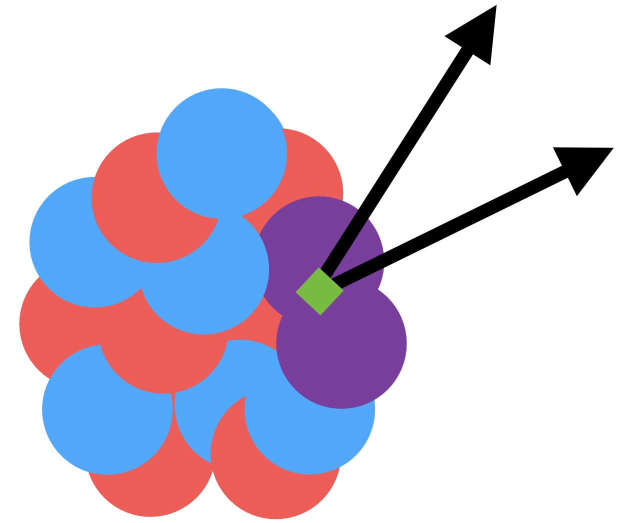
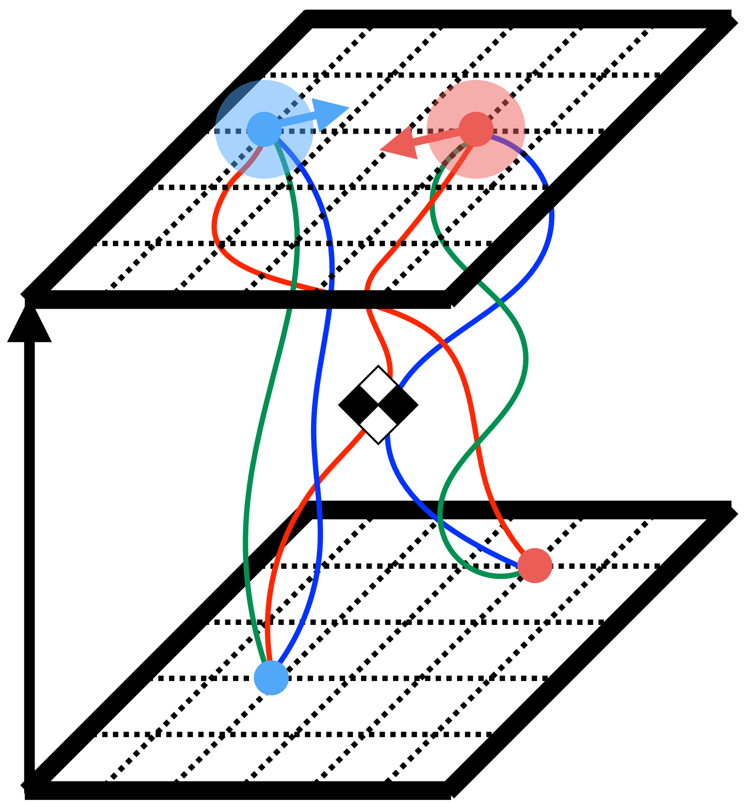


Lattice QCD and nuclear probes of BSM Physics



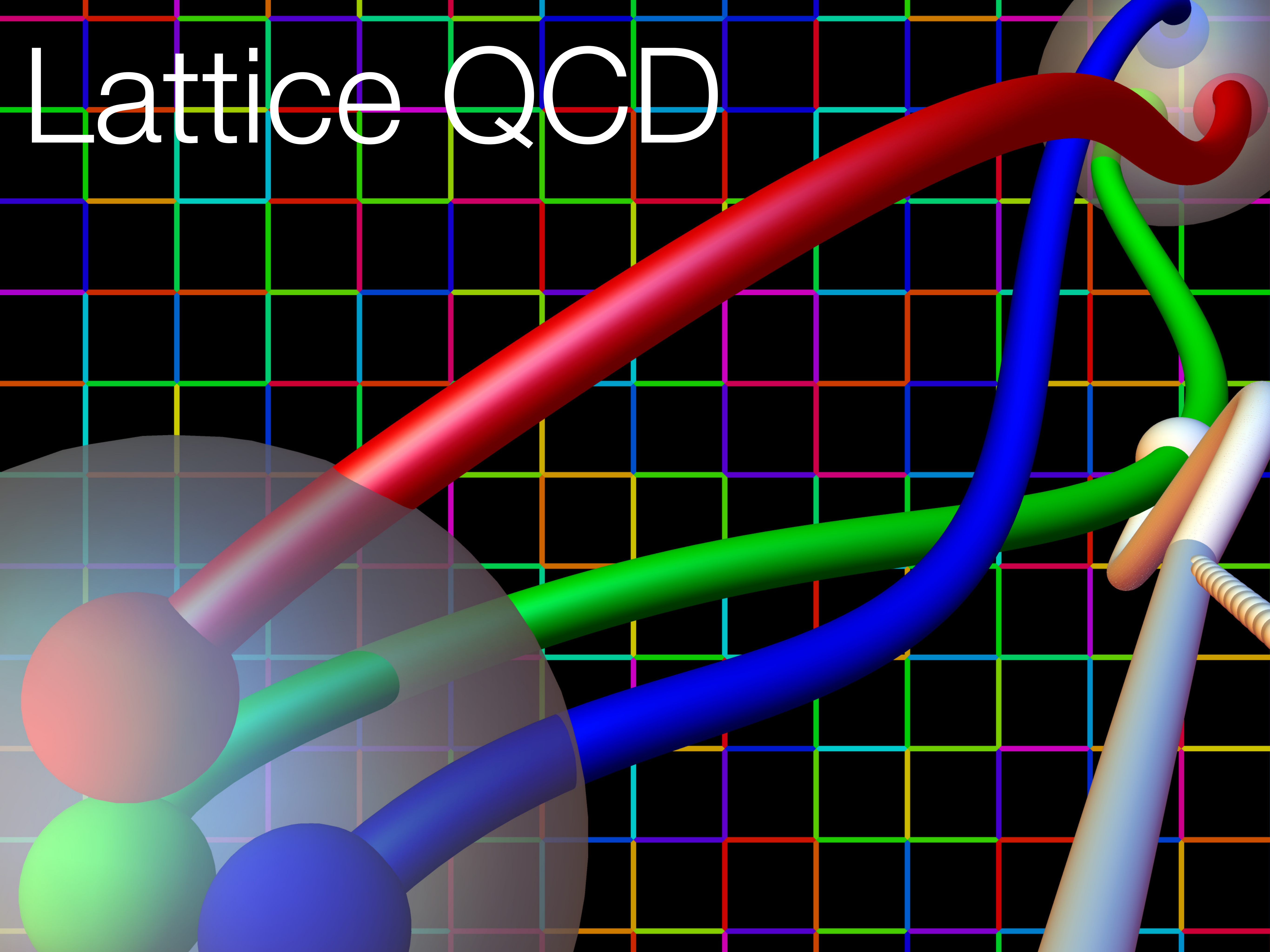
Evan Berkowitz
Institut für Kernphysik
Institute for Advanced Simulation
Forschungszentrum Jülich

Atomic Nuclei as Laboratories for BSM Physics
ECT*
17 April 2019

JÜLICH Forschungszentrum

Cal Lat

Lattice QCD

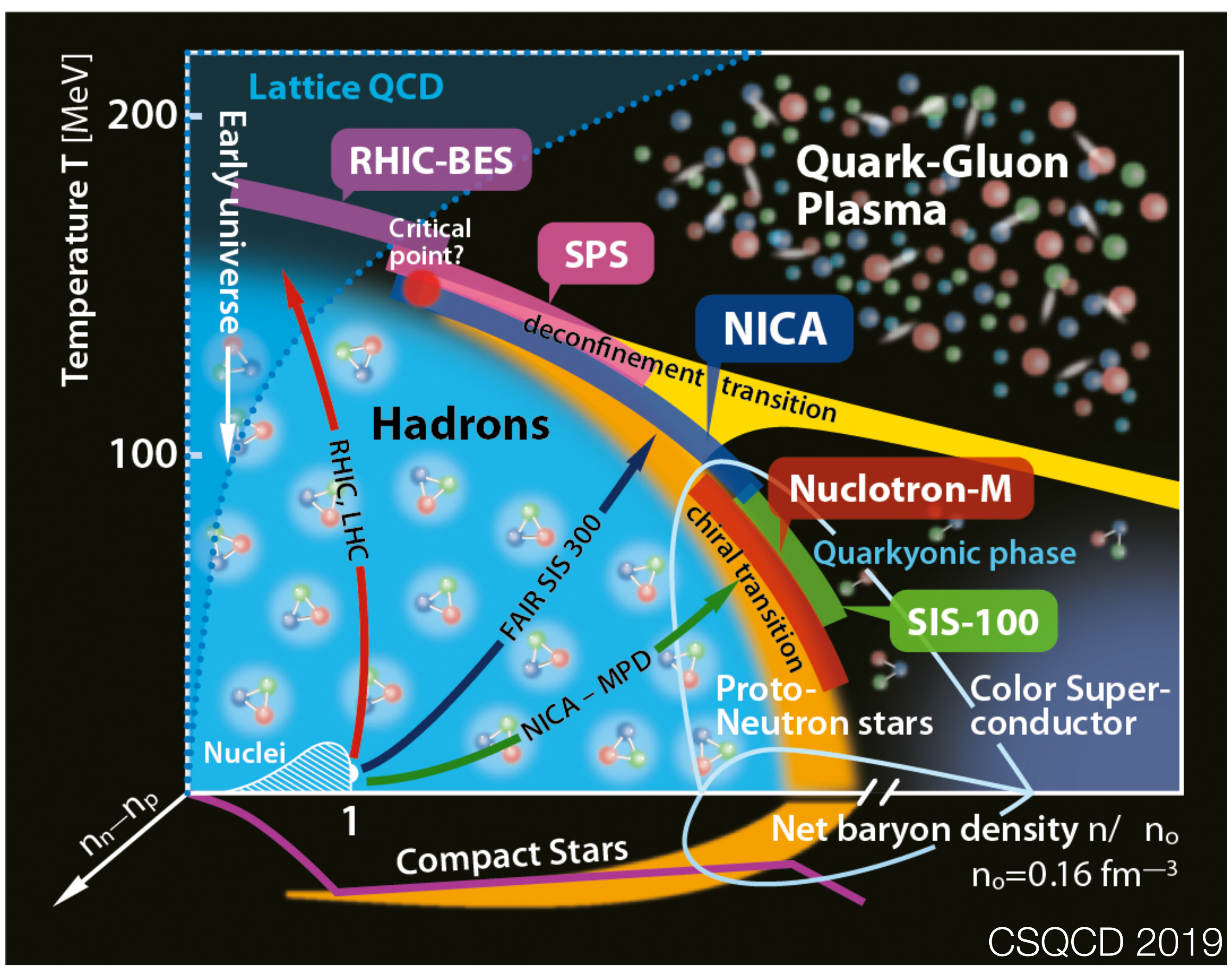


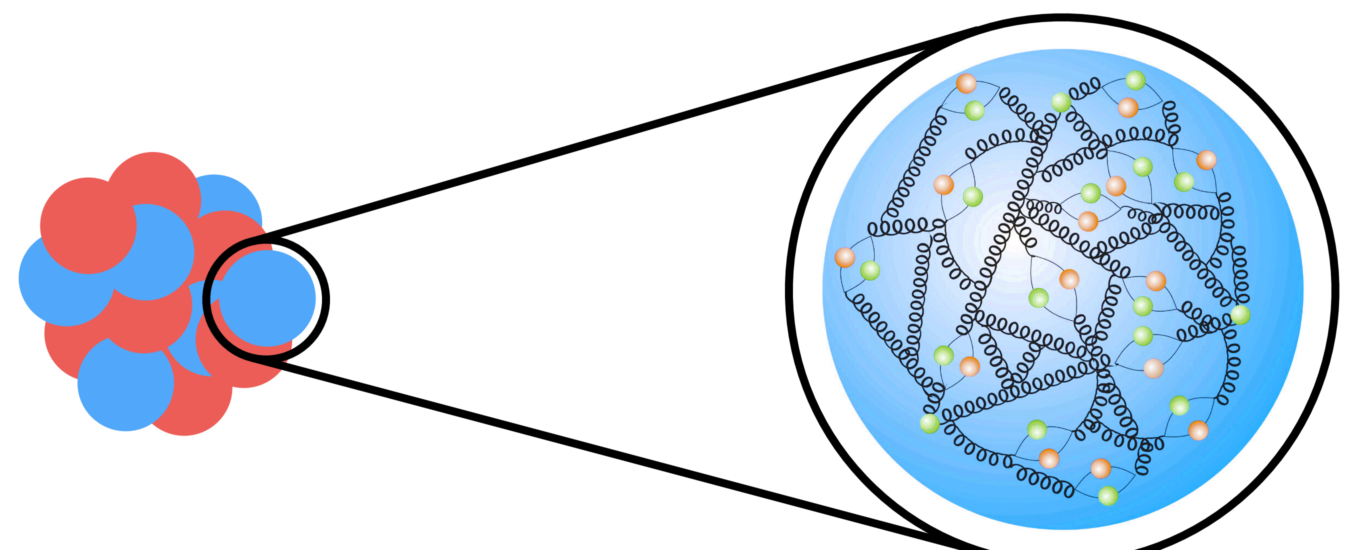
Introduction to LQCD

Glue Quarks

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

Gauge theory masses





Nucleon with quarks and gluons: DESY

Introduction to LQCD

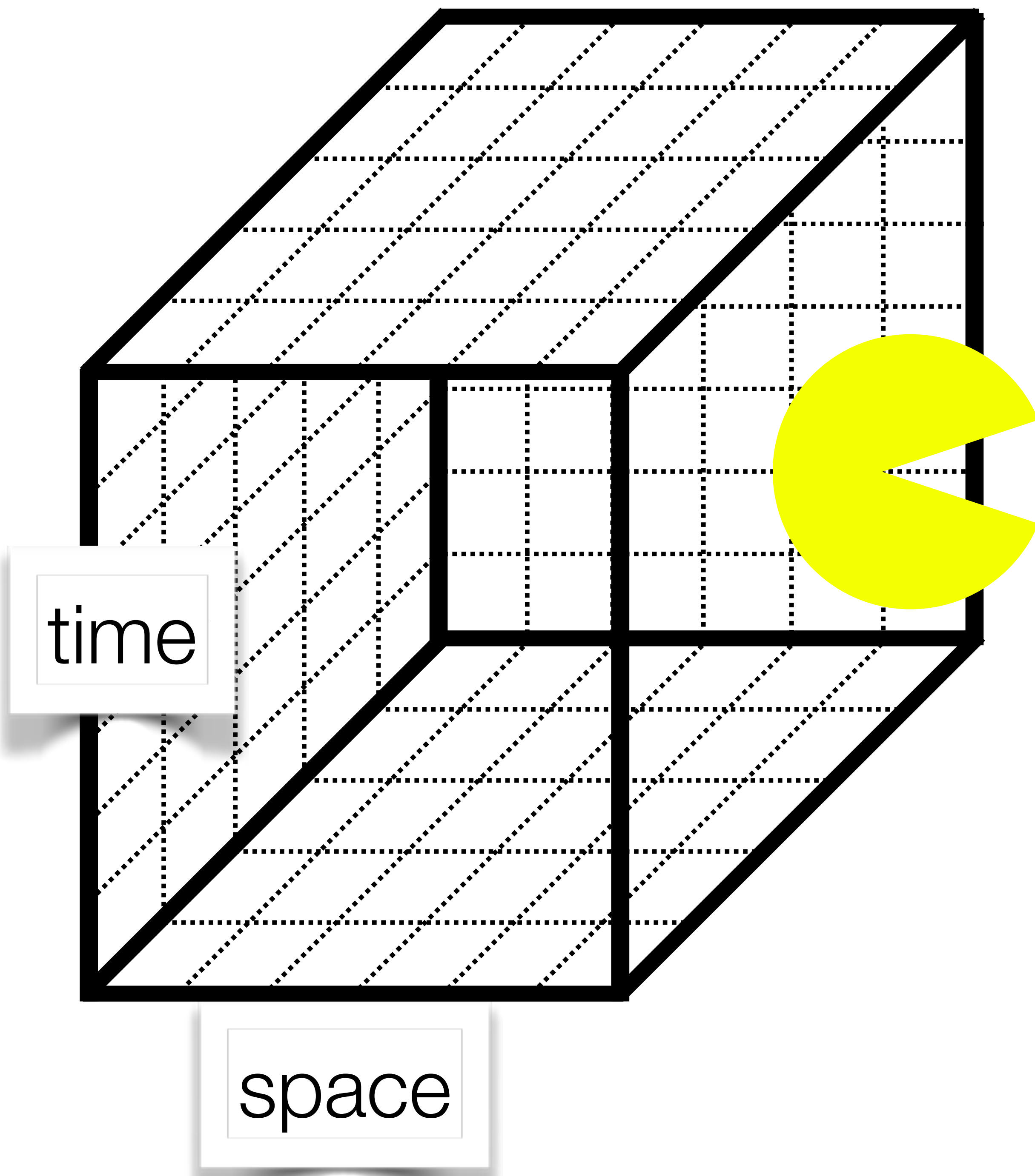
$$\mathcal{L}_{QCD} = -\frac{1}{4}F^2 + \bar{\psi}(i\not{D} + m)\psi$$

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

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

lattice

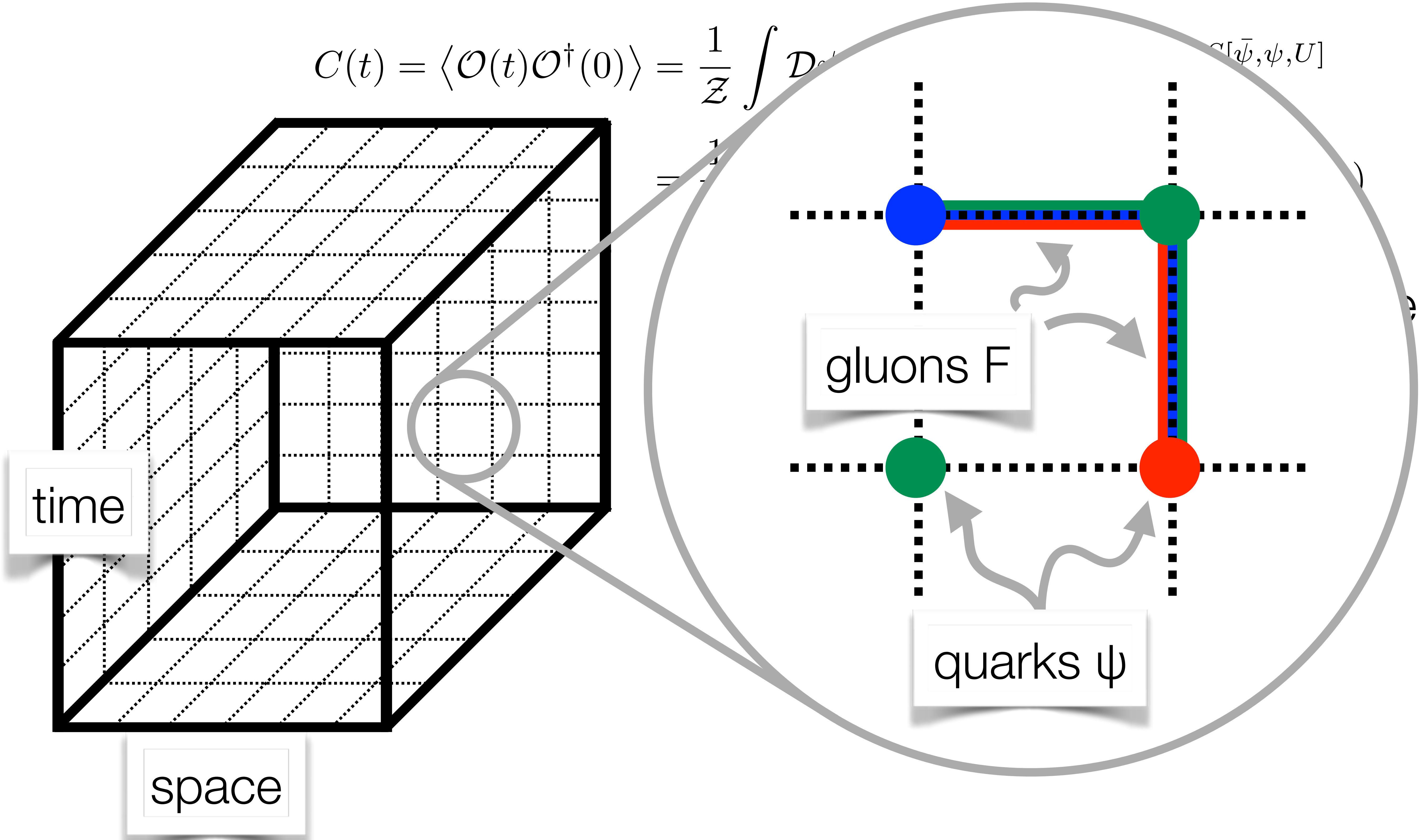
finite volume



Introduction to LQCD

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

$$C(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0) \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D} \ldots$$

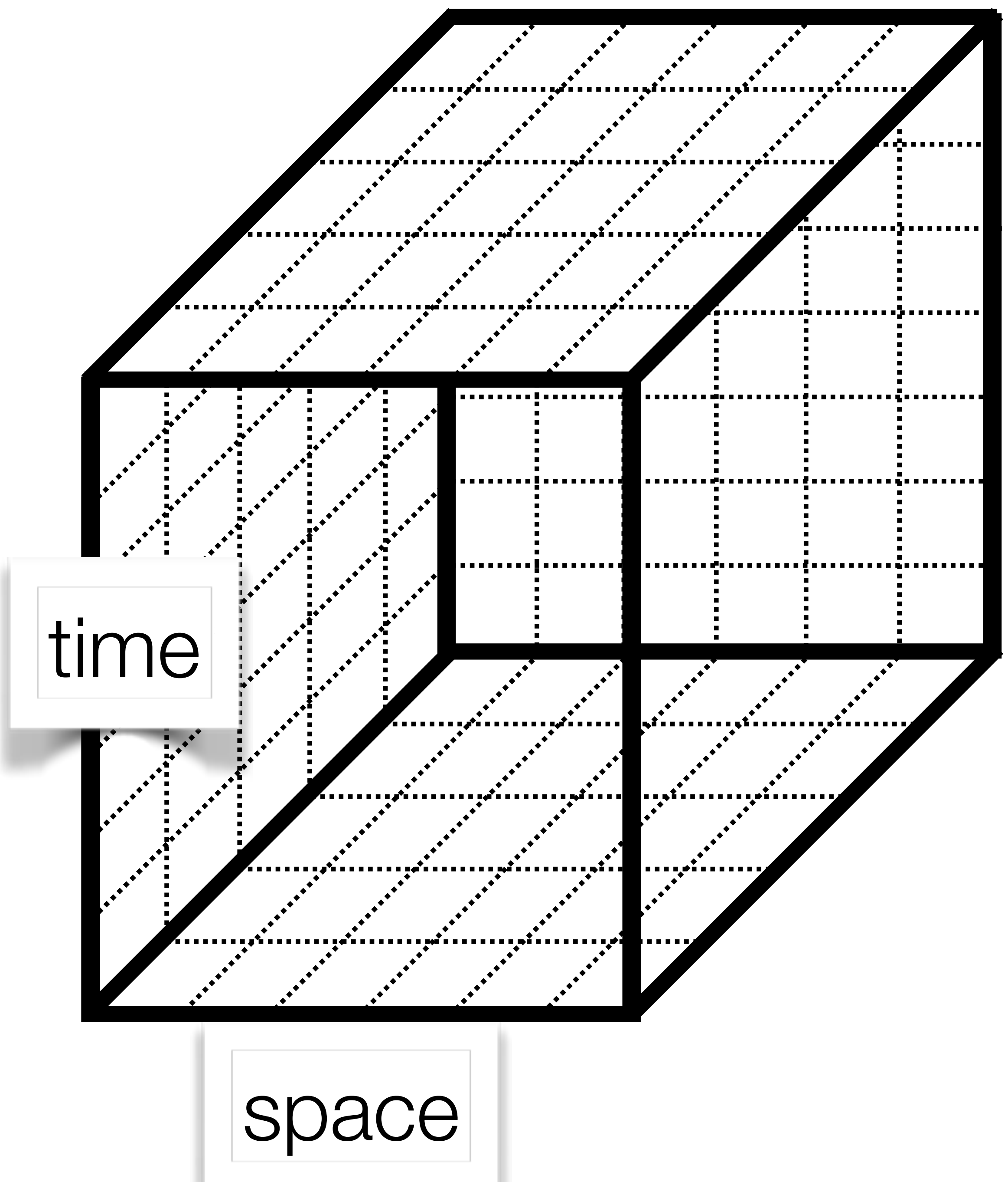


Introduction to LQCD

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

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

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



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

Markov Chain Monte Carlo

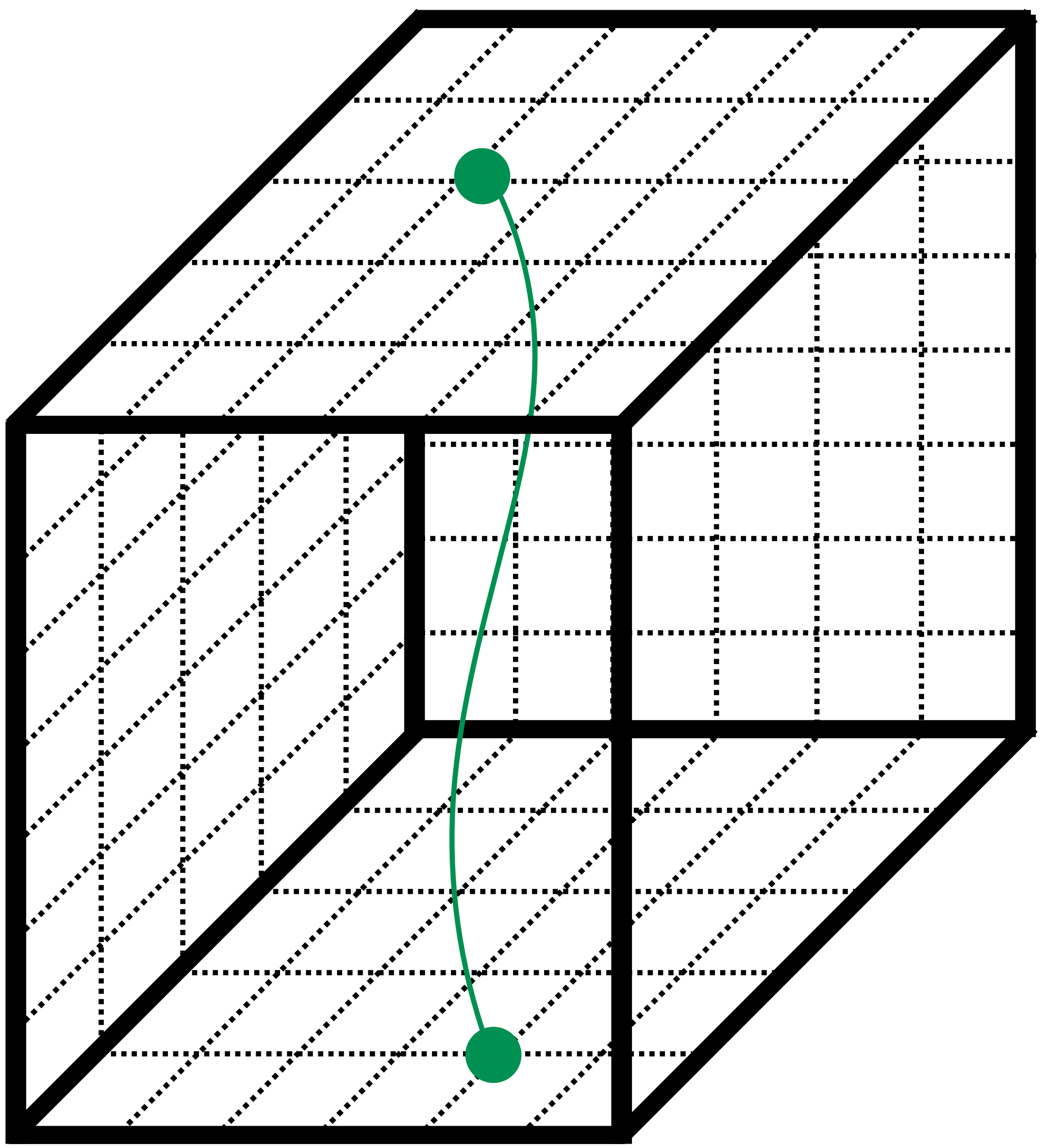
$$\approx \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}(t)\mathcal{O}^\dagger(0)[U_i] \; + O\left(\frac{1}{\sqrt{N}}\right)$$

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

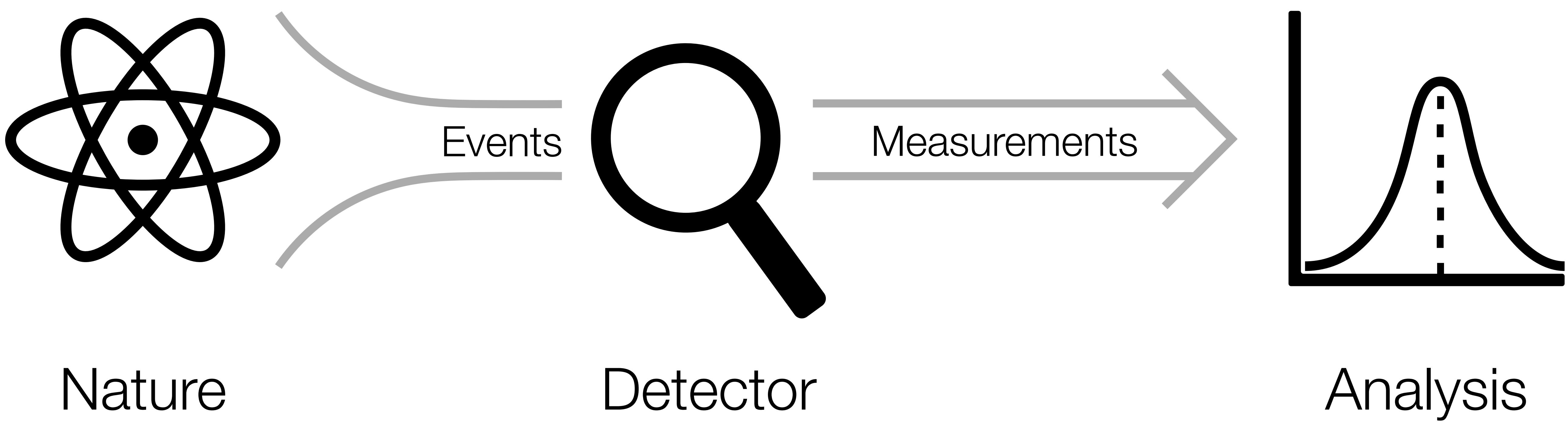
U-dependent

($N_x\ N_t\ N_c\ N_s$) on a side

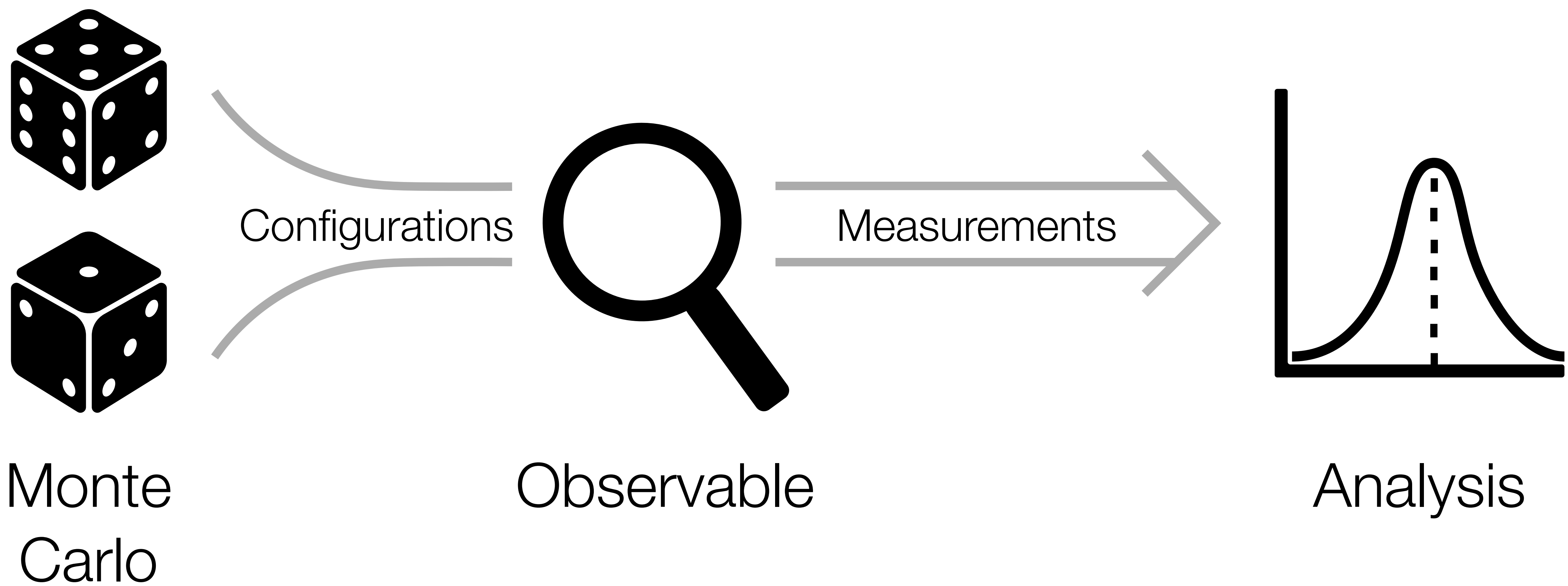
($48^3 \times 64 \times 3 \times 4$)=127 401 984

$$\left(\not{D}[U] + M\right)_{xf} S_{fi} = i\delta_{xi}$$

Analogy with Experiment

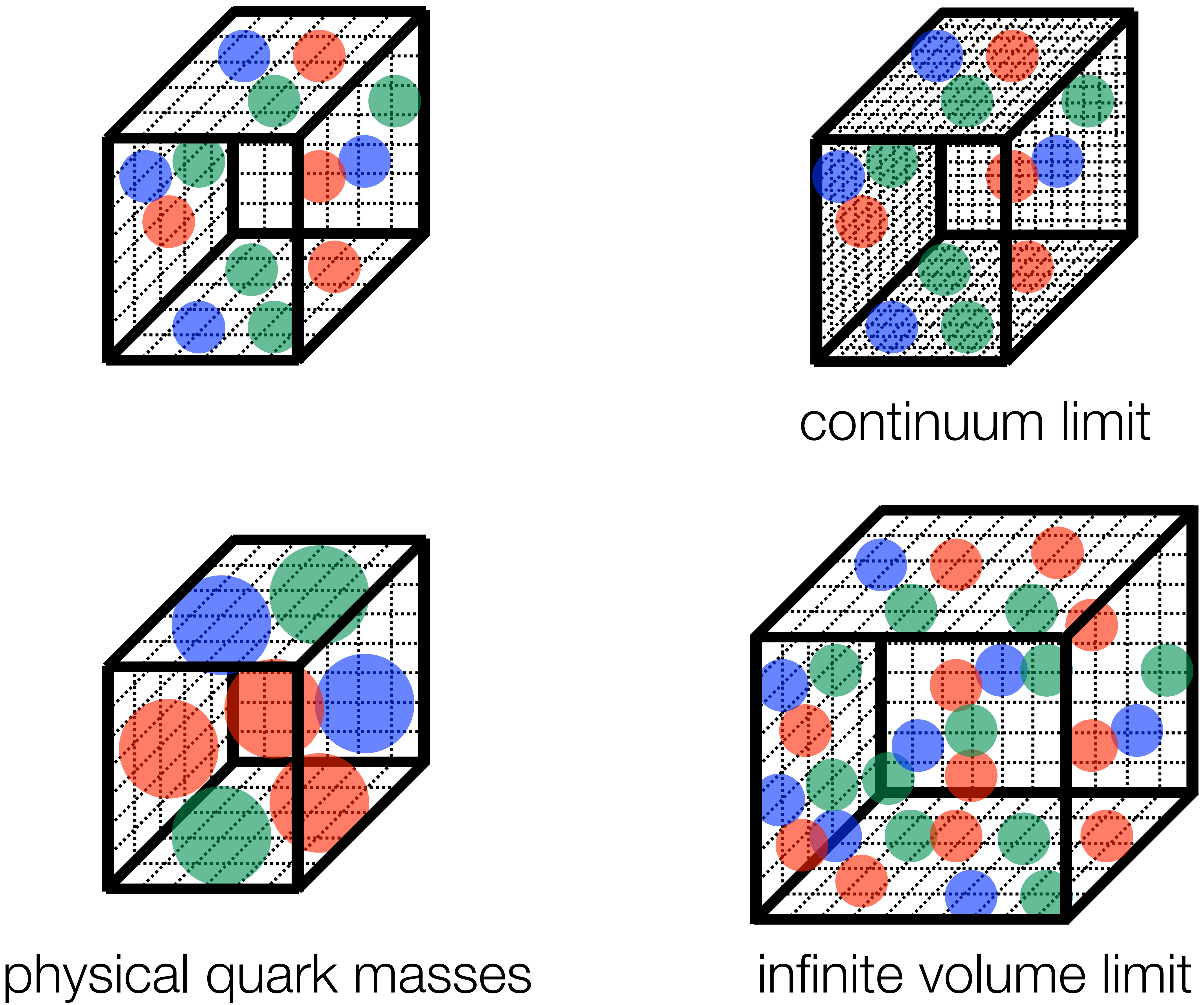


Analogy with Experiment



✓ Statistical errors are improved with run time (budget)
✓ Systematic errors are understood + controlled

LQCD Systematics



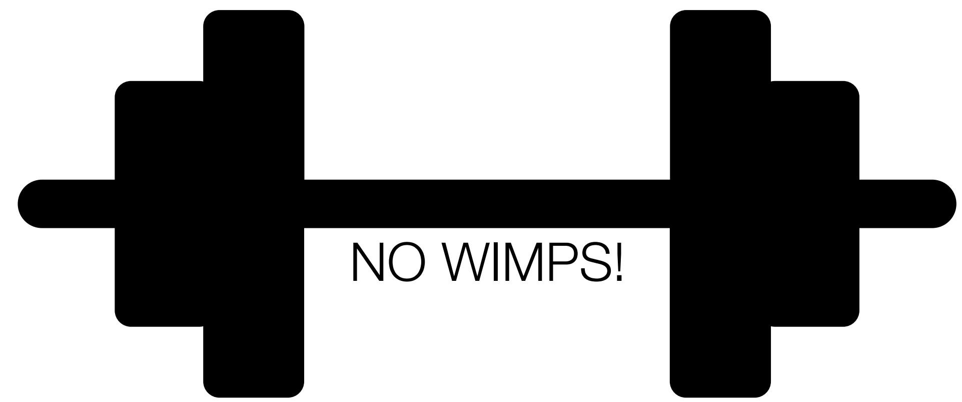
What can Lattice QCD do for BSM Physics?

Axion Cosmology

Colgate-Palmolive

1505.07455 EB, M. Buchoff
1506.00370 Kitano & Yamada
1508.06917 Borsanyi et al.
1512.06746 Bonati et al.
1606.07494 Borsanyi et al.
Nature **539** 69–71 Borsanyi et al.

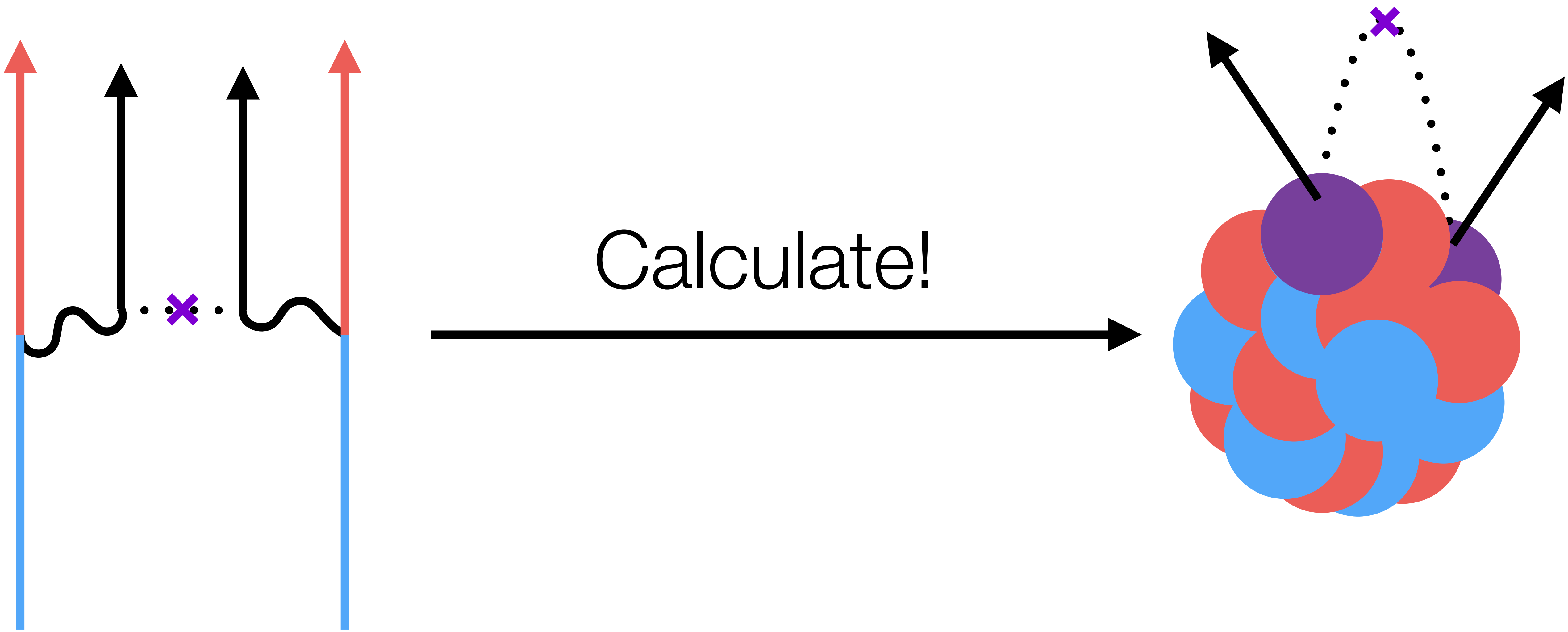
Non-abelian Dark Sectors



Reviews:
1604.04627 Kribs & Neil
1707.04591 US Cosmic Visions 2017

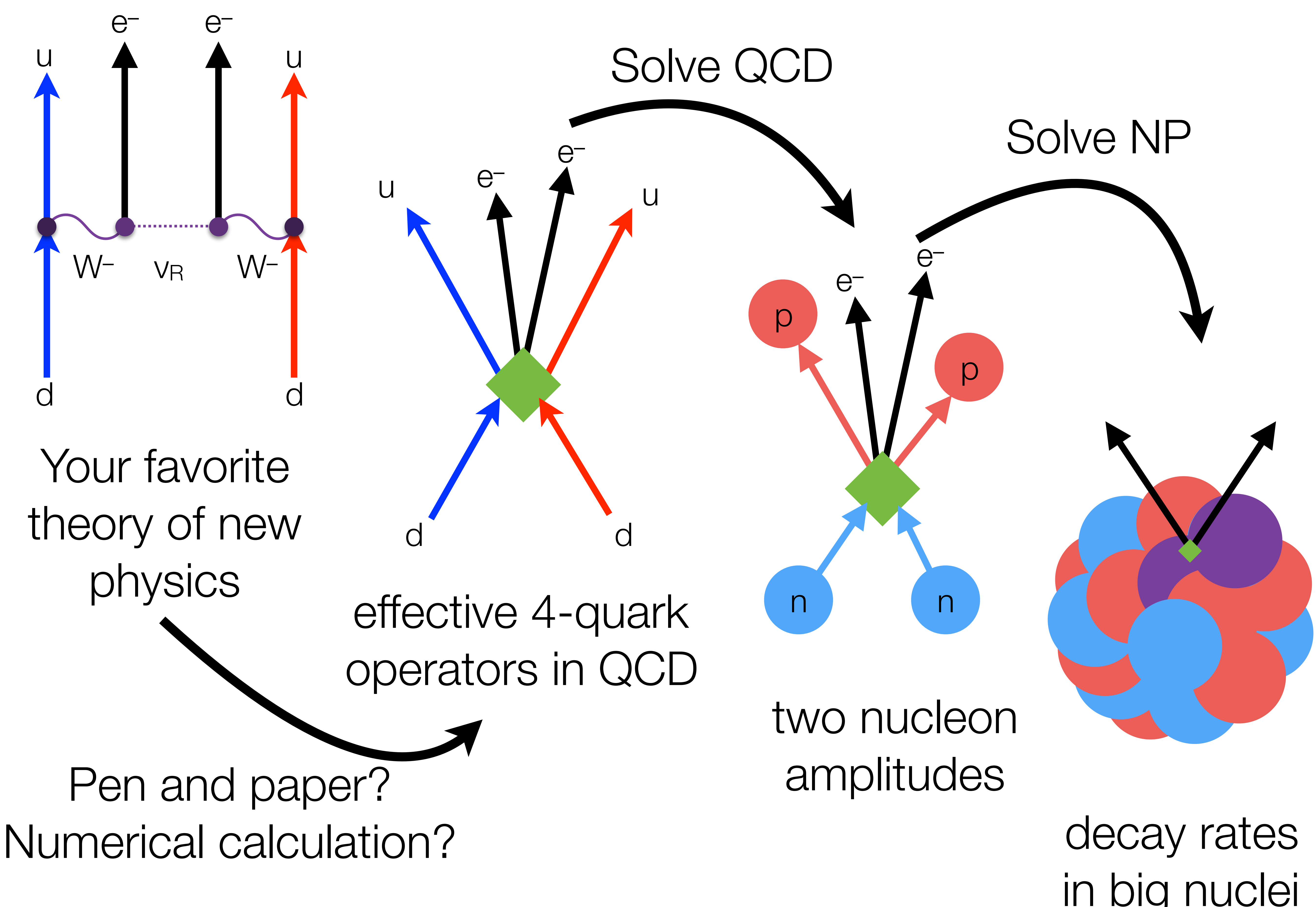
One proposal:
Stealth Dark Matter, LSD collaboration
1402.6656, 1503.04203, 1503.04205 ...

The Standard Model as an EFT: Model-Independence

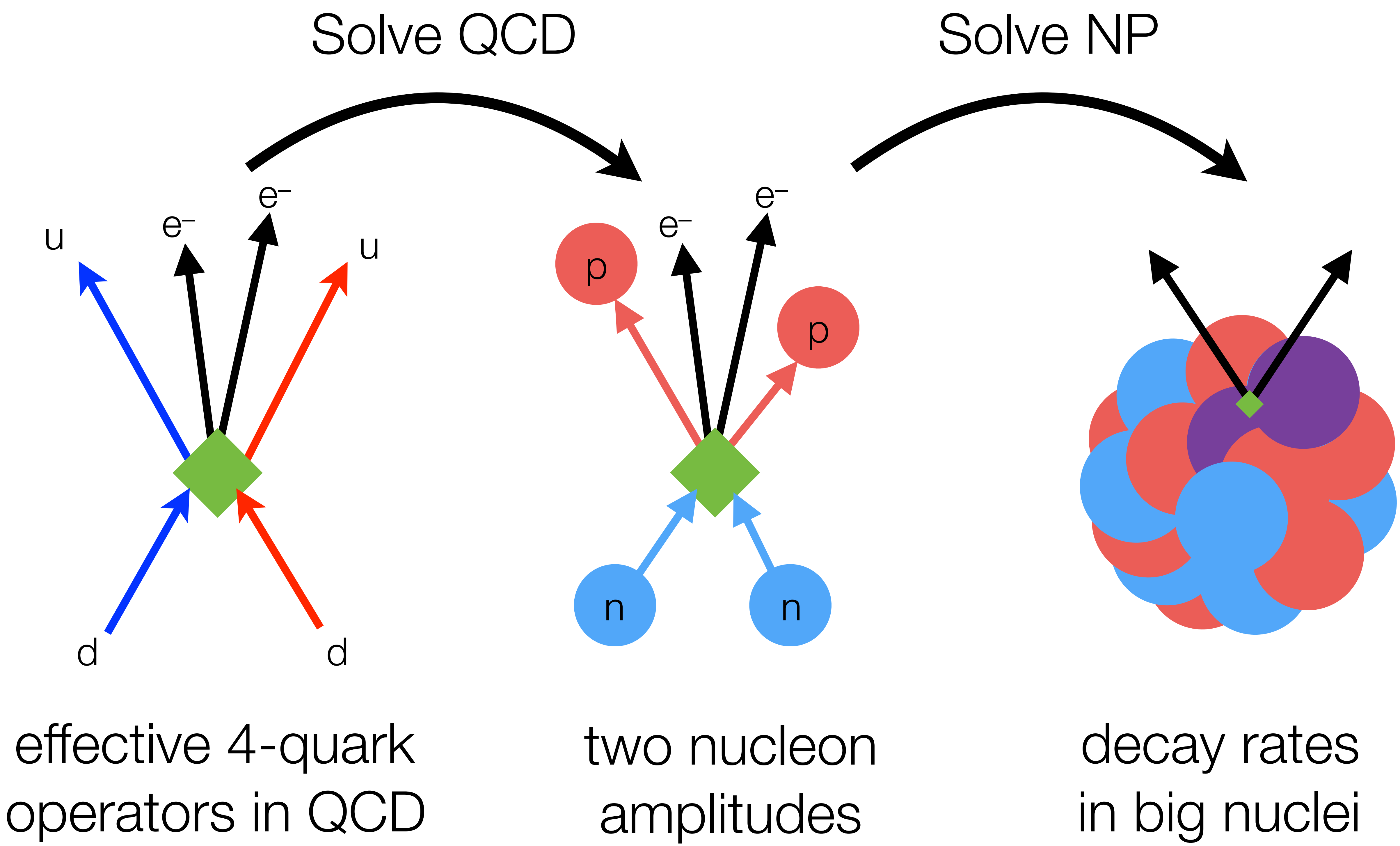


Your favorite theory of new physics

decay rates in big nuclei



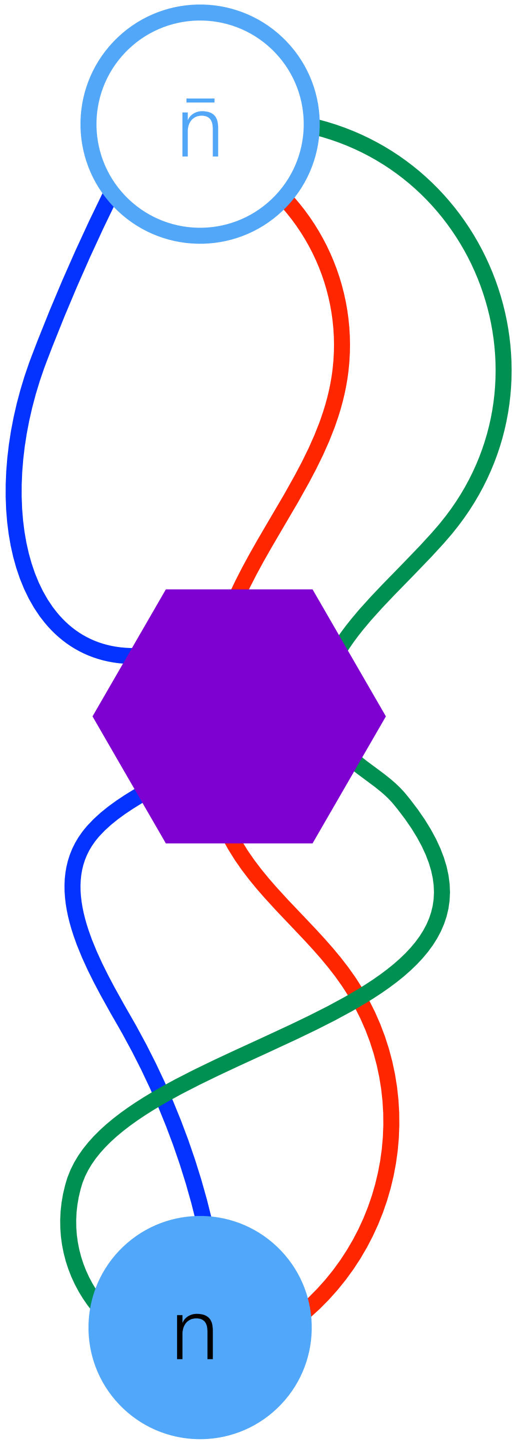
u
e−
e−
u
W−
νR
W−
d
d
Your favorite theory of new physics
Pen and paper? Numerical calculation?
Solve QCD
u
e−
e−
u
d
d
effective 4-quark operators in QCD
Solve NP
e−
e−
p
p
n
n
two nucleon amplitudes
decay rates in big nuclei


Solve QCD
Solve NP
u
e−
e−
u
d
d
p
e−
e−
p
n
n
effective 4-quark
operators in QCD
two nucleon
amplitudes
decay rates
in big nuclei

Single Nucleon Matrix Elements

n̄n Oscillations

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



✓ Physical point

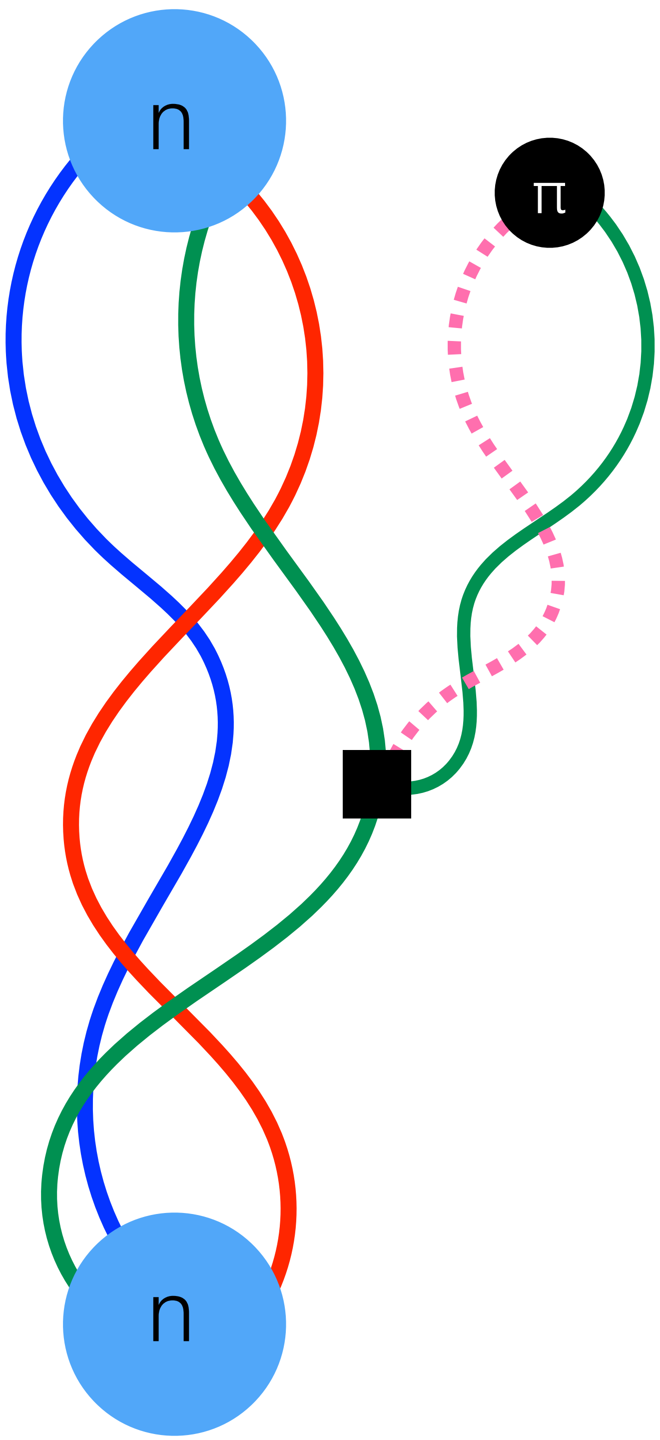
✗ continuum, infinite volume

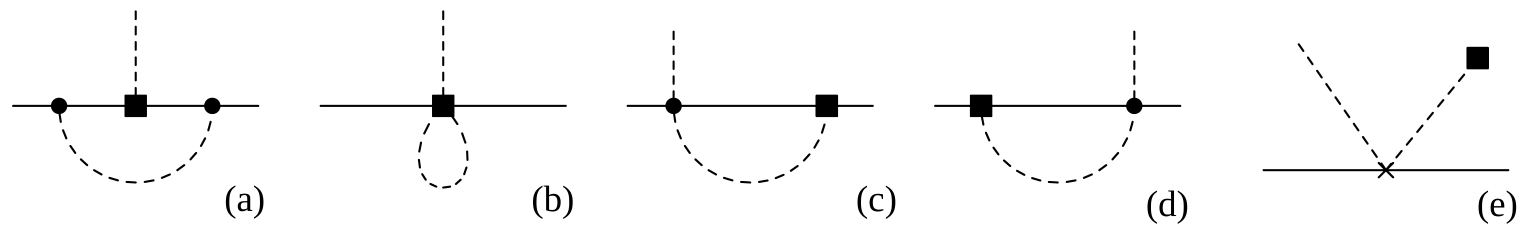
Operator	$\overline{\text{MS}}$(2 GeV), 10^{-5} GeV^6	$\frac{\overline{\text{MS}}\text{(2 GeV)}}{\text{MIT bag B}}$	Bare, 10^{-5} l.u.	χ^2/dof
Q_1	-44(19)	5.0	-3.7(1.6)	0.75
Q_2	140(40)	12.8	11.8(3.2)	0.69
Q_3	-79(23)	9.7	-6.6(1.9)	0.72
Q_5	-1.43(64)	2.1	-0.096(42)	0.73

enhancement
means experiments
have greater reach

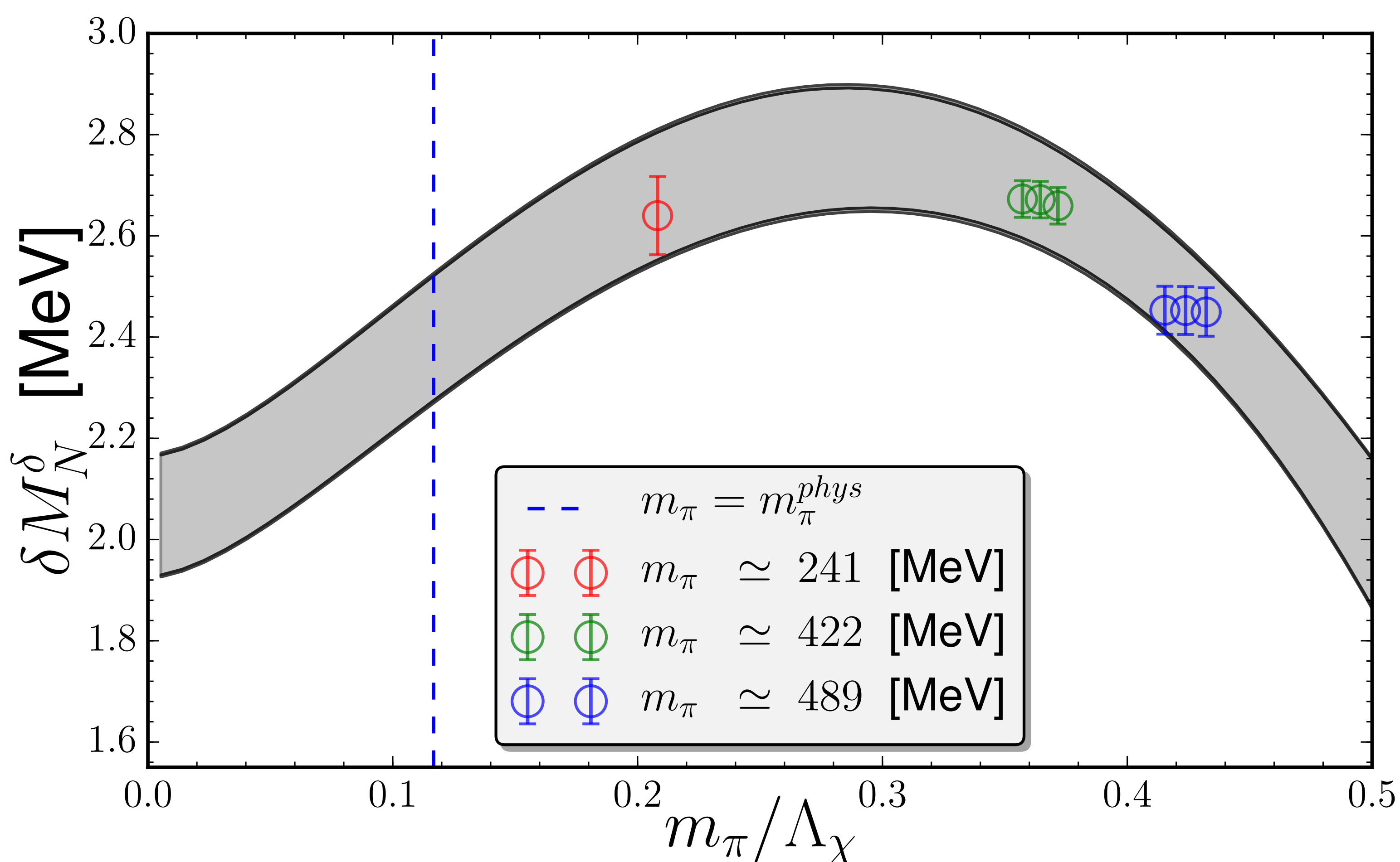
CP Violating πN Coupling

Brantley, Joo, Mastropas, Mereghetti, Monge-Camacho, Tiburzi, and Walker-Loud arXiv:1612.07733 [See also PLB 766 (2017) 254-262]





$$\bar{g}_0 = 14.7(1.8)^{stat}(1.4)^{sys}\, 10^{-3}\, \bar{\theta}\, f_\pi \sqrt{2}$$



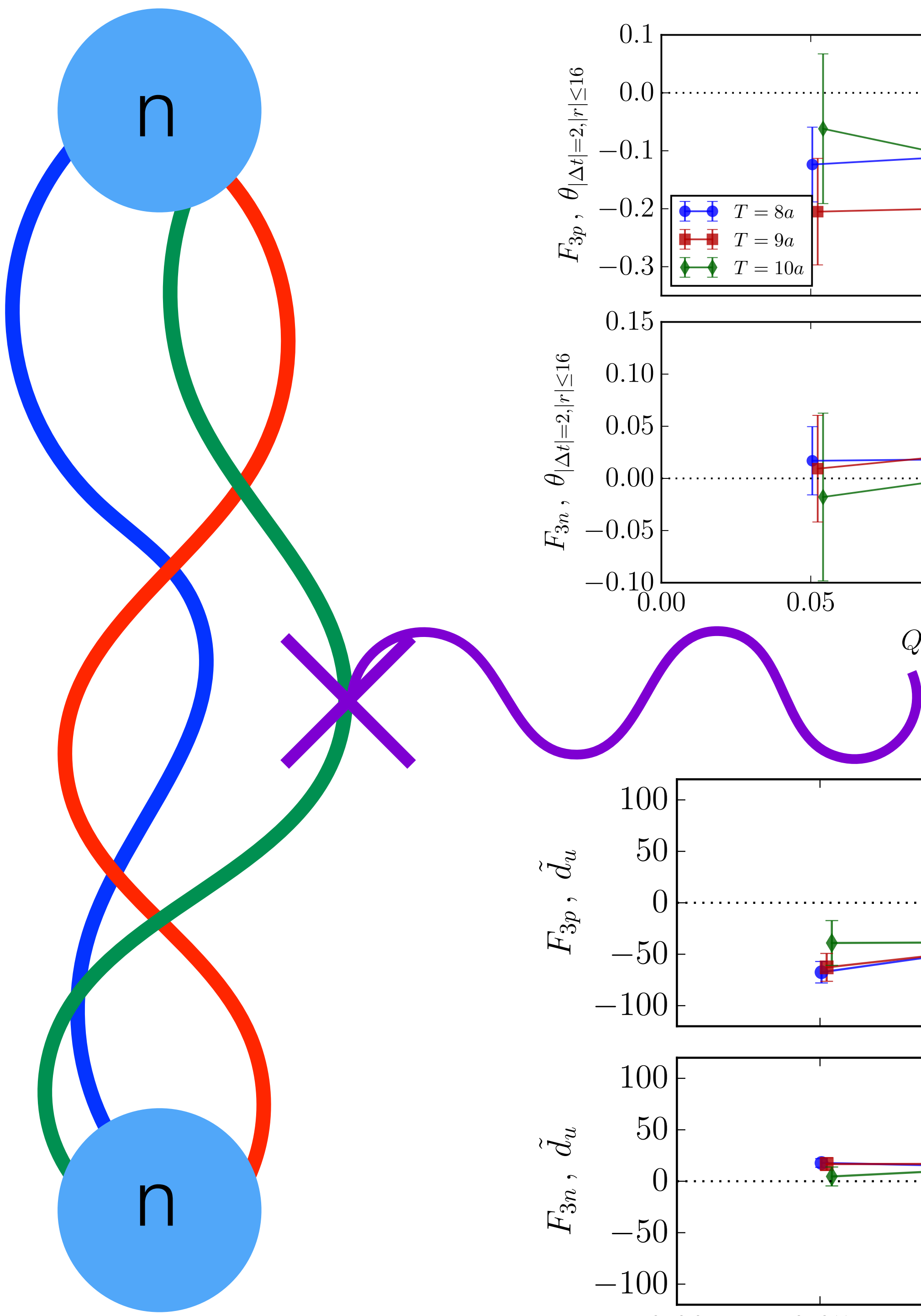
n EDM: Quark Bilinears

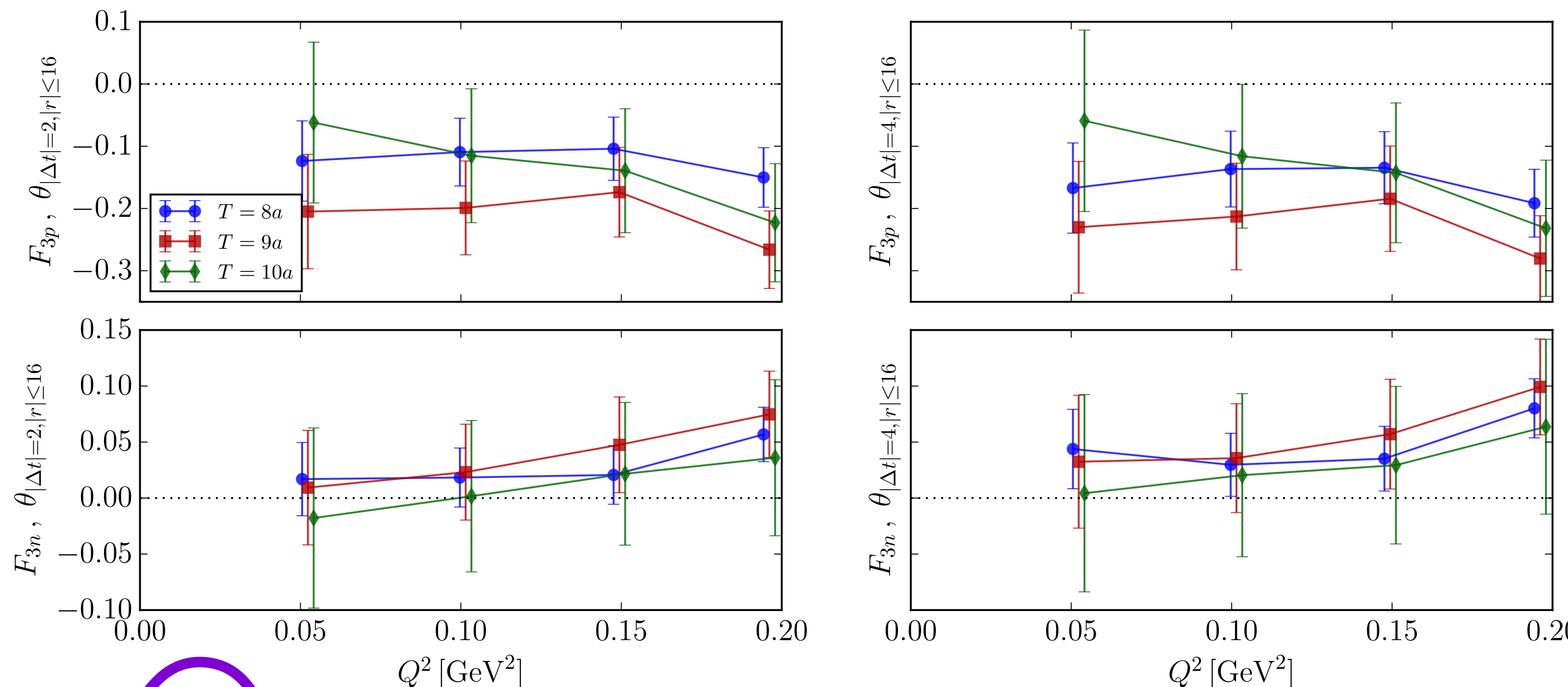
Syritsyn, Ohki, Izubuchi CIPANP 2018 1810.03721

V = $48^3\times96$ ($\times$ 24 DWF)

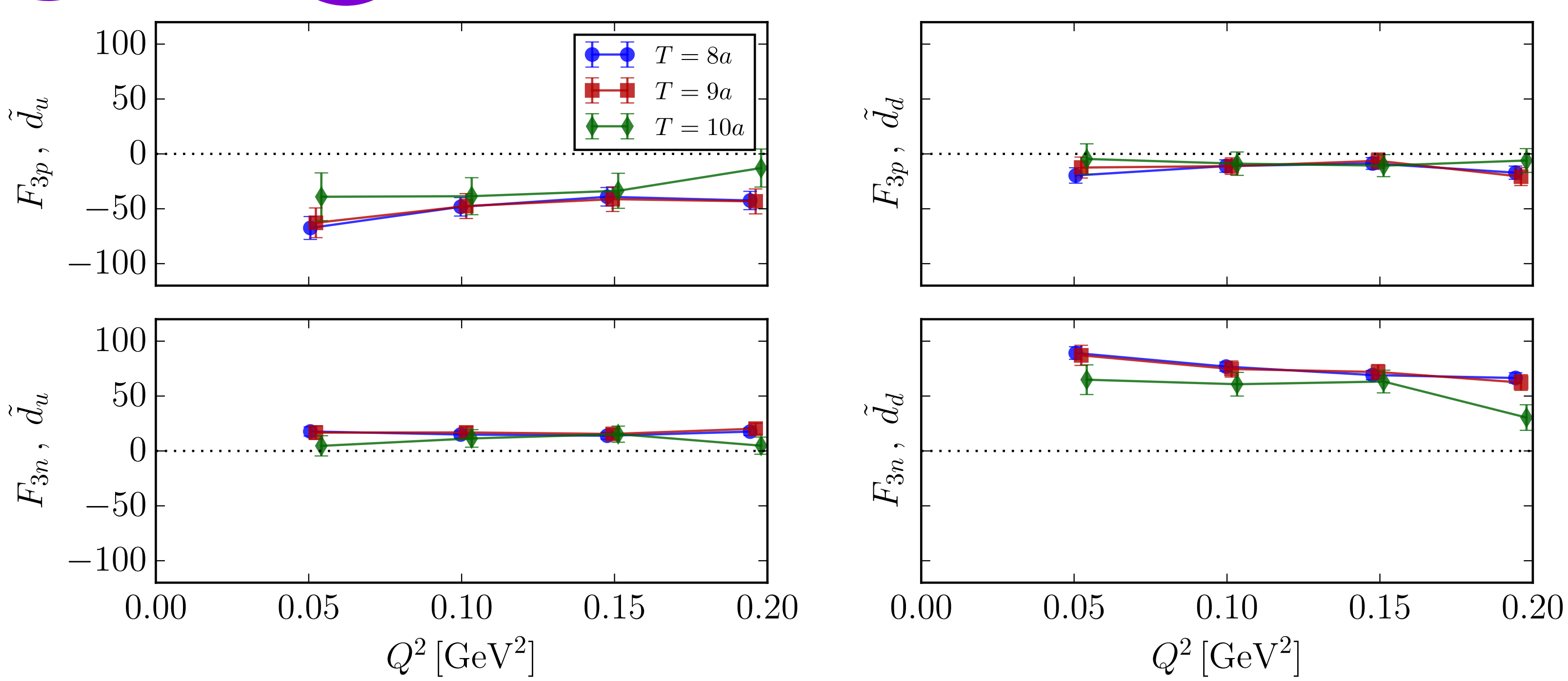
a = 0.114 fm

m_π = 139.2 MeV





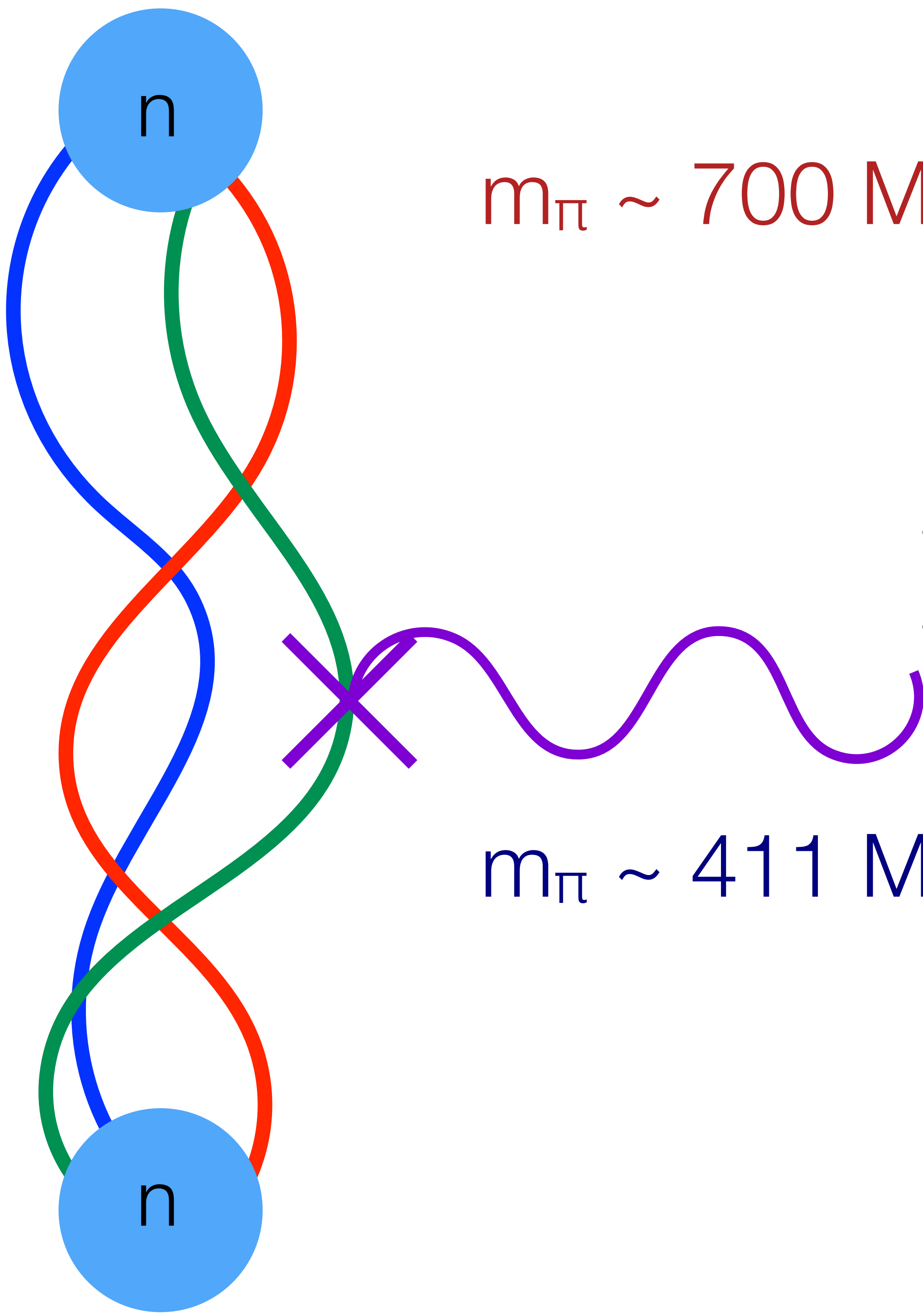
θ_{QCD}



cEDM

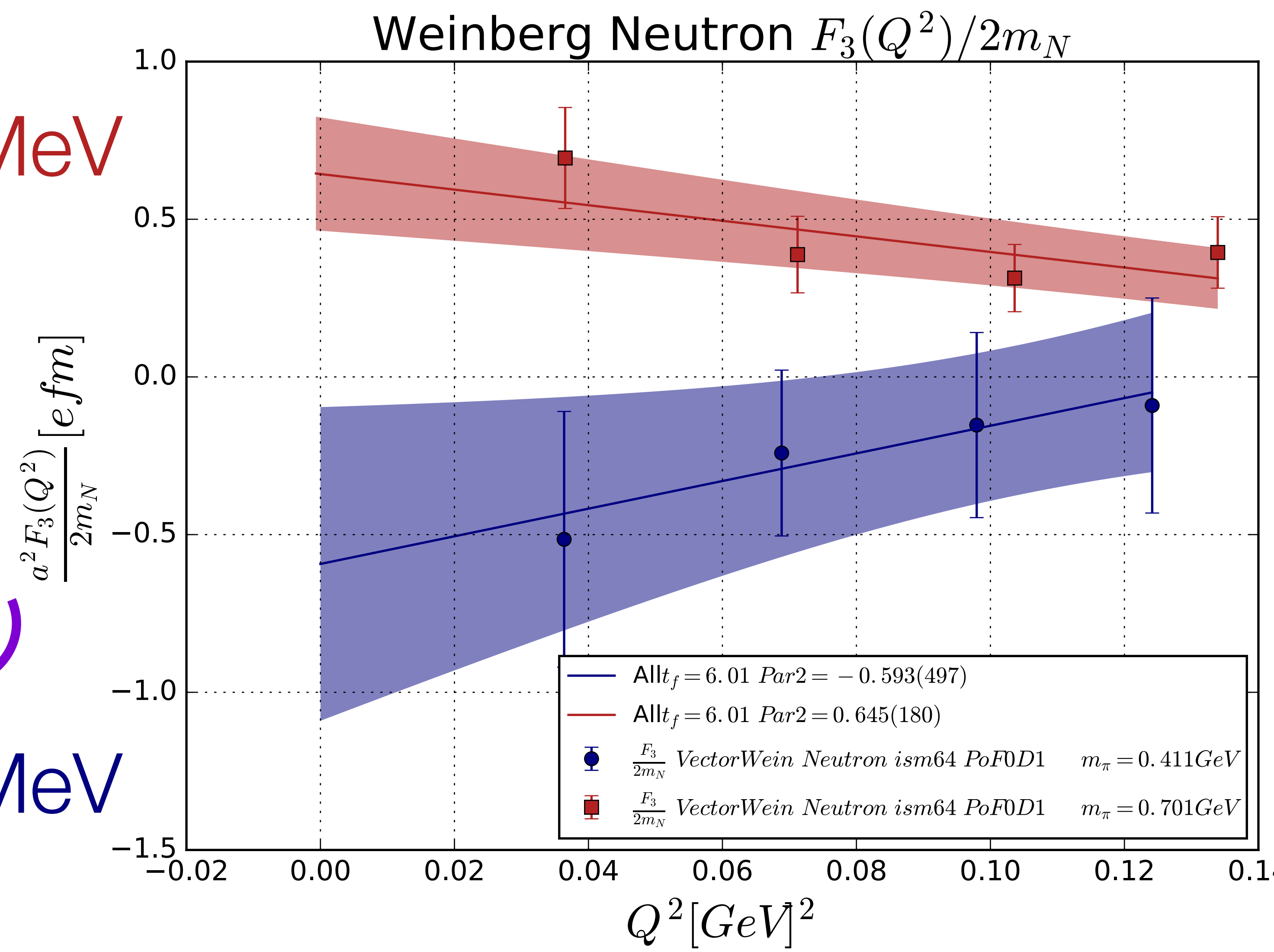
n EDM: Weinberg Operator

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



m_π ~ 700 MeV

m_π ~ 411 MeV

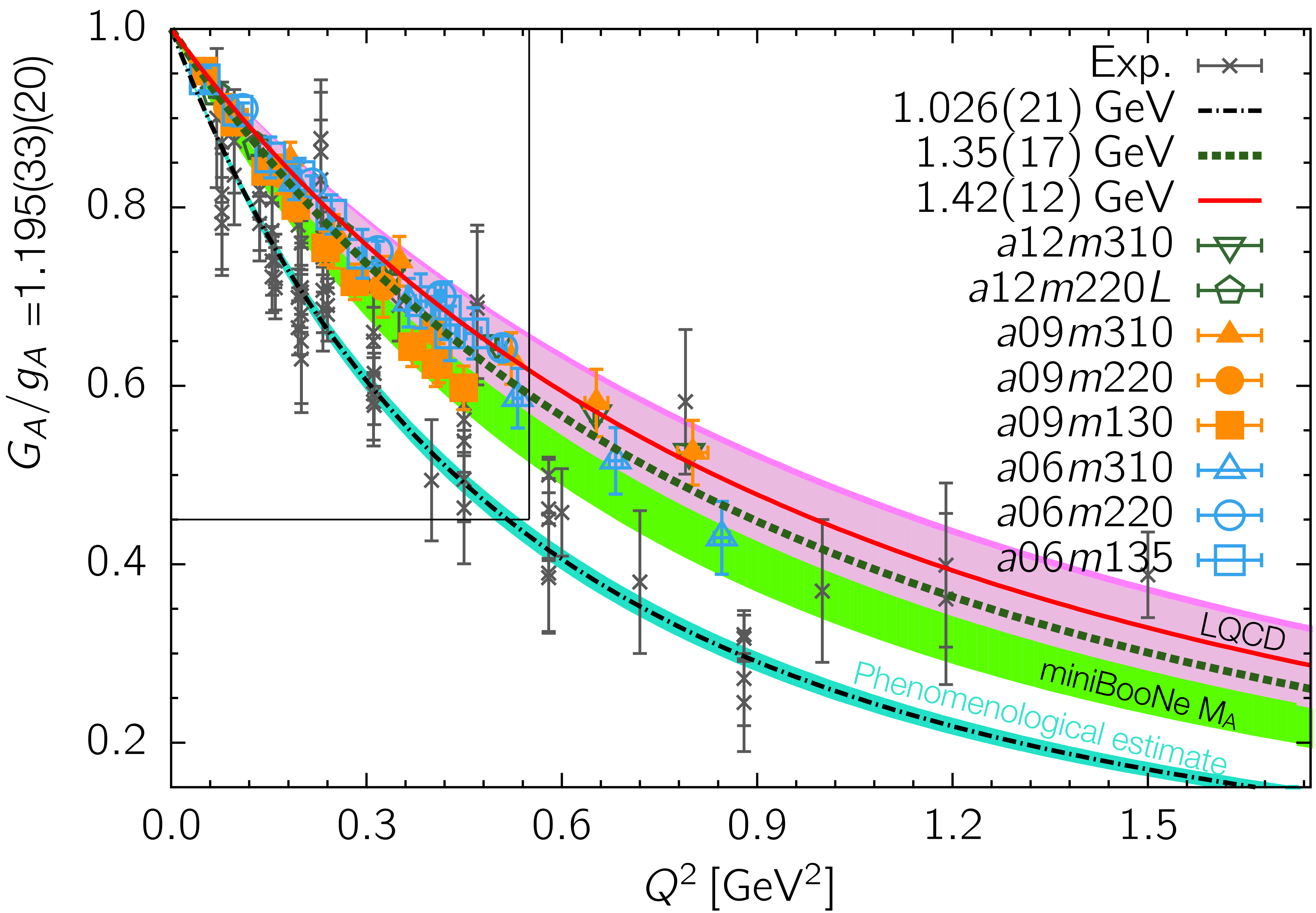


$$-i\frac{\alpha_{\tilde{G}}}{\Lambda^2}\;\frac{1}{3}f^{ABC}\tilde{G}^A_{\mu\nu}G^B_{\mu\rho}G^C_{\nu\rho}$$

see also community whitepaper 1711.07916 (PDFs, charges...)

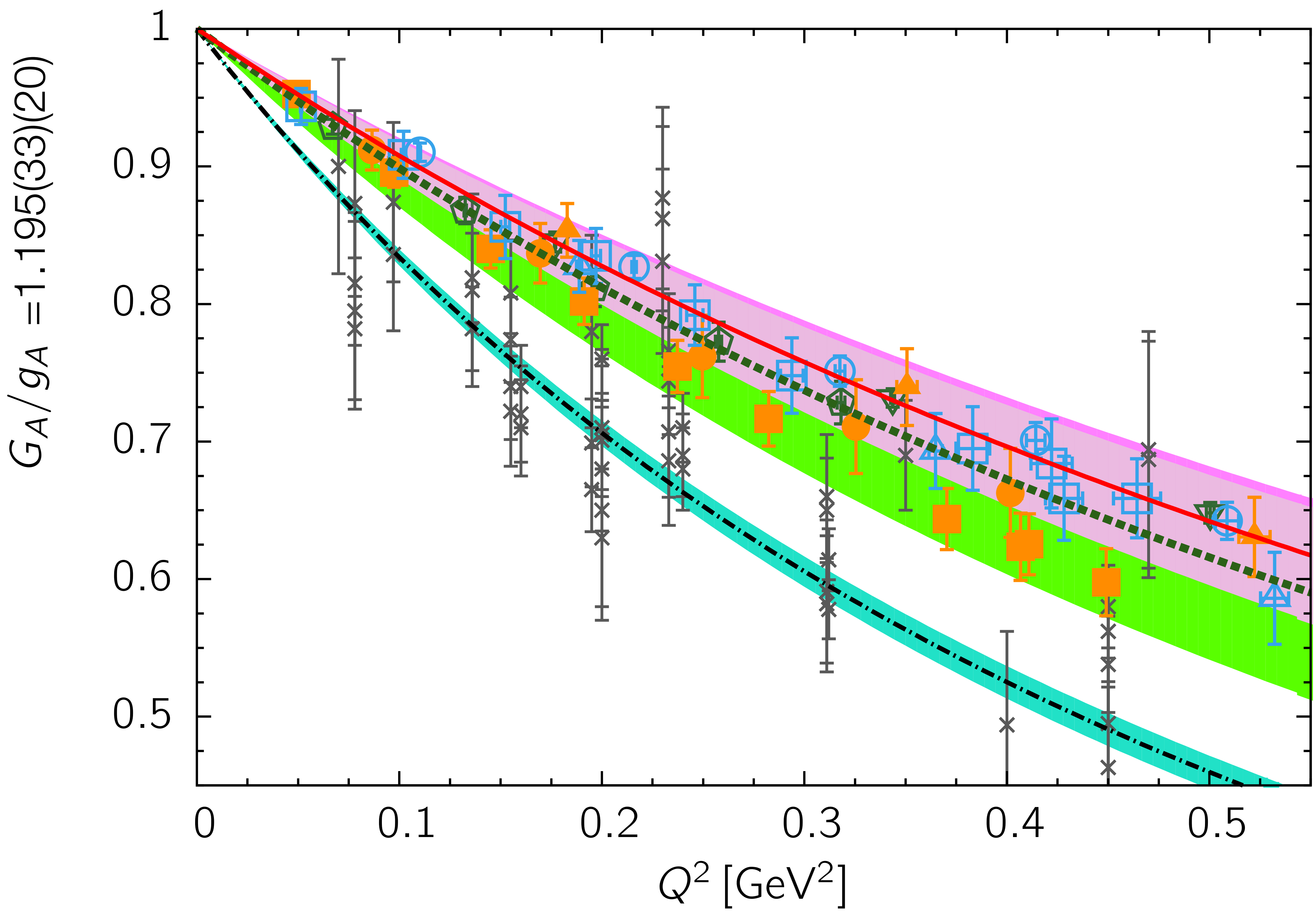
Charges + Form Factors

Gupta, Jang, Lin, Yoon, and Bhattacharya (PNDME) q=0: 1506.06411, **1606.07049** q≠0: **1705.06834**, 1801.01635 1901.00060



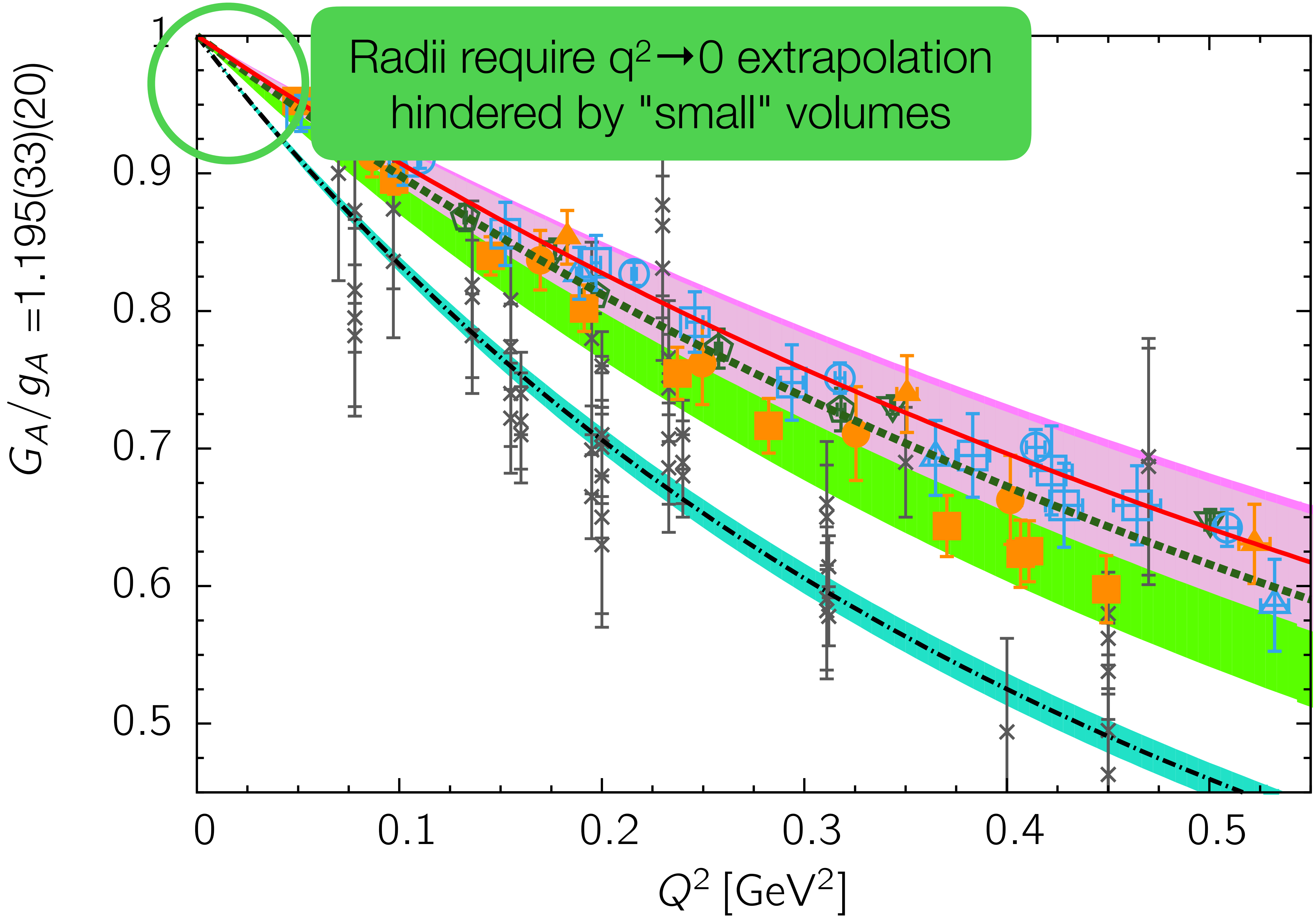
Charges + Form Factors

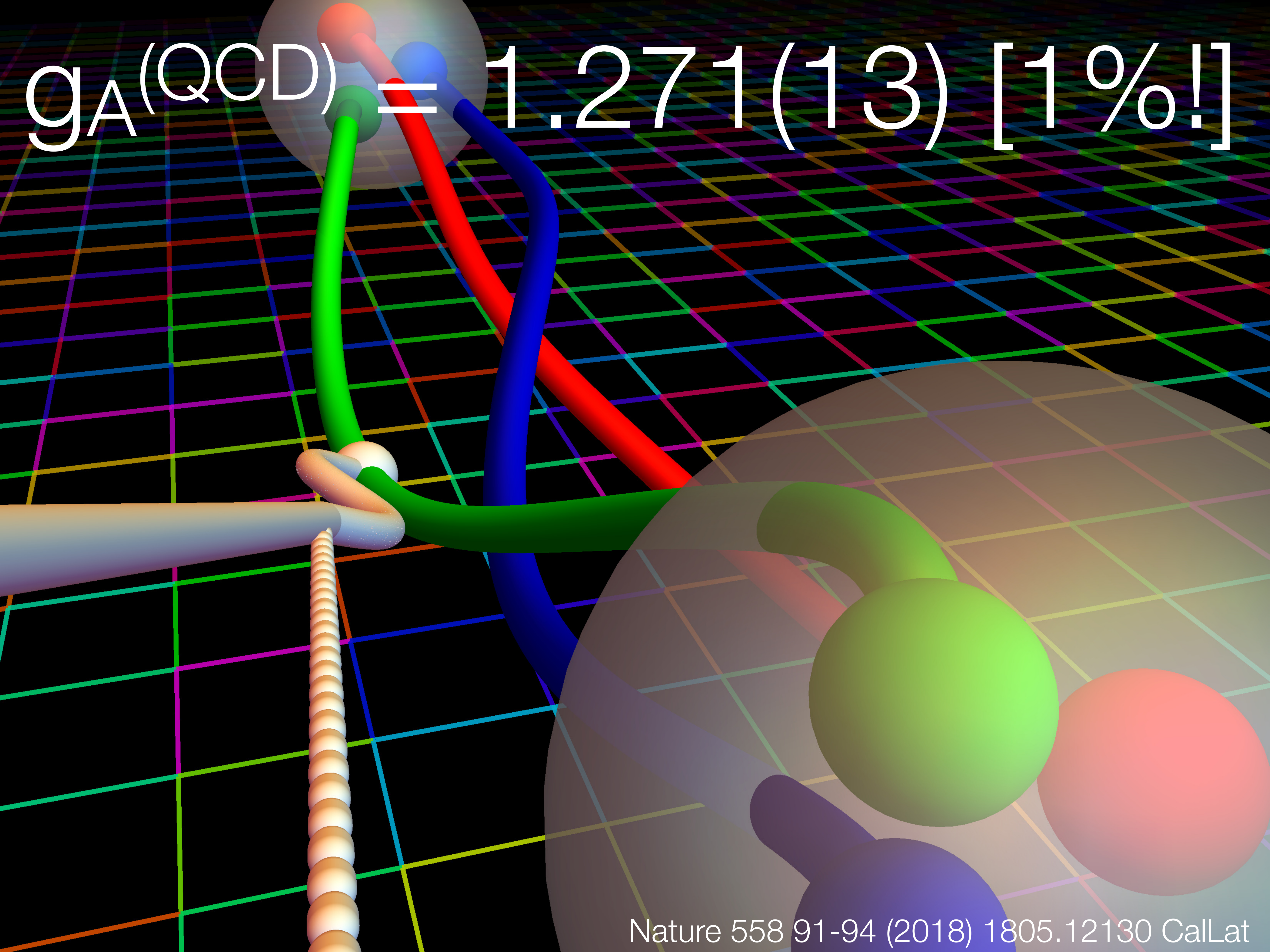
Gupta, Jang, Lin, Yoon, and Bhattacharya (PNDME) q^2=0: 1506.06411, **1606.07049** $q^2 \neq 0$: **1705.06834**, 1801.01635 1901.00060

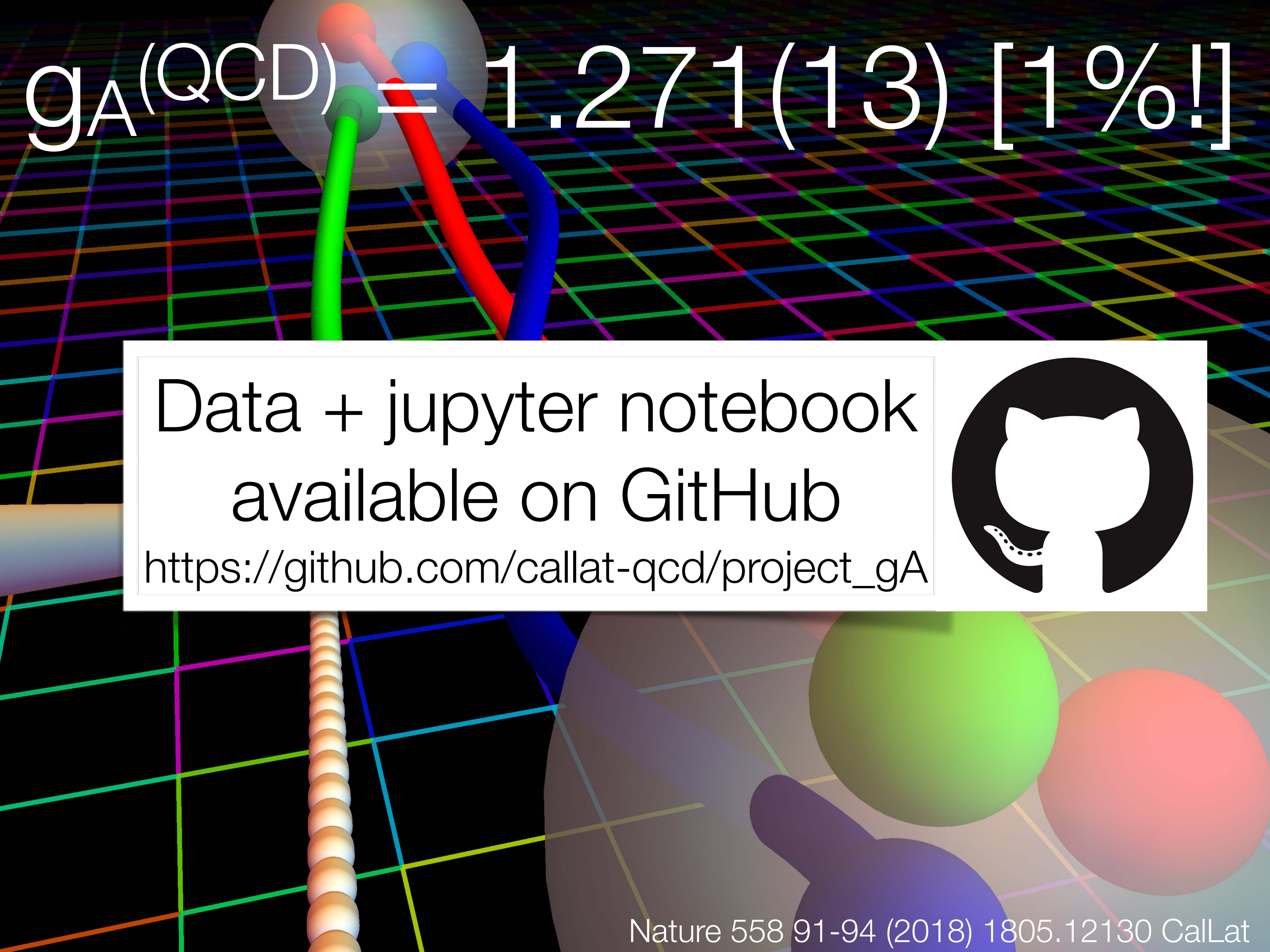


Charges + Form Factors

Gupta, Jang, Lin, Yoon, and Bhattacharya (PNDME) $q^2=0$: 1506.06411, **1606.07049** $q^2\neq0$: **1705.06834**, 1801.01635 1901.00060




$g_A^{(QCD)} = 1.271(13)$ [1%!]
Nature 558 91-94 (2018) 1805.12130 CalLat



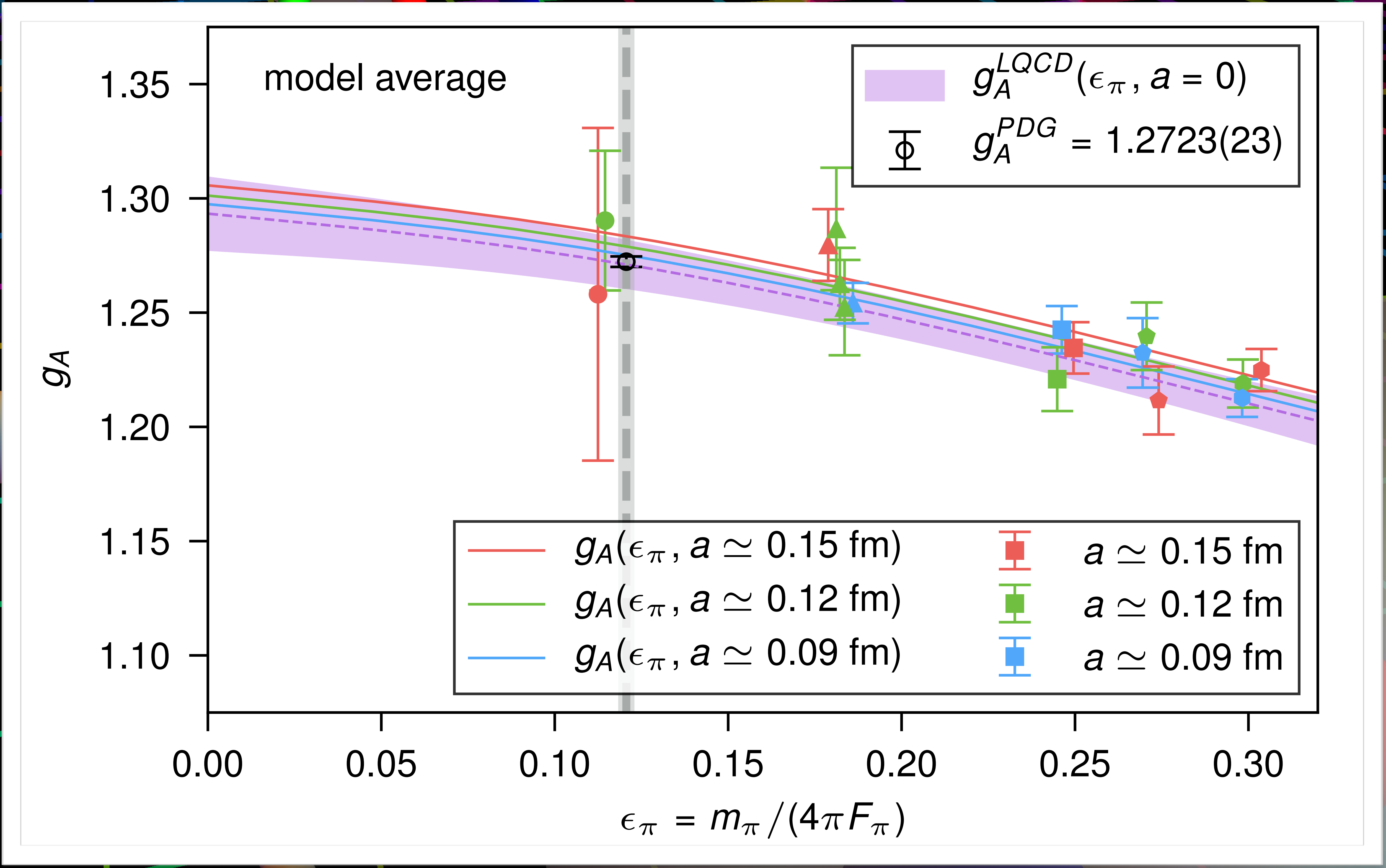
$g_A^{(QCD)} = 1.271(13)$ [1%!]

Data + jupyter notebook available on GitHub

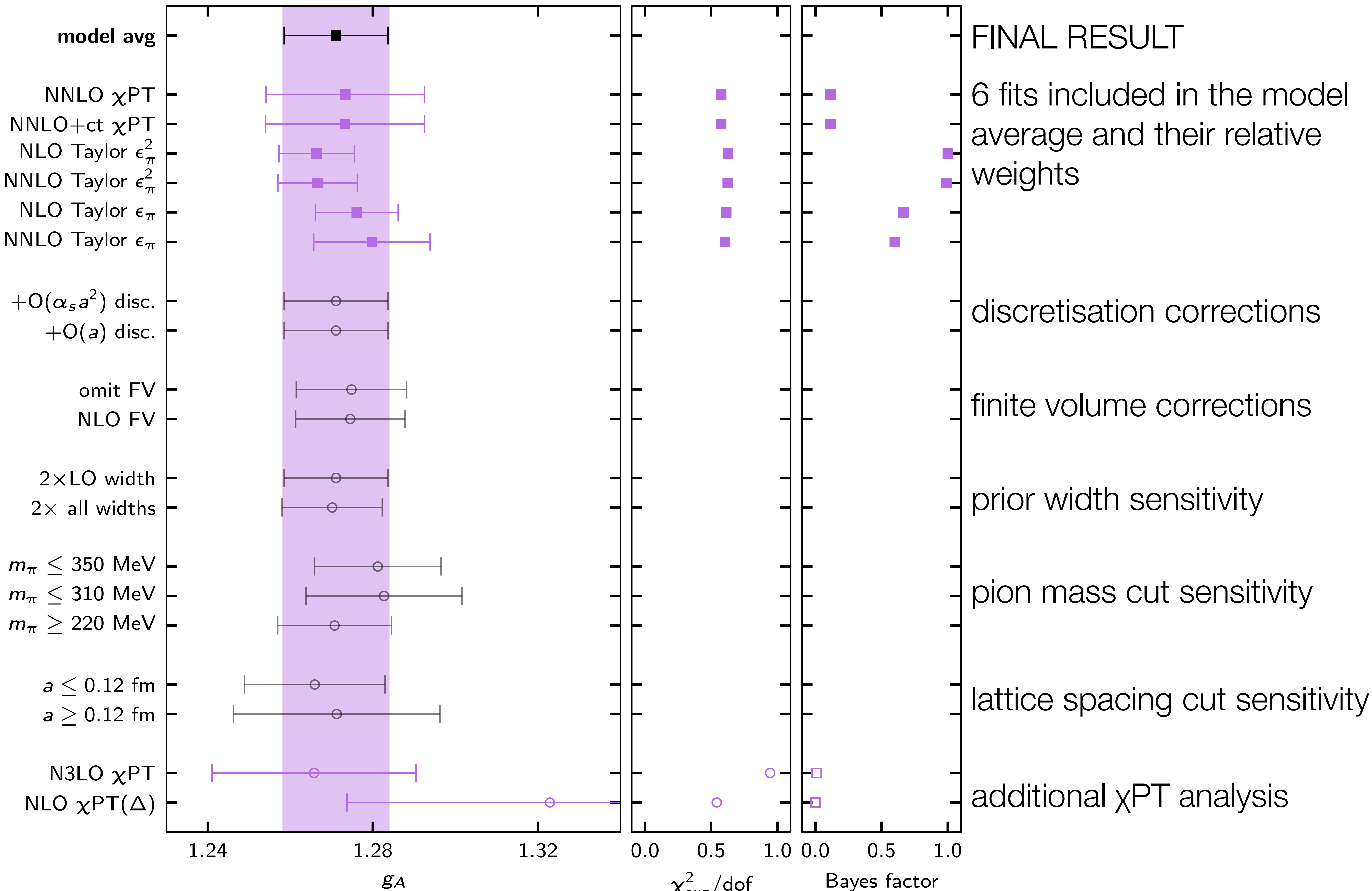
https://github.com/callat-qcd/project_gA

Nature 558 91-94 (2018) 1805.12130 CalLat

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

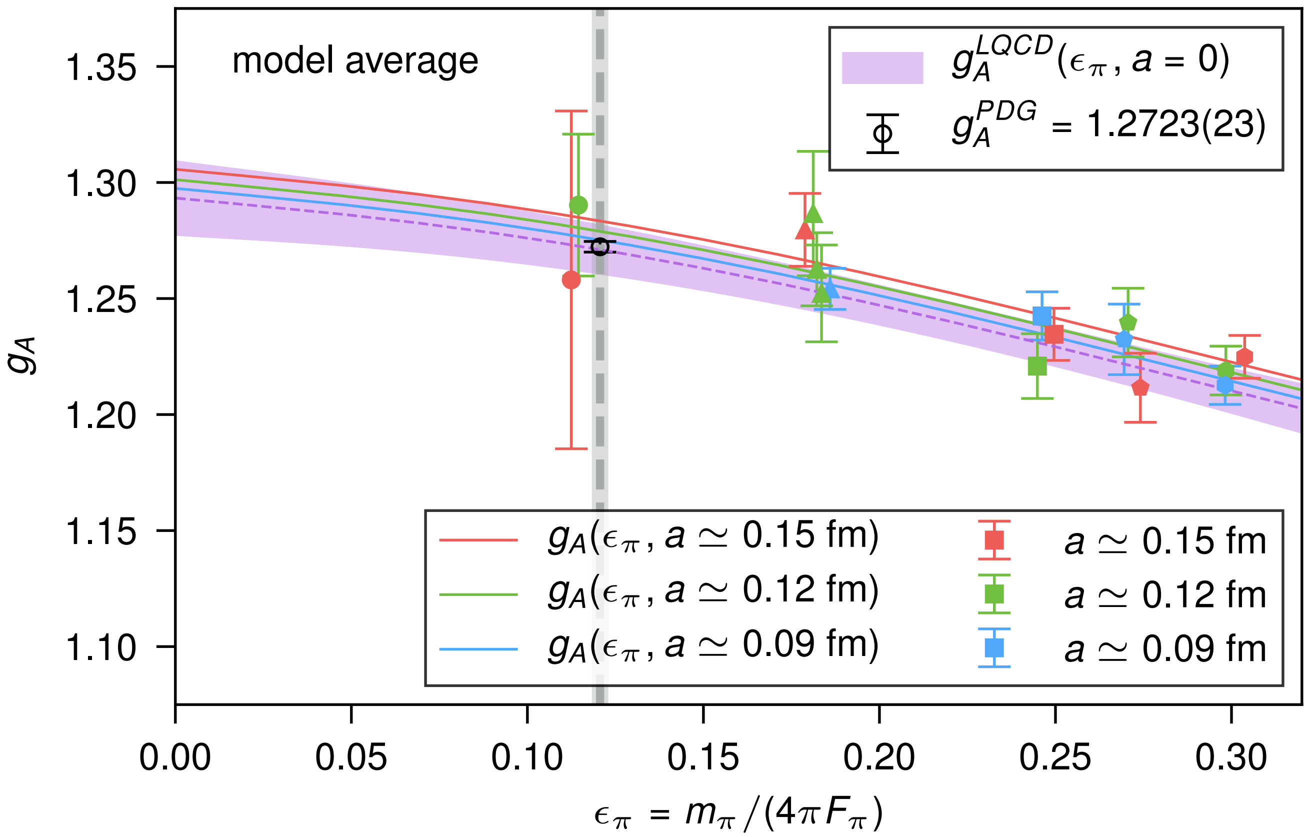


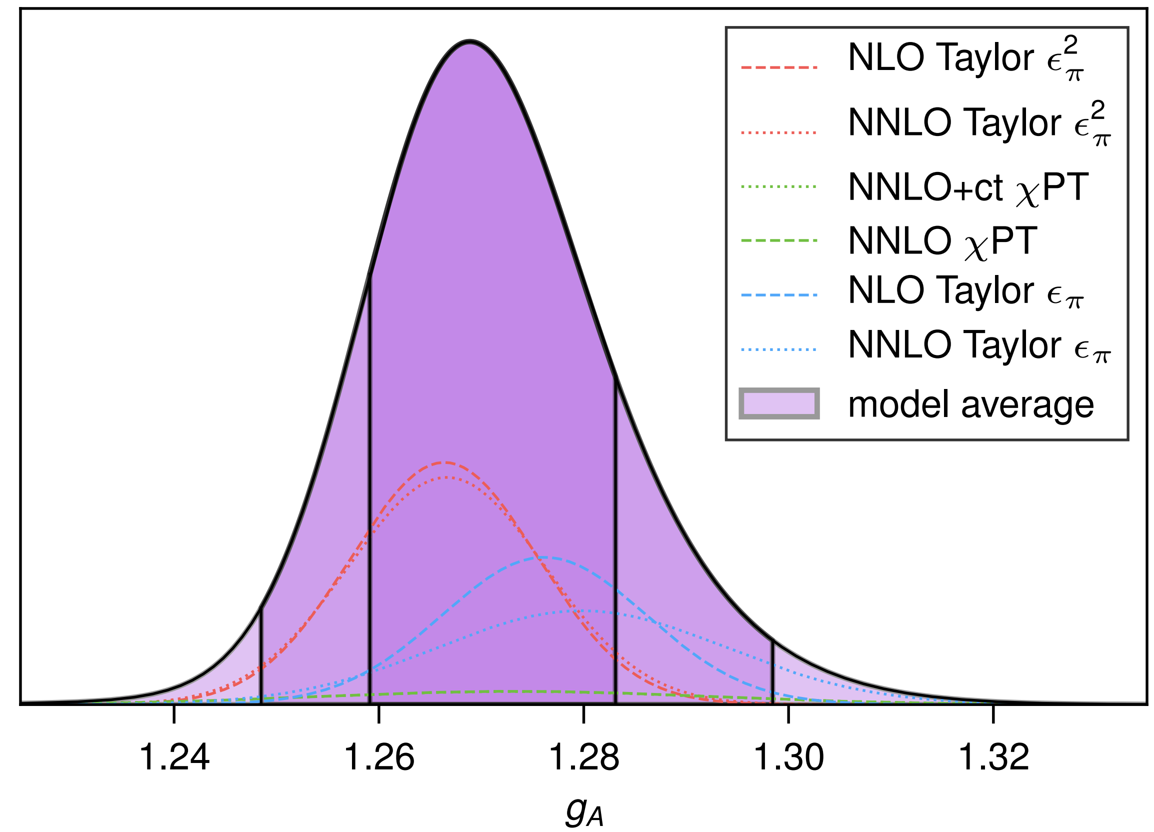
Nature 558 91-94 (2018) 1805.12130 CalLat


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
$\chi^2_{\rm aug}$/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 $g_A = 1.2711(103)^{s}(39)^{\chi}(15)^{a}(19)^{v}(04)^{I}(55)^{M}$

Nature 558 (2018) 91





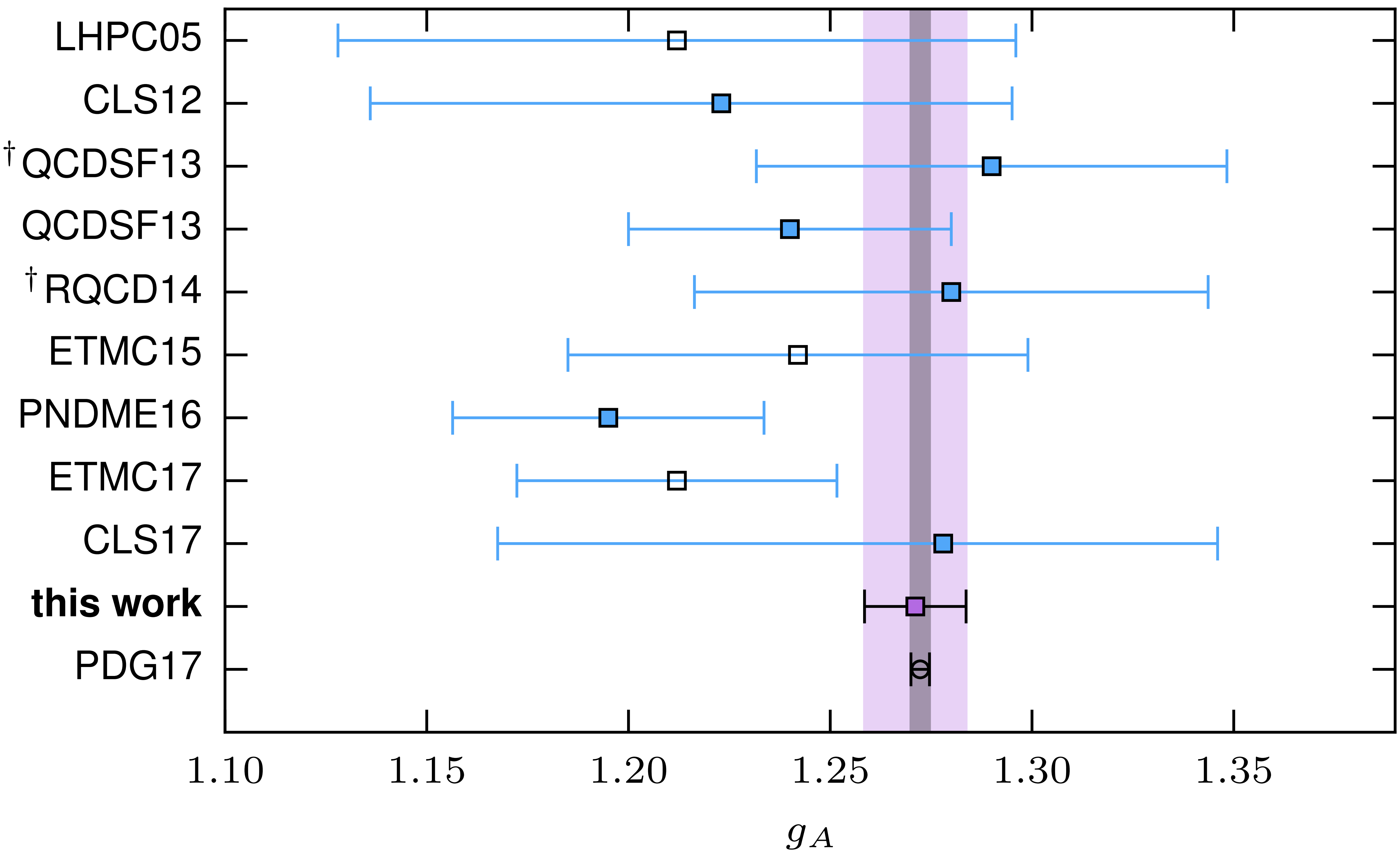
statistical	0.81%
chiral	0.30%
continuum	0.12%
infinite volume	0.15%
isospin breaking	0.03%
model selection	0.43%
total (added in quadrature)	**0.98%**

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

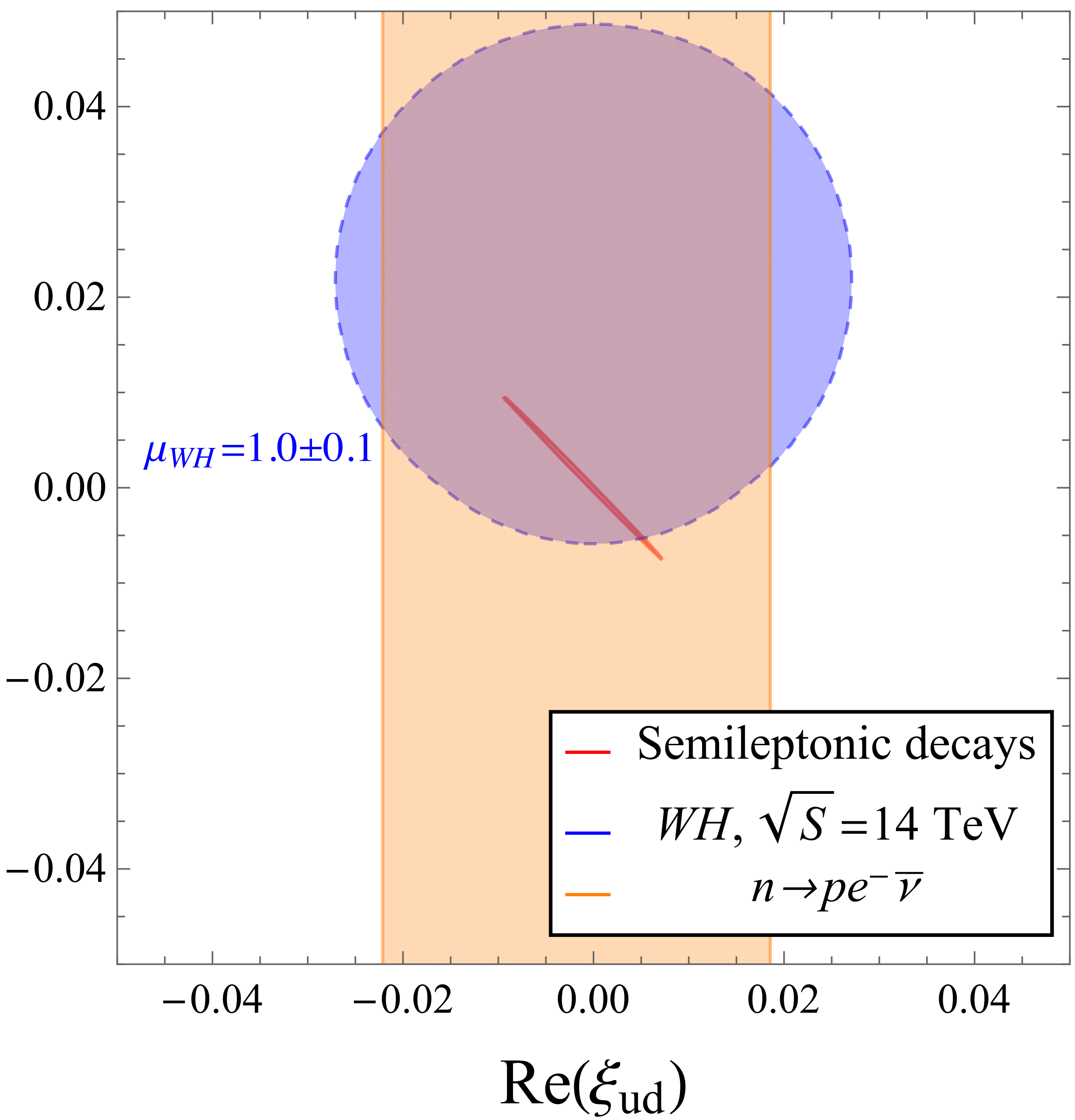
Nature 558 (2018) 91



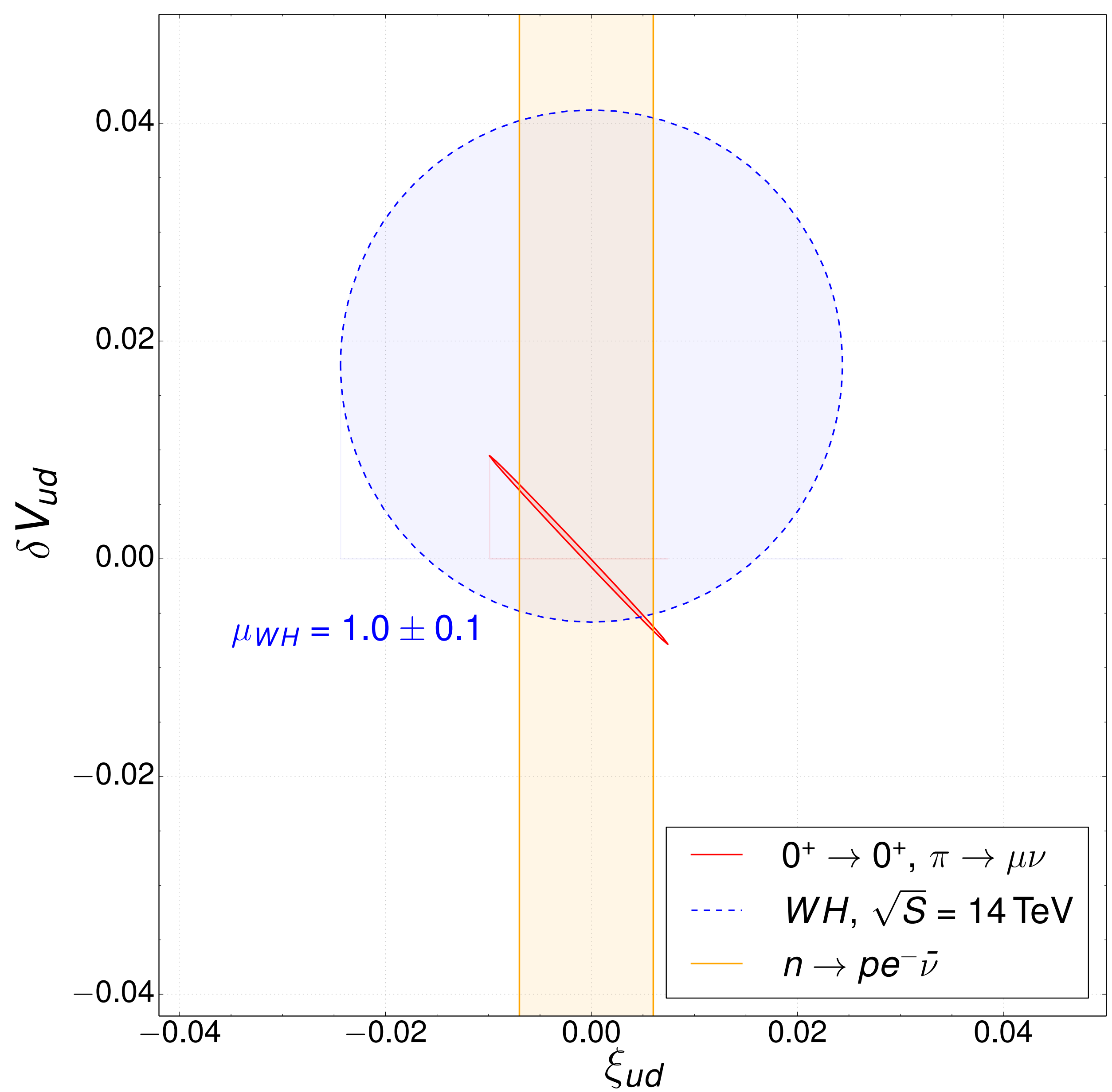
Searches for violations of V–A

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)

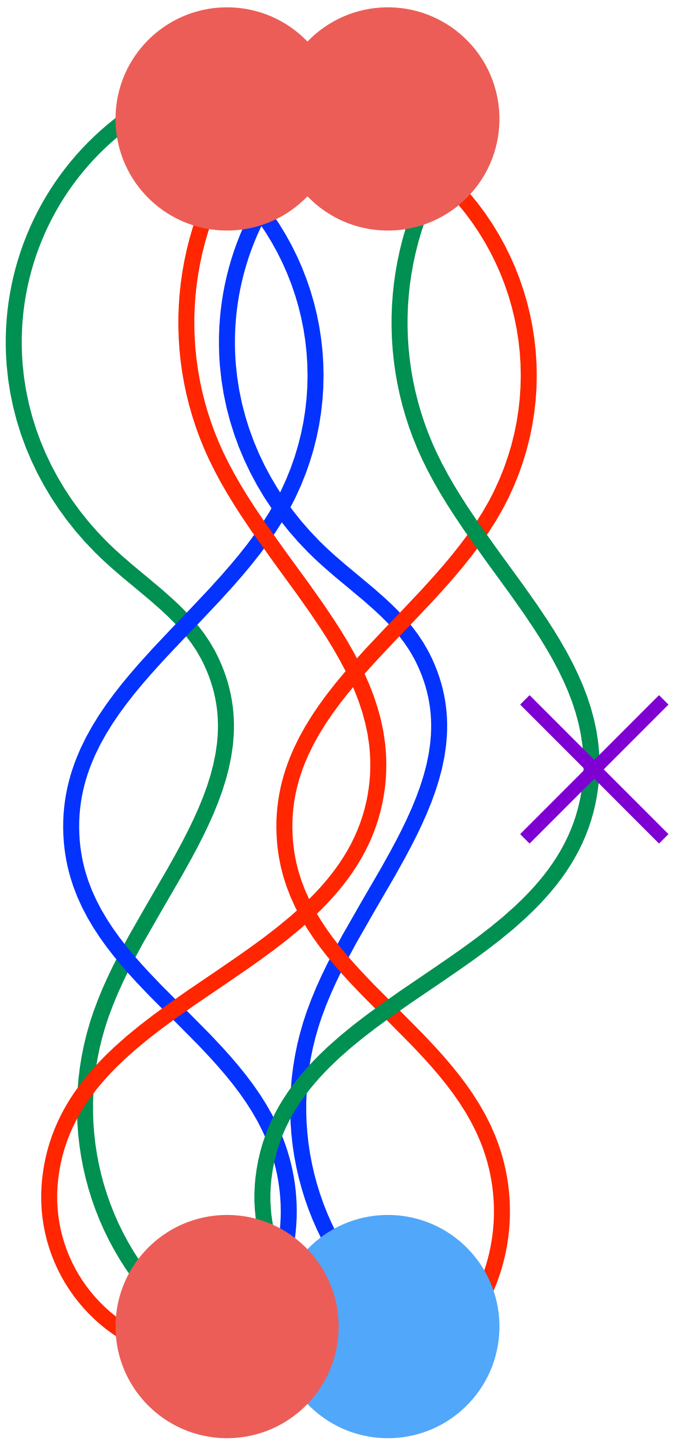


Two Nucleon Matrix Elements

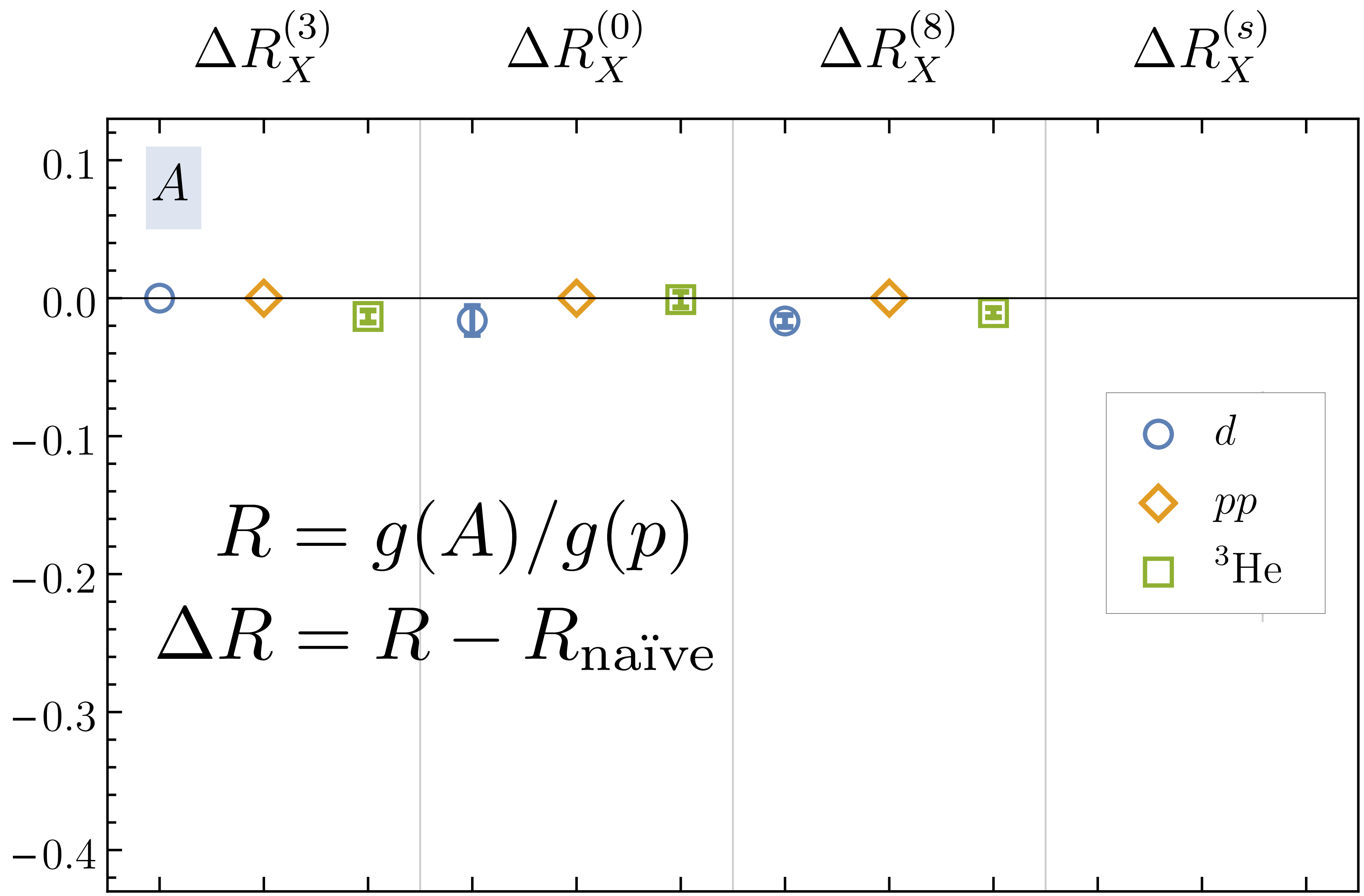
g_A Quenching?

NPLQCD PRL 120 (2018) 15 152002 arXiv:1712.03221

$m_\pi \sim 800$ MeV; a~0.145 fm



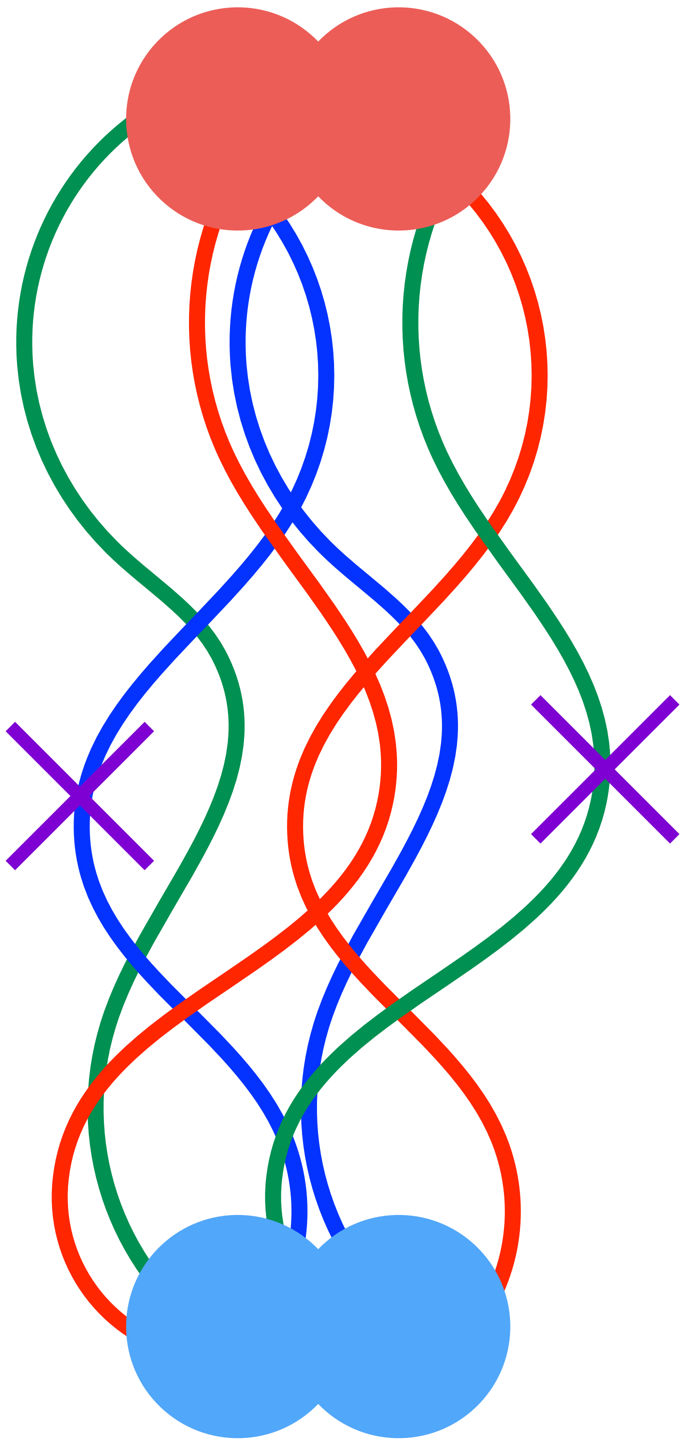
different flavor structures



Isotensor Polarizability (2βνν)

NPLQCD PRL 119 (2017) 06 062003 arXiv:1701.03456

$m_\pi \sim$ 800 MeV; a~0.145 fm



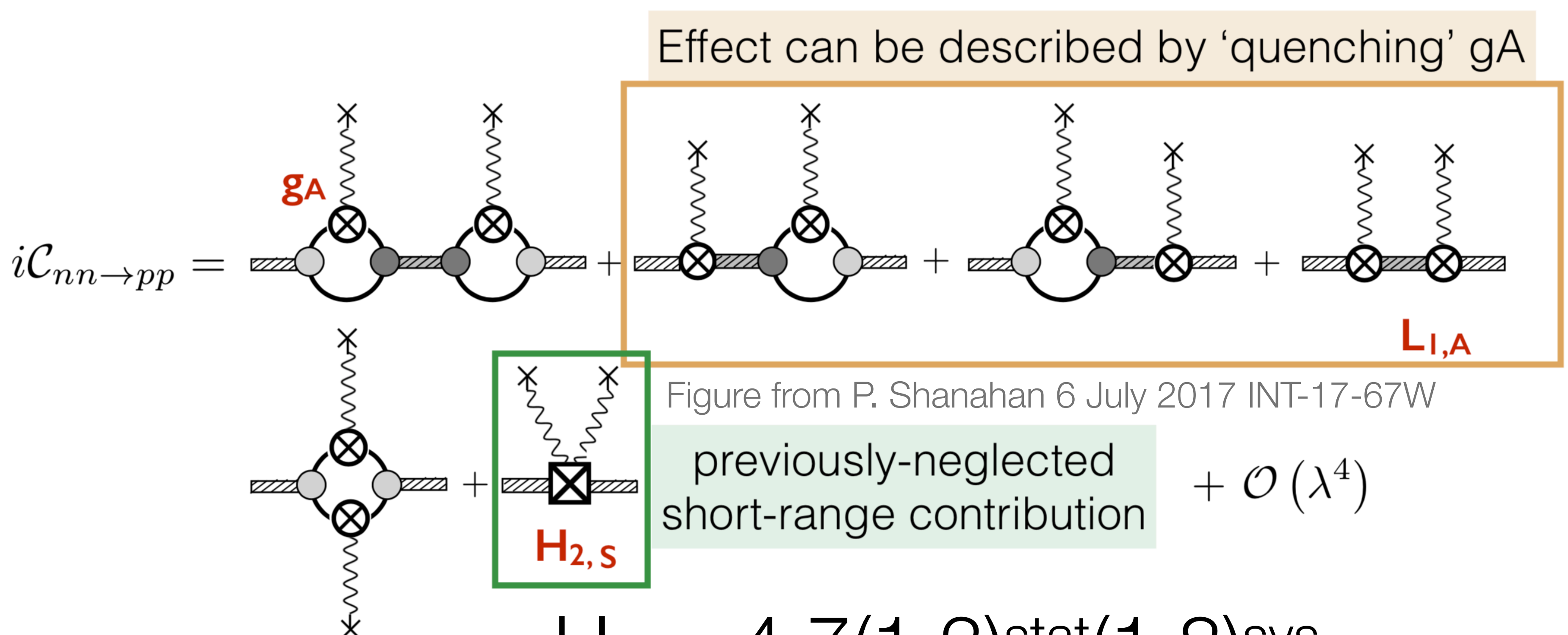


Figure from P. Shanahan 6 July 2017 INT-17-67W

$H_{2,S}$=4.7(1.3)^{stat}(1.8)^{sys}

- Pionless EFT
- Dineutron bound at 800 MeV
- Binding energies, matrix element from the lattice

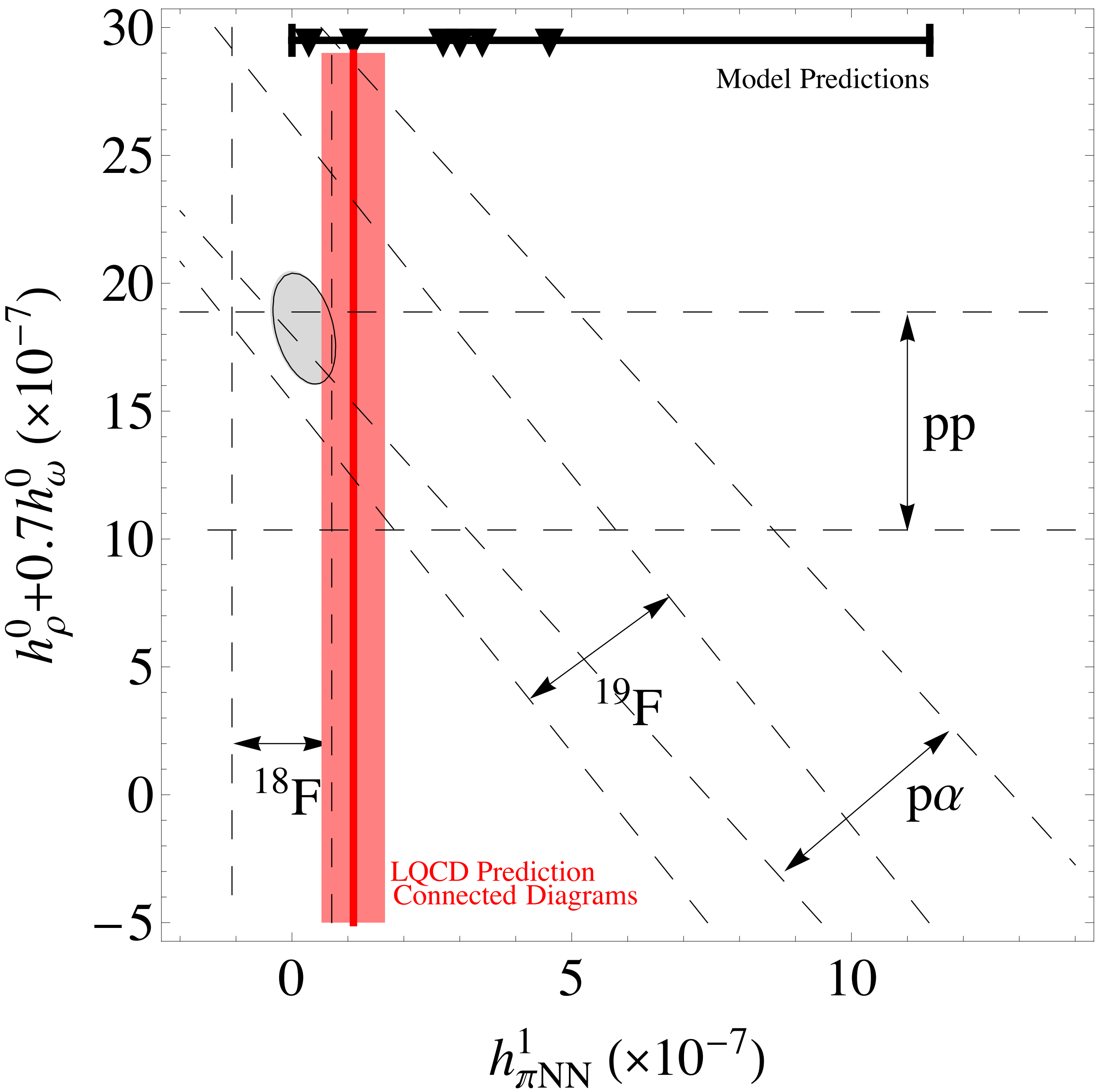
Hadronic Parity Violation

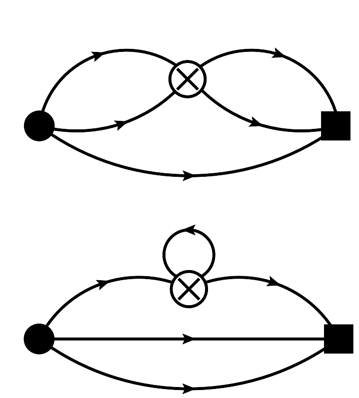
Wasem PRC85 (2012) 022501 arXiv:1108.1151

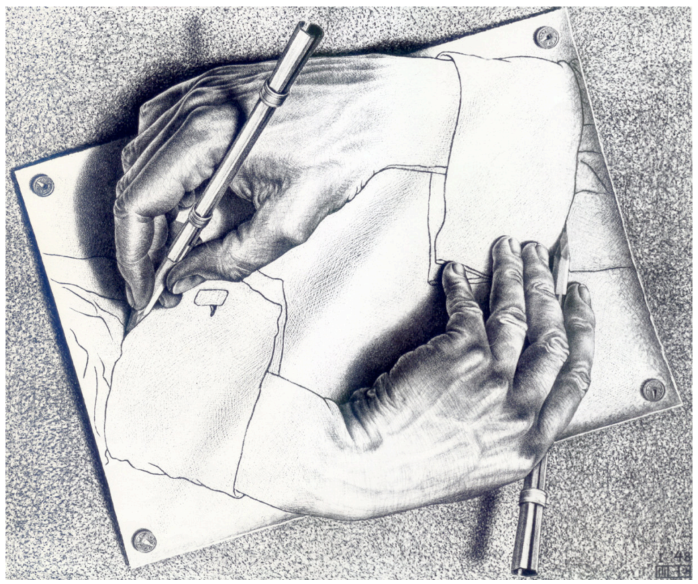
m_π ~ 389 MeV; a~0.123 fm

$$\mathcal{L}_{PV}^{\pi NN} = h_{\pi NN}^{1}\left(\bar{p}\pi^{+}n - \bar{n}\pi^{-}p\right)$$

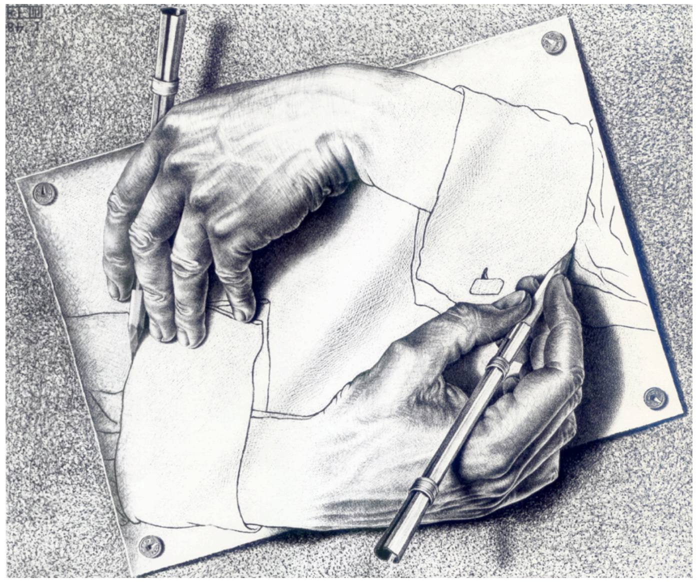
$$h_{\pi NN}^{1,con} = (1.099 \pm 0.505^{+0.058}_{-0.064})\, 10^{-7}$$







PV ≠ VP (mirrored)



Hadronic Parity Violation

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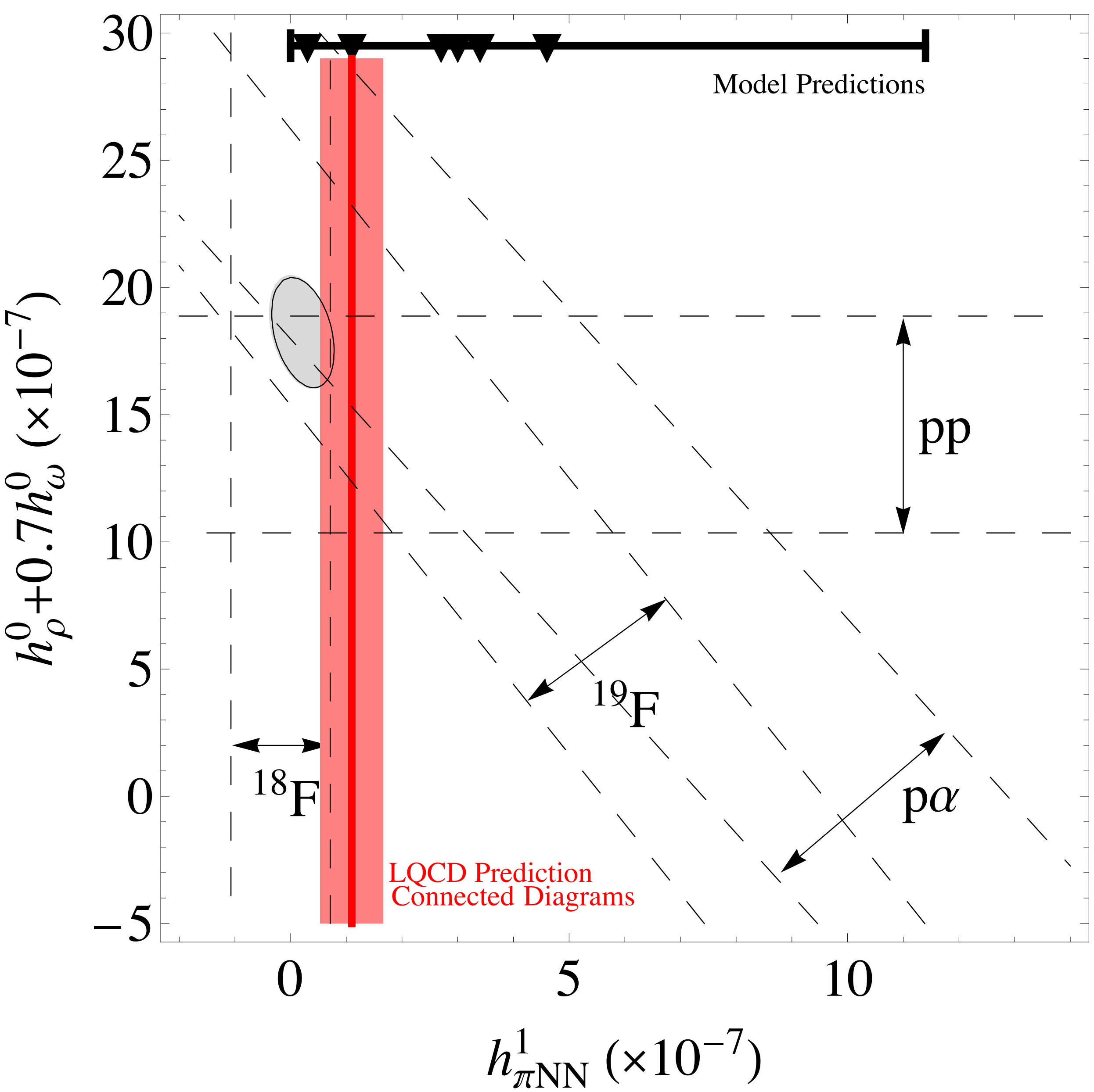
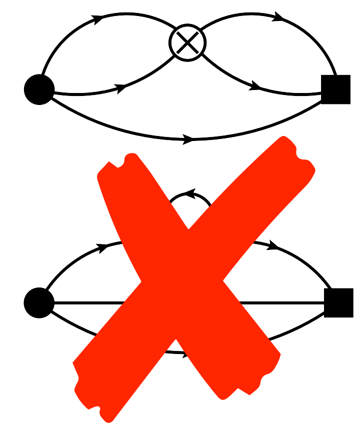
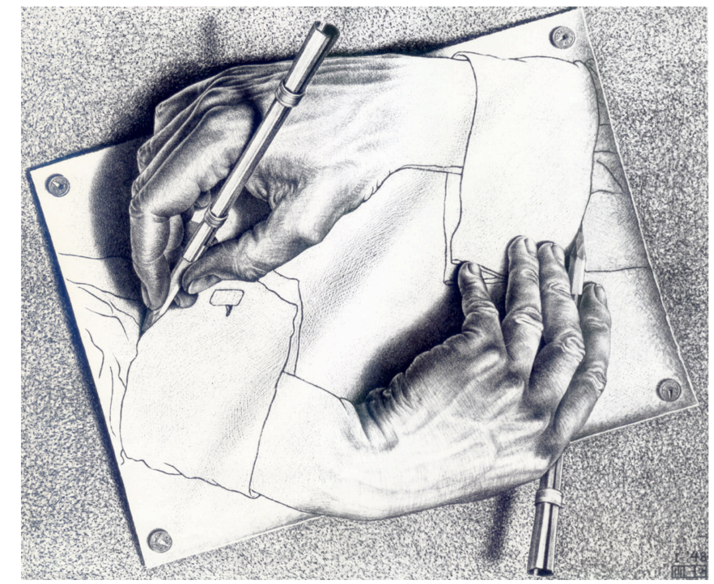
$$\mathcal{L}_{PV}^{\pi NN} = h_{\pi NN}^{1}\left(\bar{p}\pi^{+}n - \bar{n}\pi^{-}p\right)$$

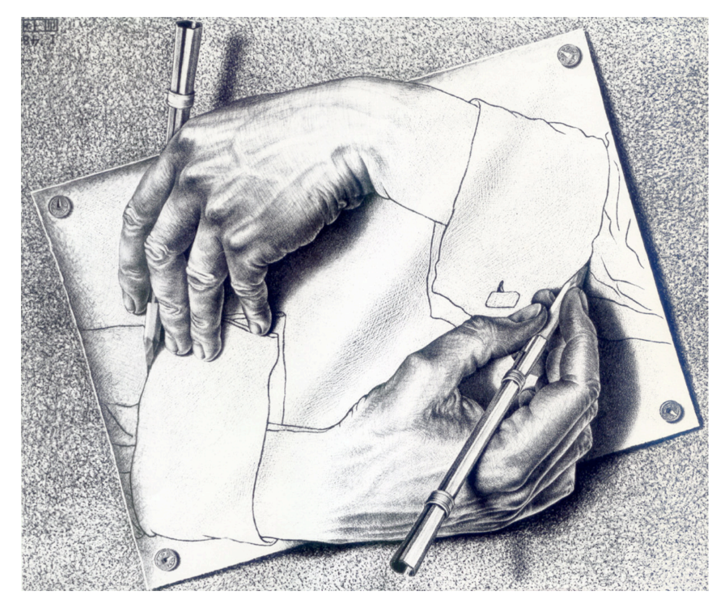
$$h_{\pi NN}^{1,con} = (1.099 \pm 0.505^{+0.058}_{-0.064})\ 10^{-7}$$





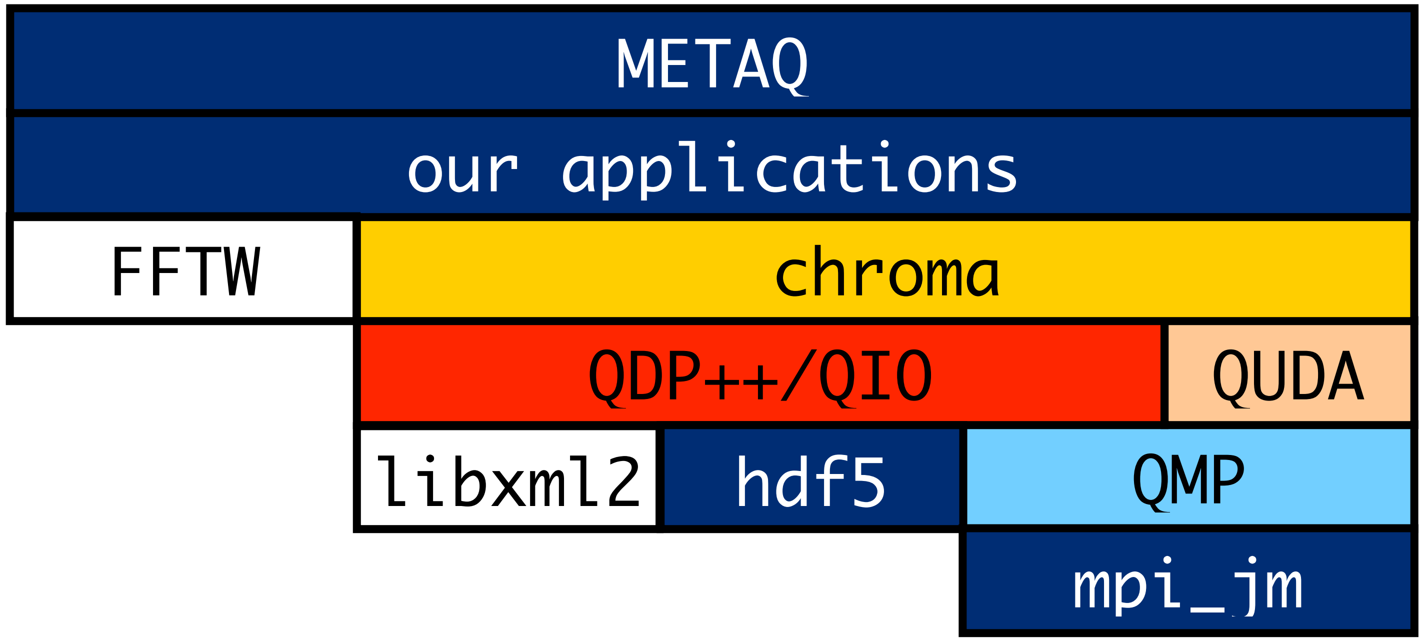


PV ≠ Vꟼ

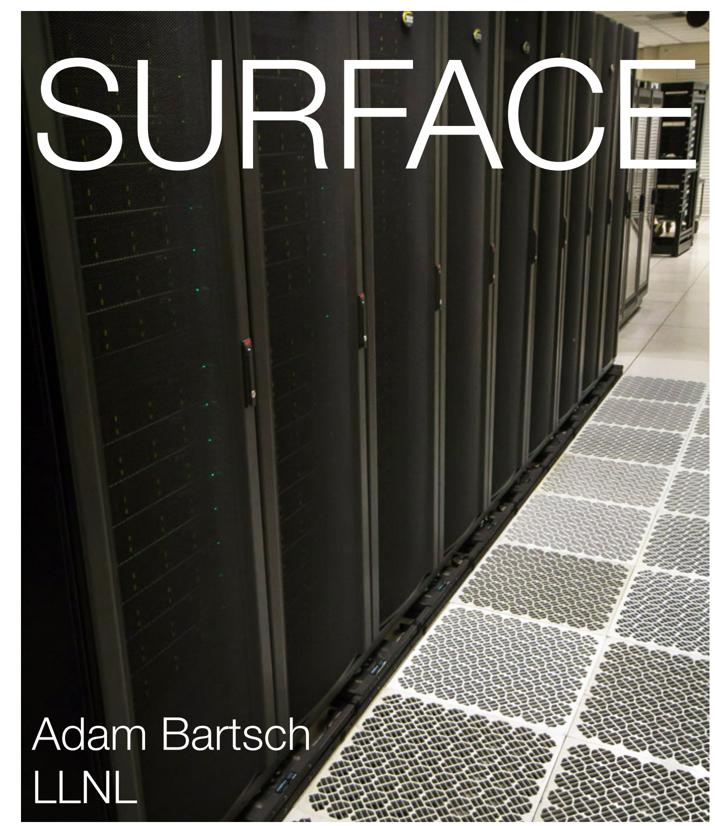


Short-Range $0\nu\beta\beta$ Matrix Elements

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



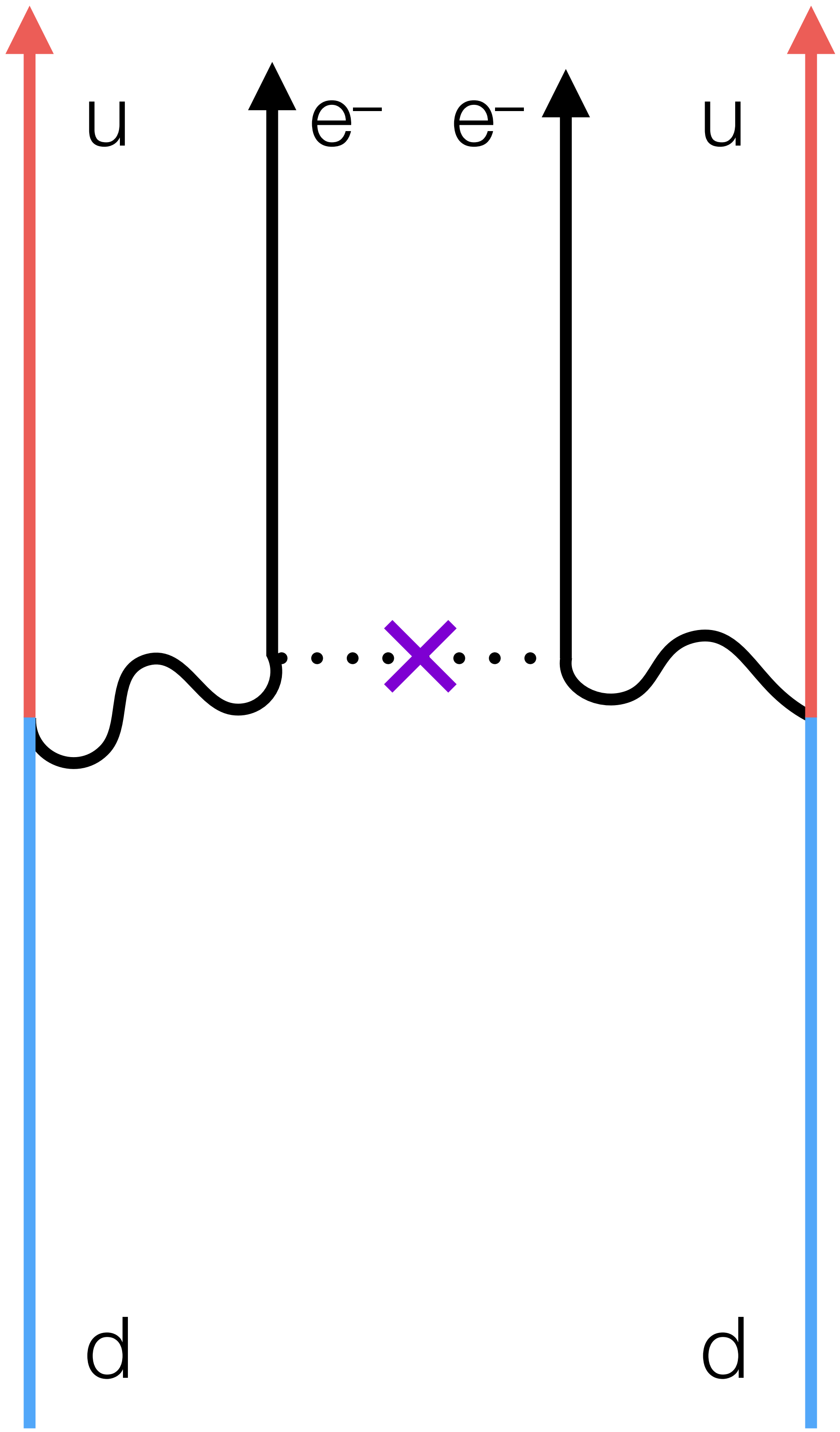
Software	References
METAQ	Berkowitz arXiv:1702.06122 github.com/evanberkowitz/metaq Berkowitz et al. EPJ (LATTICE2017) 175 09007 (2018)
chroma QDP++	Edwards and Joo (SciDAC, LHPC and UKQCD Collaborations) Nucl. Phys. Proc. Suppl 140, 832 (2005)
QUDA	Clark et al. Comput. Phys. Commun. 181 1517 (2010)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



Data + jupyter notebook available on GitHub https://github.com/callat-qcd/project_0vbb

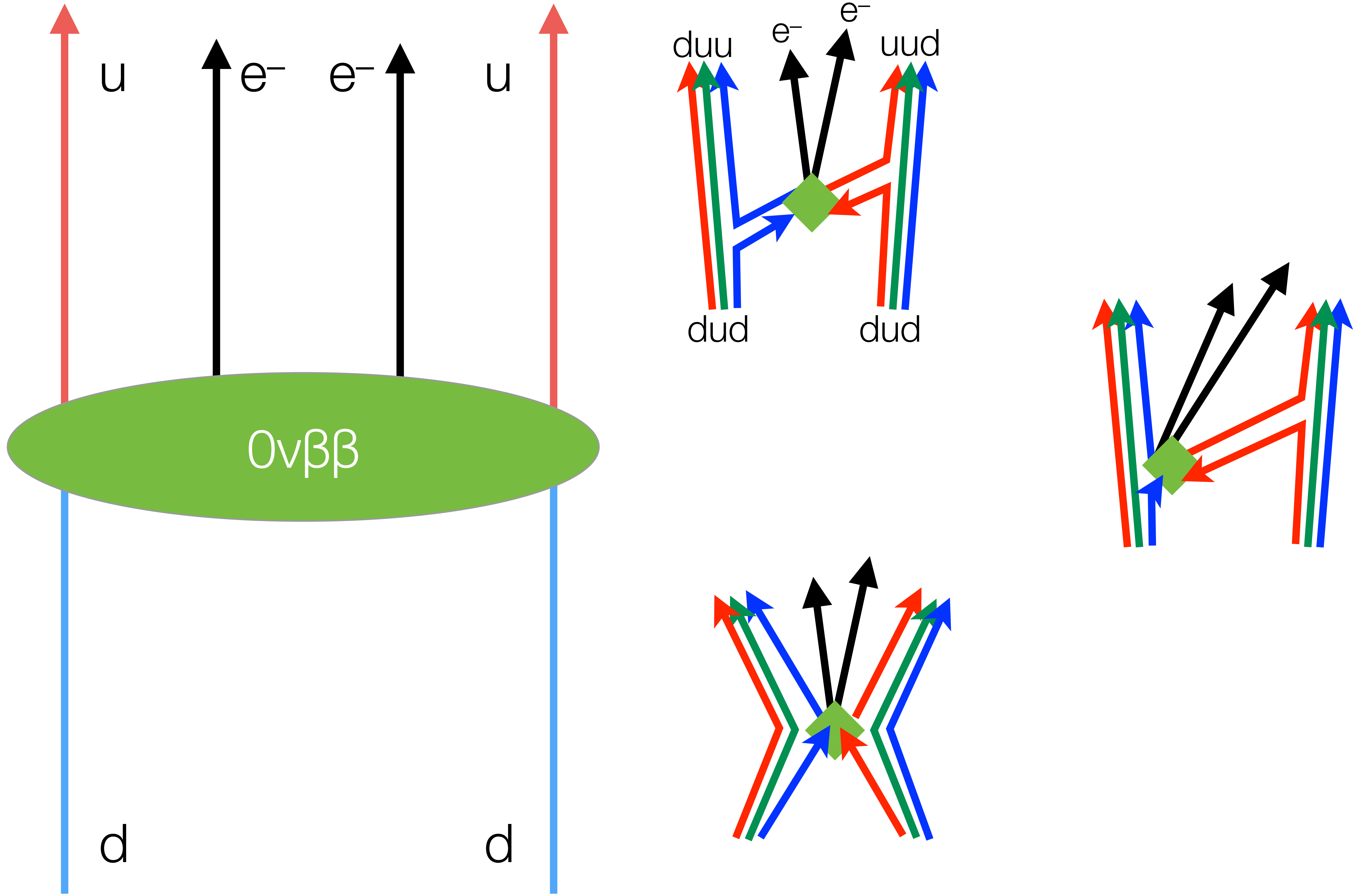
Short Range 0νββ

CalLat PRL 121 (2018) 17 172501 arXiv:1805.02634

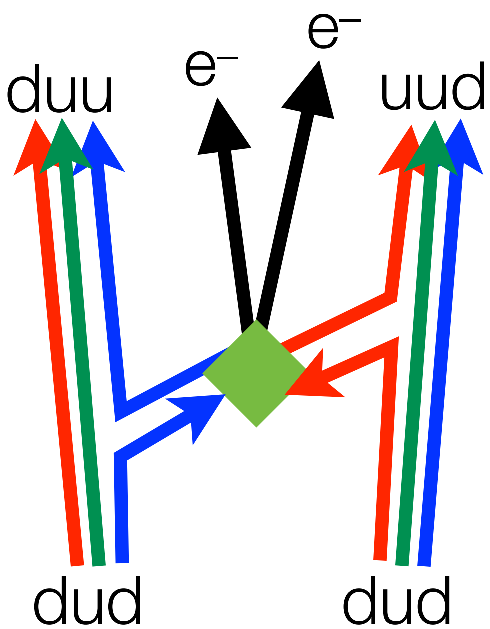


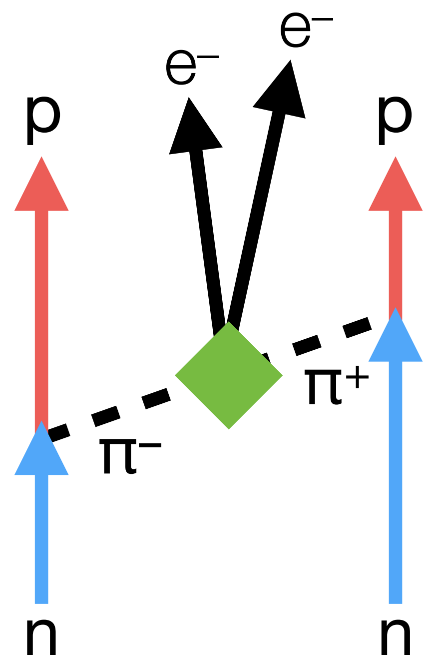
Short Range 0νββ

CalLat PRL 121 (2018) 17 172501 arXiv:1805.02634



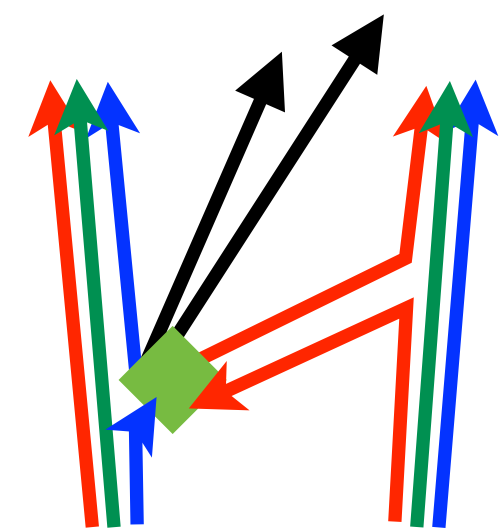
In χPT

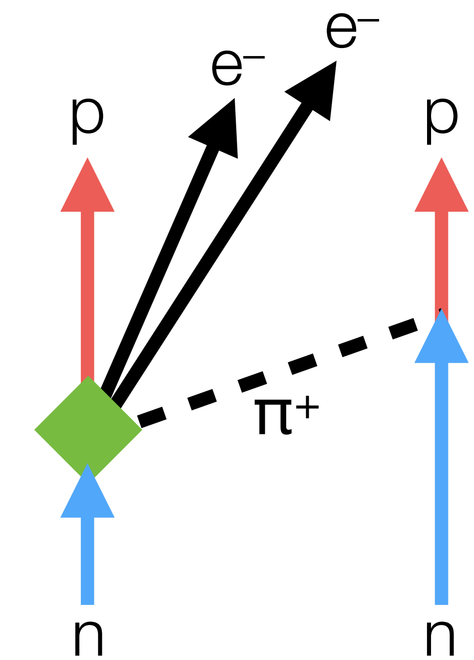


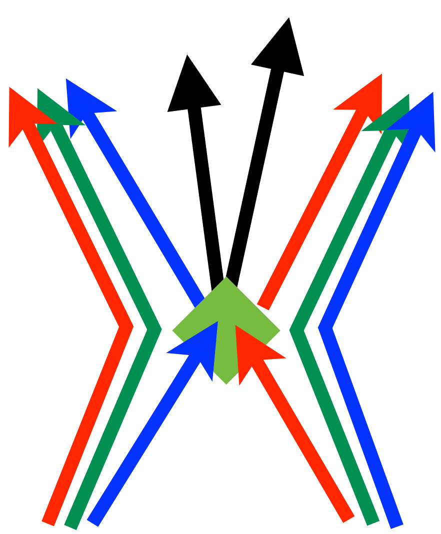


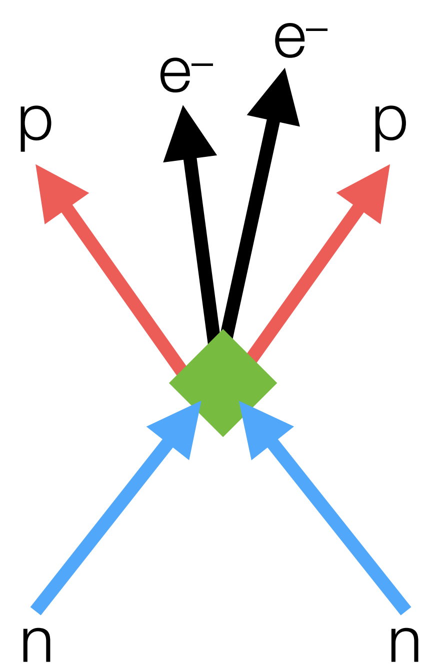
$\mathcal{O}(p^{-2})$ long-range π exchange

$\mathcal{O}(p^{-1})$ new πN vertex







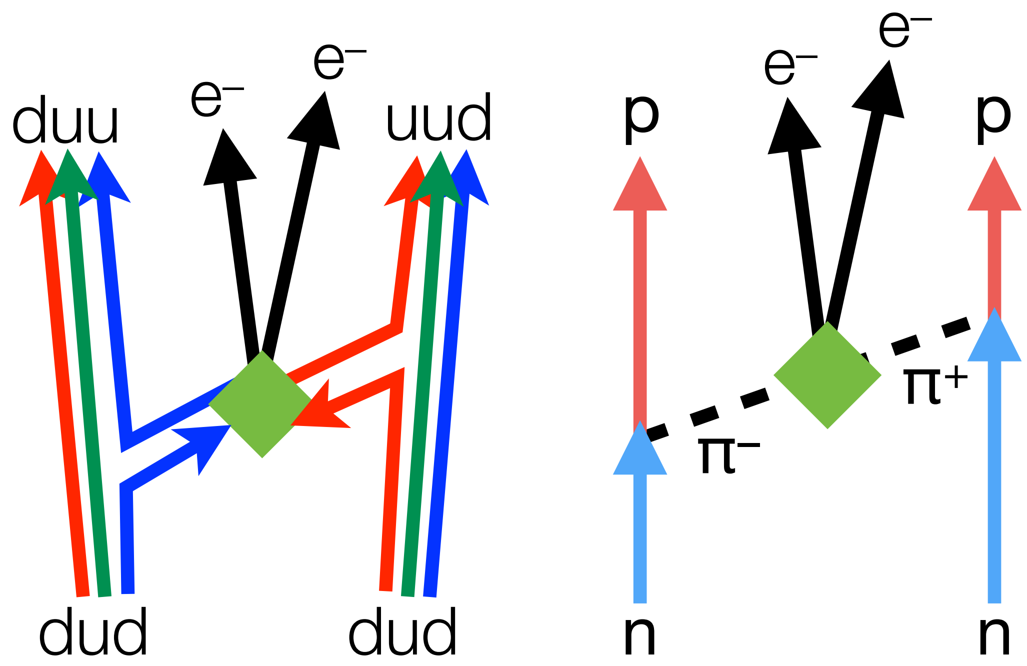


$\mathcal{O}(p^{0})$ NN contact operator

Promoted, as in Cirigliano, Dekens, Mereghetti and Walker-Loud PRC 97 (2018) 06 065501 arXiv:1710.01729
Cirigliano, Dekens, de Vries, Graesser, Mereghetti, Pastor and van Kolck, PRL 120 (2018) 202001 arXiv:1802.10097

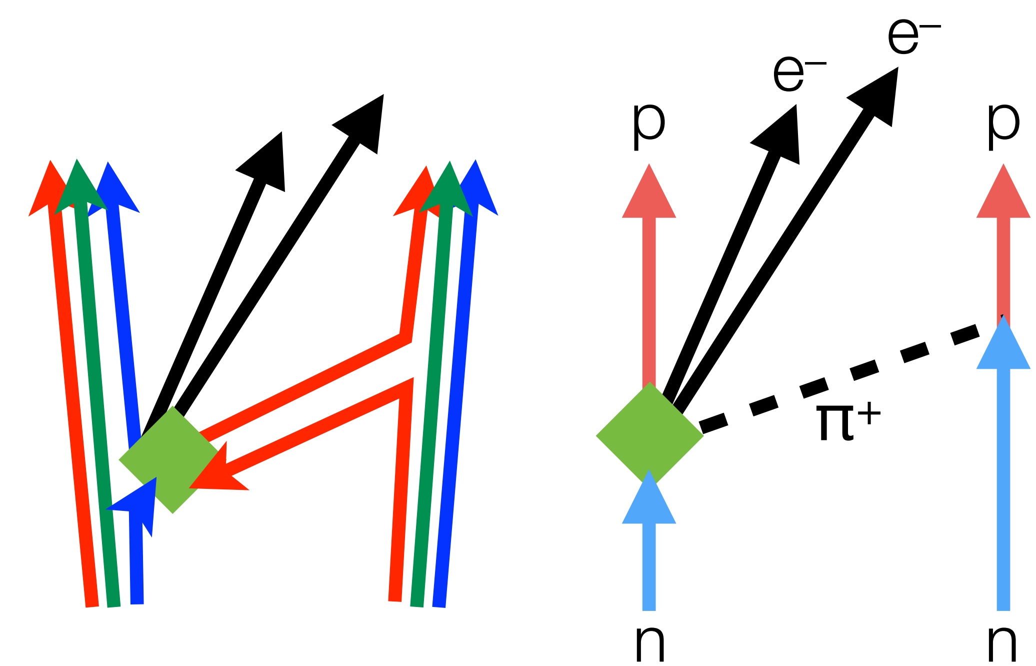
Prézeau, Ramsey-Musolf, Vogel PRD68 034016 hep-ph/0303205

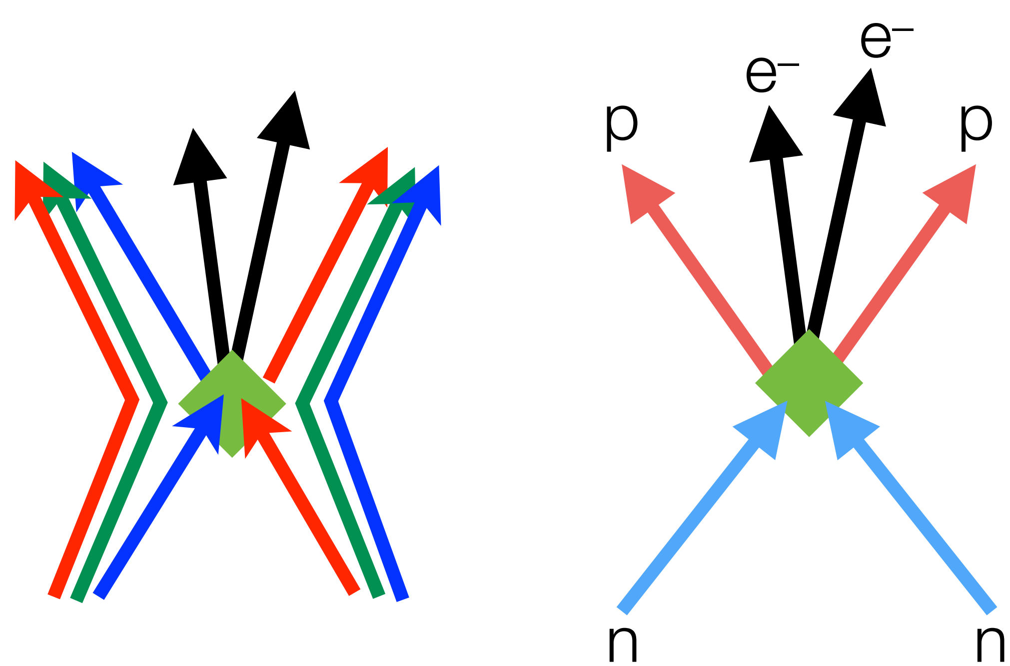
In χPT



$\mathcal{O}(p^{-2})$ long-range π exchange

$\mathcal{O}(p^{-1})$ new πN vertex

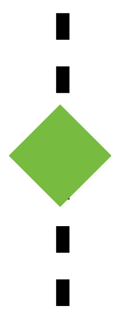
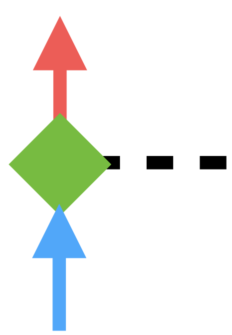
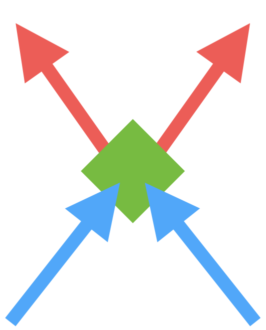


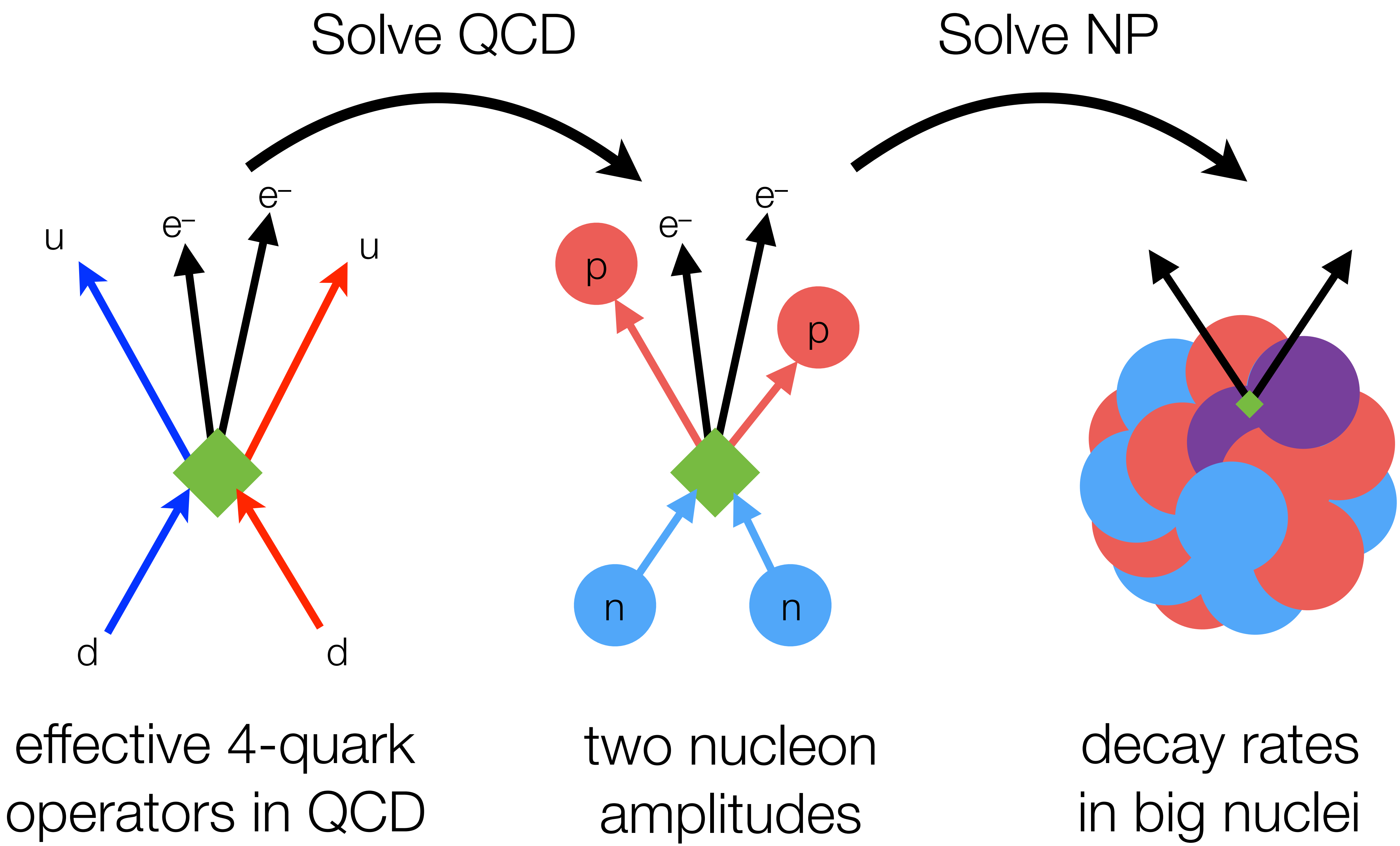


$\mathcal{O}(p^{\cancel{0}\,-2})$ NN contact operator

Promoted, as in Cirigliano, Dekens, Mereghetti and Walker-Loud PRC 97 (2018) 06 065501 arXiv:1710.01729
Cirigliano, Dekens, de Vries, Graesser, Mereghetti, Pastor and van Kolck, PRL 120 (2018) 202001 arXiv:1802.10097

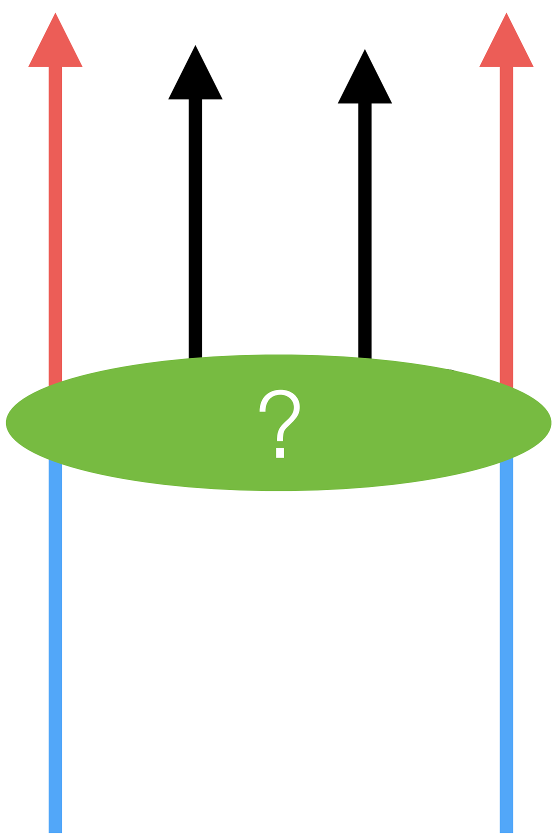
Prézeau, Ramsey-Musolf, Vogel PRD68 034016 hep-ph/0303205

	Order	No Disconnected Diagrams	Signal to Noise	Leading Order Operators Induce 0^+ to 0^+ transition
	p^{-2}	✓	✓	✓
	p^{-1}	✗	✗	✗
	~~p^{-2}~~	✓	✗✗	✓


Solve QCD
Solve NP
u
e−
e−
u
d
d
p
e−
e−
p
n
n
effective 4-quark
operators in QCD
two nucleon
amplitudes
decay rates
in big nuclei

Operators

Prézeau, Ramsey-Musolf, Vogel PRD68 (2003) 034016 hep-ph/0303205



$$\mathcal{O}_{1+}^{ab} = (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_R \tau^b \gamma_\mu q_R),$$

$$\mathcal{O}_{2\pm}^{ab} = (\bar{q}_R \tau^a q_L)(\bar{q}_R \tau^b q_L) \pm (\bar{q}_L \tau^a q_R)(\bar{q}_L \tau^b q_R),$$

$$\mathcal{O}_{3\pm}^{ab} = (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_L \tau^b \gamma_\mu q_L) \pm (\bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_R \tau^b \gamma_\mu q_R),$$

$$\mathcal{O}_{4\pm}^{ab,\mu} = (\bar{q}_L \tau^a \gamma^\mu q_L \mp \bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_L \tau^b q_R - \bar{q}_R \tau^b q_L),$$

$$\mathcal{O}_{5\pm}^{ab,\mu} = (\bar{q}_L \tau^a \gamma^\mu q_L \pm \bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_L \tau^b q_R + \bar{q}_R \tau^b q_L).$$

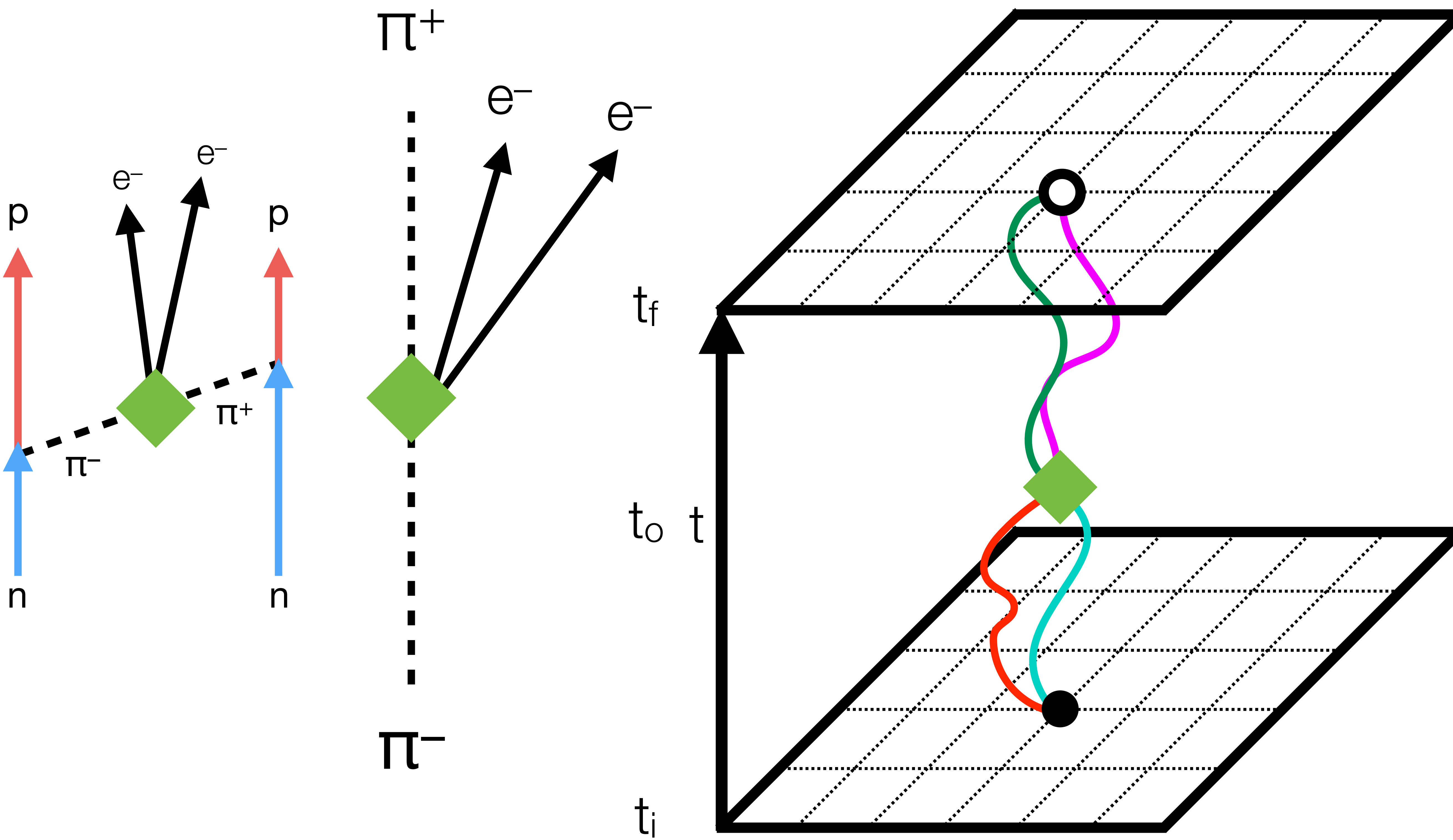
+$\mathcal{O}$' color-mixed operators:

$$(\bar{q}\Gamma_1 q]\,[\bar{q}\Gamma_2 q) = \bar{q}_a \Gamma_1 q_b \;\; \bar{q}_b \Gamma_2 q_a$$

$0\nu\beta\beta$-decay ops.	$\mathcal{O}_{1+}^{++}$	$\mathcal{O}_{2+}^{++}$	$\mathcal{O}_{2-}^{++}$	$\mathcal{O}_{3+}^{++}$	$\mathcal{O}_{3-}^{++}$	$\mathcal{O}_{4+}^{++,\mu}$	$\mathcal{O}_{4-}^{++,\mu}$	$\mathcal{O}_{5+}^{++,\mu}$	$\mathcal{O}_{5-}^{++,\mu}$
$\pi\pi ee$ LO	√	√	X	X	X	X	X	X	X
$\pi\pi ee$ NNLO	√	√	X	√	X	X	X	X	X
$NN\pi ee$ LO	X	X	√	X	X	√	√	√	√
$NN\pi ee$ NLO	X	√	X	√	X	√	√	√	√
$NNNNee$ LO	√	√	X	√	X	√	√	√	√

Short Distance 0νββ
$\pi^+ \pi^-$ Transition

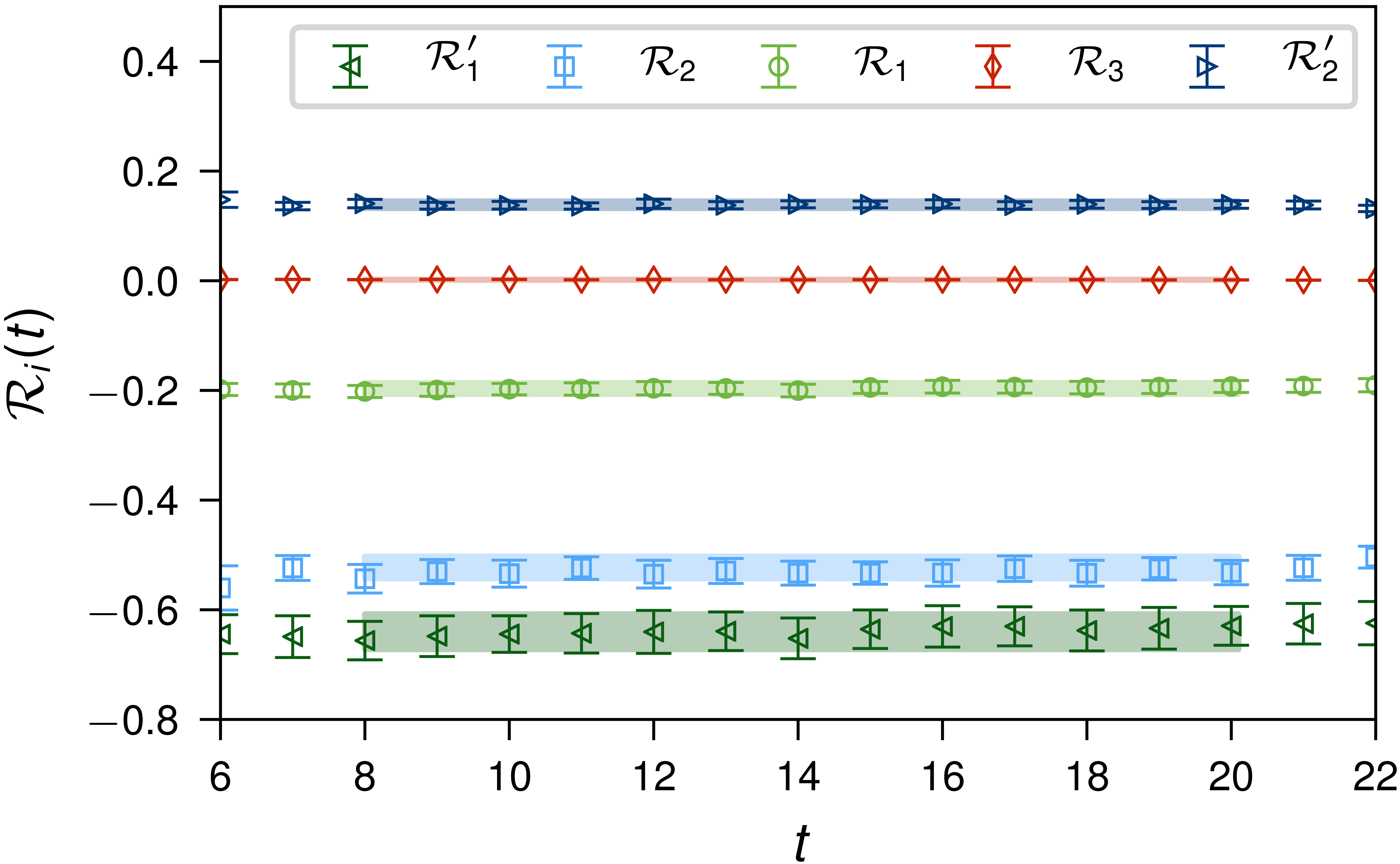
CalLat PRL 121 (2018) 17 172501 arXiv:1805.02634



Results for a Single Ensemble

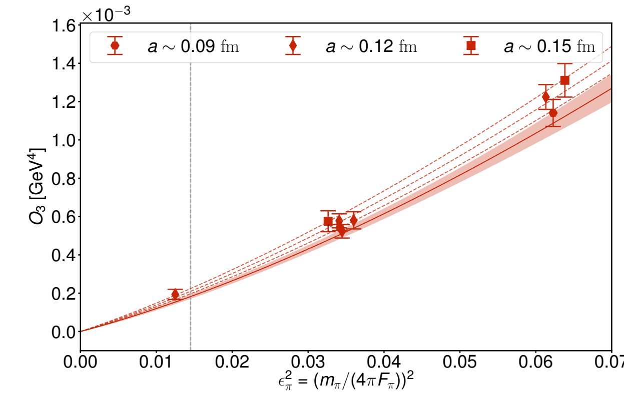
PRL 121 (2018) 172501 arXiv:1805.02634

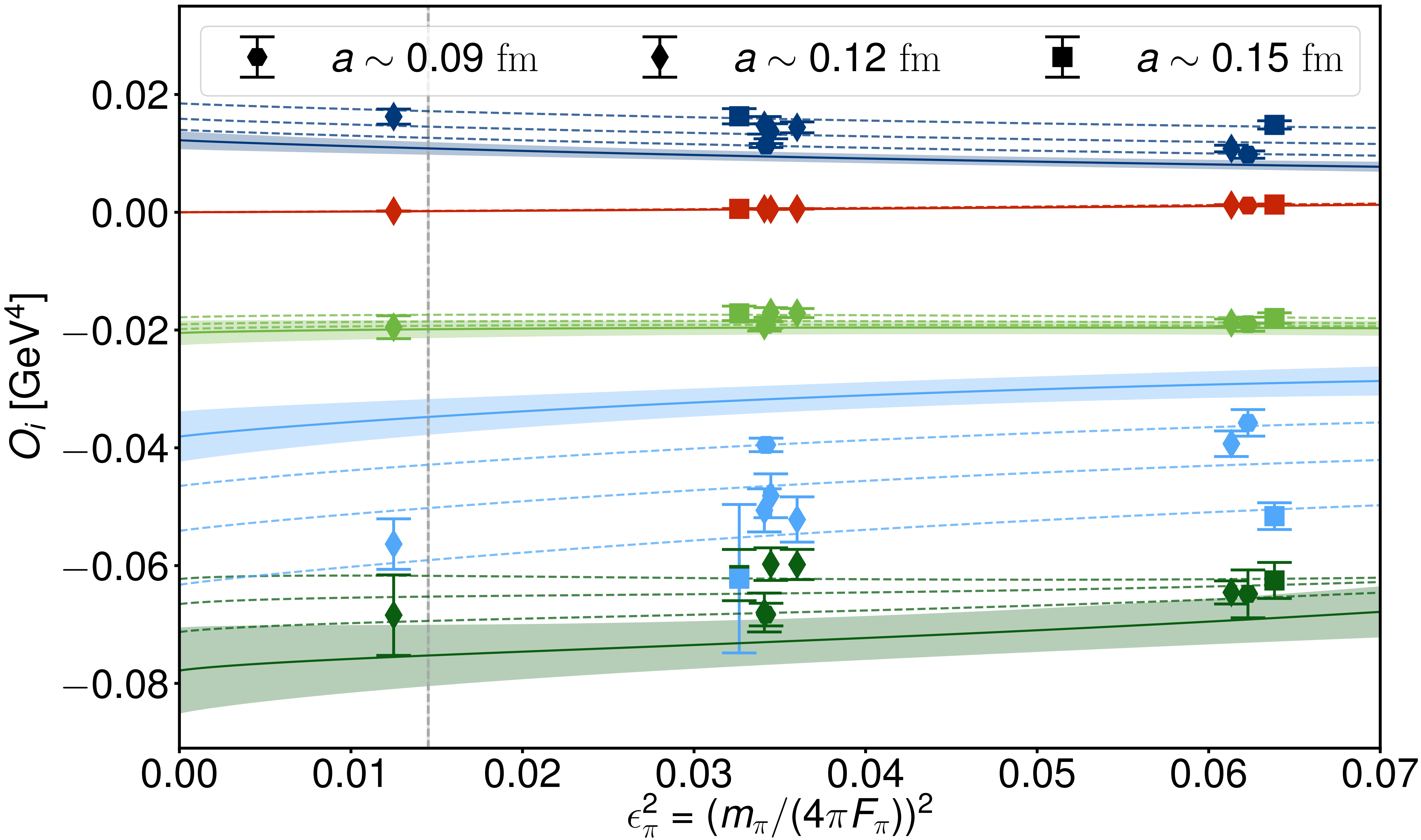
a ~ 0.12 fm
m_π ~ 130 MeV



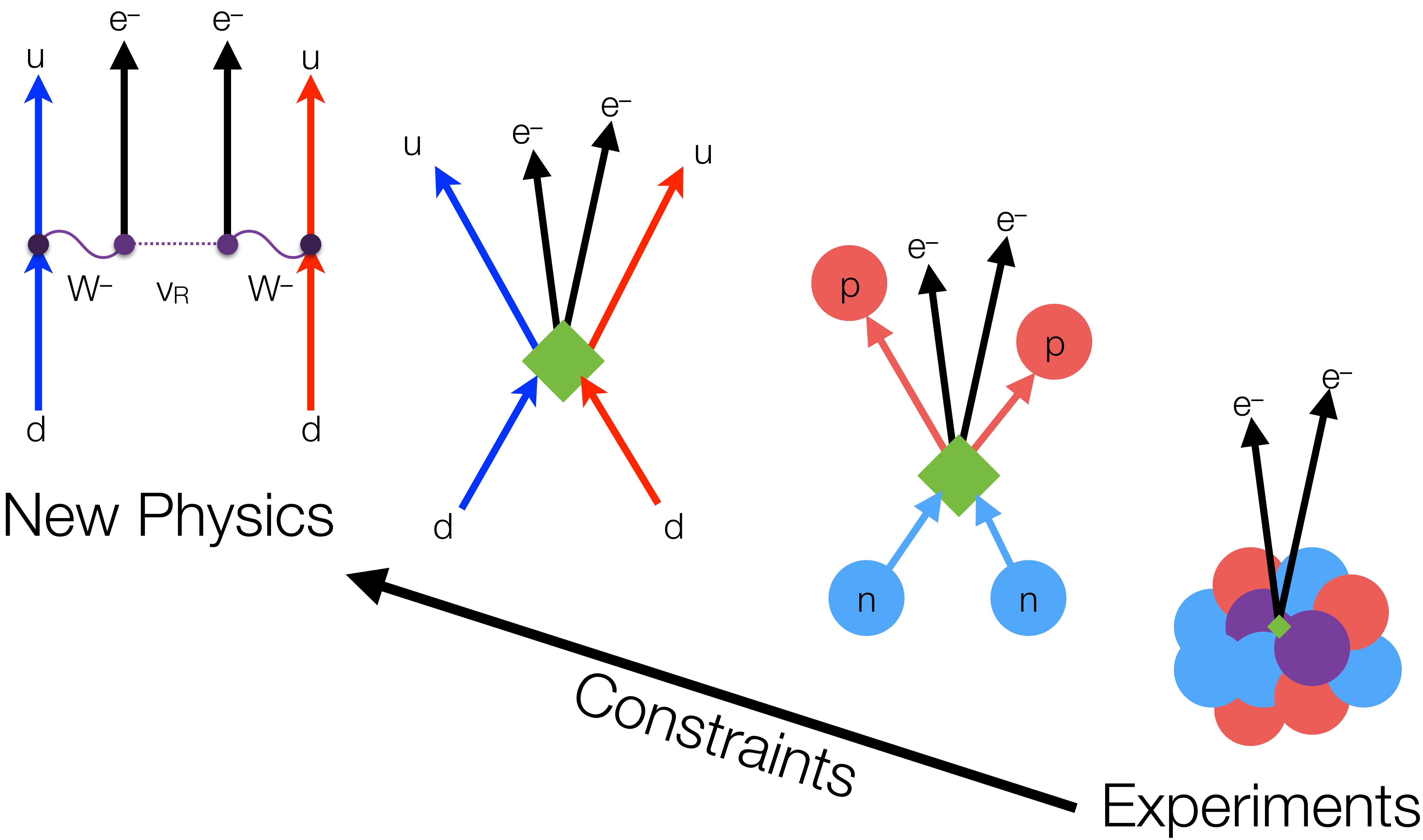
Short-distance 0νββ

CallLat PRL 121 (2018) 17 172501 arXiv:1805.02634





Nuclear Laboratory

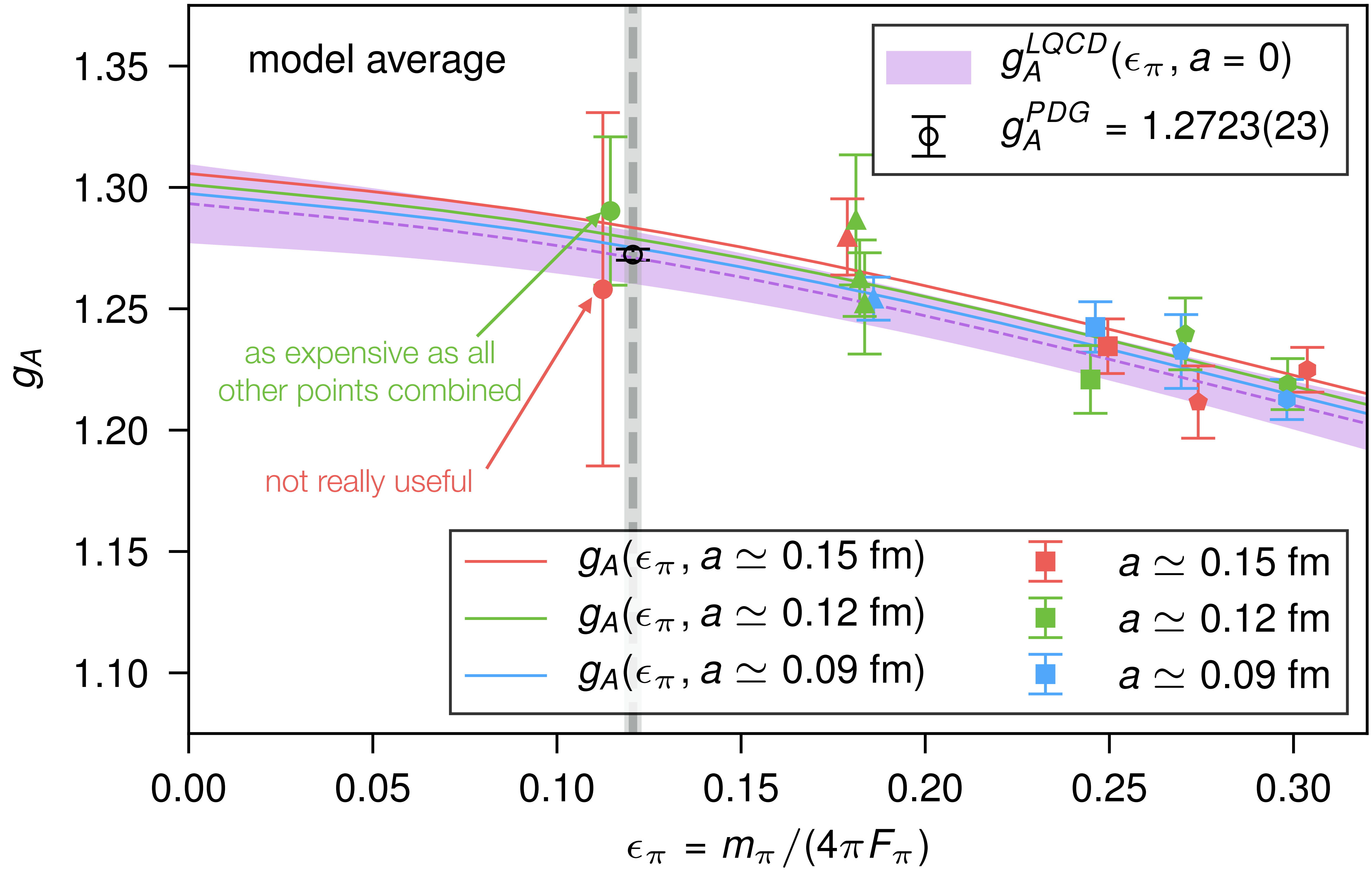



SIERRA
LLNL


summit
OLCF


LASSEN
LLNL

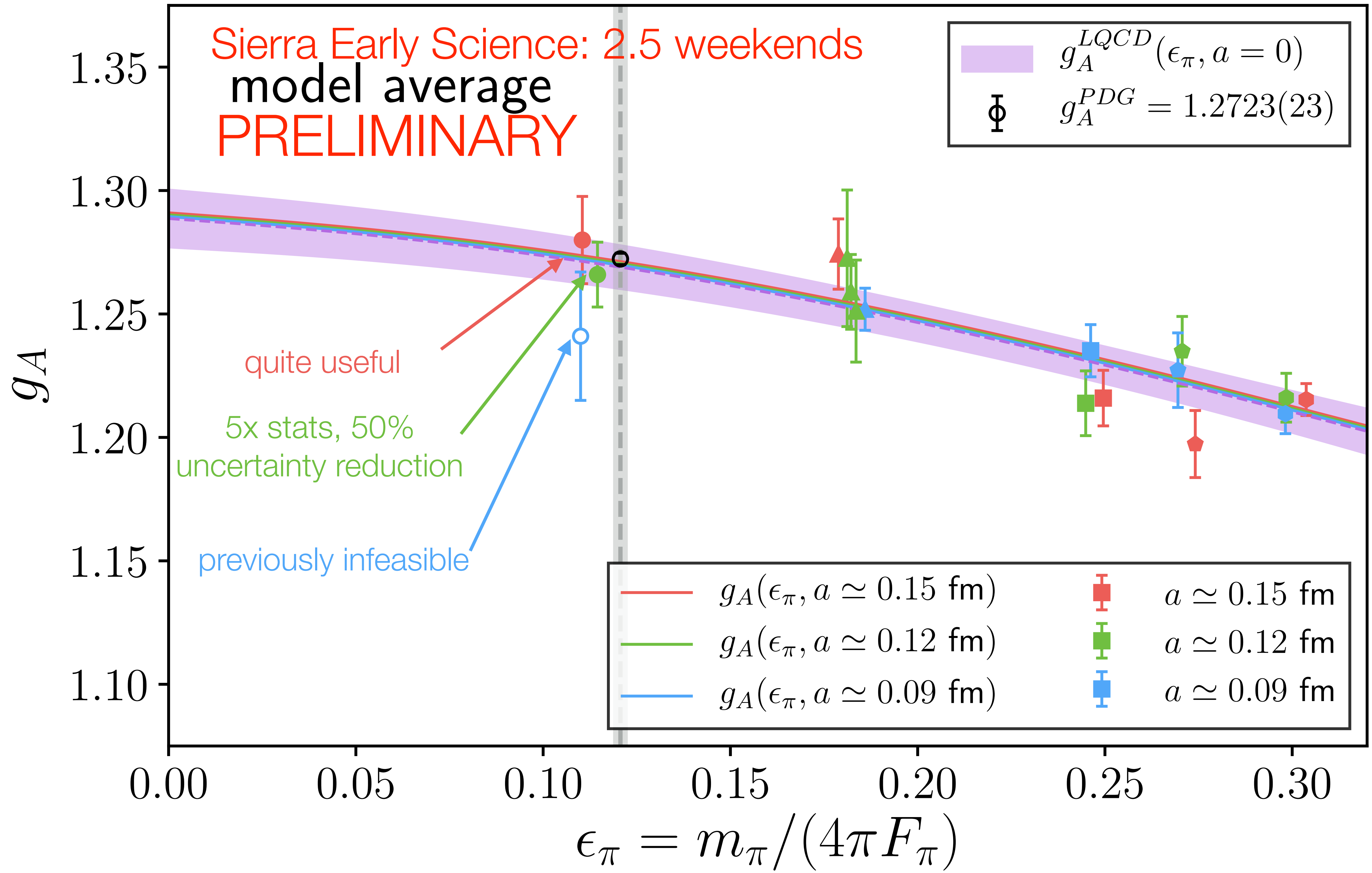
Published $g_A^{QCD} = 1.271(13)$



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

UPDATE $g_A^{QCD} = 1.2690(98)$ [0.77%] PRELIMINARY

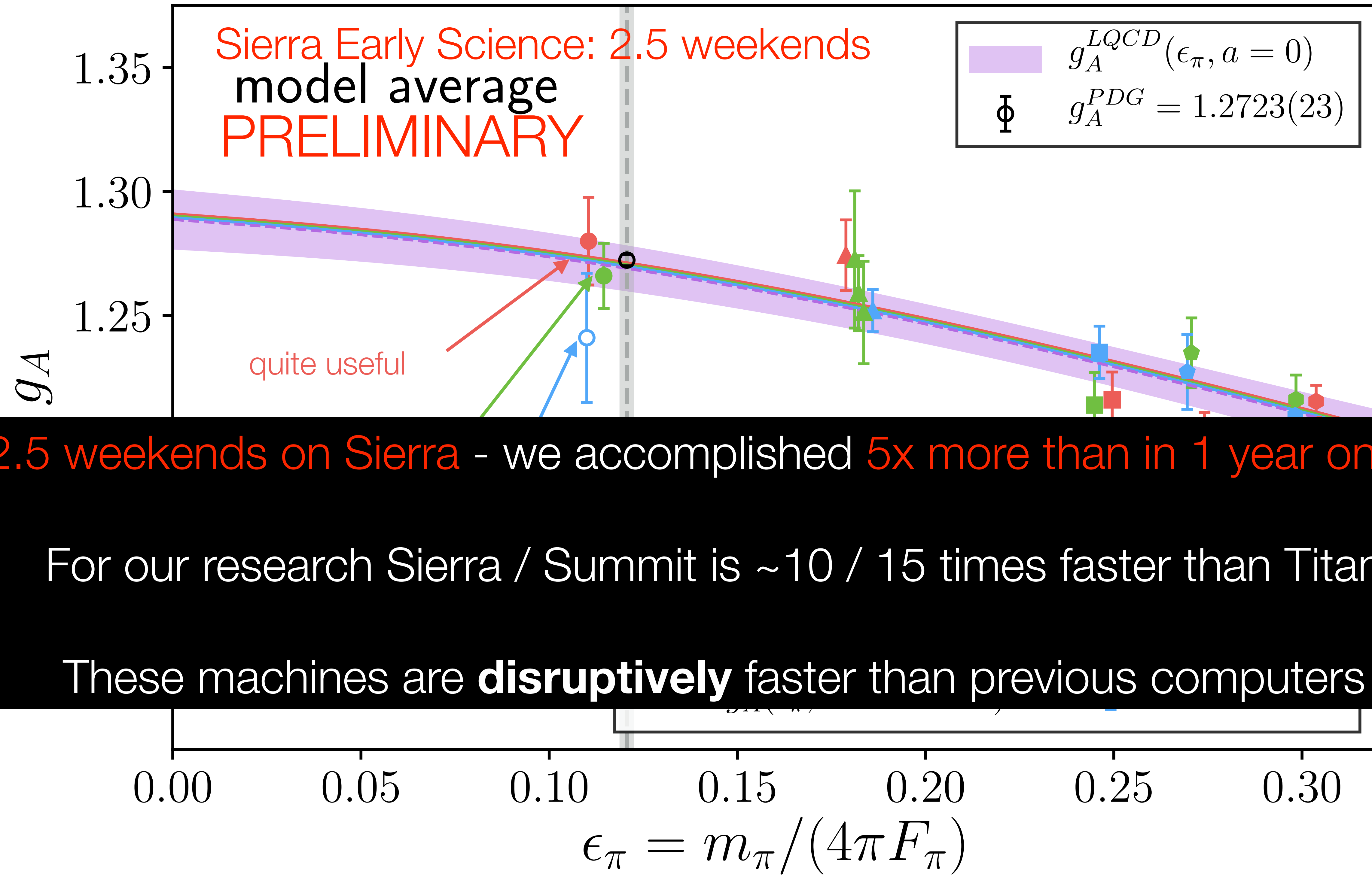
PRELIMINARY!!!!!



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

UPDATE $g_A^{QCD} = 1.2690(98)$ [0.77%] PRELIMINARY

PRELIMINARY!!!!!



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

For our research Sierra / Summit is ~10 / 15 times faster than Titan

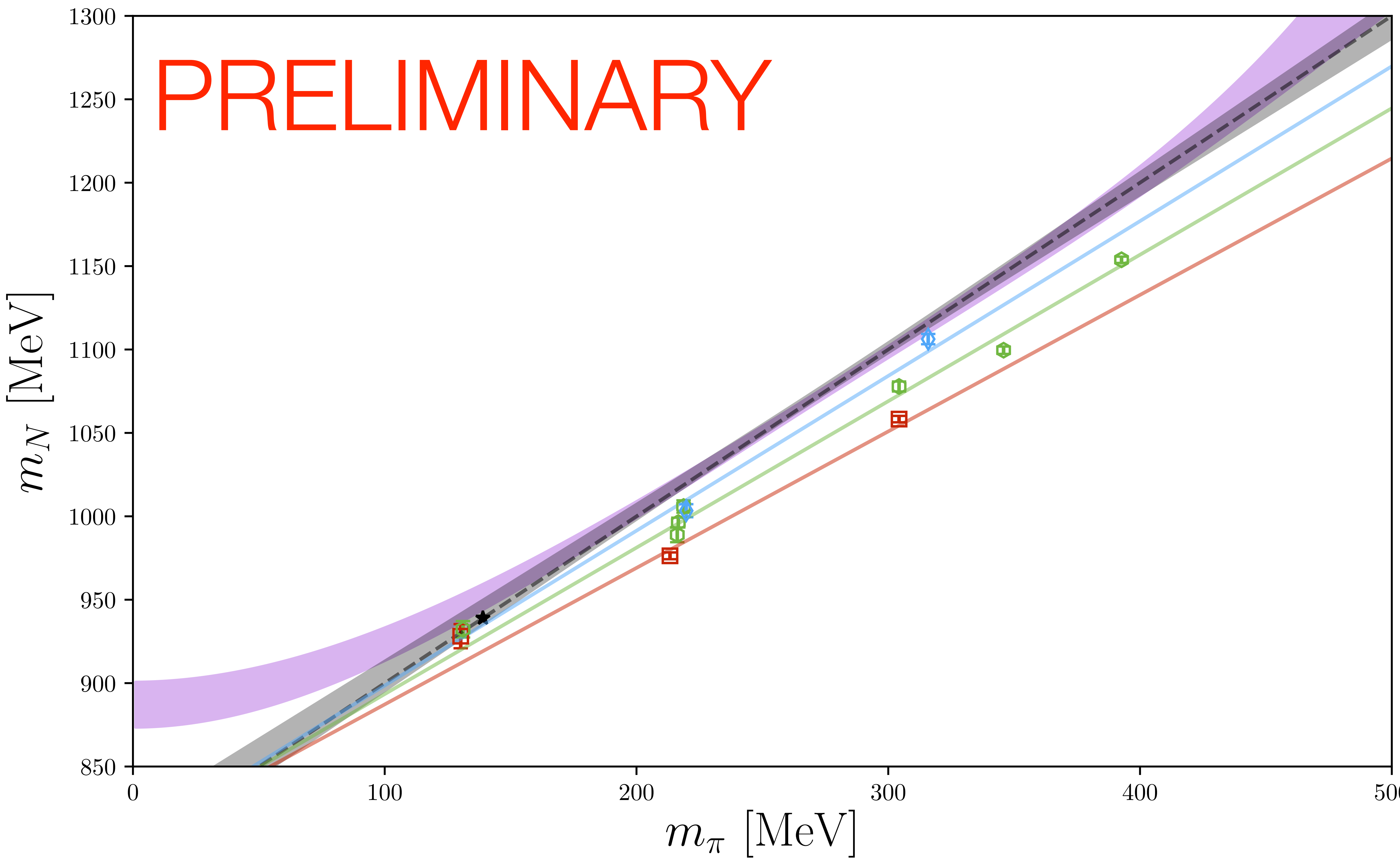
These machines are **disruptively** faster than previous computers

Summary

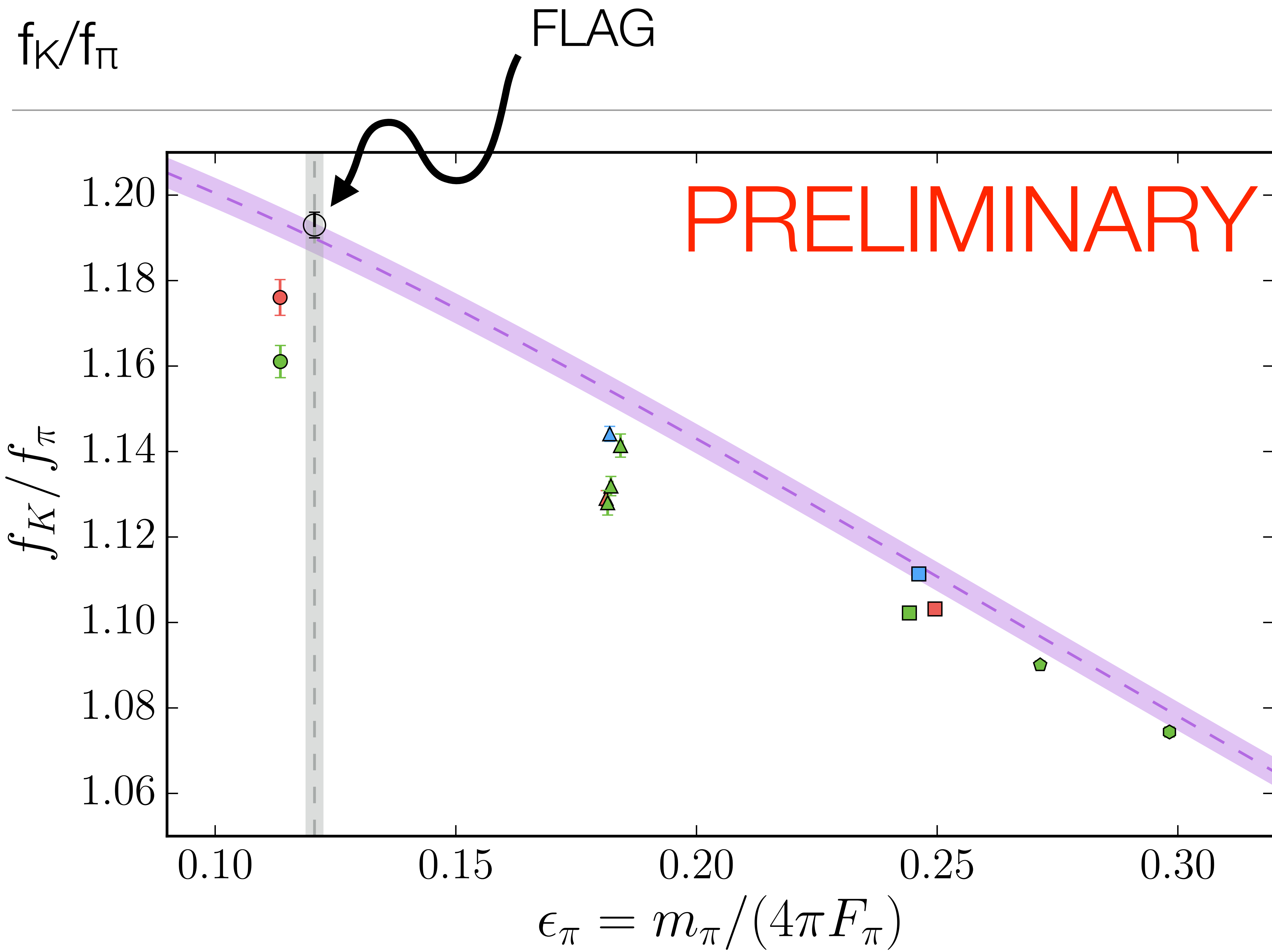
- g_A, $n\bar{n}$: Looking good!
- θEDM + cEDM: progress, but indistinguishable from zero;
  Weinberg operator: not as much progress
- CP violating πN coupling
- FFs: M_A doesn't work; new techniques + faster machines will unlock $q^2 \to 0$
  Chang, Bouchard, Orginos, Richards 1610.02354
- NN: g_A quenching, pp fusion, isotensor polarizability (2vββ), ΔI=2 Hadronic PV.
  1 lattice spacing, very heavy m_π.
- Complete $\pi^+\pi^-$ transition (0vββ) calculation!

Backup Slides

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



f_K/f_π



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

MILC Ensembles

MILC Collaboration Phys. Rev. D87 (2013) 054505
PRD 96 (2017) 054513 arXiv:1701.07559

+ additional HISQ ensembles generated at LLNL

	HISQ gauge configuration parameters							**valence parameters**							
	abbr.	$N_{\rm cfg}$	volume	$\sim a$ [fm]	m_l/m_s	$\sim m_{\pi_5}$ [MeV]	$\sim m_{\pi_5} L$	$N_{\rm src}$	L_5/a	aM_5	b_5	c_5	$am_l^{\rm val.}$	$\sigma_{\rm smr}$	$N_{\rm smr}$
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
coarser	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
coarser	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
coarser	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
coarser	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
middle	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
middle	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
middle	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
middle	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
middle	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
middle	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
finer	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
finer	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
finer	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].

$0\nu\beta\beta$ Lattices

PRL 121 (2018) 172501 arXiv:1805.02634

$a \setminus m_\pi$	310 MeV	220 MeV	135 MeV
0.15 fm	$16^3\times48$ $m_\pi L \sim 3.78$	$24^3\times48$ $m_\pi L \sim 3.99$	$32^3\times48$ $m_\pi L \sim 3.25$
0.12 fm		$24^3\times64$ $m_\pi L \sim 3.22$	
0.12 fm	$24^3\times64$ $m_\pi L \sim 4.54$	$32^3\times64$ $m_\pi L \sim 4.29$	$48^3\times64$ $m_\pi L \sim 3.91$
0.12 fm		$40^3\times64$ $m_\pi L \sim 5.36$	
0.09 fm	$32^3\times96$ $m_\pi L \sim 4.50$	$48^3\times96$ $m_\pi L \sim 4.73$	

- Möbius DWF on HISQ sea MILC Collaboration Phys. Rev. D87 (2013) 054505
- Gradient flow with very small m_{res} for reasonable L_5
  Narayanan, Neuberger (2006), Luscher (2010)
- ~1000 configurations, 1 wall and 1 point per config

Black Box Theorem: 0νββ implies Majorana Mass

Schechter and Valle PRD 25 (1982) 774