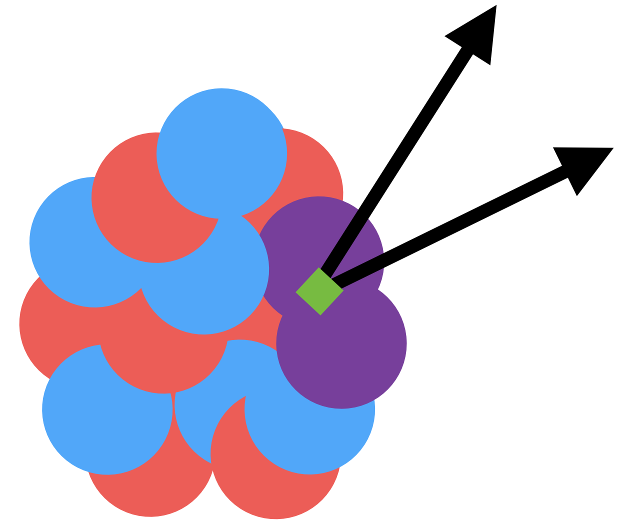
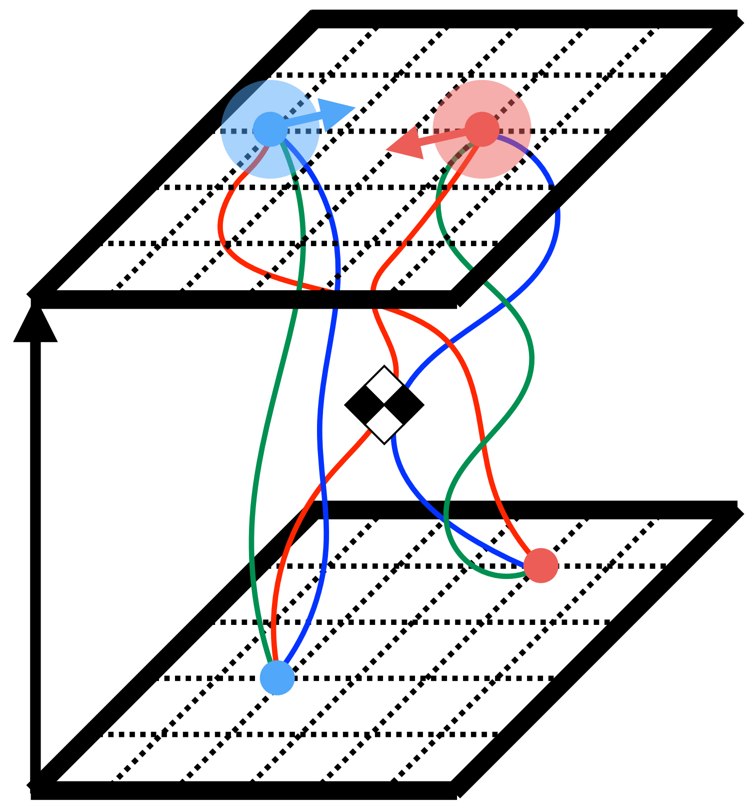
Lattice Gauge Theory Calculations of NN Weak Amplitudes





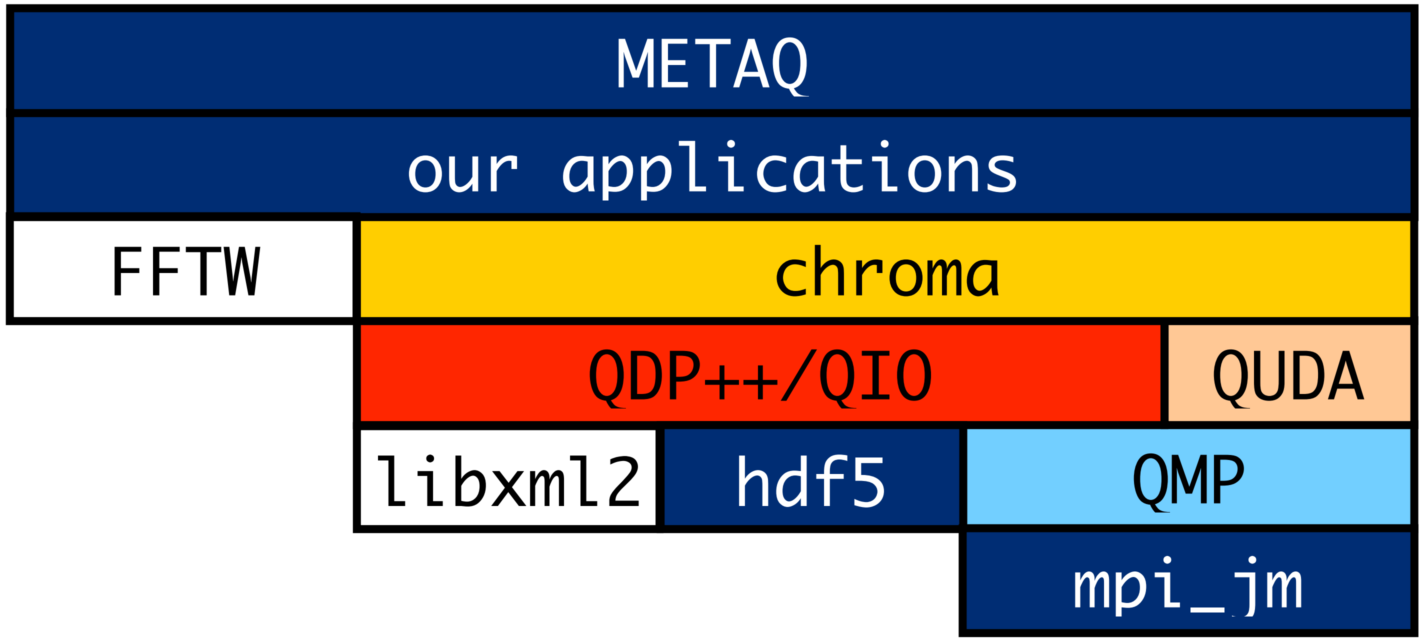
Evan Berkowitz
Institut für Kernphysik
Institute for Advanced Simulation
Forschungszentrum Jülich

Particle Physics with Neutrons at the ESS
NORDITA
11 December, 2018

JÜLICH FORSCHUNGSZENTRUM

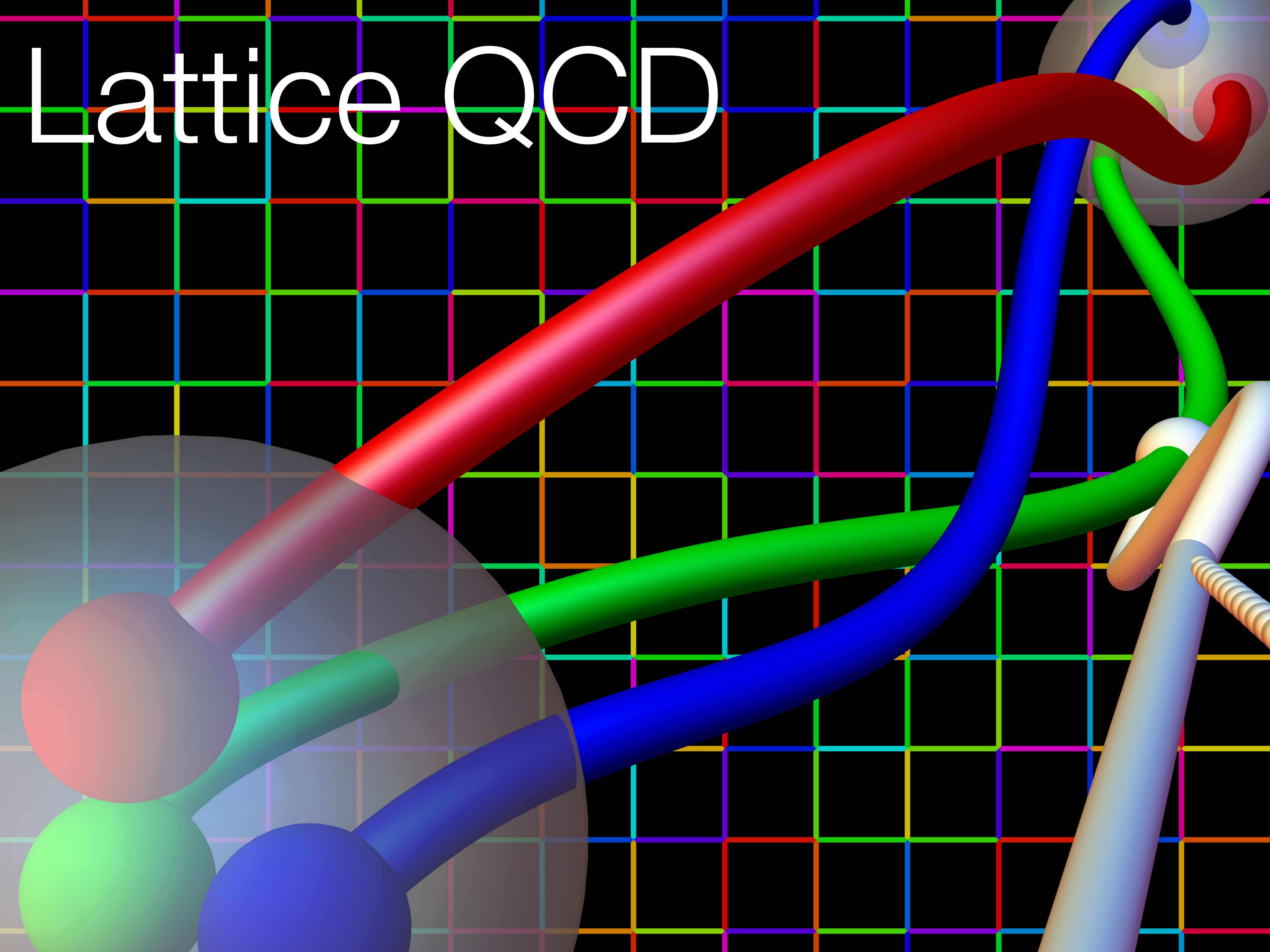
CalLat

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/

Lattice QCD



Introduction to LQCD

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

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

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

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lattice
finite volume

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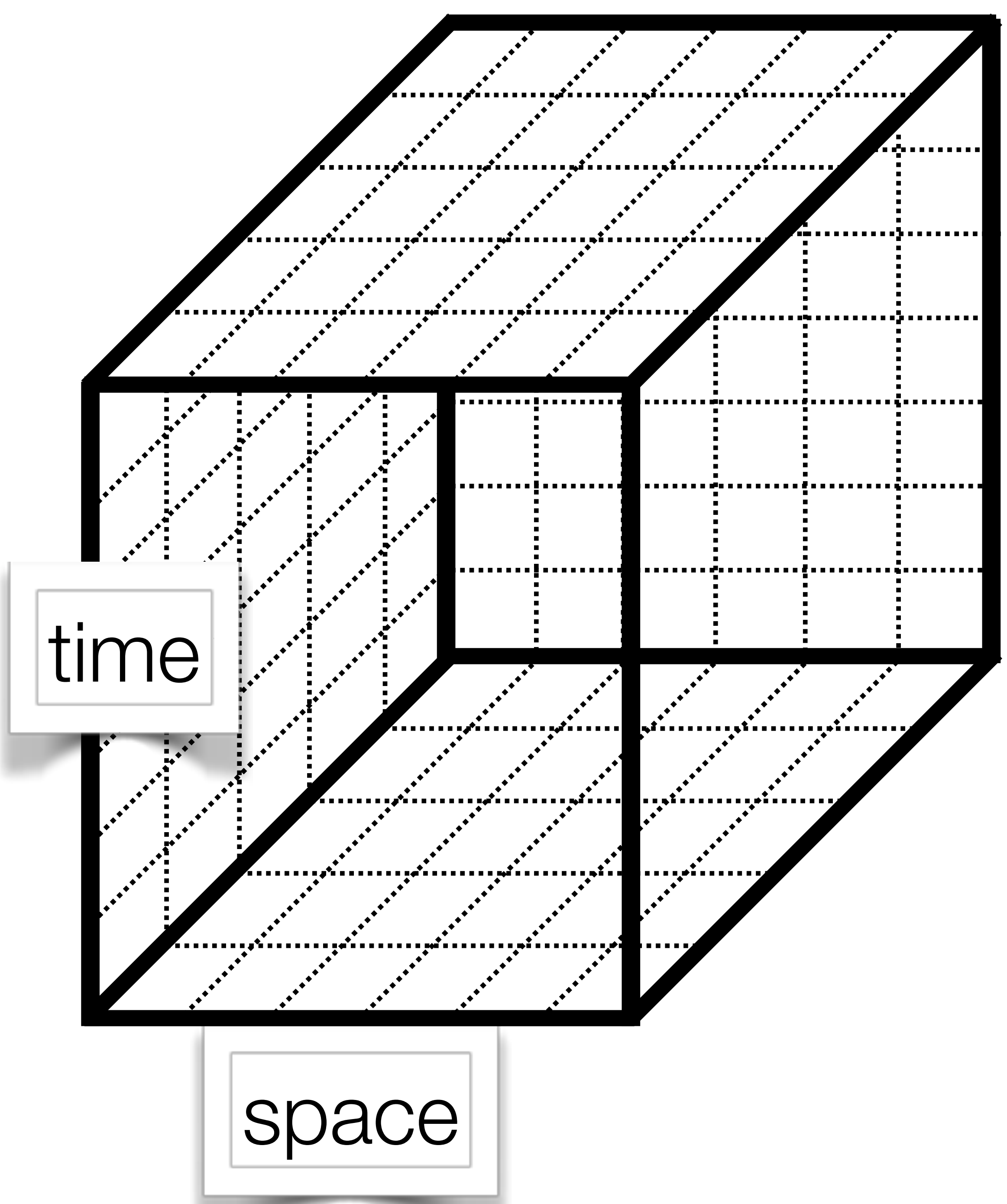

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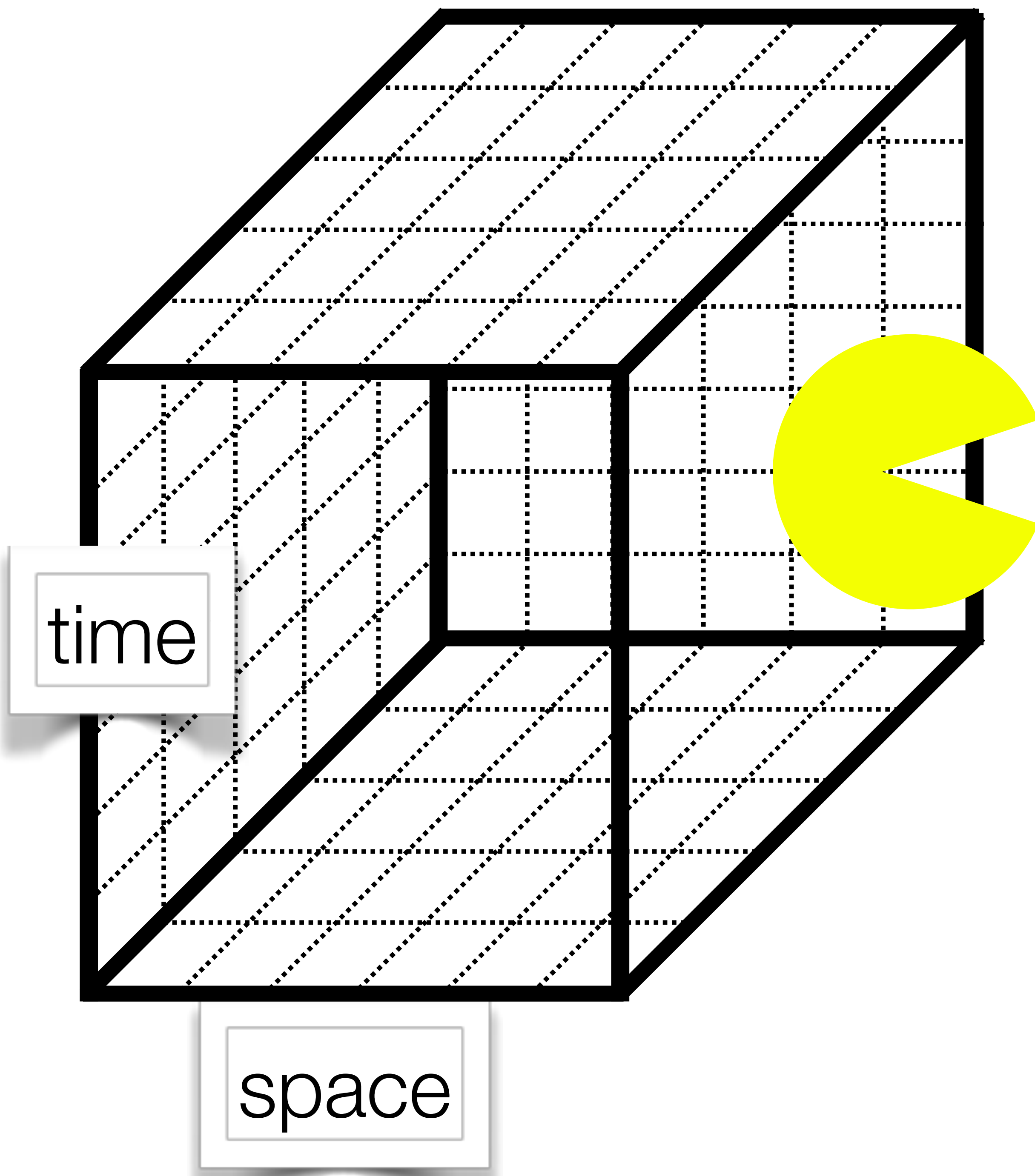

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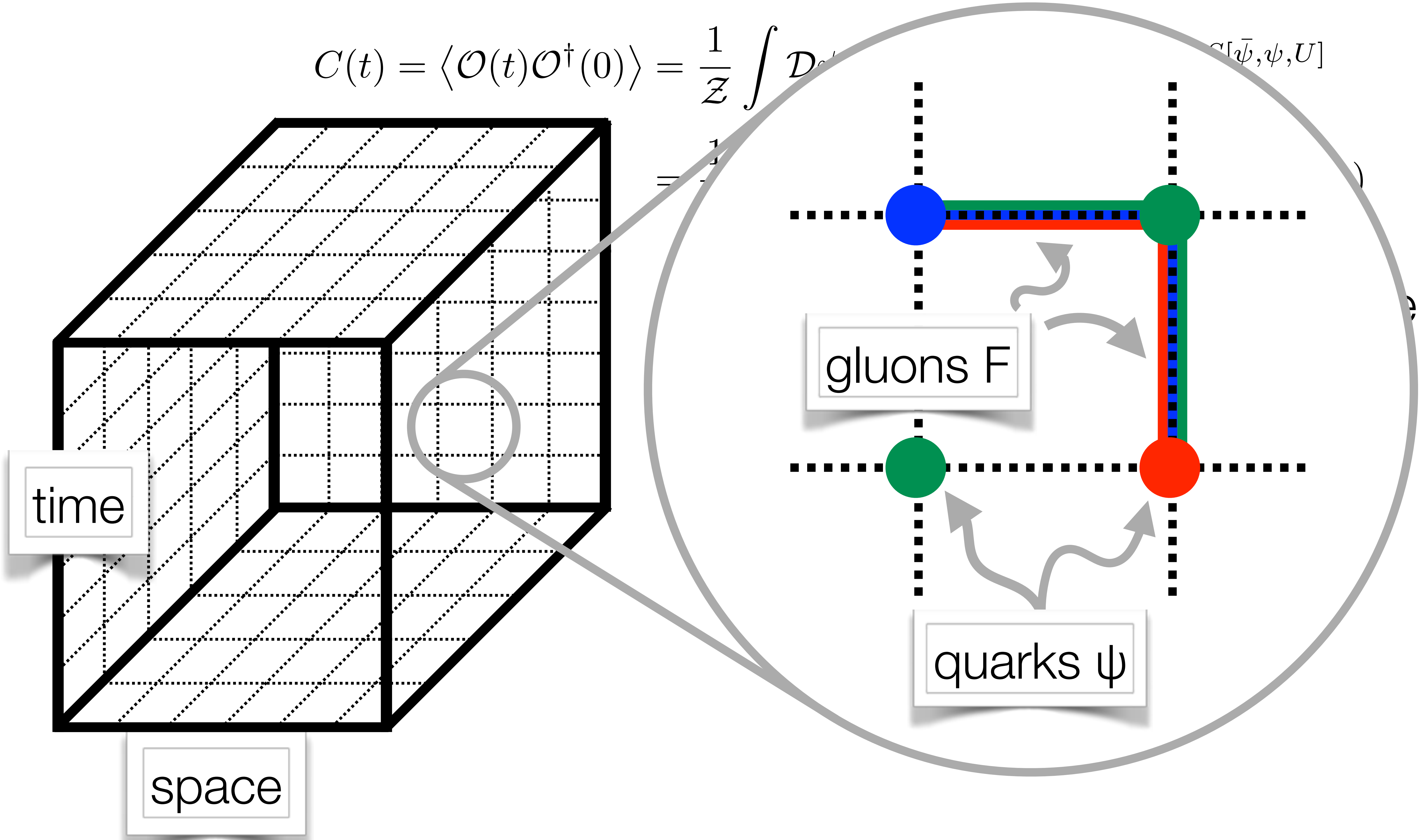

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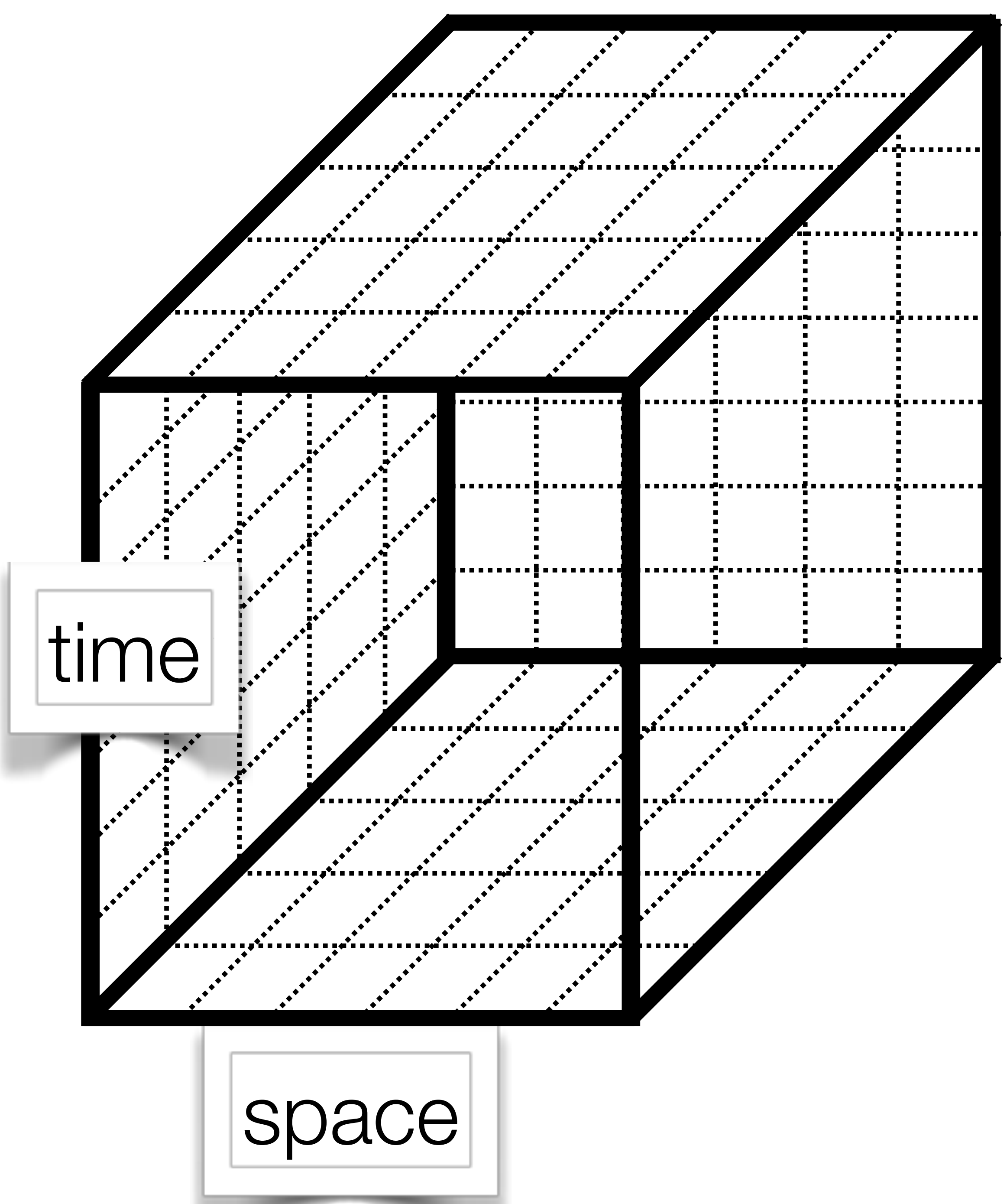
lattice
finite volume



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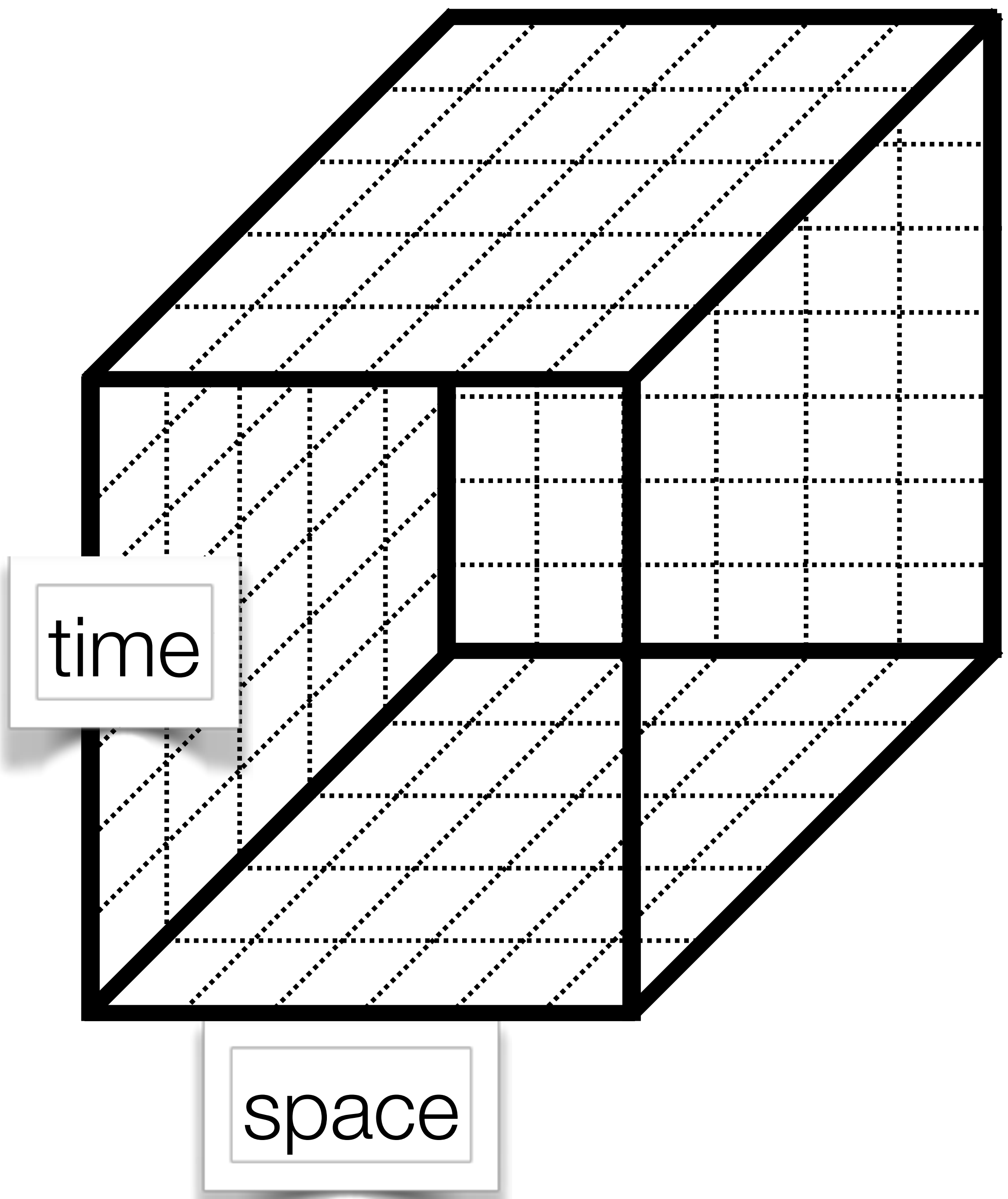
$$= \frac{1}{\mathcal{Z}} \int \mathcal{D}U \, \underbrace{\det\left(\not{D} + M\right) e^{-S[U]}}_{\text{Probability}} \; \mathcal{O}(t)\mathcal{O}^\dagger(0)$$



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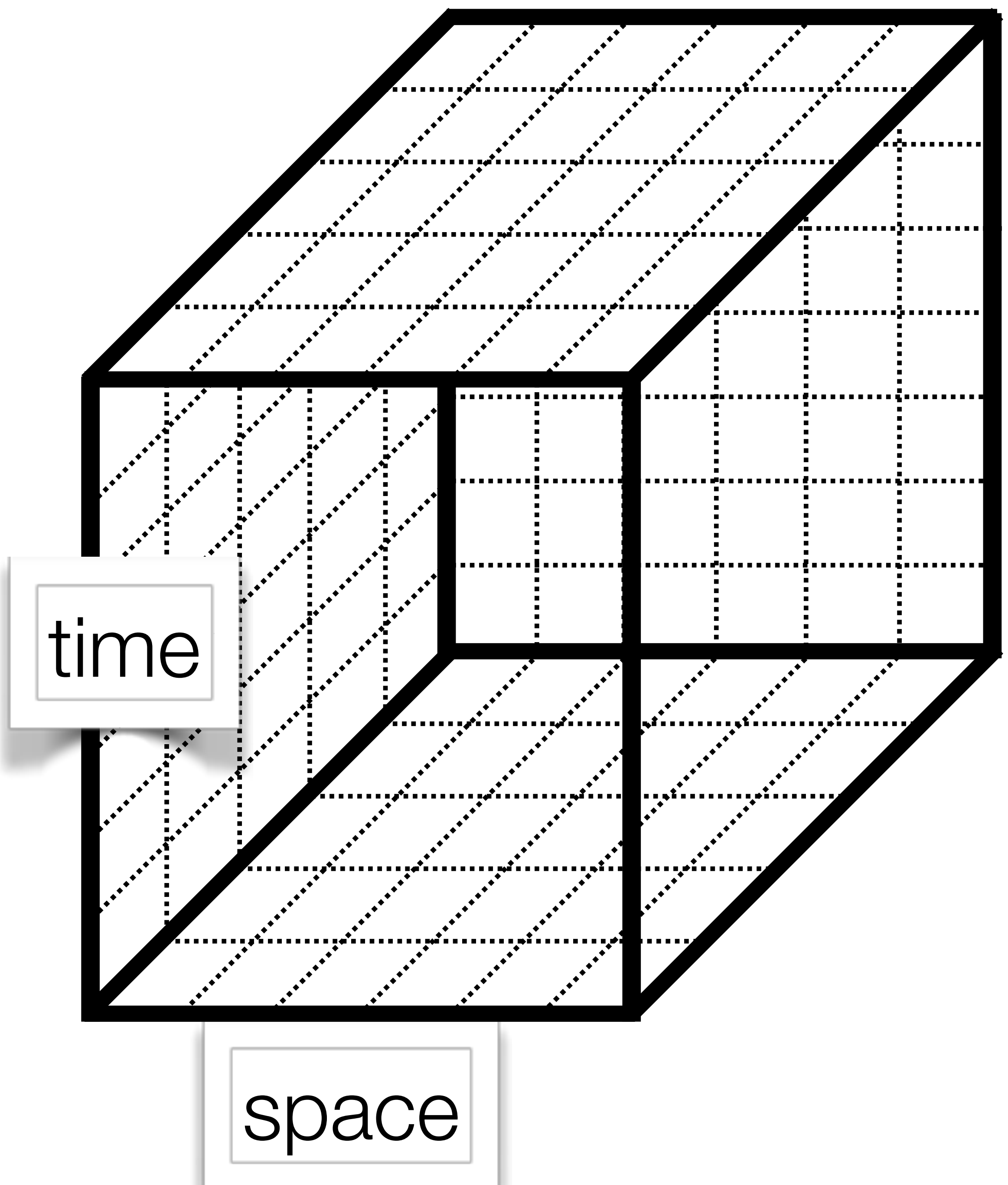
Probability



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

Markov Chain Monte Carlo

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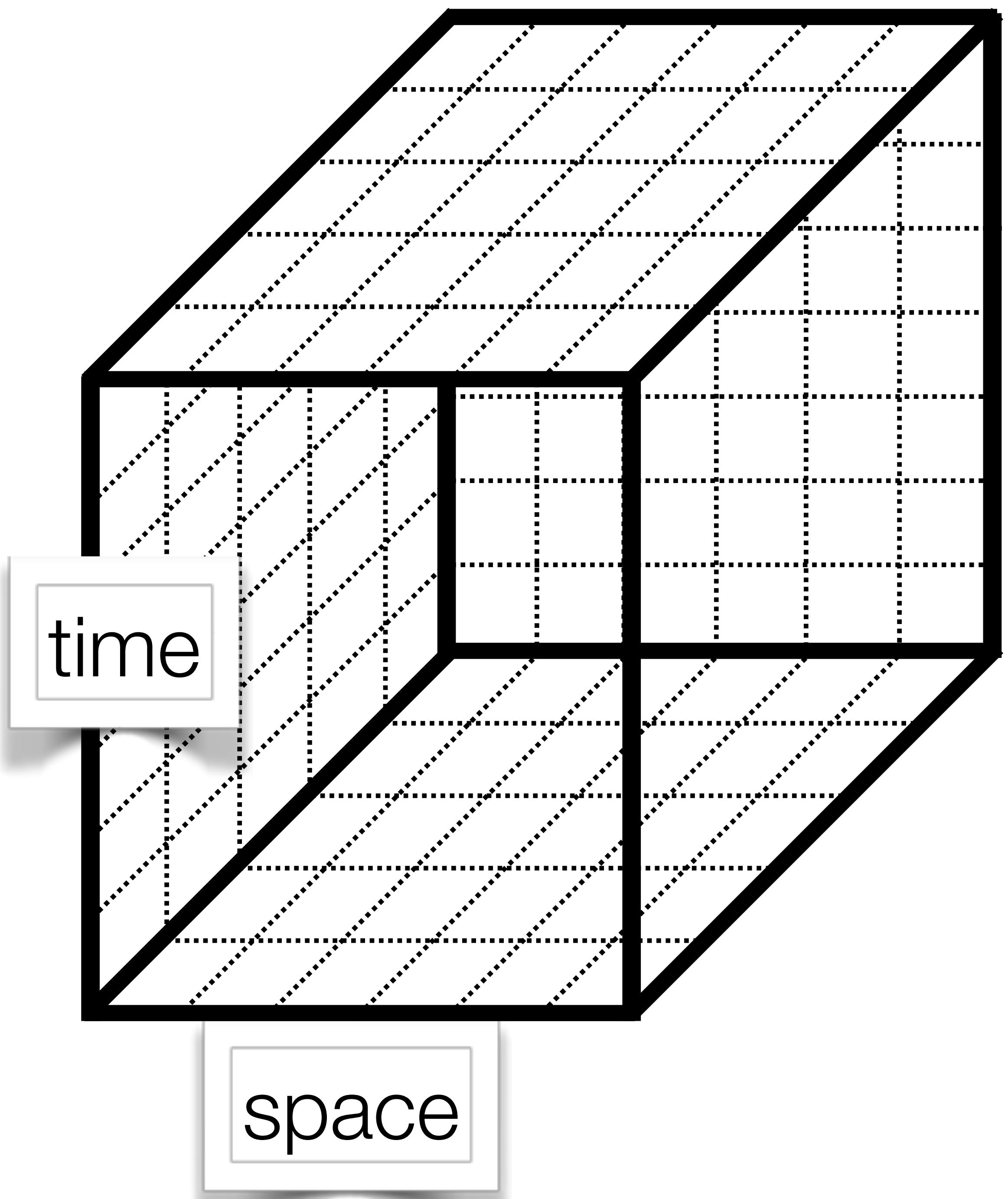
Probability



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Markov Chain Monte Carlo

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

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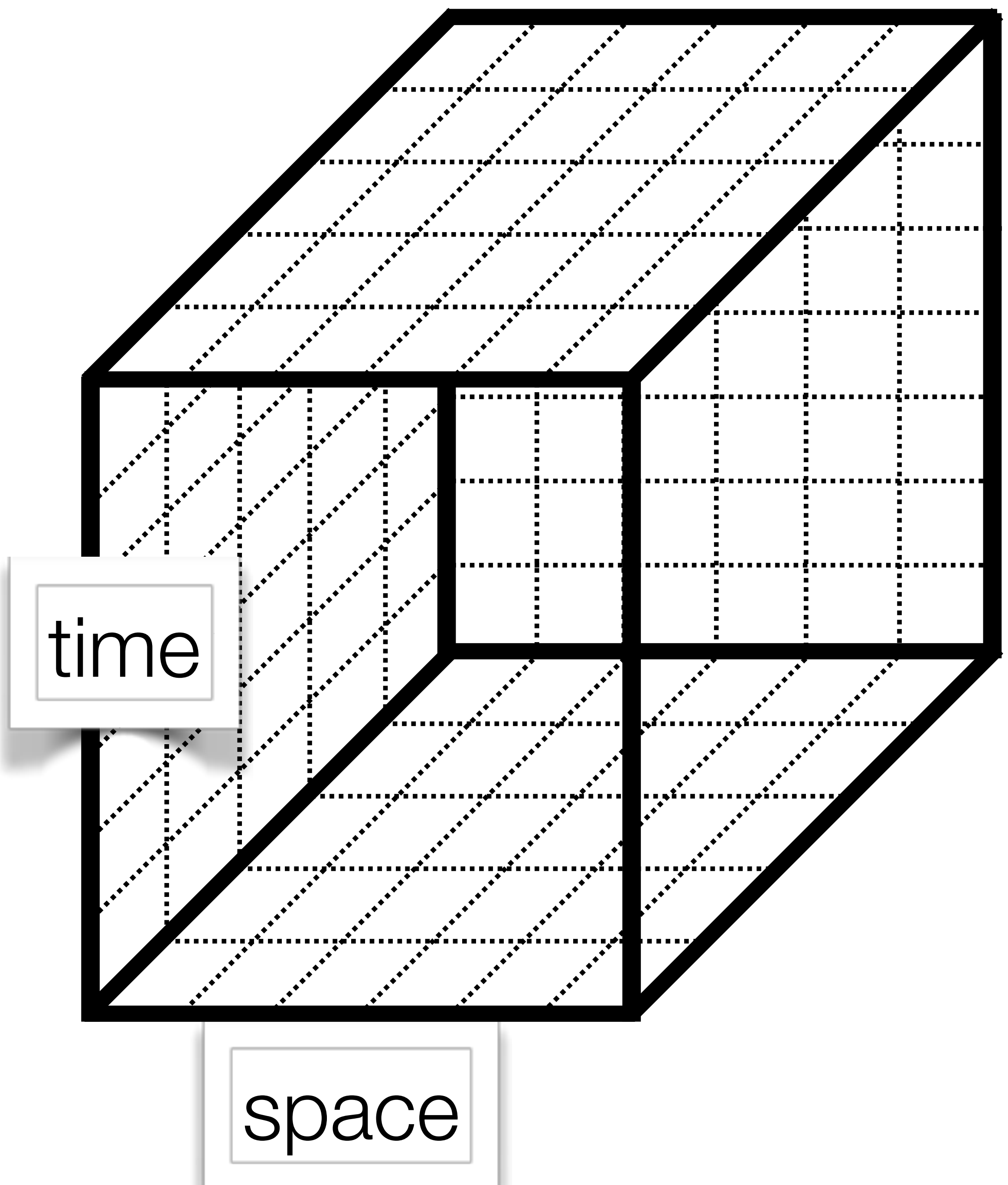
Probability



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

Markov Chain Monte Carlo

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

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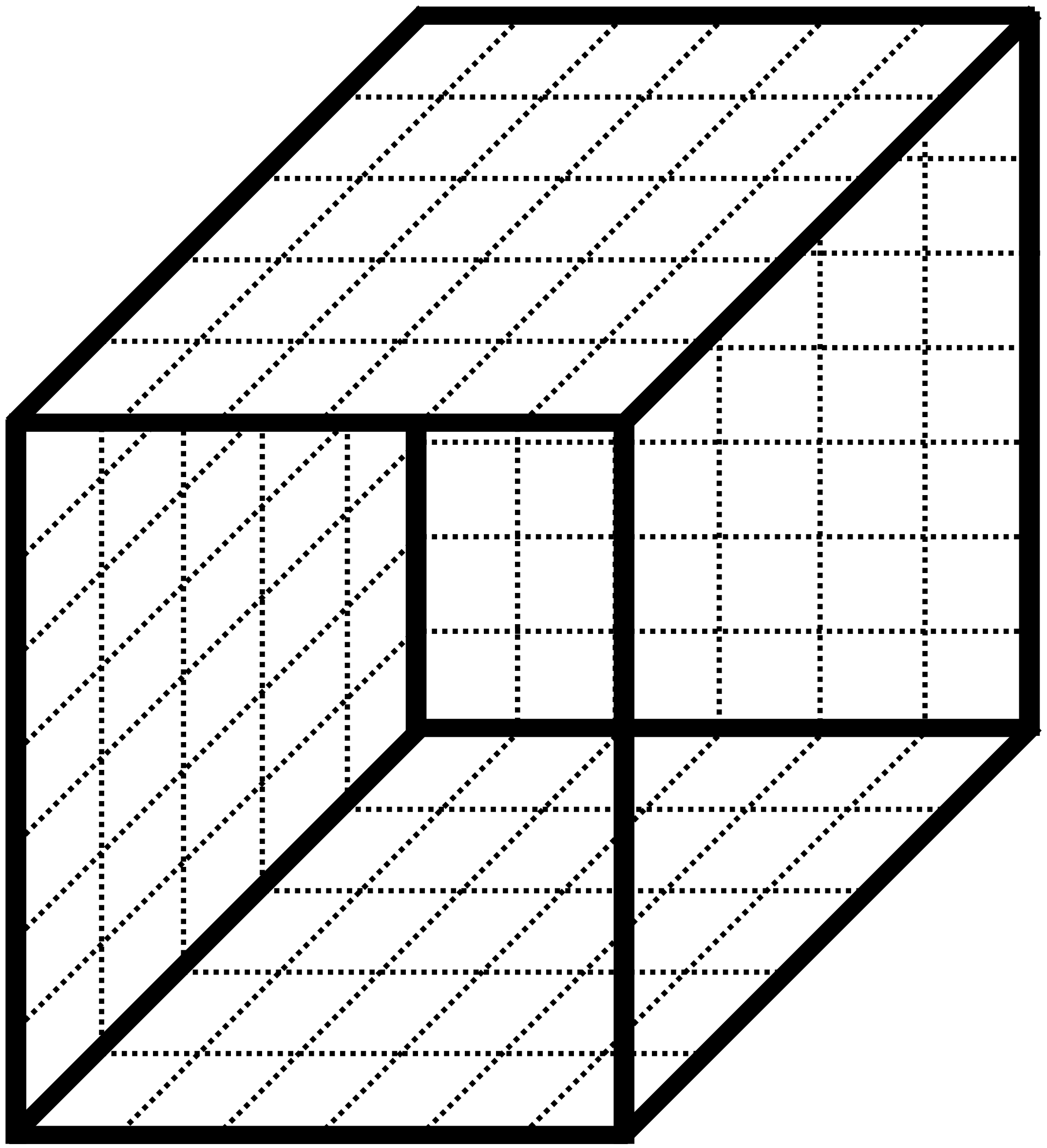

D is a sparse matrix
U-dependent
(N_x N_t N_c N_s) on a side

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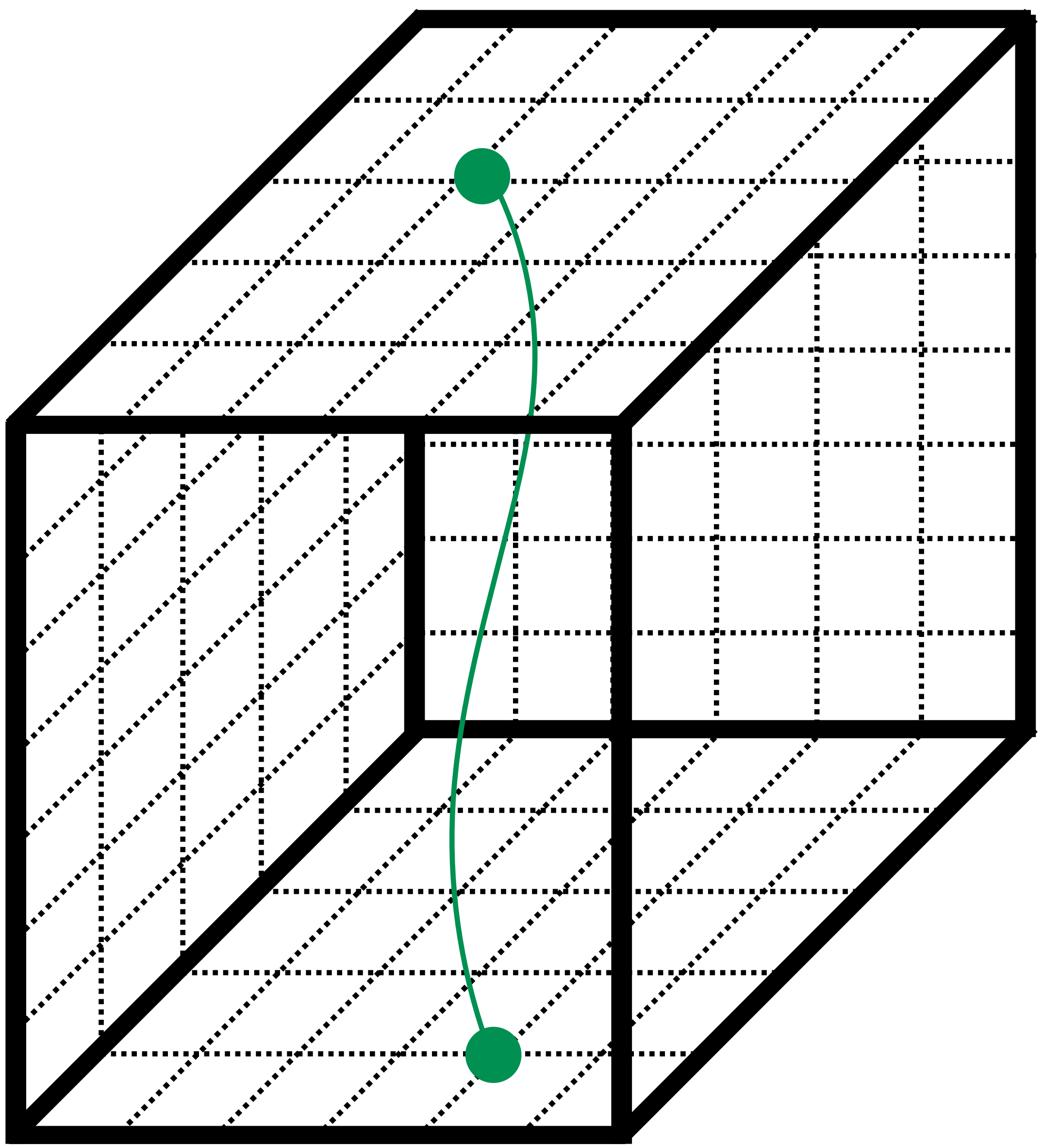

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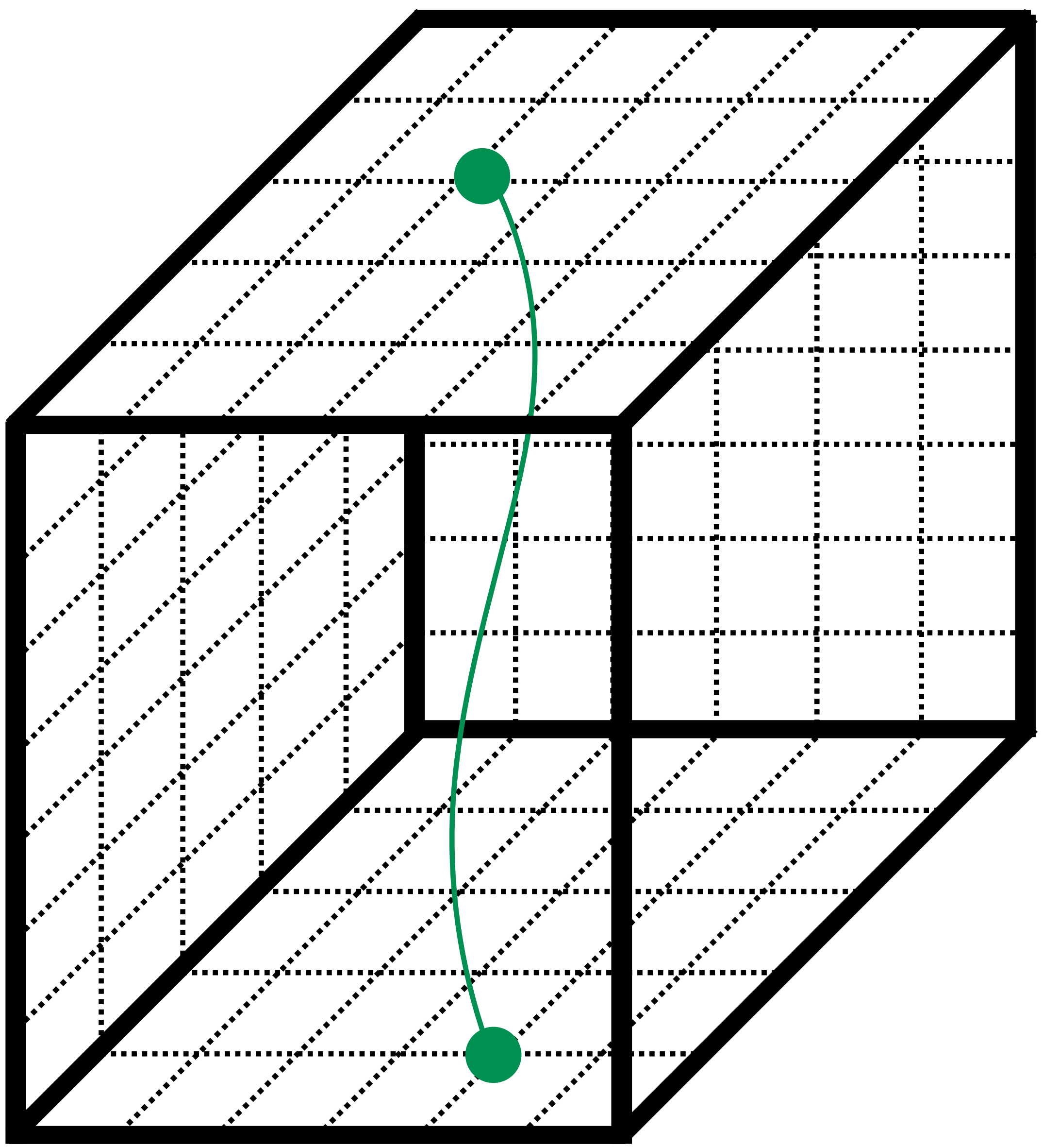

D is a sparse matrix

U-dependent

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

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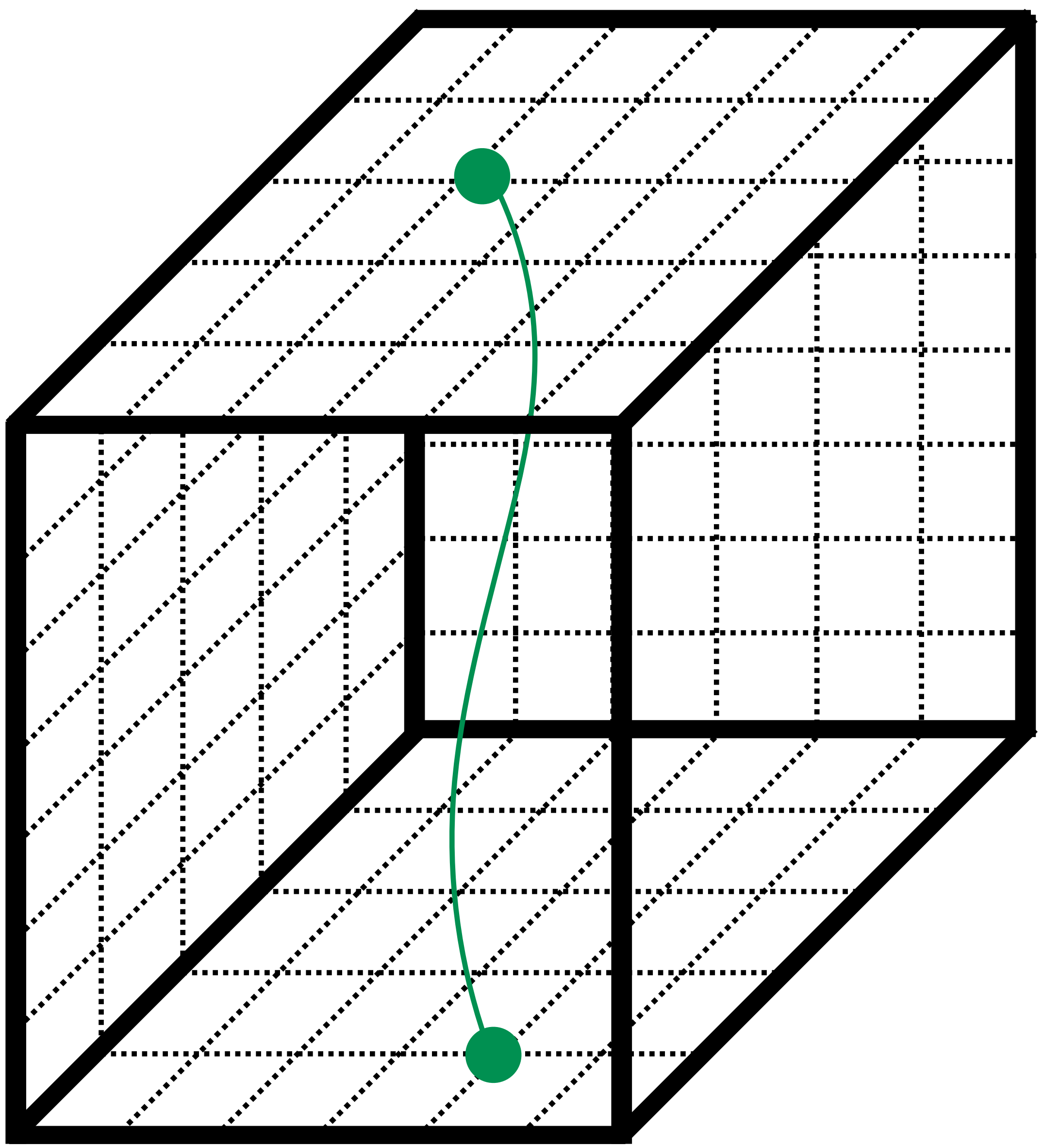


D is a sparse matrix

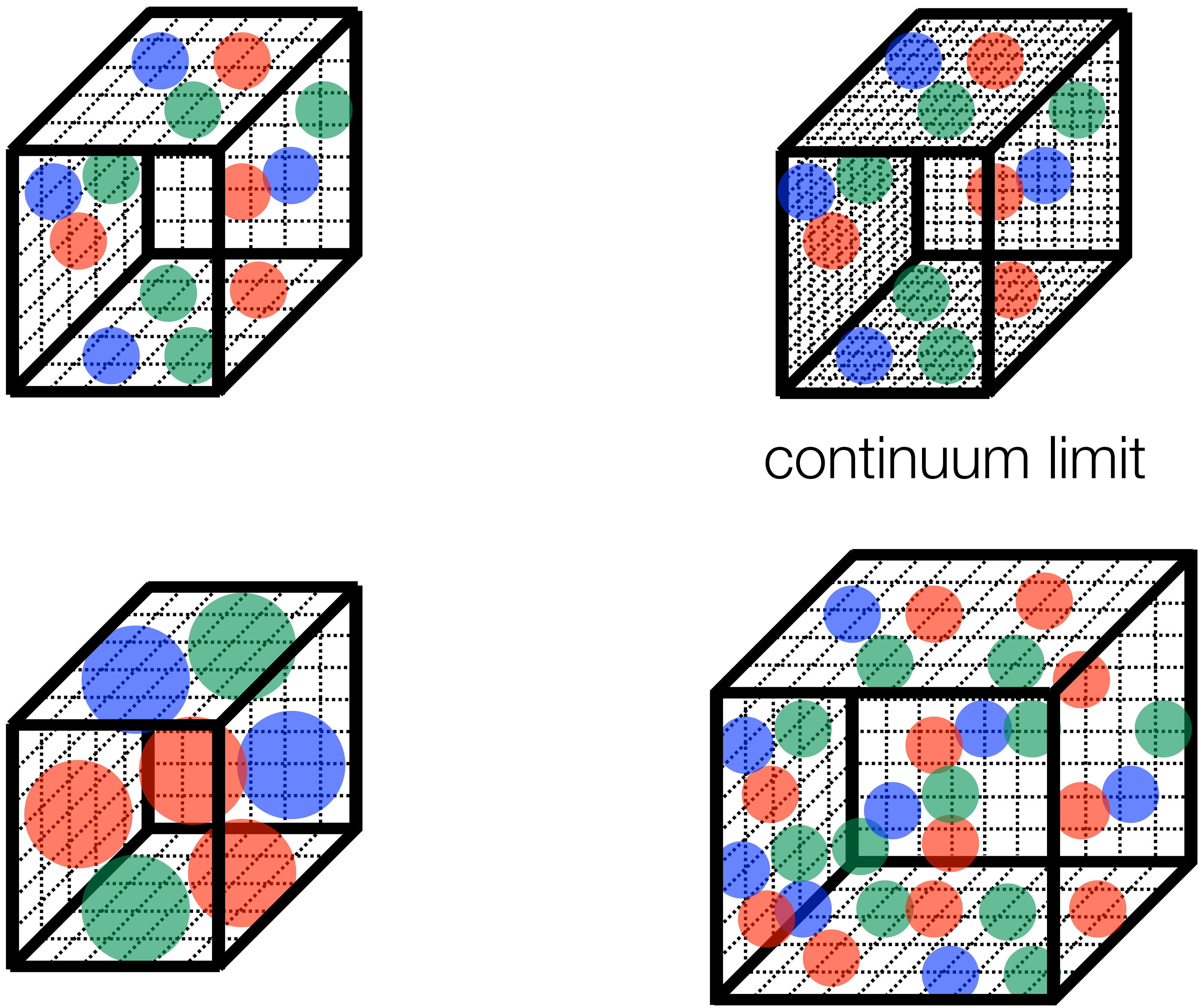
U-dependent

(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



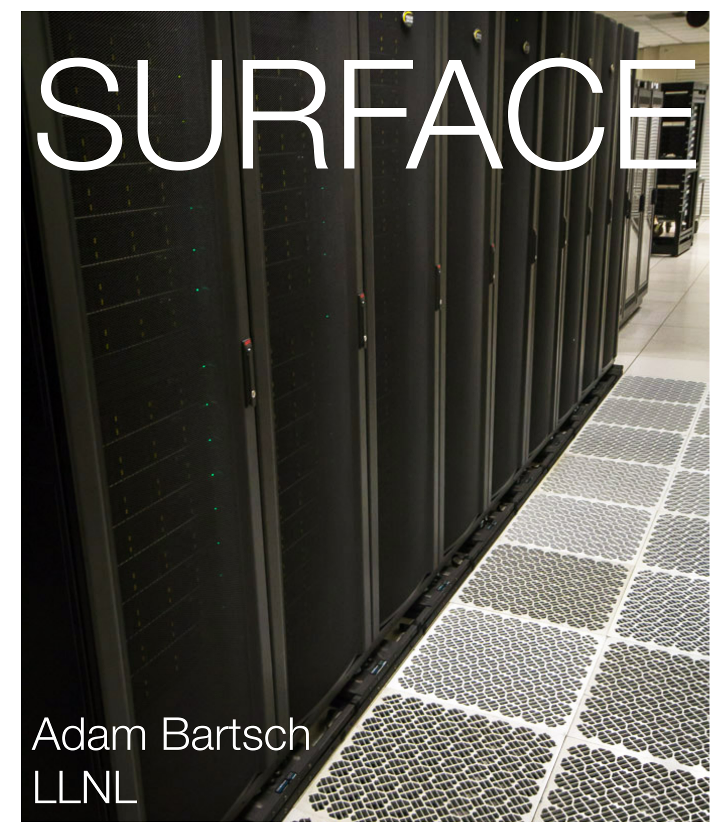
continuum limit

physical quark masses

infinite volume limit

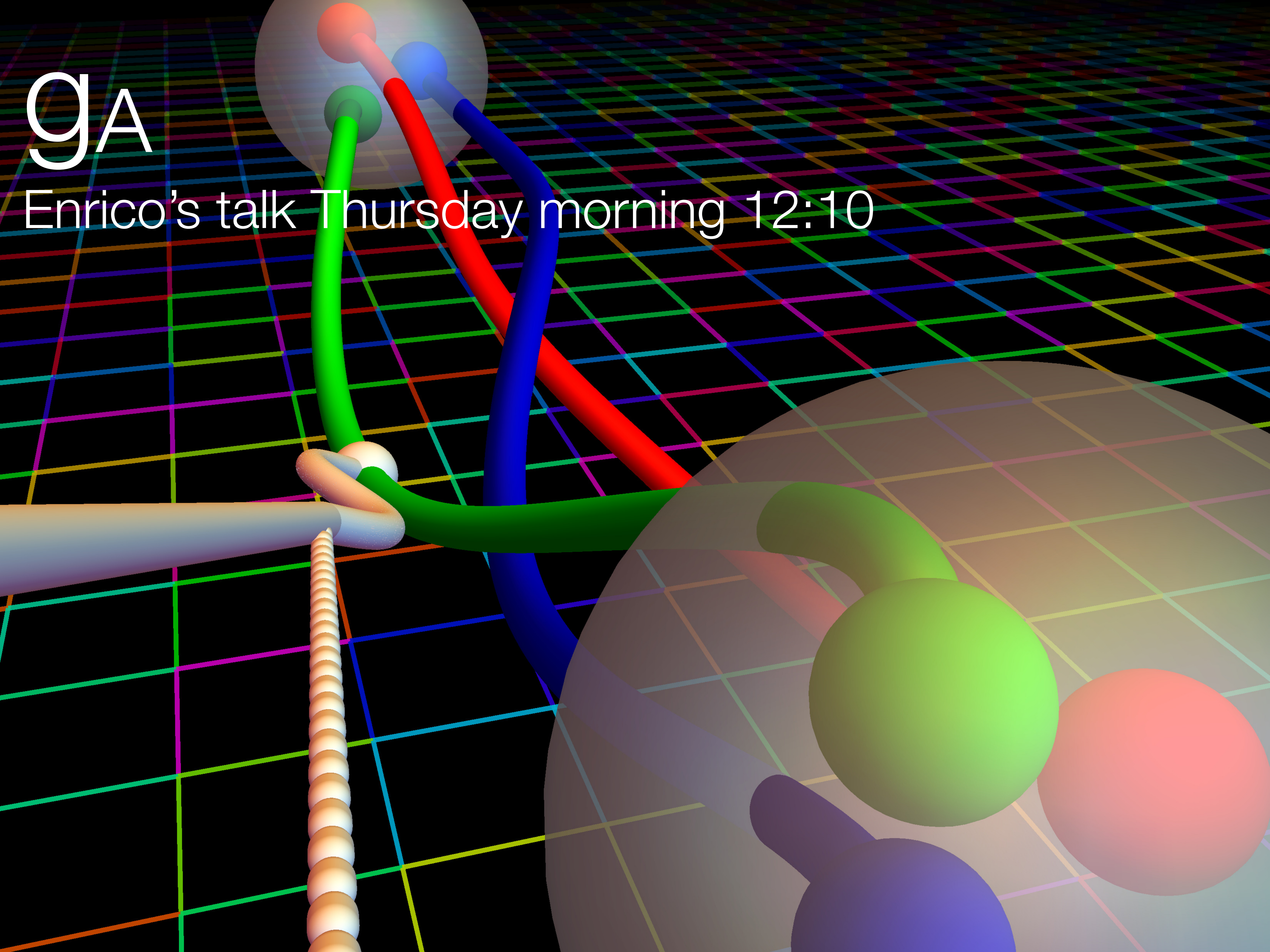

TITAN
OLCF


Edison
NERSC


SURFACE
Adam Bartsch
LLNL

g_A

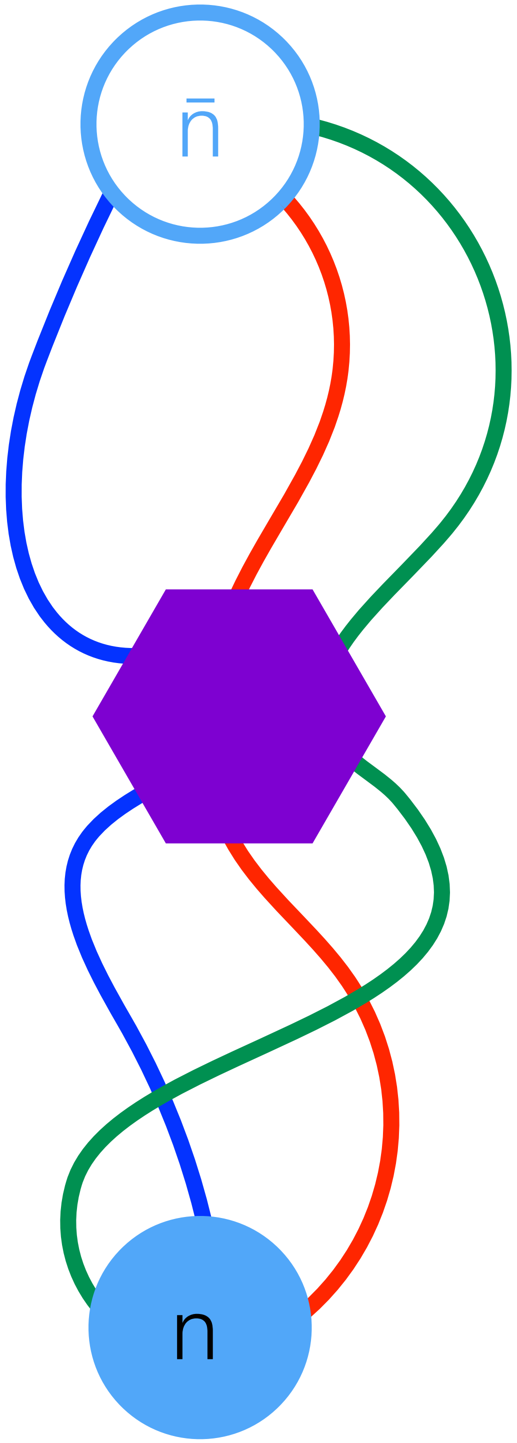
Enrico's talk Thursday morning 12:10



Enrico’s talk Thursday morning 9:25

n̄n Oscillations

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



✓ Physical point

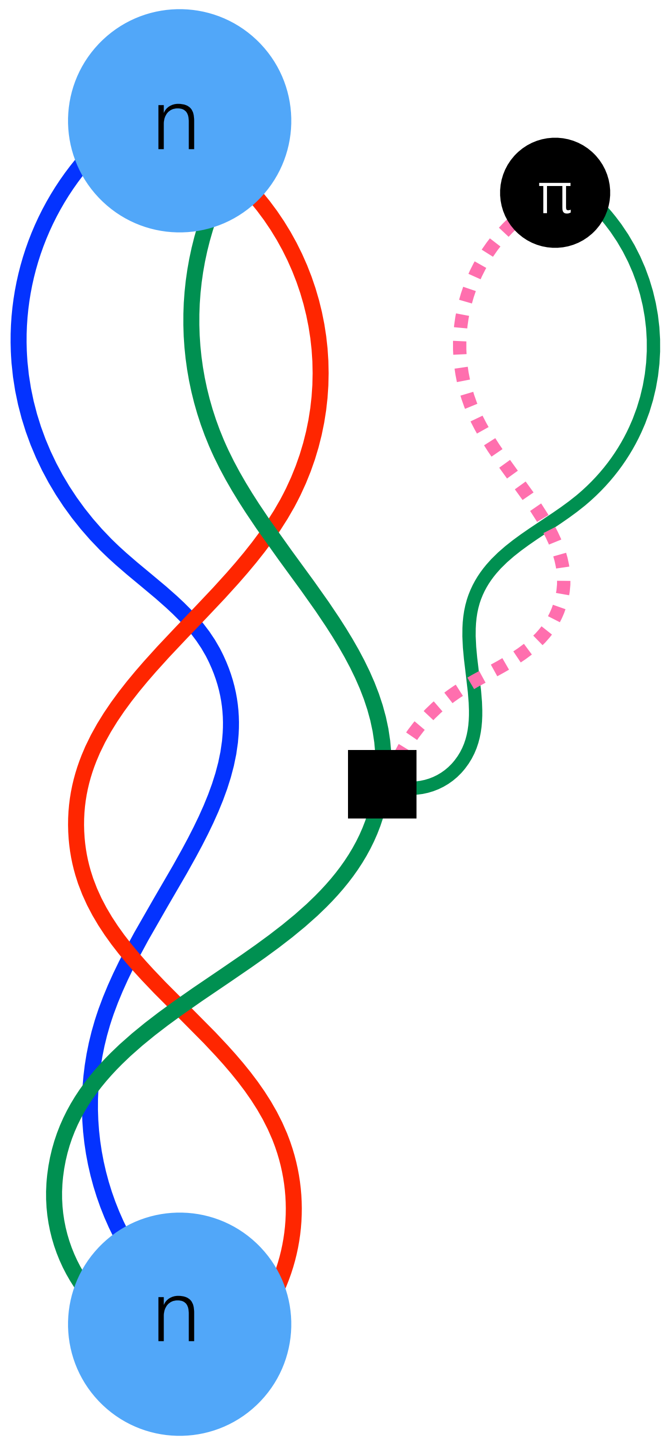
✗ continuum, infinite volume

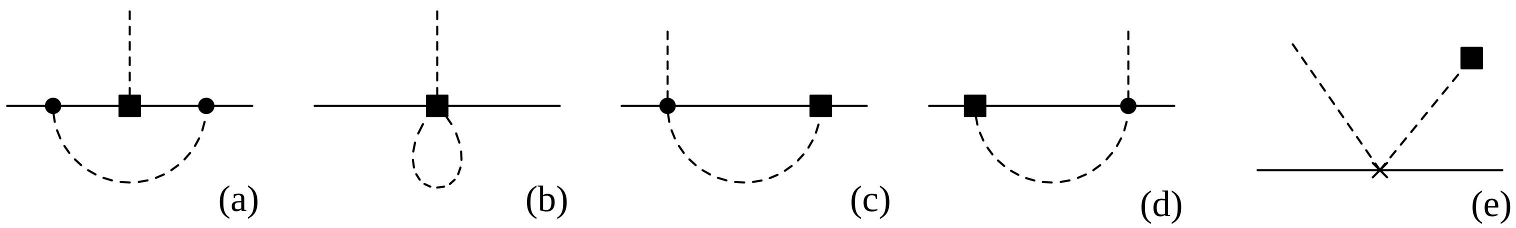
Operator	$\overline{\text{MS}}$(2 GeV), 10^{-5} GeV^6	$\frac{\overline{\text{MS}}\text{(2 GeV)}}{\text{MIT bag B}}$	Bare, 10^{-5} l.u.	χ^2/dof
Q_1	-44(19)	5.0	-3.7(1.6)	0.75
Q_2	140(40)	12.8	11.8(3.2)	0.69
Q_3	-79(23)	9.7	-6.6(1.9)	0.72
Q_5	-1.43(64)	2.1	-0.096(42)	0.73

enhancement
means experiments
have greater reach

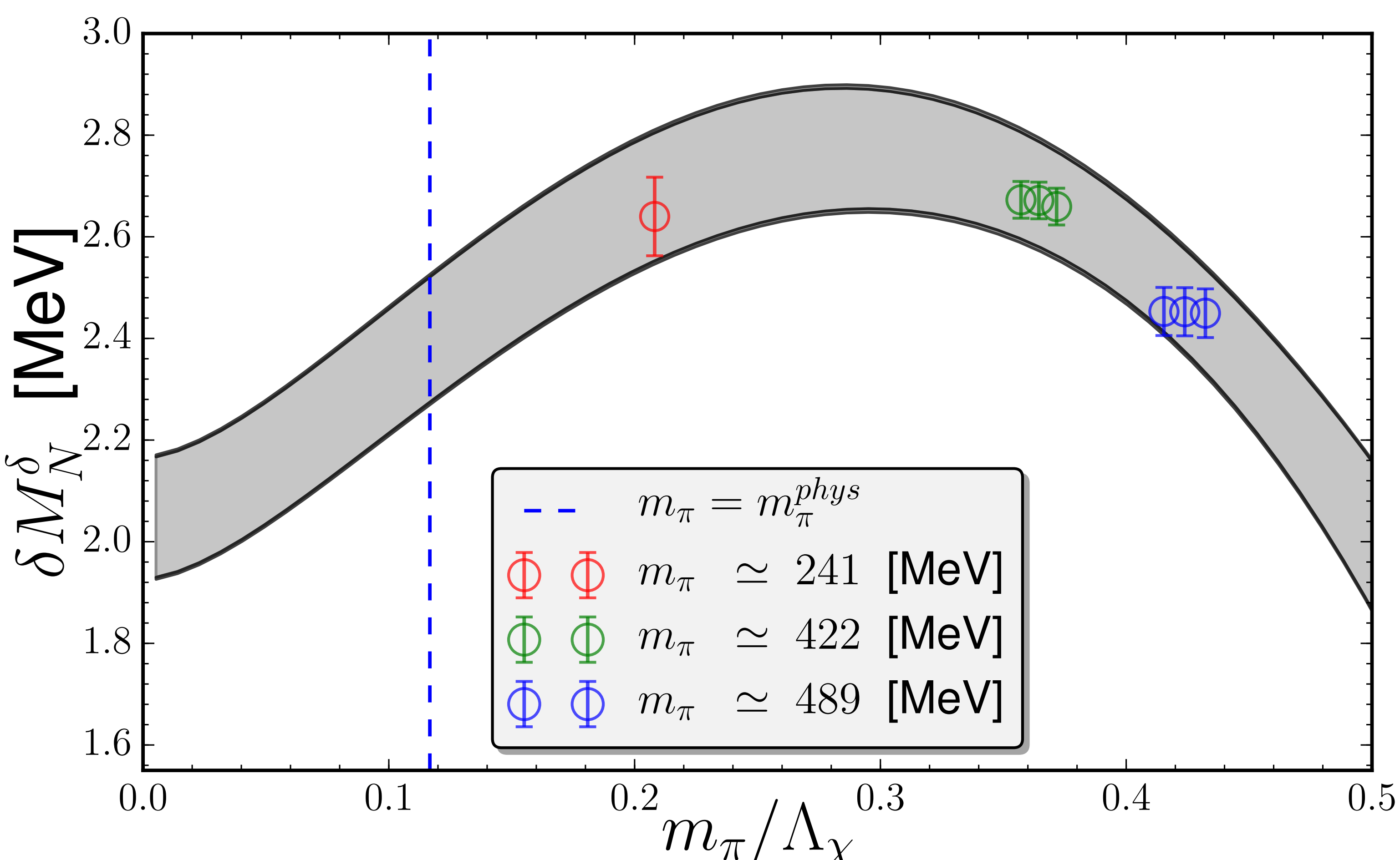
CP Violating πN Coupling

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





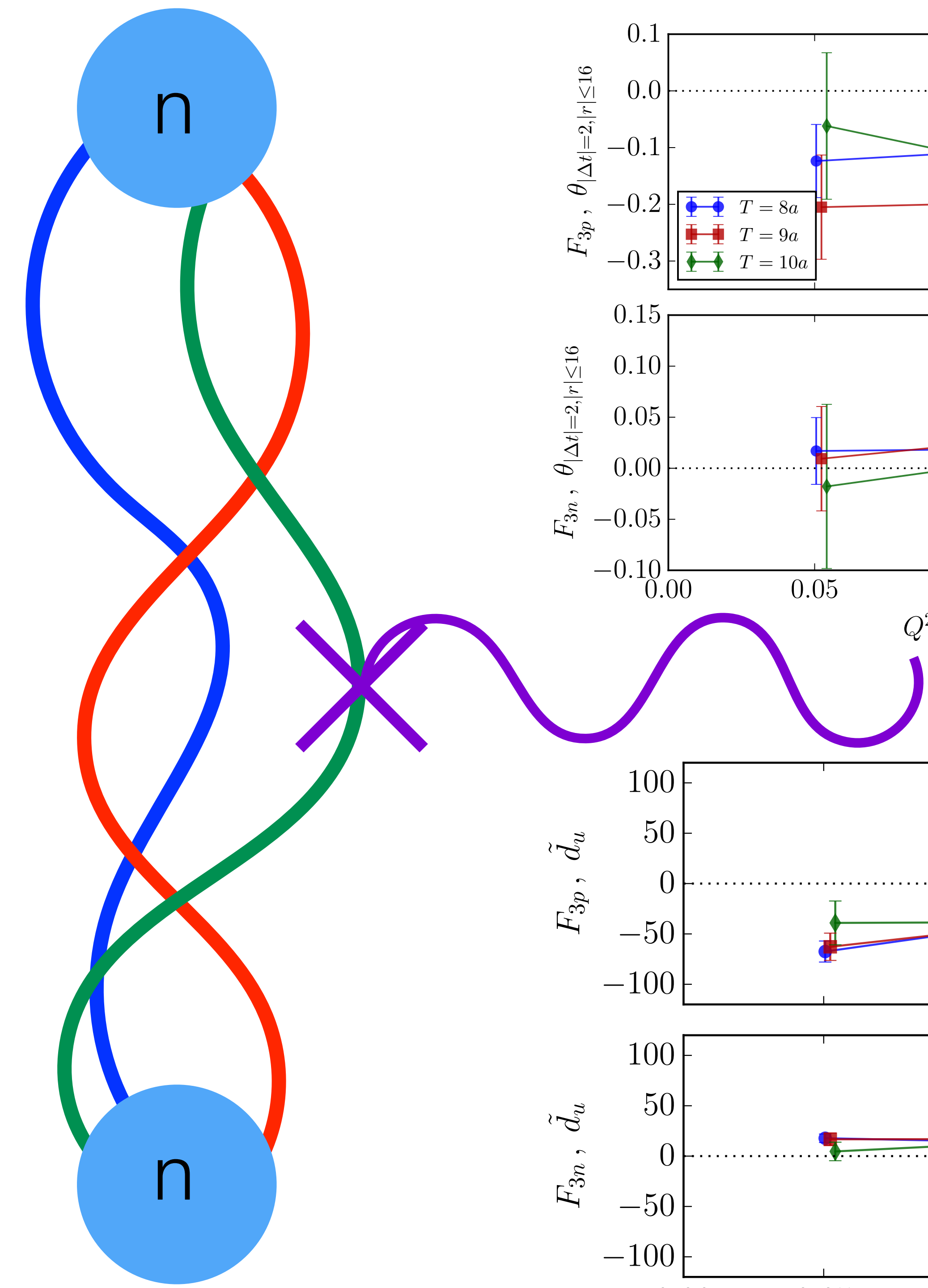
$$\bar{g}_0 = 14.7(1.8)^{stat}(1.4)^{sys}\, 10^{-3}\, \bar{\theta}\, f_\pi \sqrt{2}$$

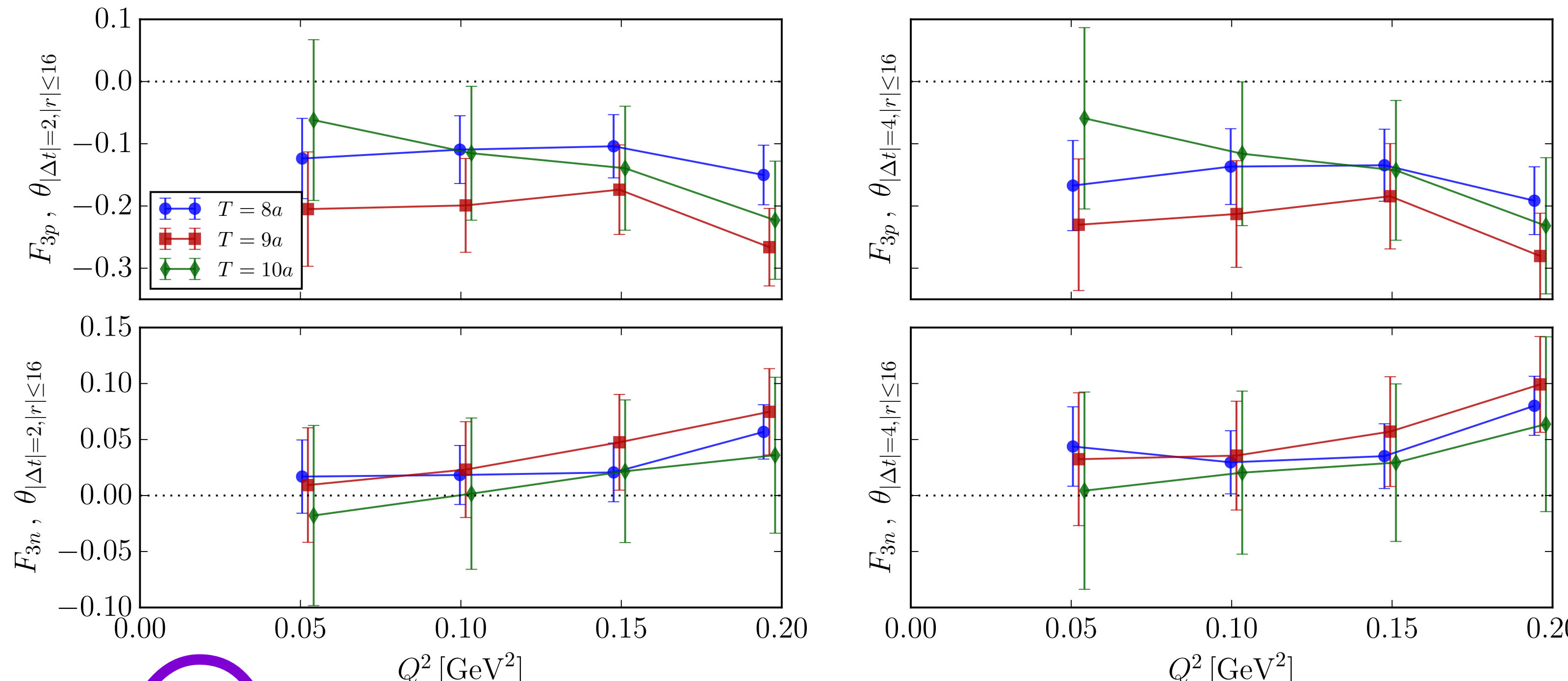


n EDM

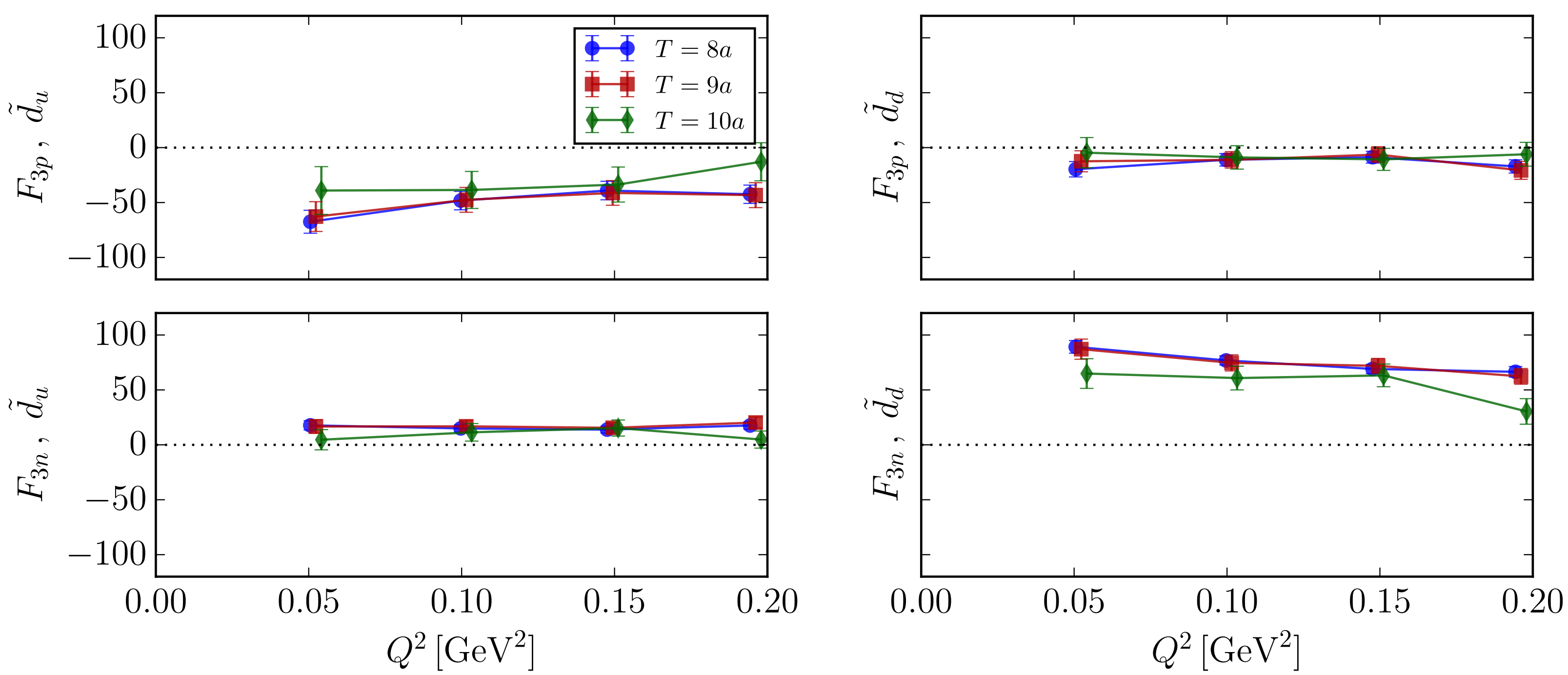
Syritsyn, Ohki, Izubuchi CIPANP 2018 1810.03721

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





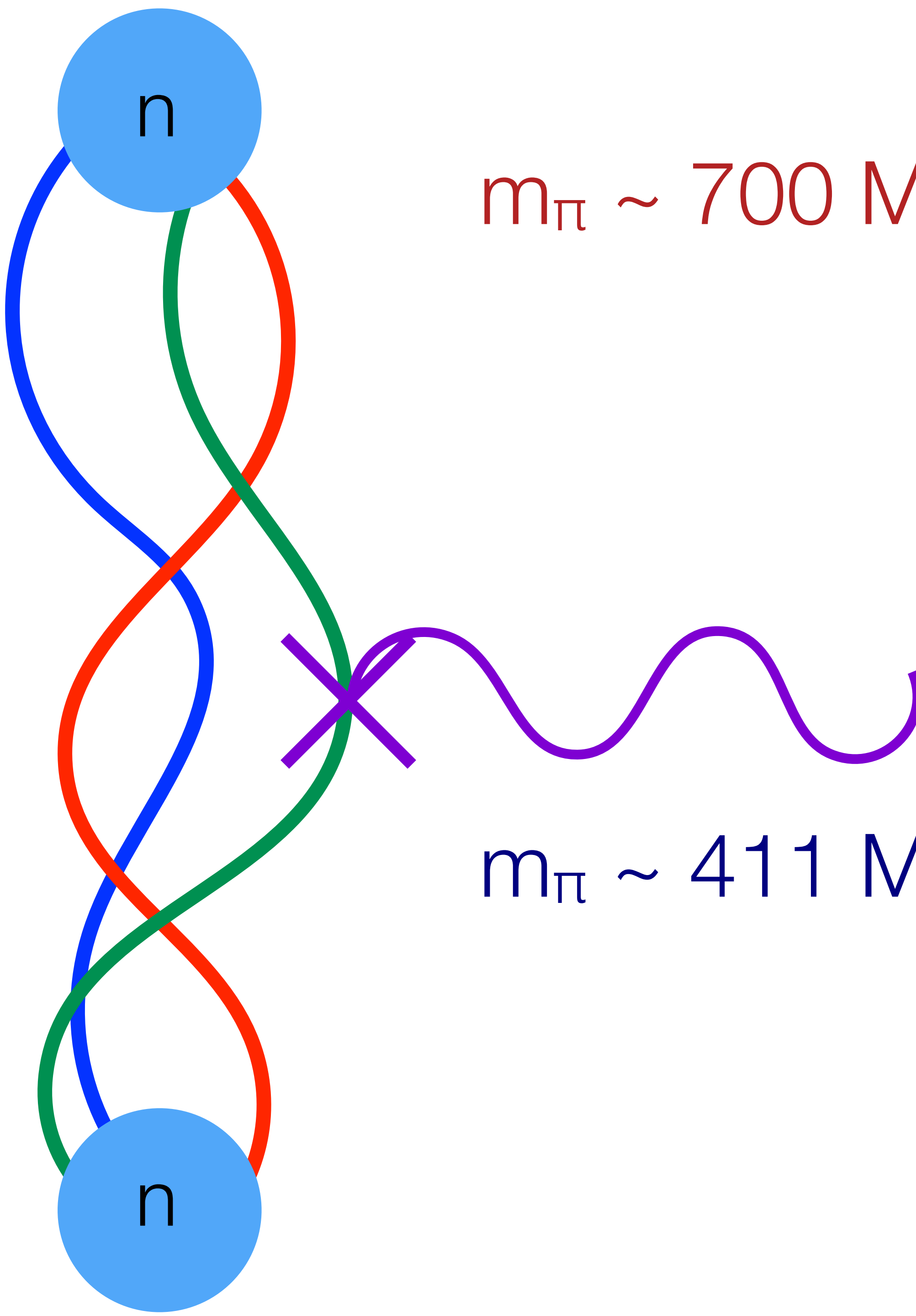
θ_{QCD}



cEDM

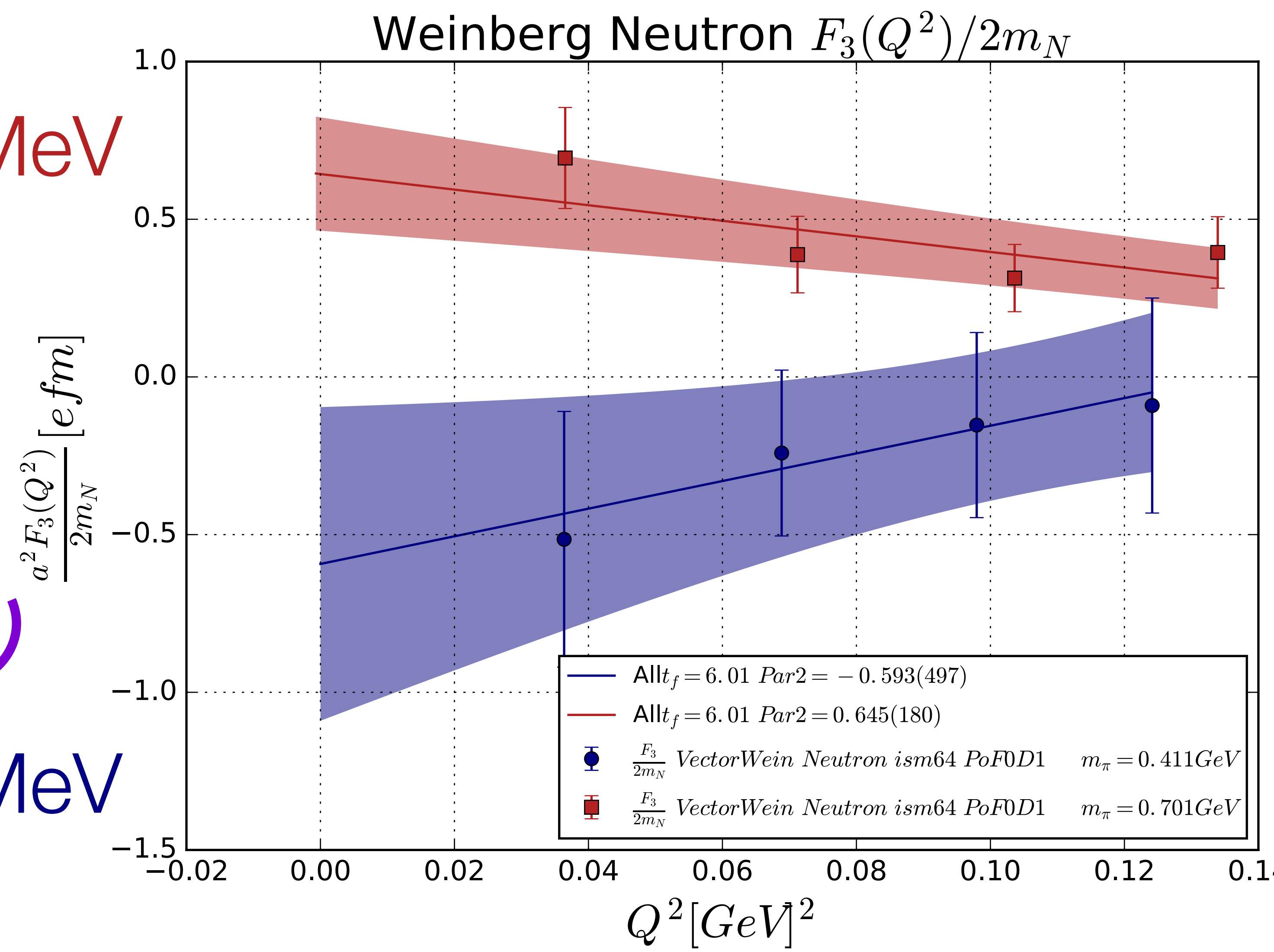
n EDM

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



m_π ~ 700 MeV

m_π ~ 411 MeV

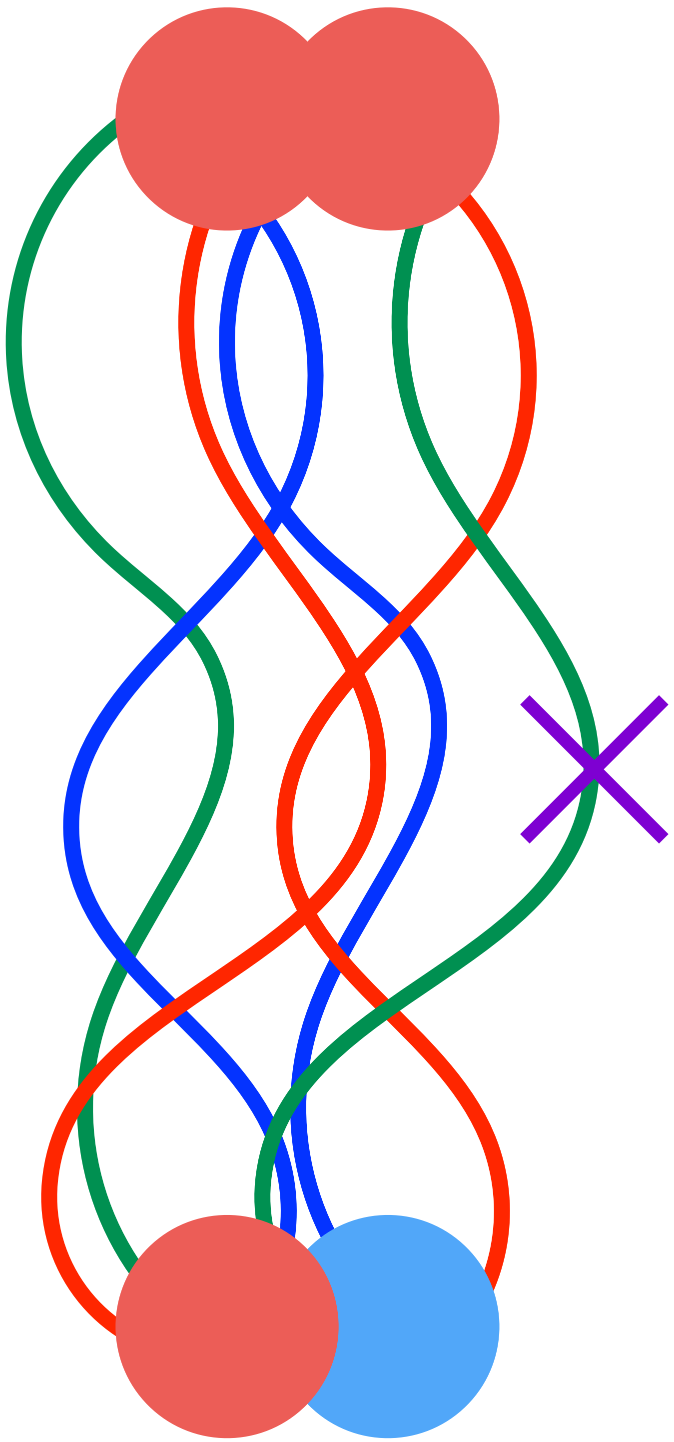


$$-i\frac{\alpha_{\tilde{G}}}{\Lambda^2}\ \frac{1}{3} f^{ABC}\tilde{G}^A_{\mu\nu}G^B_{\mu\rho}G^C_{\nu\rho}$$

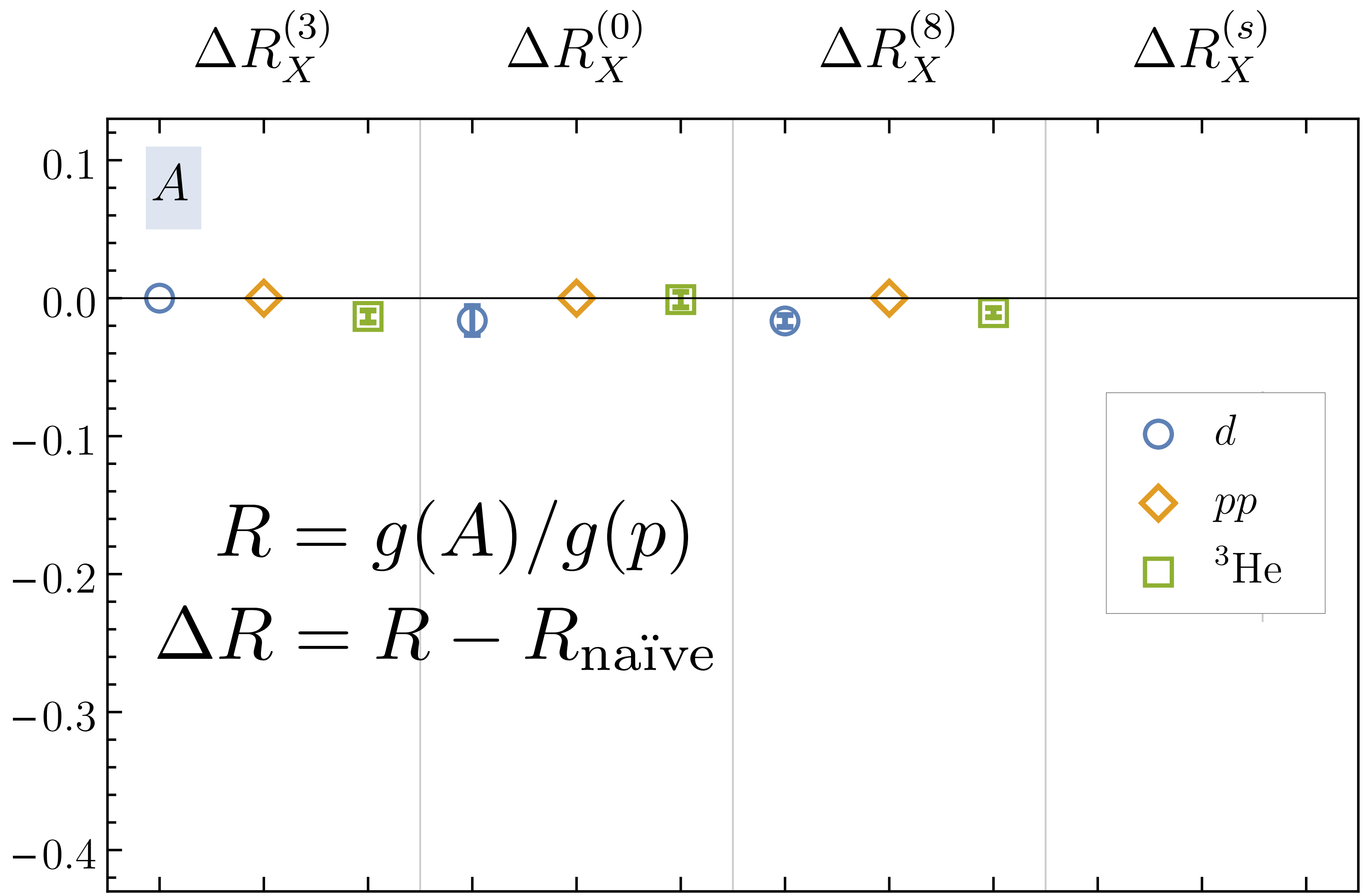
g_A Quenching

NPLQCD PRL 120 (2018) 15 152002 arXiv:1712.03221

m_π ~ 800 MeV; a~0.145 fm



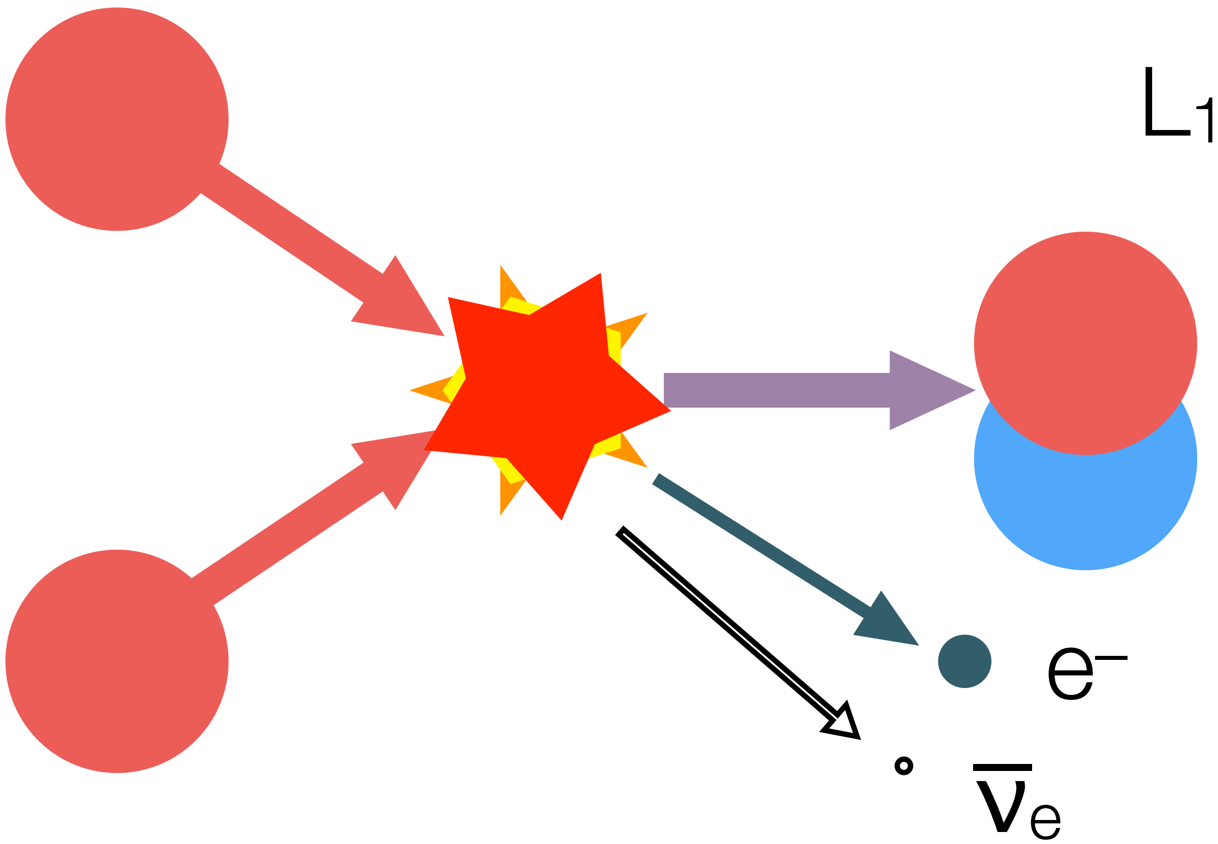
different flavor structures



pp Fusion

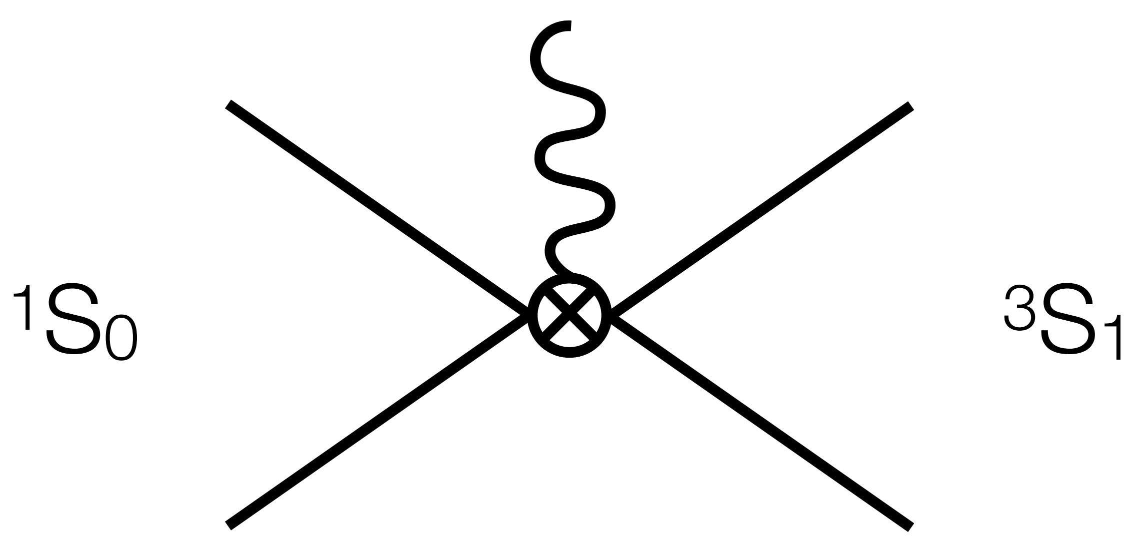
NPLQCD PRL 119 (2017) 06 062002 arXiv:1610.04545

m_π ~ 800 MeV; a~0.145 fm



$L_{1,A}$=3.9(0.2)^{stat}(1.0)^{fit}(0.4)^{mass}(0.9)^{EFT}

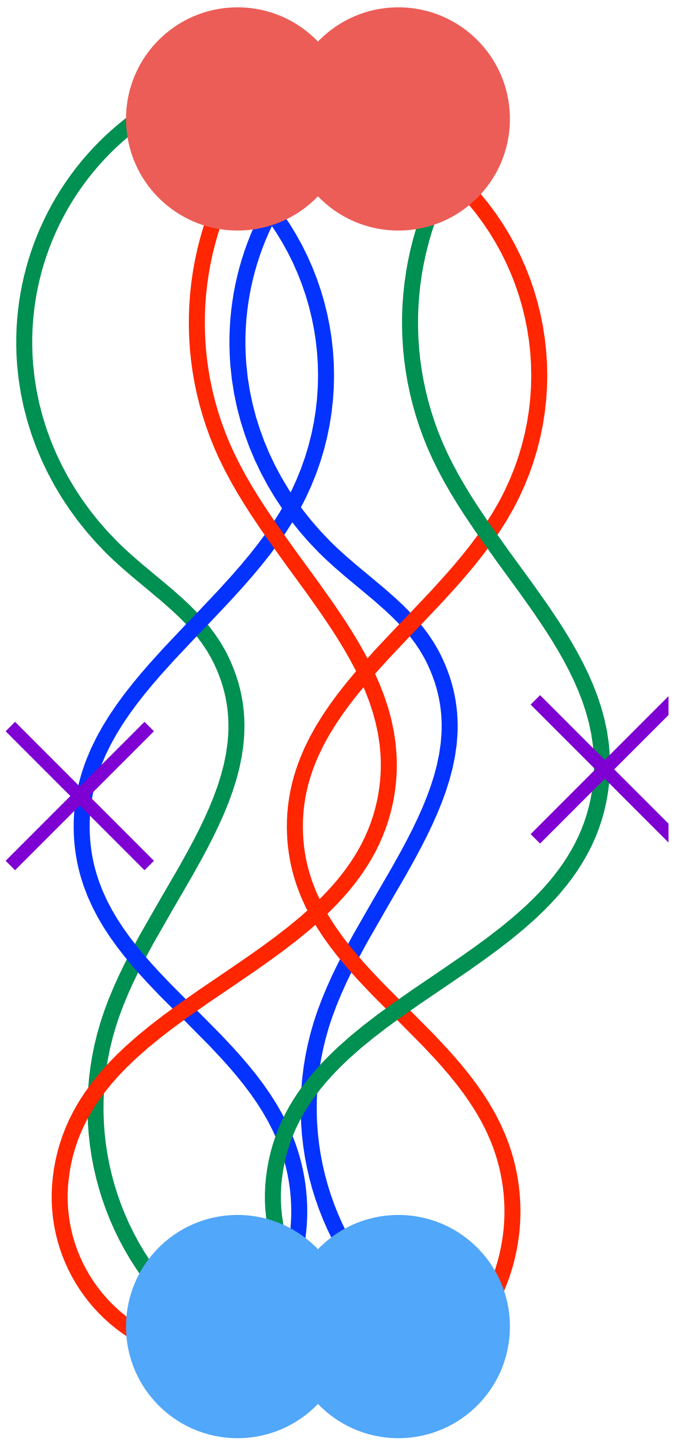
- Pionless EFT
- Dineutron bound at 800 MeV
- Just need binding energies, matrix element from the lattice



Isotensor Polarizability (2βνν)

NPLQCD PRL 119 (2017) 06 062003 arXiv:1701.03456

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



Effect can be described by ‘quenching’ gA

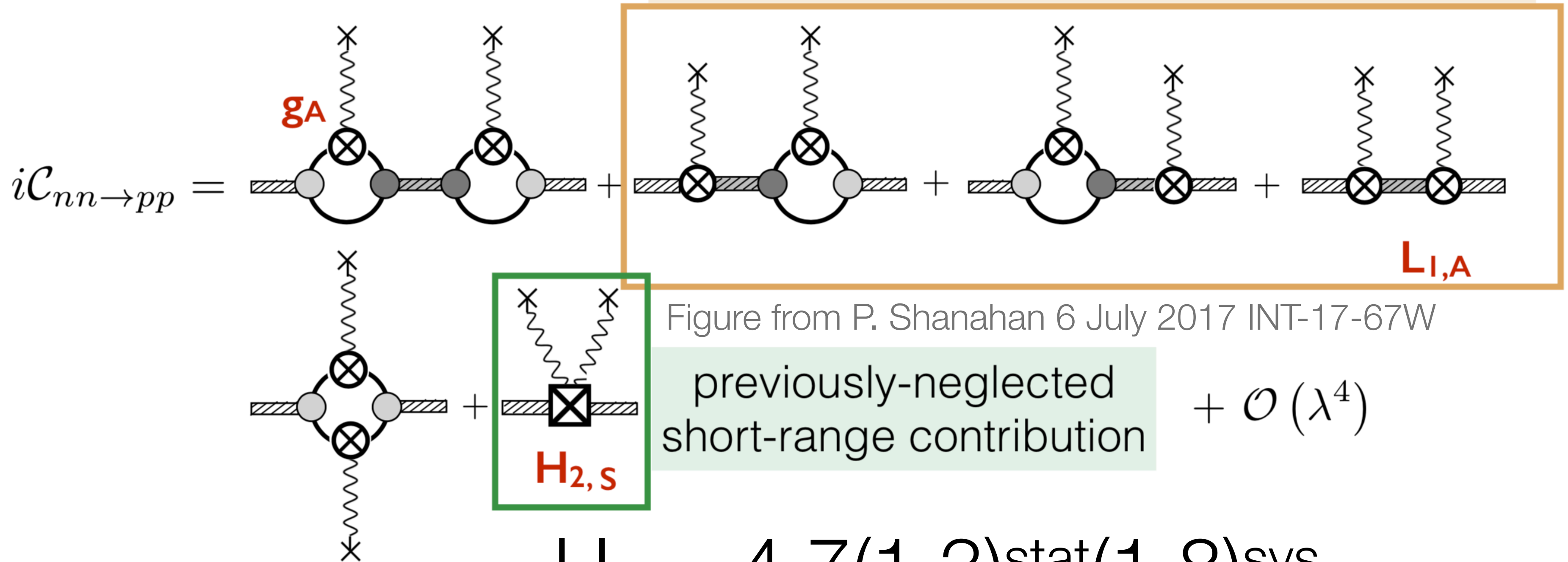


Figure from P. Shanahan 6 July 2017 INT-17-67W

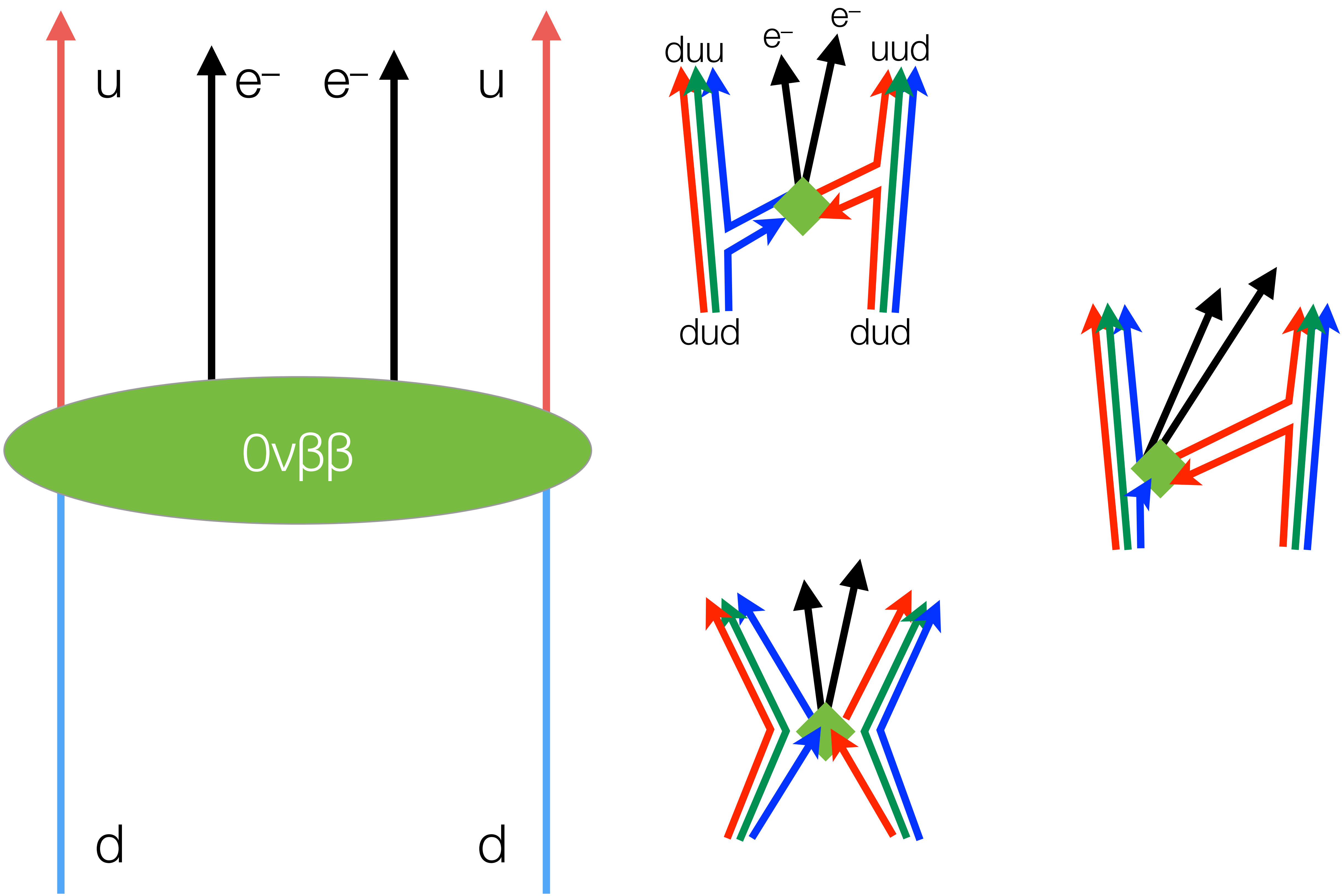
previously-neglected short-range contribution

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

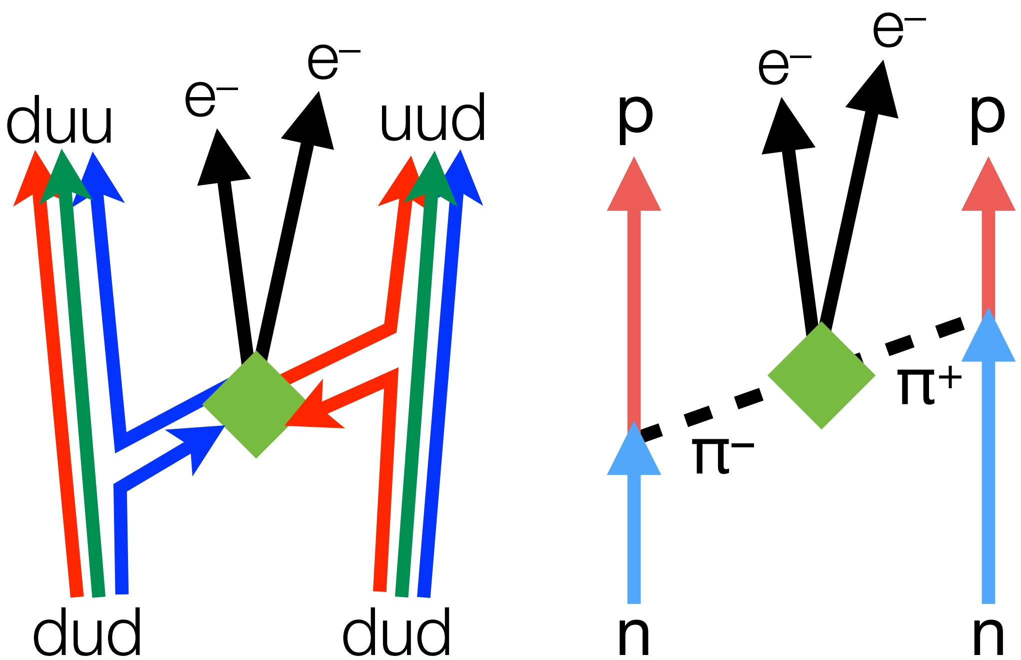
- Pionless EFT
- Dineutron bound at 800 MeV
- Binding energies, matrix element from the lattice

Short Range 0νββ

CalLat PRL 121 (2018) 17 172501 arXiv:1805.02634

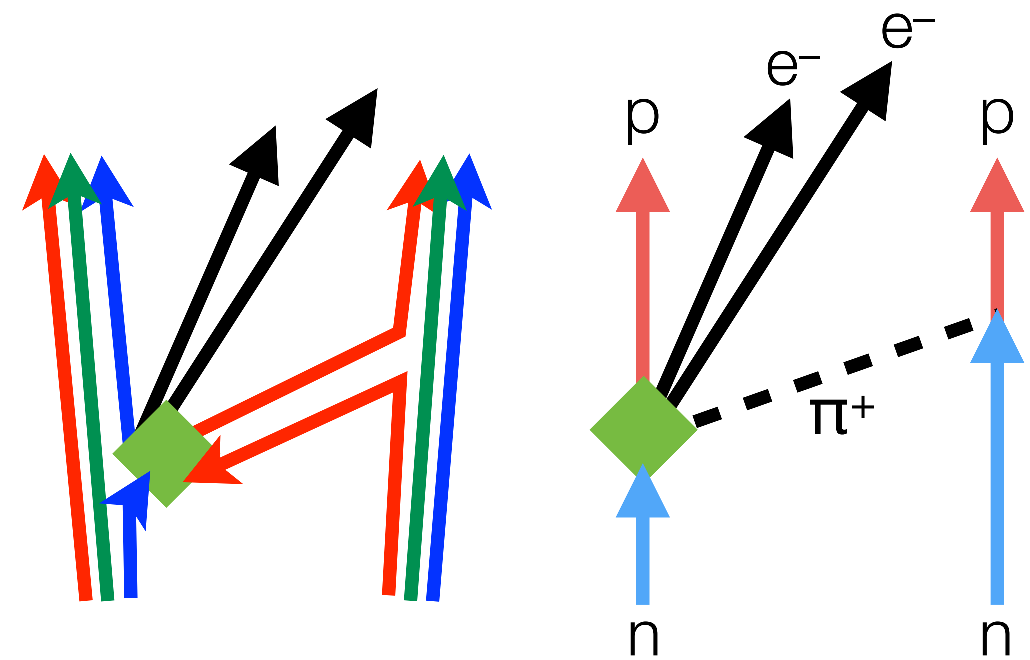


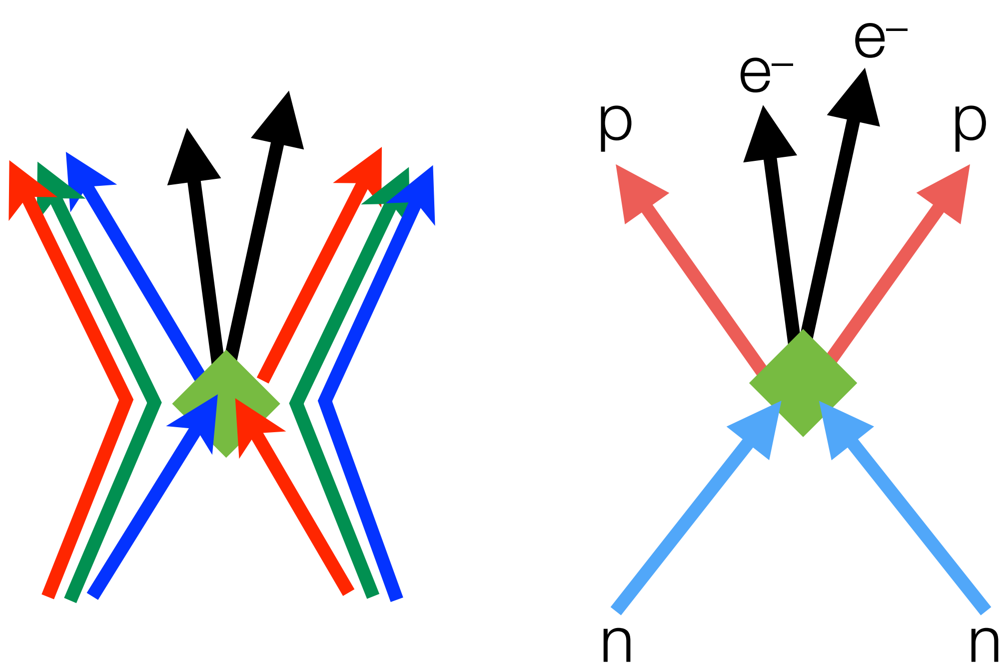
In χPT



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

$\mathcal{O}(p^{-1})$ new πN vertex





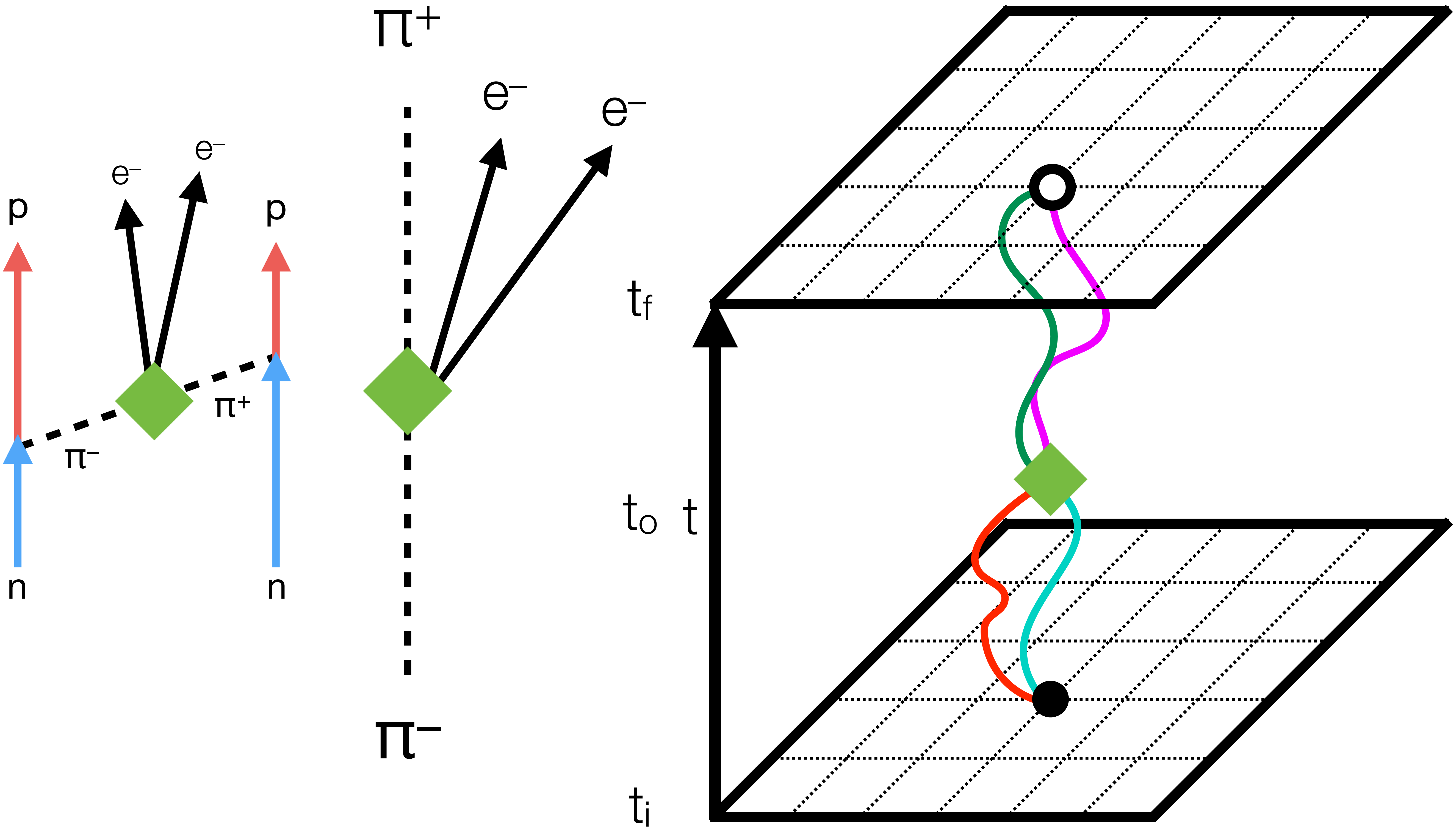
$\mathcal{O}(p^{0})$ NN contact operator

Can be promoted, as in Cirigliano, Dekens, Mereghetti and Walker-Loud PRC 97 (2018) 06 065501 arXiv:1710.01729

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

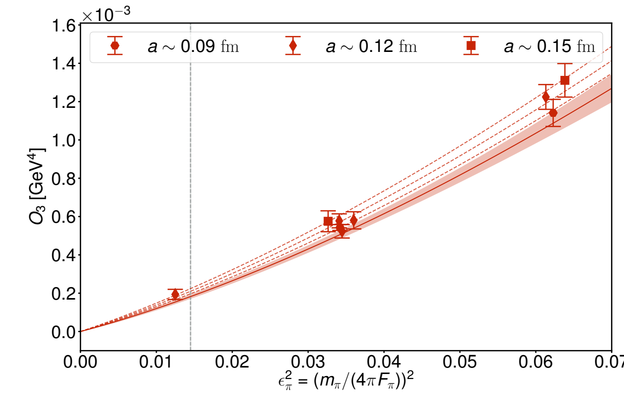
Short Distance $0\nu\beta\beta$
$\pi^+ \pi^-$ Transition

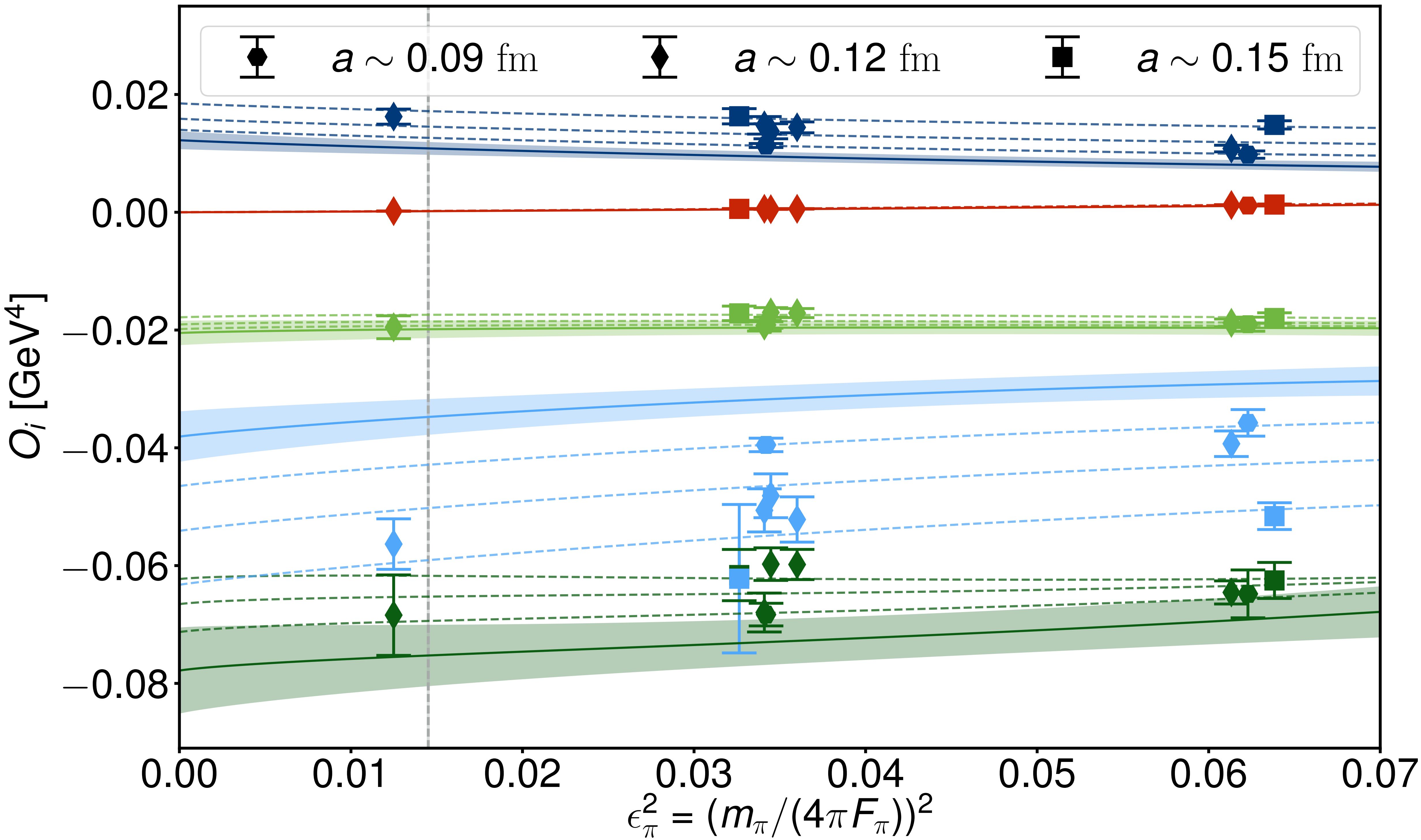
CalLat PRL 121 (2018) 17 172501 arXiv:1805.02634



Short-distance 0vββ

CallLat PRL 121 (2018) 17 172501 arXiv:1805.02634





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

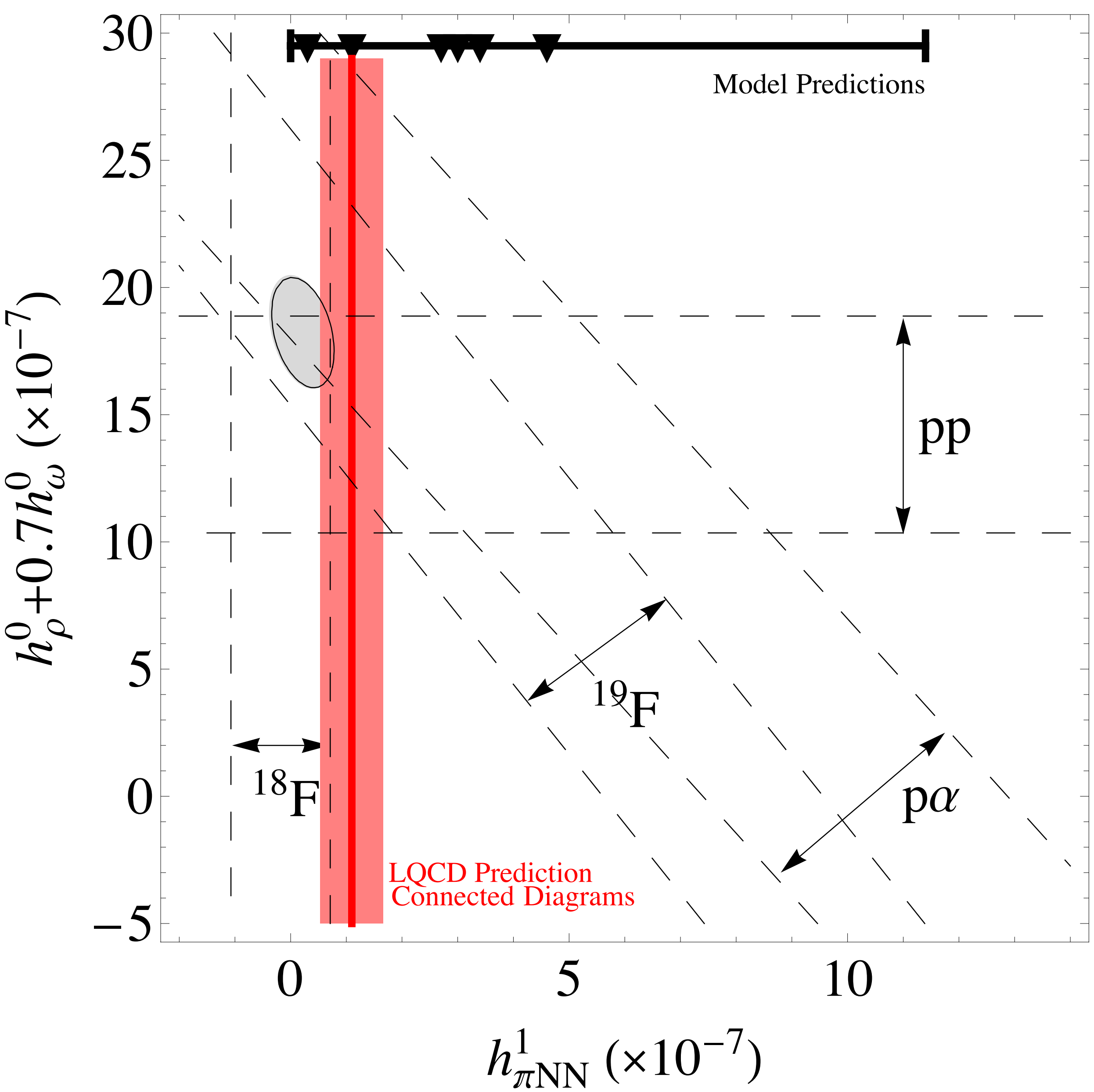
Hadronic Parity Violation

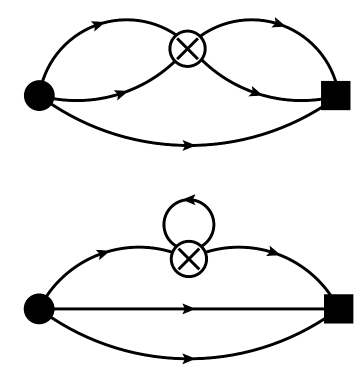
Wasem PRC85 (2012) 022501 arXiv:1108.1151

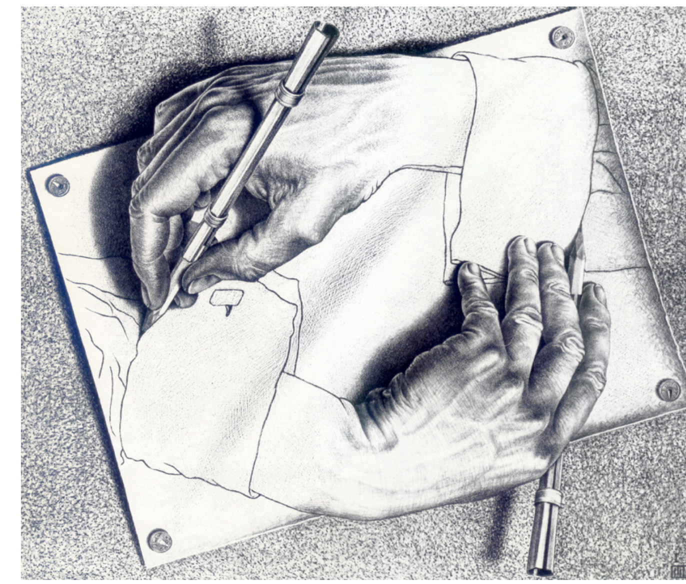
$m_\pi \sim 389$ MeV; a~0.123 fm

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

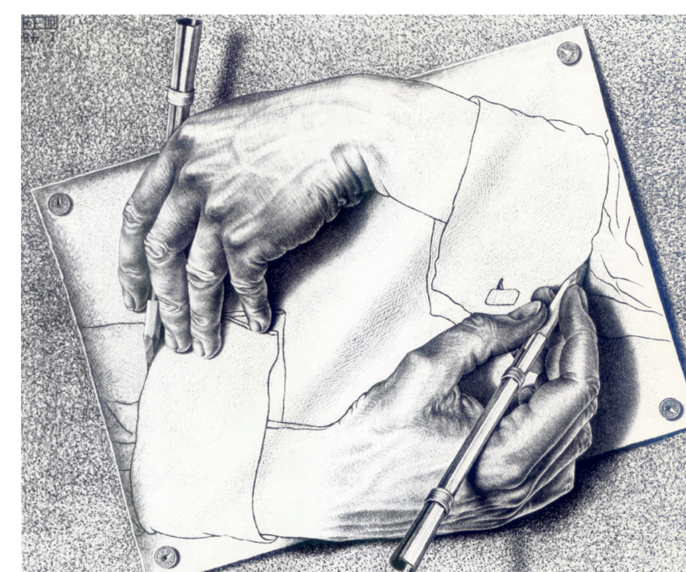
$$h_{\pi NN}^{1,con} = (1.099 \pm 0.505^{+0.058}_{-0.064})\ 10^{-7}$$







PV ≠ Vꟼ



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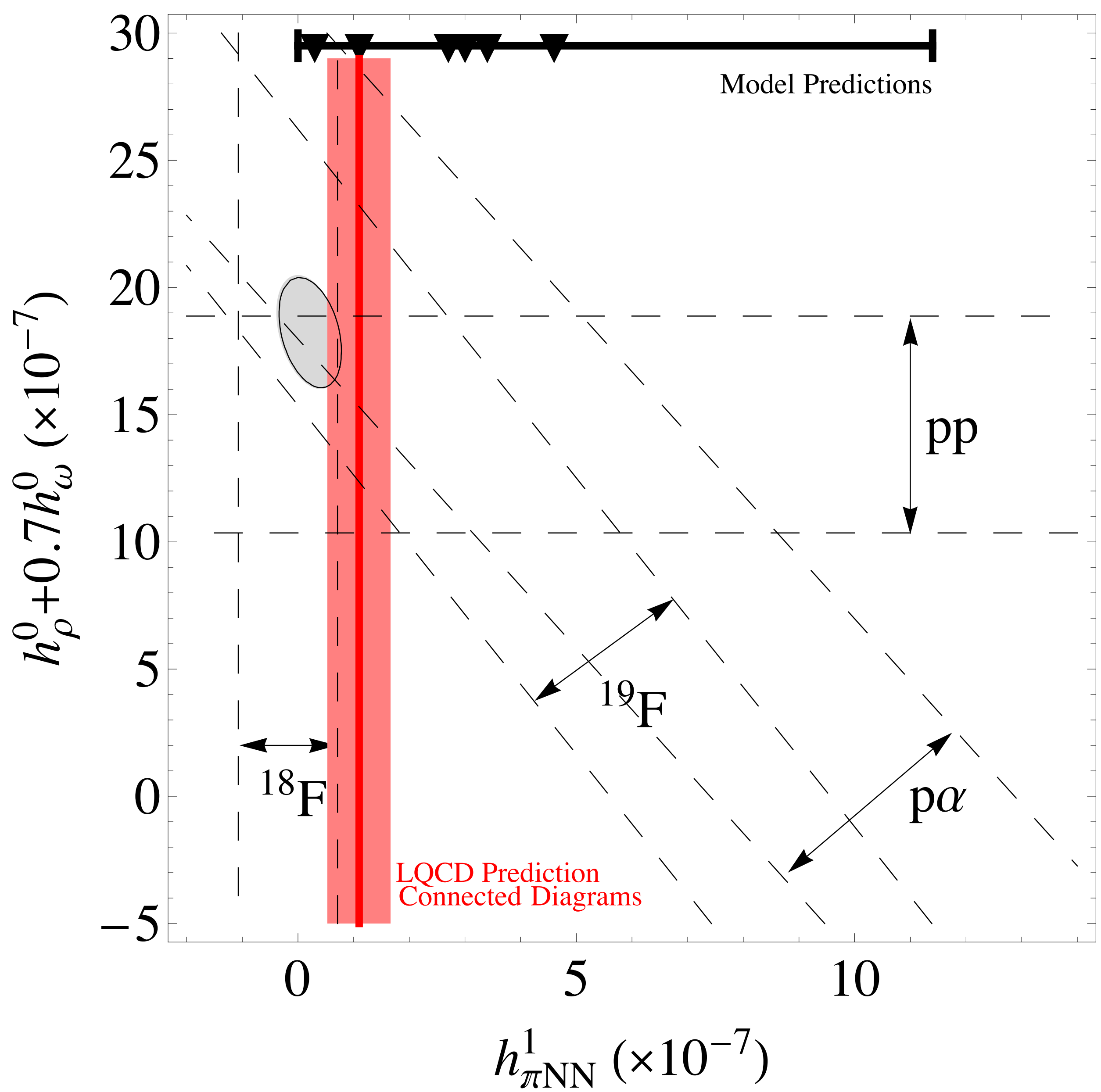
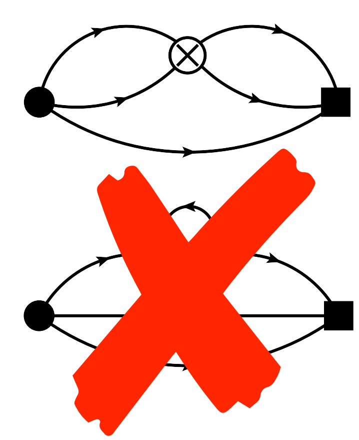
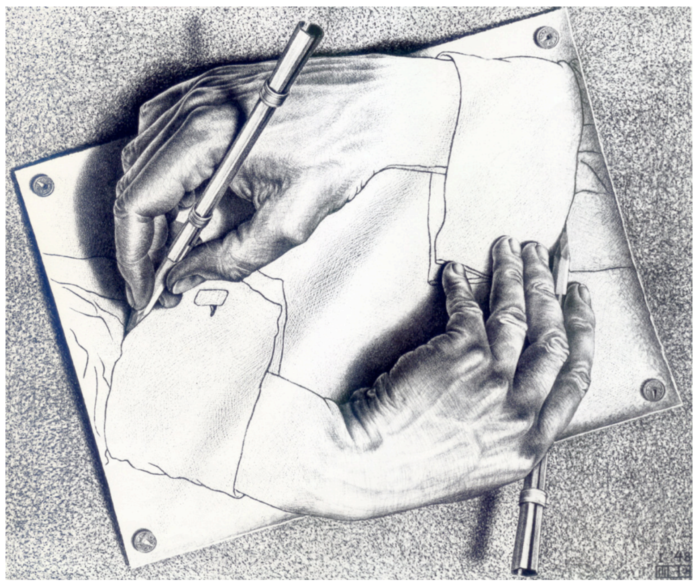
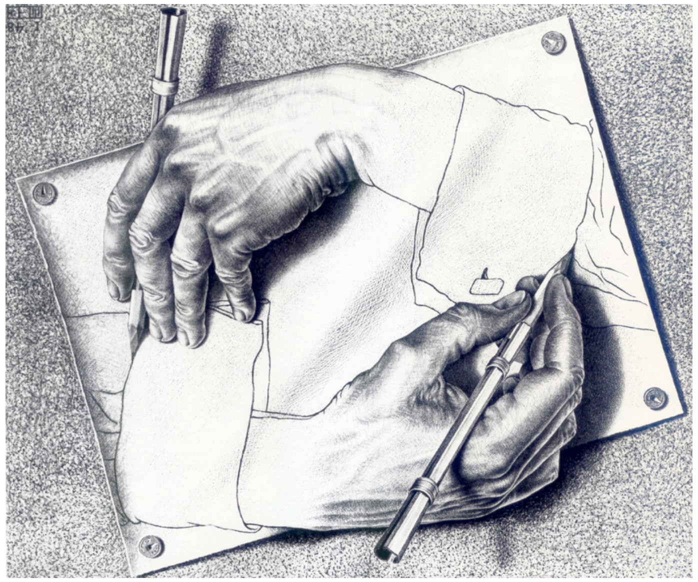






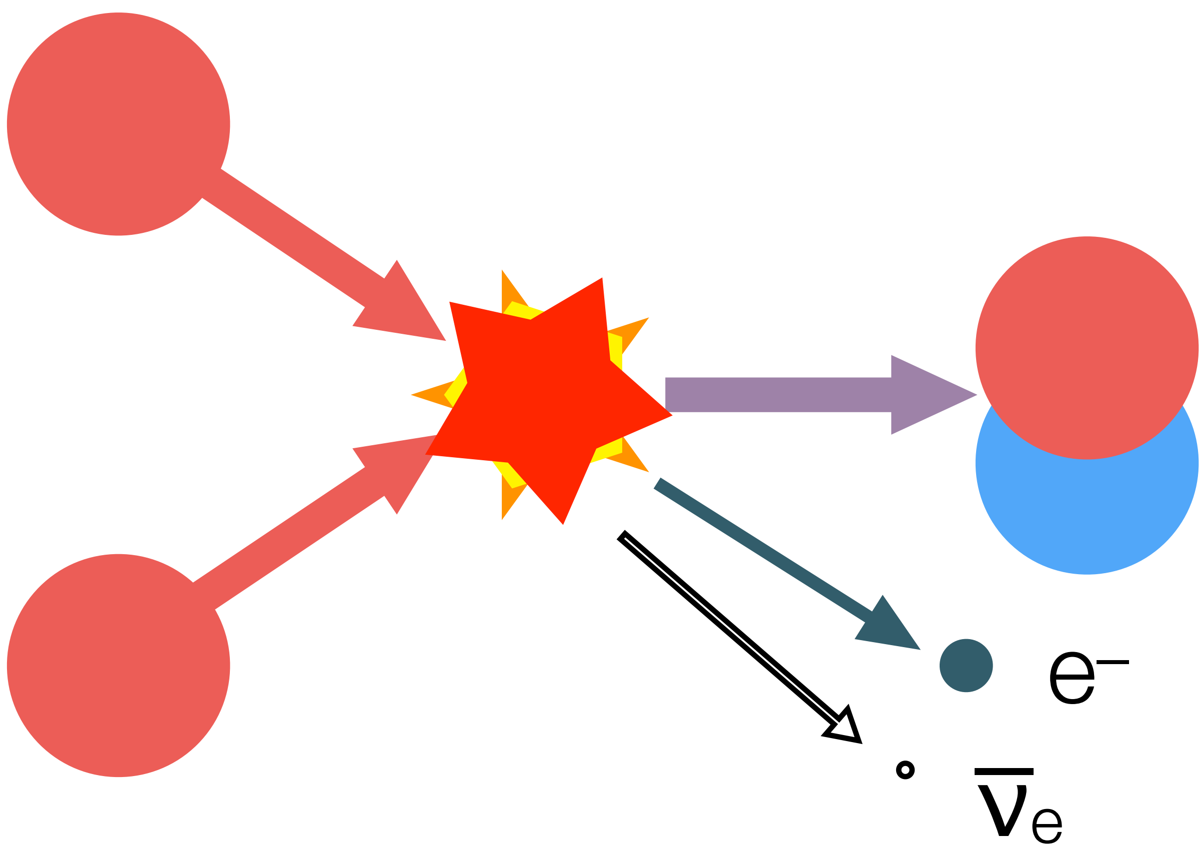
PV ≠ VԀ

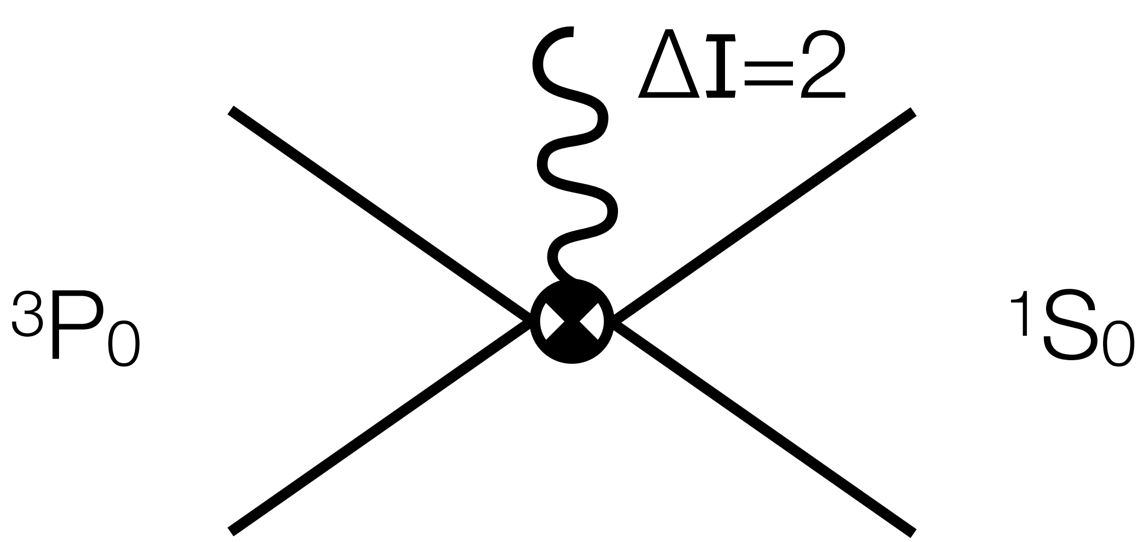


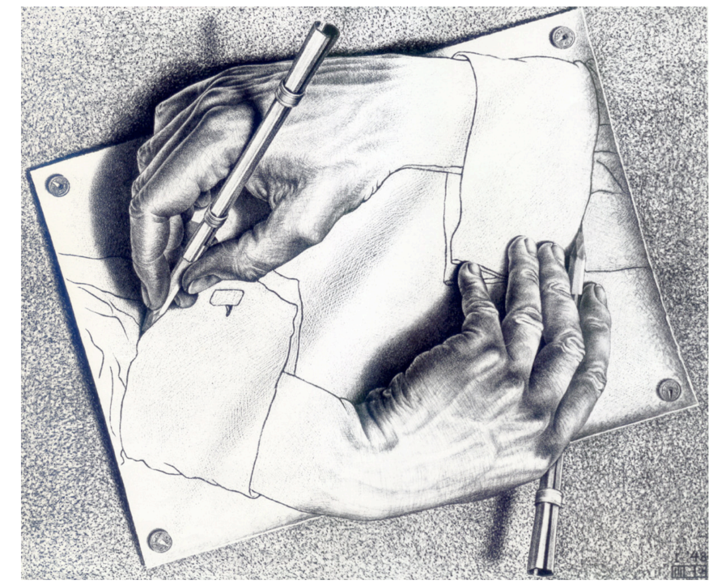
Hadronic Parity Violation

CalLat PoS(LATTICE 2015)329 arXiv:1511.02260

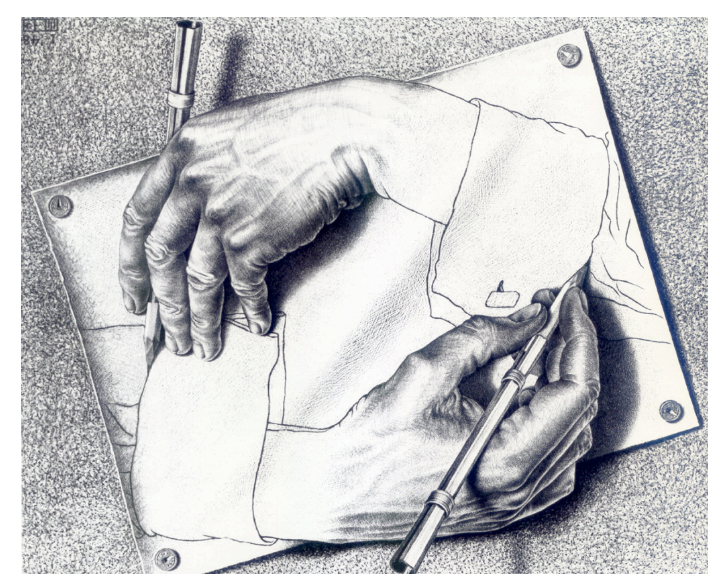
$m_\pi \sim 800$ MeV; a~0.145 fm







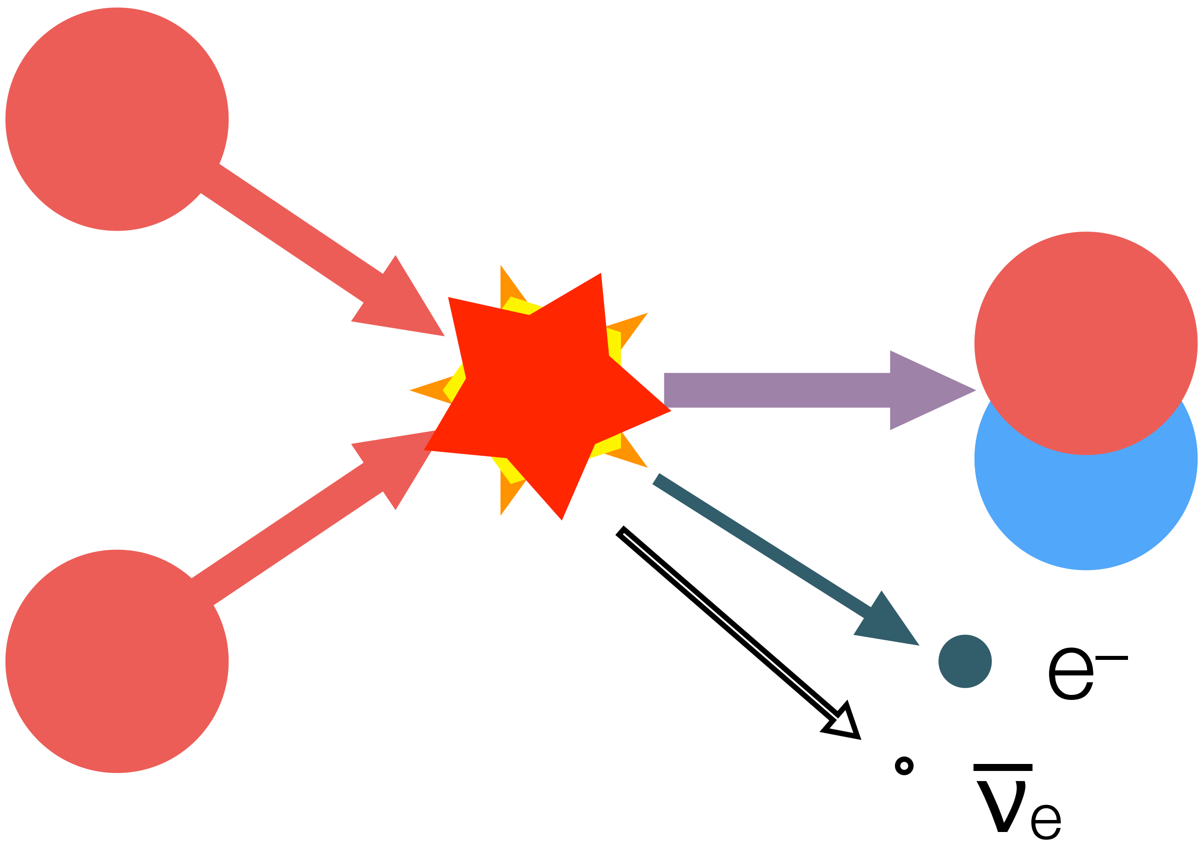
PV ≠ Vꟼ



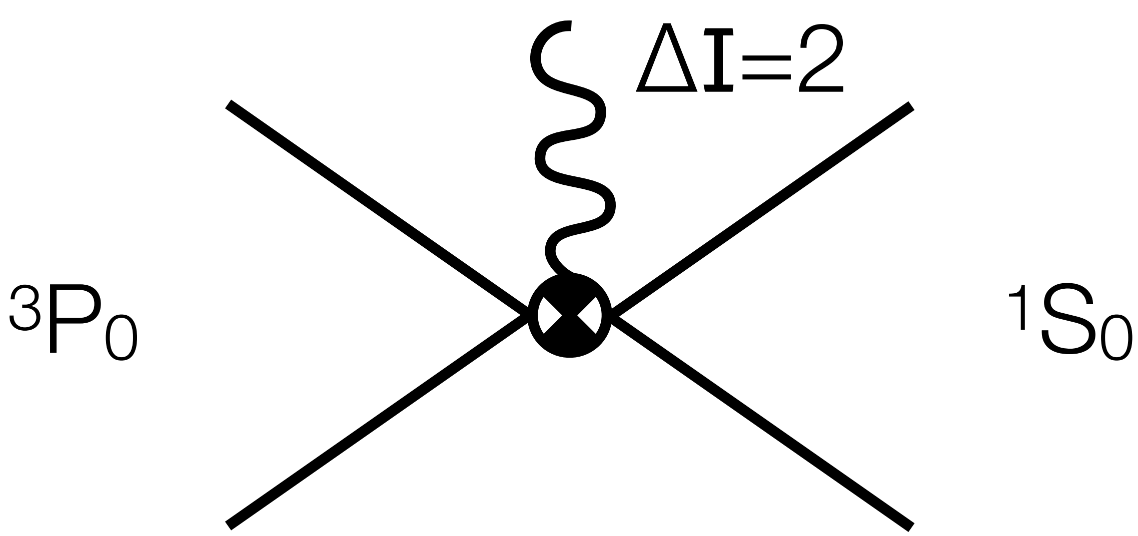
Hadronic Parity Violation

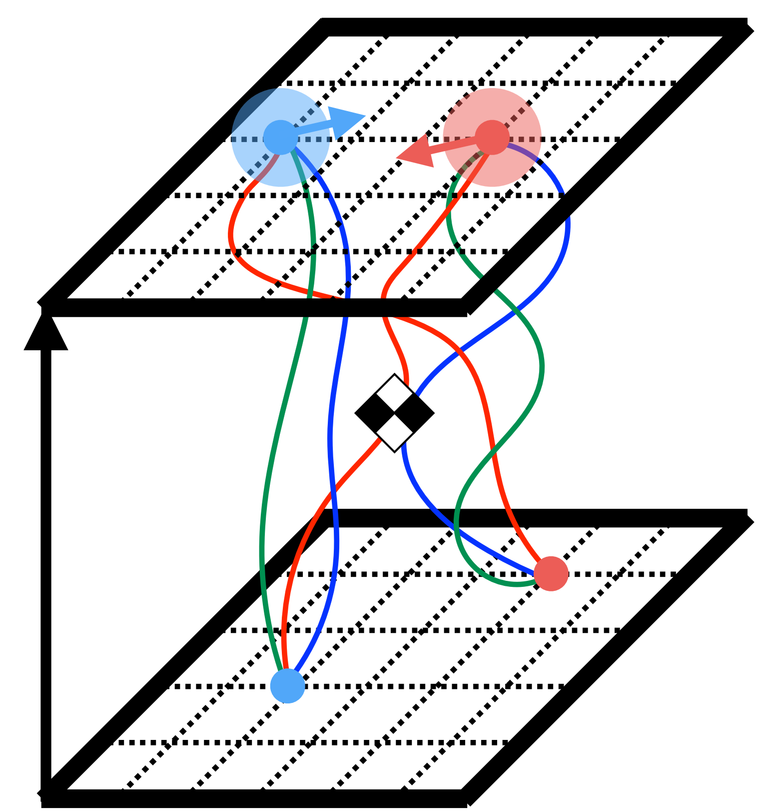
CalLat PoS(LATTICE 2015)329 arXiv:1511.02260

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



- $^3P_0$ is not bound
- Need $^1S_0$ binding energy, $^3P_0$ phase shift + derivative, and matrix element from the lattice





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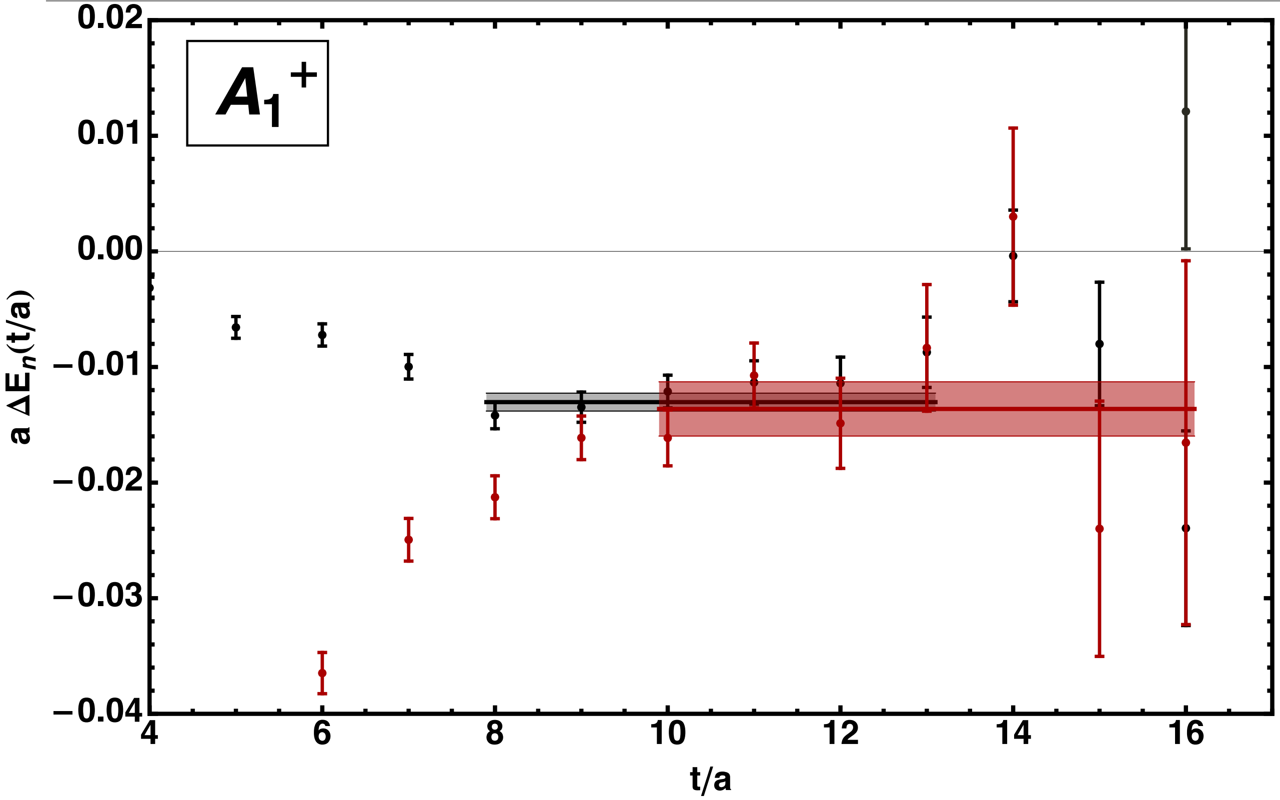

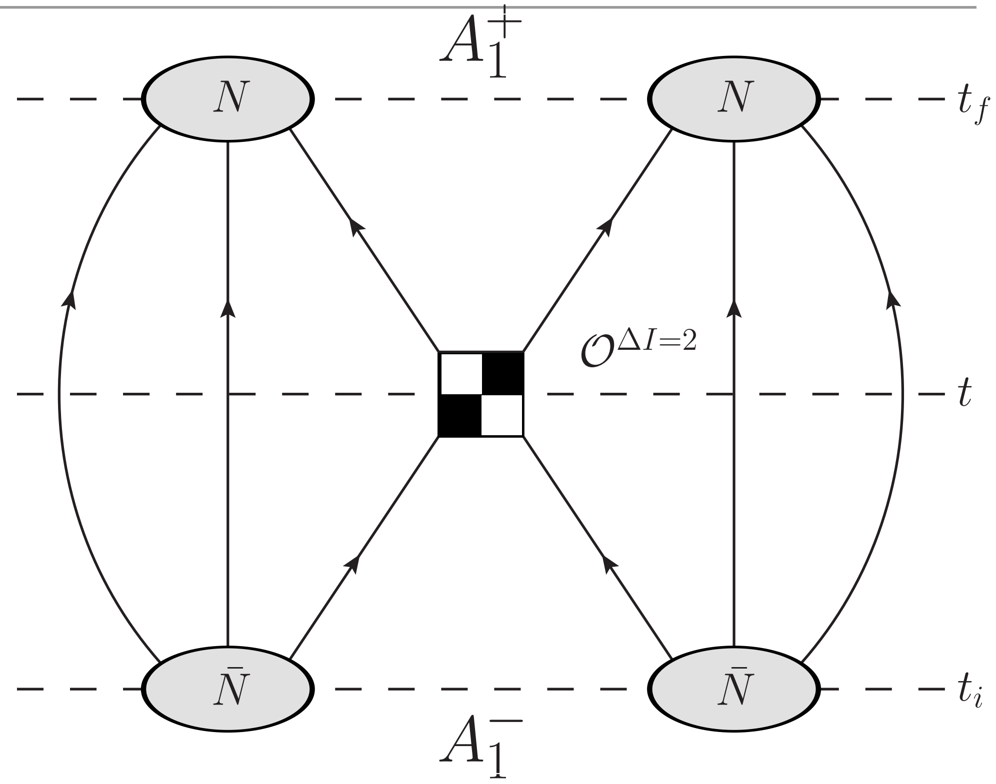

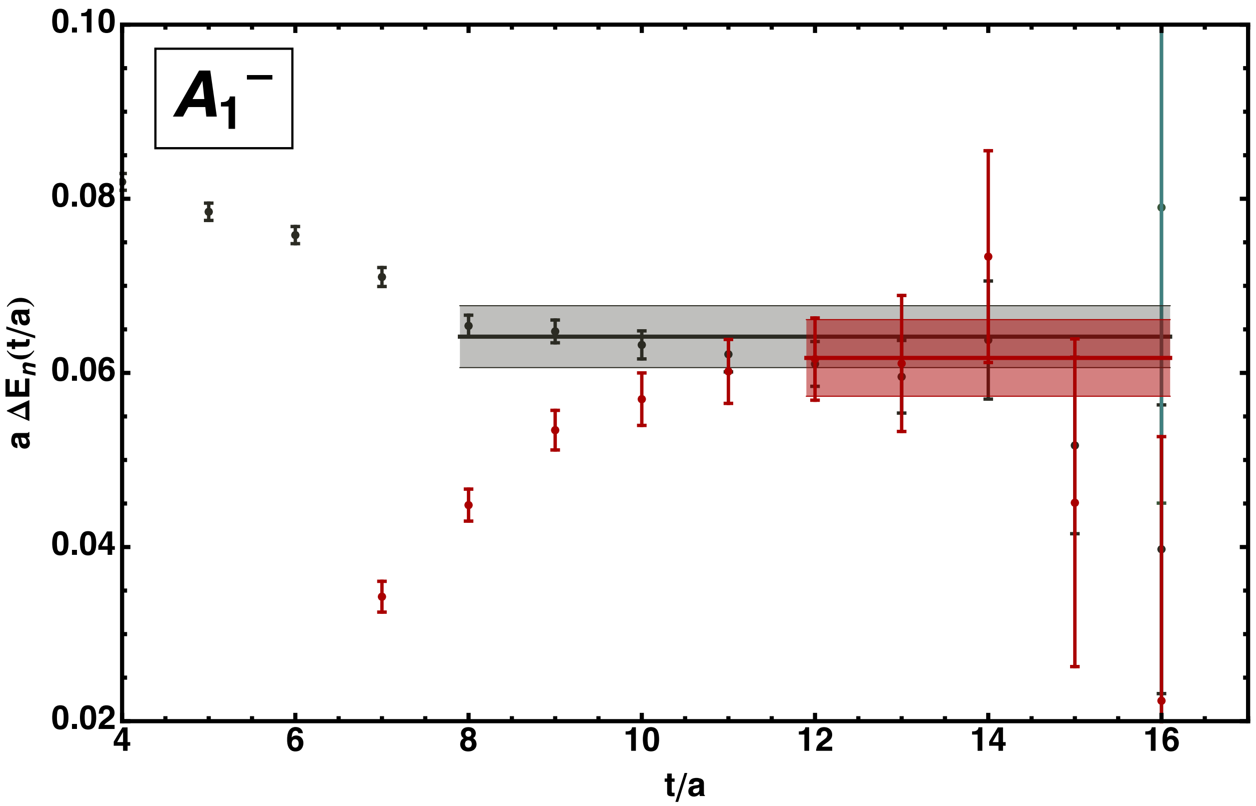

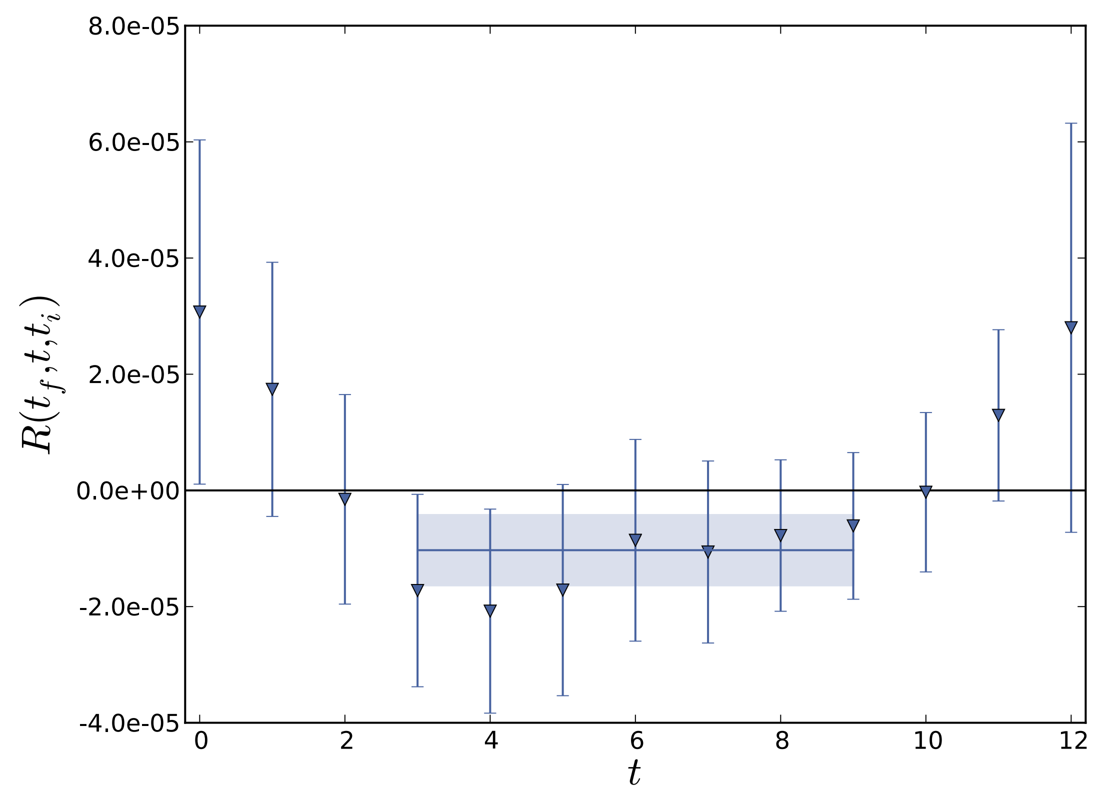

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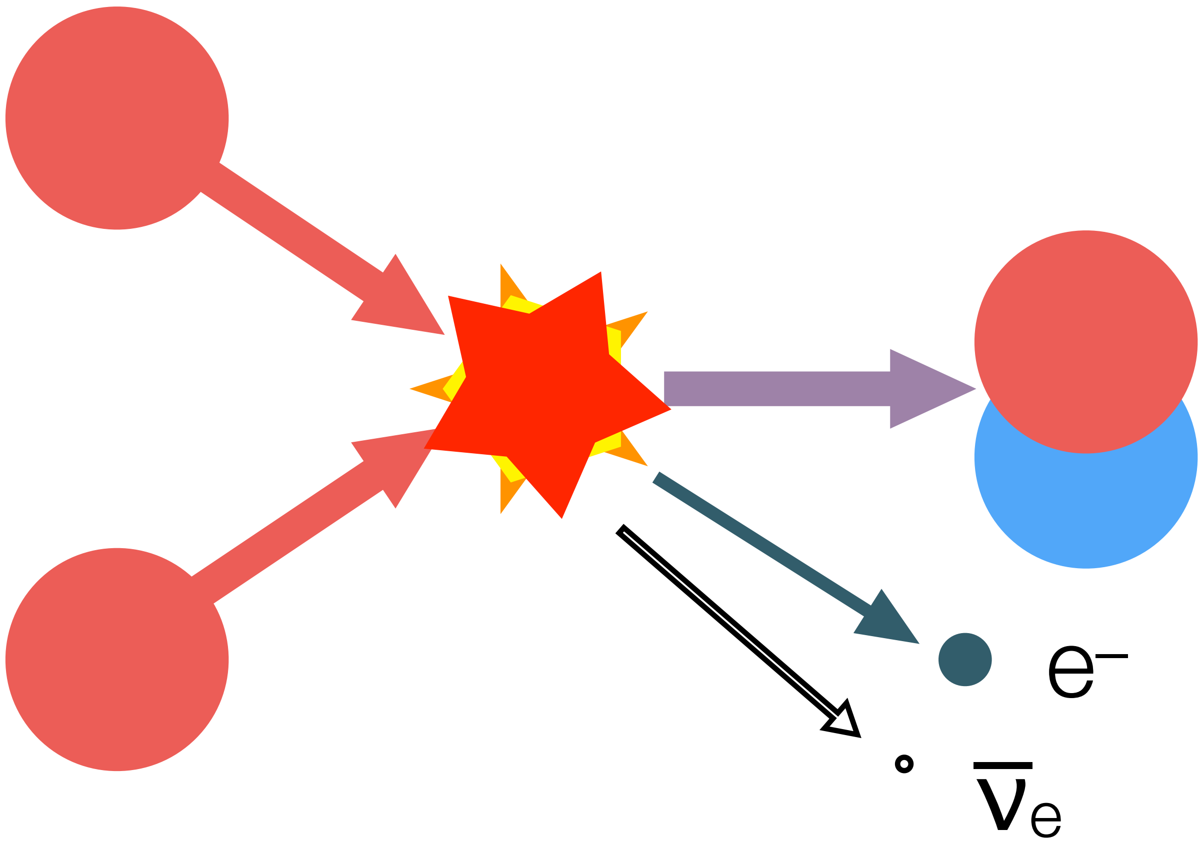

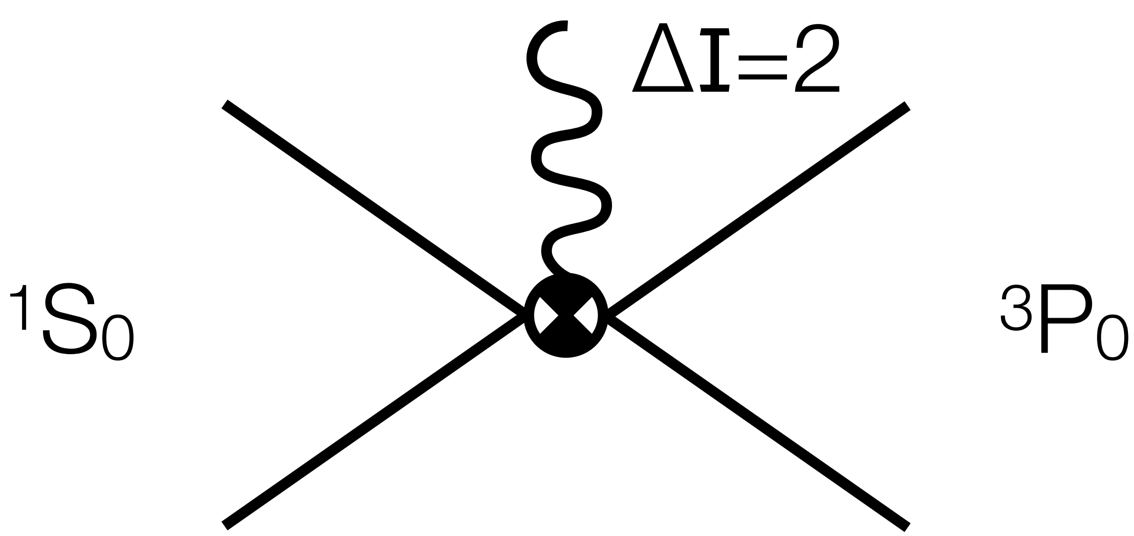

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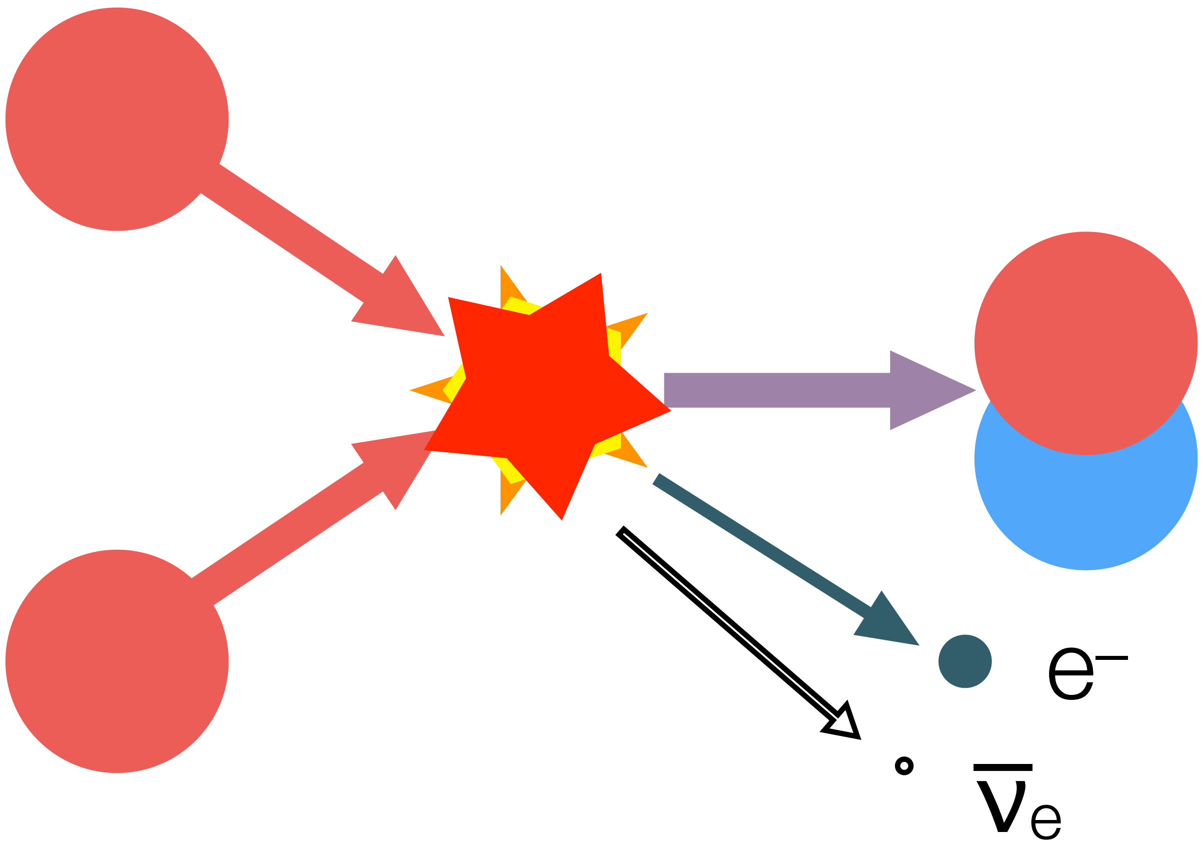

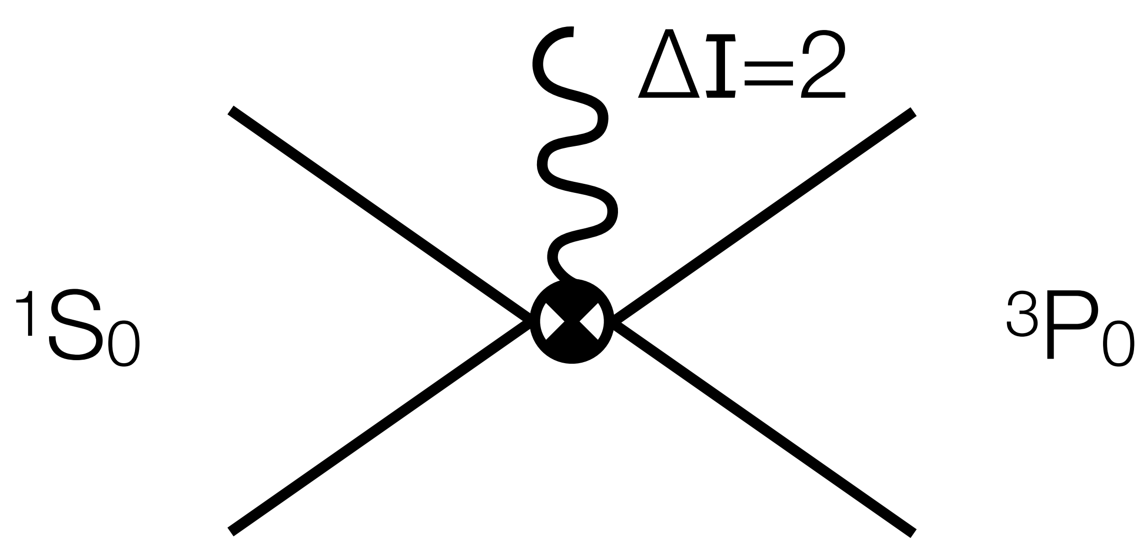

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new methods


IBM
SIERRA
LLNL


summit
OLCF


LASSEN
LLNL

Summary

- g_A, $n\bar{n}$: Looking good, but you'll hear more Thursday
- θEDM + cEDM: progress, but indistinguishable from zero; Weinberg operator: not as much progress
- CP violating πN coupling
- NN: g_A quenching, pp fusion, isotensor polarizability (2νββ)
- $\pi^+\pi^-$ transition (0νββ)
- ΔI=2 Hadronic PV

Outlook

- Single-nucleon quark-bilinear matrix elements: form factors, radii, σ term, polarizabilities
- $\not\pi$EFT can help enormously
- four-quark operators require EFT understanding / new methods (meson transitions are much simpler, for example)
- New computers + methods will yield a dramatic improvement.