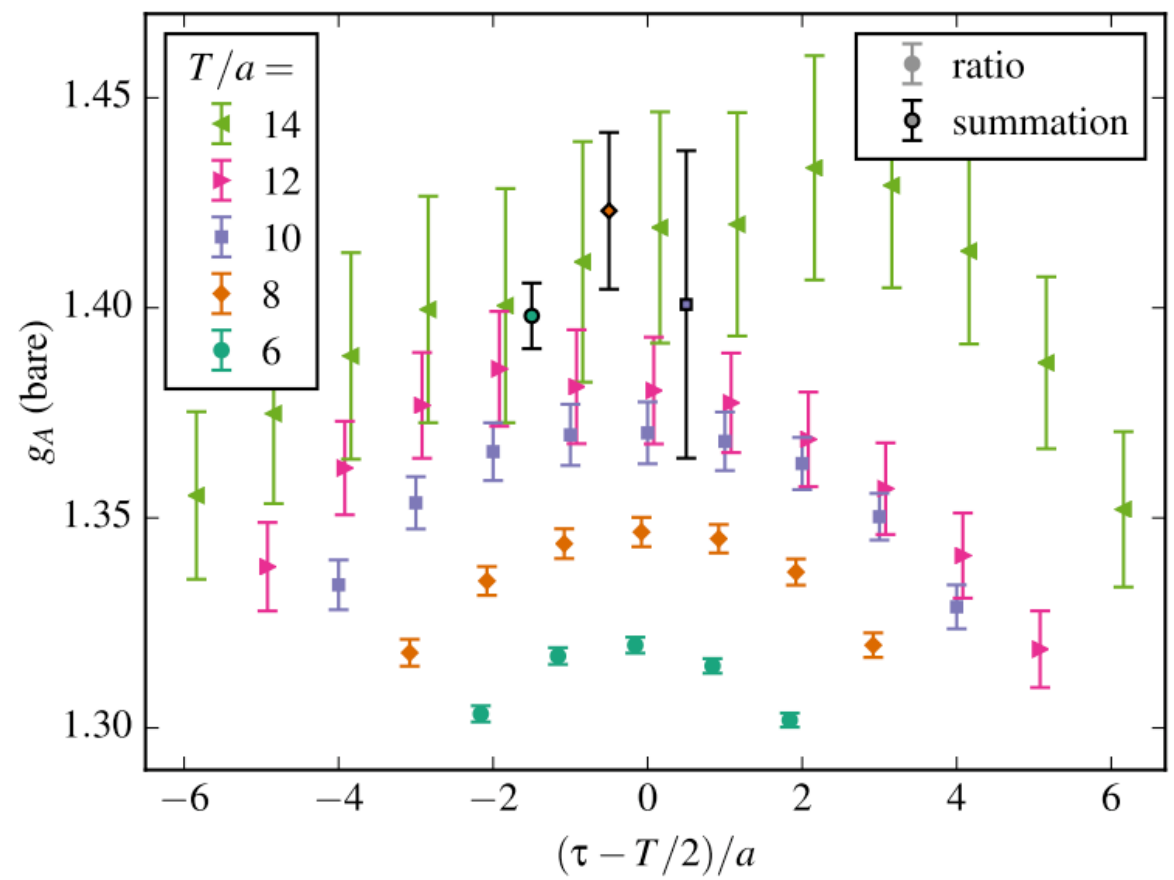

Should have a plateau at each t_{sep} if no exc. states

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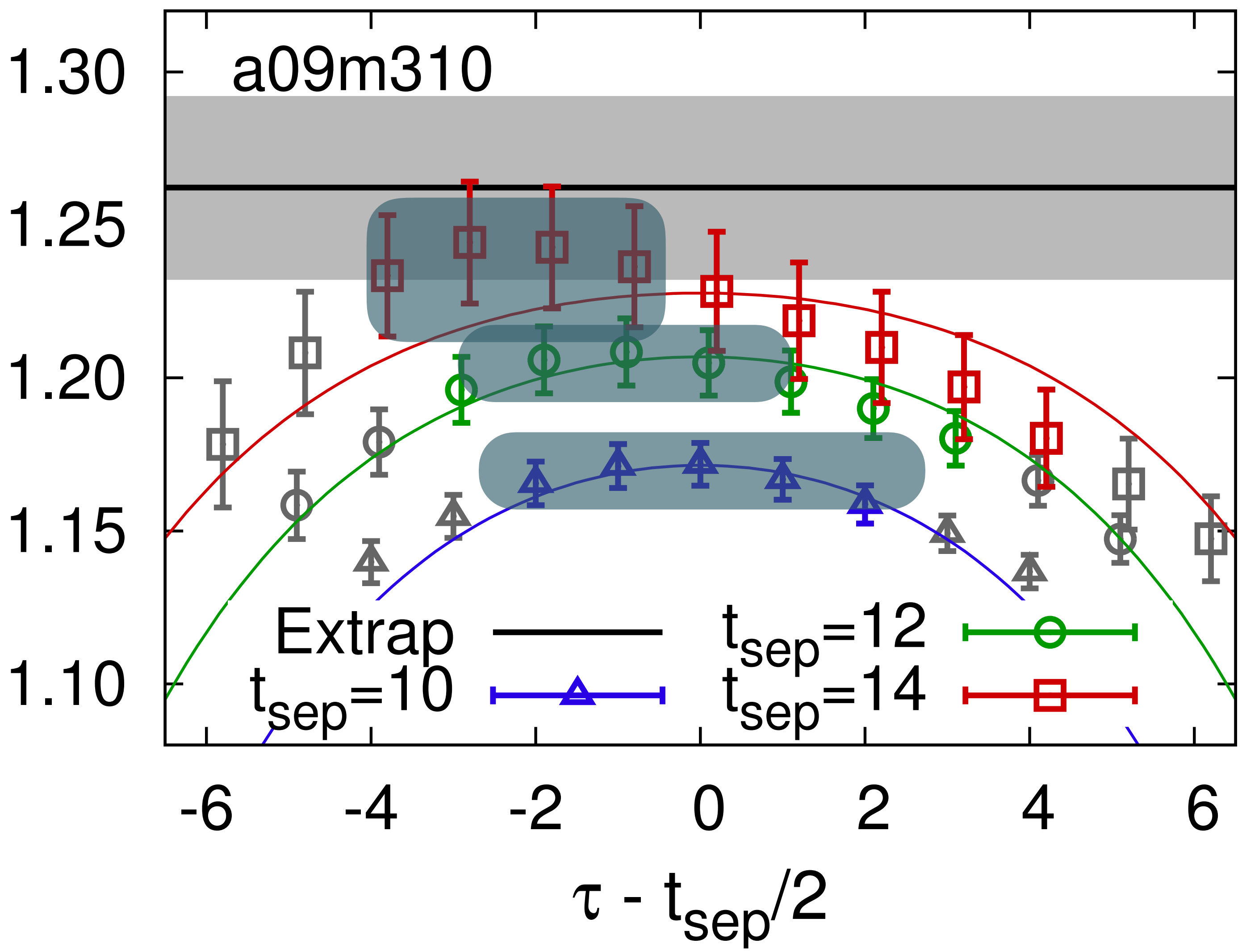

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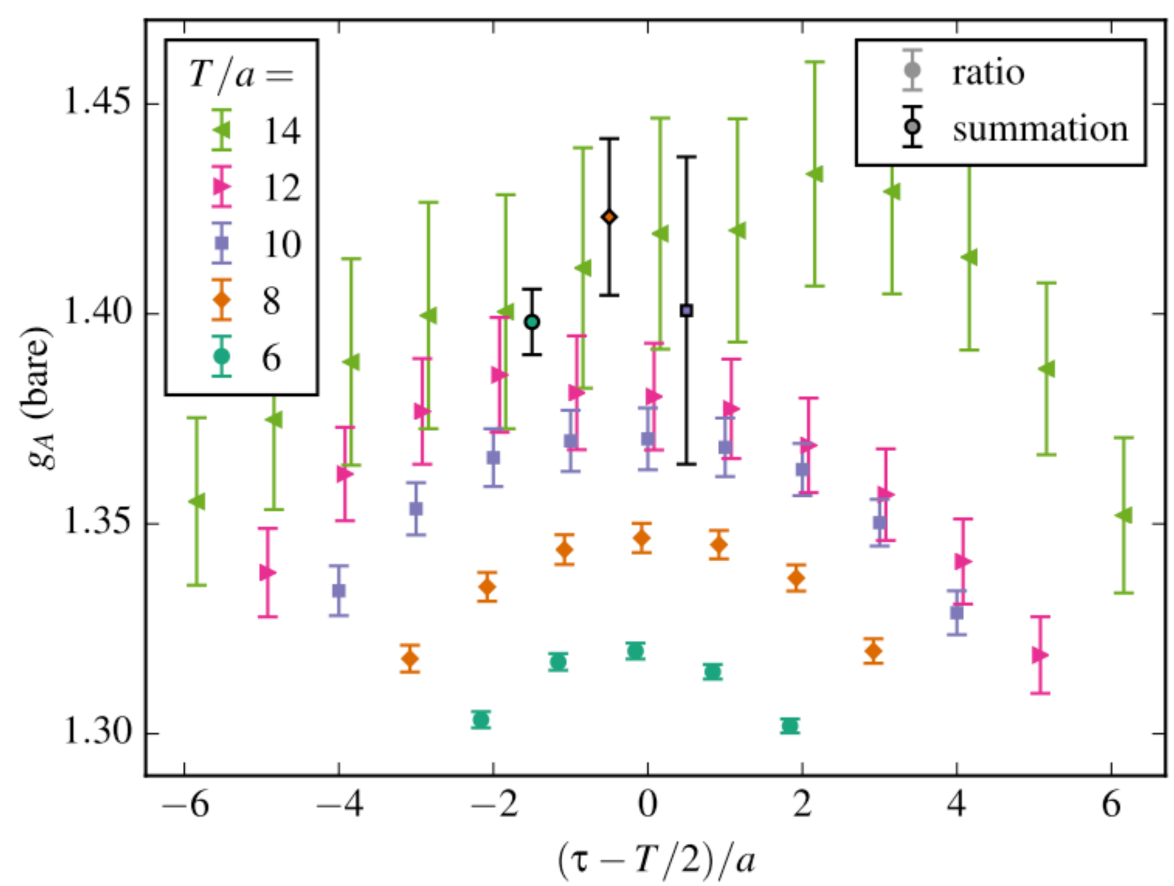

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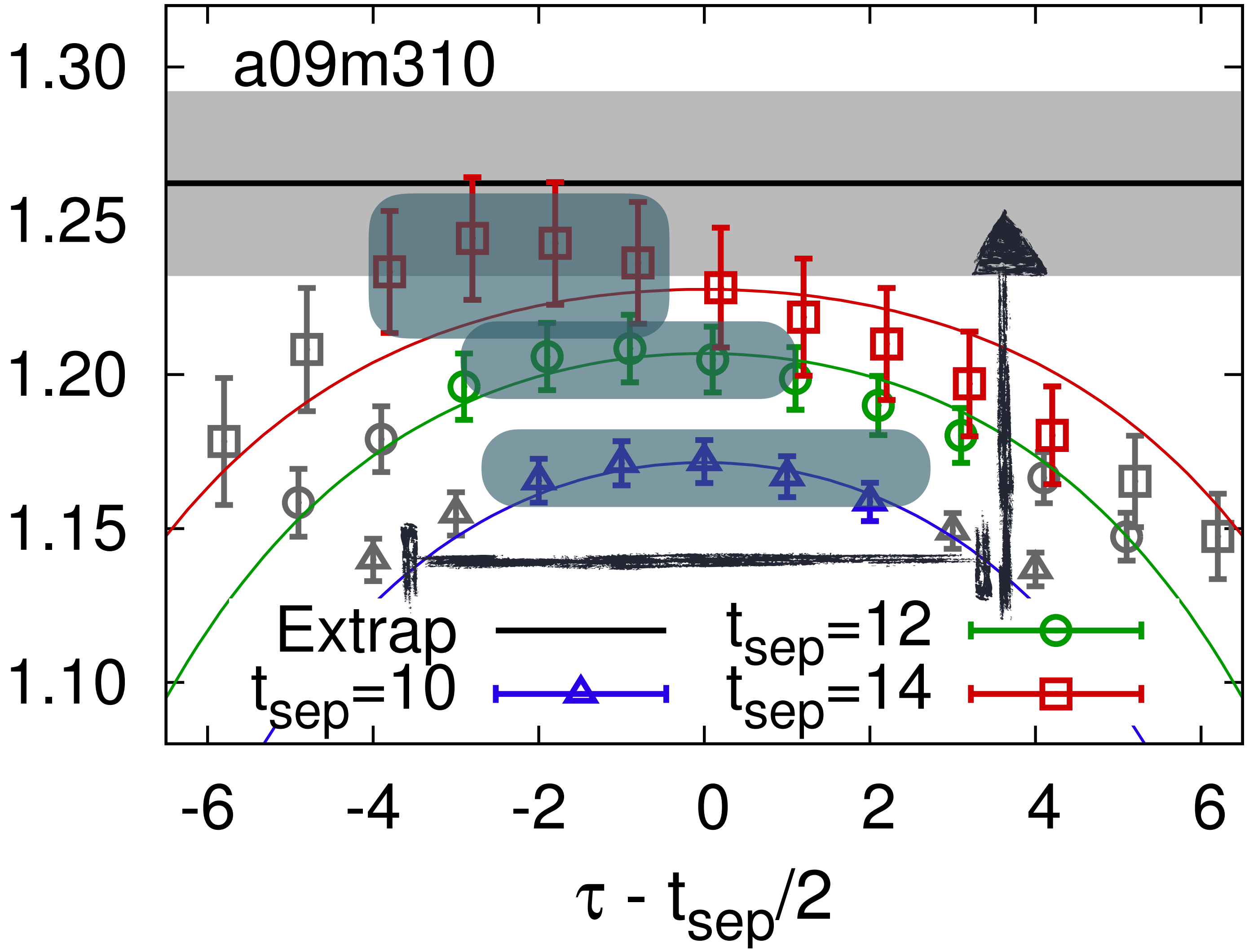

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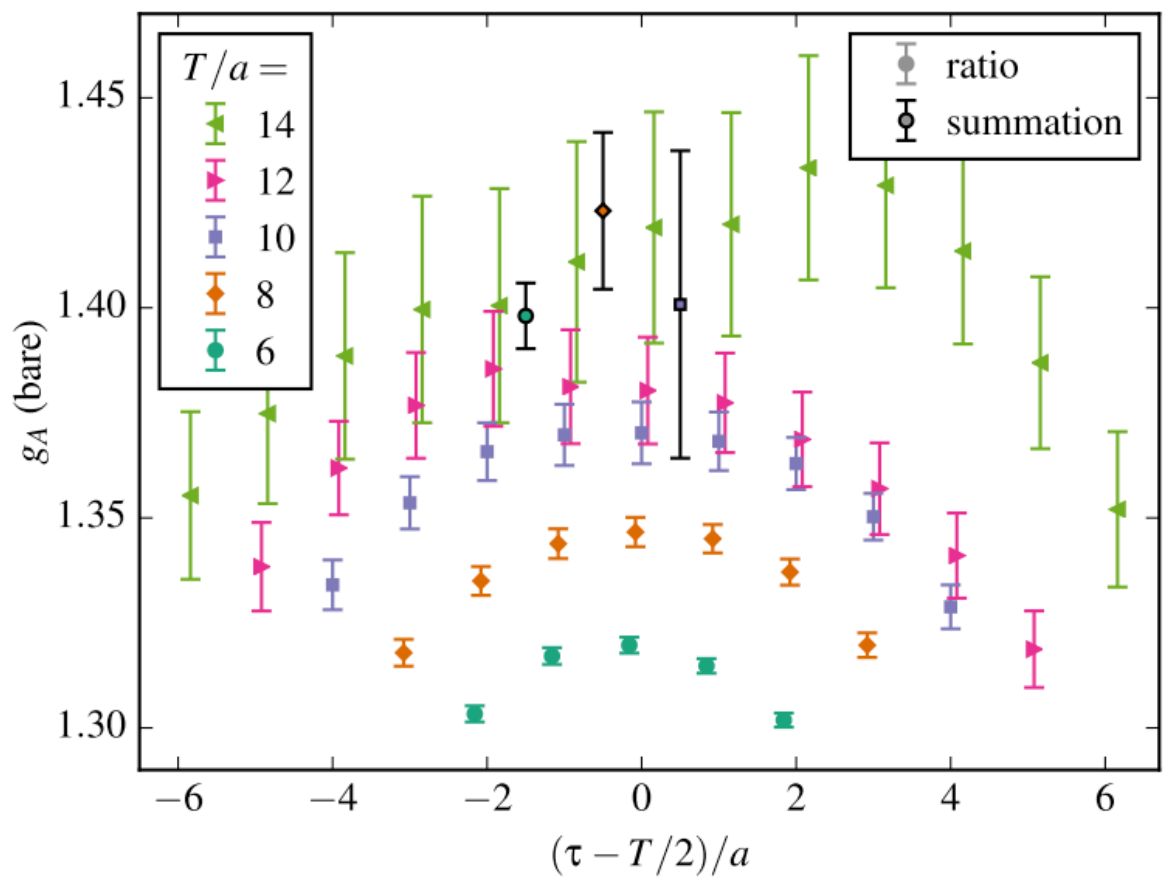
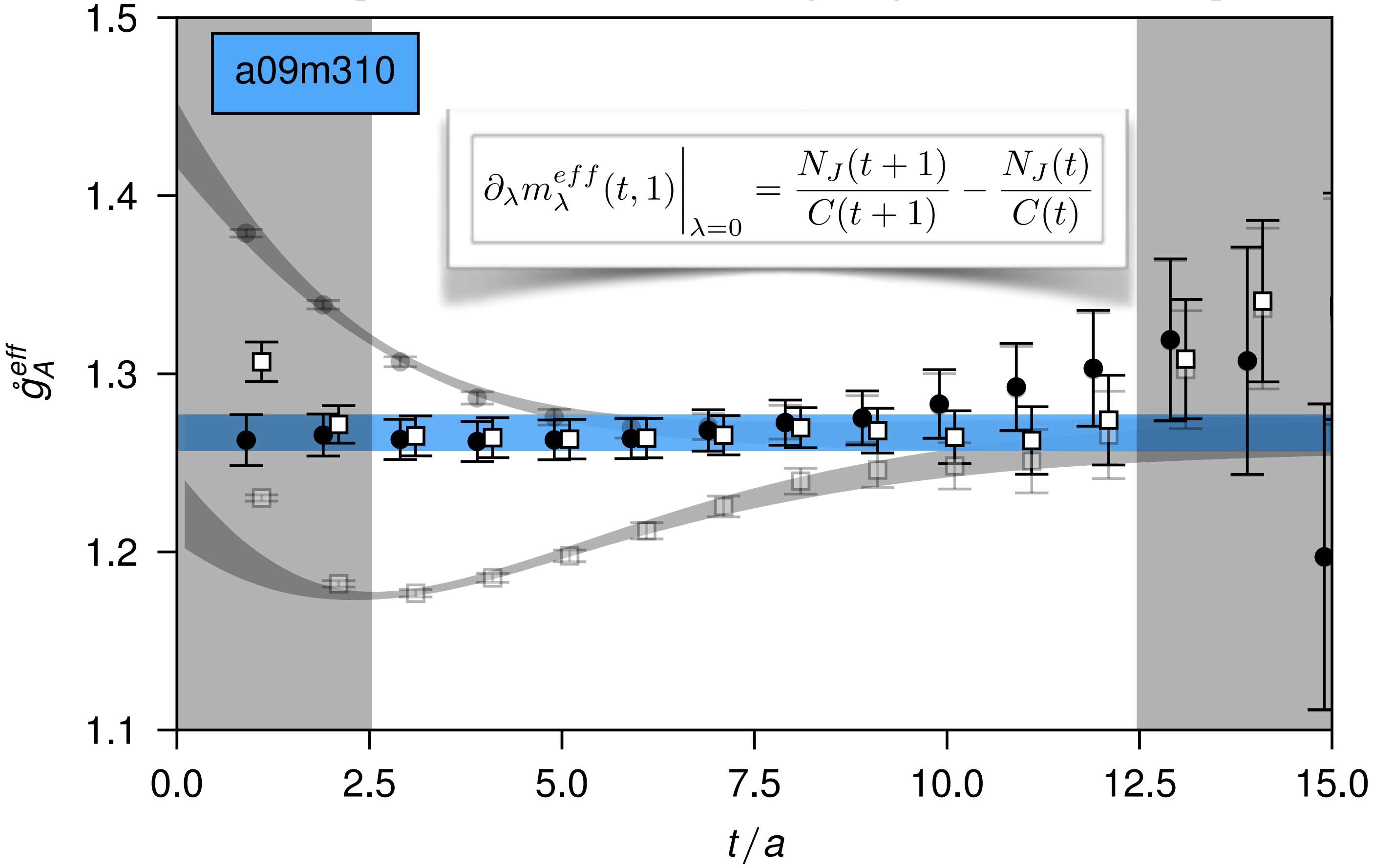


Need to fit in 2 variables: increased systematics

Should have a plateau at each t_{sep} if no exc. states

Improved method to reduce excited states

[CalLat Nature 558, 91-94 (2018), arxiv:1805.12130]



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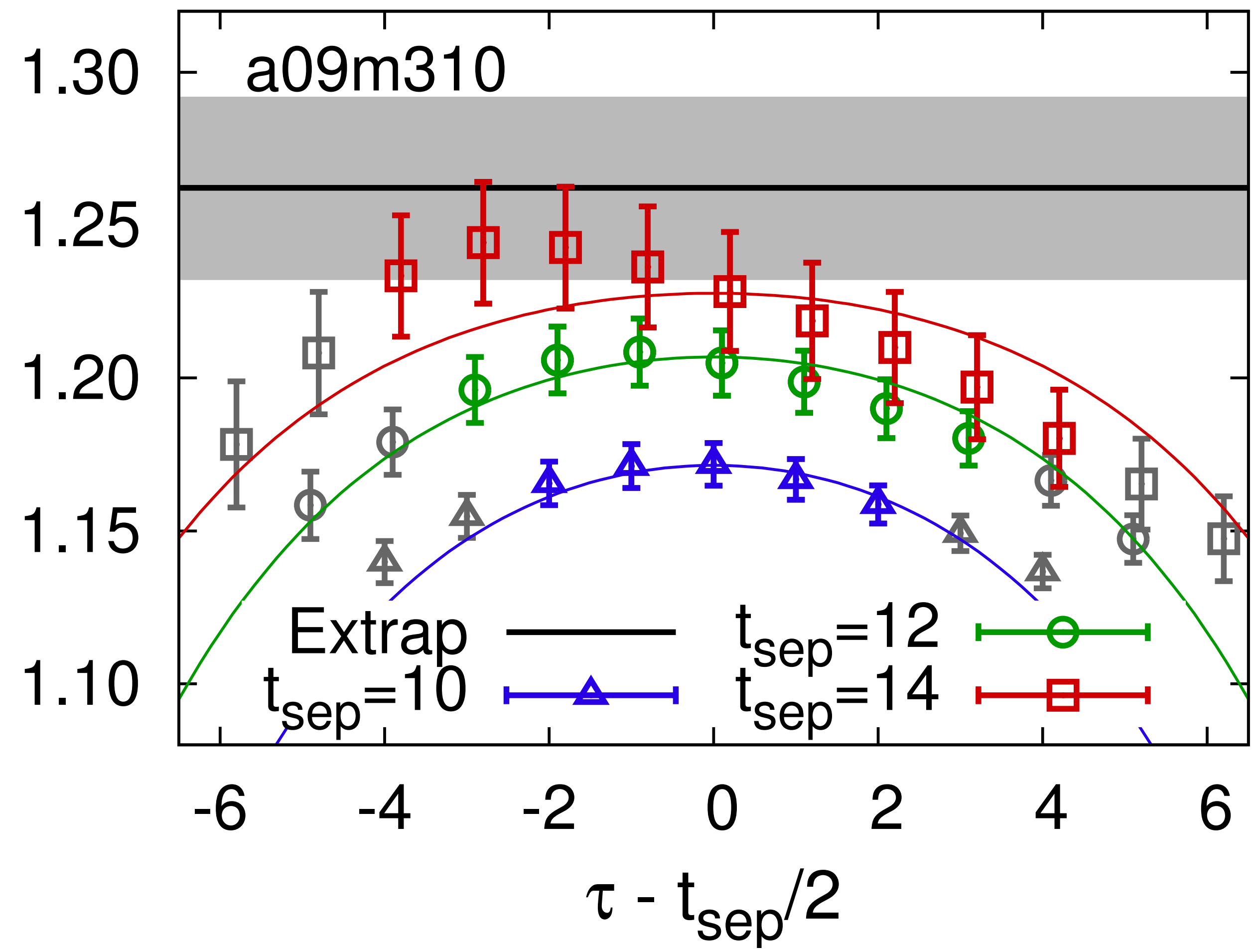

[Bouchard, Chang, Kurt, Orginos, Walker-Loud, PRD96(014504) - arxiv:1612.06963]

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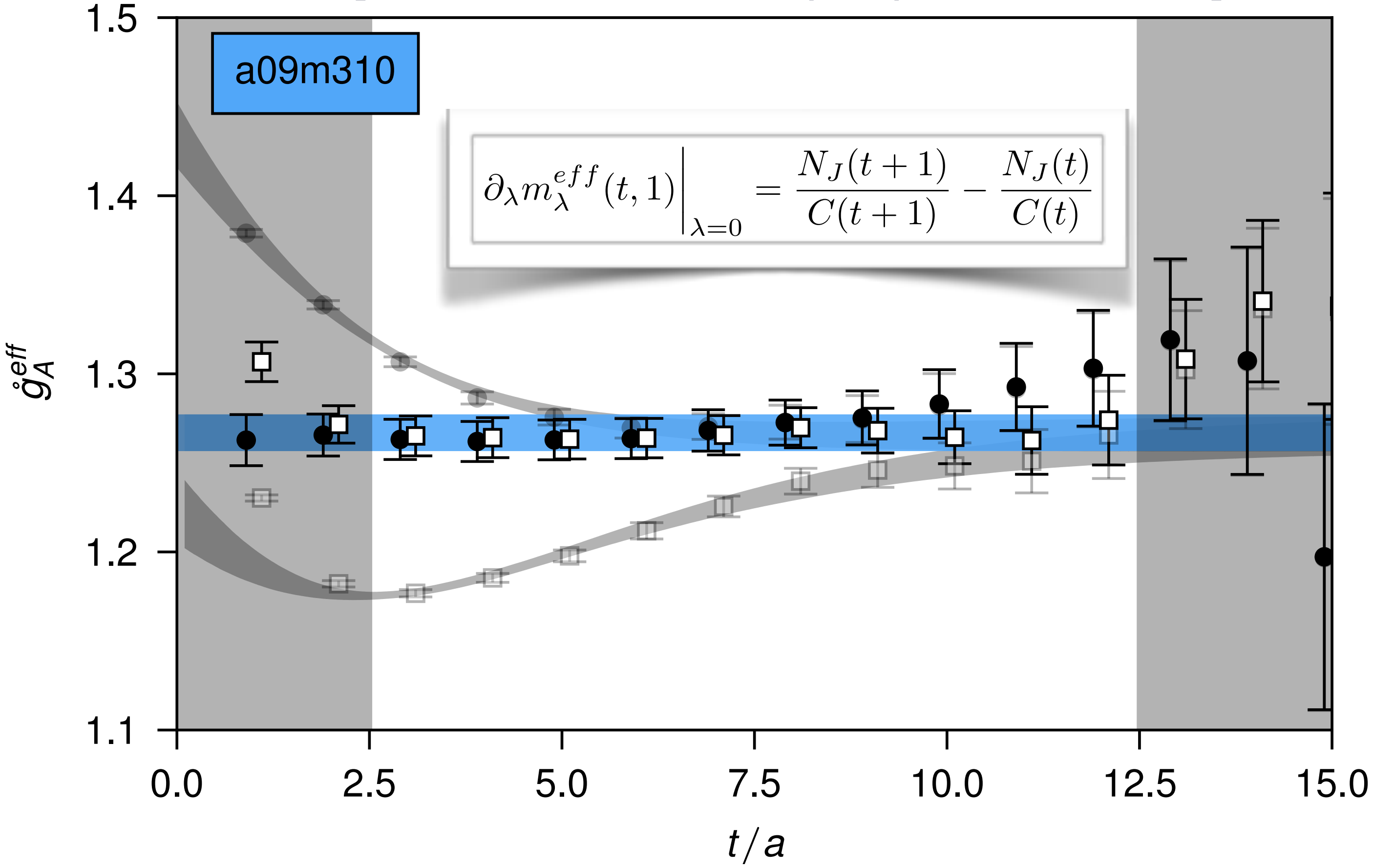

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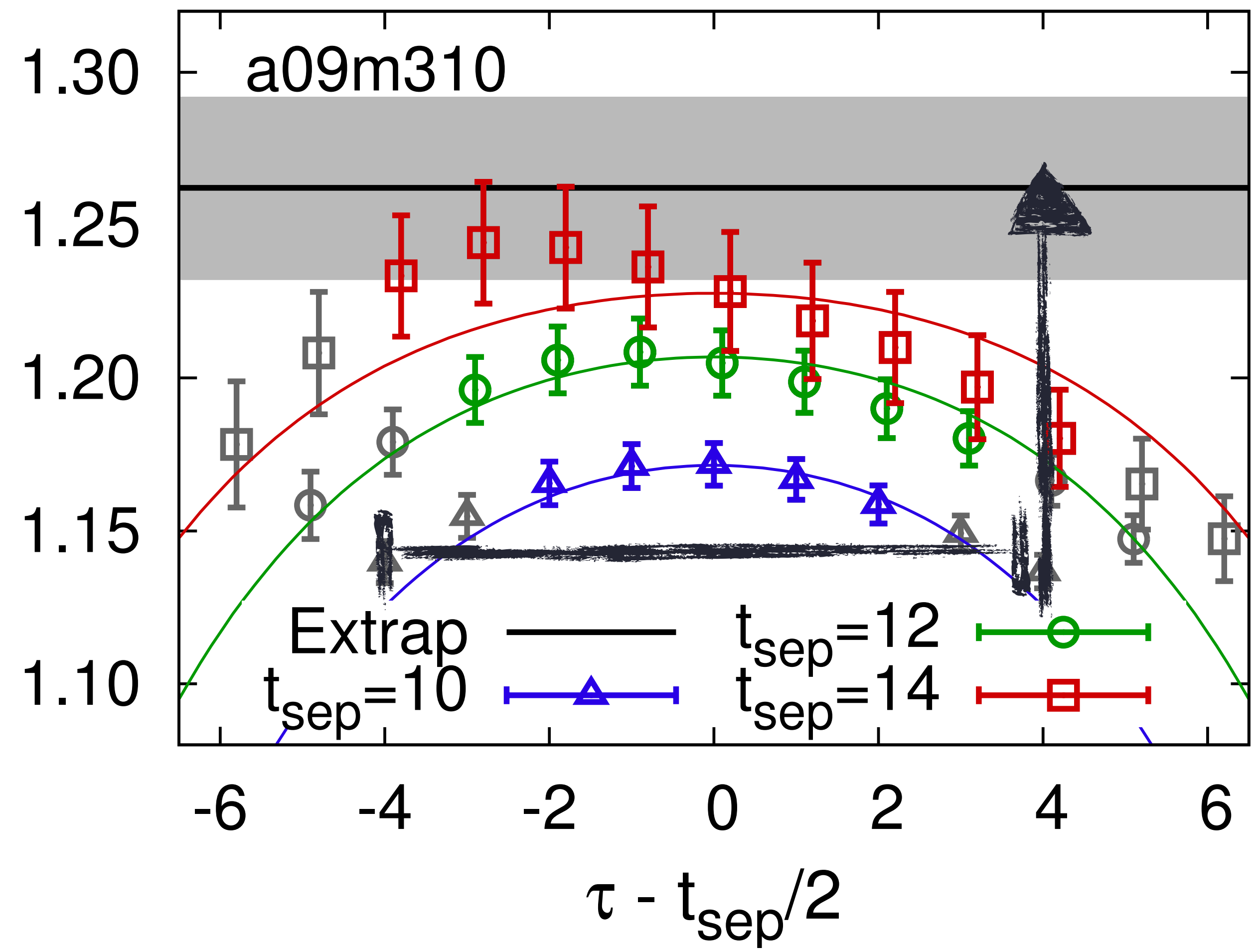

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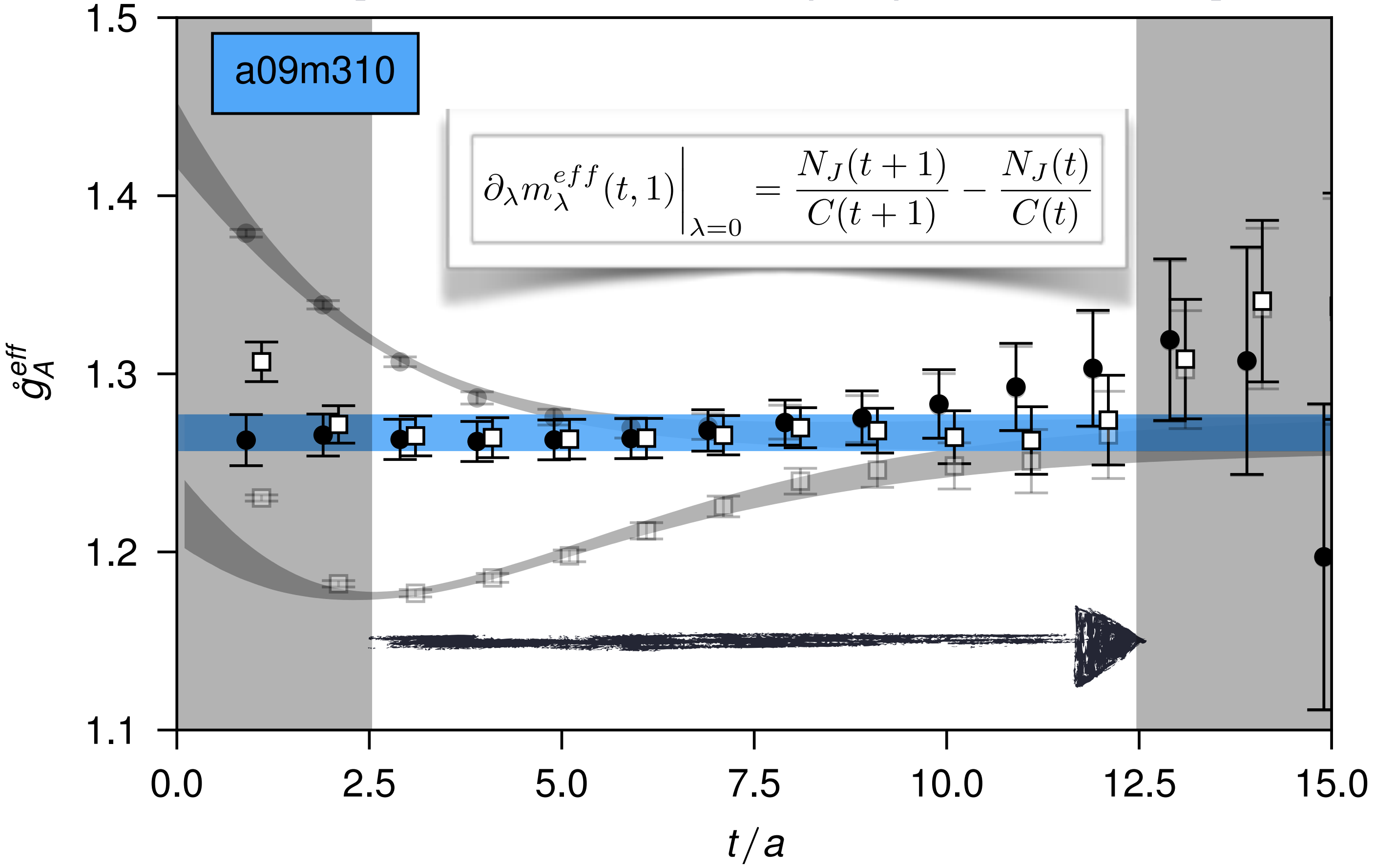

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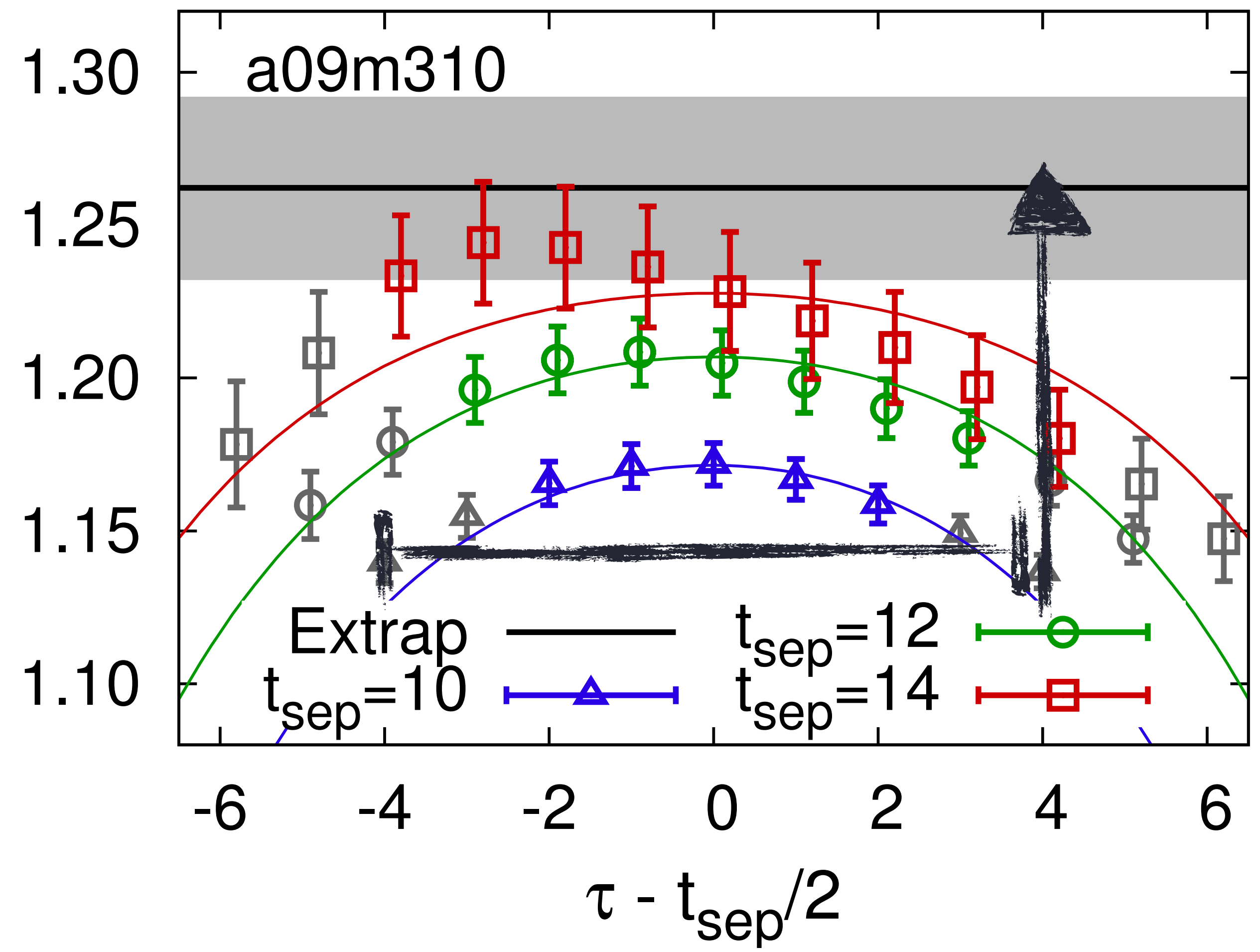

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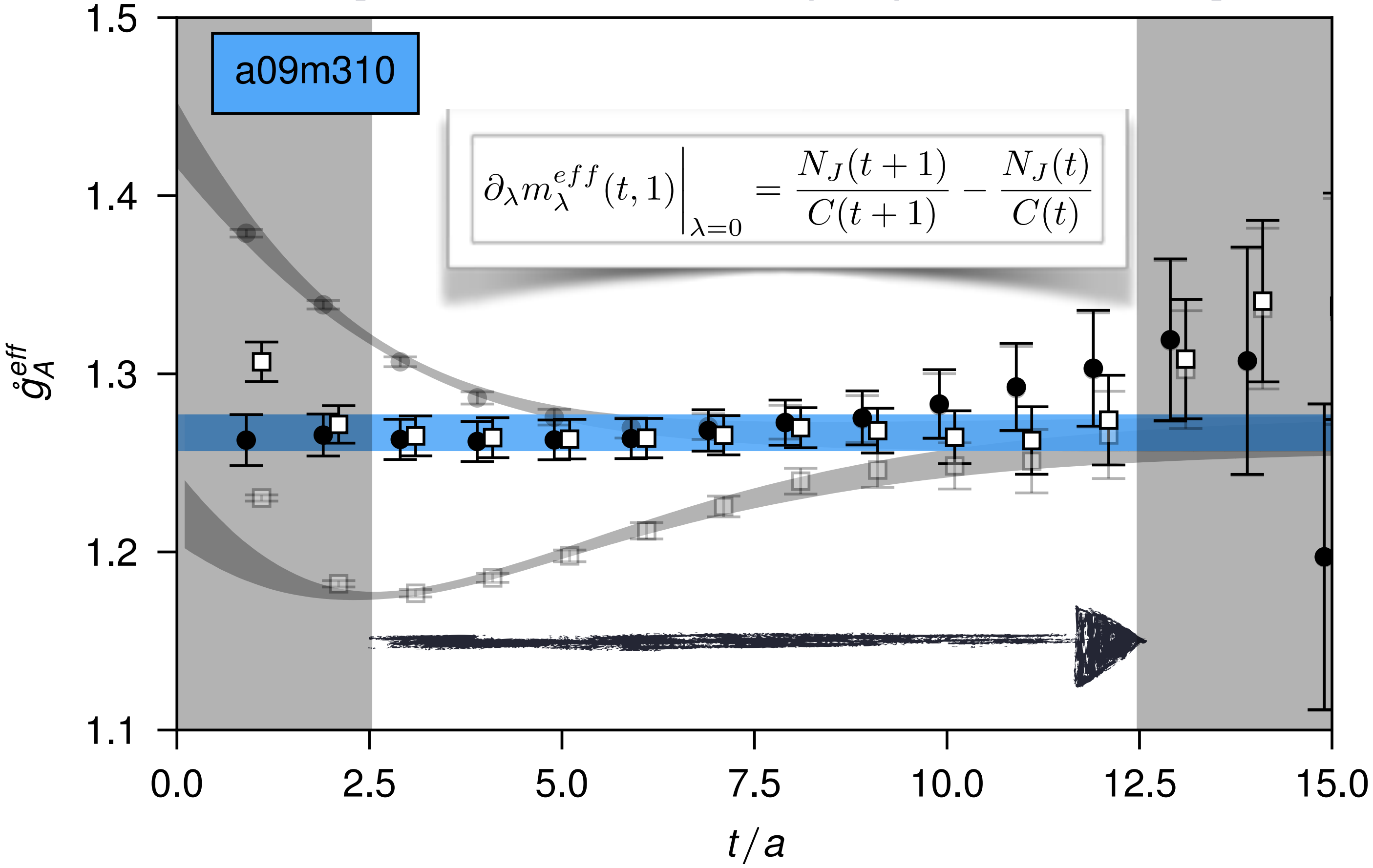

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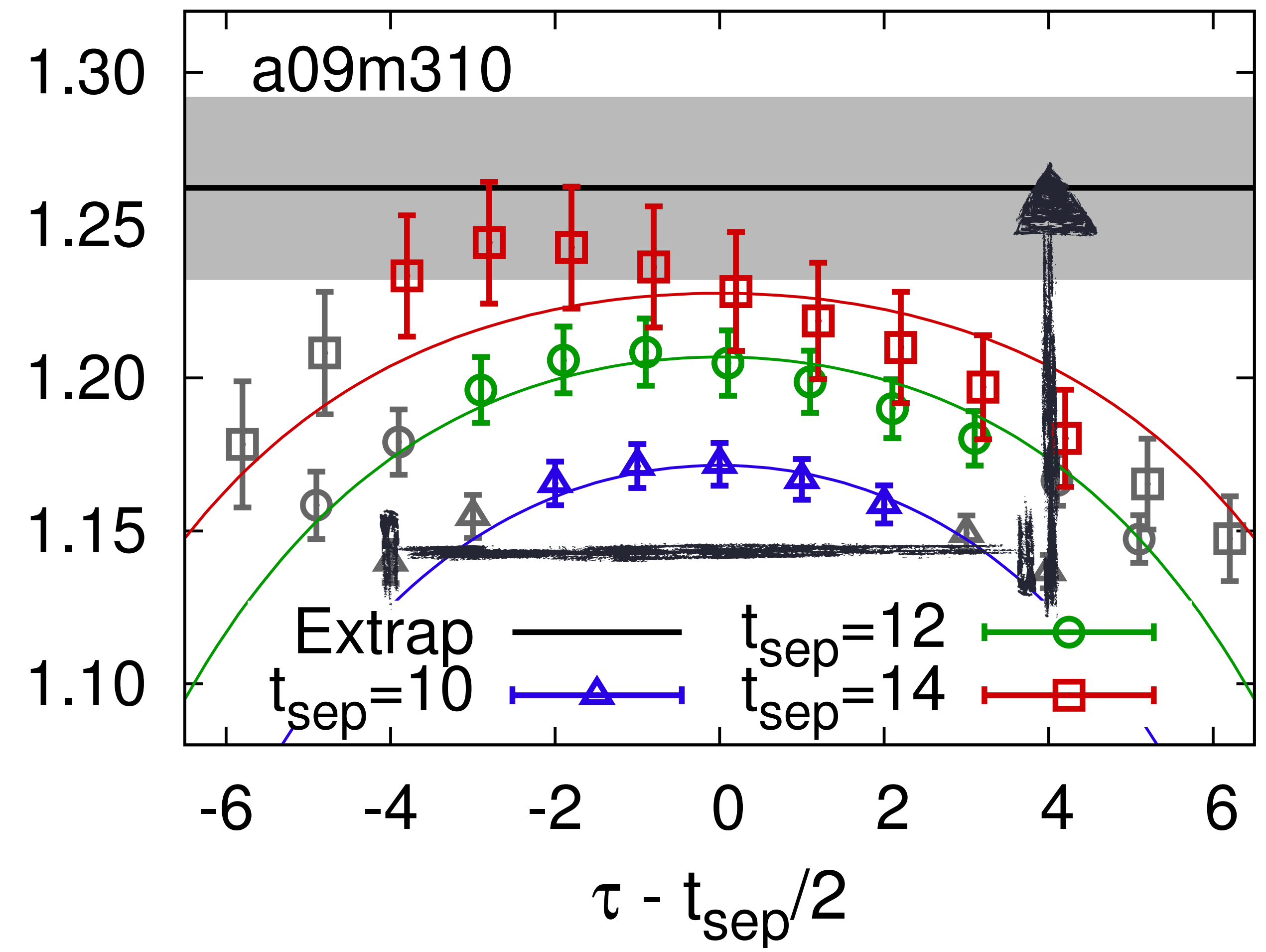
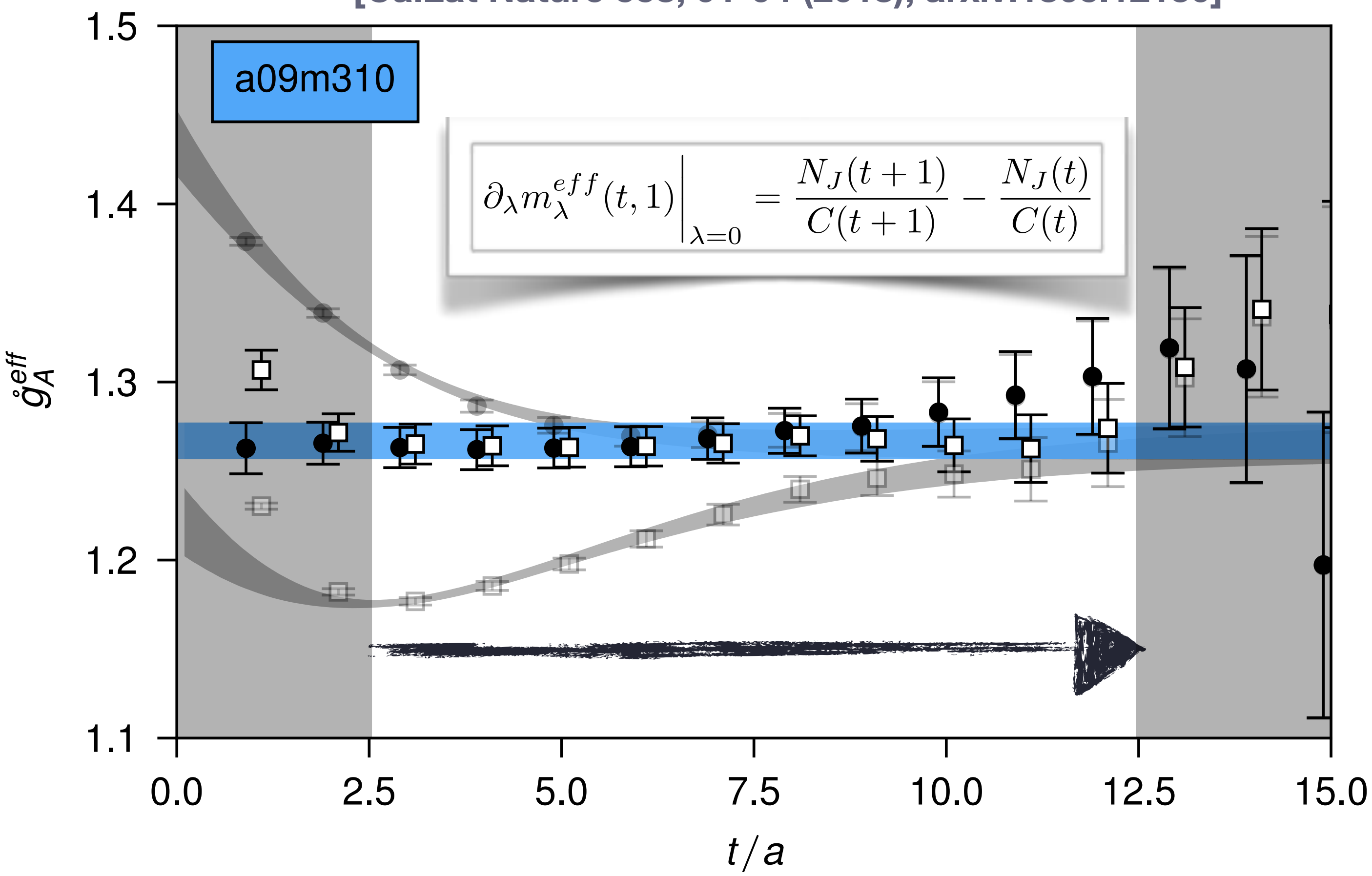


Simple functional form to isolate ground state at small times

Improved method to reduce excited states

[CalLat Nature 558, 91-94 (2018), arxiv:1805.12130]



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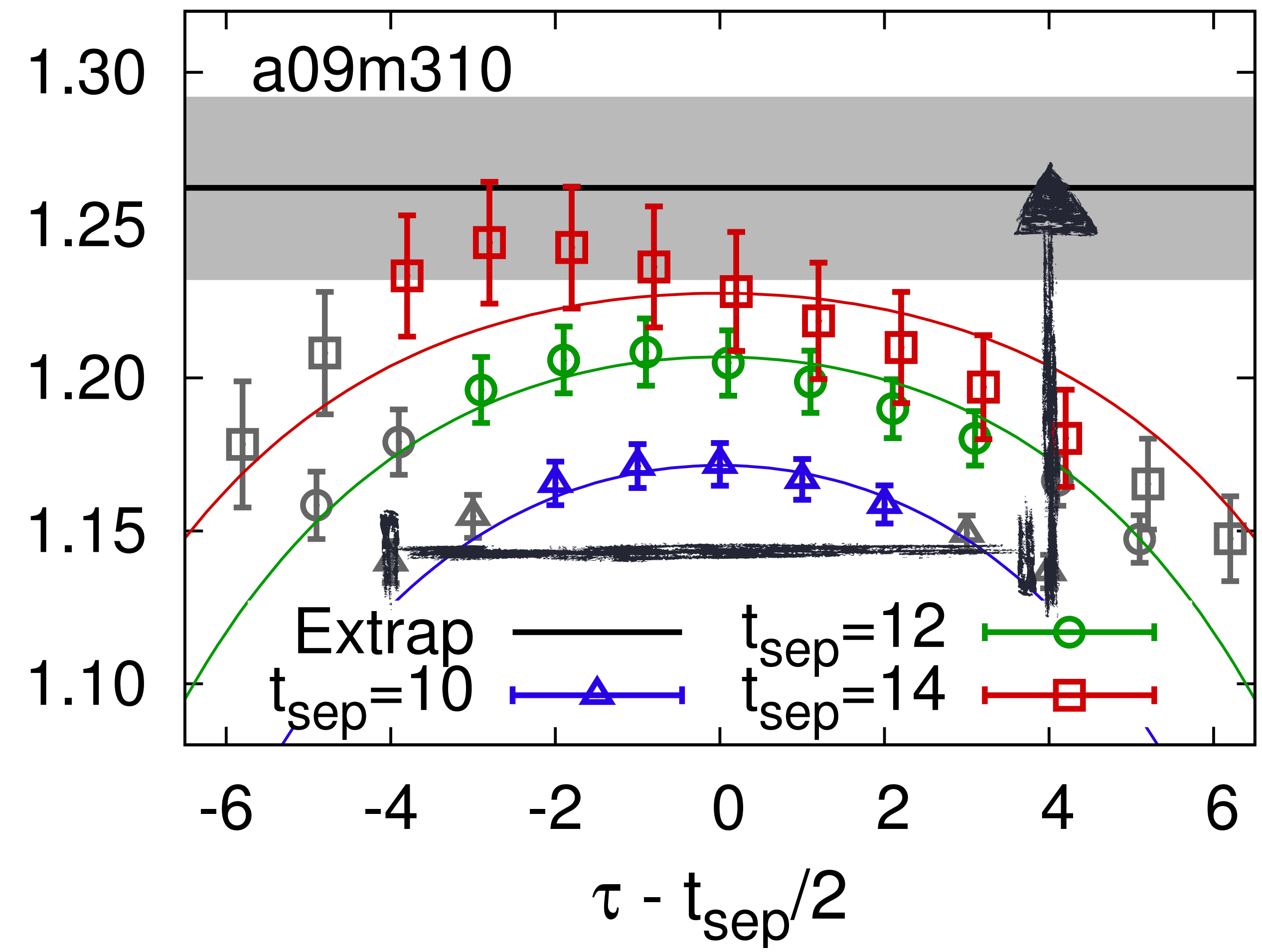
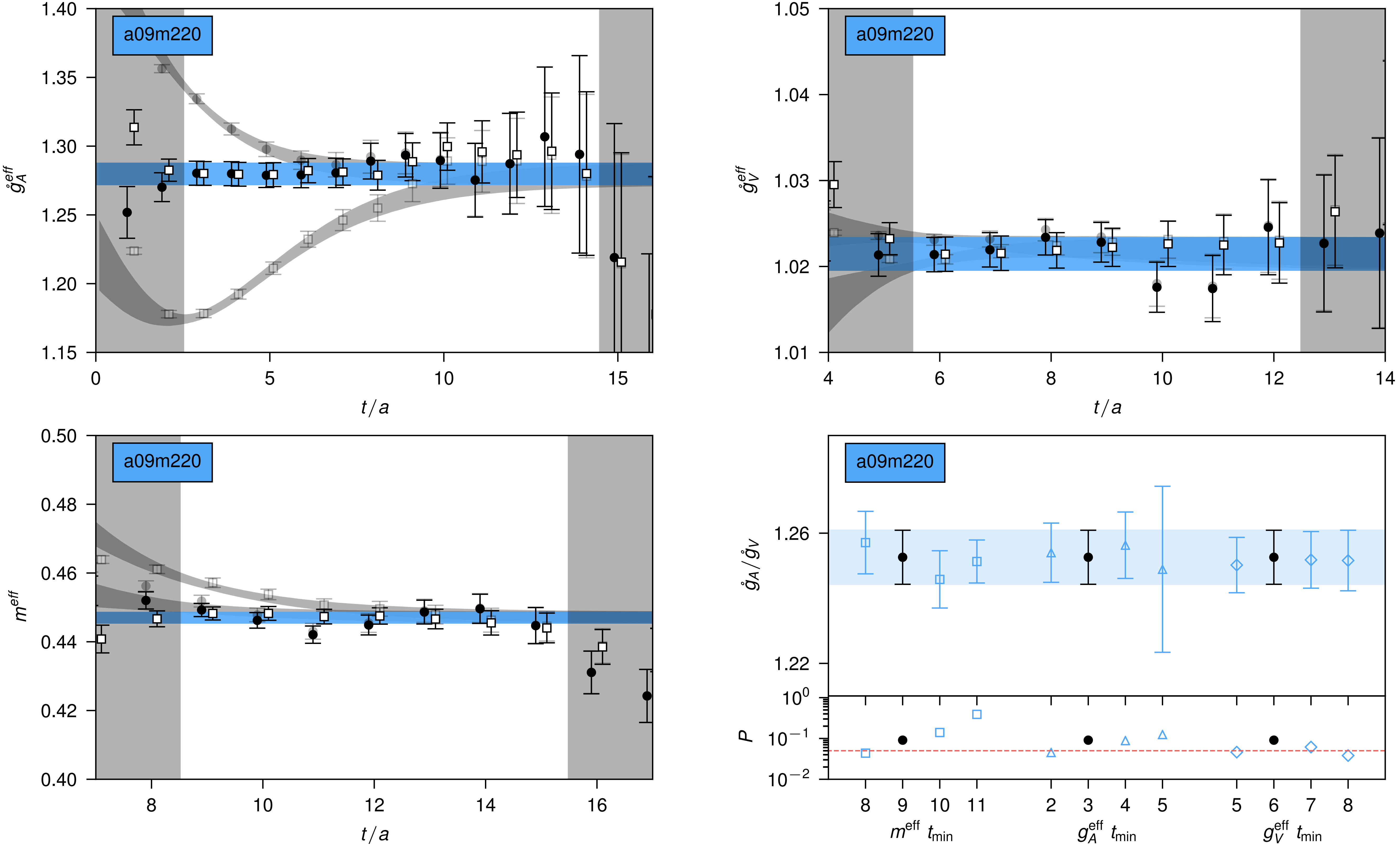


Simple functional form to isolate ground state at small times

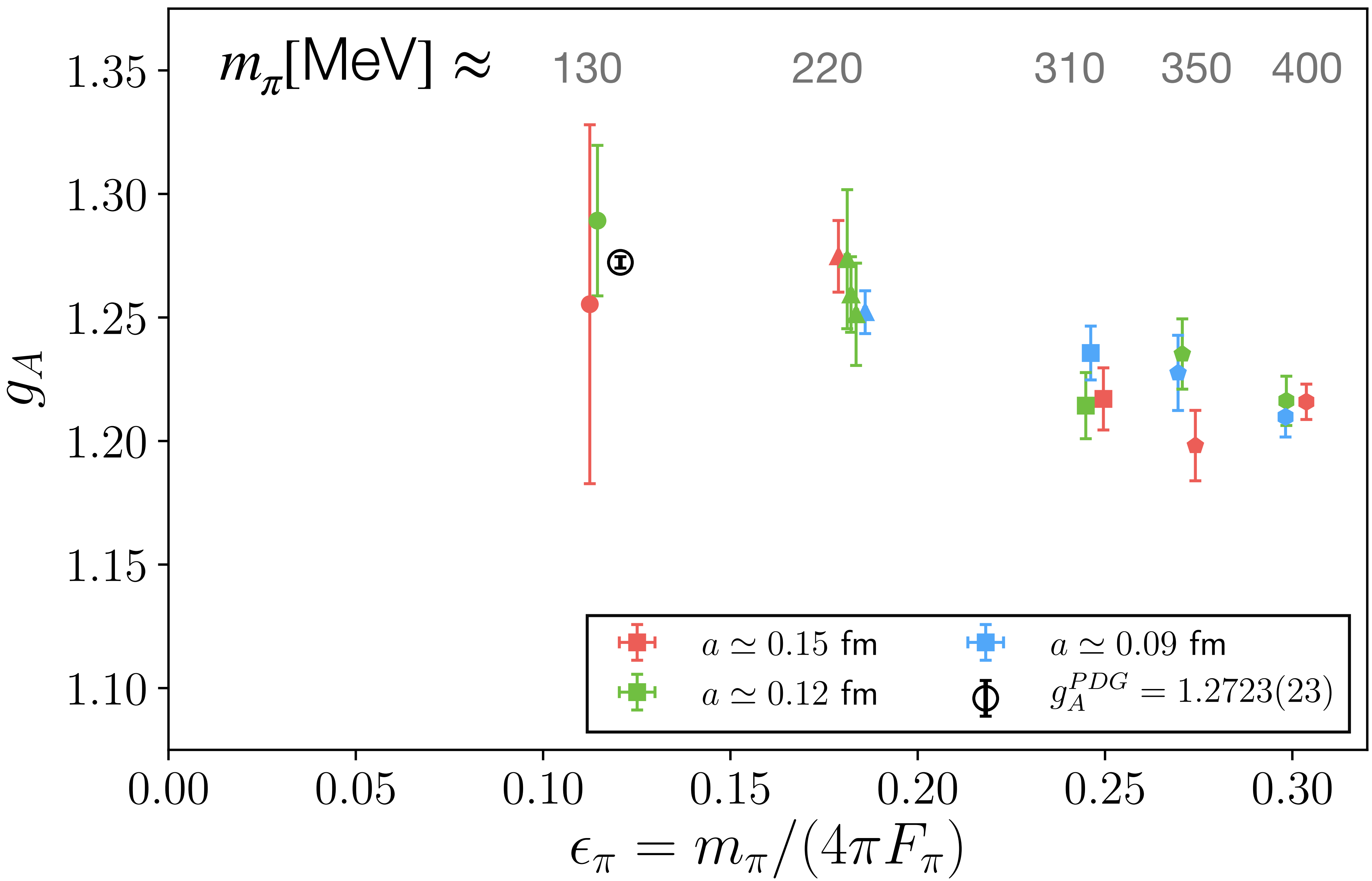
- ✓ Only one time variable parametrizes exc. states
  - ➡ **Reduced fitting systematics**
  - ➡ **Extract exponentially better signal**
- ✓ Improved method contains summation of vertex over all space-time:
  - ➡ **Improved statistical sampling**

[CallLat Nature 558, 91-94 (2018), arxiv:1805.12130]

Extracting g_A from LQCD data



Extracting g_A from LQCD data - extrapolations



Chiral and Continuum Extrapolations

SU(2) NNLO baryon χPT

$$\epsilon_\pi = \frac{m_\pi}{4\pi F_\pi} \qquad \epsilon_a^2 = \frac{1}{4\pi}\frac{a^2}{\omega_0^2}$$

m_π^2 analytic	$g_0 + c_2\epsilon_\pi^2 + c_4\epsilon_\pi^4$
non-analytic	$-\epsilon_\pi^2(g_0 + 2g_0^3)\ln(\epsilon_\pi^2) + g_0 c_3 \epsilon_\pi^3$
a^2 analytic	$a_2\epsilon_a^2 + b_4\epsilon_\pi^2\epsilon_a^2 + a_4\epsilon_a^4$
NLO FV	$(8/3)\epsilon_\pi^2[g_0^3 F_1(m_\pi L) + g_0 F_3(m_\pi L)]$

- ★ Try different chiral, continuum and infinite volume extrapolations, averaged under Bayes framework
- ★ Based on ChPT, MAEFT, and a Taylor expansion around the physical point
- ★ Fits with parameters that can not be constrained are neglected
- ★ Study stability of fits, including variations of Bayes priors, additional discretization effects and cutting data

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e.g. Taylor exp. in quark mass

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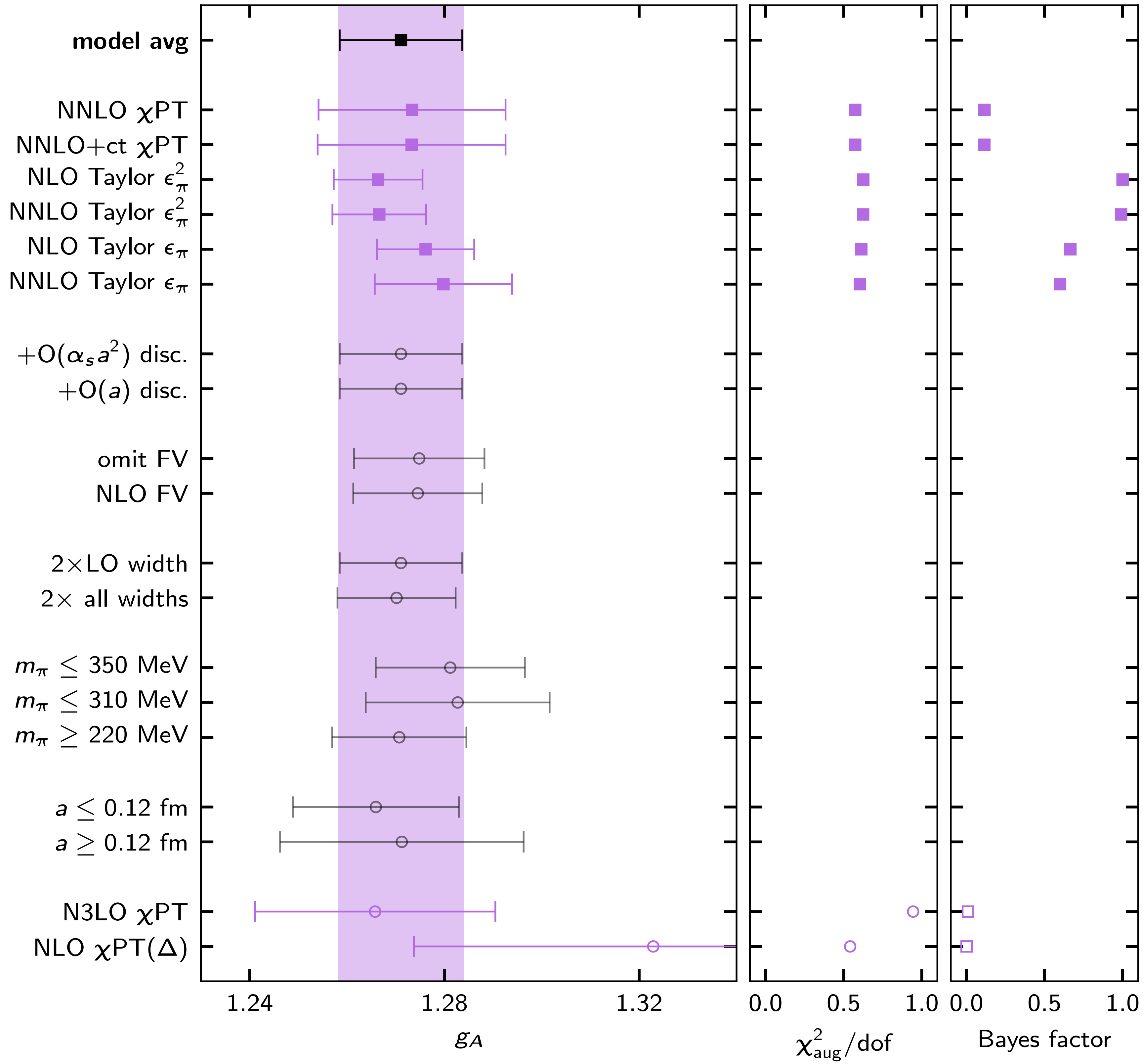
Extrapolation stability



final result

6 fits included in the model average and their relative weights

discretisation corrections

finite volume corrections

prior width sensitivity

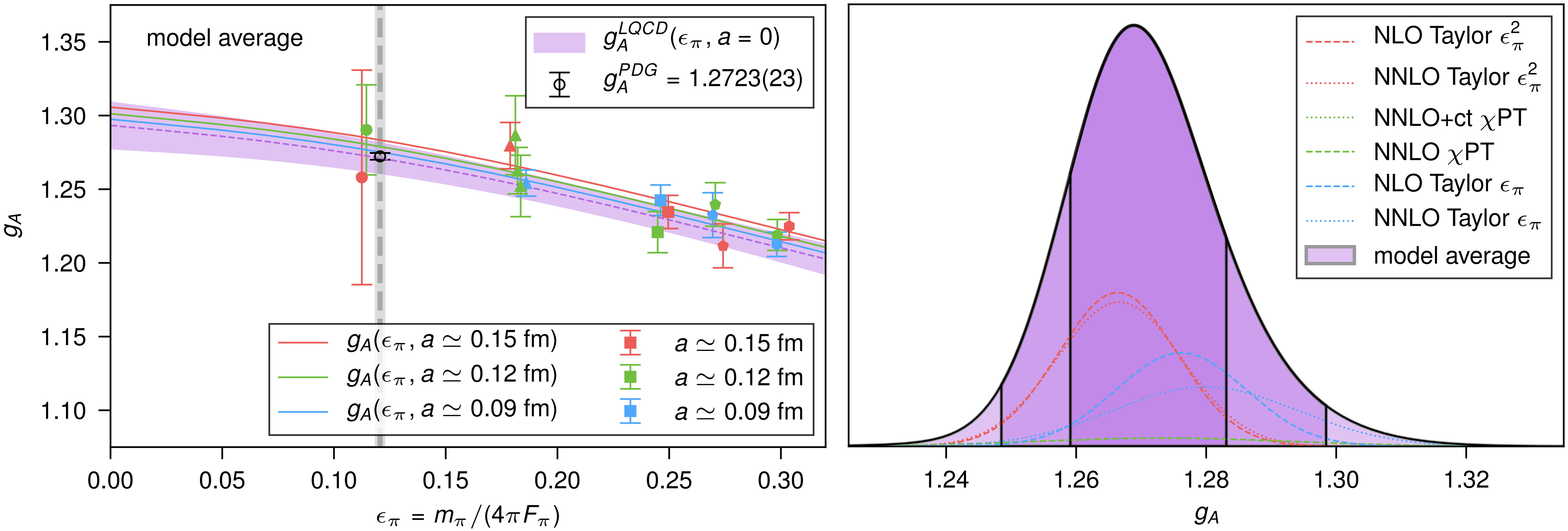
pion mass cut sensitivity

lattice spacing cut sensitivity

additional XPT analysis

[CalLat Nature 558, 91-94 (2018), arxiv:1805.12130]

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



statistical	0.81%
chiral extrapolation	0.31%
$a \to 0$	0.12%
$L \to \infty$	0.15%
isospin	0.03%
model selection	0.43%
total	0.99%

[CalLat Nature 558, 91-94 (2018), arxiv:1805.12130]

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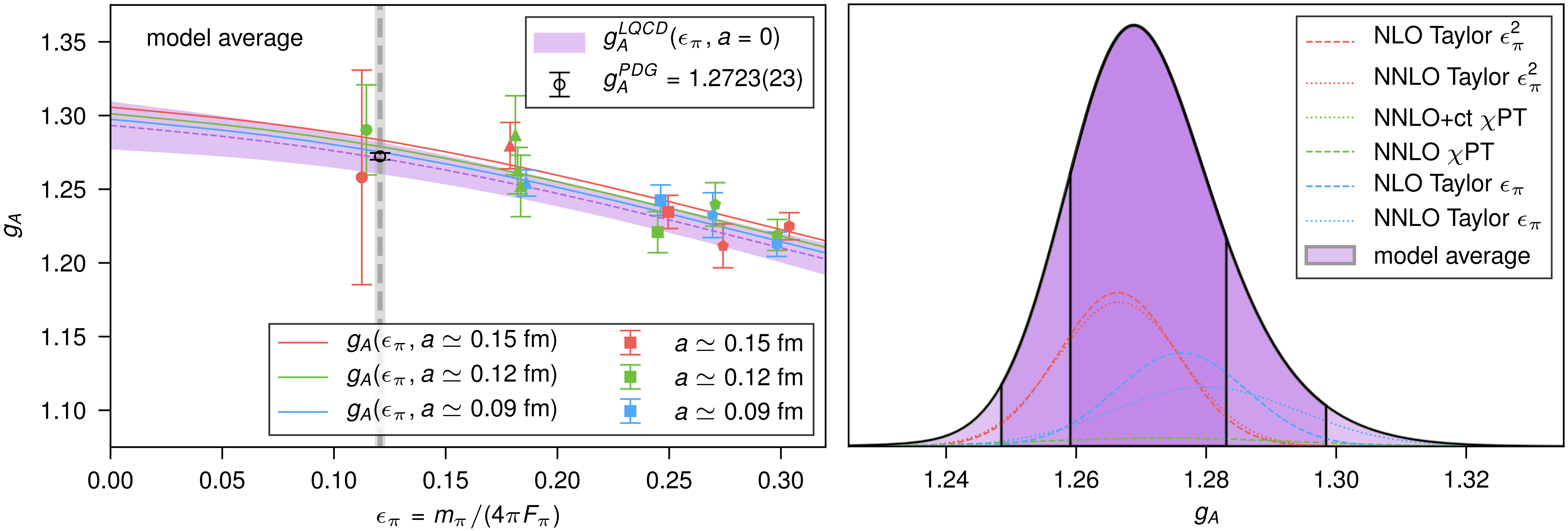

dominant sources of uncertainties

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$a \to 0$	0.12%
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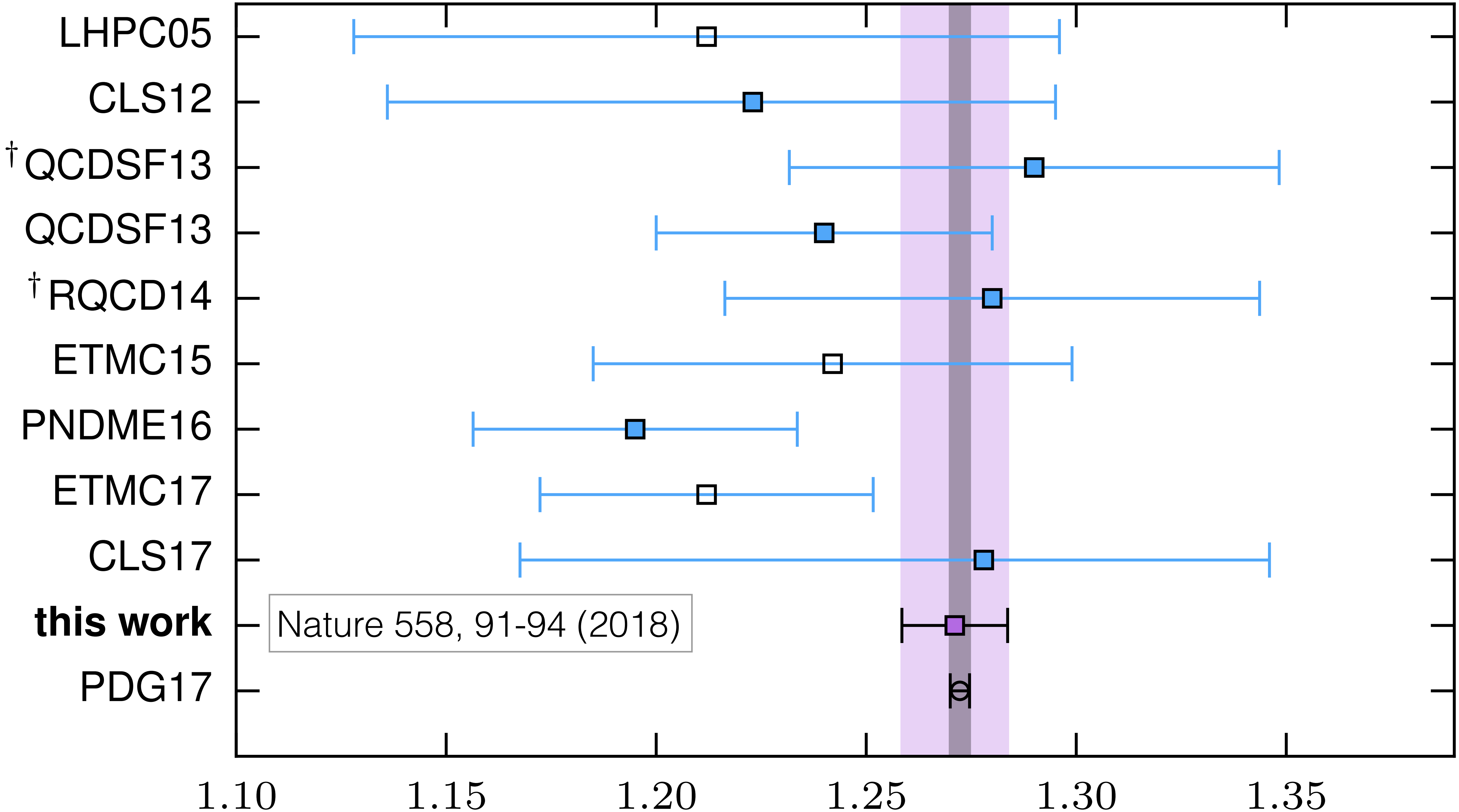

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First percent-level determination of g_A from LQCD

- result is limited by statistics
- new supercomputers help!
- all data is publicly available
https://github.com/callat-qcd/project_gA

LQCD neutron lifetime

- Use LQCD values of the axial coupling and the light quark mixing matrix element

$$\tau_n = \frac{4908.6(1.9)s}{|V_{ud}|^2(1 + 3g_A{}^2)}$$

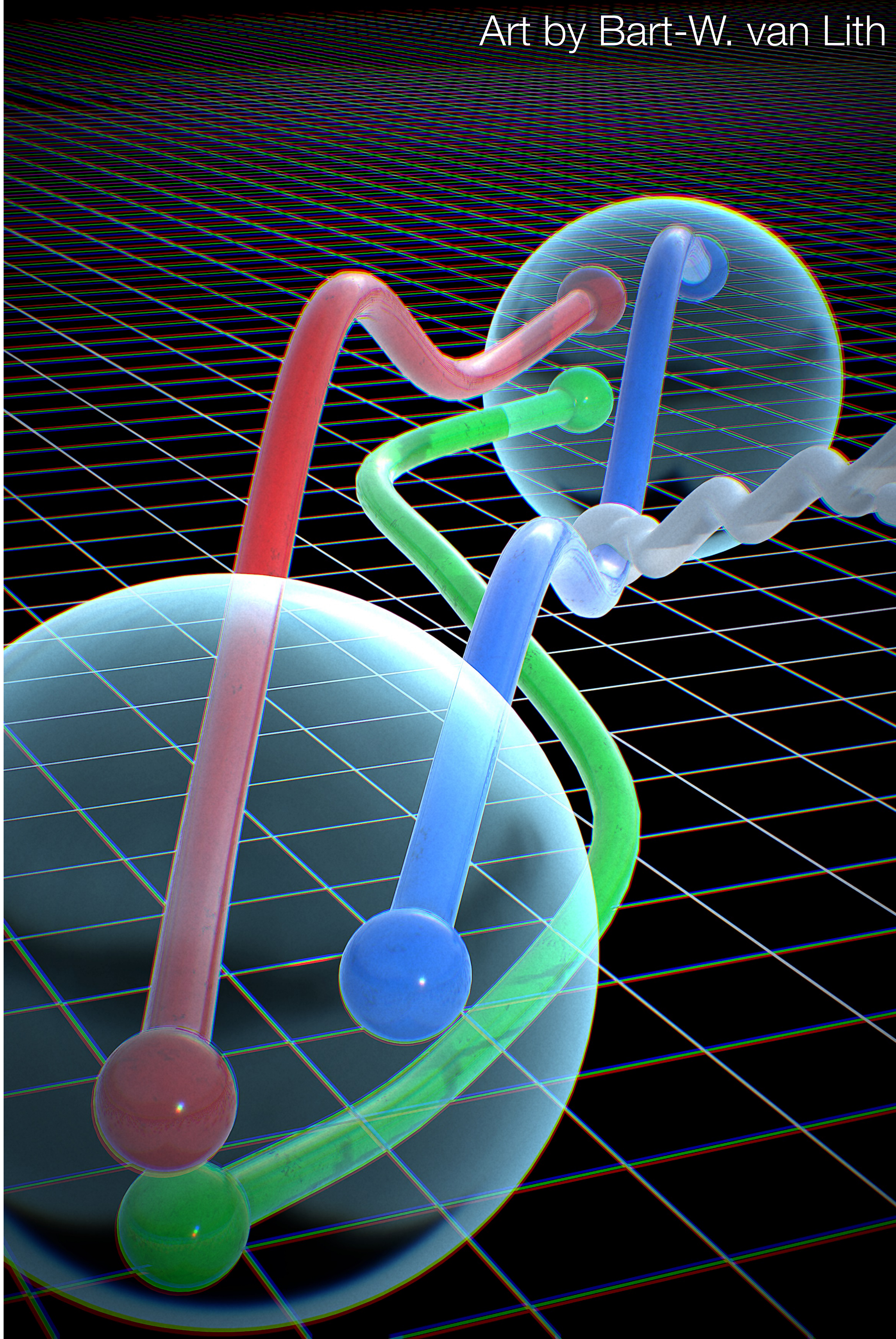
[Czarnecki, Marciano and Sirlin, Phys. Rev. Lett. 120, 202002 (2018)]

$$|V_{ud}| = 0.97438(12)$$

[MILC, Phys.Rev. D90, 074509 (2014)]

$$g_A = 1.271(13)$$

[CalLat Nature 558, 91-94 (2018), arxiv:1805.12130]



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- Use LQCD values of the axial coupling and the light quark mixing matrix element

$$\tau_n = \frac{4908.6(1.9)s}{|V_{ud}|^2(1+3g_A{}^2)}$$

[Czarnecki, Marciano and Sirlin, Phys. Rev. Lett. 120, 202002 (2018)]

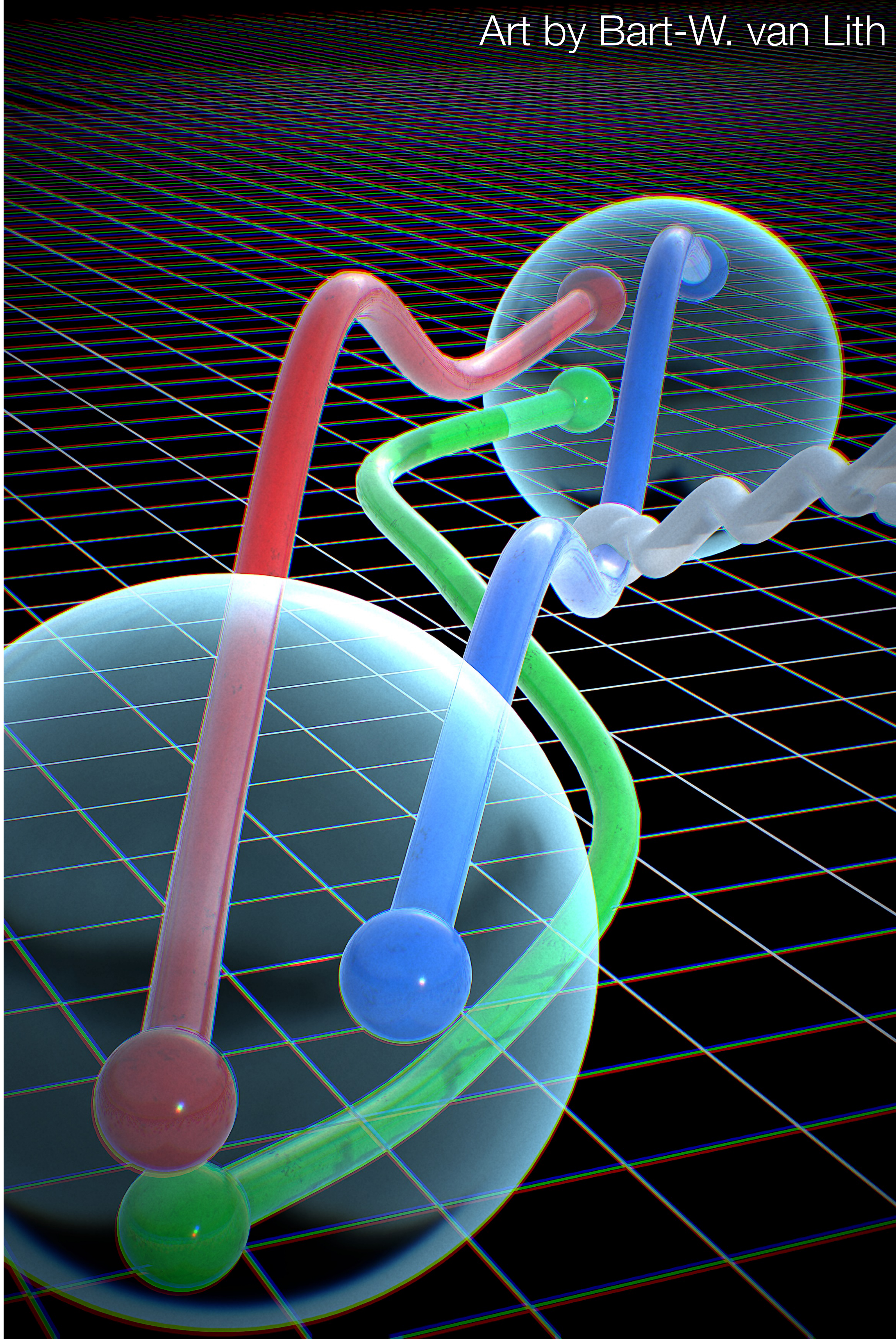
$$|V_{ud}| = 0.97438(12)$$

[MILC, Phys.Rev. D90, 074509 (2014)]

$$g_A = 1.271(13)$$

[CalLat Nature 558, 91-94 (2018), arxiv:1805.12130]

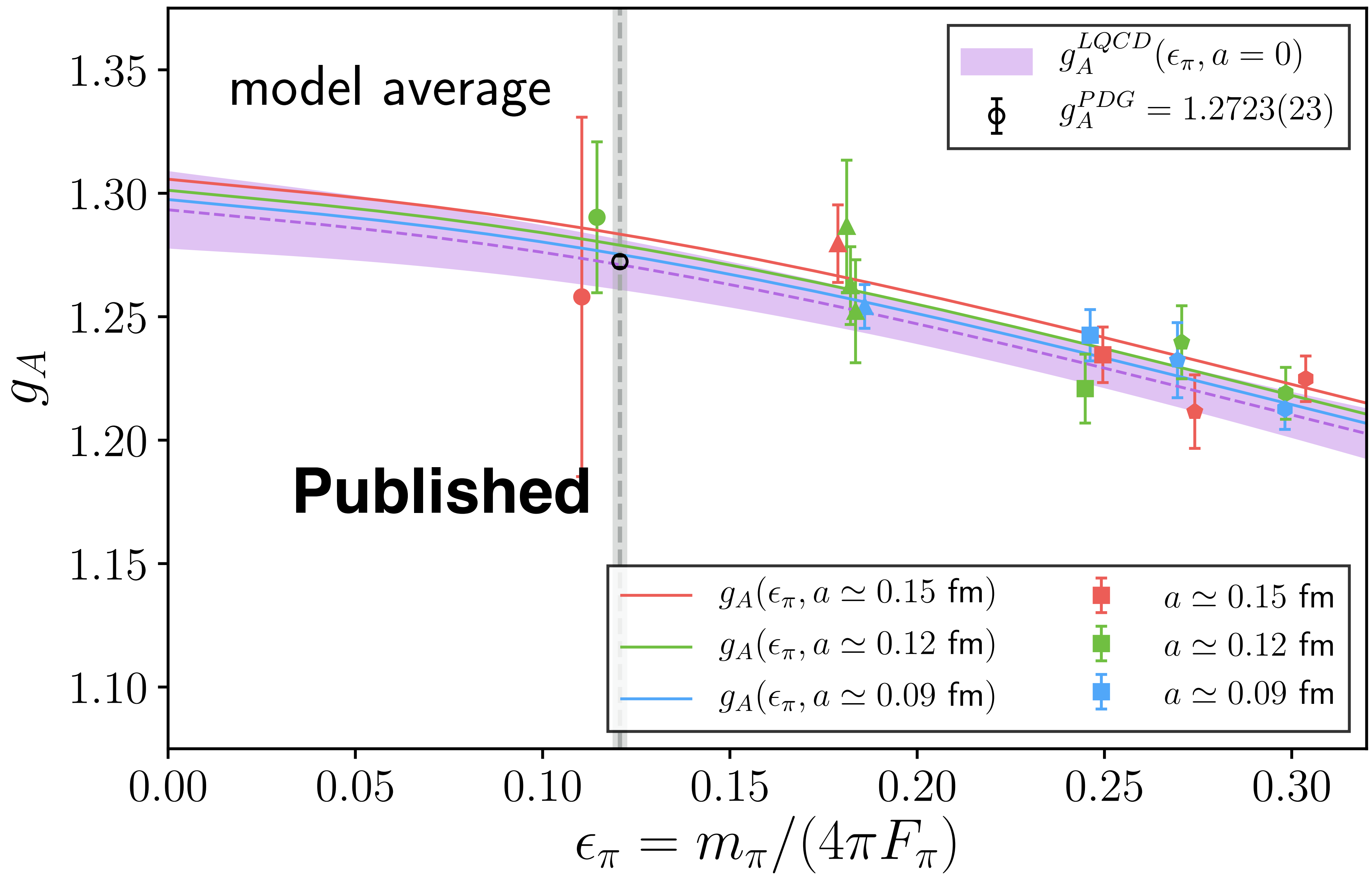
$$\tau_n = 884(15)s$$



2018 Gordon Bell Finalist
sc18.supercomputing.org/presentation/?id=gb101&sess=sess467

Simulating the weak death of the neutron in a femtoscale universe with near-Exascale computing

Evan Berkowitz, M.A. Clark, Arjun Gambhir, Ken McElvain, Amy Nicholson, Enrico Rinaldi, Pavlos Vranas, André Walker-Loud, Chia Cheng Chang, Bálint Joó, Thorsten Kurth, Kostas Orginos



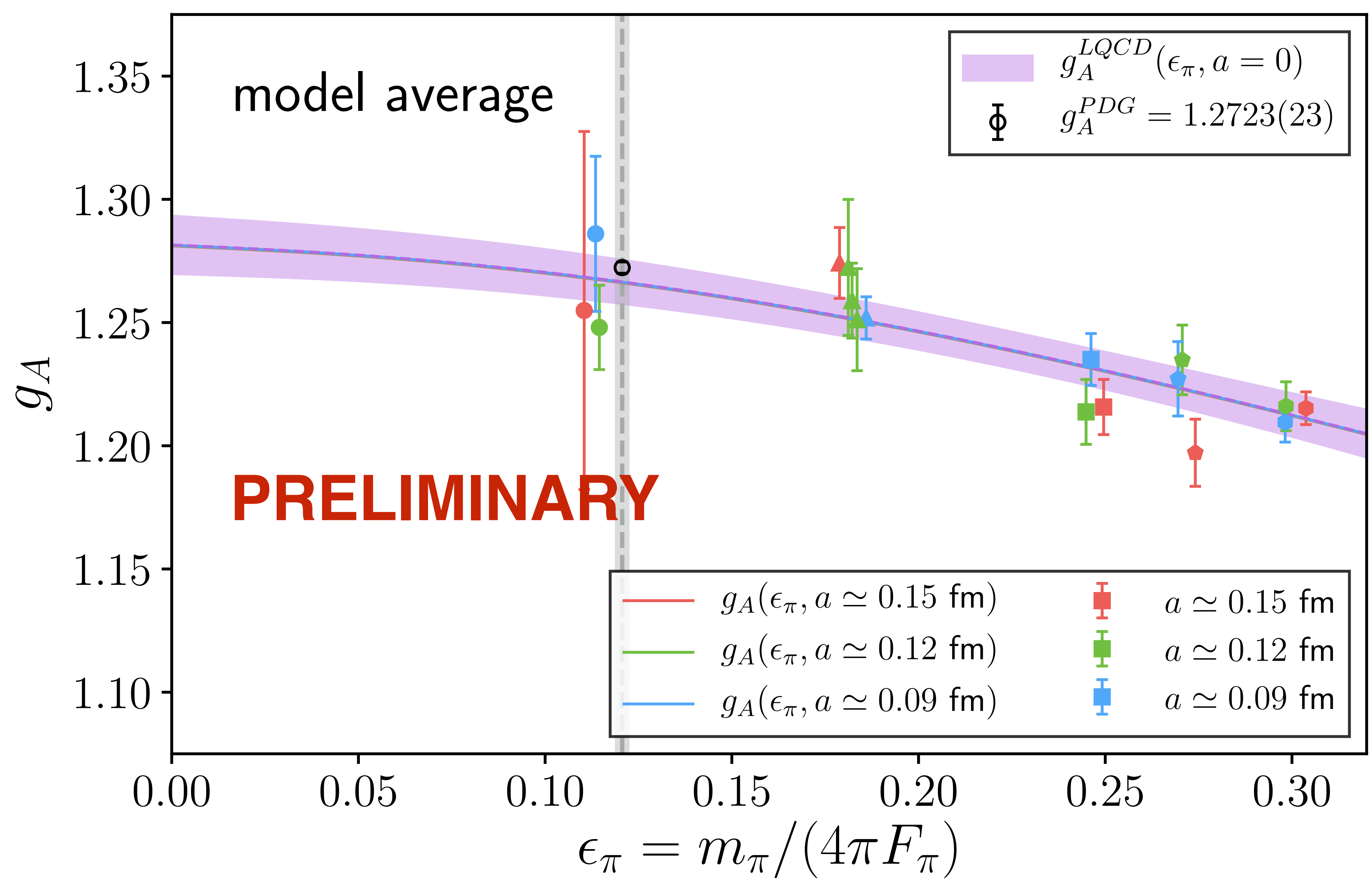
Code development from Gordon Bell + initial Sierra Early Science time result.

Increase 0.12 fm physical mass statistics by ~ 5x, 50% reduction in uncertainty.

New 0.09 fm physical mass 322 configs x 4 sources.

Preliminary update for g_A = 1.2670(97)

23% reduction in uncertainty → 0.77% relative error



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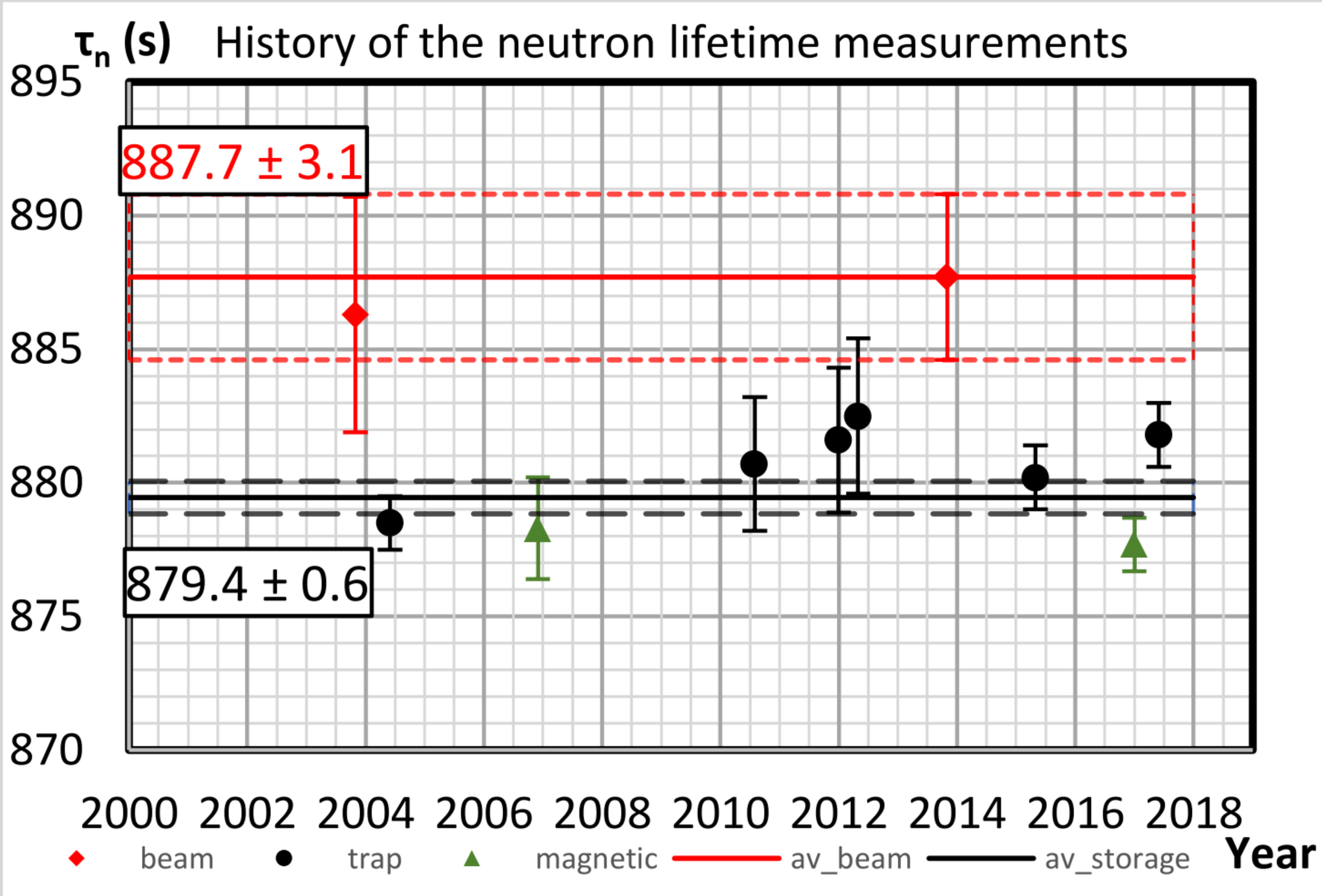
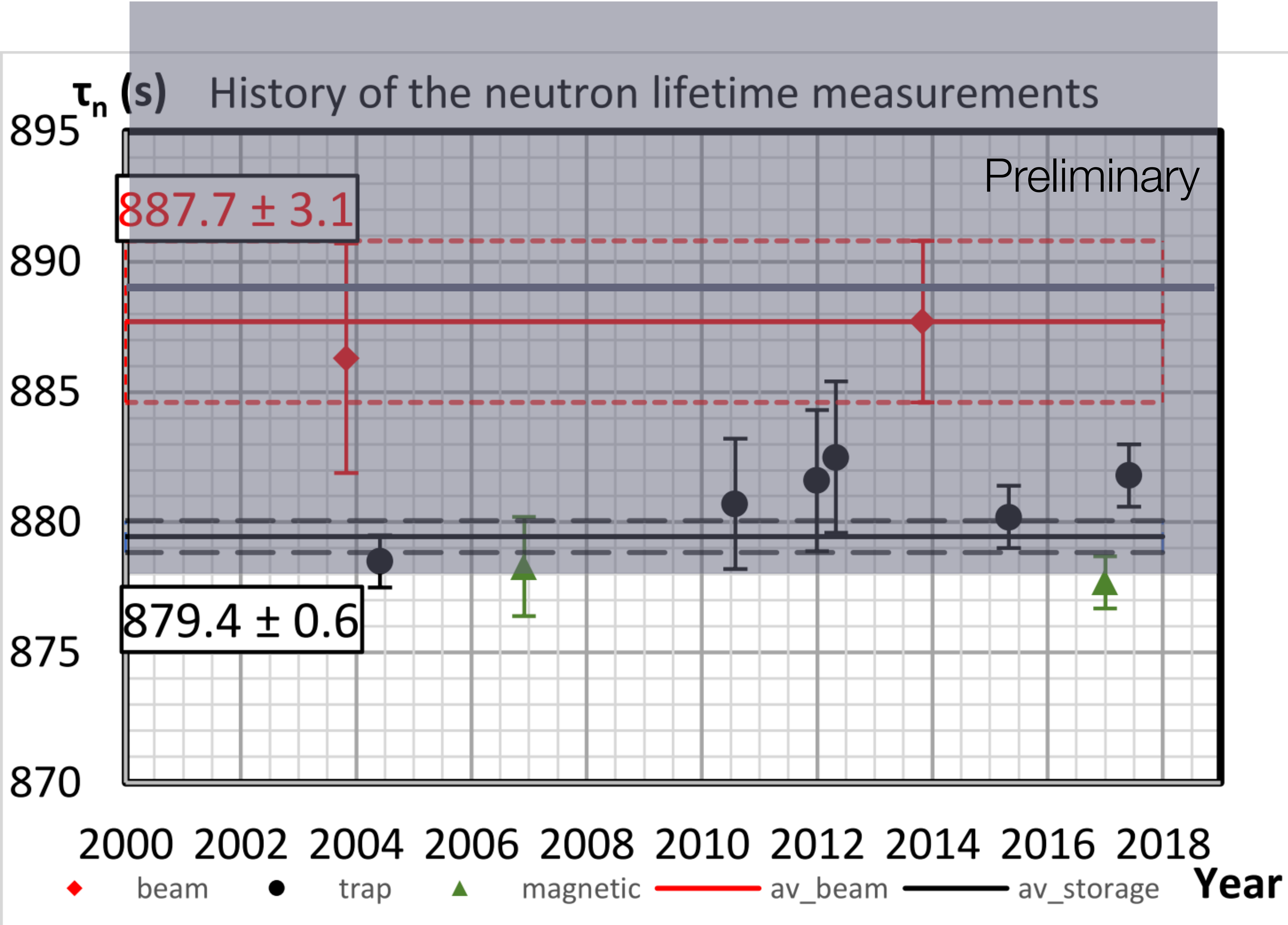


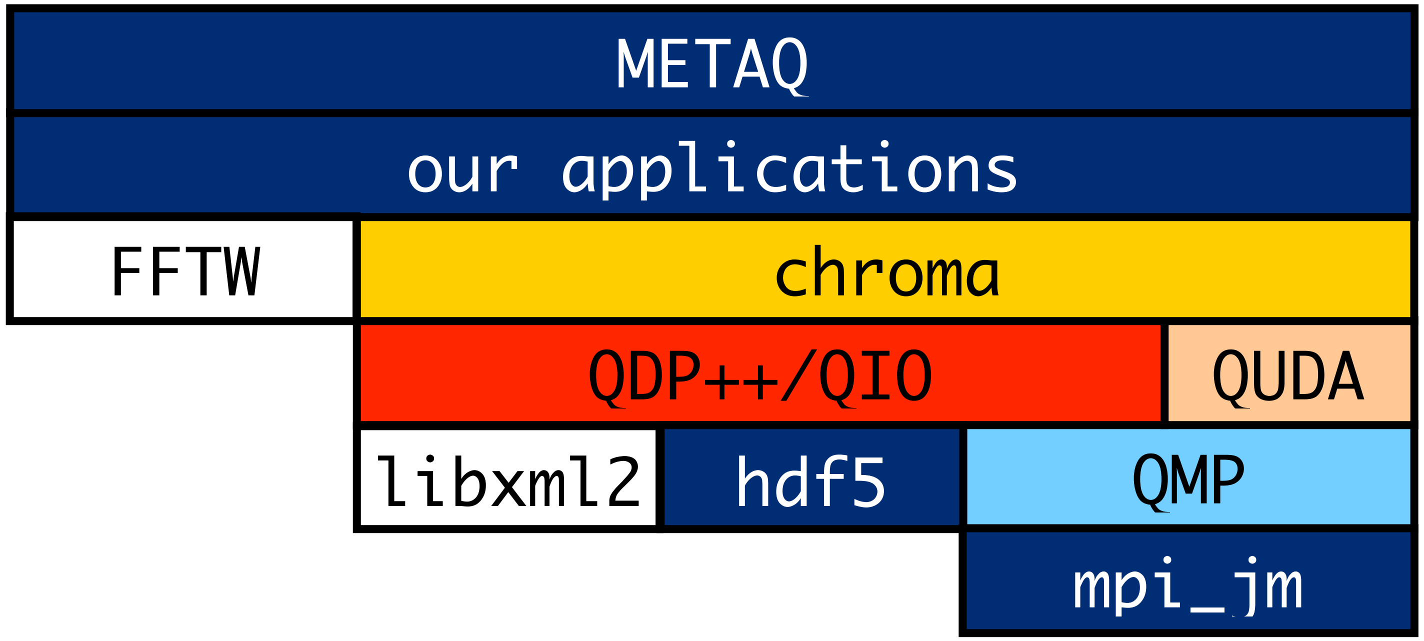
Serebrov et al. Phys. Rev. C 97 (055503) 2018



Serebrov et al. Phys. Rev. C 97 (055503) 2018

Summary

- ✓ The neutron lifetime is showing a discrepancy of ~4σ between different experimental methods
- ✓ The Standard Model predicts a precise relation which allows us to obtain a theoretical value of the neutron lifetime using Lattice QCD non-perturbative calculations
- ✓ The first percent-level calculations of the nucleon axial coupling has been obtained this year, ahead of expectations https://www.nature.com/articles/s41586-018-0161-8
    - ✓ Statistical uncertainties ~0.8% can be reduced with the next generation of supercomputers (we "only" used the no. 7 and 33 of the June 2018 *top500* list of supercomputers: https://www.top500.org/lists/2018/06/)
    - ✓ A more accurate calculation at the physical point using the no. 1 and 3 *top500* has been accepted as one of the six finalists in the Gordon Bell competition, recognizing outstanding achievement in high-performance computing (https://awards.acm.org/bell)



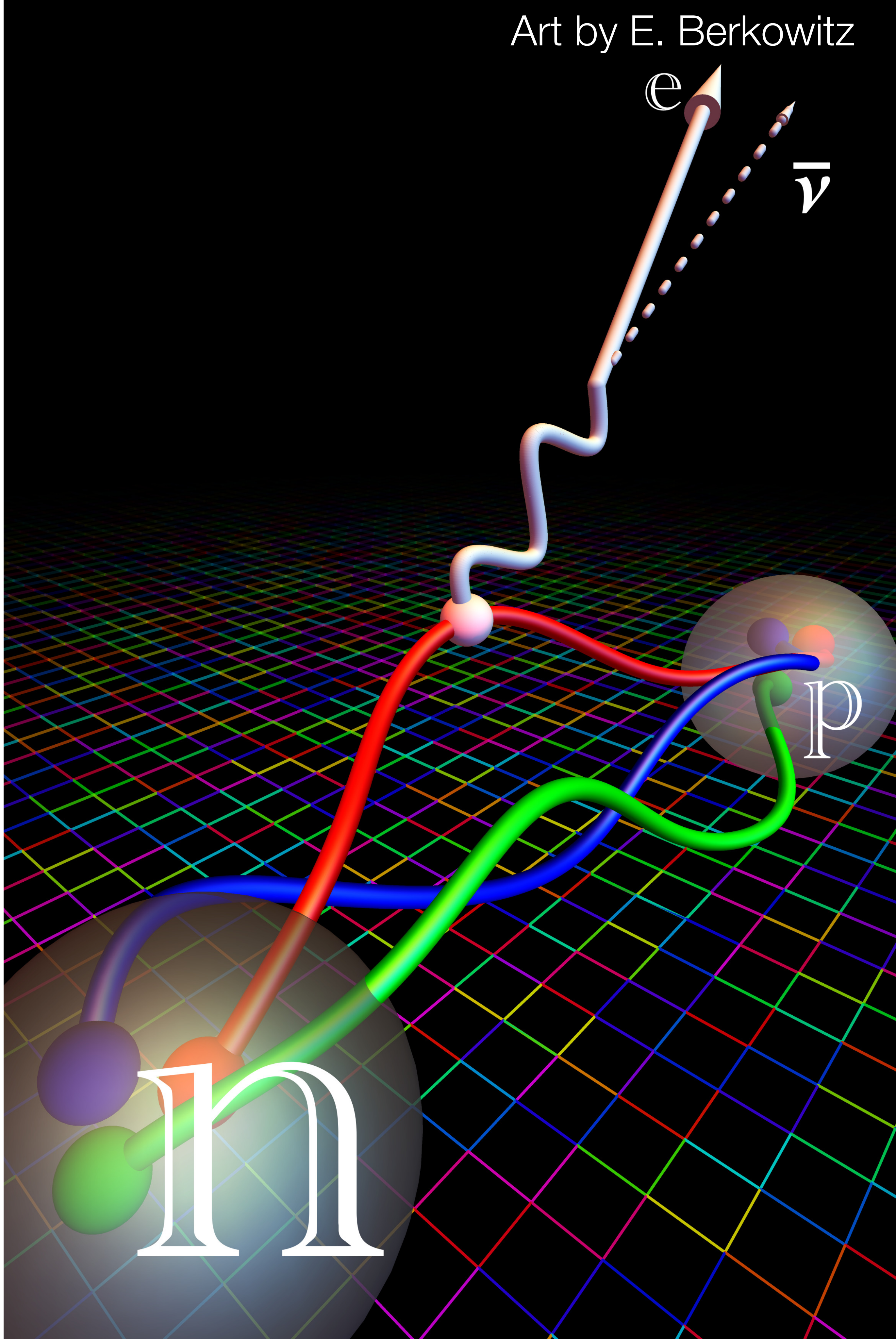
Software	References
METAQ	Berkowitz arXiv:1702.06122 github.com/evanberkowitz/metaq Berkowitz et al. EPJ (LATTICE2017) 175 09007 (2018)
chroma QDP++	Edwards and Joo (SciDAC, LHPC and UKQCD Collaborations) Nucl. Phys. Proc. Suppl 140, 832 (2005)
QUDA	Clark et al. Comput. Phys. Commun. 181 1517 (2010) 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/

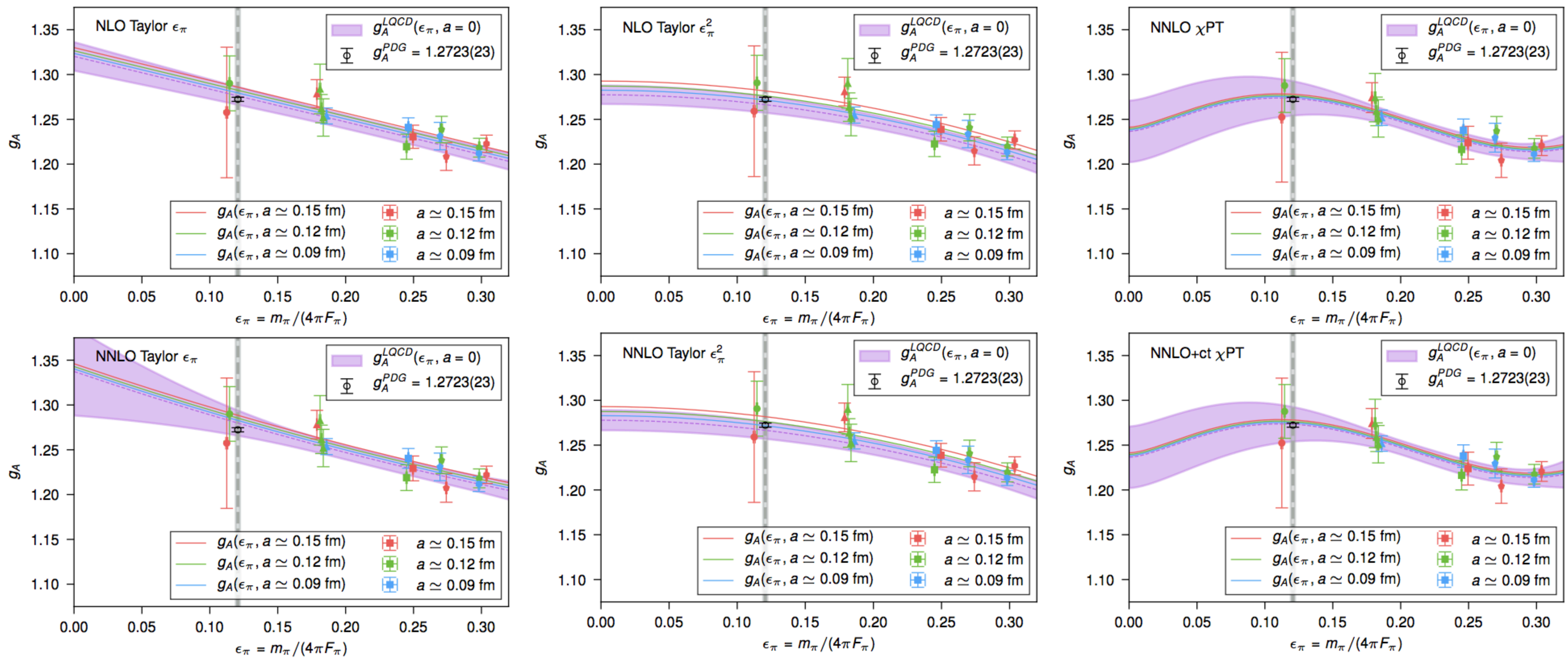
thank you

Art by Bart-W. van Lith

extra slides

background and more plots





Taylor in m_π | Taylor in $(m_\pi)^2$ | χPT

Different models for 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)

Axial coupling, g_A

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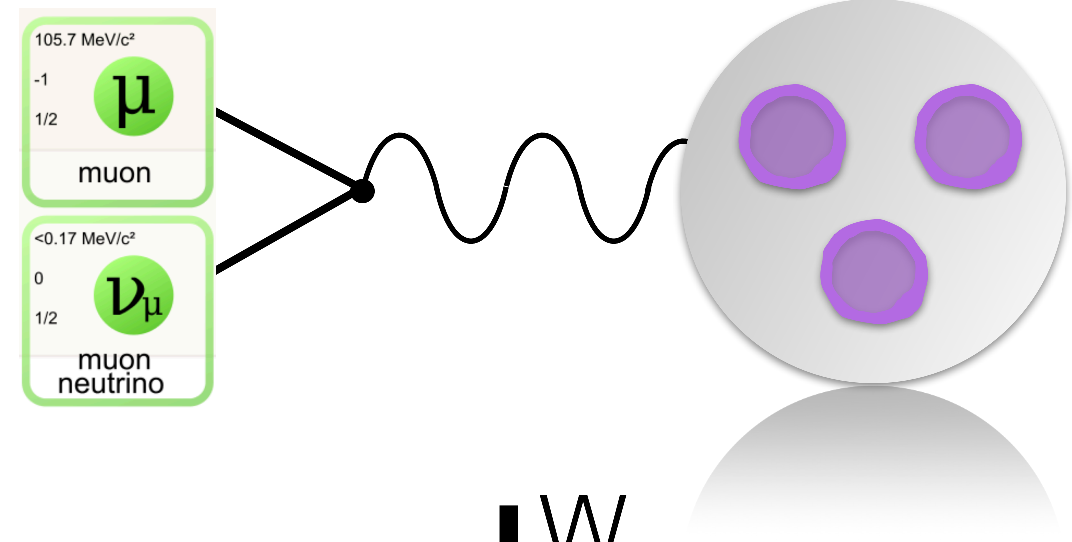
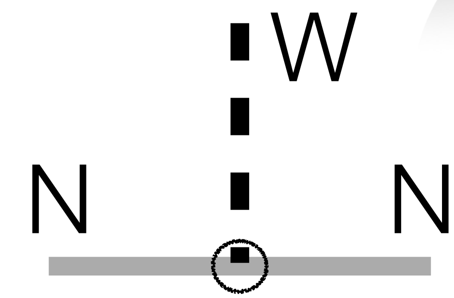
- Describes the strength of the interaction between the weak axial current and the nucleon





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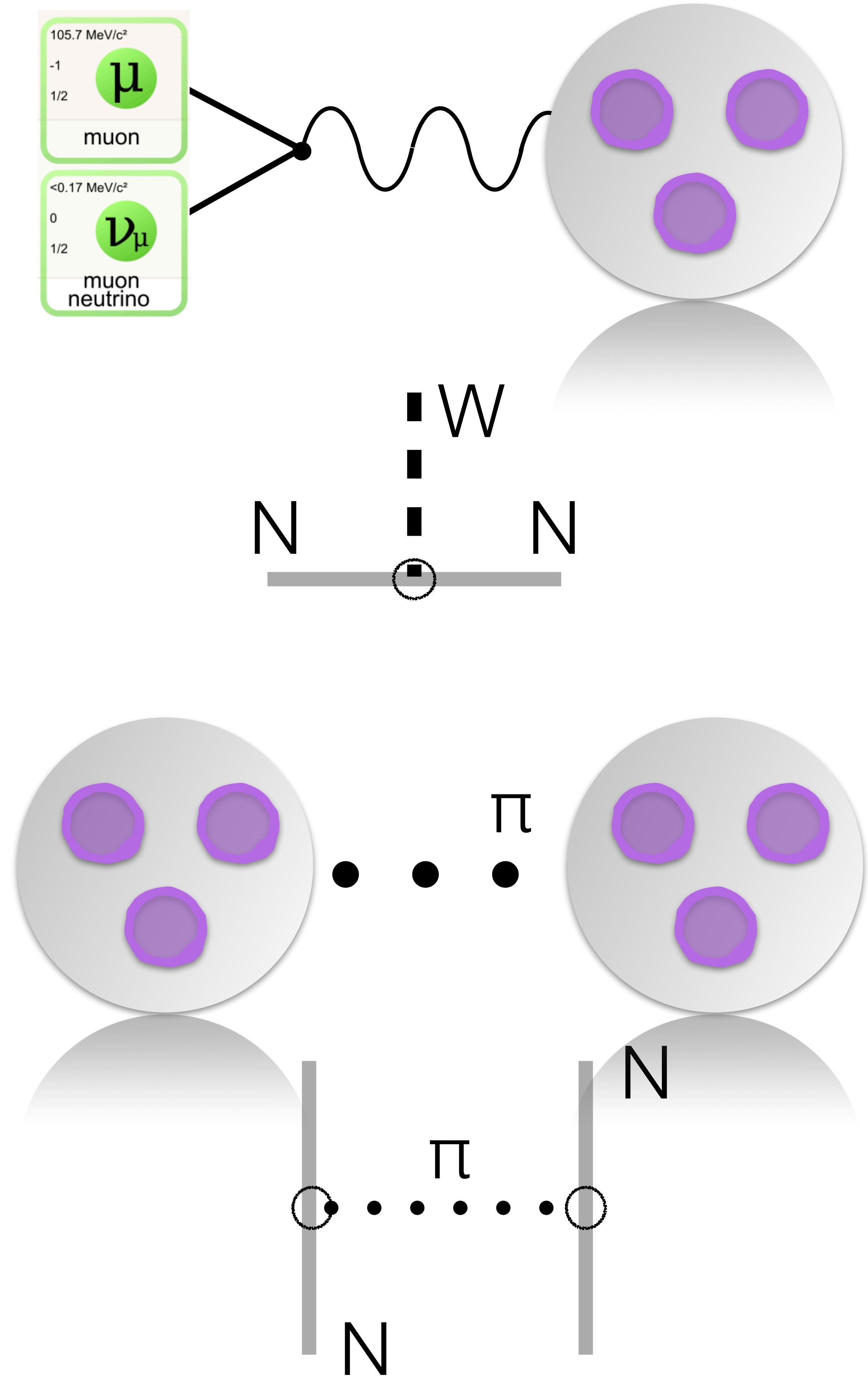

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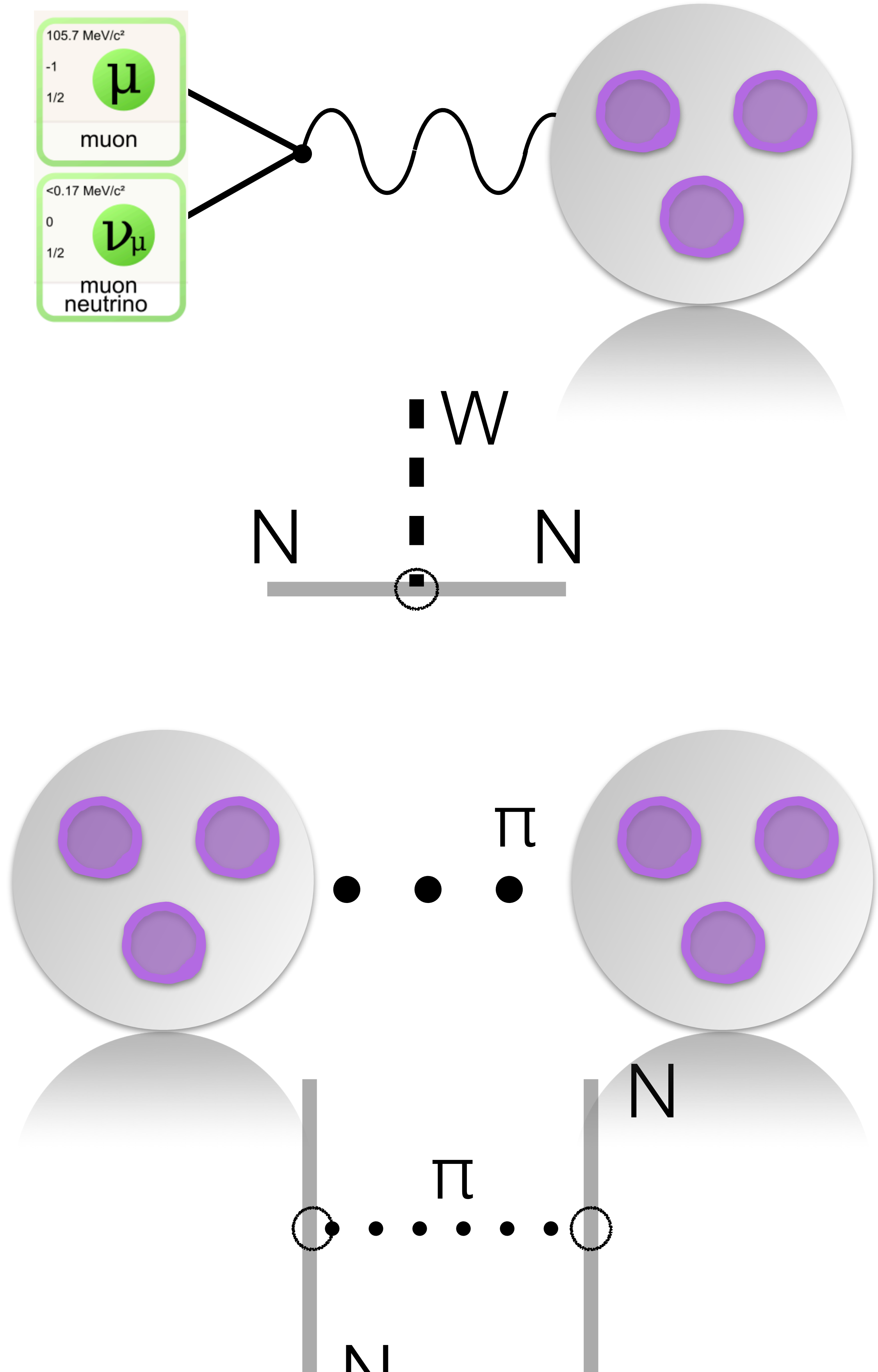

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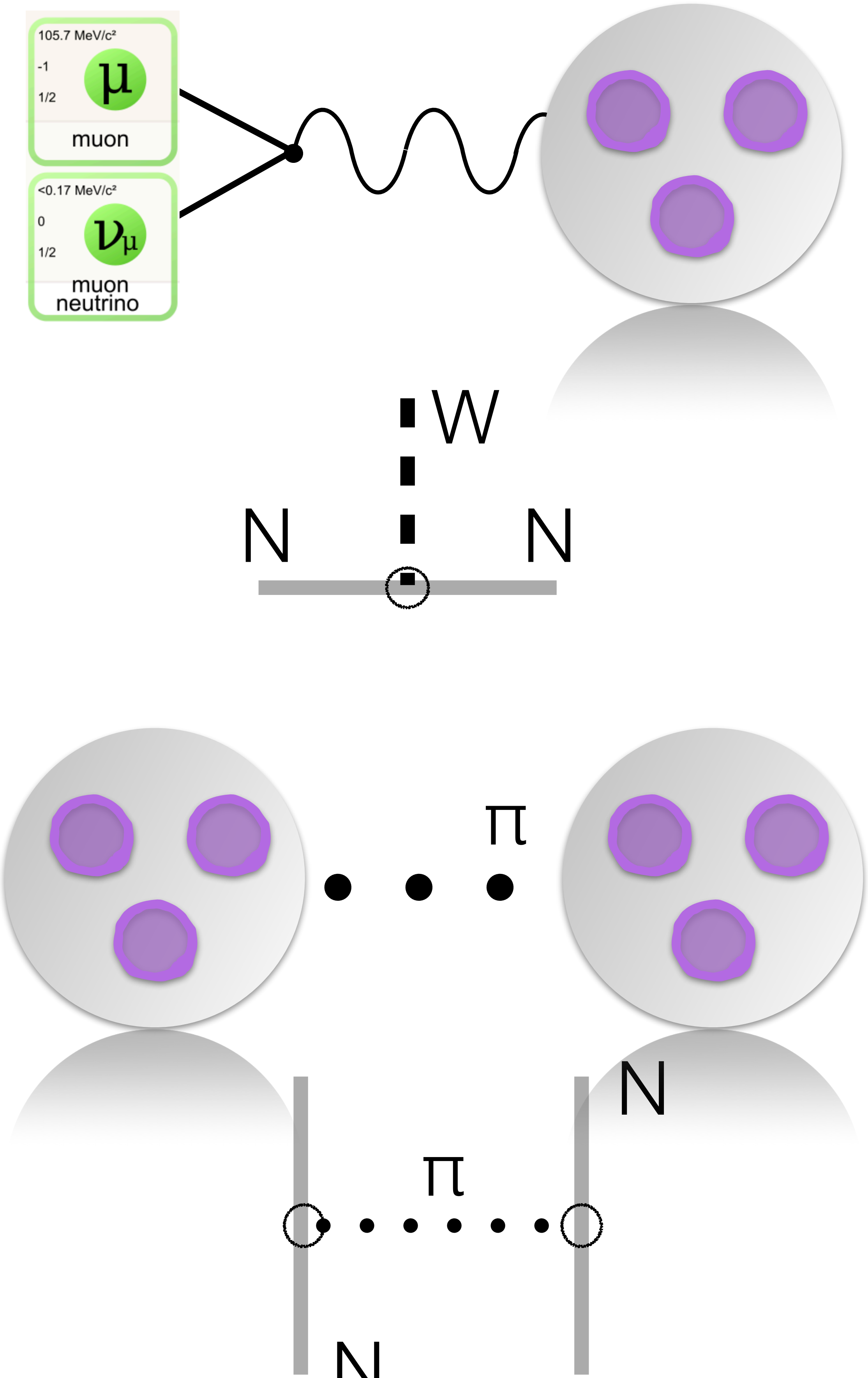

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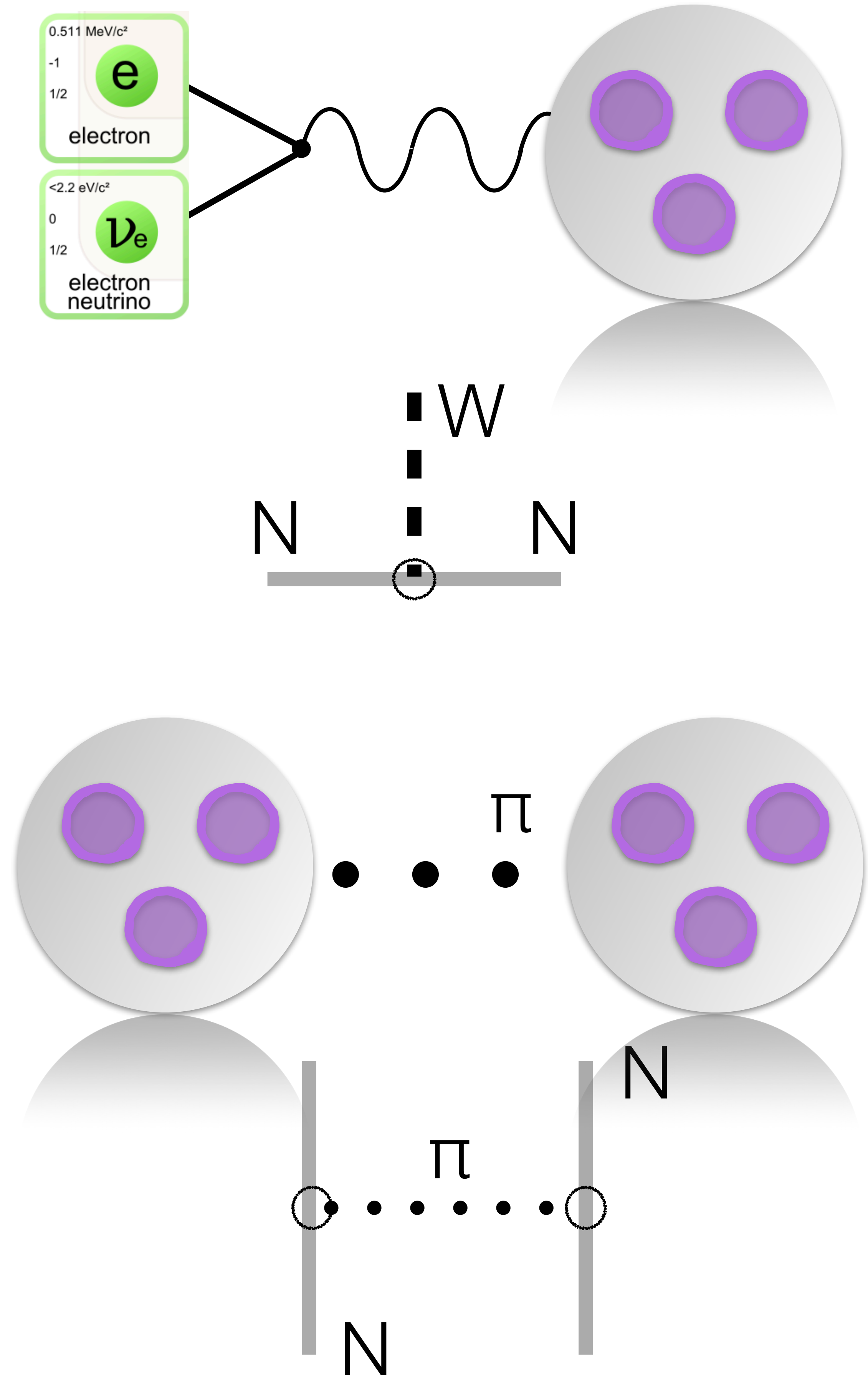

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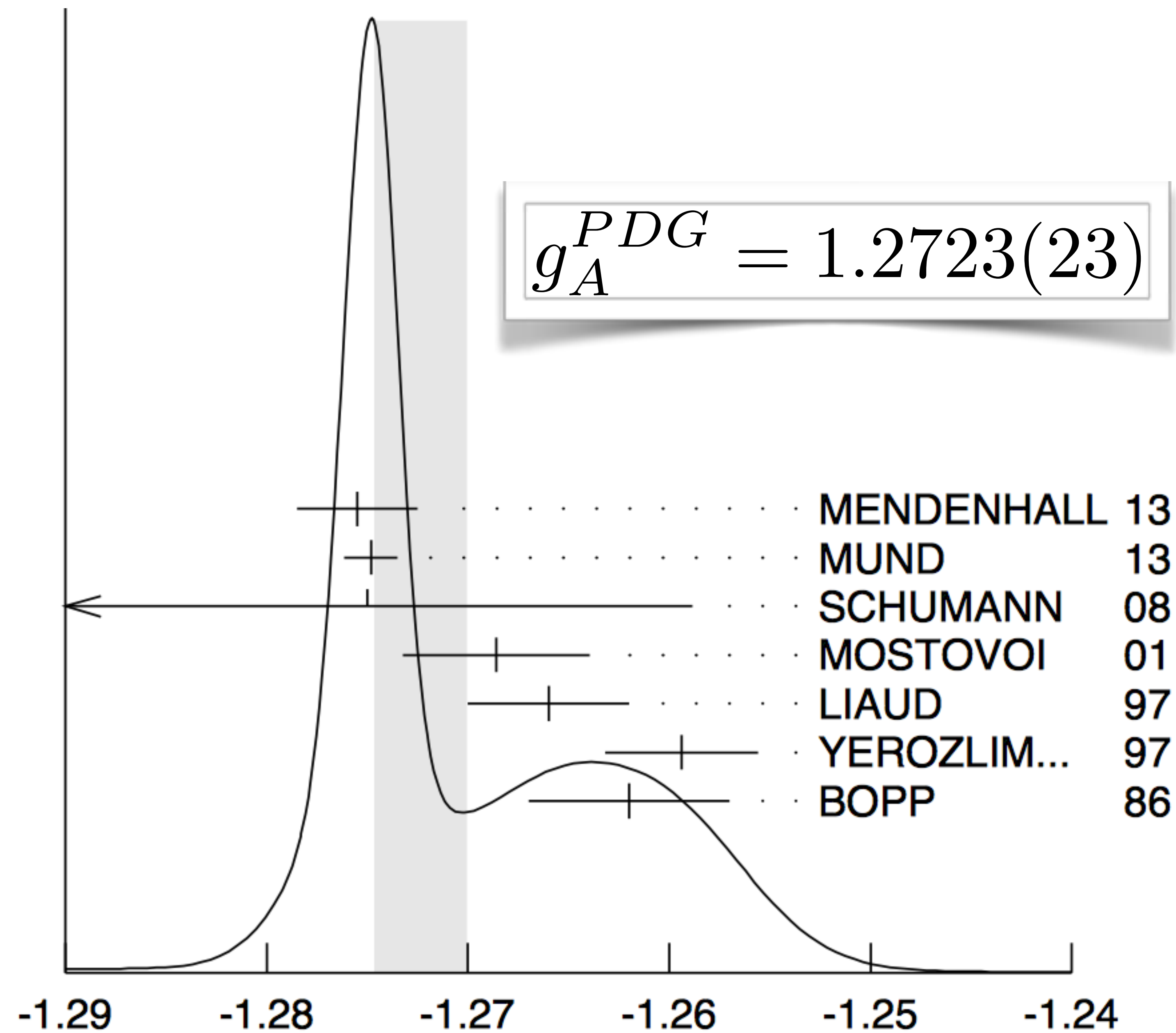
  - Very well determined experimentally ~0.2% (from angular correlations in cold neutron decays)

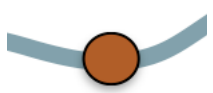


Practical implementation

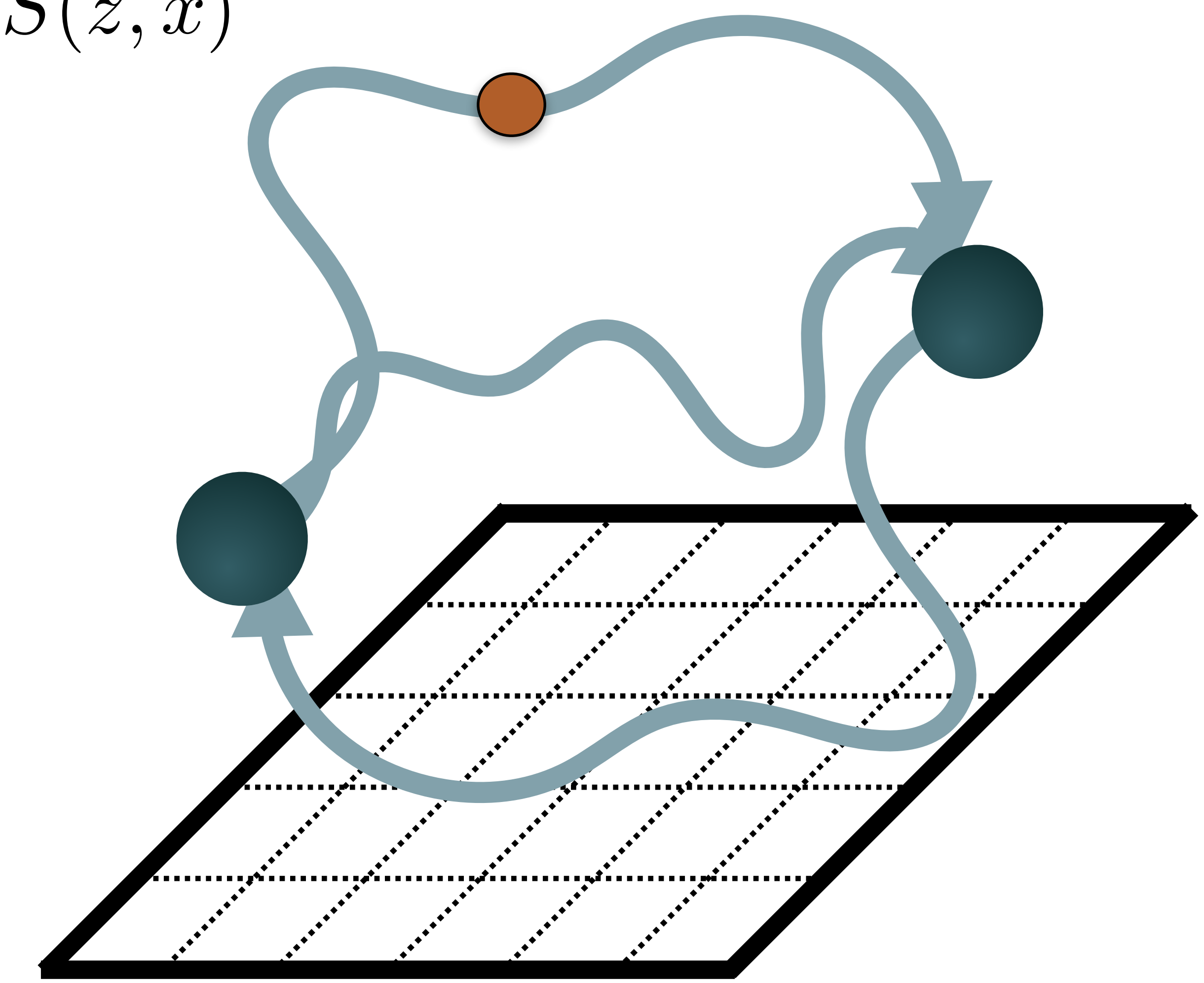
[Bouchard, Chang, Kurt, Orginos, Walker-Loud, PRD96(014504) - arxiv:1612.06963]

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

Feynman-Hellmann propagator



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



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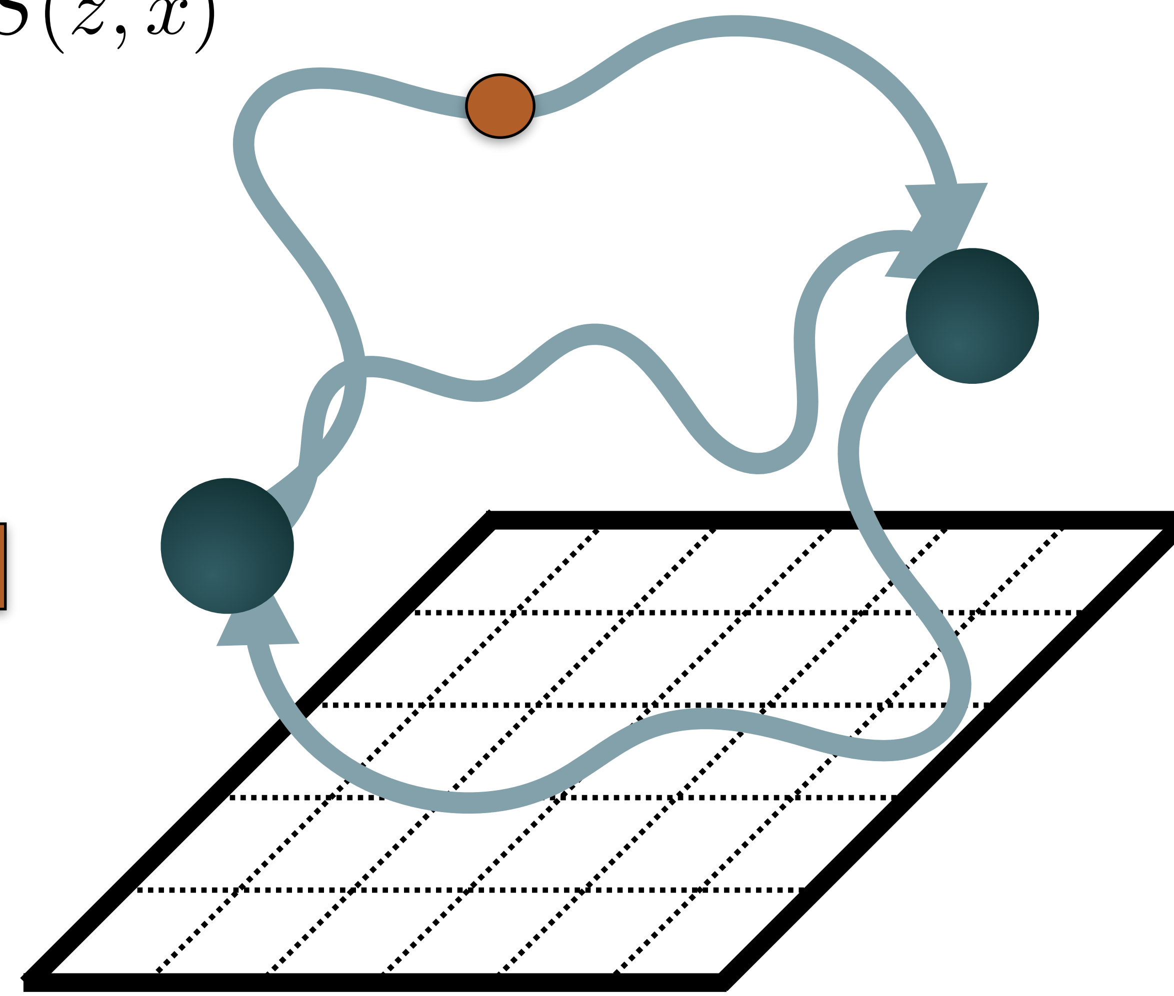

$$N_J(t) = \sum_{t'}\langle\Omega|T\{O(t)J(t')O^{\dagger}(0)\}|\Omega\rangle$$

3-pt function becomes a 2-pt function with FH-prop

Smeared Möbius Domain Wall fermions - I

- ✓ Mixed Action (MA) Lattice QCD
  - ➡ tradeoff between "economical" gauge configurations and good precision

[CallLat PRD96(054513) - arxiv:1701.07559]

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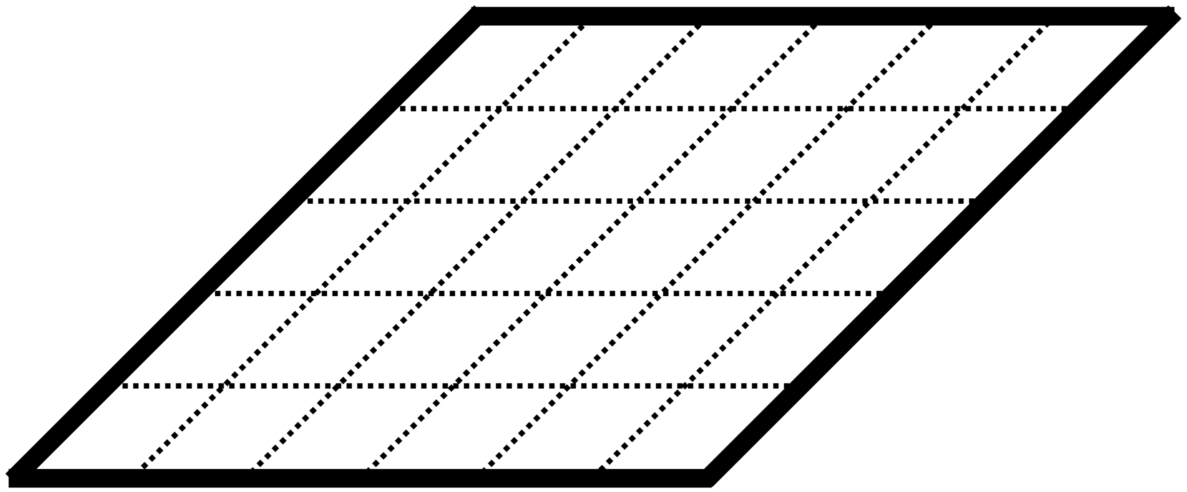

HISQ in the "sea"

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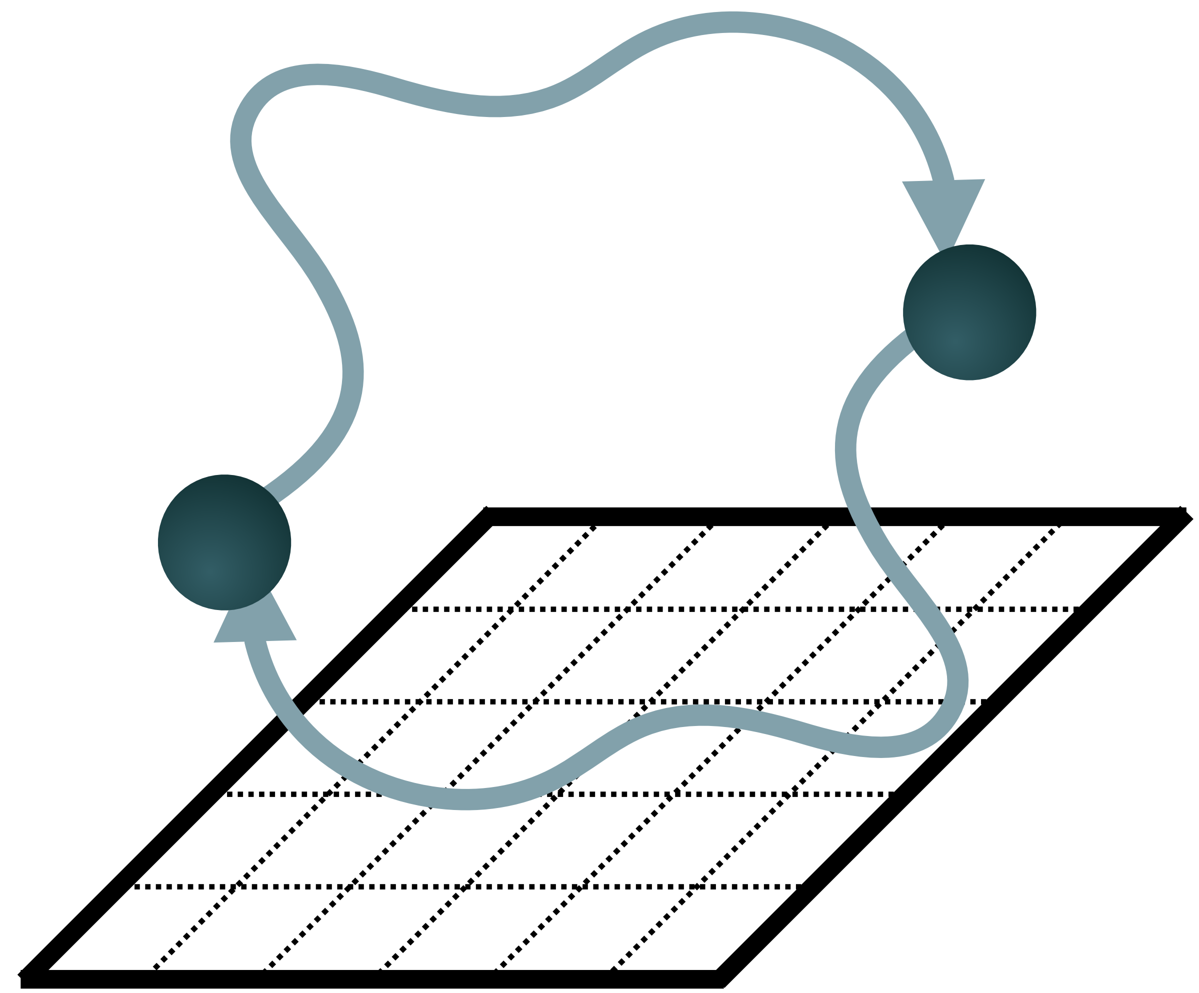
"valence" DWF



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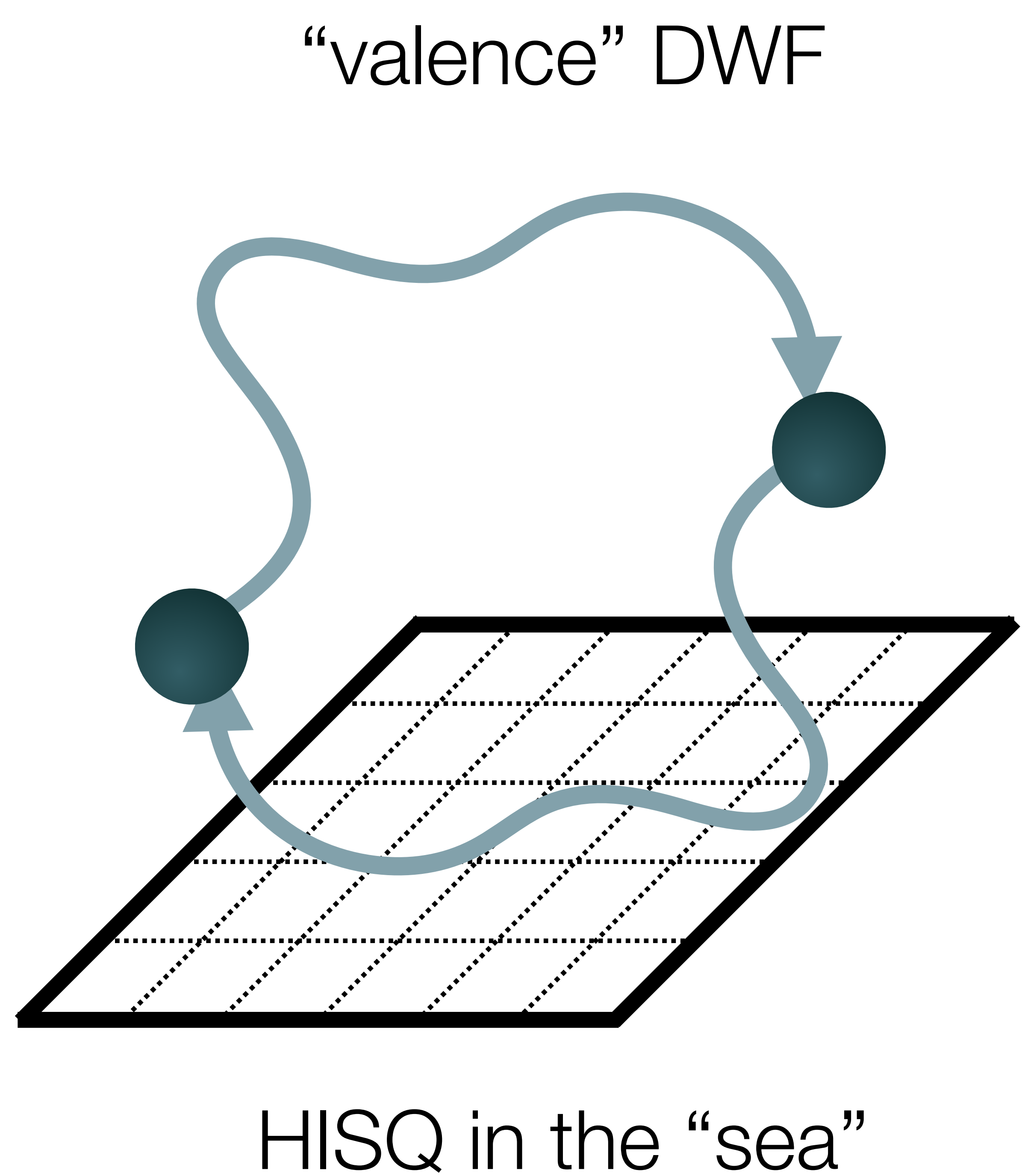
  - ➡ tradeoff between "economical" gauge configurations and good precision
- ✓ Good chiral symmetry properties:
  - ➡ reduce sources of systematics (small lattice artifacts)
  - ➡ simplify treatment of the EFT needed to extrapolate to the continuum and physical pion limit



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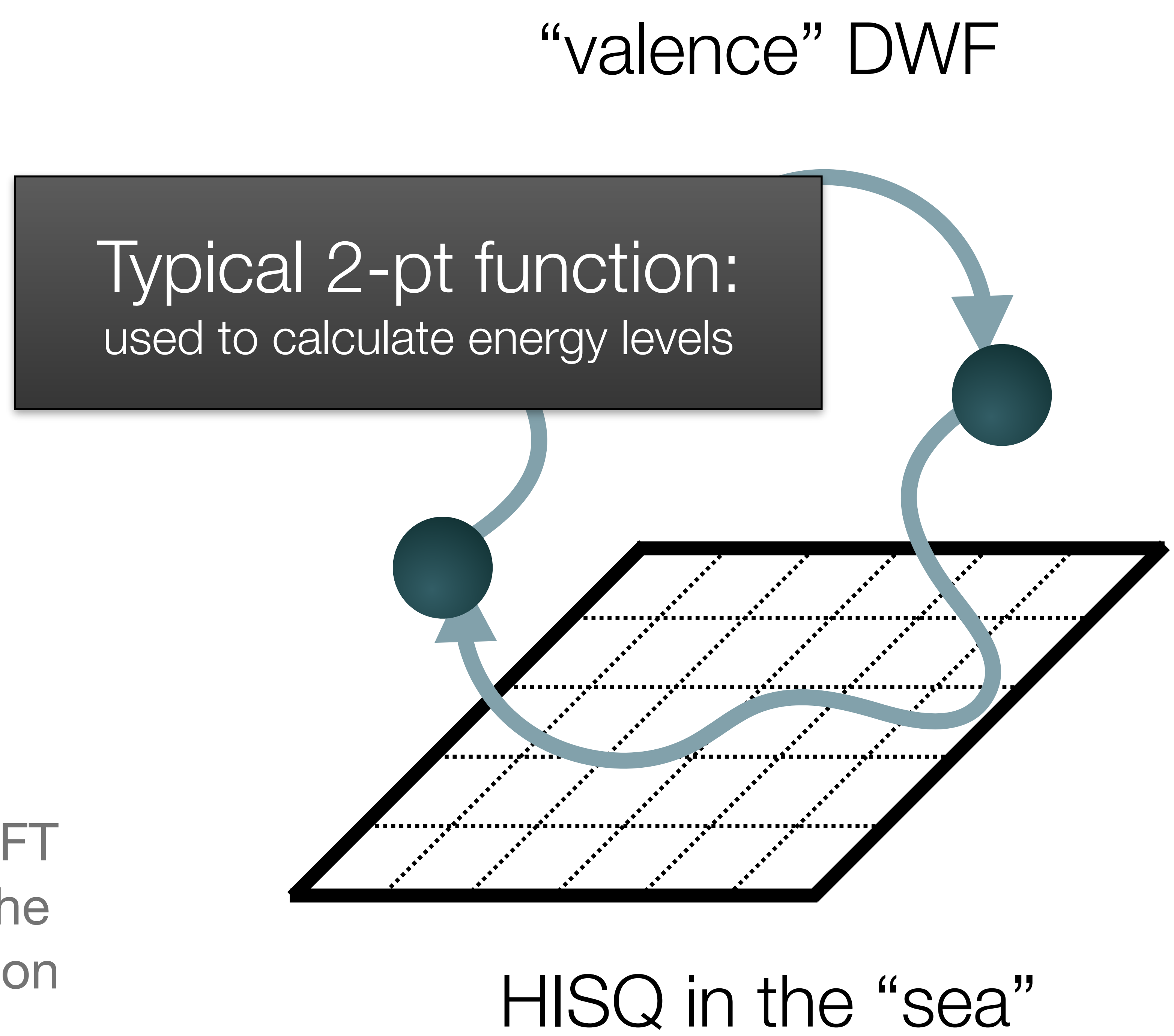
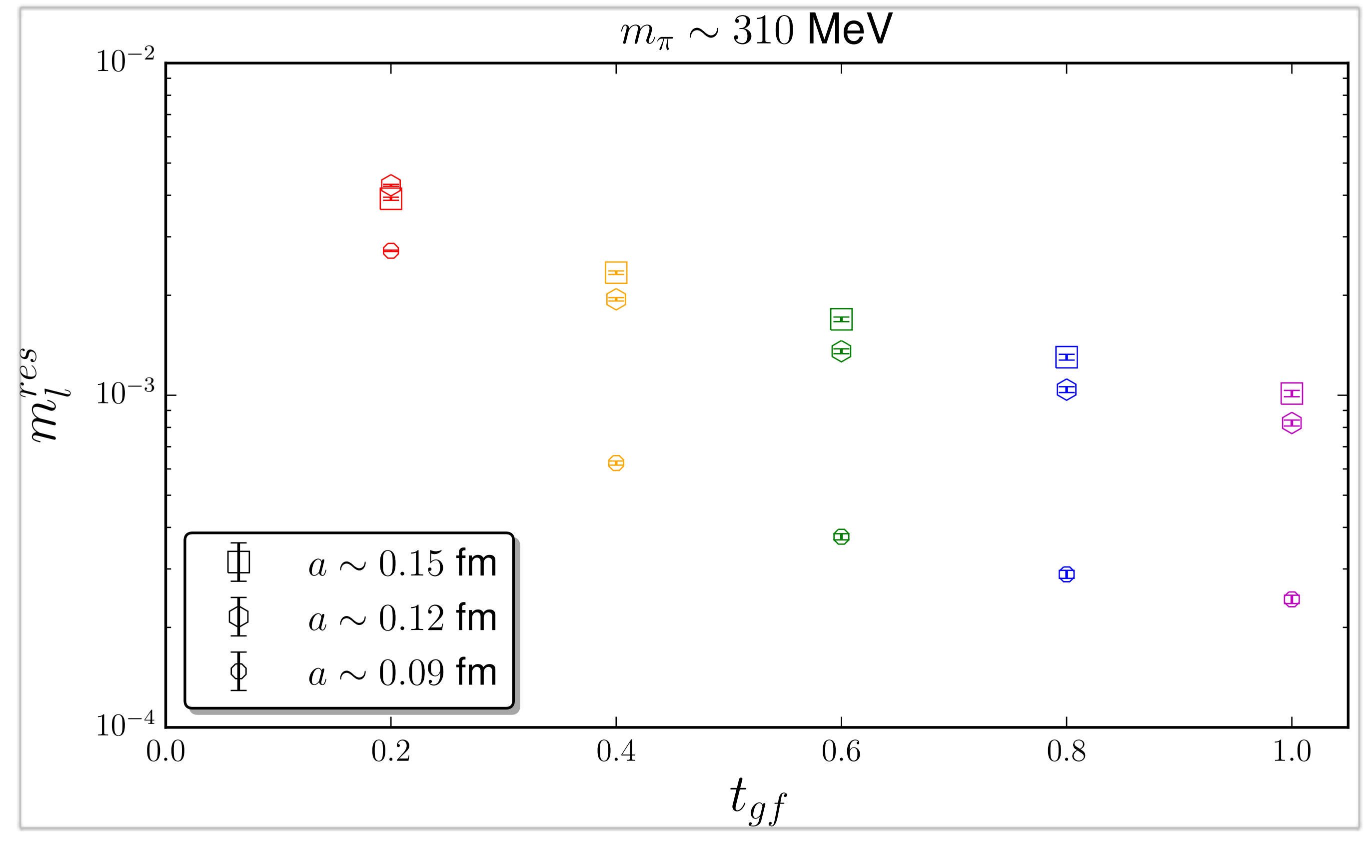


[CallLat PRD96(054513) - arxiv:1701.07559]

Smeared Möbius Domain Wall fermions - II

- ✓ Gradient flow smeared gauge links
  - ➡ parametrized by t_{gf}
- ✓ Reduces sources of residual chiral symmetry breaking
  - ➡ m_{res} is exponentially damped with L_5
  - ➡ Z_A has suppressed lattice spacing dependence and is close to unity
- ✓ Dependence on t_{gf} is removed when performing the continuum limit for physical observables



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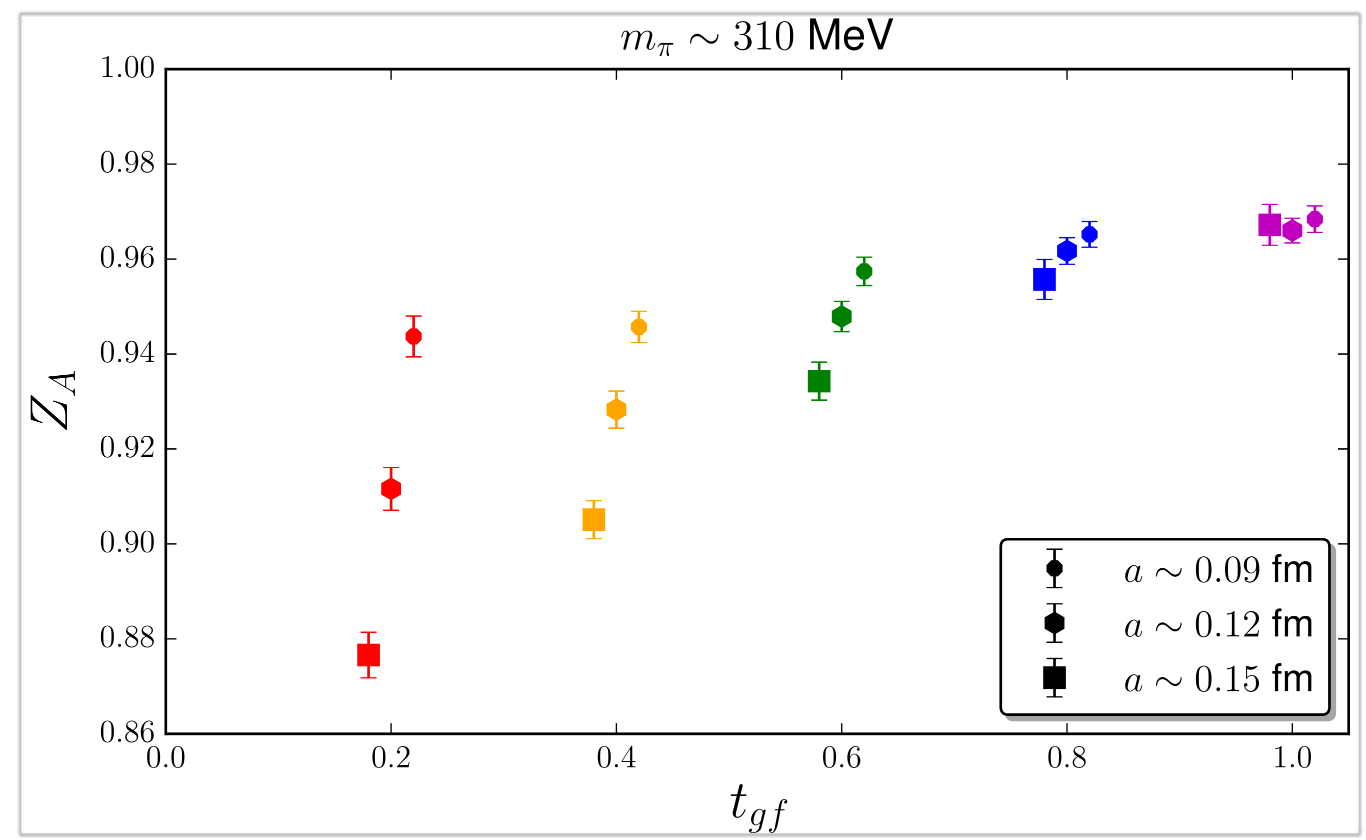

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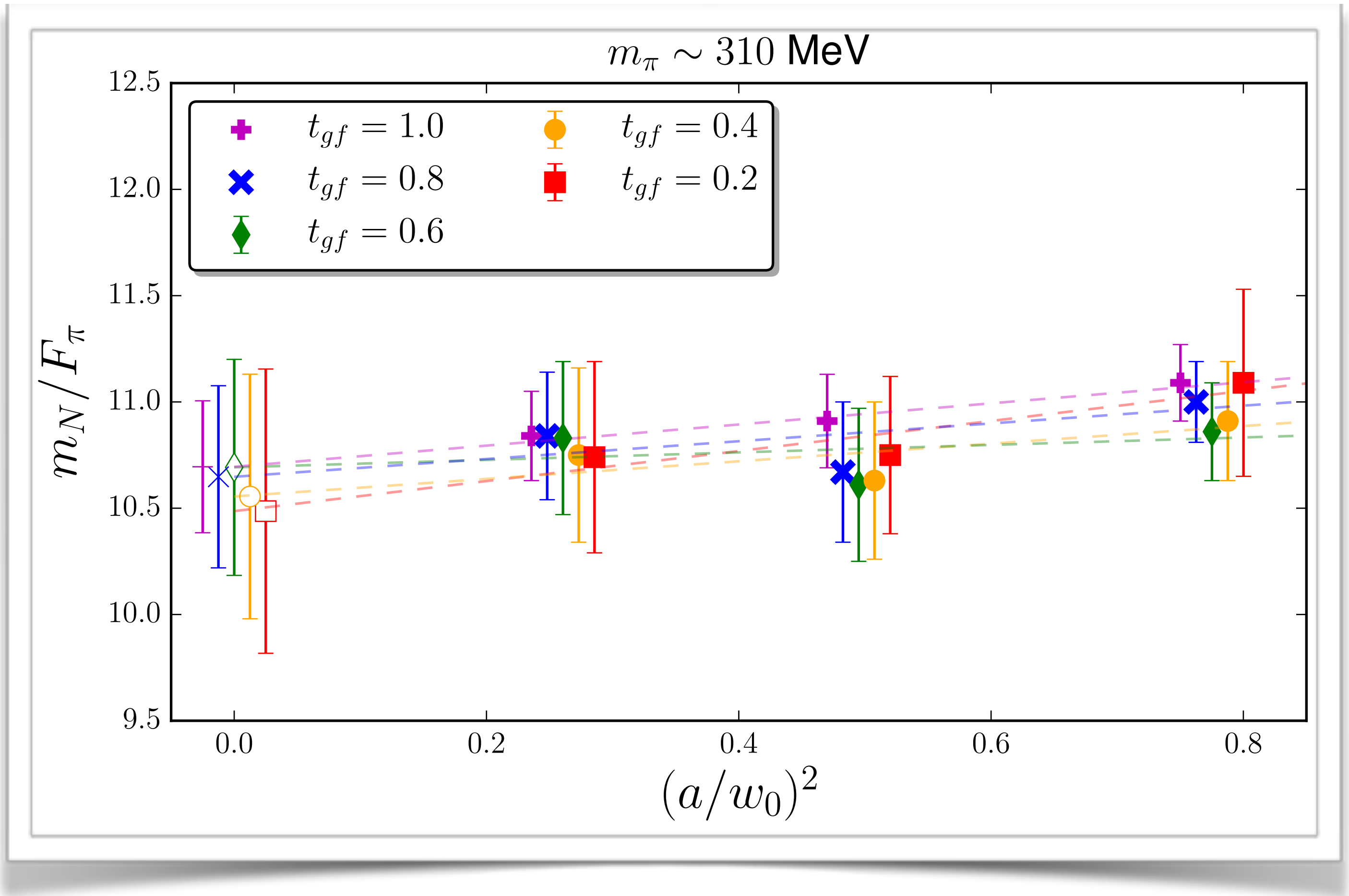

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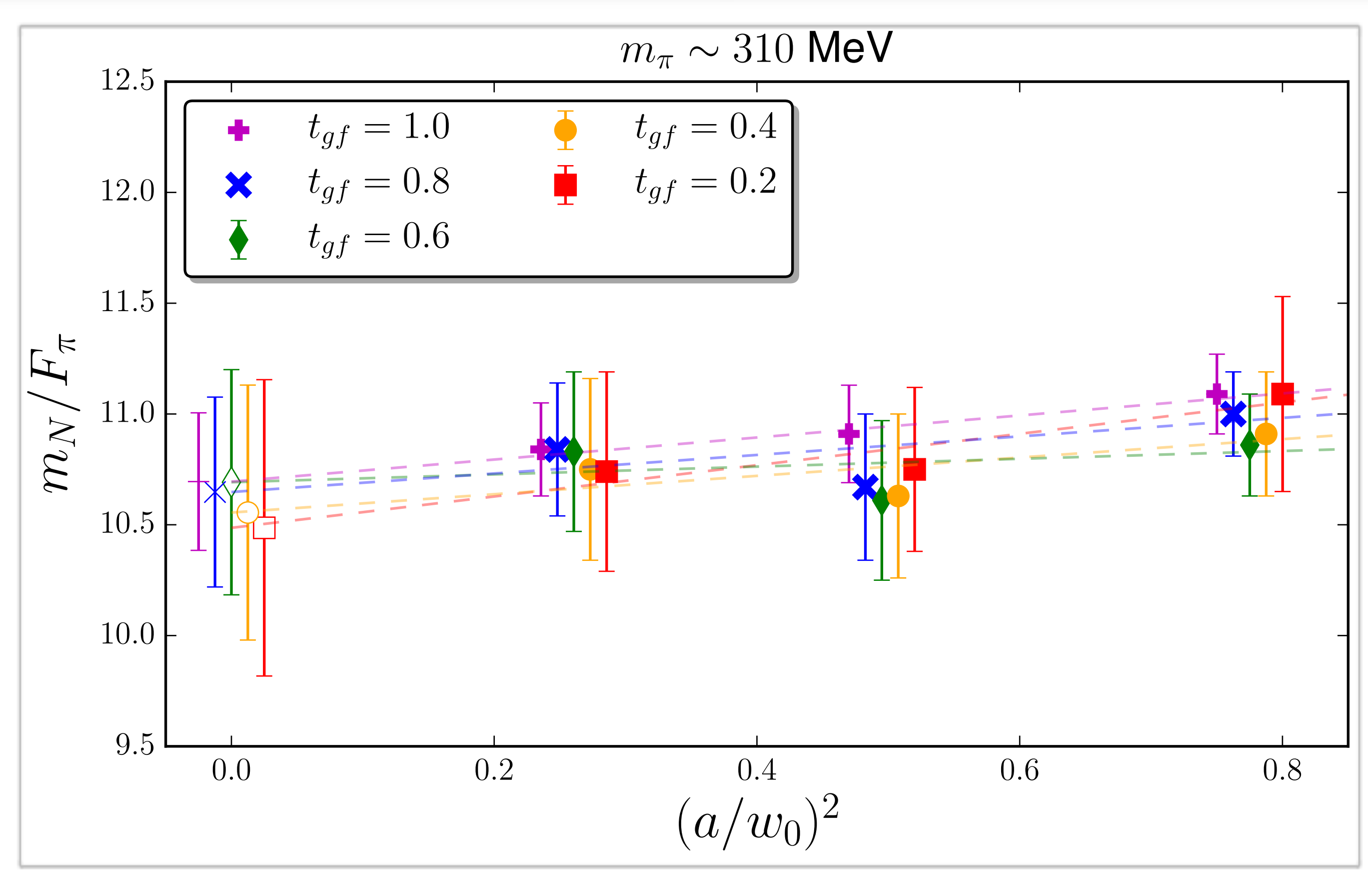
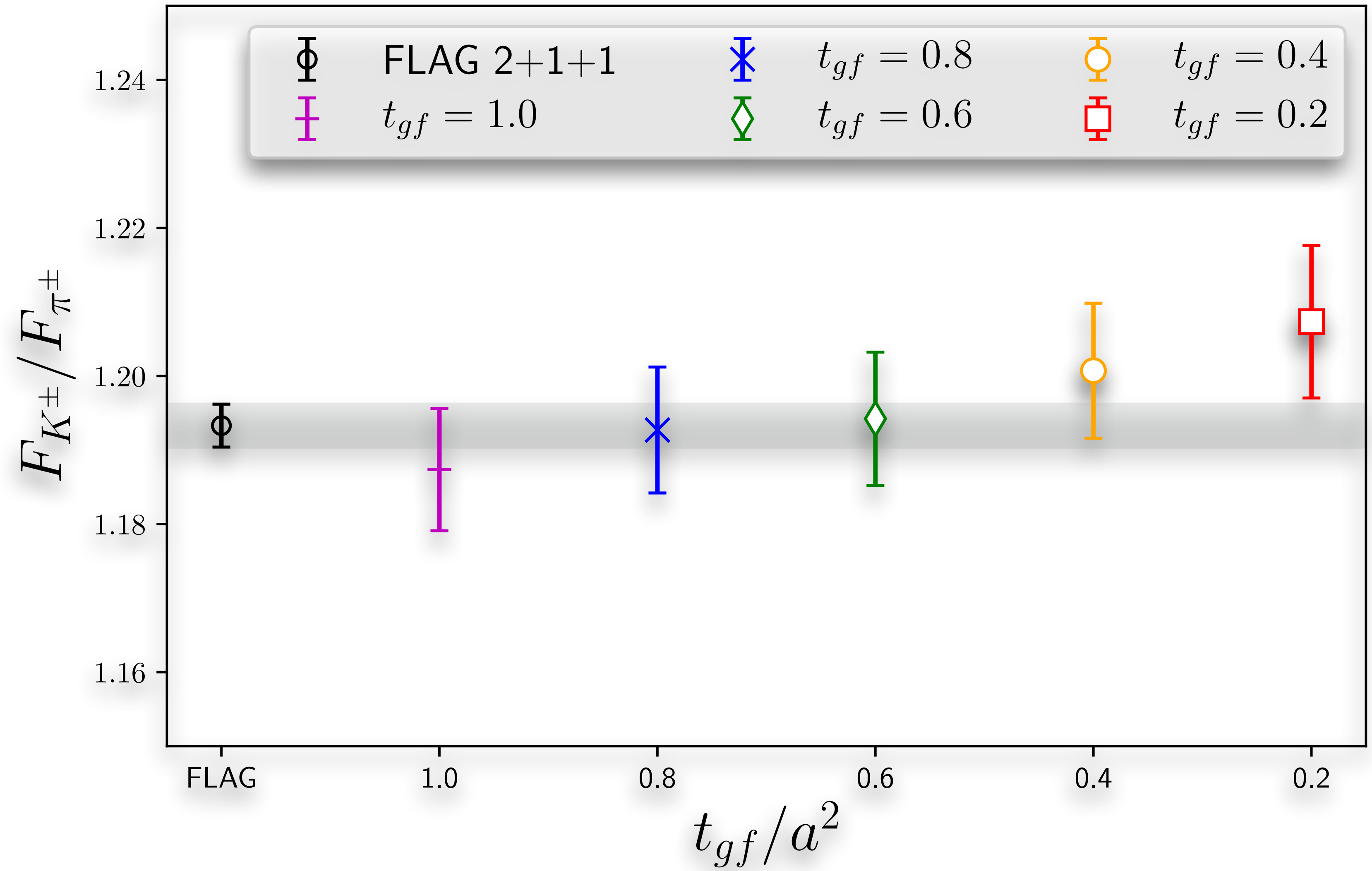


Improvement of statistical and extrapolation uncertainties

Smeared Möbius Domain Wall fermions - III

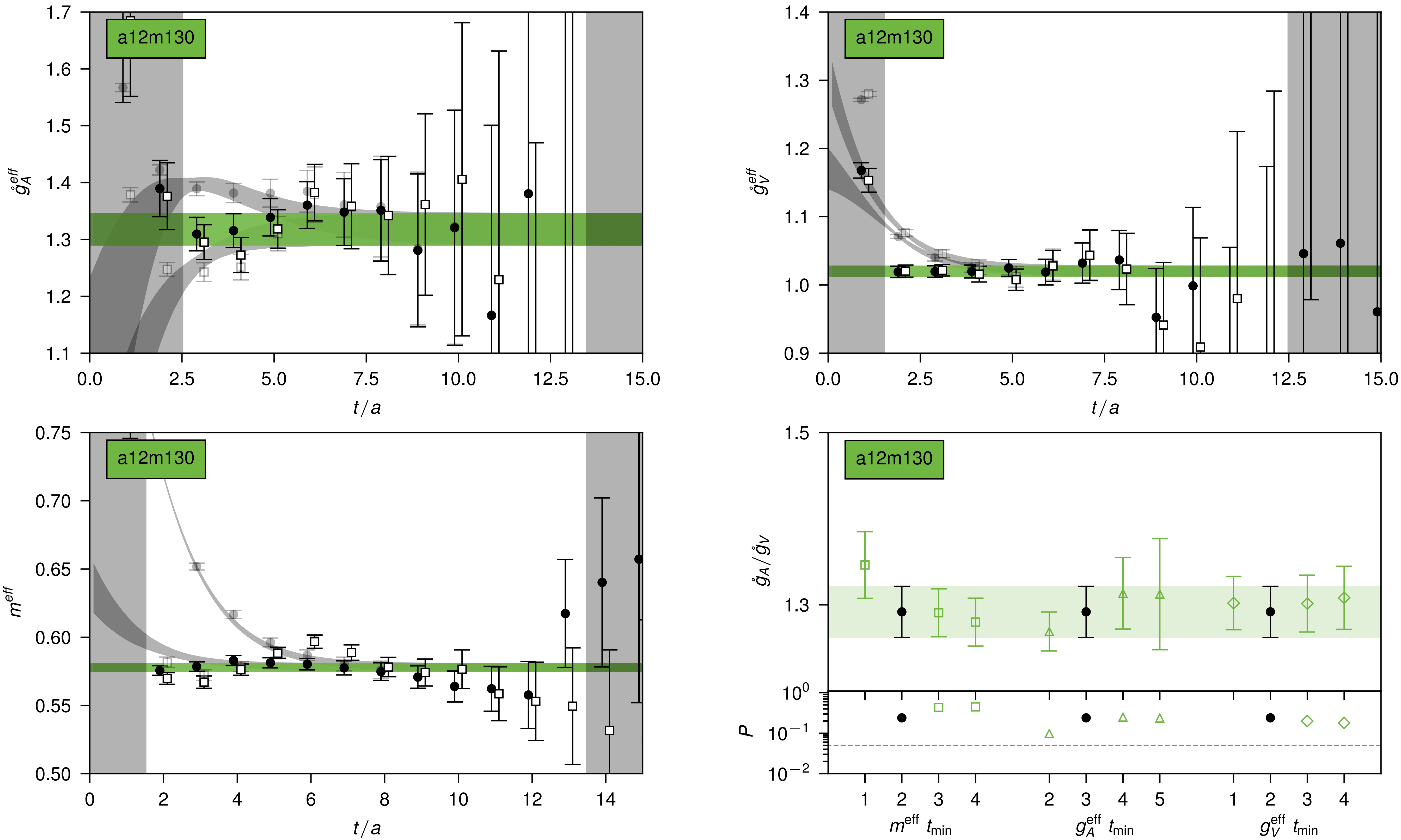
- ✓ Chiral and continuum extrapolation at various t_{gf} values:
  - ➡ 3 lattice spacings, 2 pion masses
  - ➡ include a^2 effects and NLO ChiralPT terms
  - ➡ negligible finite volume effects
- ✓ No dependence on t_{gf} and results are consistent with “world average” from FLAG

Benchmark calculation of meson decay constants



[CalLat Nature 558, 91-94 (2018), arxiv:1805.12130]

Extracting g_A from LQCD data



New method for matrix elements

[Bouchard, Chang, Kurt, Orginos, Walker-Loud, PRD96(014504) - arxiv:1612.06963]

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$$H = H_0 + \lambda H_\lambda$$

$$C_\lambda(t) = \langle \lambda | \hat{O}(t) \hat{O}^\dagger(0) | \lambda \rangle = \frac{1}{\mathcal{Z}_\lambda} \int D\Phi e^{-S-S_\lambda} O(t) O^\dagger(0)$$

$$-\frac{\partial C_\lambda}{\partial \lambda} = \frac{\partial_\lambda \mathcal{Z}_\lambda}{\mathcal{Z}_\lambda} C_\lambda(t) + \frac{1}{\mathcal{Z}_\lambda} \int D\Phi e^{-S-S_\lambda} \int d^4x' j(x')\, \mathcal{O}(t)\mathcal{O}^\dagger(0)$$

$$-\frac{\partial C_\lambda(t)}{\partial \lambda}\bigg|_{\lambda=0} = -C_\lambda(t) \int d^4x' \langle \Omega | j(x') | \Omega \rangle + \int dt' \langle \Omega | T\{\mathcal{O}(t) J(t') \mathcal{O}^\dagger(0)\} | \Omega \rangle$$

New method for matrix elements

[Bouchard, Chang, Kurt, Orginos, Walker-Loud, PRD96(014504) - arxiv:1612.06963]

- Handle the next major source of systematic effects: excited states contamination.
- Based on the Feynman-Hellmann theorem
  - relates matrix elements to linear variations in the energy spectrum with respect to external source
  - ➡ rewording: relates a 3-point correlation function to a change in a 2-point function induced by an external source
  - related to the background field method (but no need for multiple field values) [NPLQCD arxiv:1610.04545]

$$\frac{\partial E_n}{\partial \lambda} = \langle n | H_\lambda | n \rangle$$

$$H = H_0 + \lambda H_\lambda$$

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$$-\frac{\partial C_\lambda(t)}{\partial \lambda}\bigg|_{\lambda=0} = -C_\lambda(t) \int d^4x' \langle \Omega | j(x') | \Omega \rangle + \int dt' \langle \Omega | T\{\mathcal{O}(t) J(t') \mathcal{O}^\dagger(0)\} | \Omega \rangle$$

References related to the new method

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:

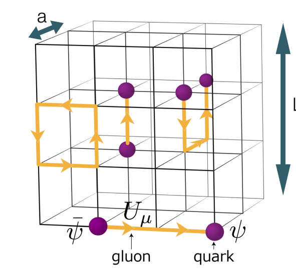
S. Capitani *et. al.* Phys. Rev. D 86, 074502

Similar propagator construction:

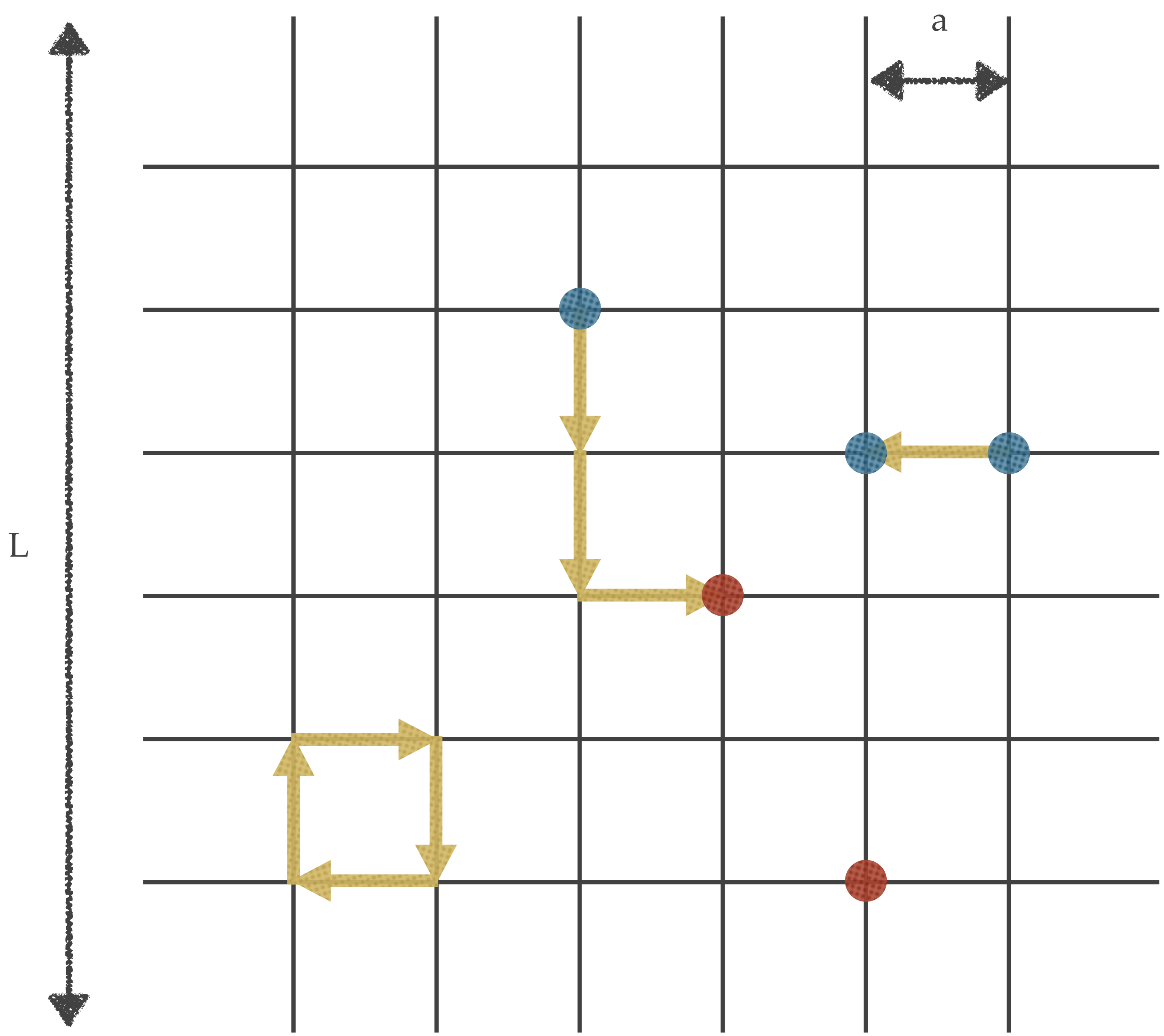
L. Maiani *et. al.* Nucl. Phys. B293 (1987)

G.M. de Divitiis *et. al.* Phys. Lett. B718 (2012)

[KEK-Japan]

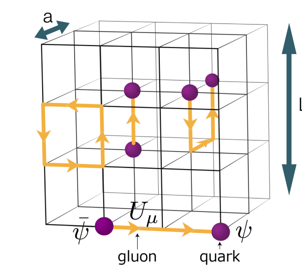


Lattice QCD - basics

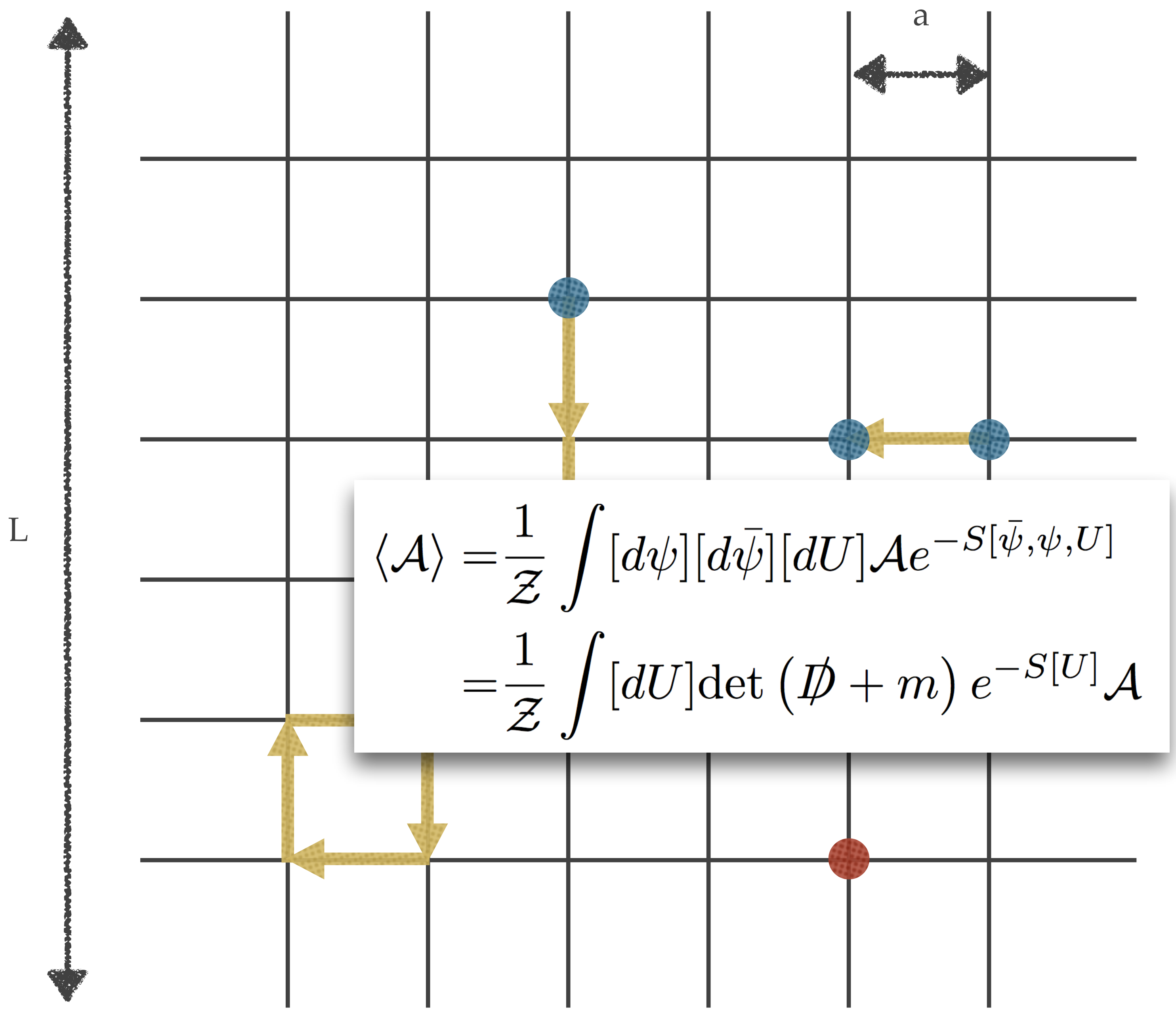


- Discretize space and time
  - lattice spacing “a”
  - lattice size “L”
- Keep all d.o.f. of the theory
  - not a model!
  - no simplifications
- Amenable to numerical methods
  - Monte Carlo sampling
  - use supercomputers
- Precisely quantifiable and improvable errors
  - Systematic
  - Statistical

[KEK-Japan]



Lattice QCD - basics



$$\langle \mathcal{A} \rangle = \frac{1}{\mathcal{Z}} \int [d\psi][d\bar{\psi}][dU] \mathcal{A} e^{-S[\bar{\psi},\psi,U]}$$

$$= \frac{1}{\mathcal{Z}} \int [dU] \det\left(\not{D} + m\right) e^{-S[U]} \mathcal{A}$$

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