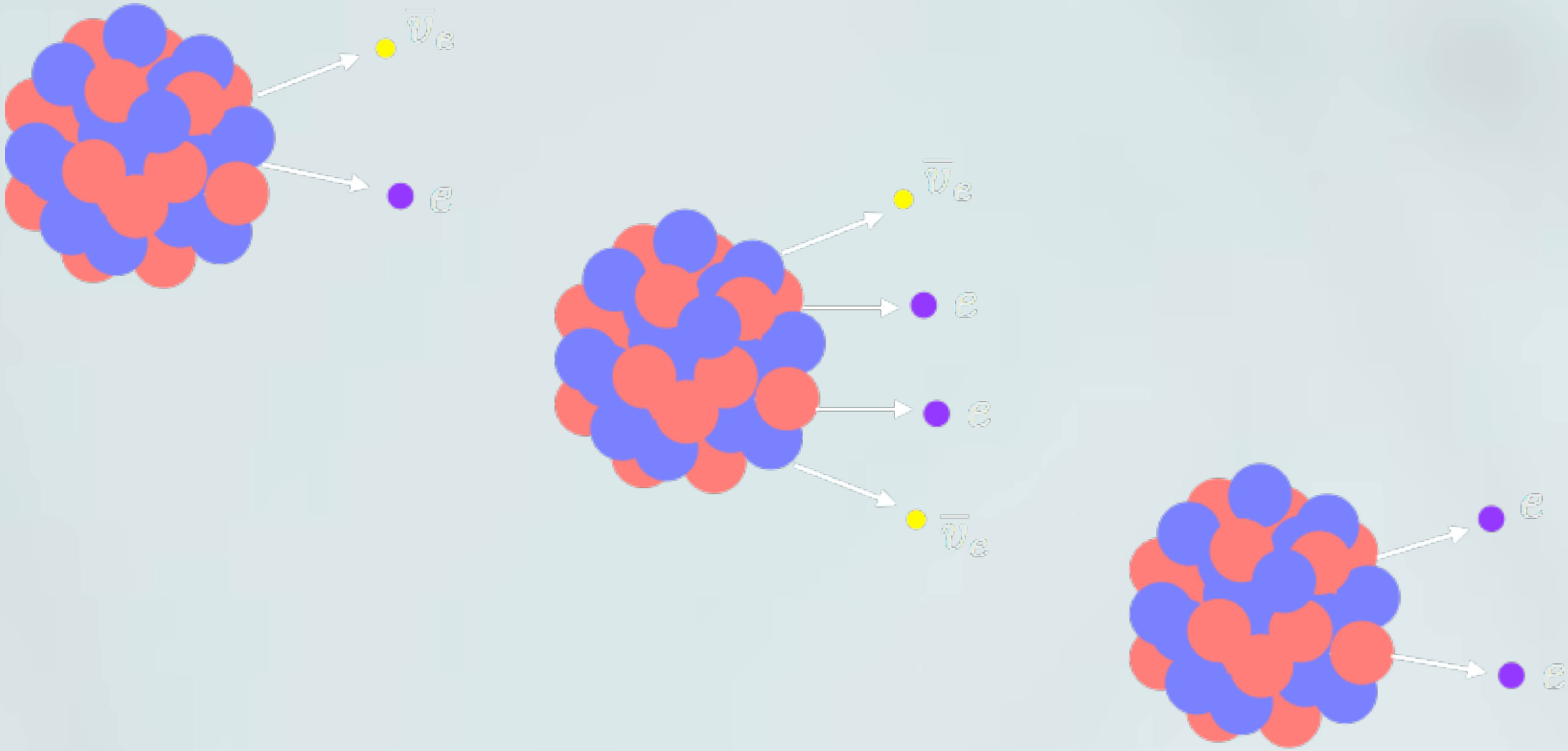


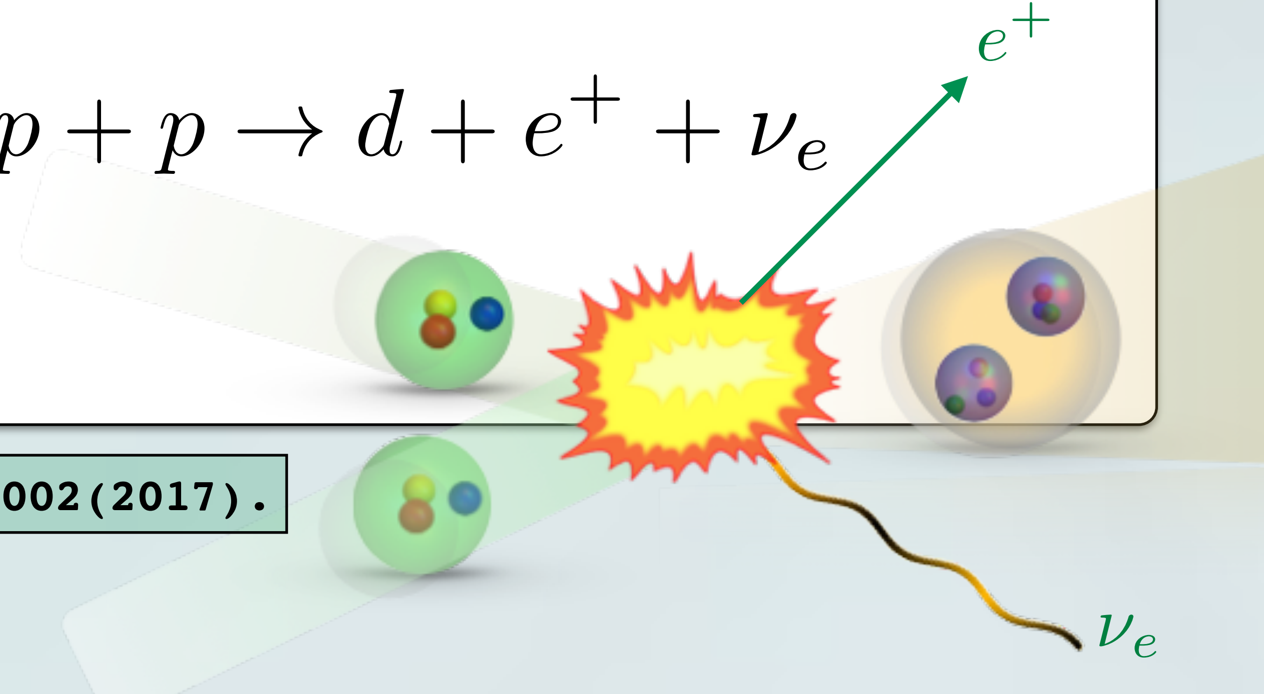
INT WORKSHOP ON FUNDAMENTAL PHYSICS WITH ELECTROWEAK PROBES OF IGHT NUCLEI, JUNE 2018

AXIAL PROPERTIES OF NUCLEI FROM LATTICE QCD AND EFT

ZOHREH DAVOUDI, UNIVERSITY OF MARYLAND
AND RIKEN FELLOW

SINGLE-WEAK PROCESSES

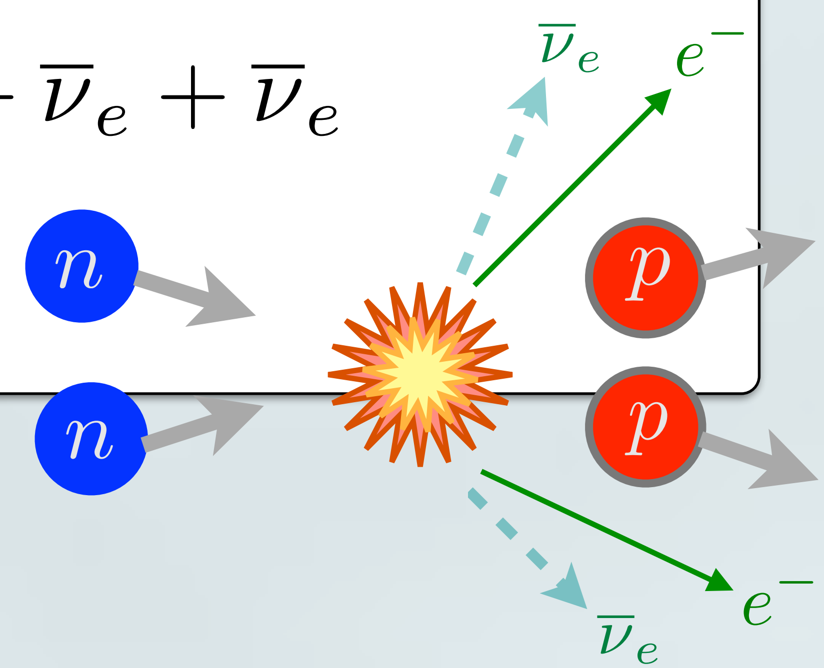
$^3\text{H} \rightarrow {}^3\text{He} + e^- + \overline{\nu}_e \qquad p + p \rightarrow d + e^+ + \nu_e$



Savage et al (NPLQCD), Phys.Rev.Lett.119,062002(2017).

A DOUBLY-WEAK PROCESS

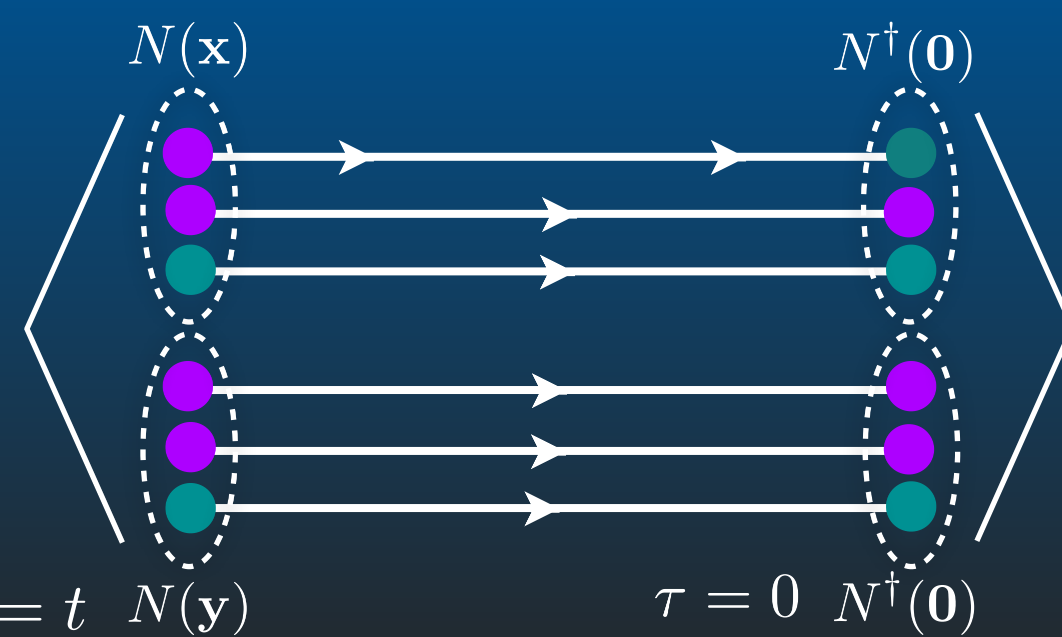
$n + n \rightarrow p + p + e^- + e^- + \overline{\nu}_e + \overline{\nu}_e$



Tiburzi et al (NPLQCD), Phys.Rev.D96,054505(2017),
Shanahan et al (NPLQCD), Phys.Rev.Lett.119,062003(2017).

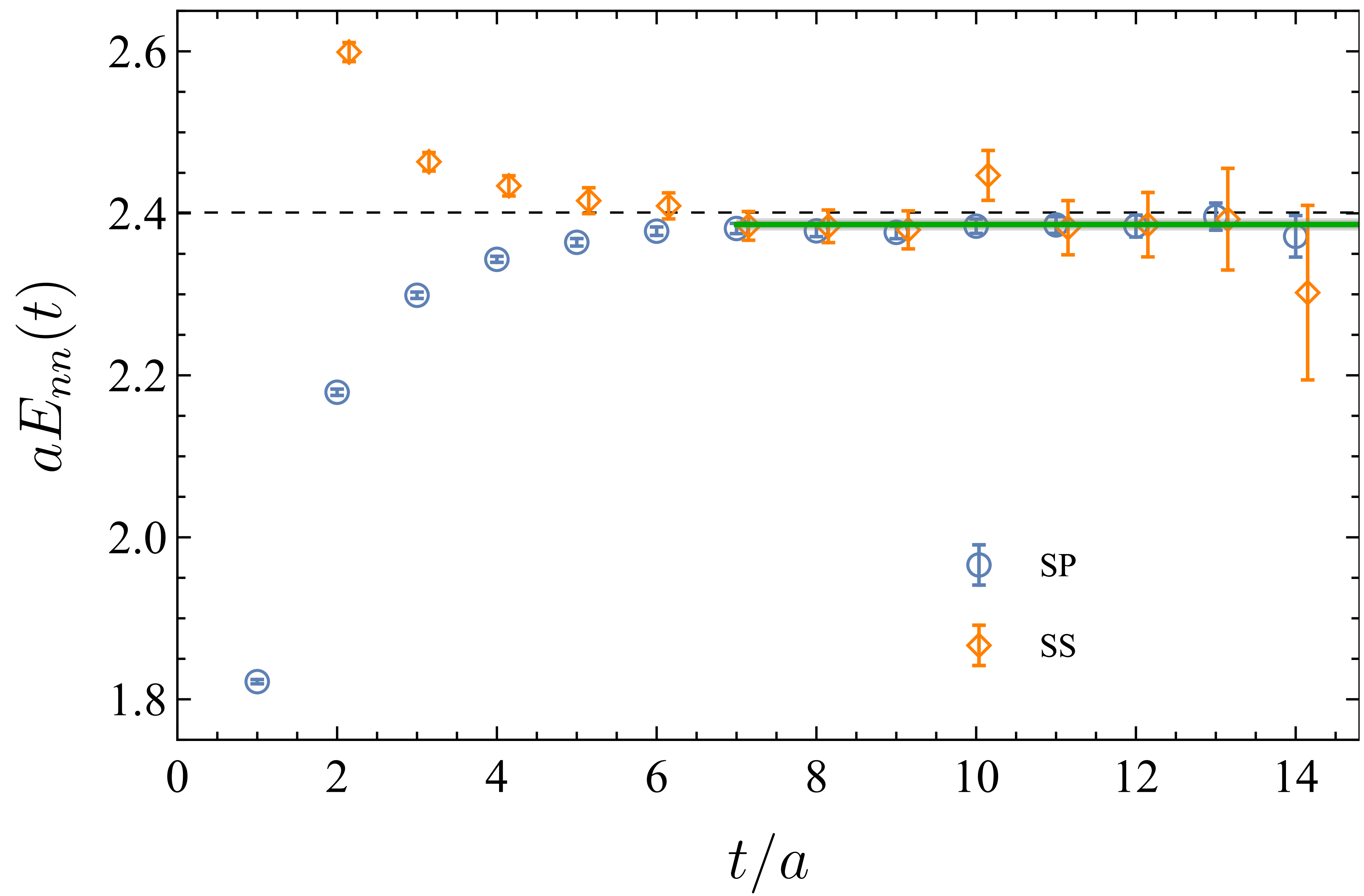
ENERGIES FROM TWO-NUCLEON CORRELATION FUNCTIONS

$$C(\mathbf{P};t,t_O) = \sum_{\mathbf{p}_1+\mathbf{p}_2=\mathbf{P}} \sum_{\mathbf{x},\mathbf{y},\mathbf{z}} e^{i\mathbf{p}_1\cdot\mathbf{x}+i\mathbf{p}_2\cdot\mathbf{y}} \times$$



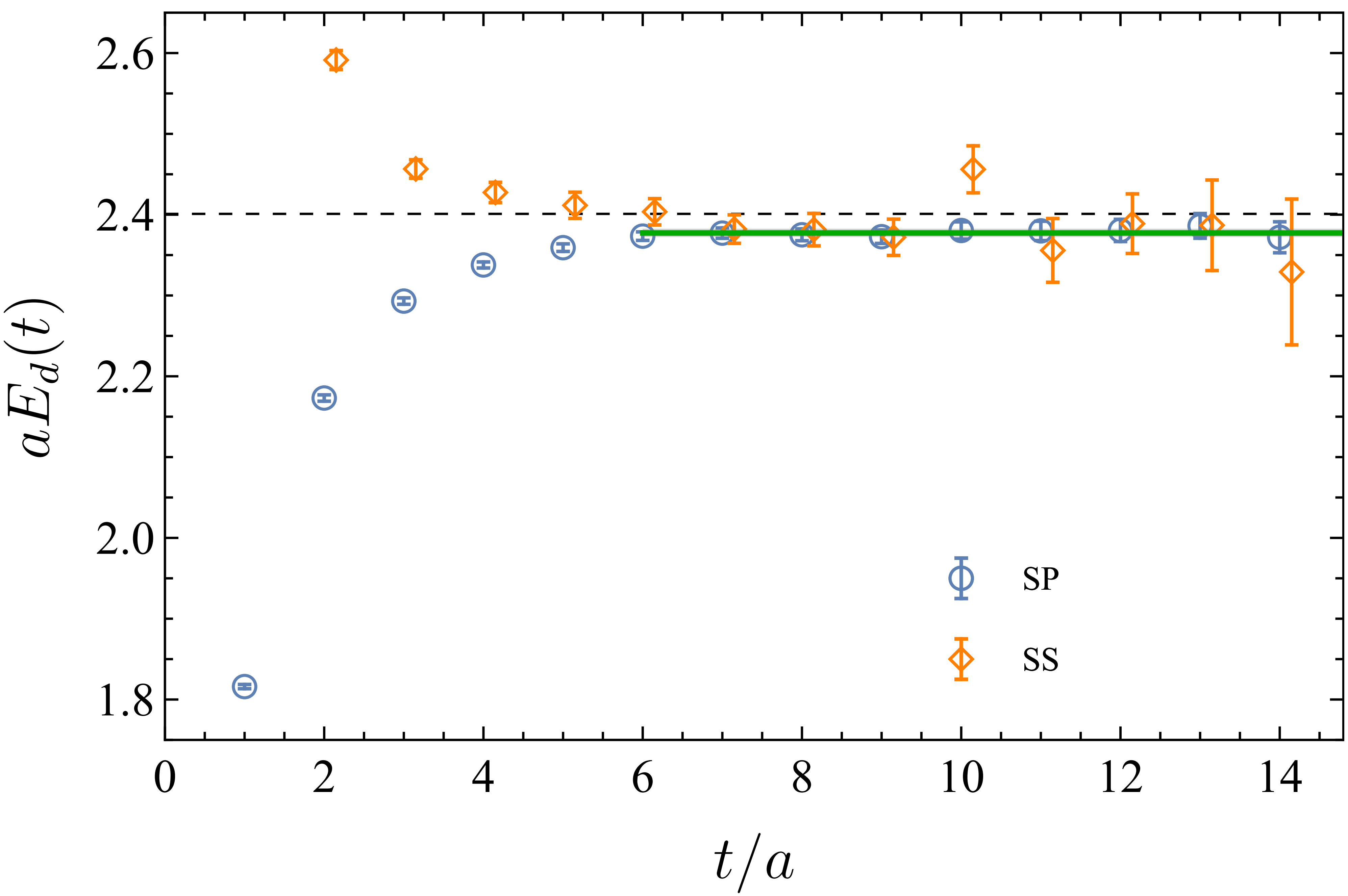
$$C_{\hat{\mathcal{O}},\hat{\mathcal{O}}'}(\tau;\mathbf{d}) = \sum_{\mathbf{x}} e^{2\pi i\mathbf{d}\cdot\mathbf{x}/L}\langle 0|\hat{\mathcal{O}}'(\mathbf{x},\tau)\hat{\mathcal{O}}^\dagger(\mathbf{0},0)|0\rangle = \mathcal{Z}_0'\mathcal{Z}_0^\dagger e^{-E^{(0)}\tau} + \mathcal{Z}_1'\mathcal{Z}_1^\dagger e^{-E^{(1)}\tau} + \ldots$$

ENERGIES FROM TWO-BARYON CORRELATION FUNCTIONS



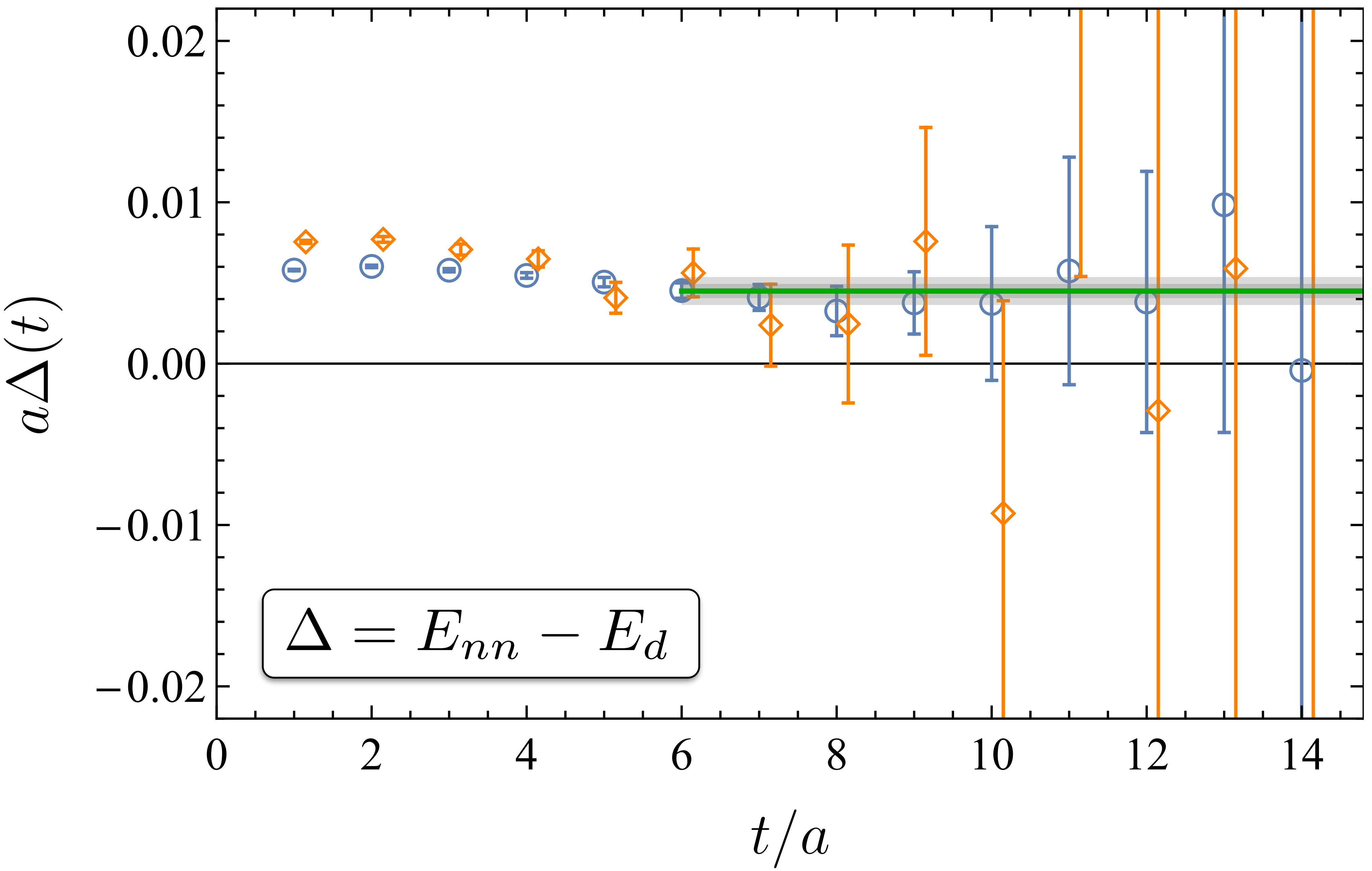
$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$

ENERGIES FROM TWO-BARYON CORRELATION FUNCTIONS



$N_f = 3,\ m_\pi = 0.806$ GeV$,\ a = 0.145(2)$ fm

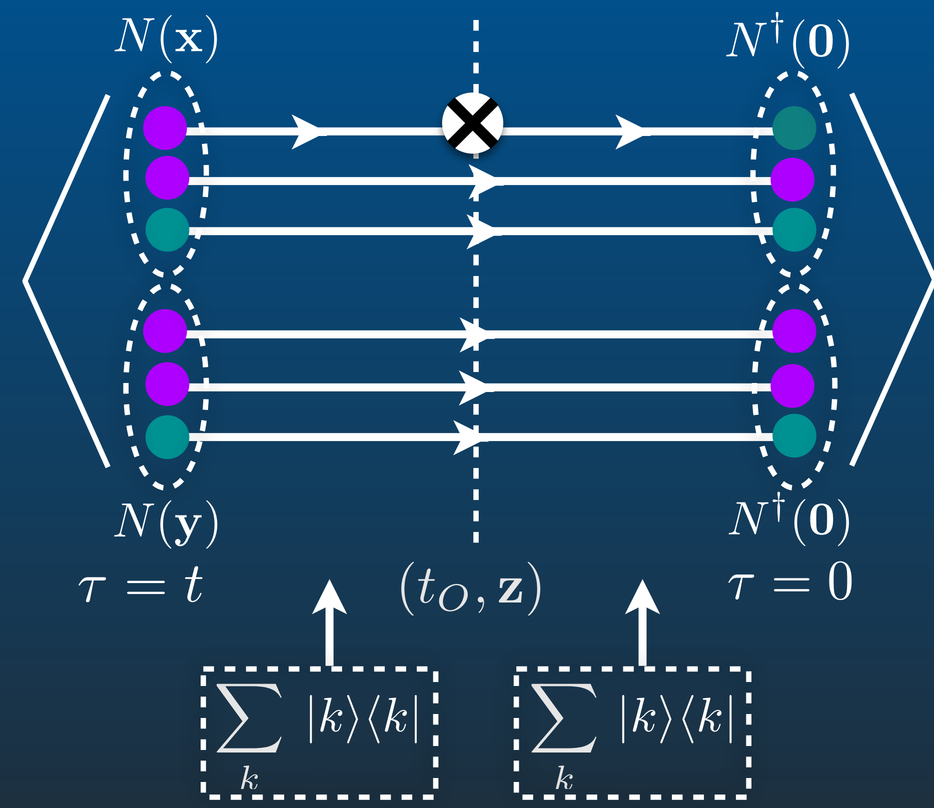
ENERGIES FROM TWO-BARYON CORRELATION FUNCTIONS



$N_f = 3, \; m_\pi = 0.806$ GeV, $a = 0.145(2)$ fm

TRADITIONAL MATRIX ELEMENT CALCULATIONS: 3-POINT FUNCTIONS

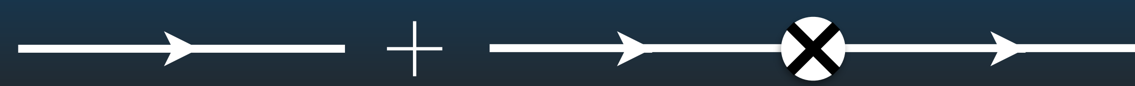
$$C(\mathbf{P};t,t_O) = \sum_{\mathbf{p}_1+\mathbf{p}_2=\mathbf{P}} \sum_{\mathbf{x},\mathbf{y},\mathbf{z}} e^{i\mathbf{p}_1\cdot\mathbf{x}+i\mathbf{p}_2\cdot\mathbf{y}} \times$$



$$= Z^{\text{src}}_{0,pp} {Z^{\text{snk}}_{0,d}}^\dagger e^{-E_{0,pp}t_O} e^{-E_{0,d}(t-t_O)} \langle pn \,|A|\, pp\rangle_L + \ldots$$

MATRIX ELEMENTS FROM A COMPOUND PROPAGATOR/BACKGROUND FIELD

$$S^{(q)}_{\lambda_q;\Gamma}(x,y) = S^{(q)}(x,y) + \lambda_q \int dz\ S^{(q)}(x,z)\Gamma S^{(q)}(z,y)$$

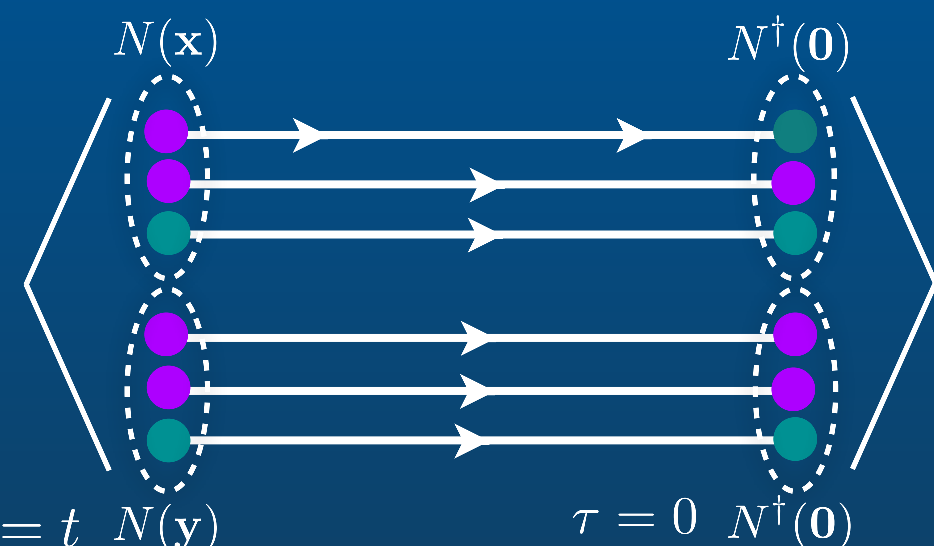


Savage et al (NPLQCD), Phys.Rev.Lett.119,062002(2017).

Buochard et al (CALLATT), Phys.Rev.D96,014504(2017).

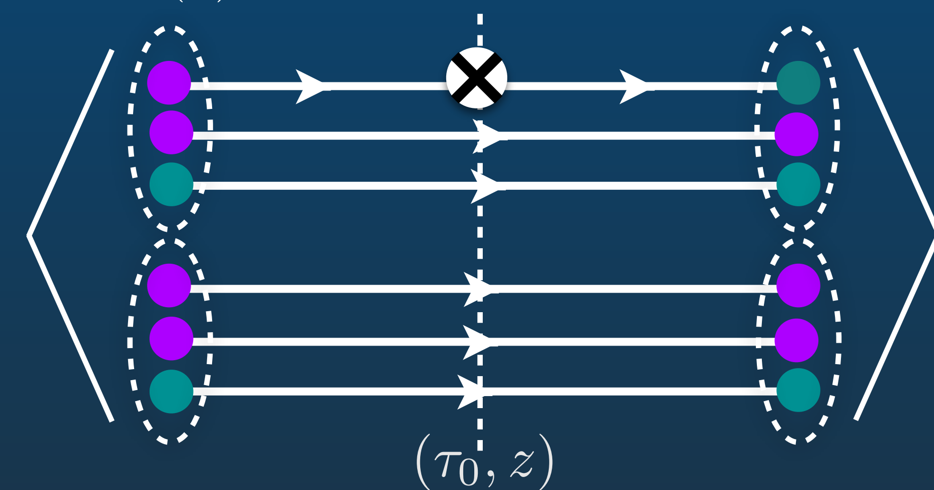
MATRIX ELEMENTS FROM A COMPOUND PROPAGATOR/BACKGROUND FIELD

$$C_\lambda(\mathbf{P};t,t_O) = \sum_{\mathbf{p}_1+\mathbf{p}_2=\mathbf{P}} \sum_{\mathbf{x},\mathbf{y},\mathbf{z}} e^{i\mathbf{p}_1\cdot\mathbf{x}+i\mathbf{p}_2\cdot\mathbf{y}} \times$$



ALL POSSIBILITIES →

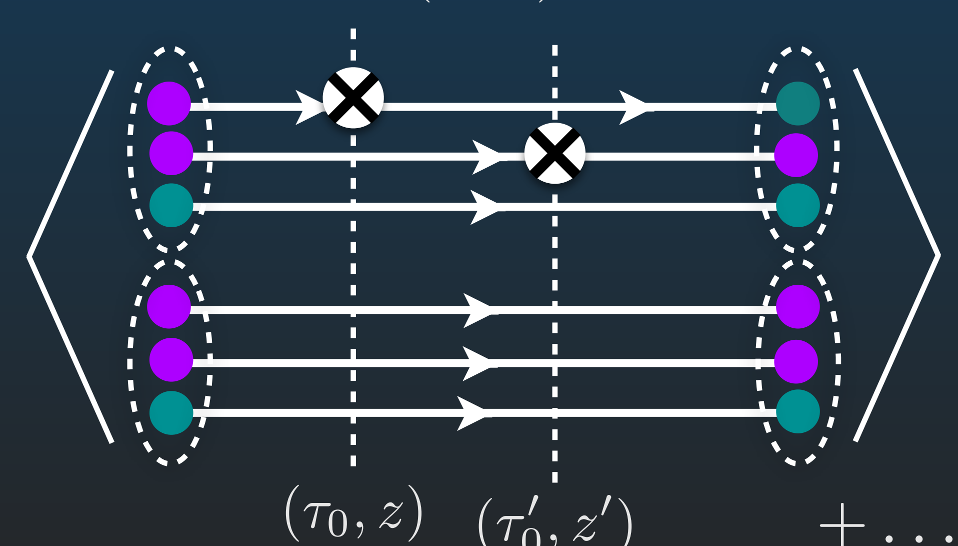
$$+\lambda \sum_{\tau_0=0}^{T} \sum_{z}$$



TIME-ORDERED PRODUCT ↓

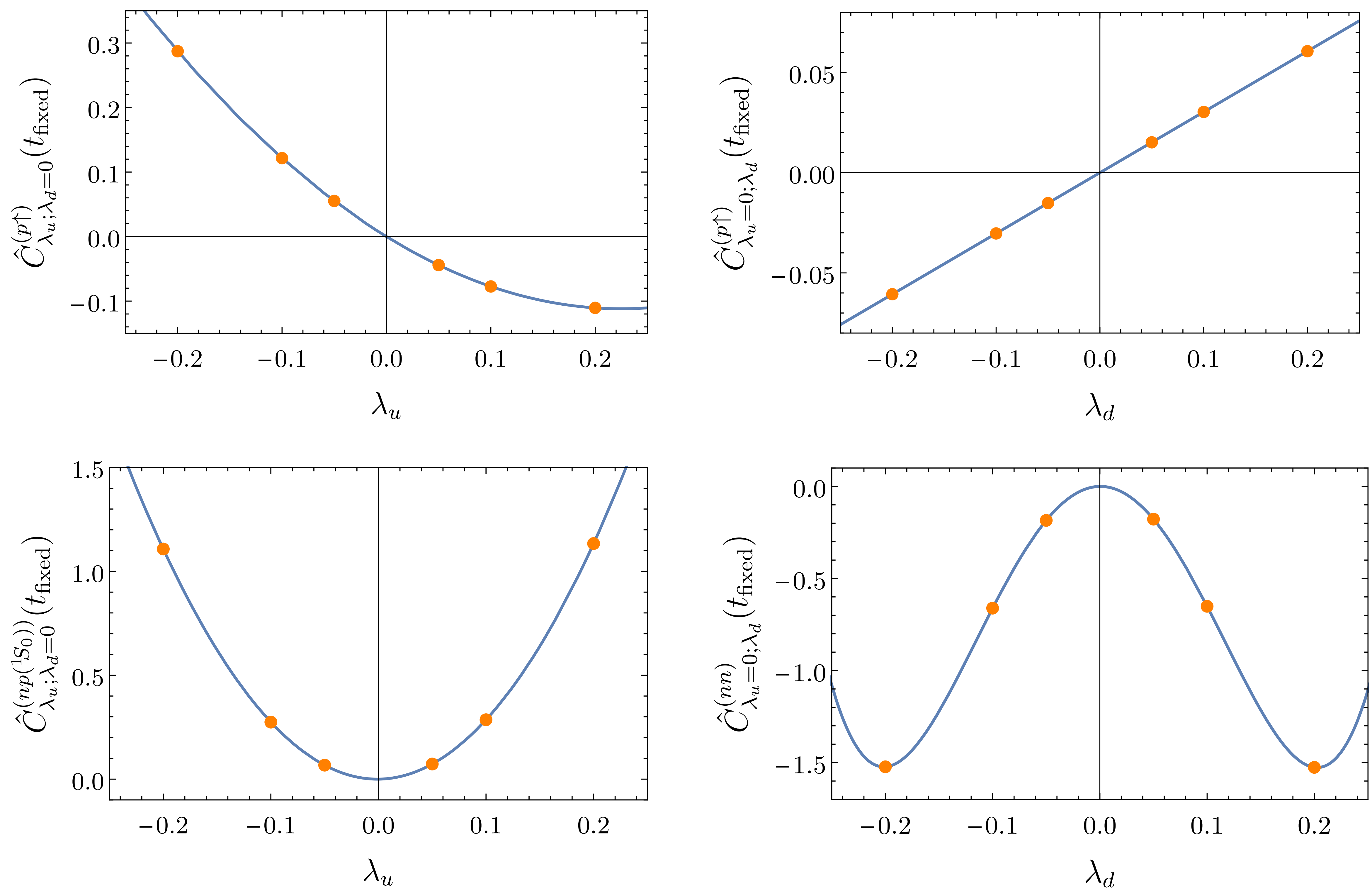
ALL POSSIBILITIES →

$$+\lambda^2 \sum_{\tau_0=0}^{T} \sum_{\tau_0'=0}^{T} \sum_{z} \sum_{z'}$$



DOUBLE-CURRENT MES ARE EXACT FOR ISOTENSOR QUANTITIES.

MATRIX ELEMENTS FROM A COMPOUND PROPAGATOR/BACKGROUND FIELD

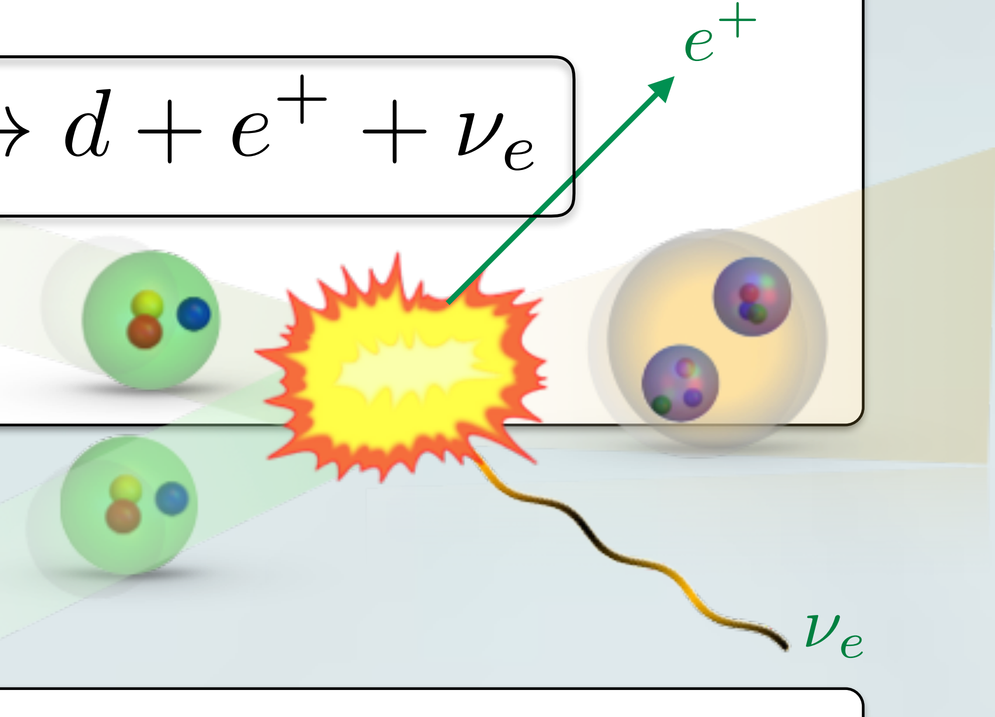


Tiburzi et al (NPLQCD), Phys. Rev. D 96, 054505 (2017).

SINGLE-WEAK PROCESSES

$$^{3}\mathrm{H} \to {}^{3}\mathrm{He} + e^{-} + \overline{\nu}_e$$

$$p + p \to d + e^{+} + \nu_e$$

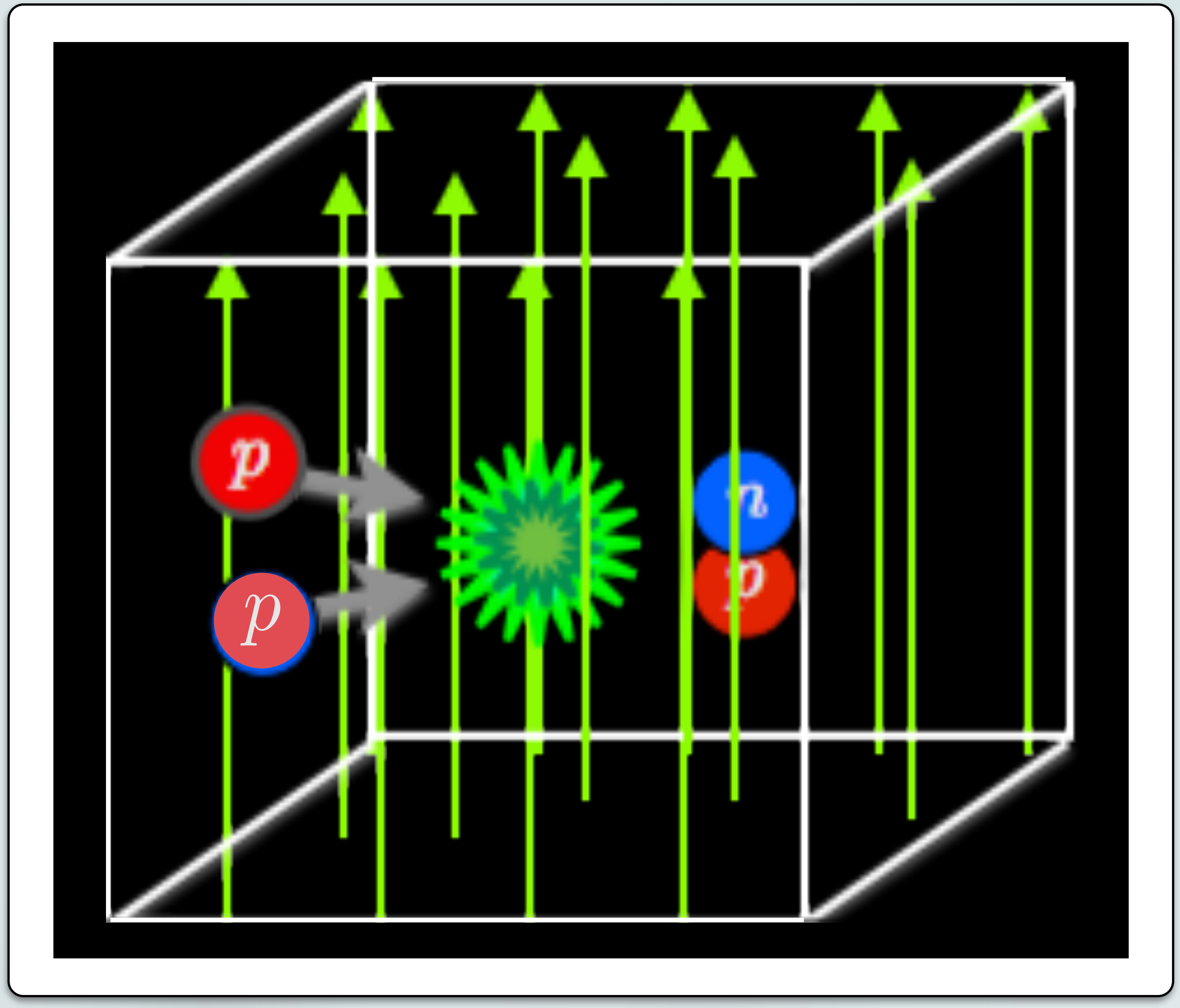


Savage et al (NPLQCD), Phys.Rev.Lett.119,062002(2017).

PRIMARY REACTION IN THE *pp* CHAIN THAT POWERS SUN.
UNCERTAINTIES LARGE AT LOW INCIDENT VELOCITIES RELEVANT TO ENERGY PRODUCTION IN SUN.

Savage et al (NPLQCD), Phys.Rev.Lett.119,062002(2017).

FIRST-ORDER RESPONSE TO AN AXIAL BACKGROUND FIELD

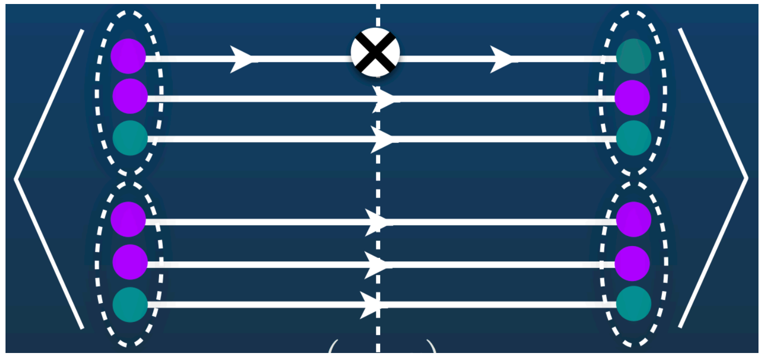


Savage et al (NPLQCD), Phys.Rev.Lett.119,062002(2017).

FIRST-ORDER RESPONSE TO AN AXIAL BACKGROUND FIELD

$$C^{(^3S_1,^1S_0)}_{\lambda_u;\lambda_d=0}(t) = \lambda_u \sum_{t_1=0}^{t} \sum_{\boldsymbol{x},\boldsymbol{y}} \langle 0|\chi_{^3S_1}(\boldsymbol{x},t) J_3^{(u)}(\boldsymbol{y},t_1) \chi^\dagger_{^1S_0}(0)|0\rangle + c_2\lambda_u^2 + c_3\lambda_u^3$$

$$C^{(^3S_1,^1S_0)}_{\lambda_u=0;\lambda_d}(t) = \lambda_d \sum_{t_1=0}^{t} \sum_{\boldsymbol{x},\boldsymbol{y}} \langle 0|\chi_{^3S_1}(\boldsymbol{x},t) J_3^{(d)}(\boldsymbol{y},t_1) \chi^\dagger_{^1S_0}(0)|0\rangle + b_2\lambda_d^2 + b_3\lambda_d^3,$$



DINEUTRON-DEUTERON MASS DIFFERENCE

GROUND-STATE MATRIX ELEMENT

$$C^{(^3S_1,^1S_0)}_{\lambda_u;\lambda_d=0}(t)\Big|_{\mathcal{O}(\lambda_u)} = Z_d Z^\dagger_{np(^1S_0)} e^{-\overline{E}t}\left[\sinh\left(\frac{\Delta t}{2}\right)\left\{\frac{\langle d|\tilde{J}_3^{(u)}|np(^1S_0)\rangle}{a\Delta/2} + c_-\right\} + \cosh\left(\frac{\Delta t}{2}\right) c_+ + \mathcal{O}(e^{-\tilde{\delta}t})\right]$$

OVERLAP FACTORS

DEPEND ON EXCITED-STATES

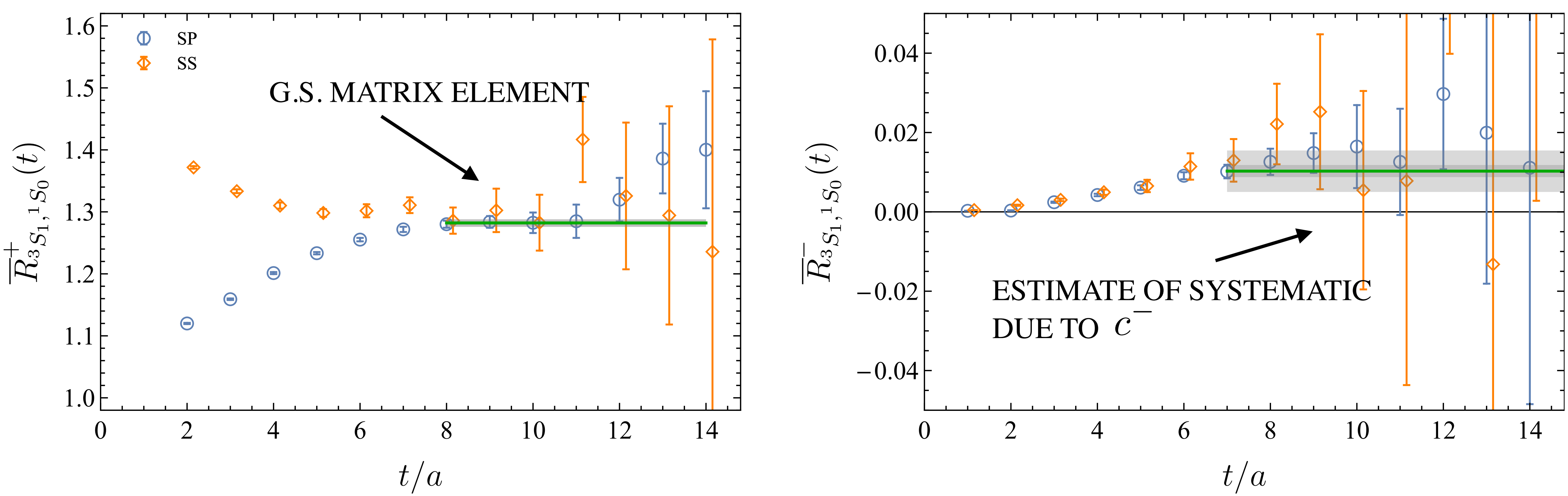
SINCE $a\Delta < 0.01$, WE ARE ABLE TO FIT THE GROUND-STATE ME UP TO A SMALL SYSTEMATICS.

Savage et al (NPLQCD), Phys.Rev.Lett.119,062002(2017).

MATRIX ELEMENT FROM QCD

$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$

Savage et al (NPLQCD), arXiv:1610.04545.



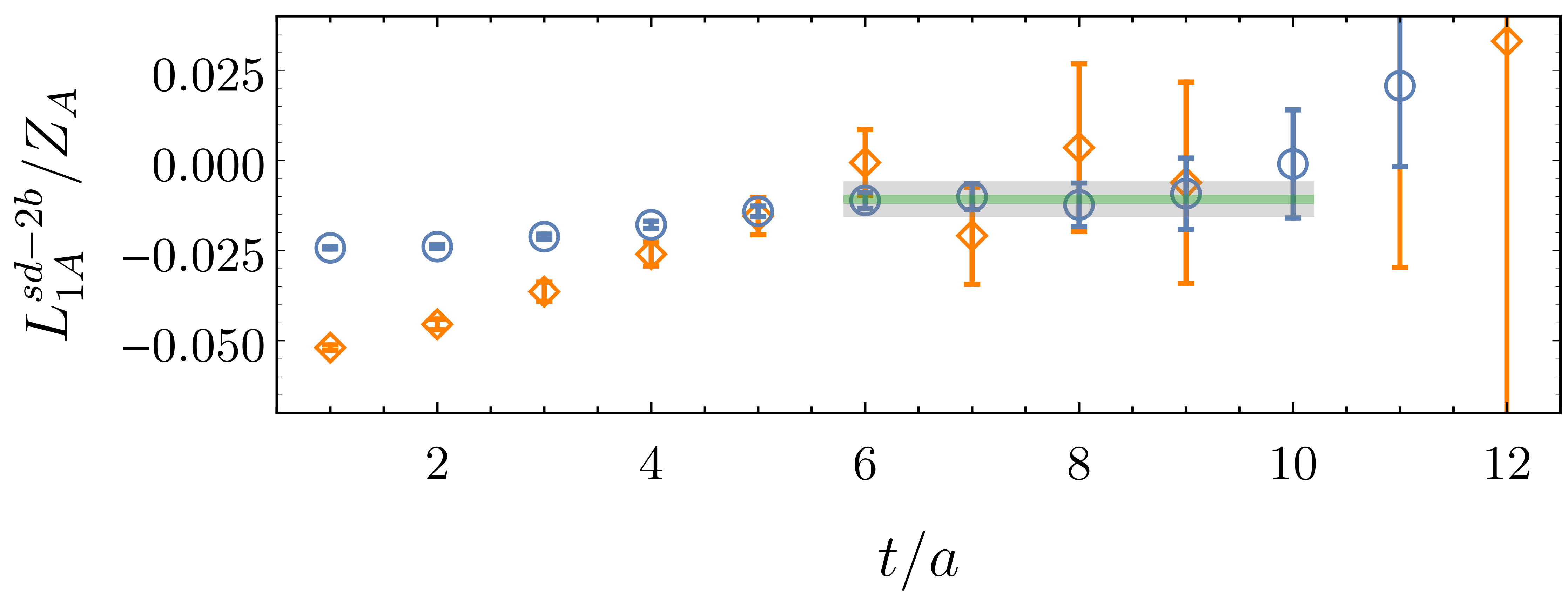
AVERAGE AND DIFFERENCE OF CORRELATOR AND TIME-REVERSED CORREALTOR

$$R^{\pm}_{^3S_1,^1S_0}(t) = \frac{1}{2}\frac{C^{\pm}_{\lambda_u;\lambda_d=0}(t)\Big|_{\mathcal{O}(\lambda_u)} - C^{\pm}_{\lambda_u=0;\lambda_d}(t)\Big|_{\mathcal{O}(\lambda_d)}}{\sqrt{C^{(^3S_1)}_{0;0}(t)\,C^{(^1S_0)}_{0;0}(t)}}$$

MATRIX ELEMENT FROM QCD

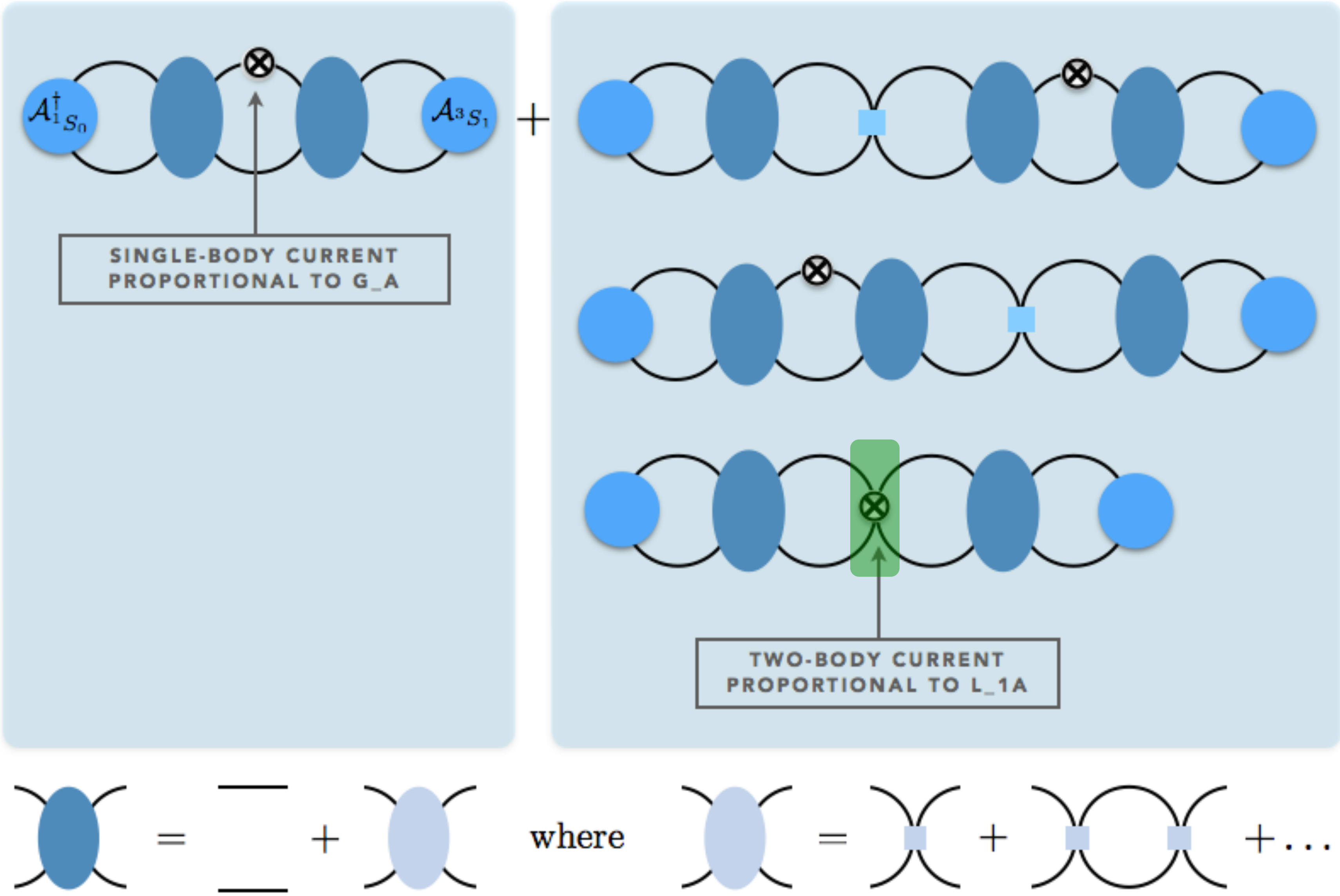
$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$

Savage et al (NPLQCD), arXiv:1610.04545.



$$L_{1,A}^{sd-2b} \equiv \frac{|\langle pp|A_3^+|d\rangle| - g_A}{Z_A} = -0.011(01)(15)$$

MATRIX ELEMENT FROM EFT



Detmold and Savage, Nucl.Phys. A743 (2004) 170.
Briceno and ZD, Phys. Rev. D 88, 094507 (2013).

Chen et al, Phys.Rev. C67 (2003) 025801.

$$\left|\langle d; j\left|A_k^-\right|pp\rangle\right| \equiv g_A C_\eta \sqrt{\frac{32\pi}{\gamma^3}}\,\Lambda(p)\,\delta_{jk}$$

$$\Lambda(0) = \frac{1}{\sqrt{1-\gamma\rho}}\{e^\chi - \gamma a_{pp}[1-\chi e^\chi \Gamma(0,\chi)] + \frac{1}{2}\gamma^2 a_{pp}\sqrt{r_1\rho}\} - \frac{1}{2g_A}\gamma a_{pp}\sqrt{1-\gamma\rho}\; L_{1,A}^{sd-2b}$$

TWO-NUCLEON SHORT-DISTANCE COUPLING

FROM TRITON LIFETIME:

$$L_{1,A} \approx 2.0(2.4)\ \mathrm{fm}^3 \quad @ \quad \mu = m_\pi^{\mathrm{phys.}} = 140\ \mathrm{MeV}$$

De-Leon, Platter and Gazit, arXiv:1611.10004 (2016).

THIS WORK:

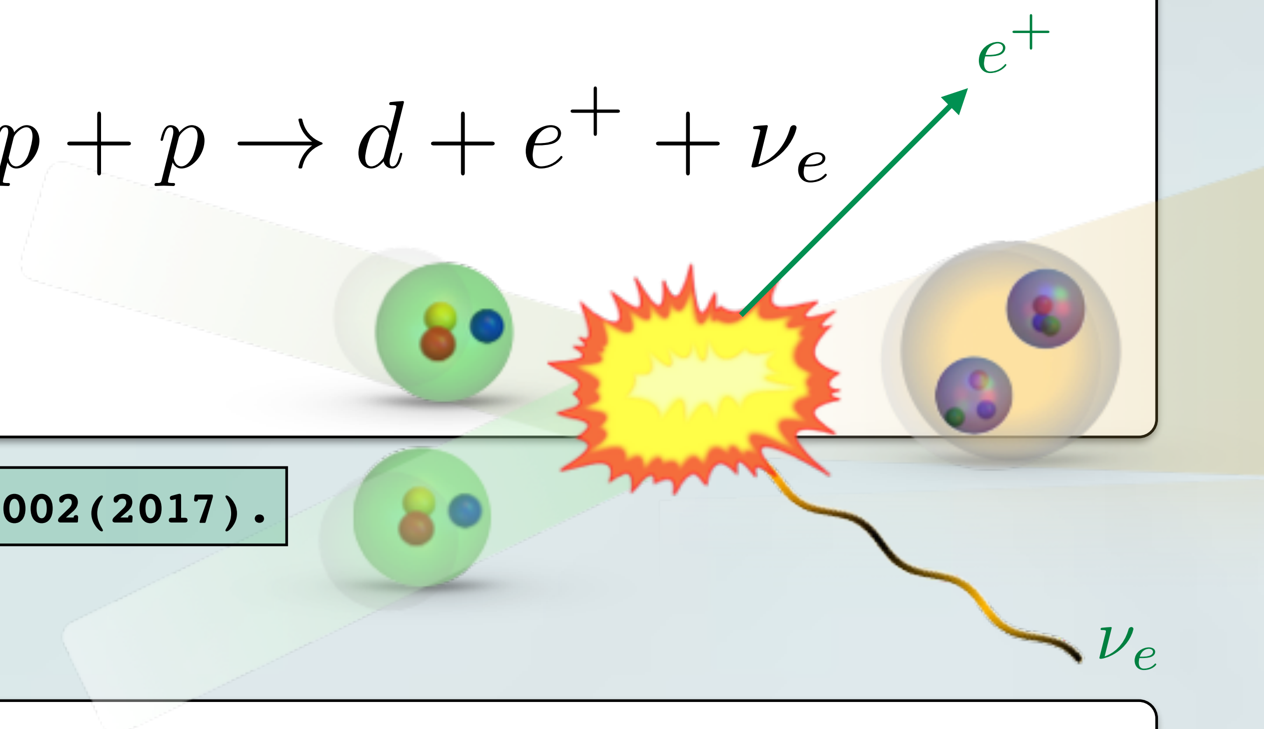
$$L_{1,A} \approx 3.9(0.2)(1.0)(0.4)(0.9)\ \mathrm{fm}^3 \quad @ \quad \mu = m_\pi^{\mathrm{phys.}} = 140\ \mathrm{MeV}$$

Savage et al (NPLQCD), Phys.Rev.Lett.119,062002(2017).

SINGLE-WEAK PROCESSES

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \overline{\nu}_e$$

$$p + p \rightarrow d + e^+ + \nu_e$$



Savage et al (NPLQCD), Phys.Rev.Lett.119,062002(2017).

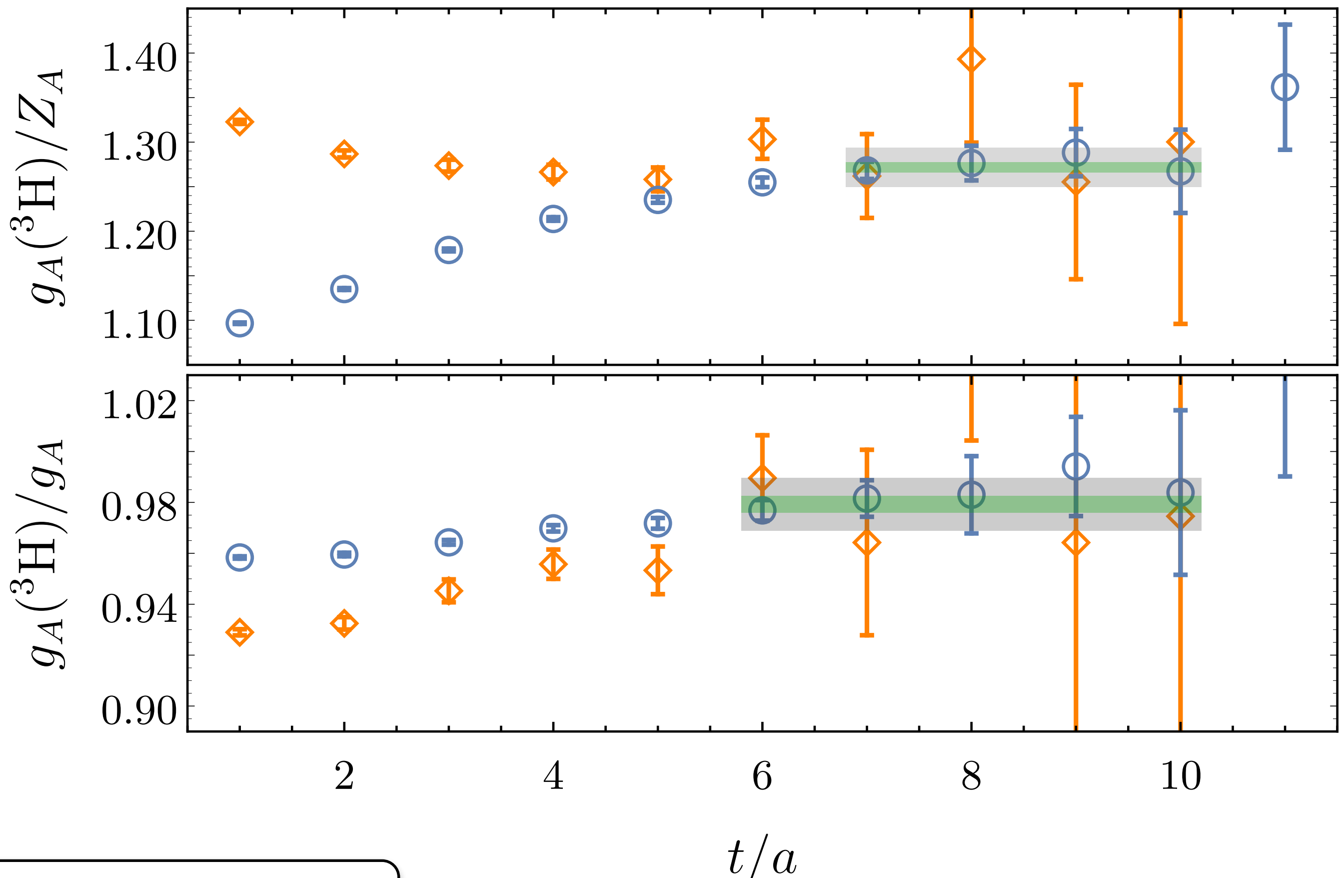
A SUPER-ALLOWED PROCESS, PROVIDES CONSTRAINTS ON THE ANTI-NEUTRINO MASS. THEORETICAL UNCERTAINTIES ARISE FROM GAMOV-TELLER MATRIX ELEMENTS (POOR CONSTRAINTS ON L_1A OF PIONLESS EFT).

Savage et al (NPLQCD), Phys.Rev.Lett.119,062002(2017).

MATRIX ELEMENT FROM QCD

$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$

AXIAL CHARGE OF THE TRITON



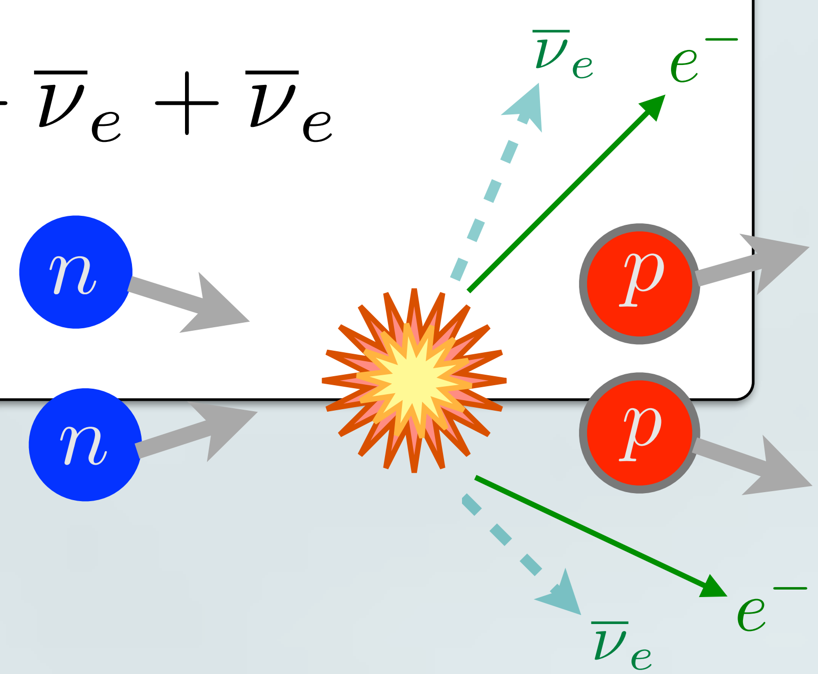
$$\langle {}^3\text{He}|\bar{q}\gamma_k\gamma_5\tau^+ q|{}^3\text{H}\rangle = \bar{u}\gamma_k\gamma_5\tau^+ u\ g_A \langle \mathbf{GT}\rangle$$

$$\frac{g_A(^3\text{H})}{g_A} = 0.979(3)(10)$$

$$\frac{(1+\delta_R)f_V}{K/G_V^2} t_{1/2} = \frac{1}{\langle \mathbf{F}\rangle^2 + f_A/f_V\, g_A^2 \langle \mathbf{GT}\rangle^2}$$

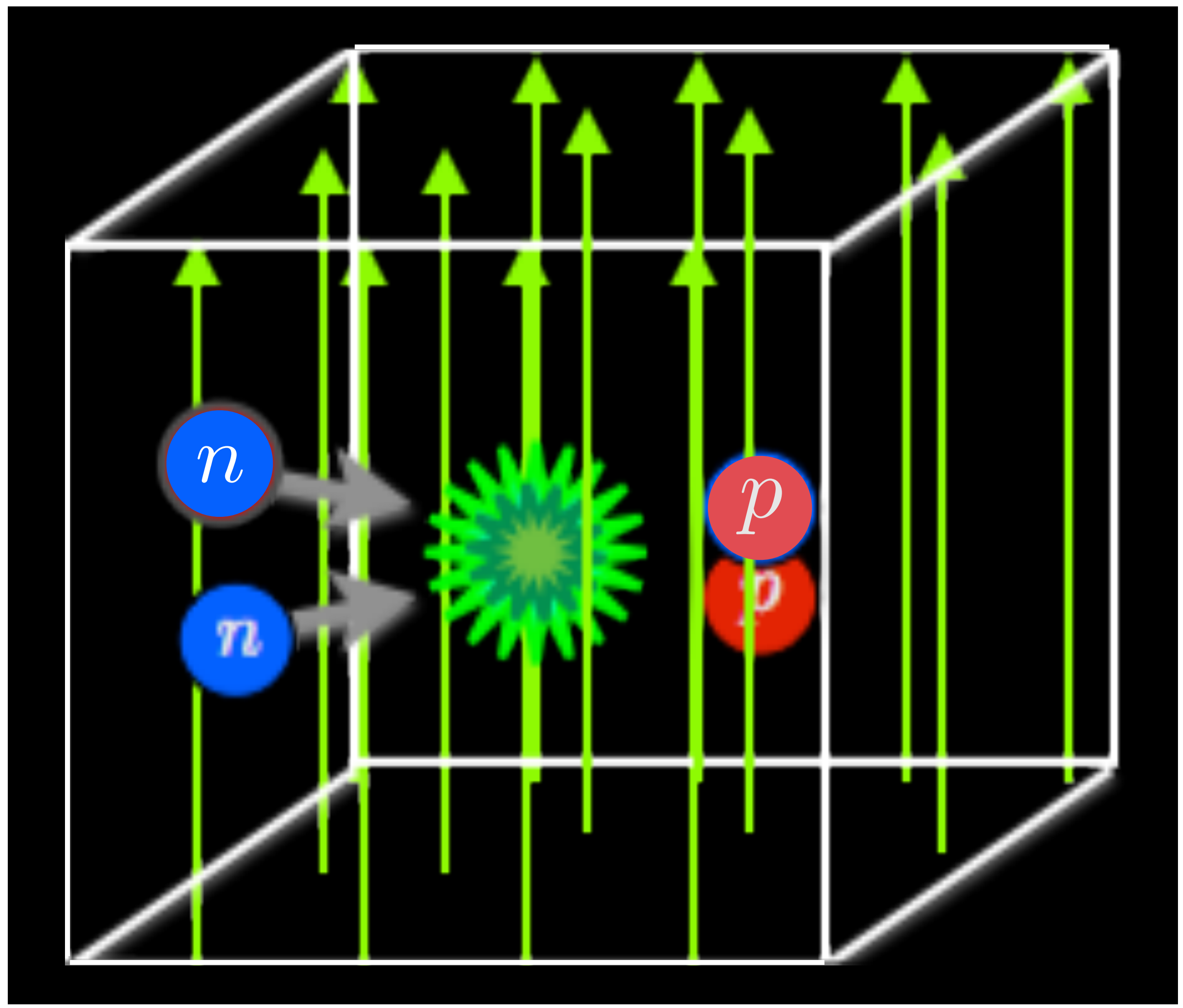
A DOUBLY-WEAK PROCESS

$$n + n \rightarrow p + p + e^- + e^- + \overline{\nu}_e + \overline{\nu}_e$$



Tiburzi et al (NPLQCD),Phys.Rev.D96,054505(2017),
Shanahan et al (NPLQCD),Phys.Rev.Lett.119,062003(2017).

SECOND-ORDER RESPONSE TO AN AXIAL BACKGROUND FIELD



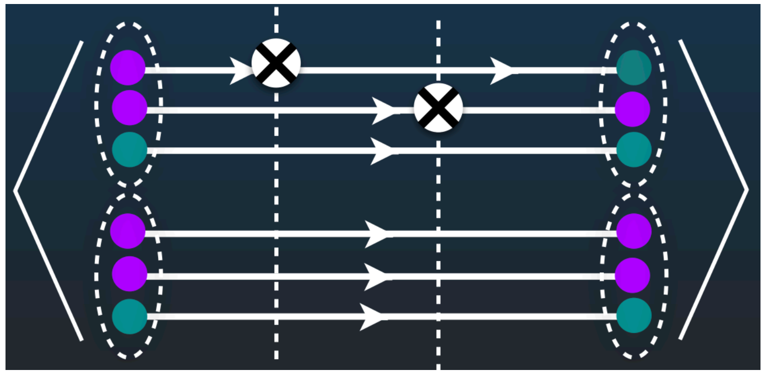
Tiburzi et al (NPLQCD),Phys.Rev.D96,054505(2017),
Shanahan et al (NPLQCD),Phys.Rev.Lett.119,062003(2017).

SECOND-ORDER RESPONSE TO AN AXIAL BACKGROUND FIELD

$$C_{nn\to pp}(t) = 2\, C^{(np(^1S_0))}_{\lambda_u;\lambda_d=0}(t)\Big|_{\mathcal{O}(\lambda_u^2)} - C^{(nn)}_{\lambda_u;\lambda_d=0}(t)\Big|_{\mathcal{O}(\lambda_u^2)} - C^{(nn)}_{\lambda_u=0;\lambda_d}(t)\Big|_{\mathcal{O}(\lambda_d^2)}$$

↓

$$C^{(np(^1S_0))}_{\lambda_u;\lambda_d=0}(t) = \sum_{\boldsymbol{x}} \langle 0|\chi_{np}(\boldsymbol{x},t)\chi^\dagger_{np}(0)|0\rangle + \lambda_u \sum_{\boldsymbol{x},\boldsymbol{y}} \sum_{t_1=0}^{t} \langle 0|\chi_{np}(\boldsymbol{x},t) J_3^{(u)}(\boldsymbol{y},t_1)\chi^\dagger_{np}(0)|0\rangle$$
$$+ \frac{\lambda_u^2}{2} \sum_{\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}} \sum_{t_1=0}^{t} \sum_{t_2=0}^{t} \langle 0|\chi_{np}(\boldsymbol{x},t) J_3^{(u)}(\boldsymbol{y},t_1) J_3^{(u)}(\boldsymbol{z},t_2)\chi^\dagger_{np}(0)|0\rangle + g_3\lambda_u^3,$$



ALREADY CONSTRAINED FROM ZEROTH AND FIRST ORDERS!

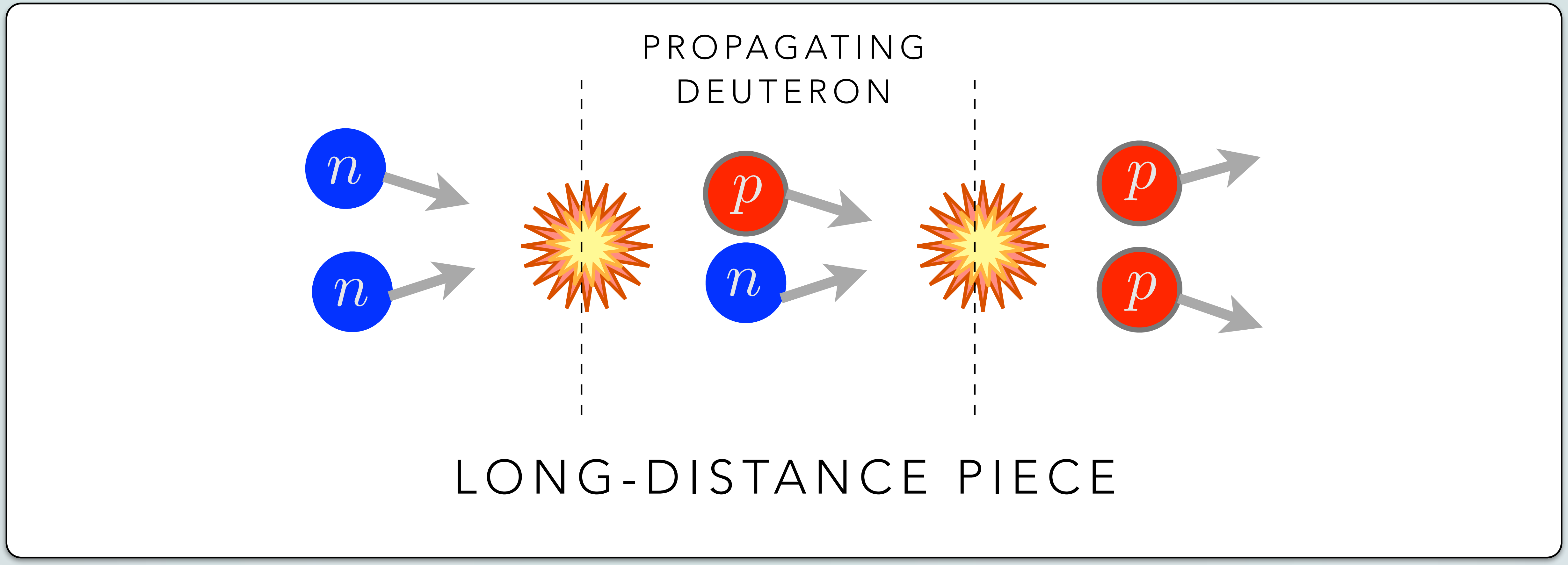
SHORT-DISTANCE G.S. TO G.S. ME

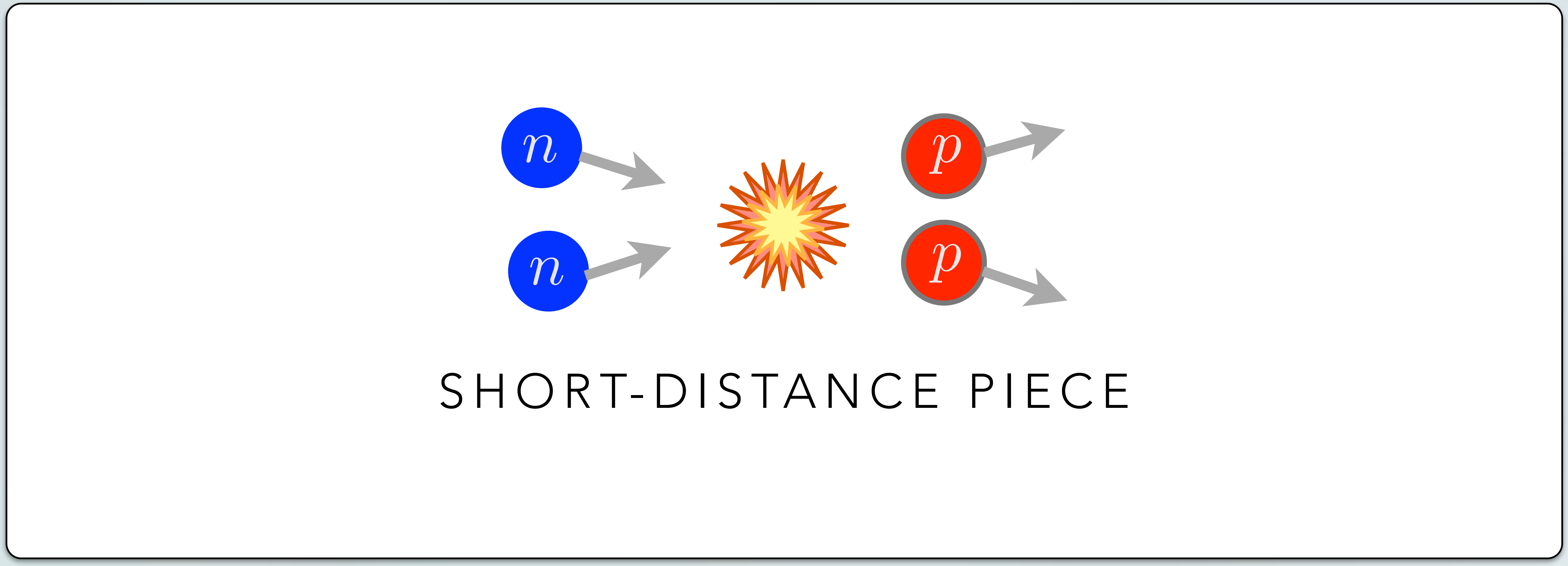
$$a^2\mathcal{R}_{nn\to pp}(t) = \left[-t + \frac{e^{\Delta t}-1}{\Delta}\right] \frac{\langle pp|\tilde{J}_3^+|d\rangle\langle d|\tilde{J}_3^+|nn\rangle}{\Delta} + t \sum_{\mathfrak{l}'\neq d} \frac{\langle pp|\tilde{J}_3^+|\mathfrak{l}'\rangle\langle \mathfrak{l}'|\tilde{J}_3^+|nn\rangle}{\delta_{\mathfrak{l}'}}$$
$$+ c + d\, e^{\Delta t} + \mathcal{O}(e^{-\delta t}, e^{-\delta' t}),$$

STUFF THAT DEPEND ON EXCITED STATES

HERE THE FACT THAT $\Delta \neq 0$ RESCUES US!

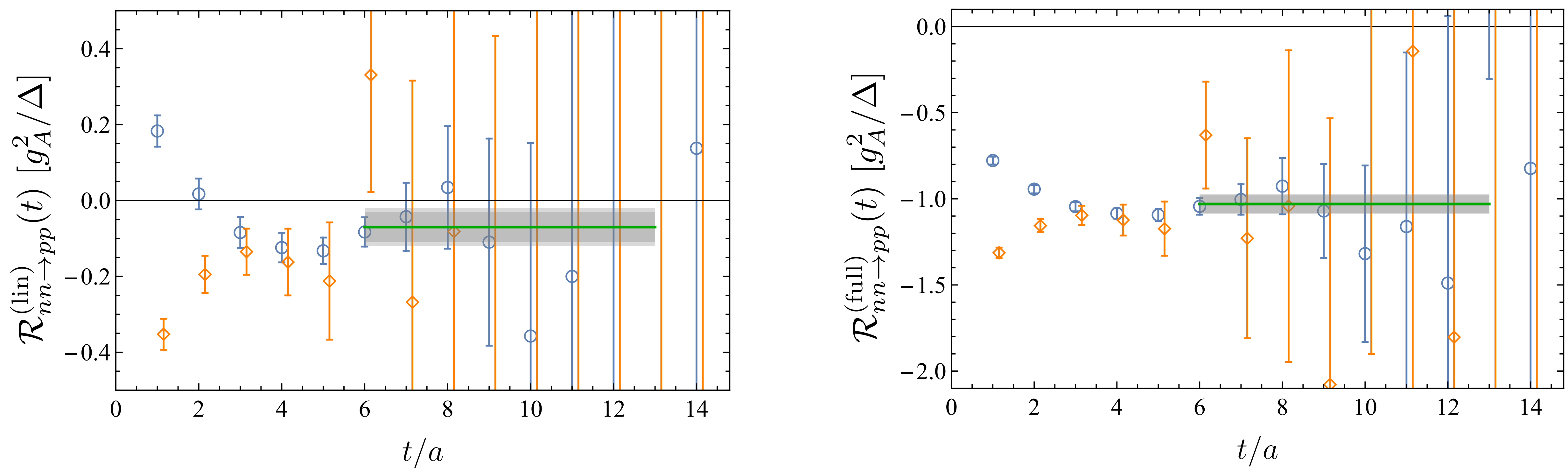
Savage et al (NPLQCD), Phys.Rev.Lett.119,062002(2017).


PROPAGATING
DEUTERON
n
n
p
n
p
p
LONG-DISTANCE PIECE

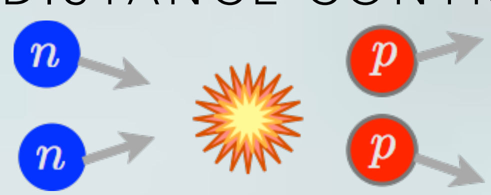

n
n
p
p
SHORT-DISTANCE PIECE

MATRIX ELEMENT FROM QCD

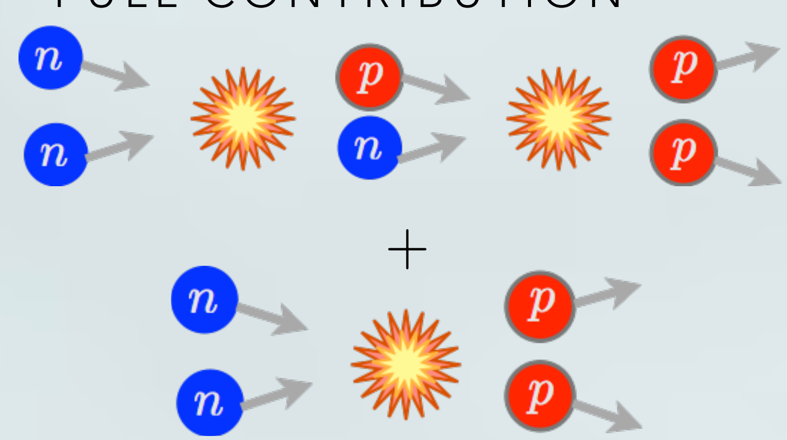
$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$



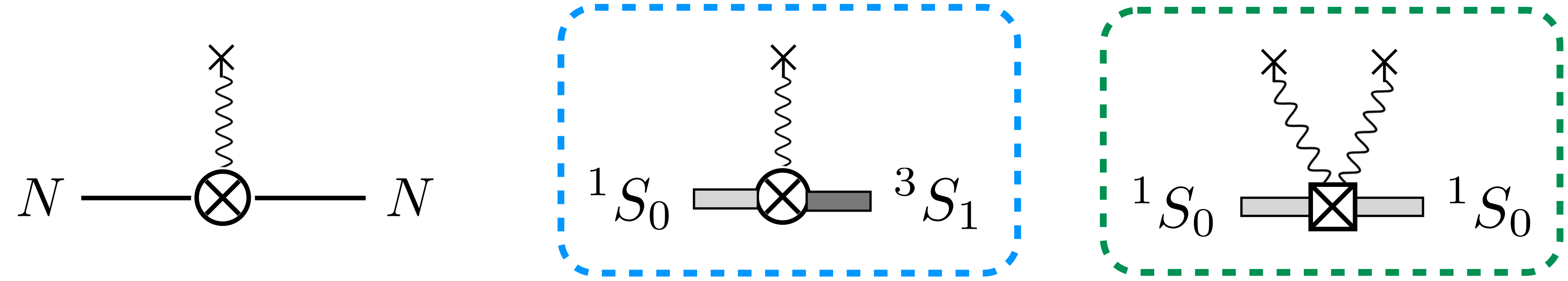
SHORT-DISTANCE CONTRIBUTION

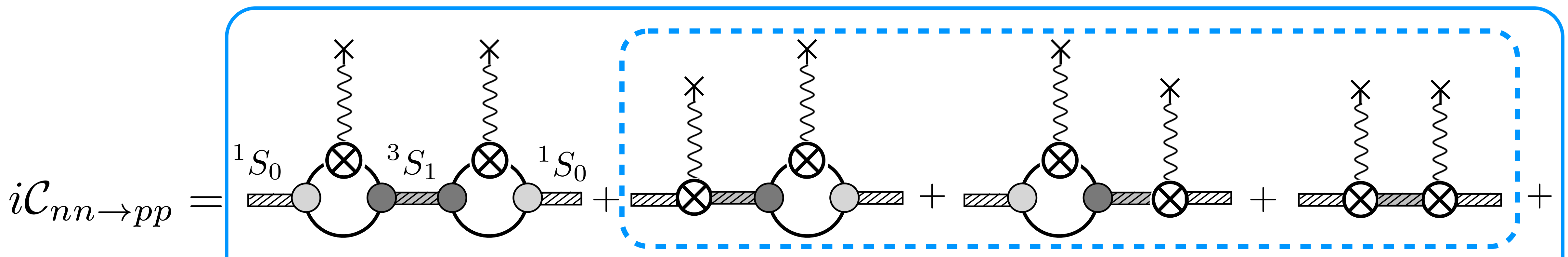


FULL CONTRIBUTION



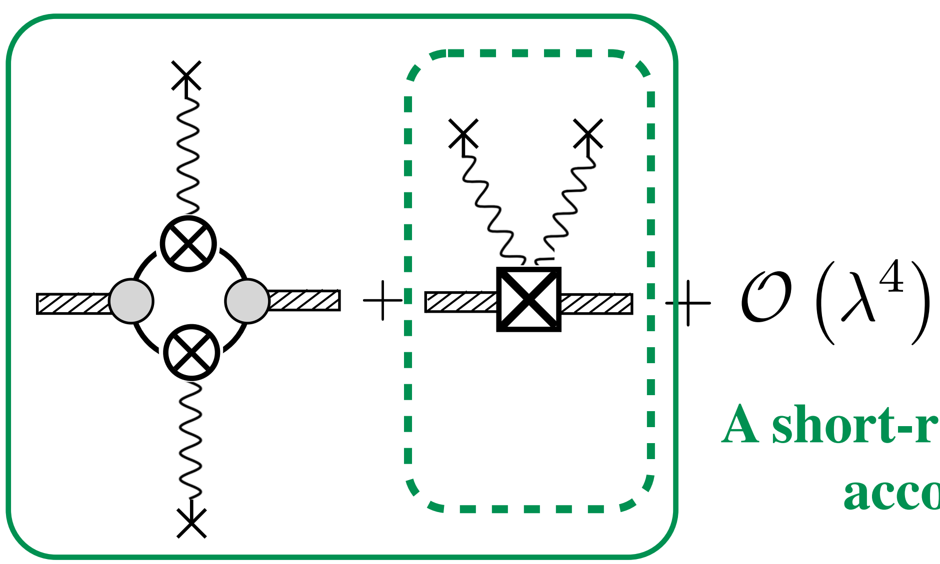
EFT VERTICES AND CORRELATION FUNCTIONS USING DIBARYONS





Quenching of axial charge

Give partly the dominant long-range contribution



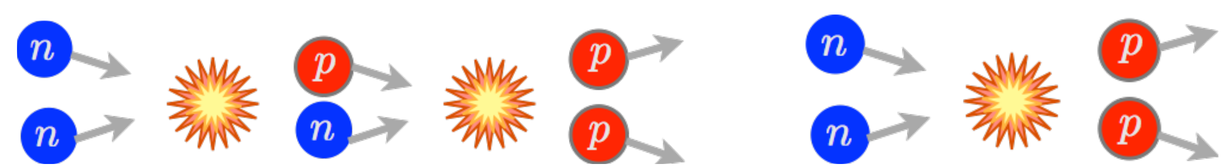
A short-range contribution not accounted for before

EFT CONSTRAINED WITH LQCD.

$$M_{pp\to d} = g_A(1+S) + \mathbb{L}_{1,A}$$

AND

$$M_{nn\to pp} = -\frac{|M_{pp\to d}|^2}{\Delta} + \frac{M g_A^2}{4\gamma_s^2} - \mathbb{H}_{2,S}$$



$$\mathbb{H}_{2,S} = 4.7(1.3)(1.8)\ \mathtt{fm}$$

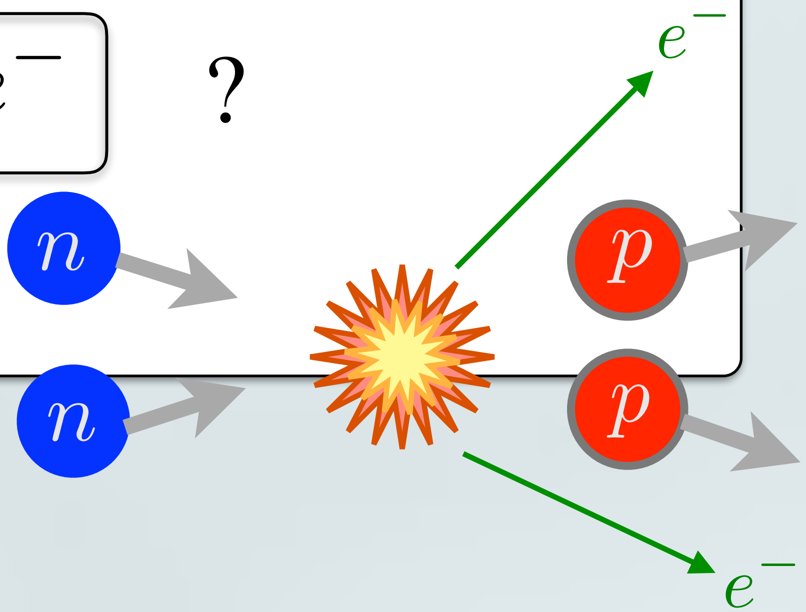
$$@\ \ m_\pi \approx 800\ \mathrm{MeV}$$

LESSON FROM 800 MEV WORLD:

AXIAL POLARIZABILITY COULD BE IMPORTANT. CANNOT BE CONSTRAINED BY SINGLE-BETA DECAY PROCESSES.

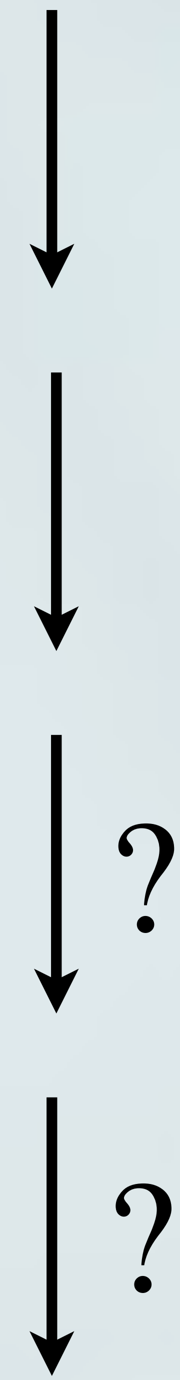
A DOUBLY-WEAK PROCESS

$$n + n \to p + p + e^- + e^-$$?



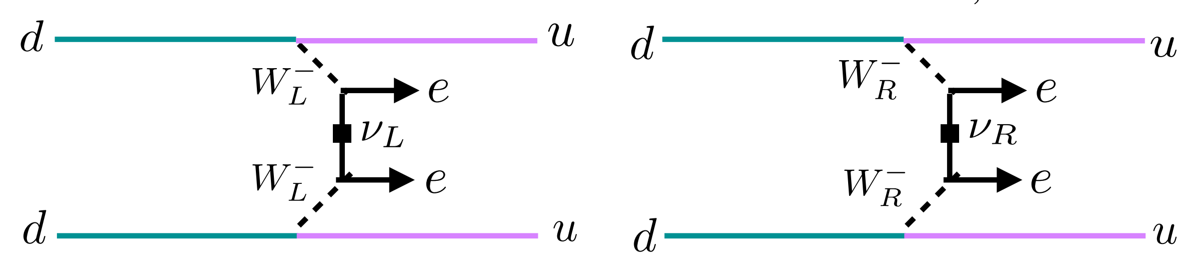
Tiburzi et al (NPLQCD), Phys.Rev.D96,054505(2017),
Shanahan et al (NPLQCD), Phys.Rev.Lett.119,062003(2017).

MATCHING HIGH SCALE TO LOW SCALE



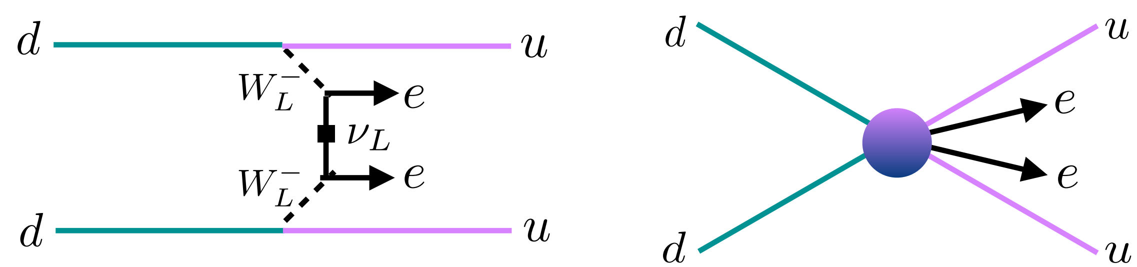
$\Lambda > \text{TeV}$

START WITH YOUR FAVORITE HIGH-SCALE MODEL, E.G.:



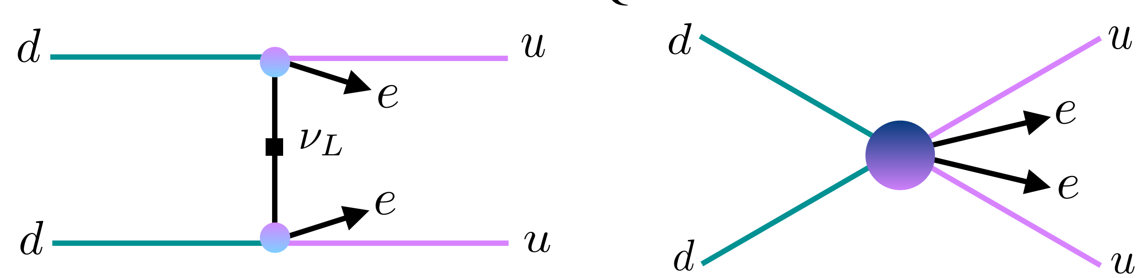
$\Lambda \sim 10^2$ GeV

RUN IT DOWN TO THE SCALE WHERE THE HIGH-SCALE PHYSICS CAN BE INTEGRATED OUT:



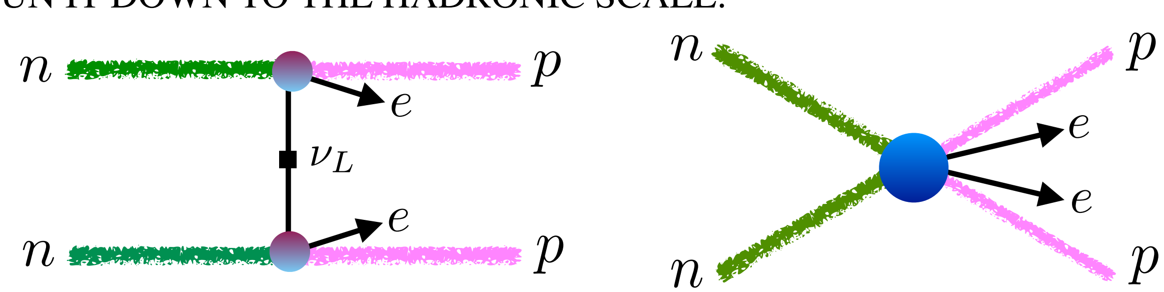
$\Lambda \sim 2$ GeV

RUN IT DOWN TO PERTURBATIVE QUARK-LEVEL MATRIX ELEMENTS:



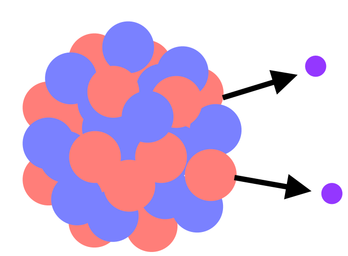
$\Lambda < \text{GeV}$

RUN IT DOWN TO THE HADRONIC SCALE:



$\Lambda < \text{MeV}$

USE NUCLEAR MANY-BODY CALCULATION TO MATCH IT TO NUCLEAR MATRIX ELEMENTS:



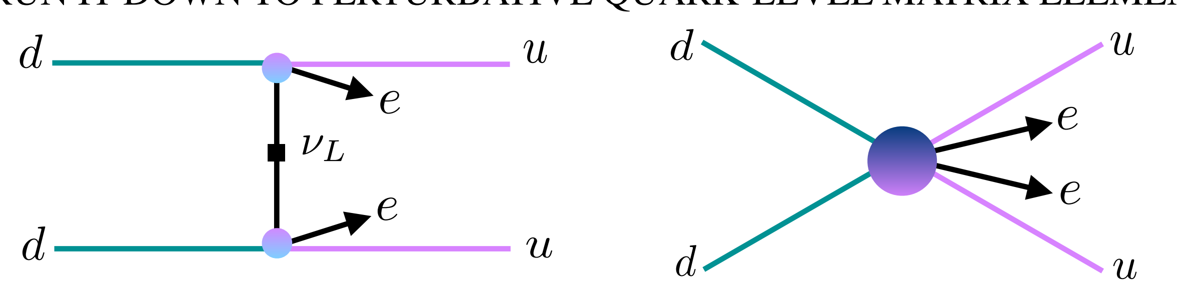
MATCHING HIGH SCALE TO LOW SCALE

$\Lambda > \text{TeV}$ — START WITH YOUR FAVORITE HIGH-SCALE MODEL, E.G.:

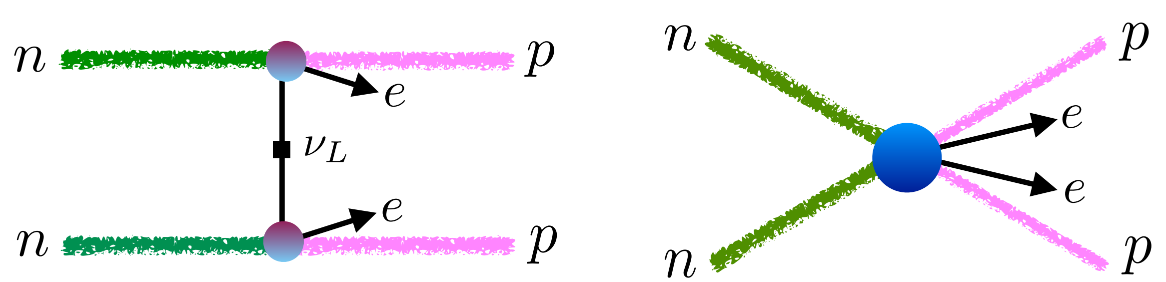
Savage, Phys. Rev. C59, 2293 (1999), arXiv:nucl-th/9811087 [nucl-th].
Prezeau, Ramsey-Musolf, Vogel Phys.Rev. D68 03401 (2003).
Cirigliano, Dekens, Graesser and Mereghetti, arXiv:1701.01443 [hep-ph].
Nicholson, Berkowitz, Chang, Clark, Joo, Kurth, Rinaldi, Tiburzi, Vranas and Walker-Loud, arXiv:1608.04793 [hep-lat]

RUN IT DOWN TO THE SCALE WHERE THE HIGH-SCALE PHYSICS CAN BE INTEGRATED OUT:

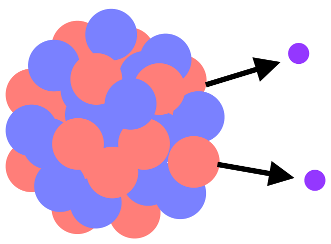
$\Lambda \sim 2$ GeV — RUN IT DOWN TO PERTURBATIVE QUARK-LEVEL MATRIX ELEMENTS:

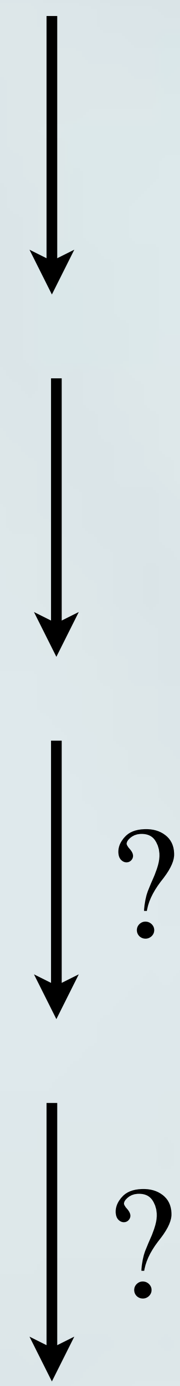


$\Lambda <$ GeV — RUN IT DOWN TO THE HADRONIC SCALE:



$\Lambda <$ MeV — USE NUCLEAR MANY-BODY CALCULATION TO MATCH IT TO NUCLEAR MATRIX ELEMENTS:






NPLQCD

THANK YOU