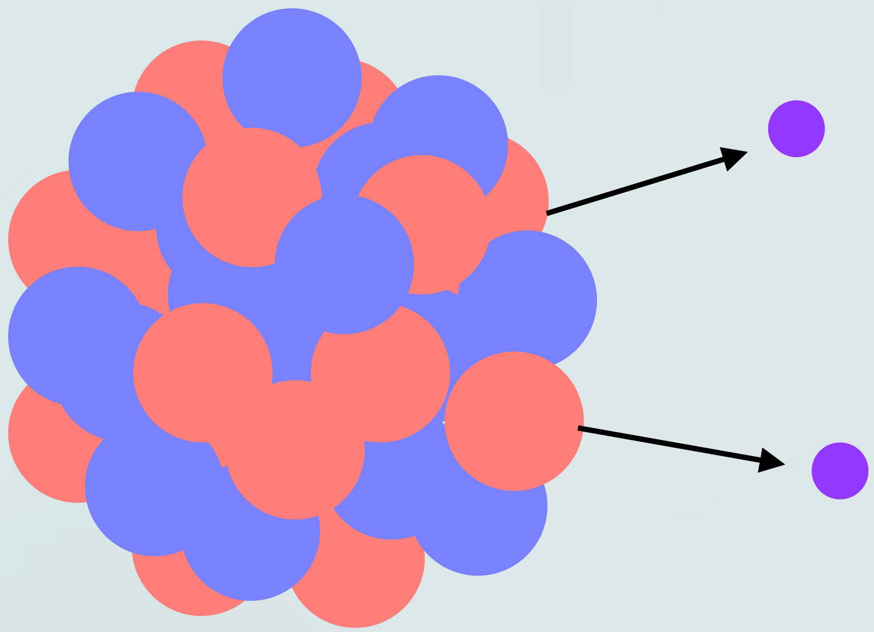
LATTICE QCD FOR NEUTRINOLESS DOUBLE-BETA DECAY

ZOHREH DAVOUDI
UNIVERSITY OF MARYLAND AND RIKEN FELLOW

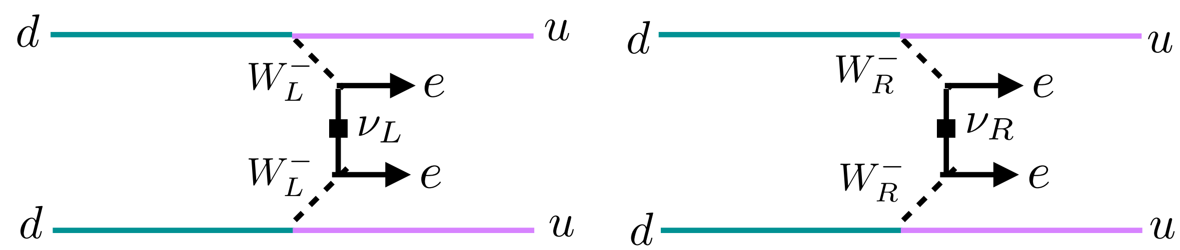


PROGRESS AND CHALLENGES IN NEUTRINOLESS DOUBLE BETA DECAY
ECT*, Trento, Italy, July 15-19, 2019

THE ROADMAP FOR *0vBB* DECAY

$\Lambda > \mathrm{TeV}$

START WITH A GIVEN HIGH-SCALE MODEL, e.g., LEFT-RIGHT SYMMETRIC MODEL:



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

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$\Lambda > \mathrm{TeV}$

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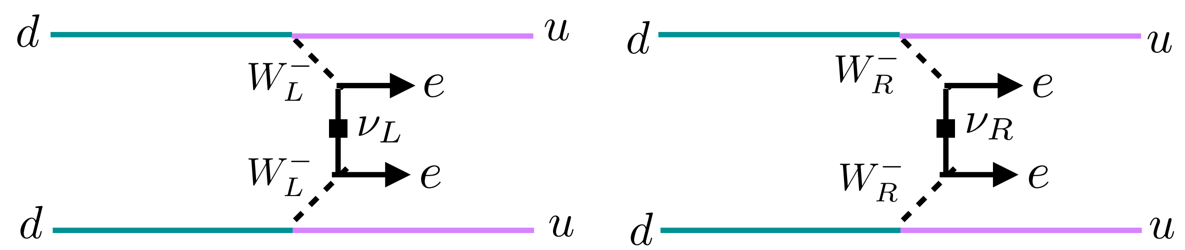

$\Lambda \sim 10^2\ \mathrm{GeV}$

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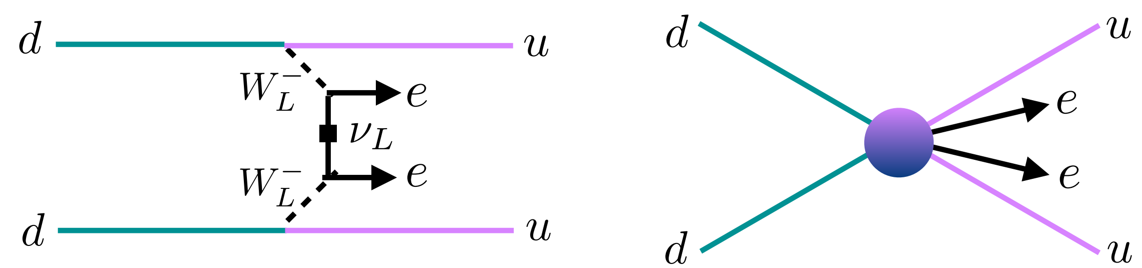

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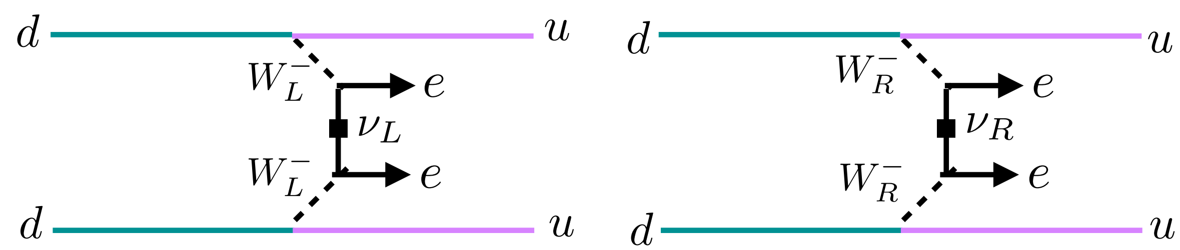

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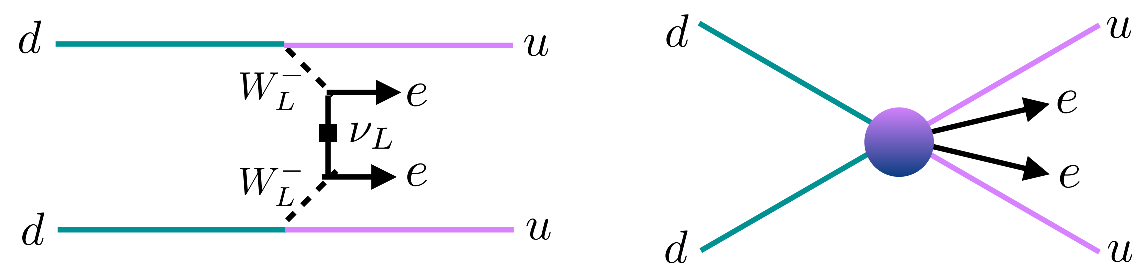
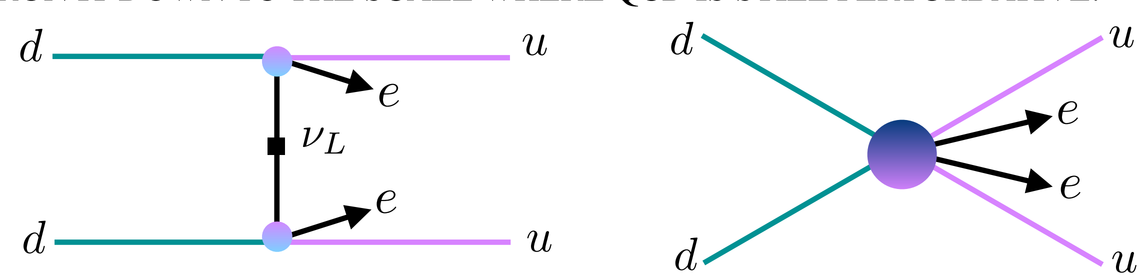


$\Lambda \sim 2\ \text{GeV}$

RUN IT DOWN TO THE SCALE WHERE QCD IS STILL PERTURBATIVE:



THE ROADMAP FOR *0vBB* DECAY

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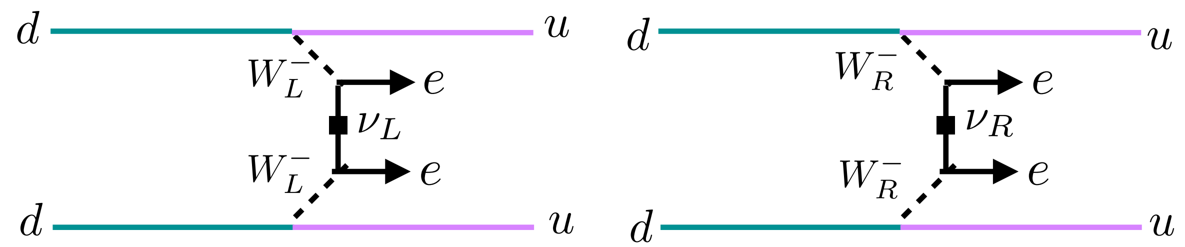

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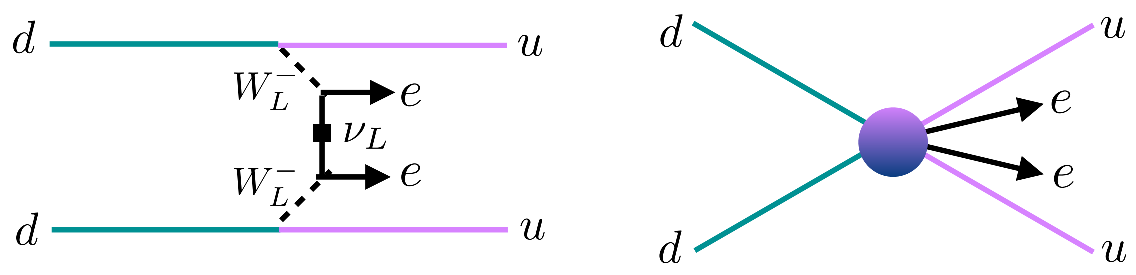

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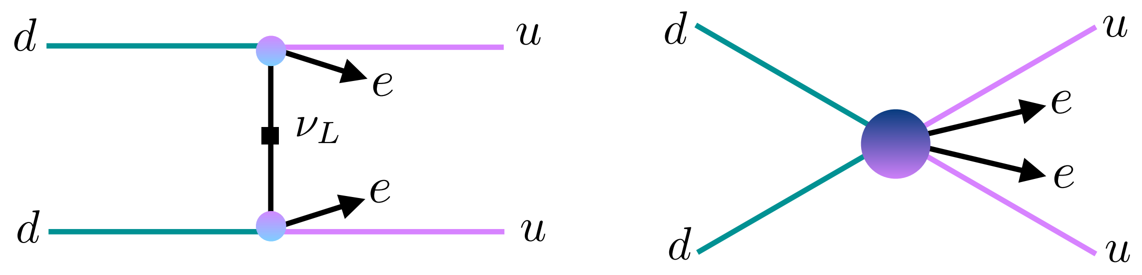
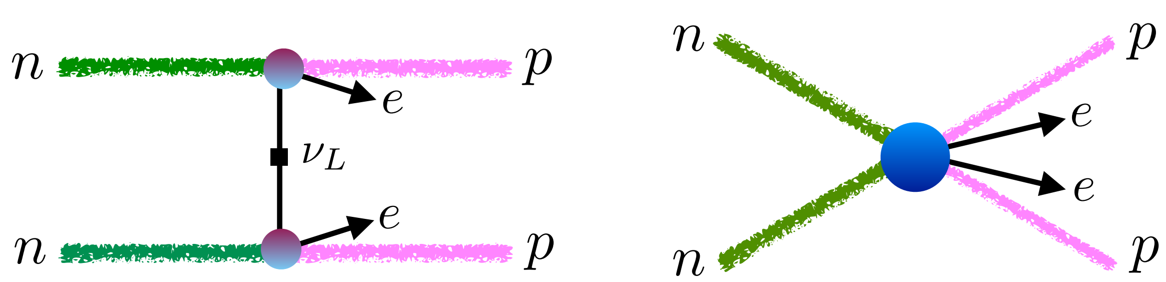


$\Lambda <$ GeV

RUN IT DOWN TO HADRONIC SCALE:



THE ROADMAP FOR *0vBB* DECAY

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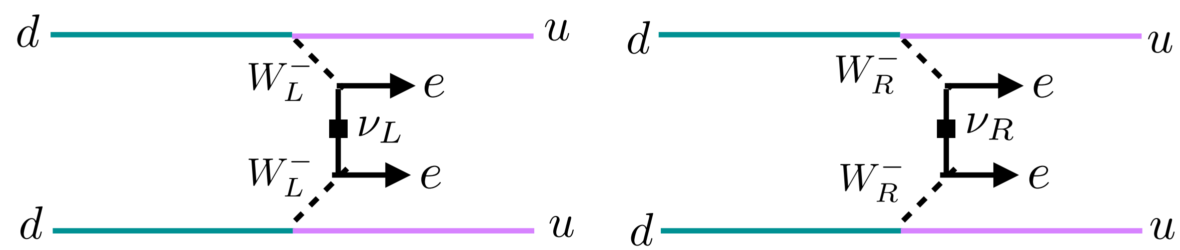

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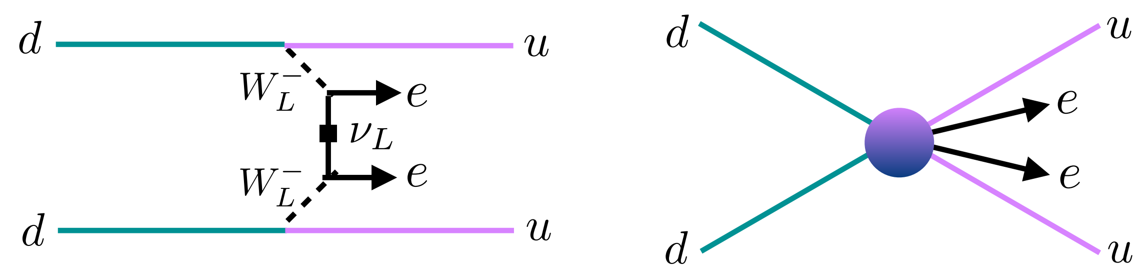

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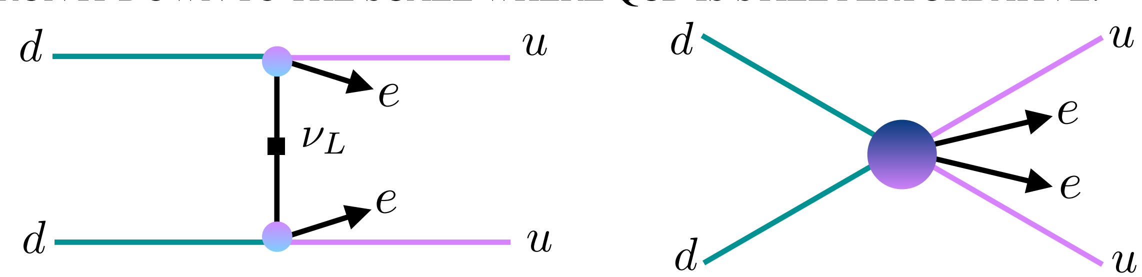
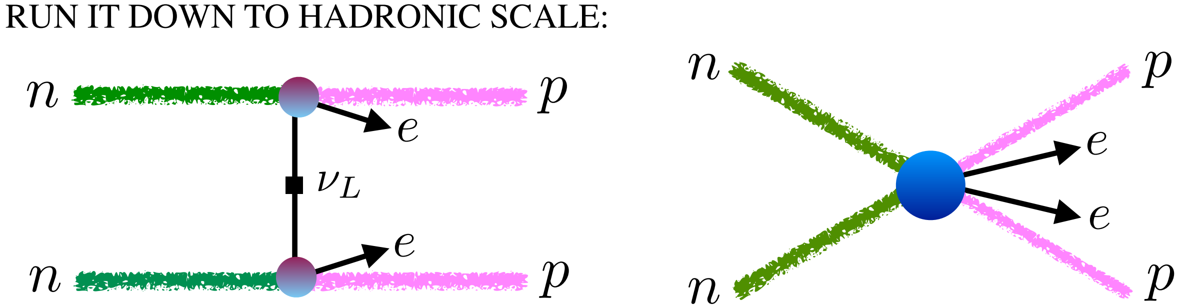


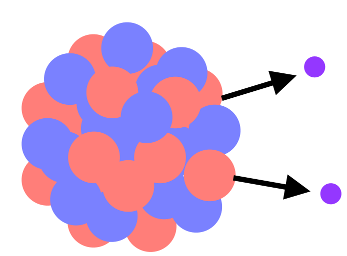
$\Lambda < \text{GeV}$

RUN IT DOWN TO HADRONIC SCALE:

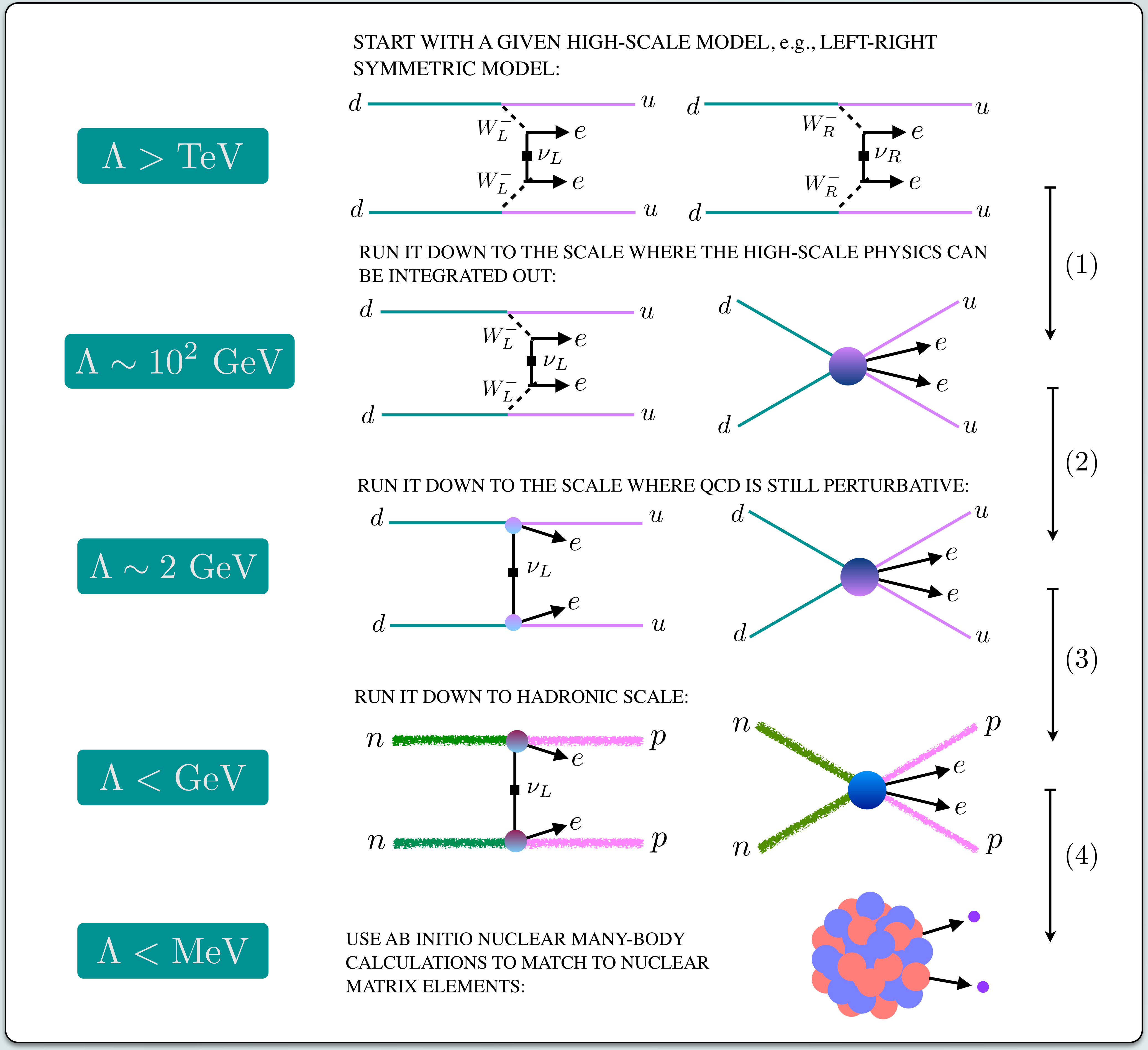


$\Lambda < \text{MeV}$

USE AB INITIO NUCLEAR MANY-BODY CALCULATIONS TO MATCH TO NUCLEAR MATRIX ELEMENTS:



THE ROADMAP FOR *0vBB* DECAY



NON-LOCAL MATRIX ELEMENTS OF TWO DIMENSION-6 FOUR-FERMION SM WEAK CURRENTS

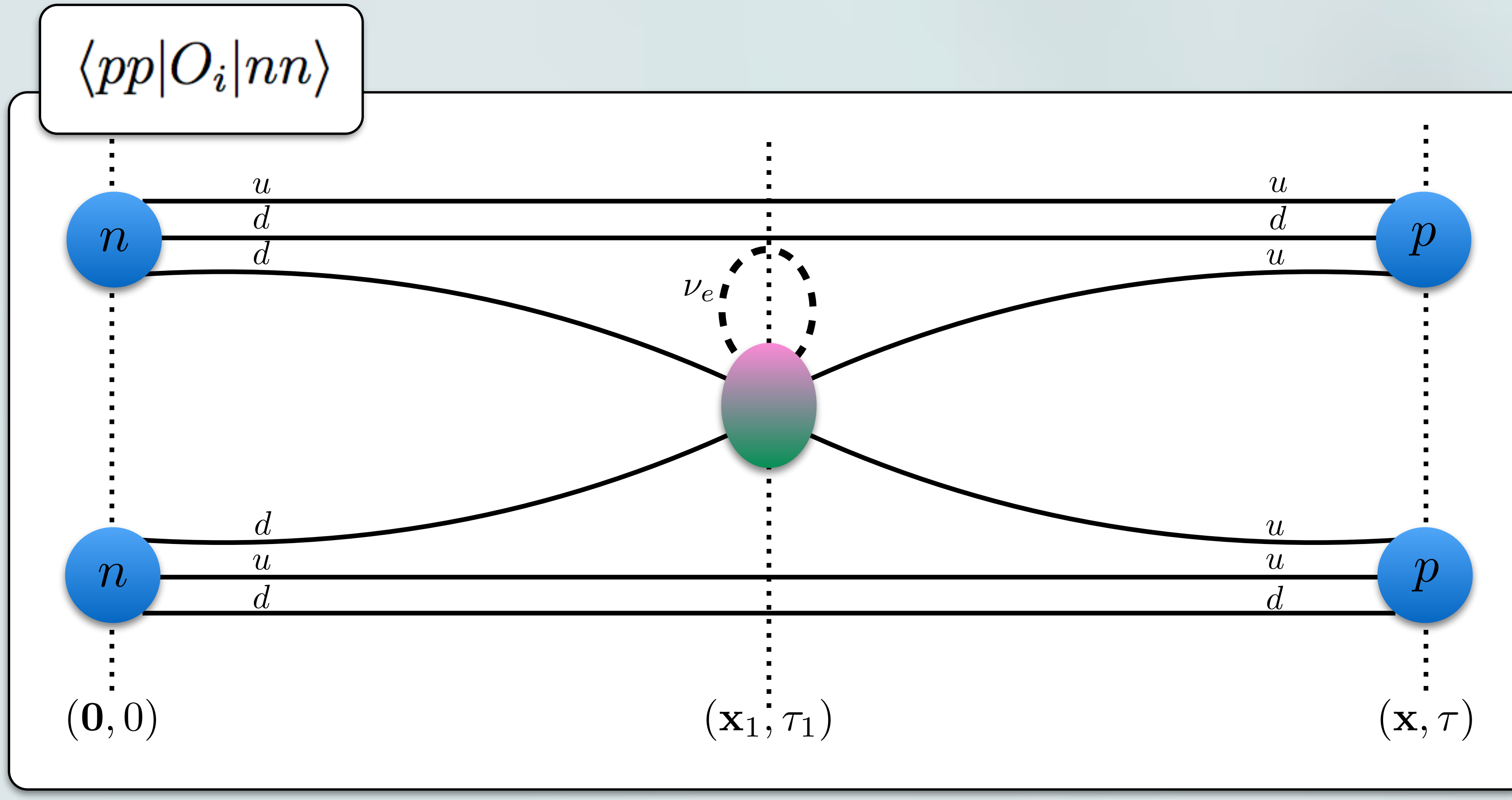
Constrains more reliably the limits on the effective Majorana neutrino mass (a combination of masses and mixing angles) in the minimal extension of SM.

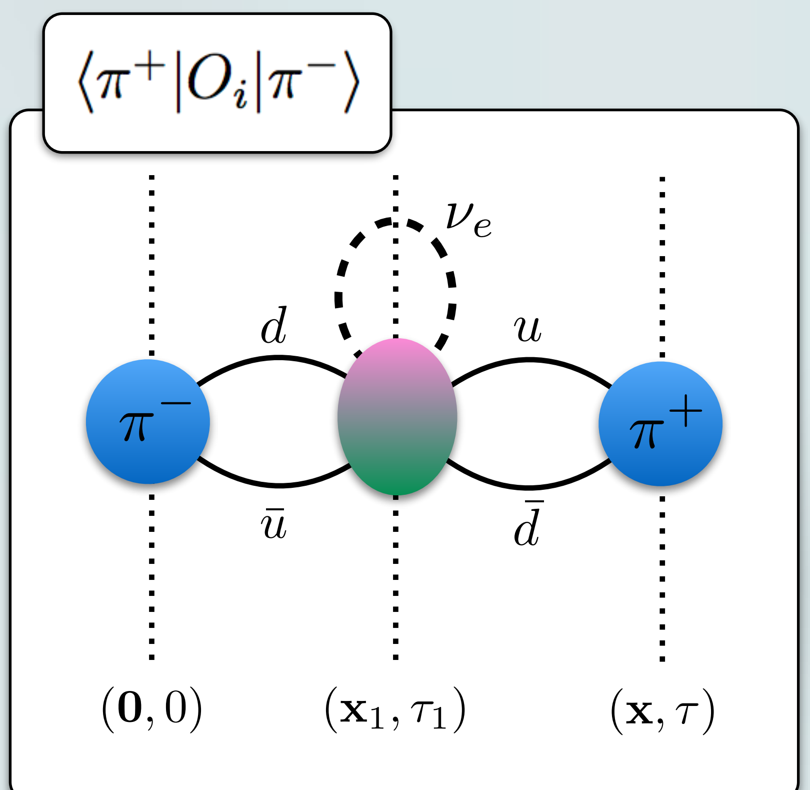
LOCAL MATRIX ELEMENTS OF DIMENSION-9 SIX-FERMION OPERATORS

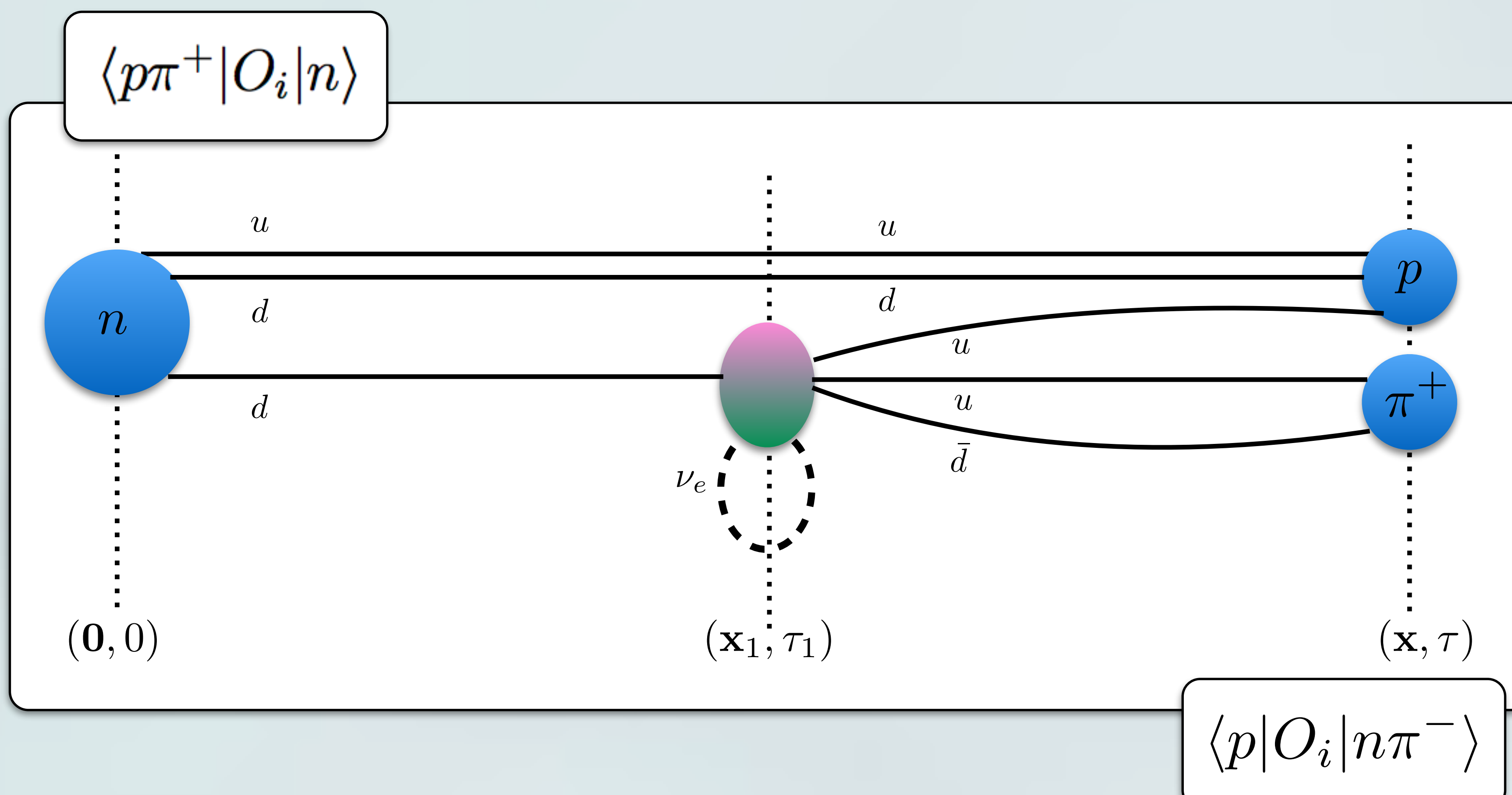
Helps to find out if predictions of high-scale models are within the reach of current and future experimental limits. Will eventually constrain such models more reliably.

LOCAL MATRIX ELEMENTS OF DIMENSION-9 SIX-FERMION OPERATORS

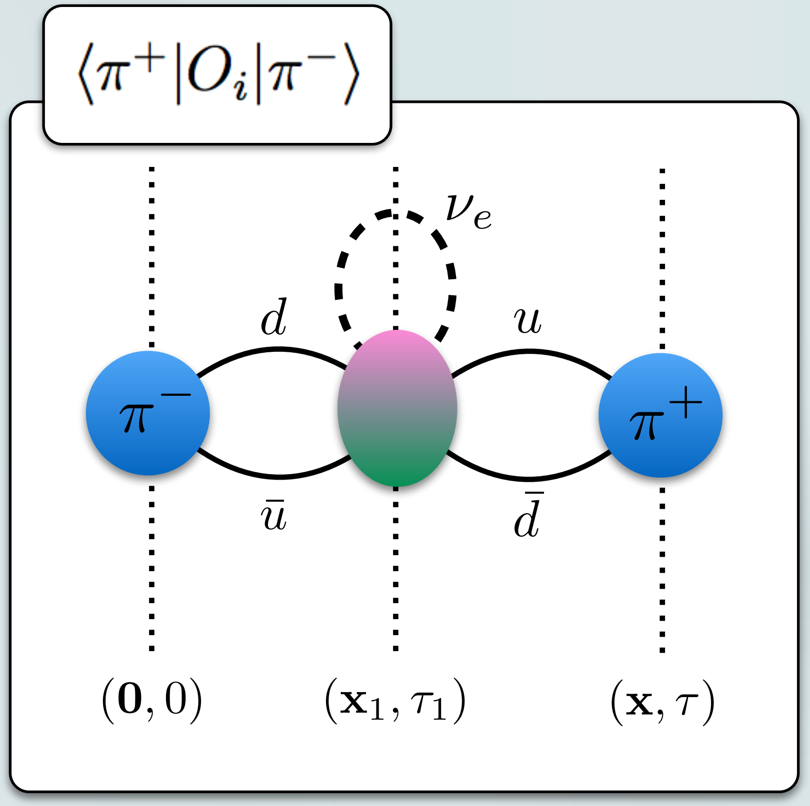
MATRIX ELEMENTS OF **LOCAL** FOUR-QUARK OPERATORS







MATRIX ELEMENTS OF **LOCAL** FOUR-QUARK OPERATORS



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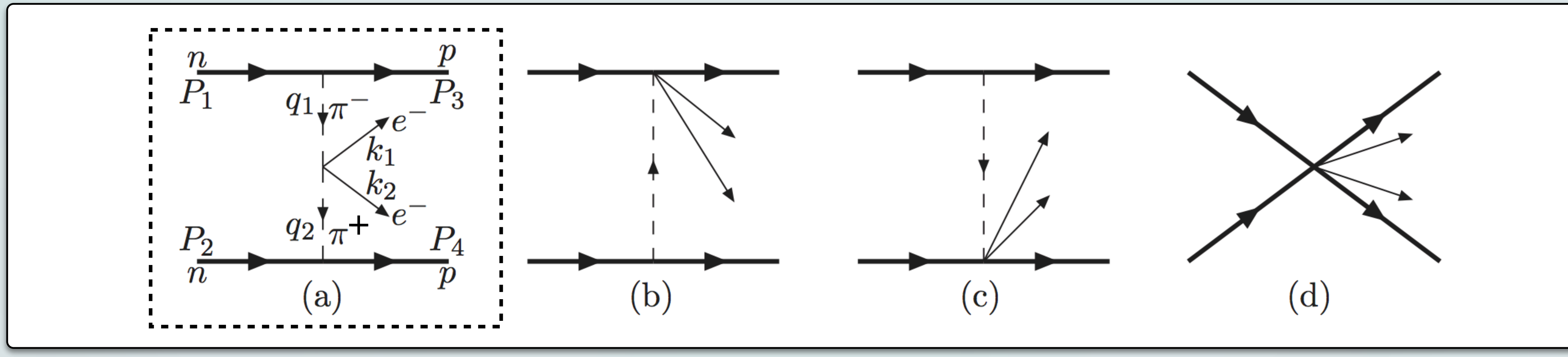
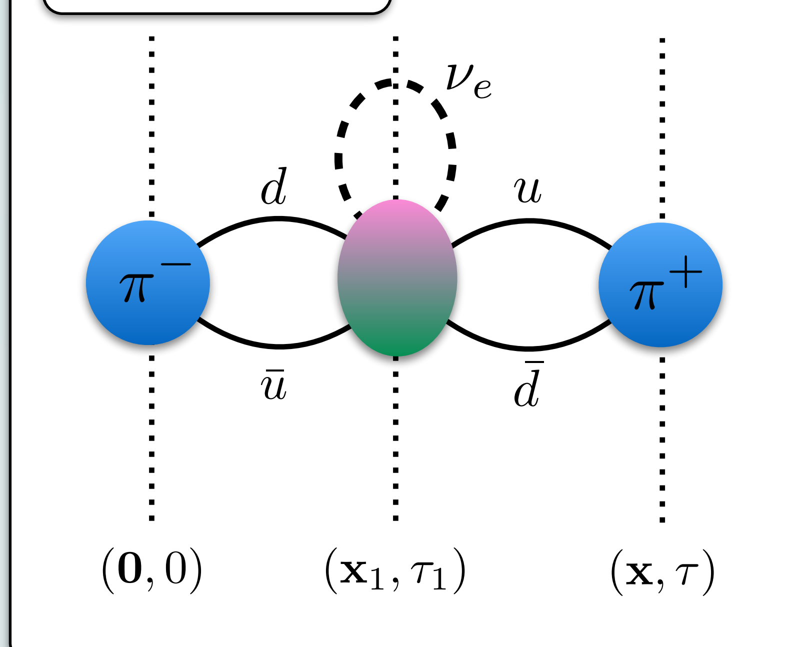
Prezeau, Ramsey-Musolf, Vogel Phys.Rev. D68 03401 (2003).



$\langle \pi^+ | O_i | \pi^- \rangle$



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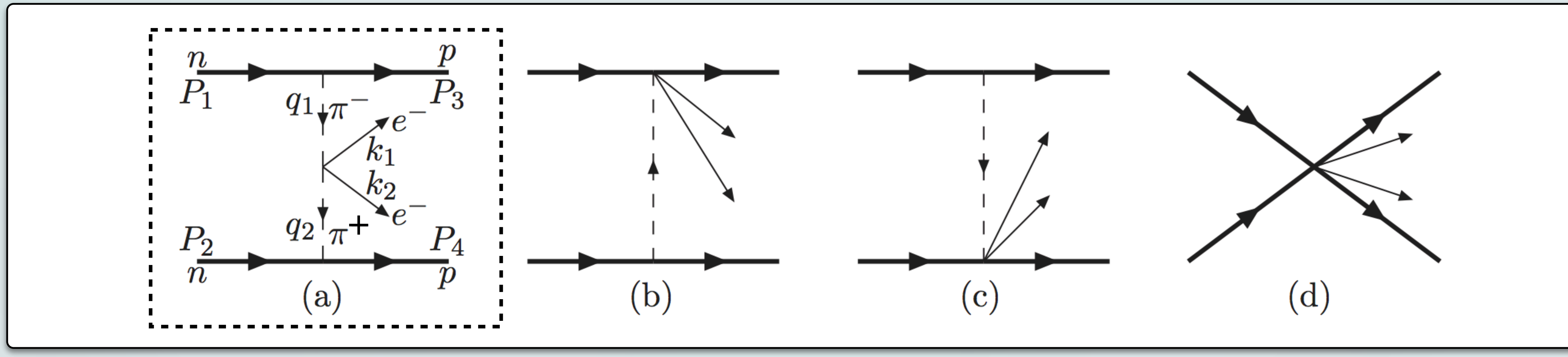

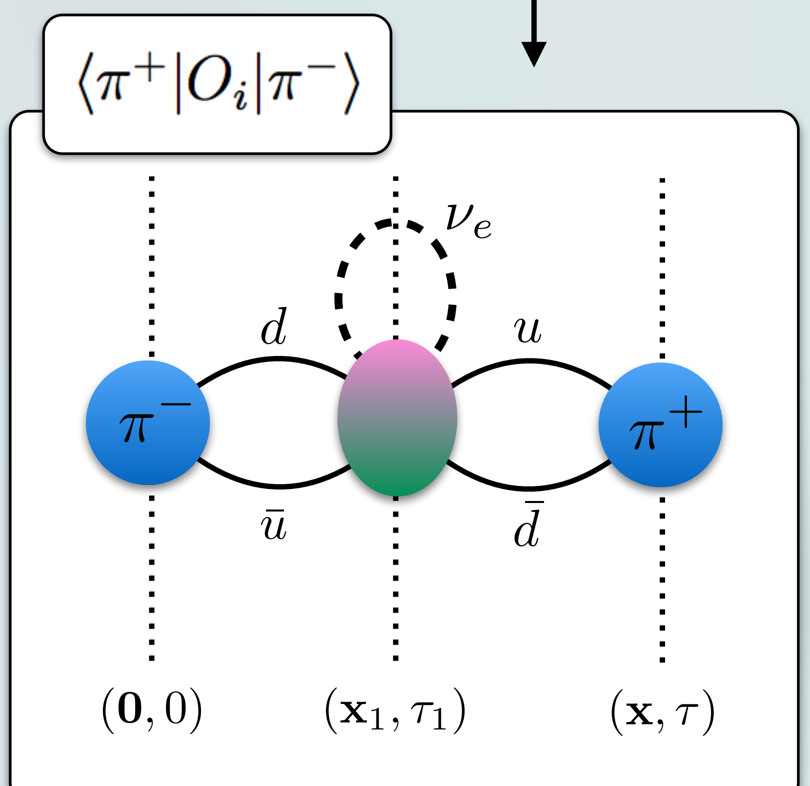

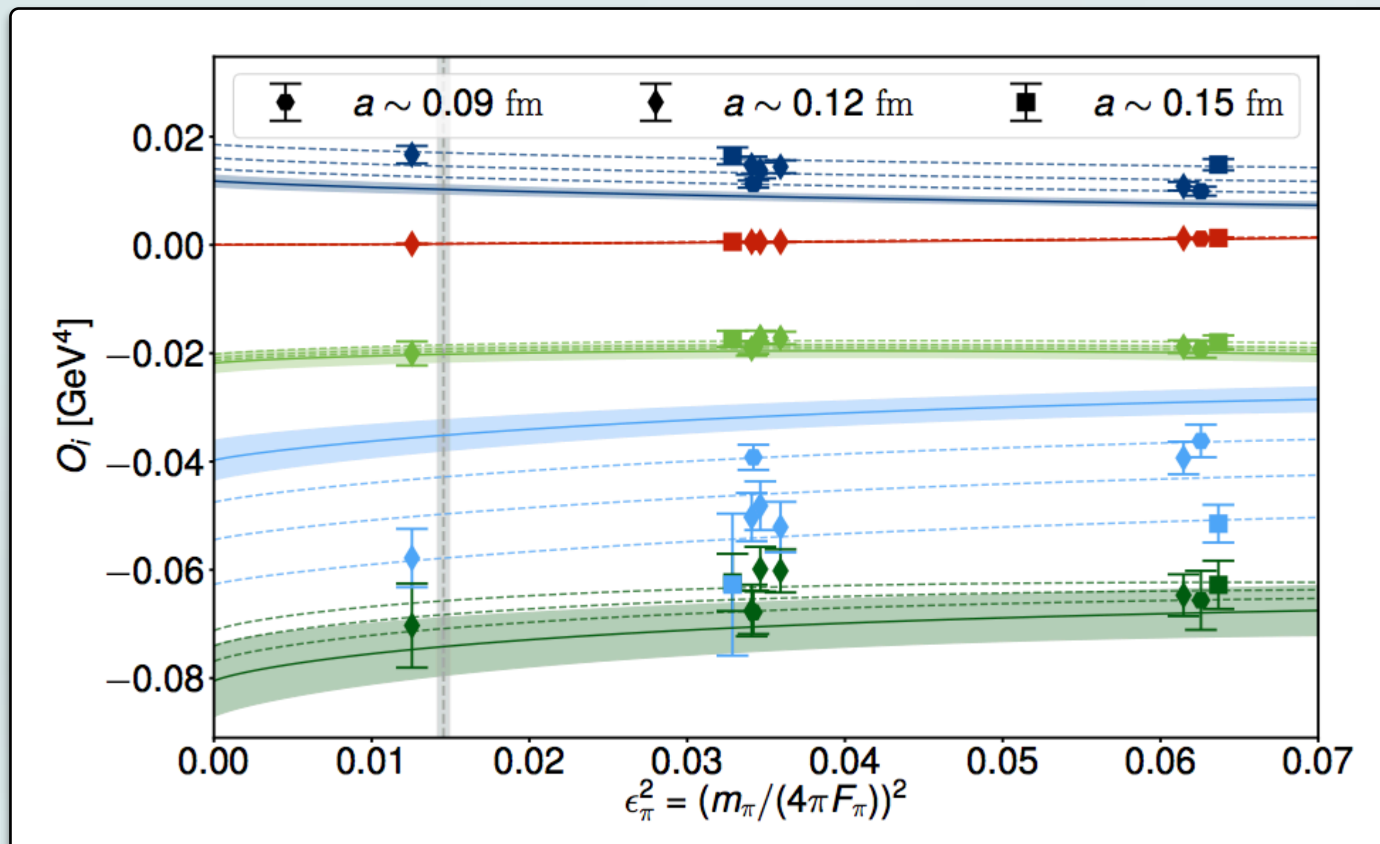

Nicholson, Berkowitz, Monge-Camacho, Brantley, Garron, Chang, Rinaldi, Clark, Joo, Kurth, Tiburzi, Vranas and Walker-Loud (CALLATT collaboration), Phys. Rev. Lett. 121, 172501 (2018), arXiv:1805.02634 [nucl-th].

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Savage, Phys. Rev. C59, 2293 (1999), arXiv:nucl-th/9811087 [nucl-th].
Cirigliano, Dekens, Graesser and Mereghetti, PLB Volume 769, 2017, Pages 460-464, arXiv:1701.01443 [hep-ph].

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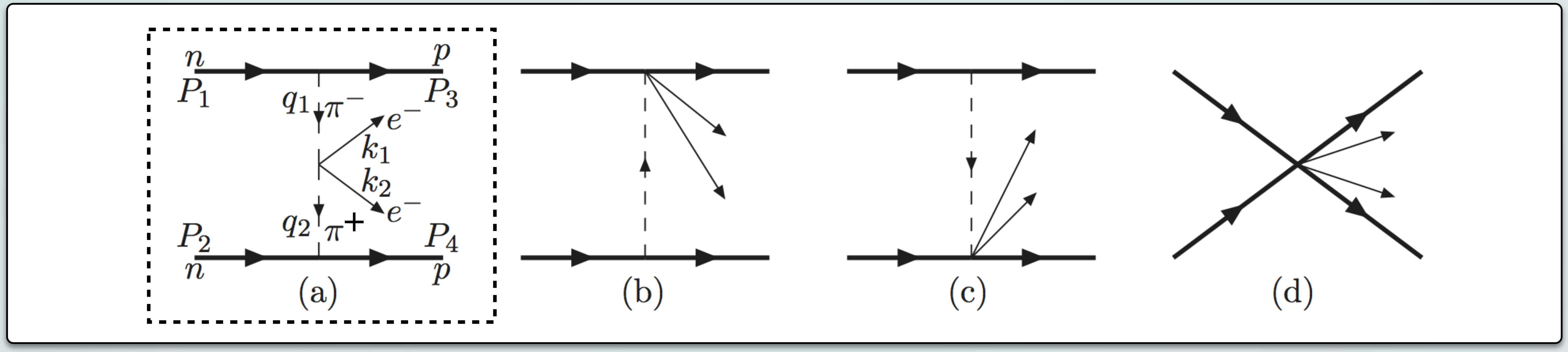

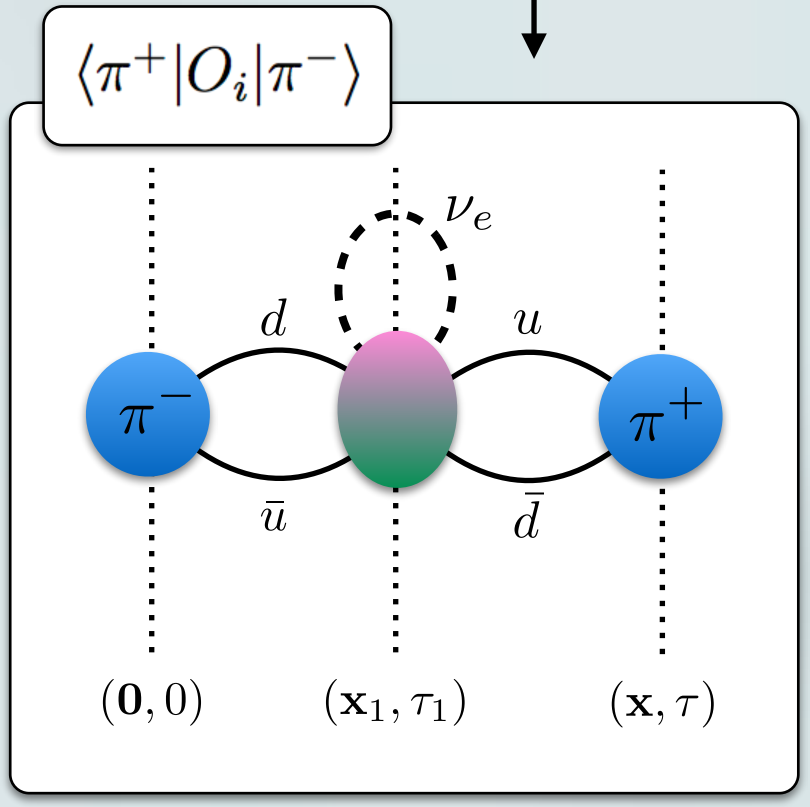

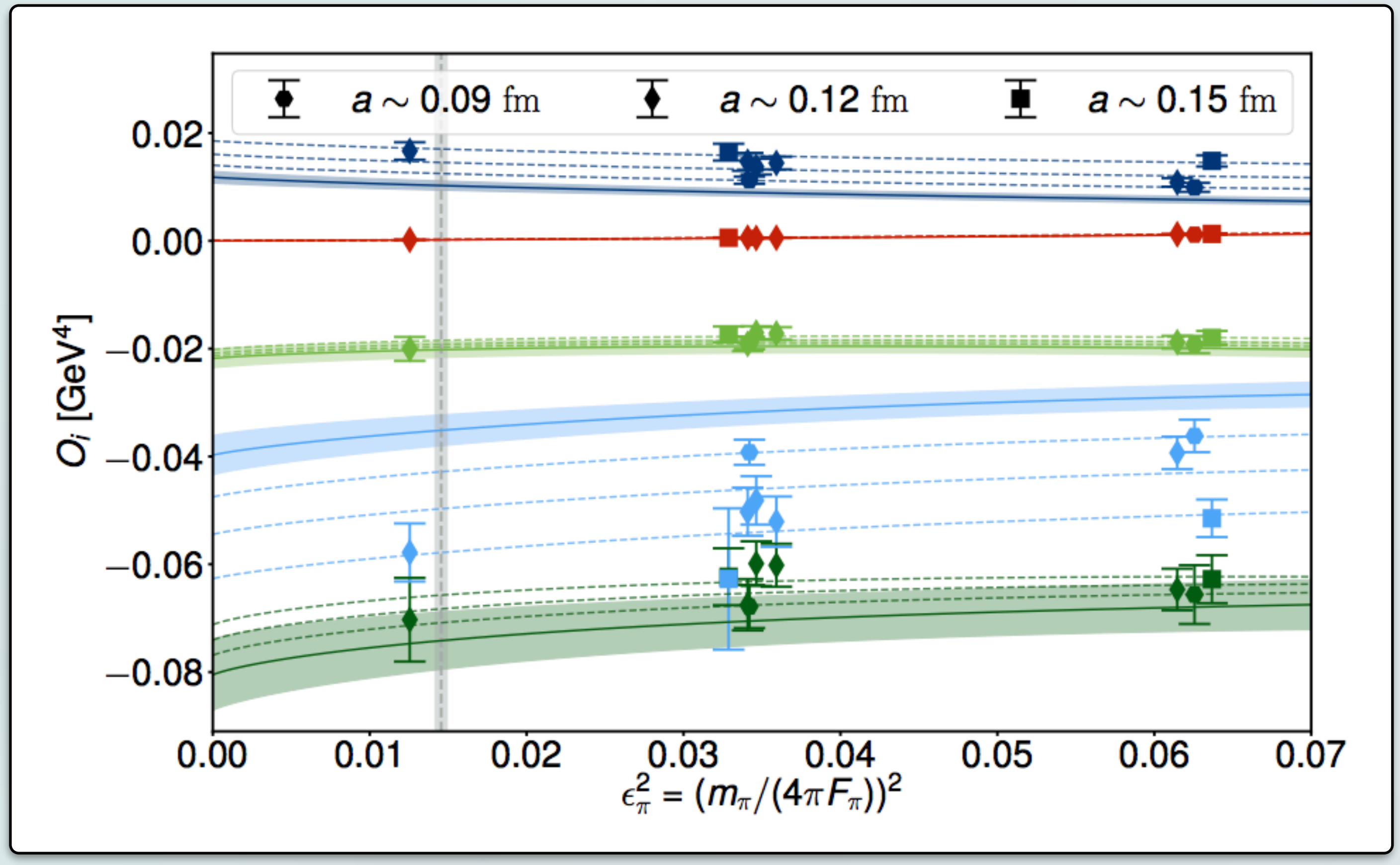

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NON-LOCAL MATRIX ELEMENTS OF TWO DIMENSION-6 FOUR-FERMION SM WEAK CURRENTS

MATRIX ELEMENTS OF
NON-LOCAL TWO-QUARK
SM WEAK OPERATORS

$$S_{NL} = \int dx\, dy\, S_0(x-y)\; T\left(J_\alpha^+(x) J_\beta^+(y)\right)\; g^{\alpha\beta}$$

$$J_\alpha^+ = \bar{u}\gamma_\alpha(1-\gamma_5)d$$

MATRIX ELEMENTS OF
NON-LOCAL TWO-QUARK
SM WEAK OPERATORS

SEE JORDY'S TALKS.

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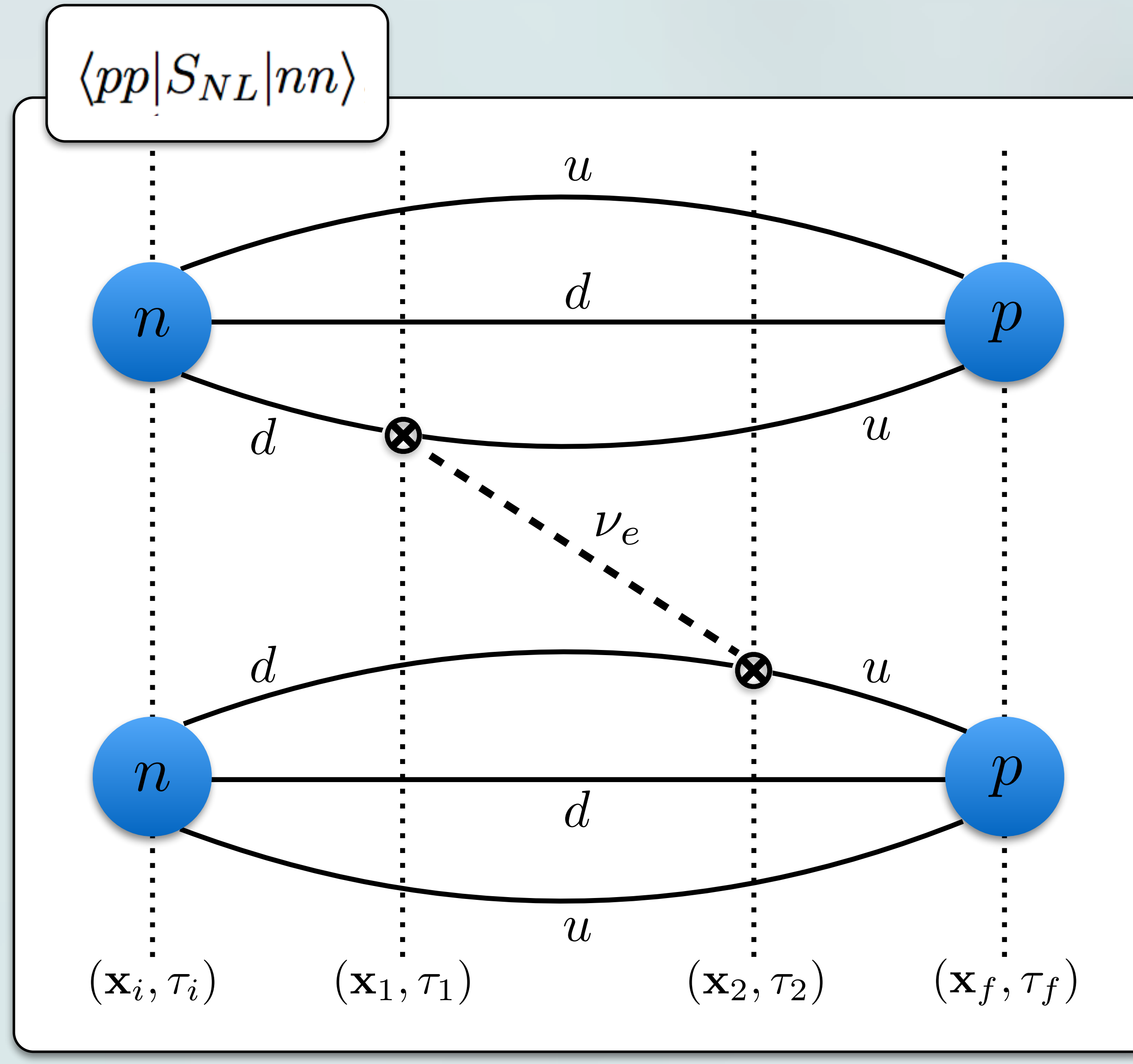
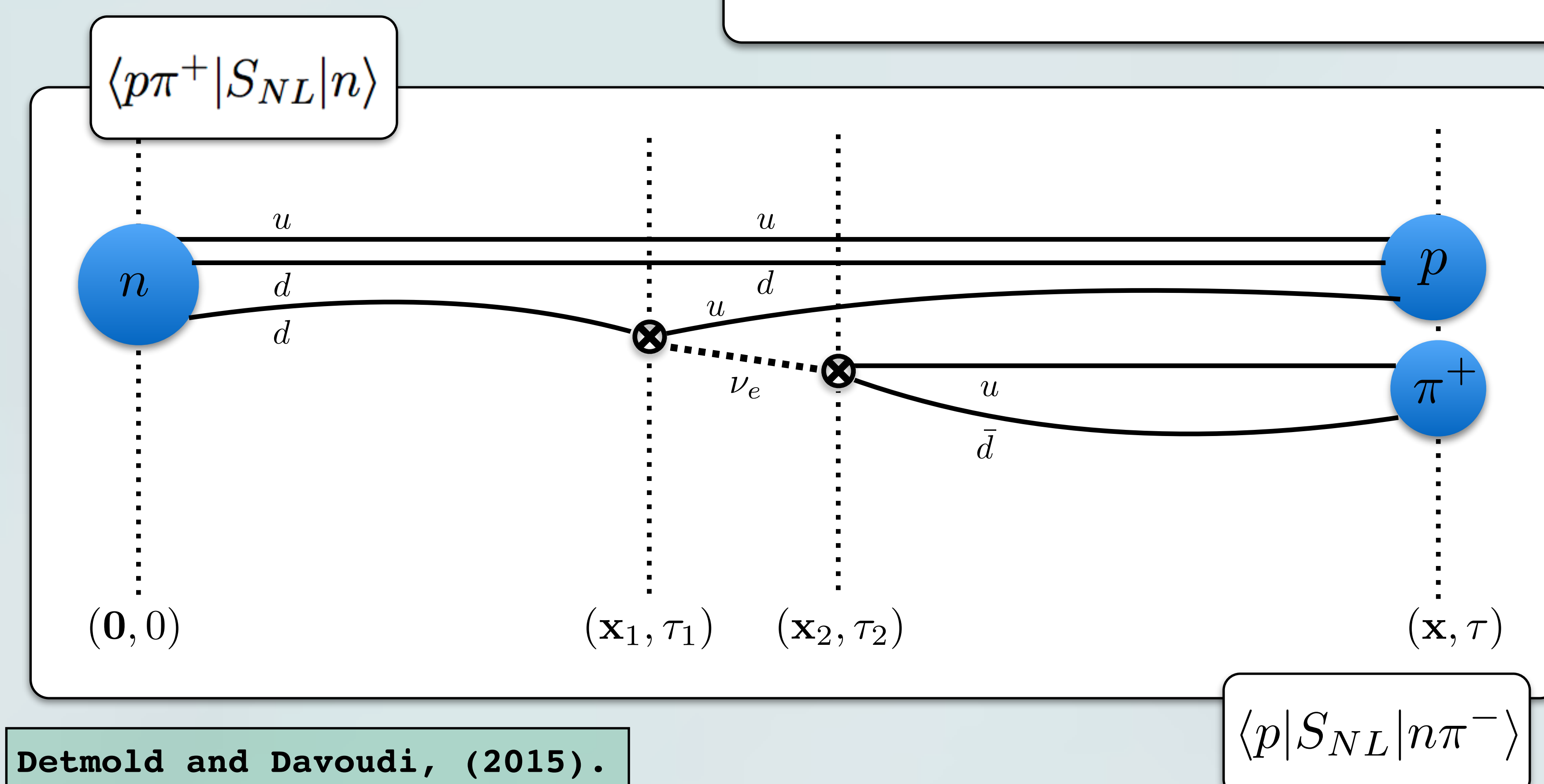
EFT approach makes the case for LQCD even stronger, see e.g., Cirigliano, Dekens, De Vries, Graesser, Mereghetti, Pastore, and Van Kolck, Phys. Rev. Lett. 120, 202001 (2018), arXiv:1802.10097 [hep-ph].





Detmold and Davoudi, (2015).

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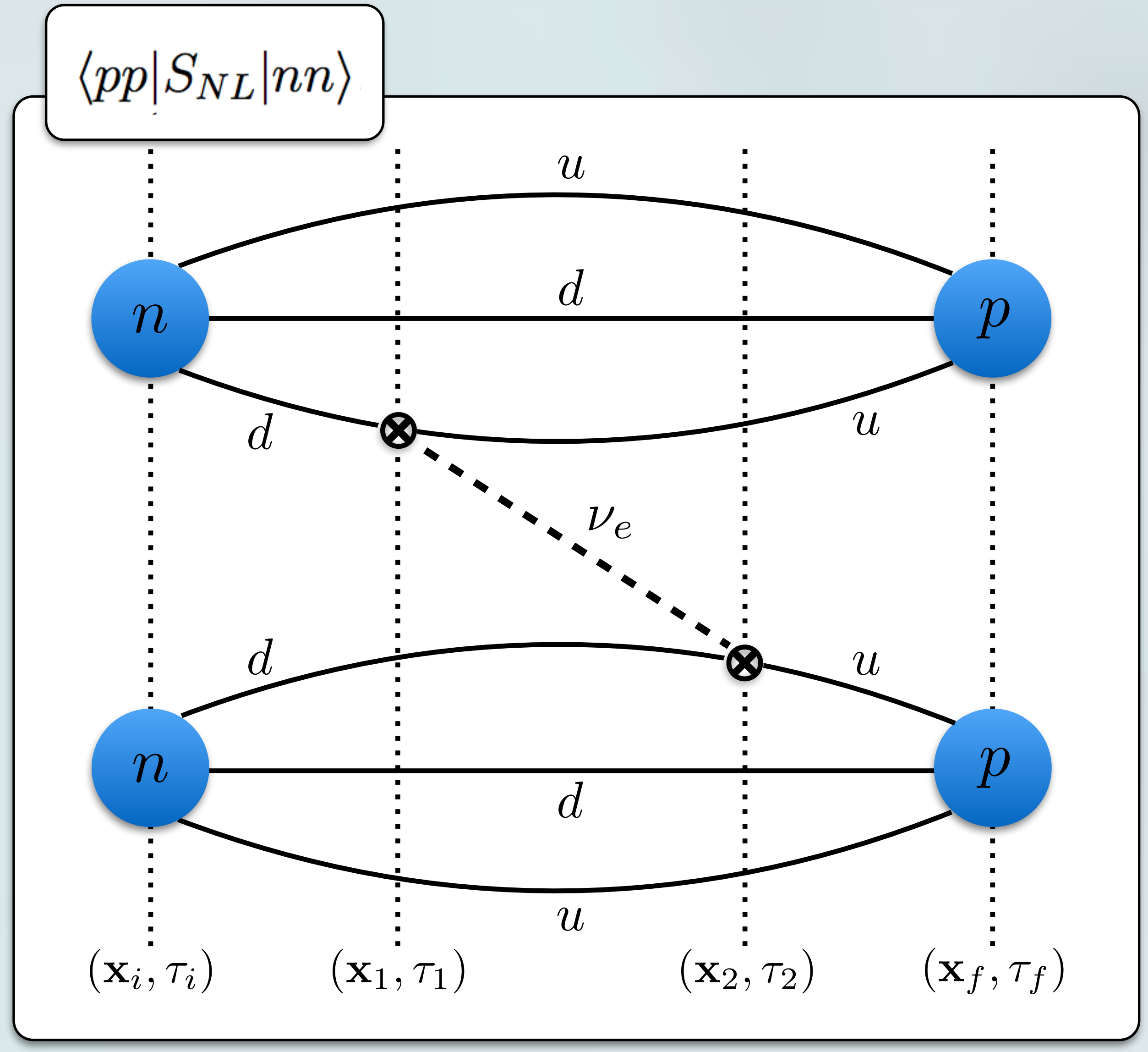

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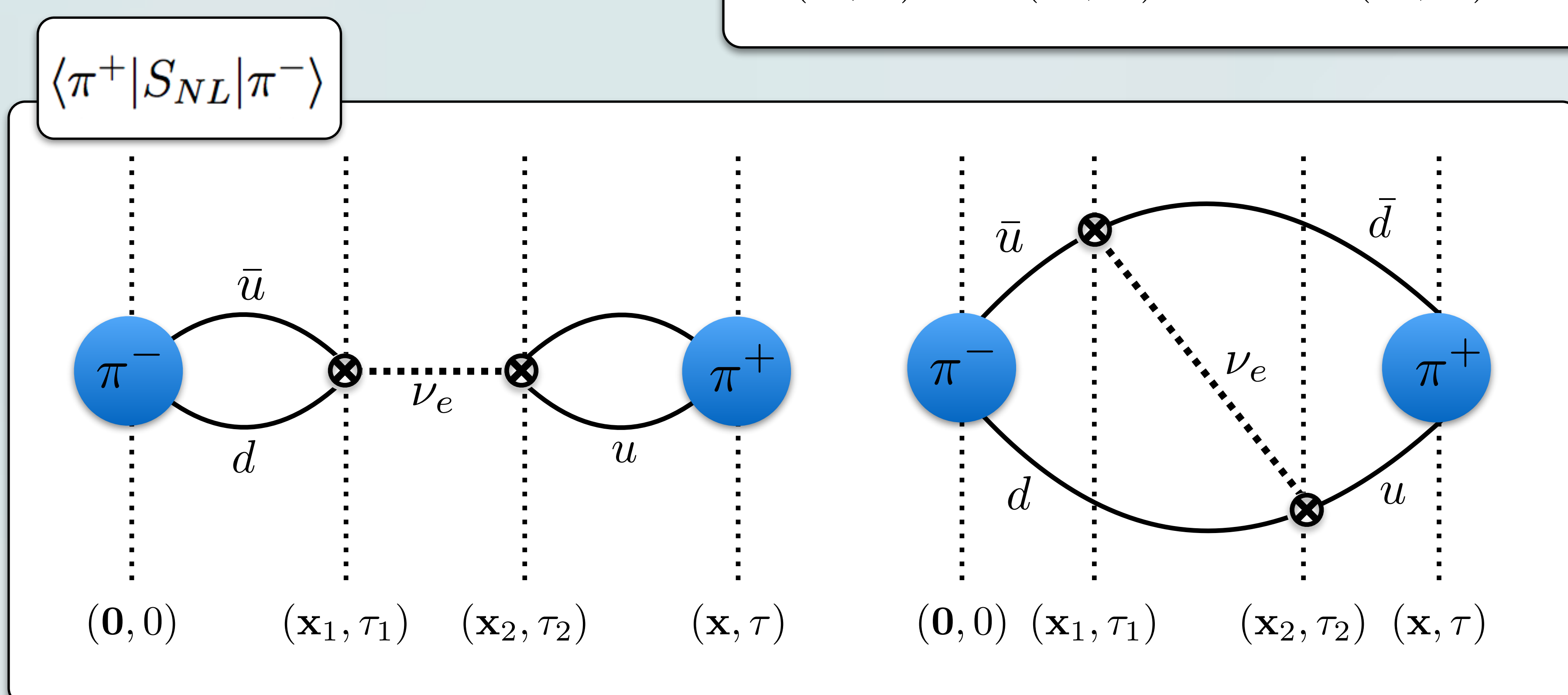

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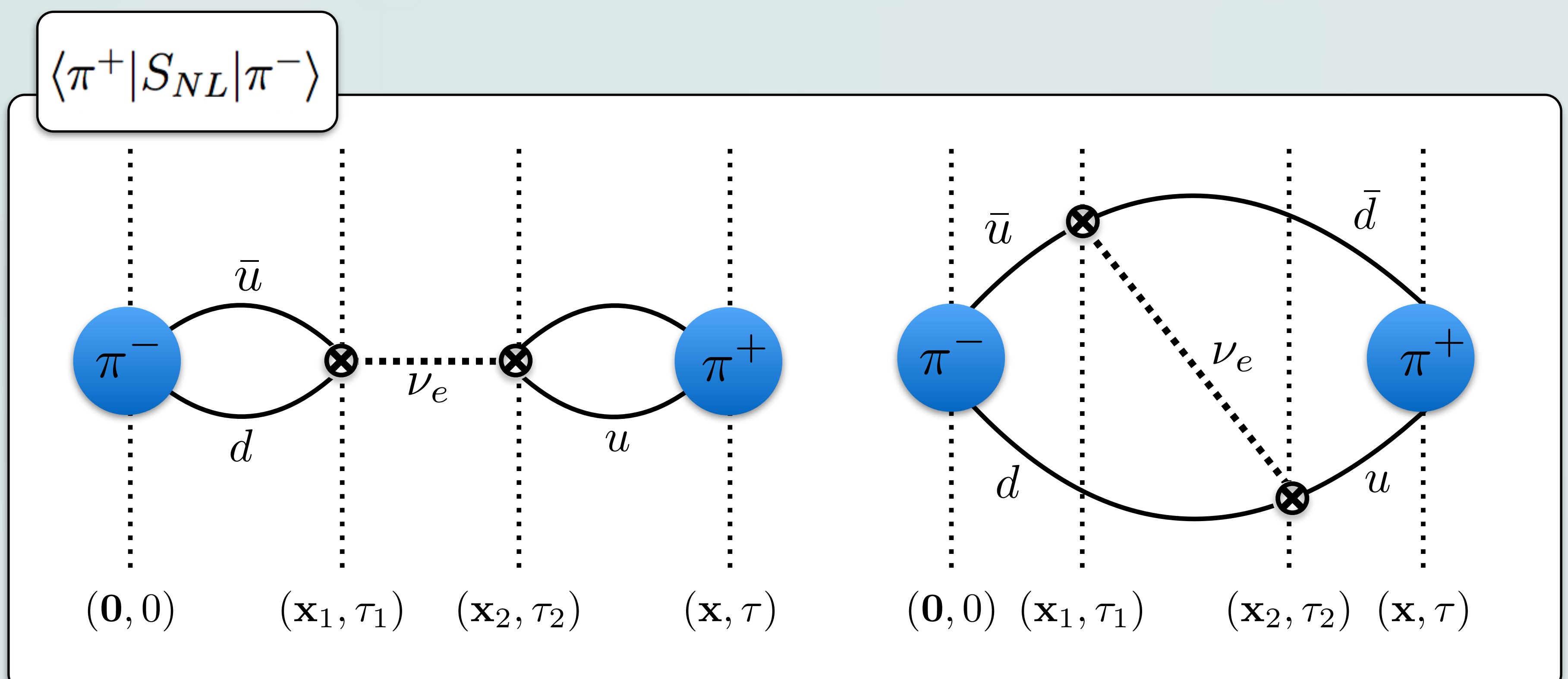
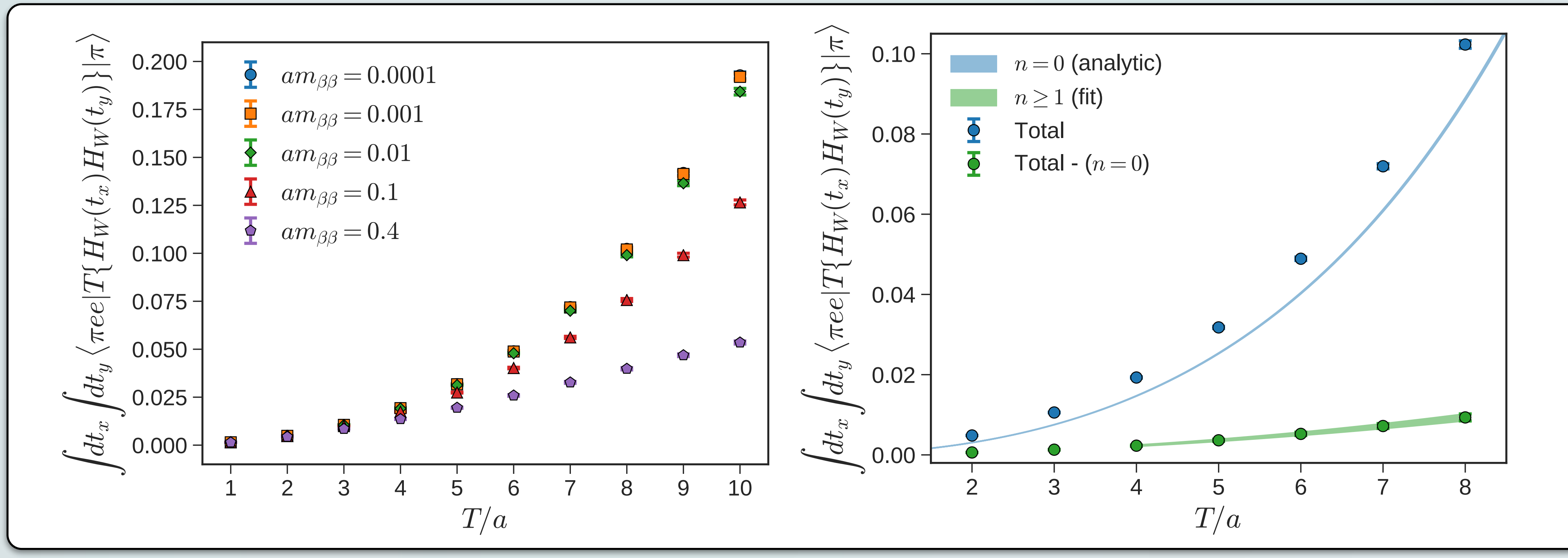


Detmold and Davoudi, (2015).

MATRIX ELEMENTS OF **NON-LOCAL** TWO-QUARK SM WEAK OPERATORS

SEE DAVID'S TALK.

Detmold and Murphy, (2018) arXiv:1811.05554 [hep-lat].



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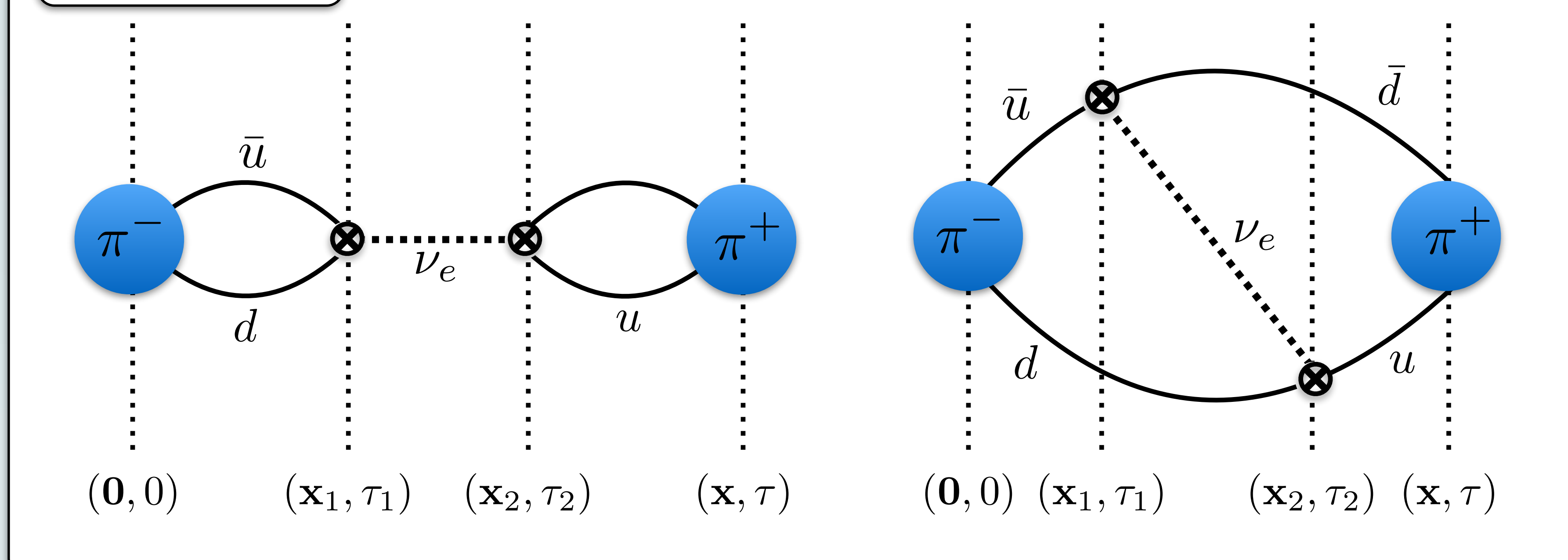

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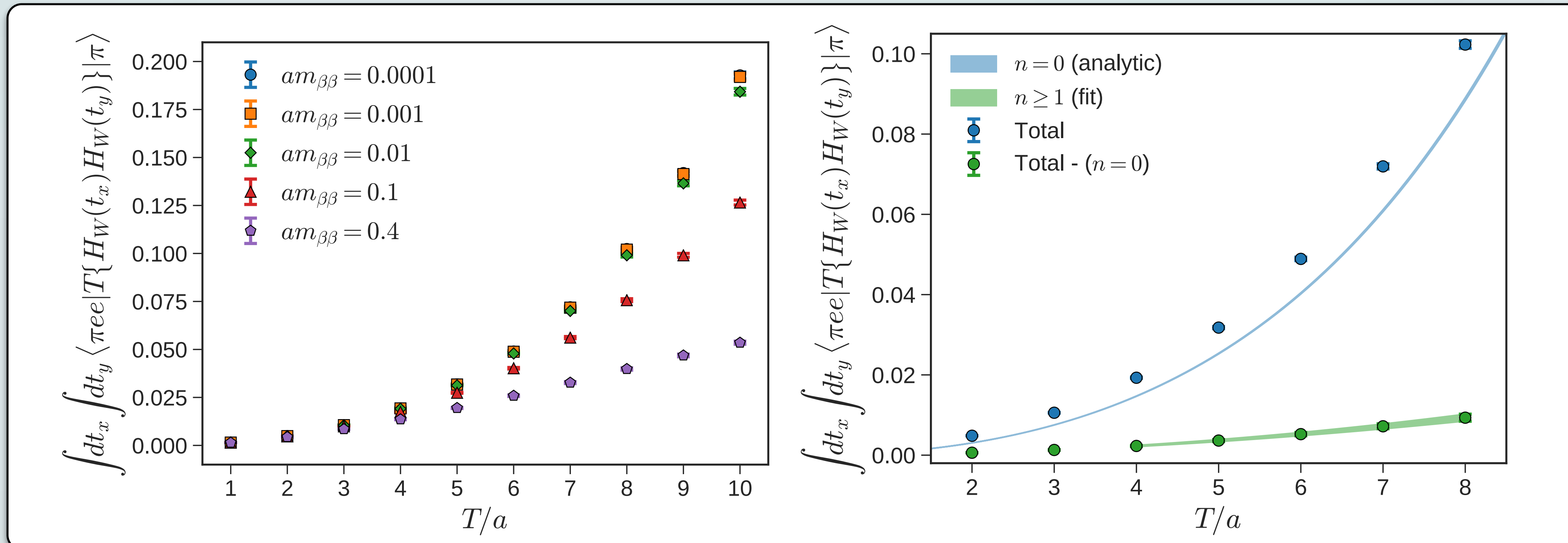
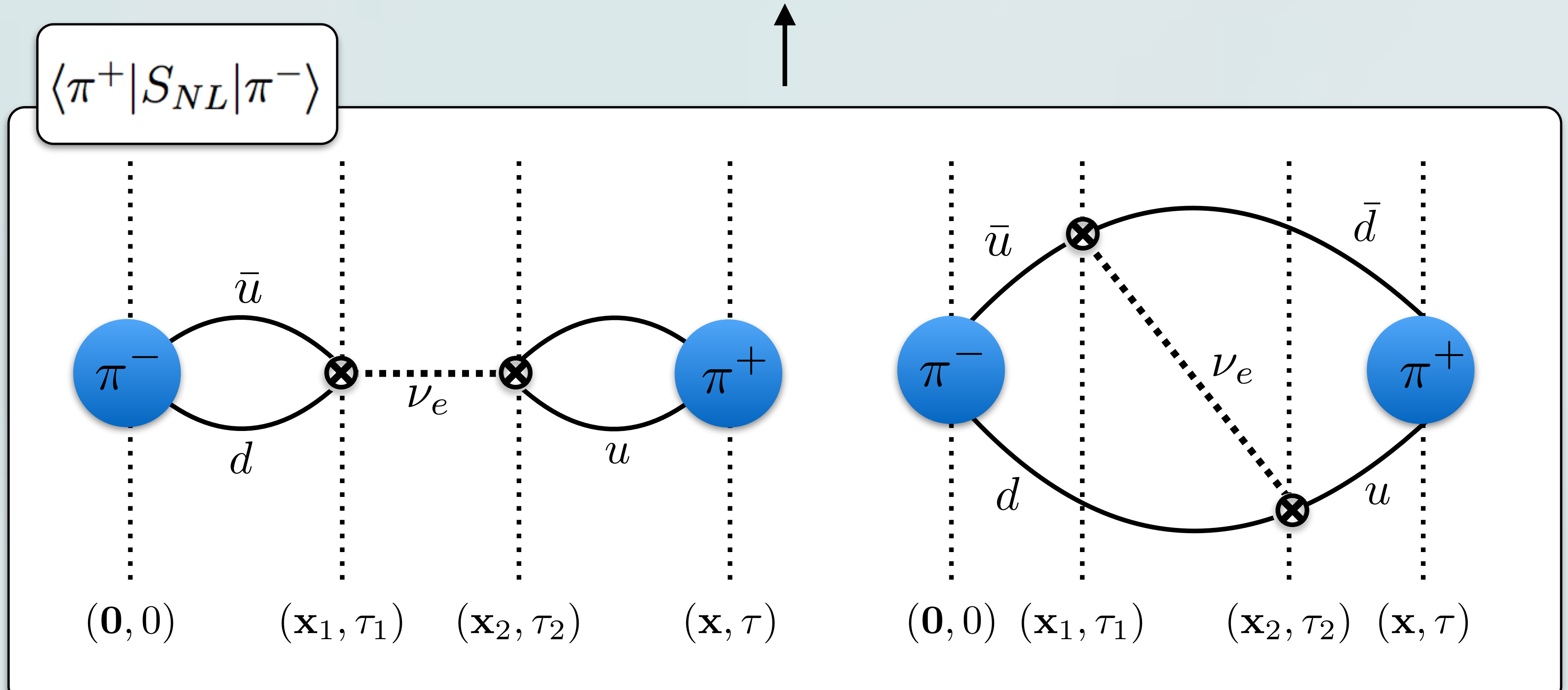
Another nice calculation on pipi to ee process: Feng, Jin, Tuo, and Xia, Phys. Rev. Lett. 122, 022001 (2019), arXiv: 1809.10511 [hep-lat].

SEE Xu's TALK.





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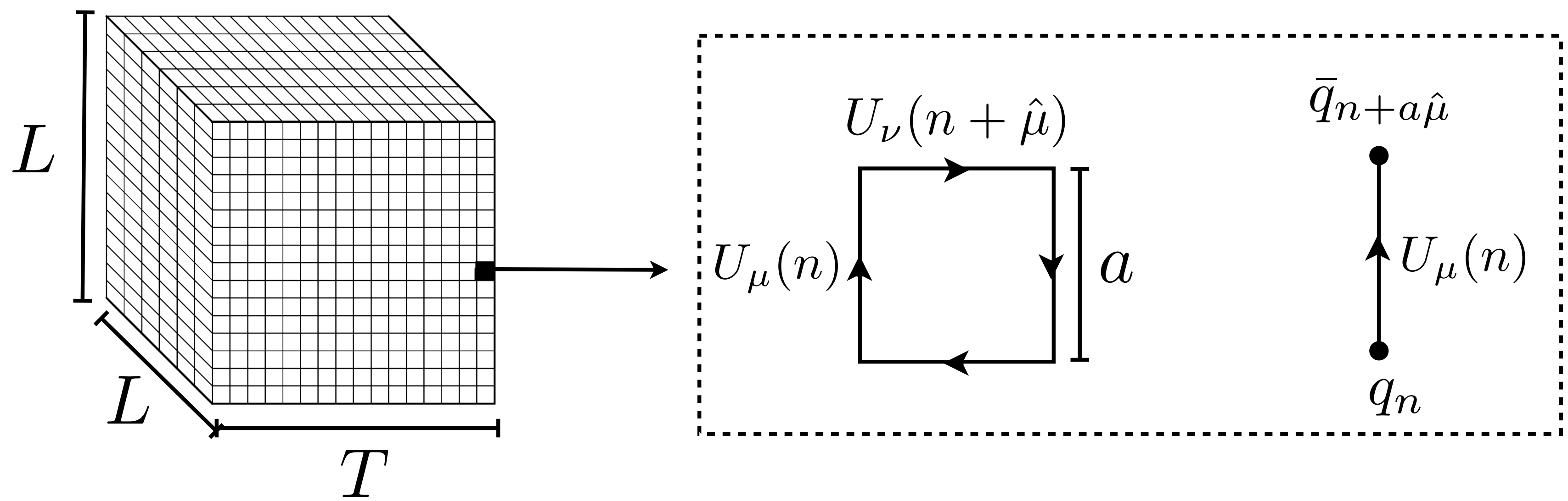
SOME BACKGROUND ON
THE LATTICE QCD METHODOLOGY…

STEP I: DISCRETIZE THE QCD ACTION IN BOTH SPACE AND TIME. WICK ROTATE TO IMAGINARY TIMES. CONSIDER A FINITE HYPERCUBIC LATTICE.



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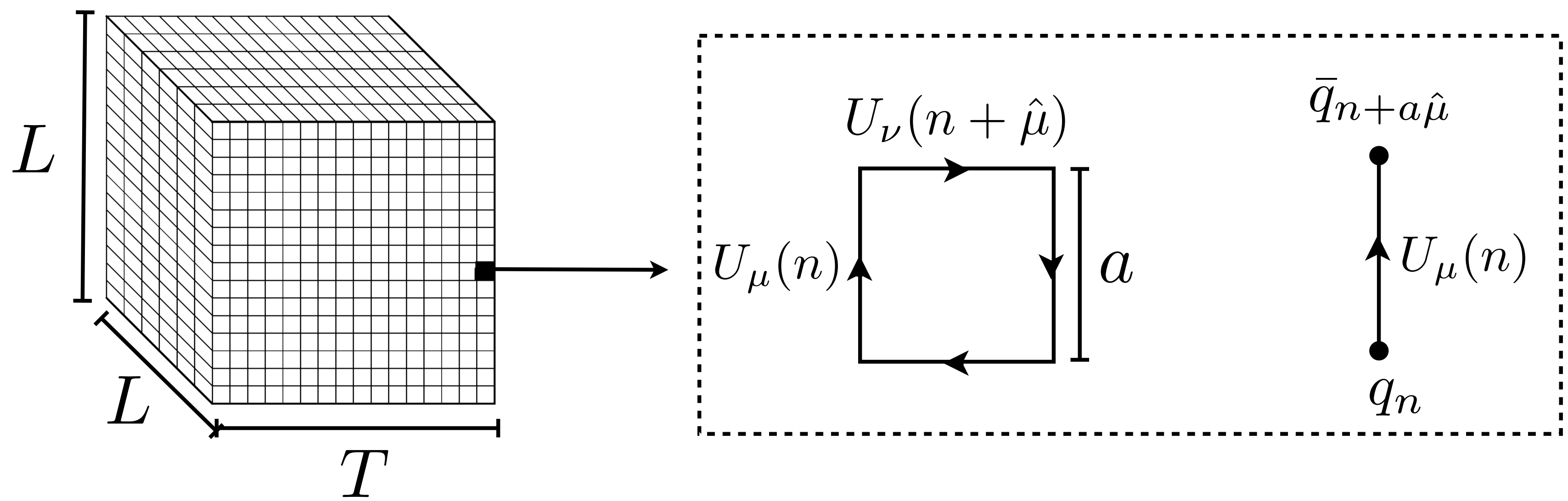


STEP II: GENERATE A LARGE SAMPLE OF THERMALIZED DECORRELATED VACUUM CONFIGURATIONS.

$$\langle \hat{\mathcal{O}} \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}U_\mu \mathcal{D}q\mathcal{D}\bar{q}\; e^{-S^{(G)}_{\text{lattice}}[U]-S^{(F)}_{\text{lattice}}[U,q,\bar{q}]}\; \hat{\mathcal{O}}[U,q,\bar{q}]$$

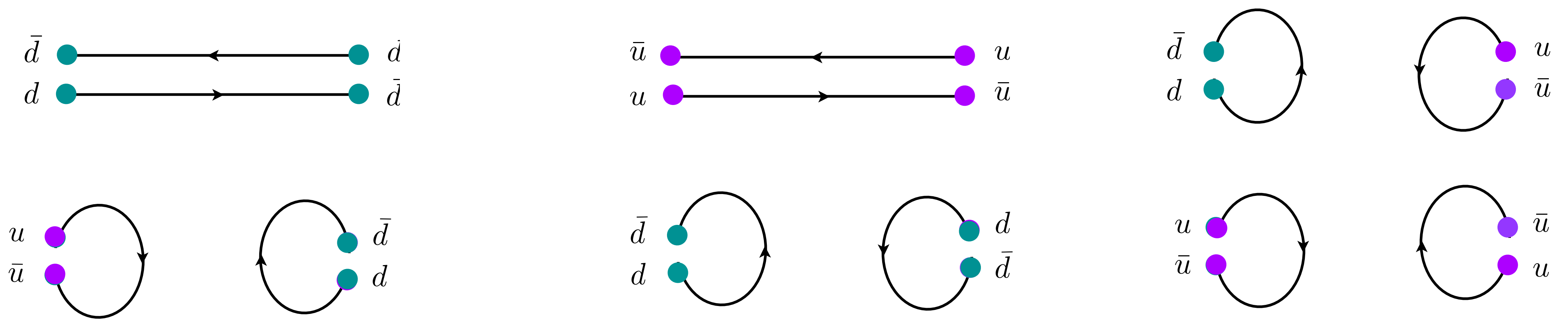
$$\Downarrow$$

$$\langle \hat{\mathcal{O}} \rangle = \frac{1}{N}\sum_i^N \langle \hat{\mathcal{O}}\rangle_F [U^{(i)}]$$

$U^{(i)}$ SAMPLED FROM THE DISTRIBUTION: $\frac{1}{\mathcal{Z}} e^{-S^{(G)}_{\text{lattice}}[U]} \prod_f \det D_f$

STEP III: FORM THE CORRELATION FUNCTIONS BY CONTRACTING THE QUARKS. NEED TO SPECIFY THE INTERPOLATING OPERATORS FOR THE STATE UNDER STUDY.

e.g., $\hat{O} = \frac{1}{\sqrt{2}}(\overline{u}\gamma^5 u - \overline{d}\gamma^5 d)$



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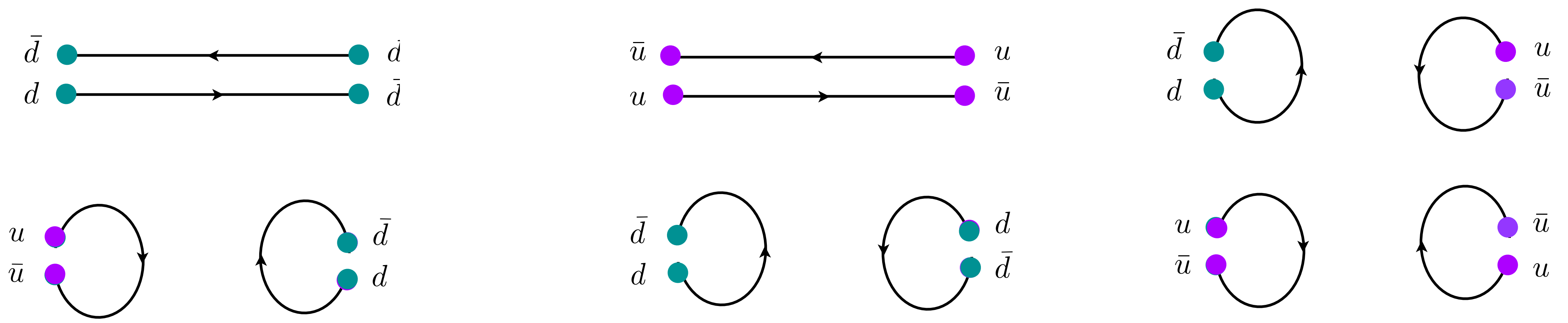
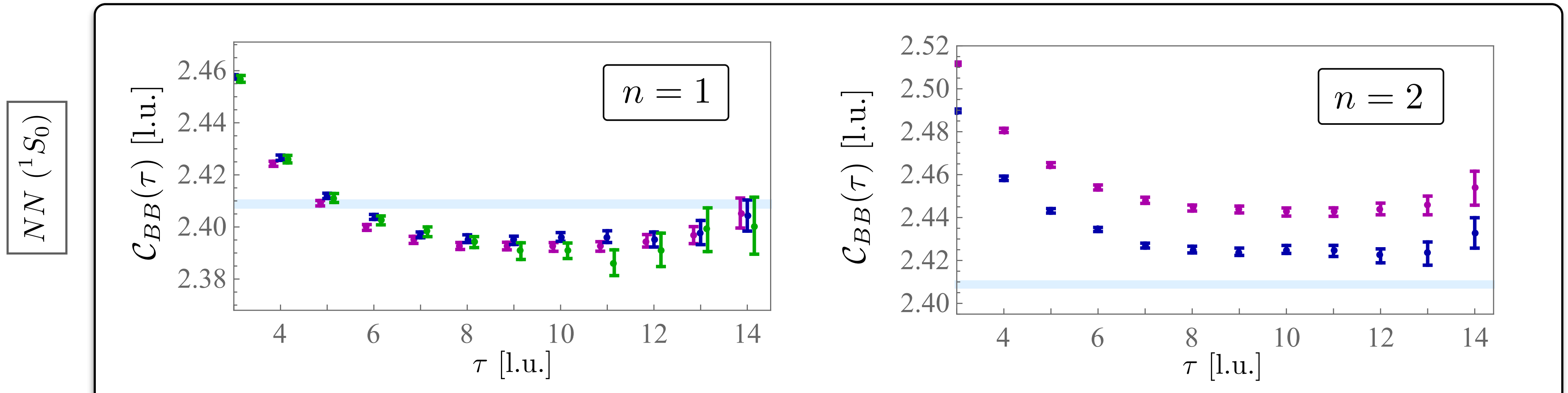
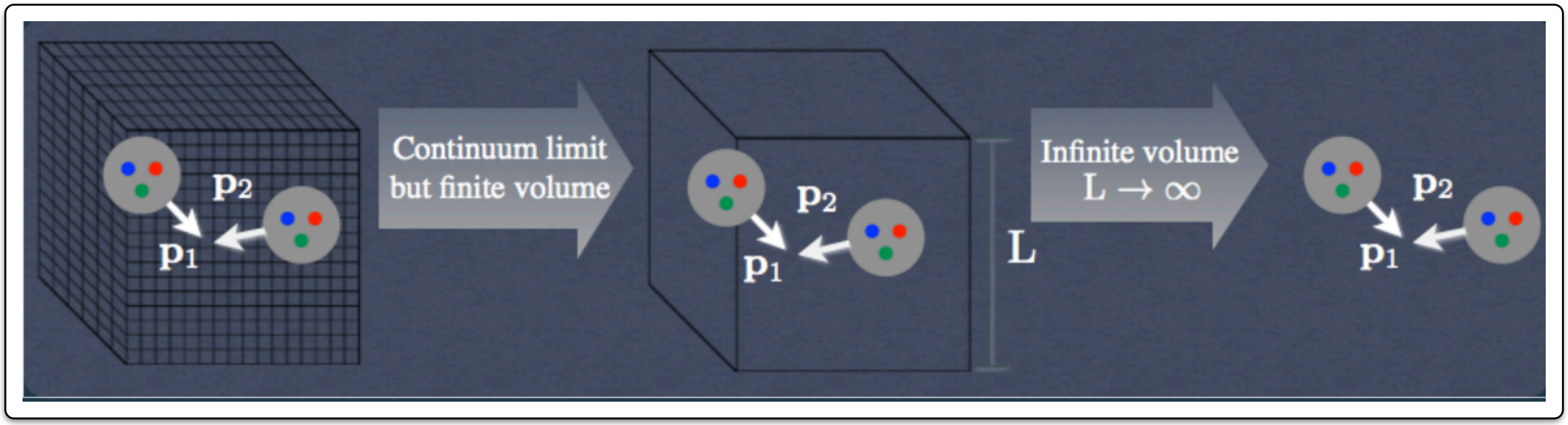


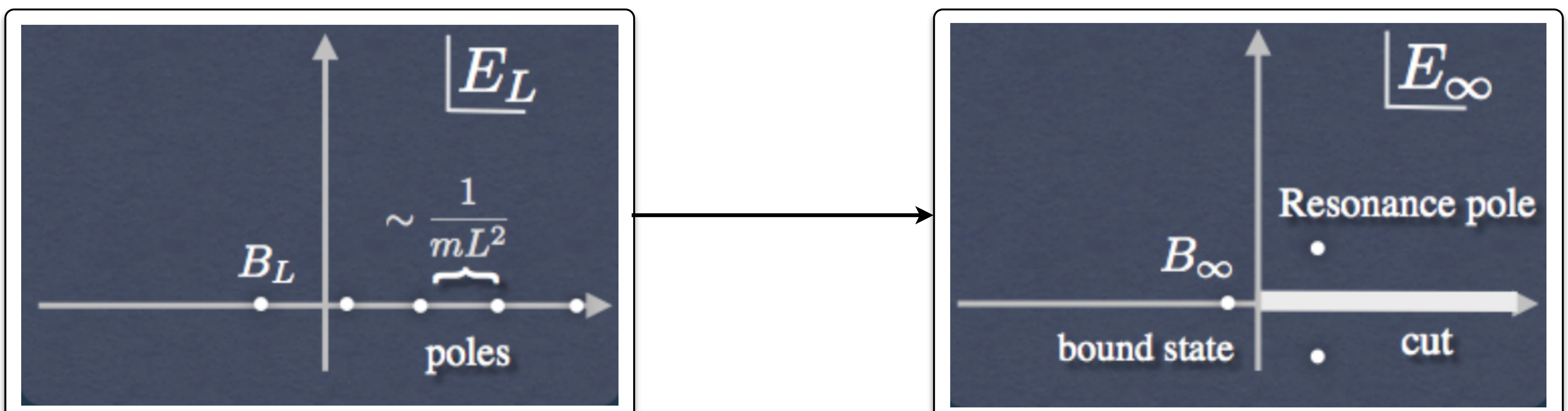
STEP IV: EXTRACT ENERGIES AND MATRIX ELEMENTS FROM CORRELATION FUNCTIONS

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



STEP V: MAKE CONNECTION TO PHYSICAL OBSERVABLES, SUCH AS SCATTERING AMPLITUDES, DECAY RATES, ETC. STILL NOT FULLY DEVELOPED AND PRESENTS CHALLENGE IN MULTI-HADRON SYSTEMS.





SEE TALKS BY RAUL AND MATTHIAS AND XU FOR TREATMENT OF THIS PROBLEM FOR MATRIX ELEMENTS RELEVANT TO 0vBB DECAY.

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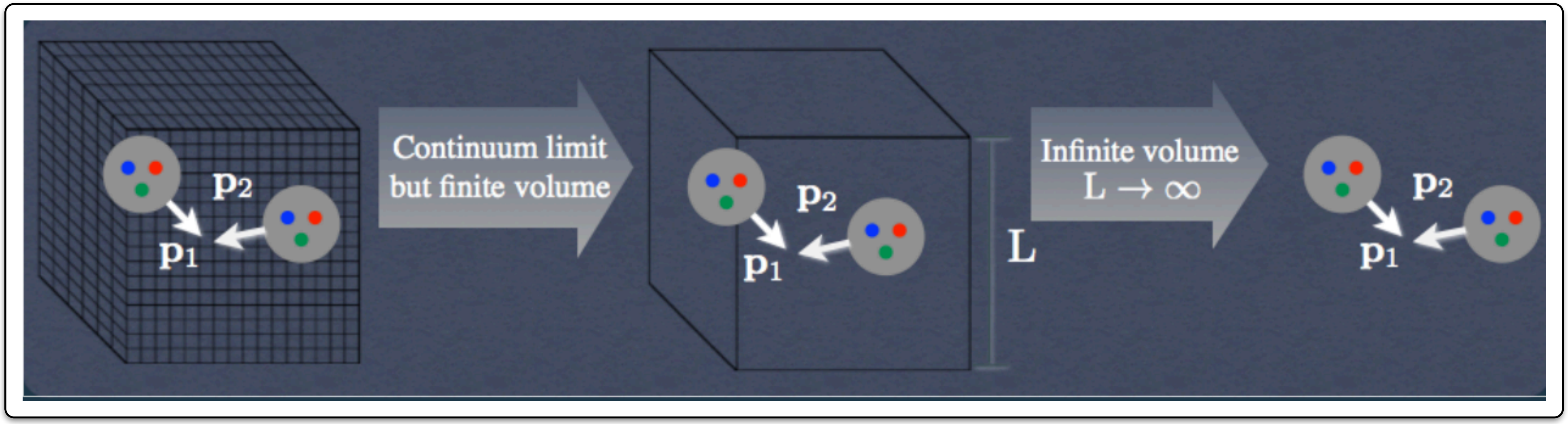
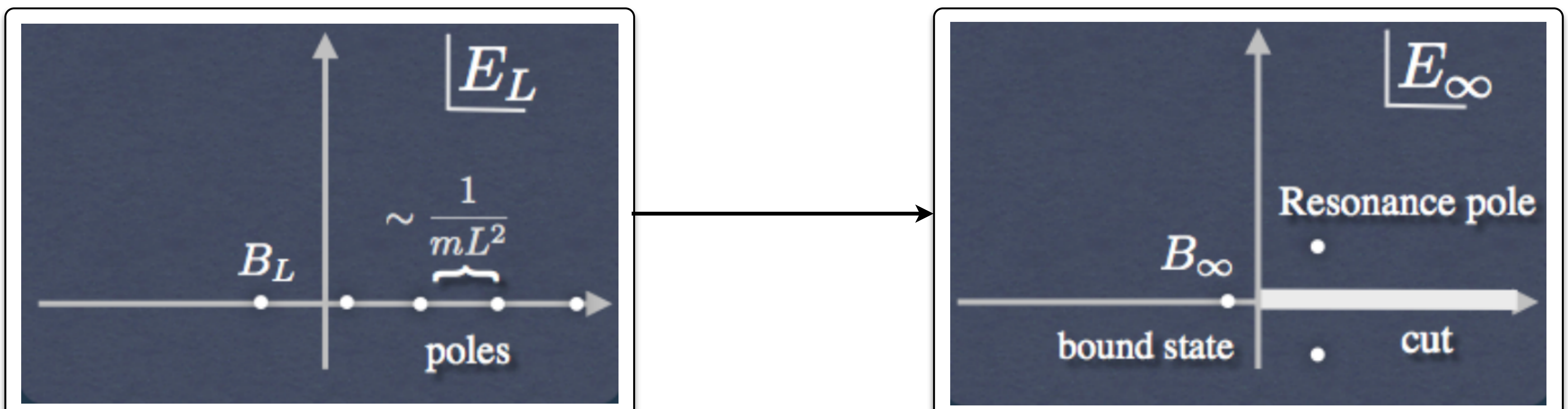
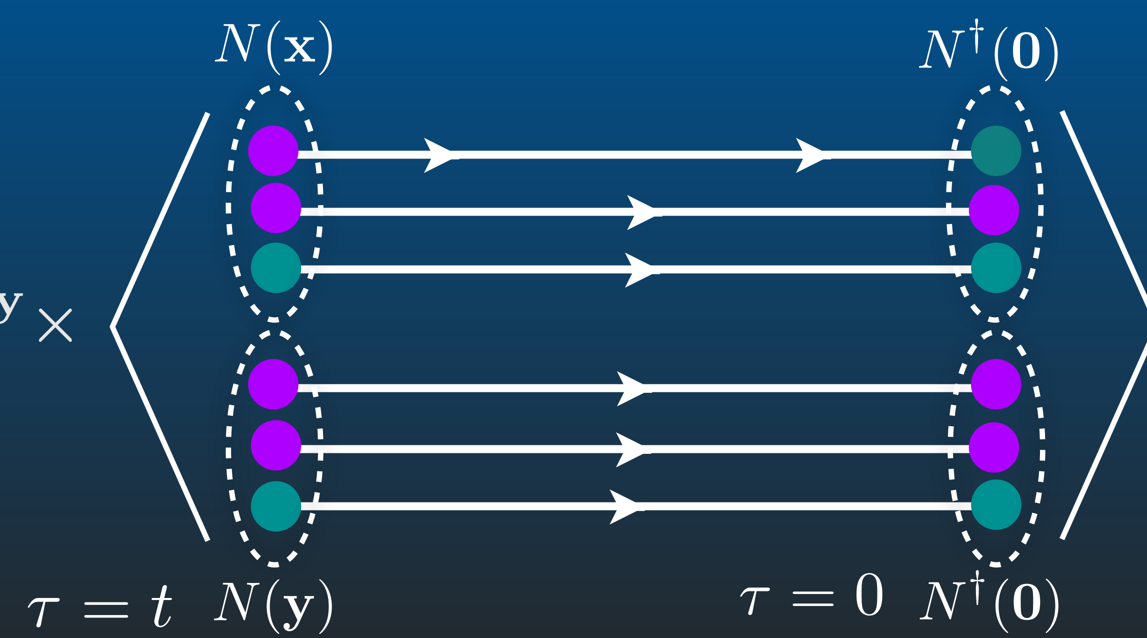




NPLQCD APPROACH TO THE PROBLEM OF WEAK AMPLITUDES OF LIGHT NUCLEI

ENERGIES FROM NUCLEAR CORRELATION FUNCTIONS

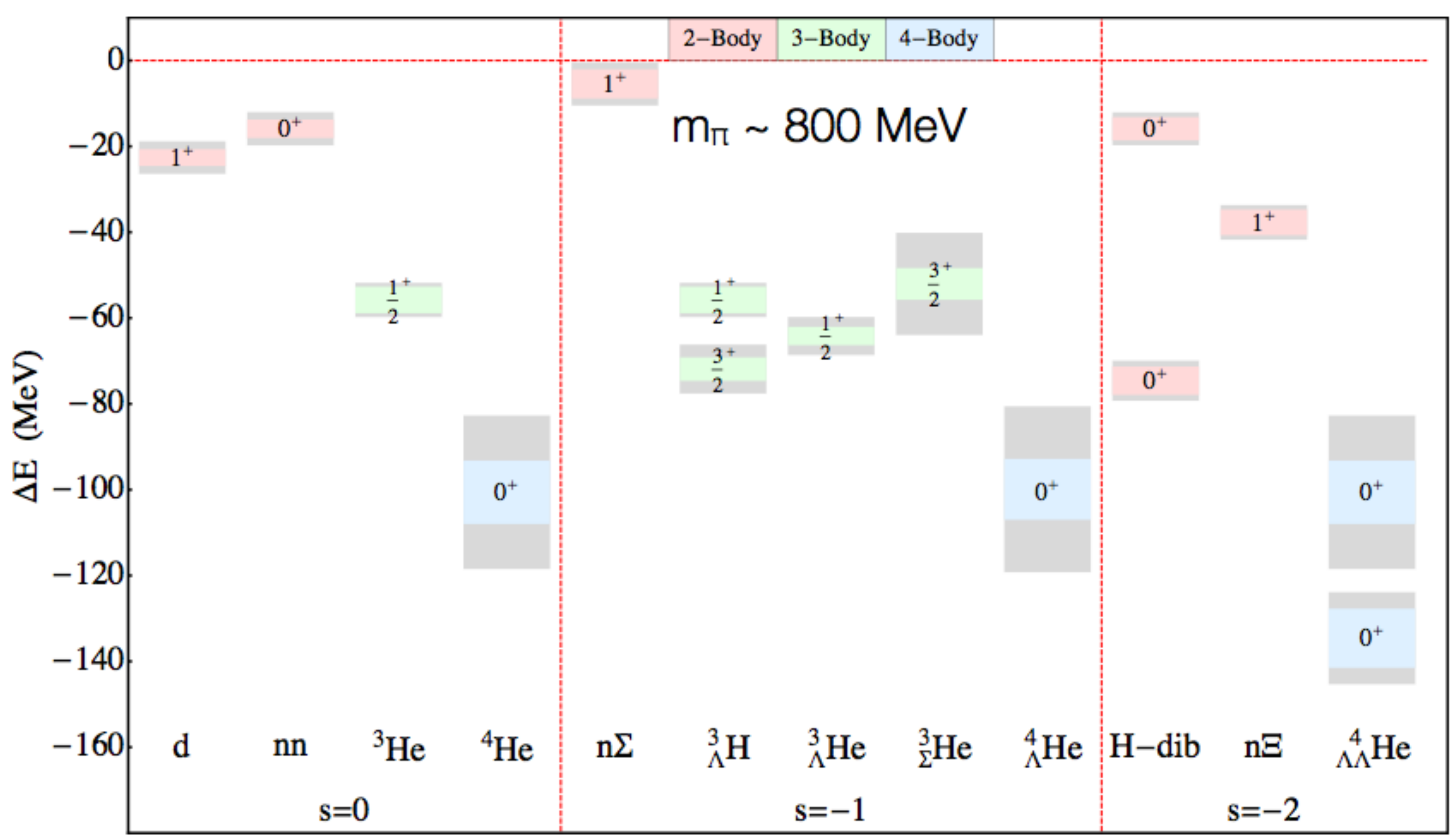
$$C(\mathbf{P};t,t_O) = \sum_{\mathbf{p}_1+\mathbf{p}_2=\mathbf{P}} \sum_{\mathbf{x},\mathbf{y},\mathbf{z}} e^{i\mathbf{p}_1\cdot\mathbf{x}+i\mathbf{p}_2\cdot\mathbf{y}} \times$$



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

NUCLEI FROM QCD IN A WORLD WITH HEAVIER QUARKS

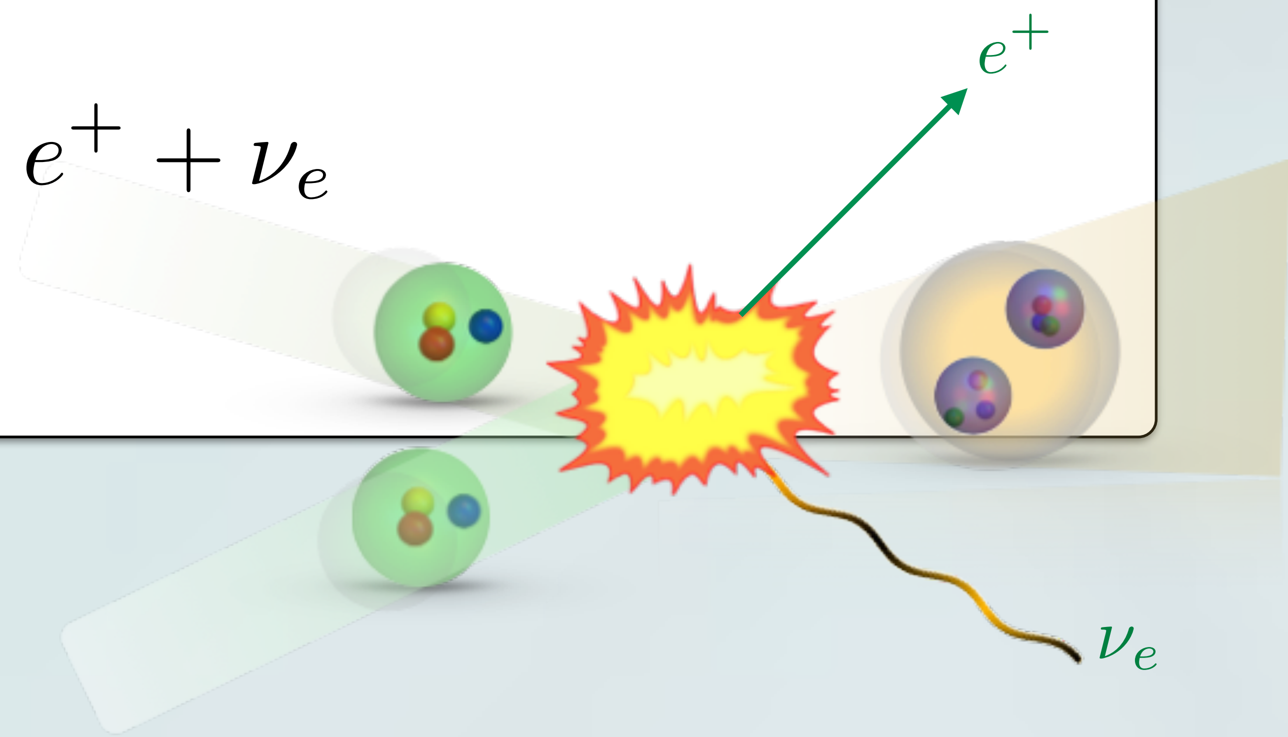
$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$



Beane, et al. (NPLQCD), Phys.Rev. D87 (2013), Phys.Rev. C88 (2013)

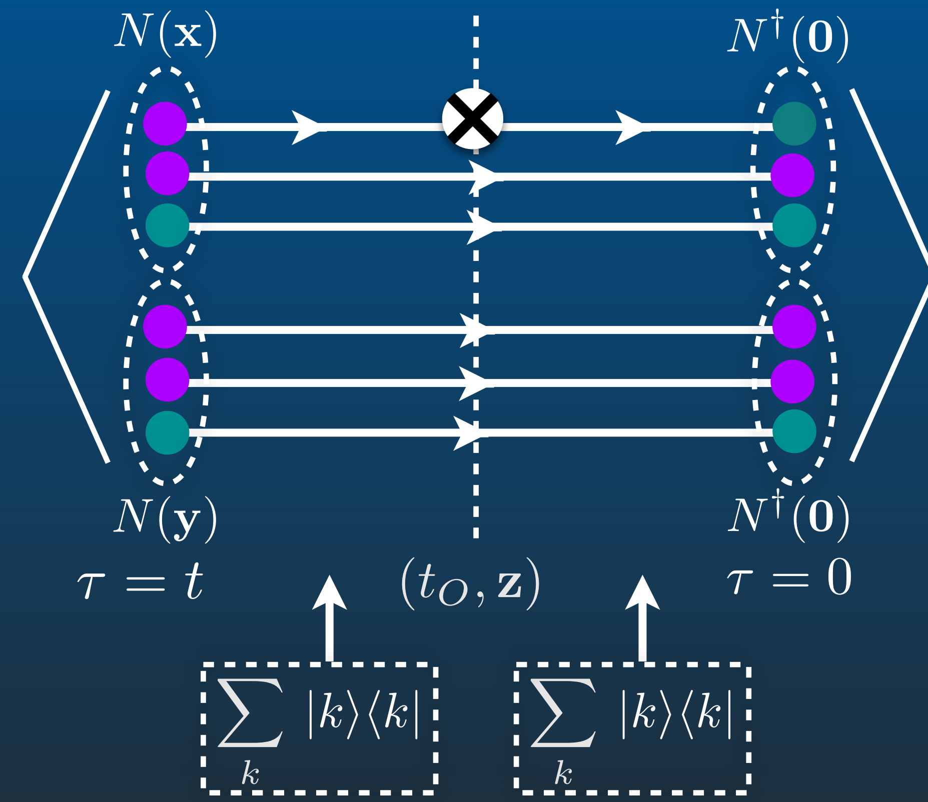
SINGLE-WEAK PROCESSES

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



TRADITIONAL MATRIX ELEMENT CALCULATIONS: 3-POINT FUNCTIONS

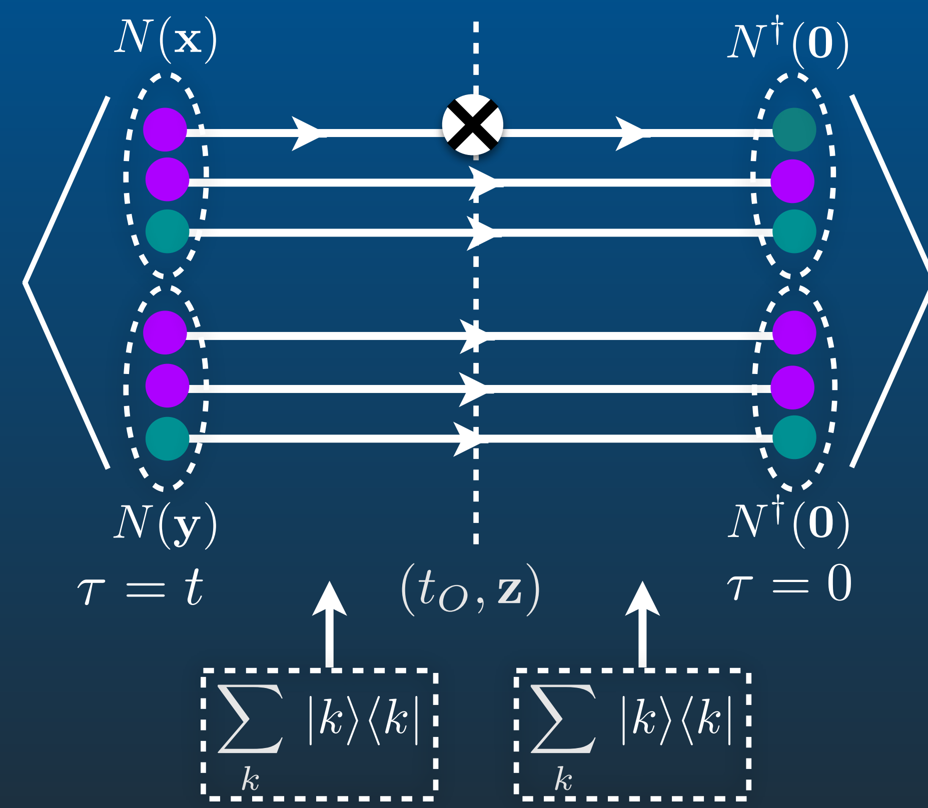
$$C(\mathbf{P}; t, t_O) = \sum_{\mathbf{p}_1+\mathbf{p}_2=\mathbf{P}} \sum_{\mathbf{x},\mathbf{y},\mathbf{z}} e^{i\mathbf{p}_1\cdot\mathbf{x}+i\mathbf{p}_2\cdot\mathbf{y}} \times$$



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

TRADITIONAL MATRIX ELEMENT CALCULATIONS: 3-POINT FUNCTIONS

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



$$= Z_{0,pp}^{\mathrm{src}} Z_{0,d}^{\mathrm{snk}\,\dagger} e^{-E_{0,pp}t_O} e^{-E_{0,d}(t-t_O)} \left\langle pn \left| A \right| pp \right\rangle_L + \ldots$$

MATRIX ELEMENTS FROM A COMPOUND PROPAGATOR/BACKGROUND FIELD

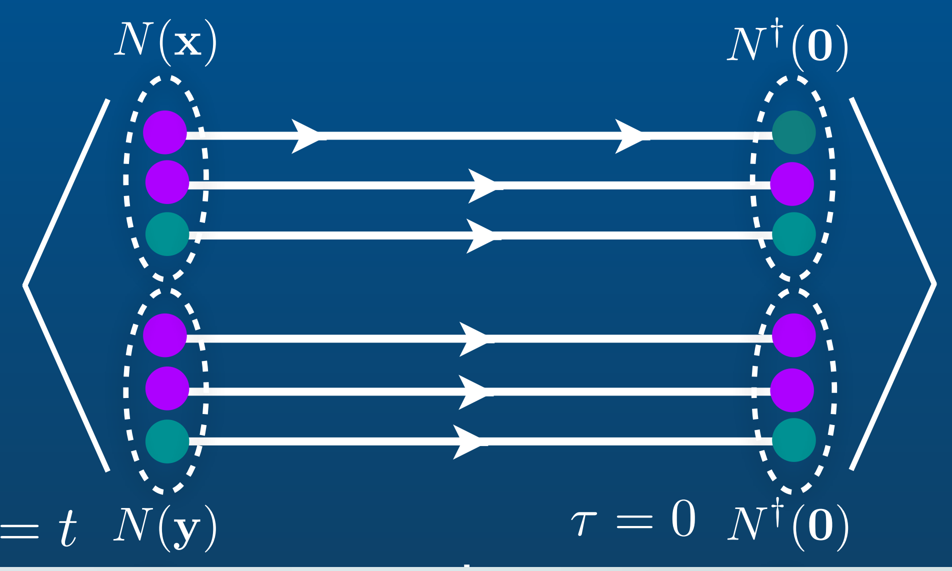
$$S^{(q)}_{\lambda_q;\Gamma}(x,y) = S^{(q)}(x,y) + \lambda_q \int dz\; S^{(q)}(x,z)\Gamma S^{(q)}(z,y)$$

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

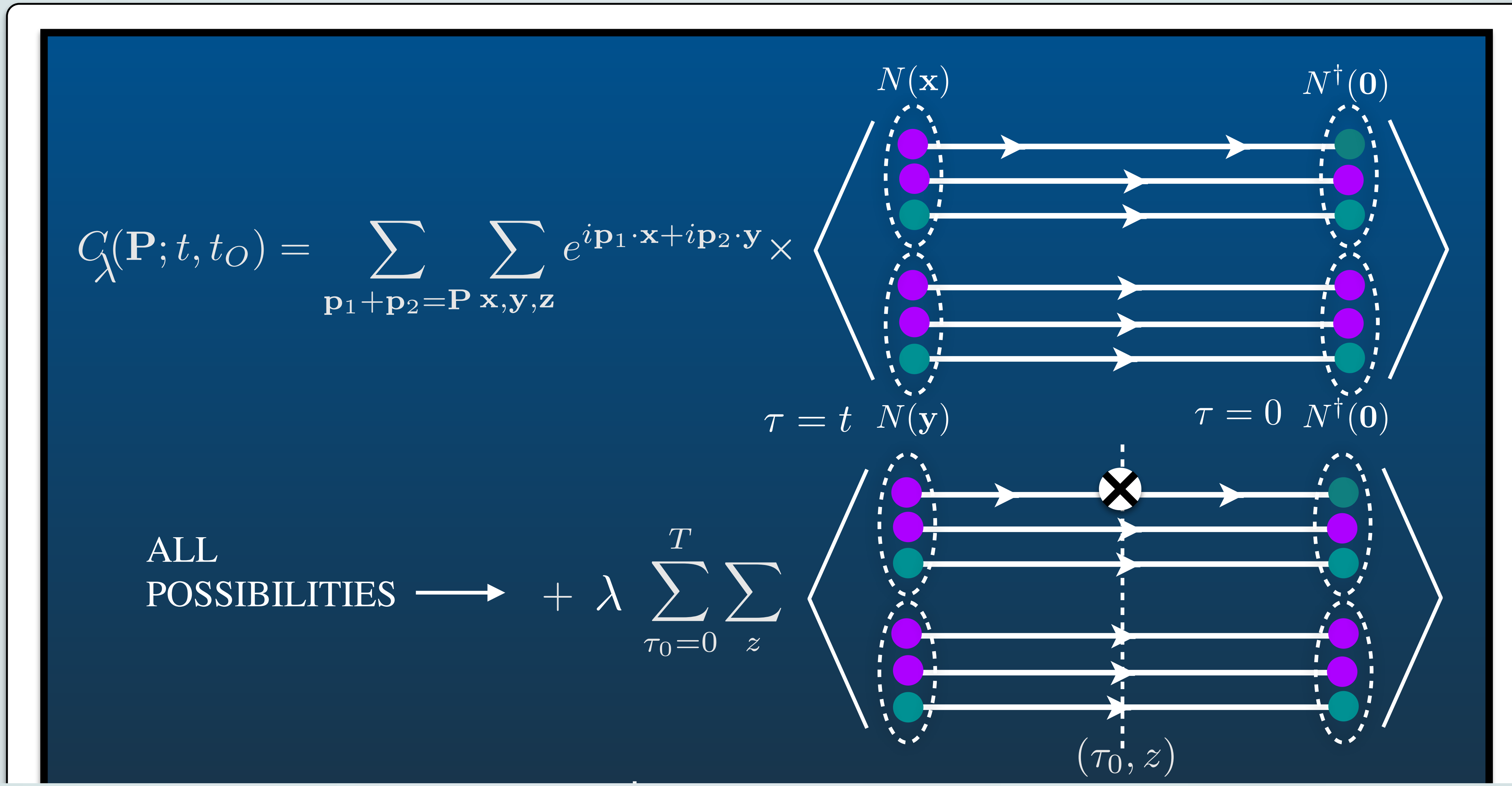
Buochard et al (CALLATT), Phys.Rev.D96,014504(2017).

MATRIX ELEMENTS FROM A COMPOUND PROPAGATOR/BACKGROUND FIELD

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

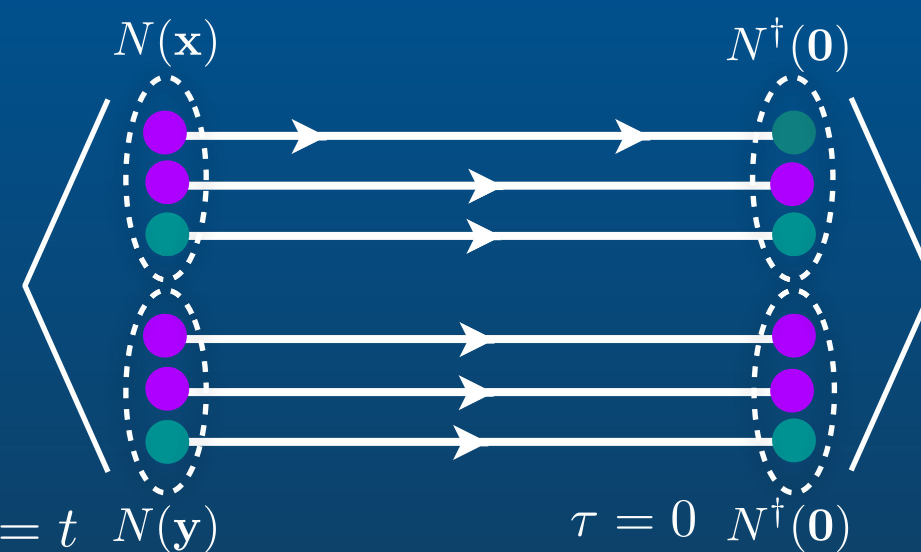


MATRIX ELEMENTS FROM A COMPOUND PROPAGATOR/BACKGROUND FIELD



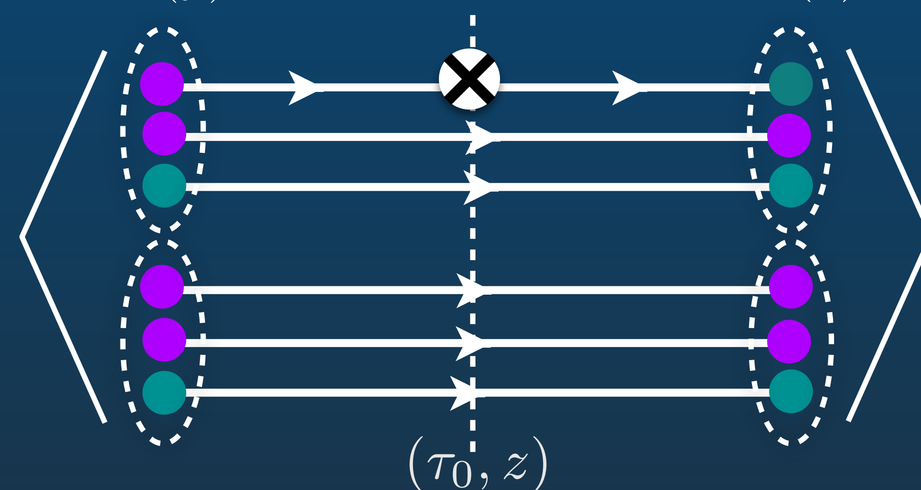
MATRIX ELEMENTS FROM A COMPOUND PROPAGATOR/BACKGROUND FIELD

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



ALL POSSIBILITIES →

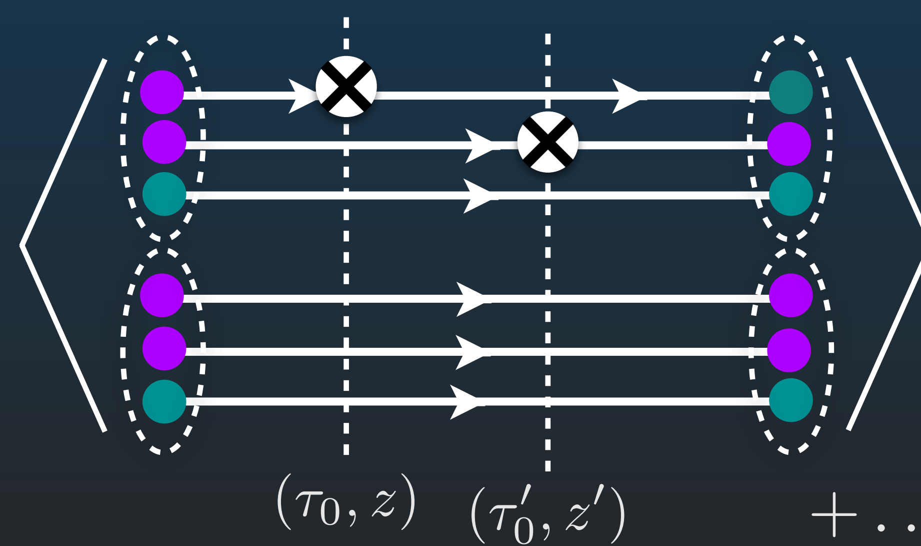
$$+\lambda \sum_{\tau_0=0}^{T} \sum_{z}$$



TIME-ORDERED PRODUCT ↓

ALL POSSIBILITIES →

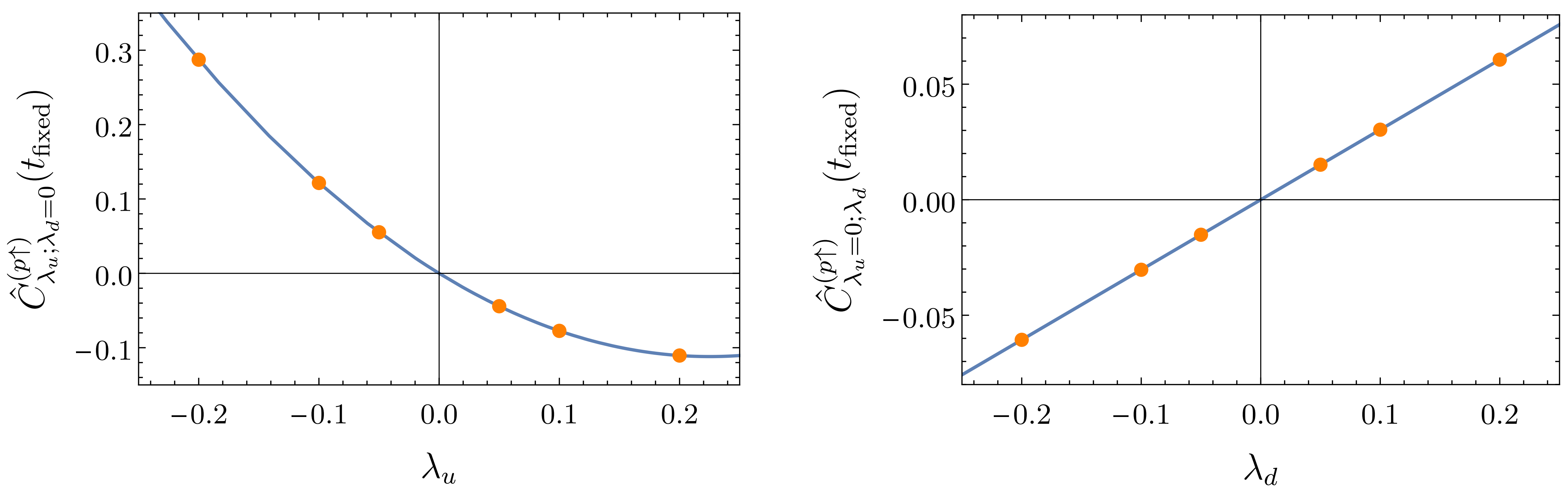
$$+\lambda^2 \sum_{\tau_0=0}^{T} \sum_{\tau_0'=0}^{T} \sum_{z} \sum_{z'}$$



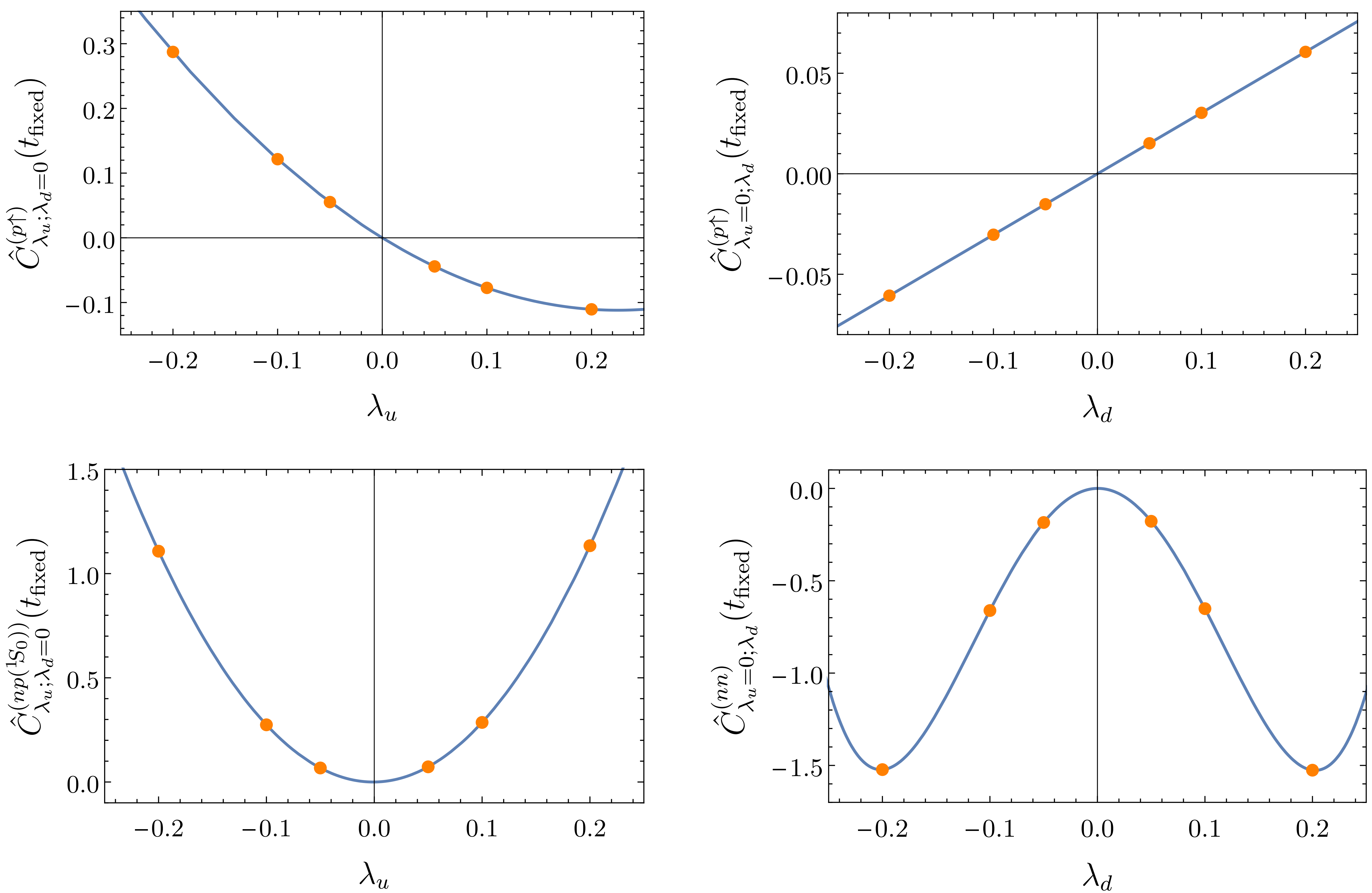
$+ \ldots$

DOUBLE-CURRENT MES ARE EXACT FOR ISOTENSOR QUANTITIES.

MATRIX ELEMENTS FROM A COMPOUND PROPAGATOR/BACKGROUND FIELD



MATRIX ELEMENTS FROM A COMPOUND PROPAGATOR/BACKGROUND FIELD

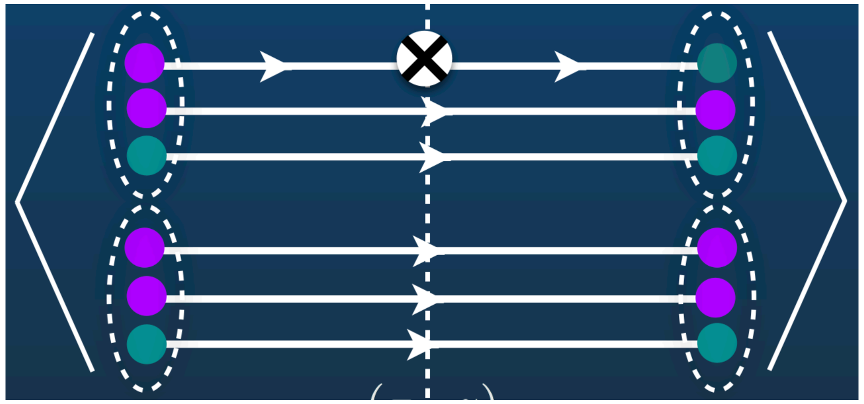


Tiburzi et al (NPLQCD), Phys. Rev. D 96, 054505 (2017).

FIRST-ORDER RESPONSE TO AN AXIAL BACKGROUND FIELD

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

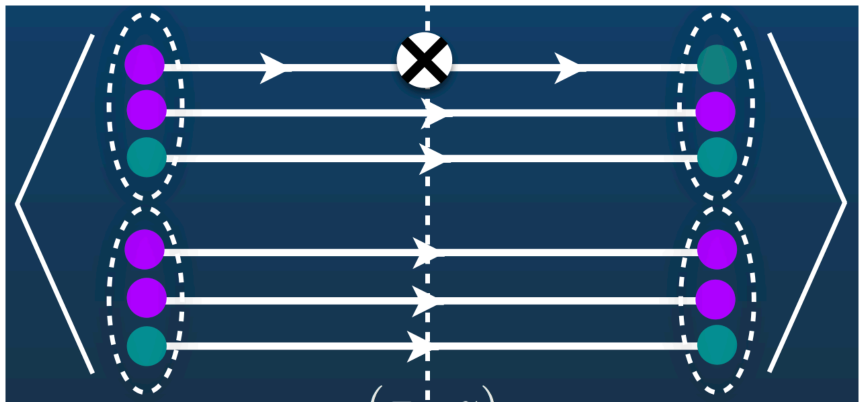
$$C^{({}^3S_1,{}^1S_0)}_{\lambda_u=0;\lambda_d}(t) = \lambda_d \sum_{t_1=0}^{t} \sum_{\boldsymbol{x},\boldsymbol{y}} \langle 0|\chi_{{}^3S_1}(\boldsymbol{x},t) J_3^{(d)}(\boldsymbol{y},t_1)\chi^\dagger_{{}^1S_0}(0)|0\rangle + \; b_2\lambda_d^2 + b_3\lambda_d^3,$$



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).

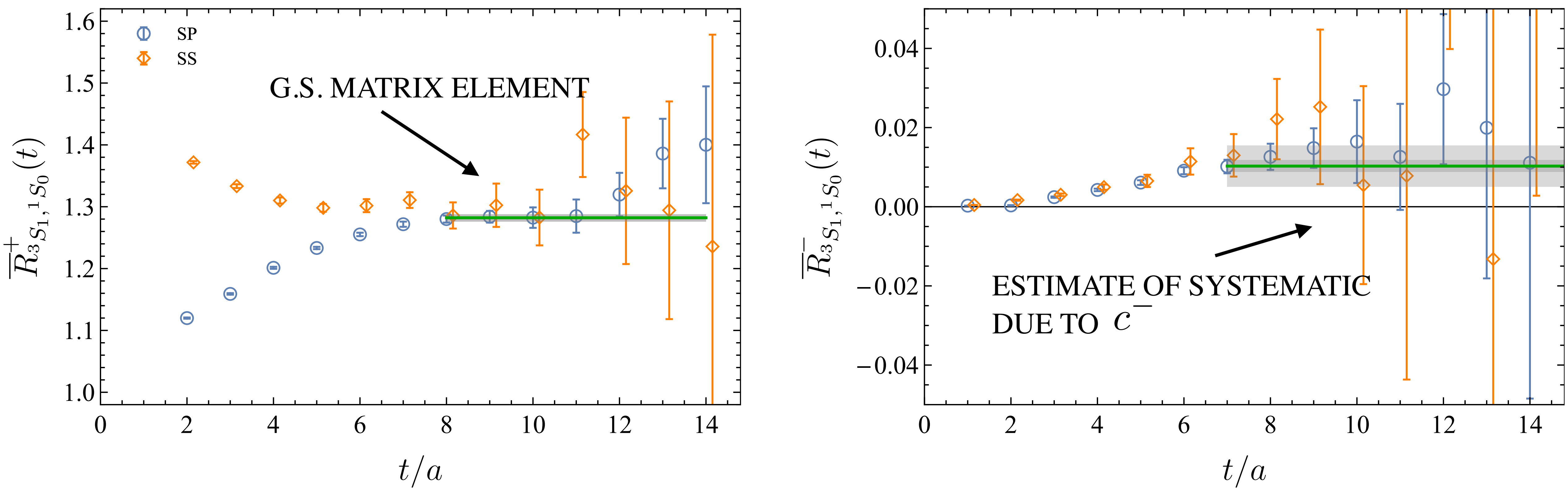
MATRIX ELEMENT FROM QCD

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), Phys. Rev. Lett.119,062002(2017).

AVERAGE AND DIFFERENCE OF CORRELATOR AND TIME-REVERSED CORREALTOR

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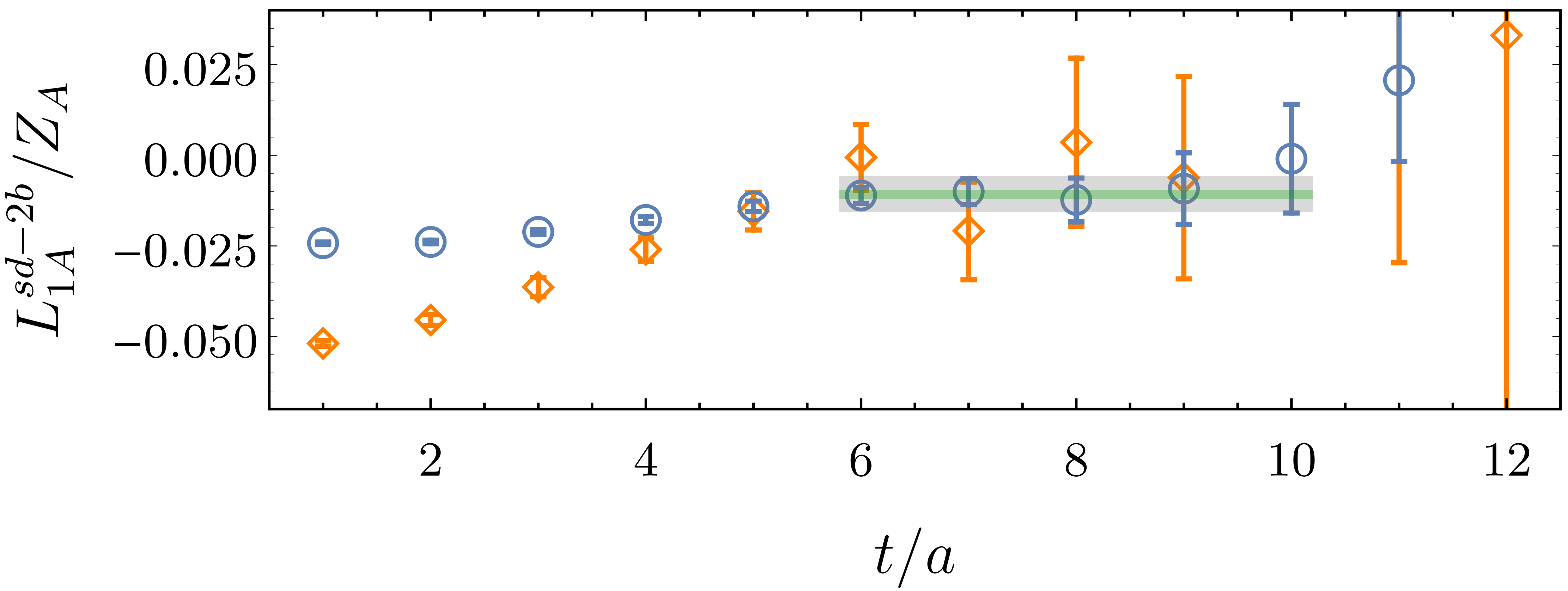
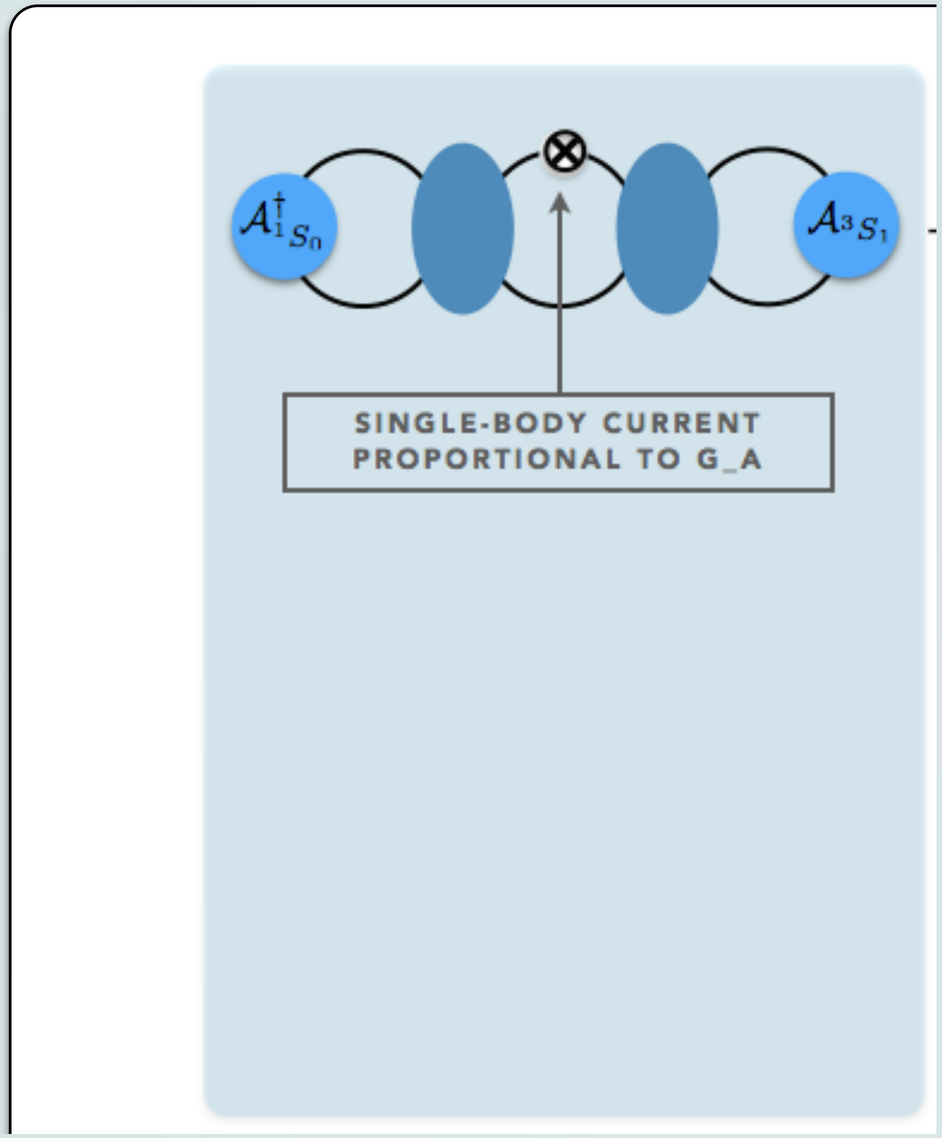


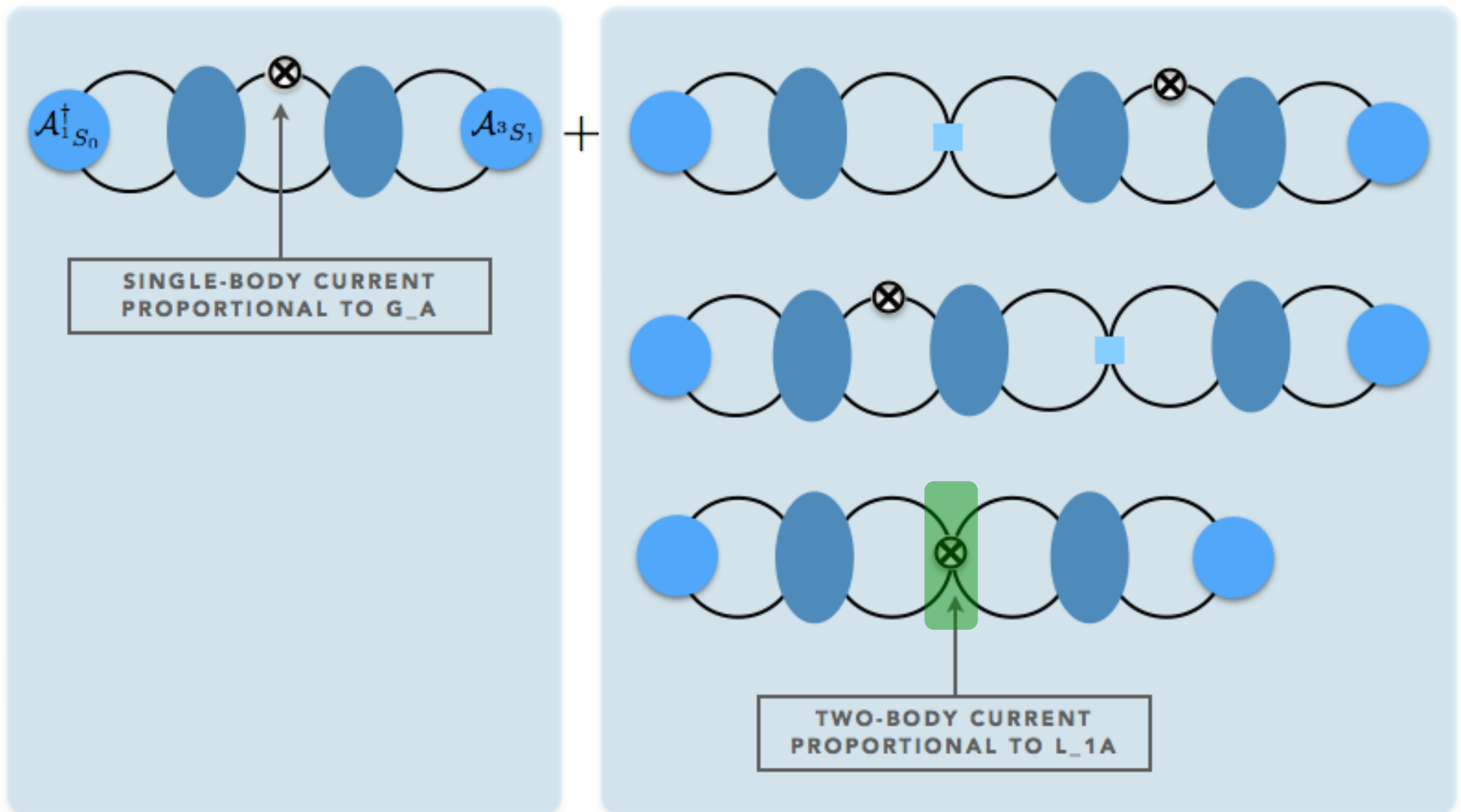
Savage et al (NPLQCD), Phys. Rev. Lett.119,062002(2017).

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

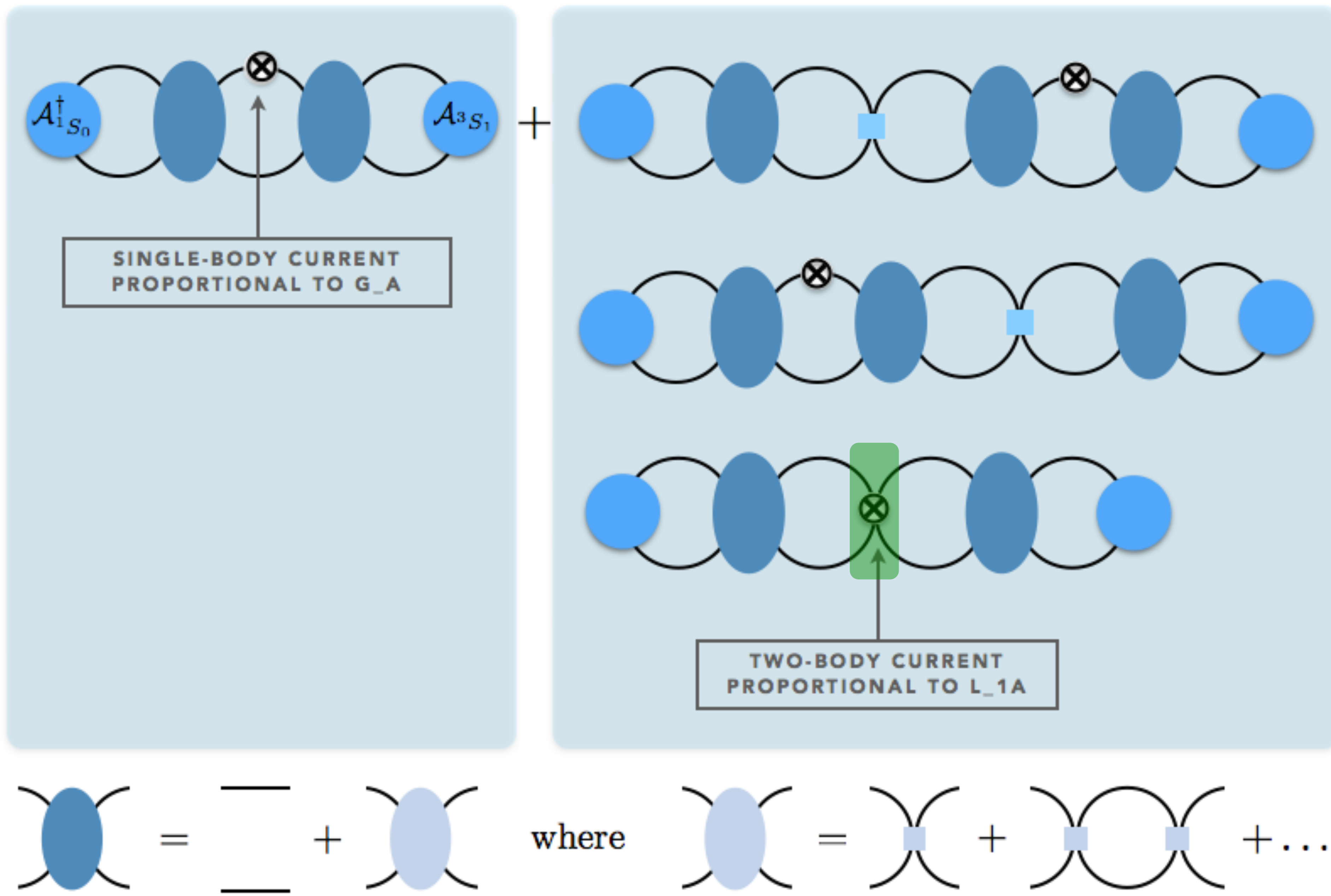
MATRIX ELEMENT FROM EFT



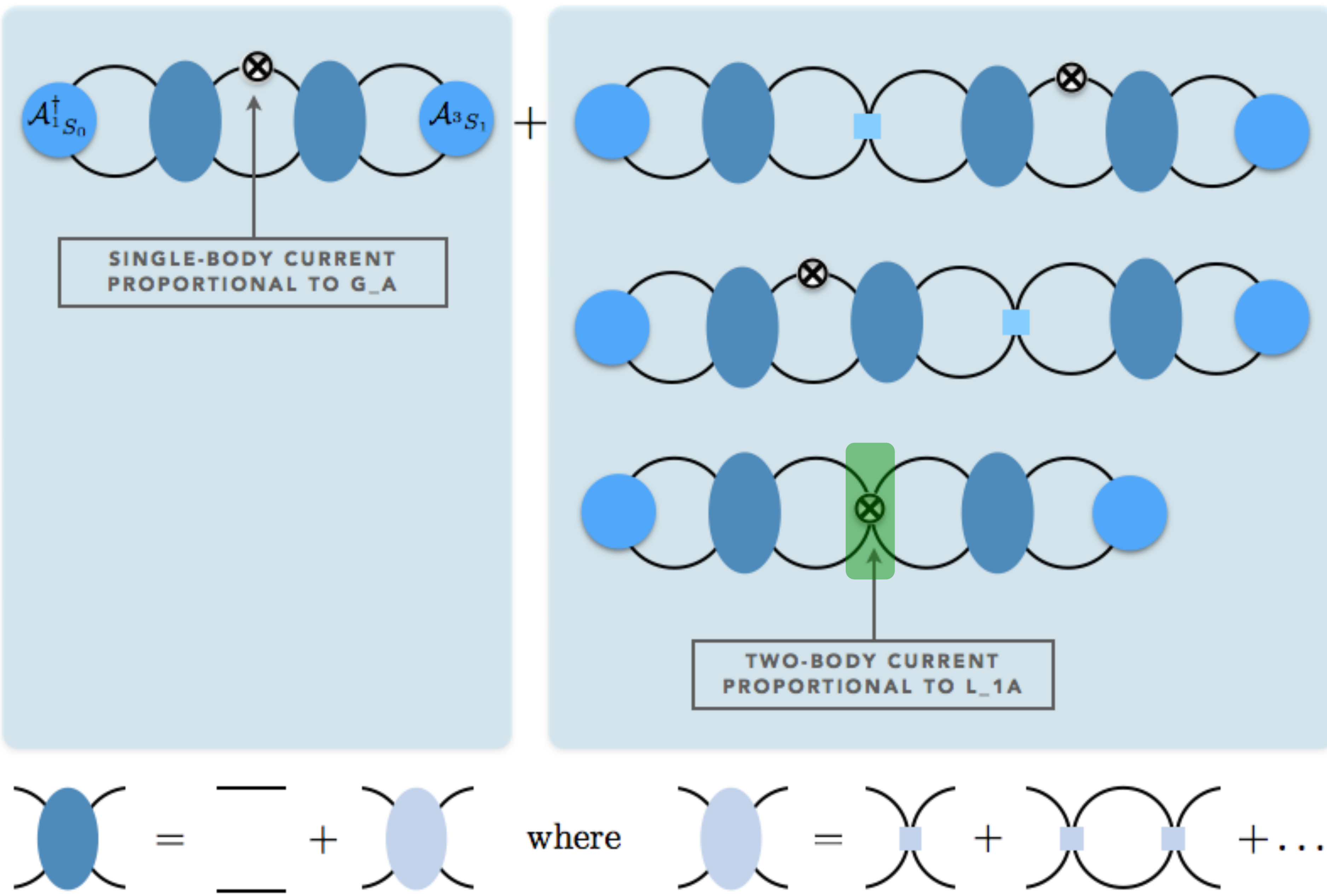
MATRIX ELEMENT FROM EFT



MATRIX ELEMENT FROM EFT



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.

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

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

TWO-NUCLEON SHORT-DISTANCE COUPLING

FROM TRITON LIFETIME:

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

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

TWO-NUCLEON SHORT-DISTANCE COUPLING

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

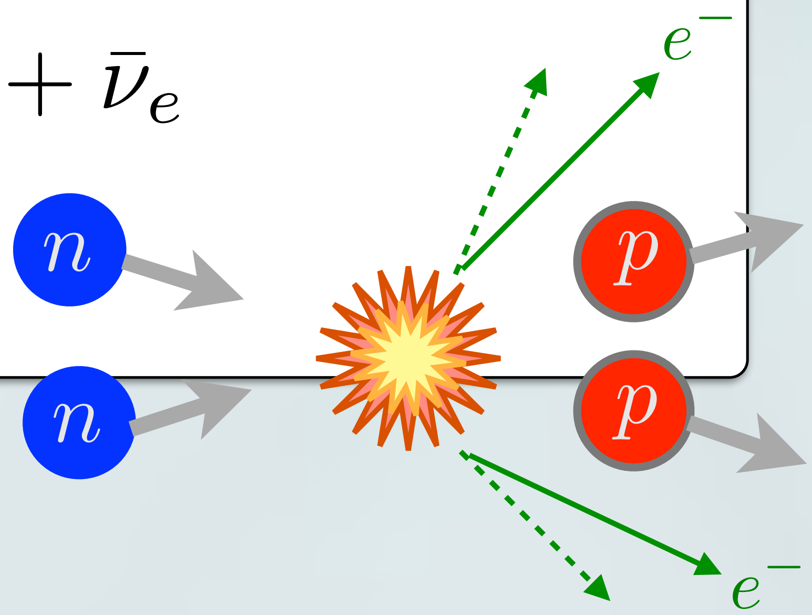
THIS WORK:

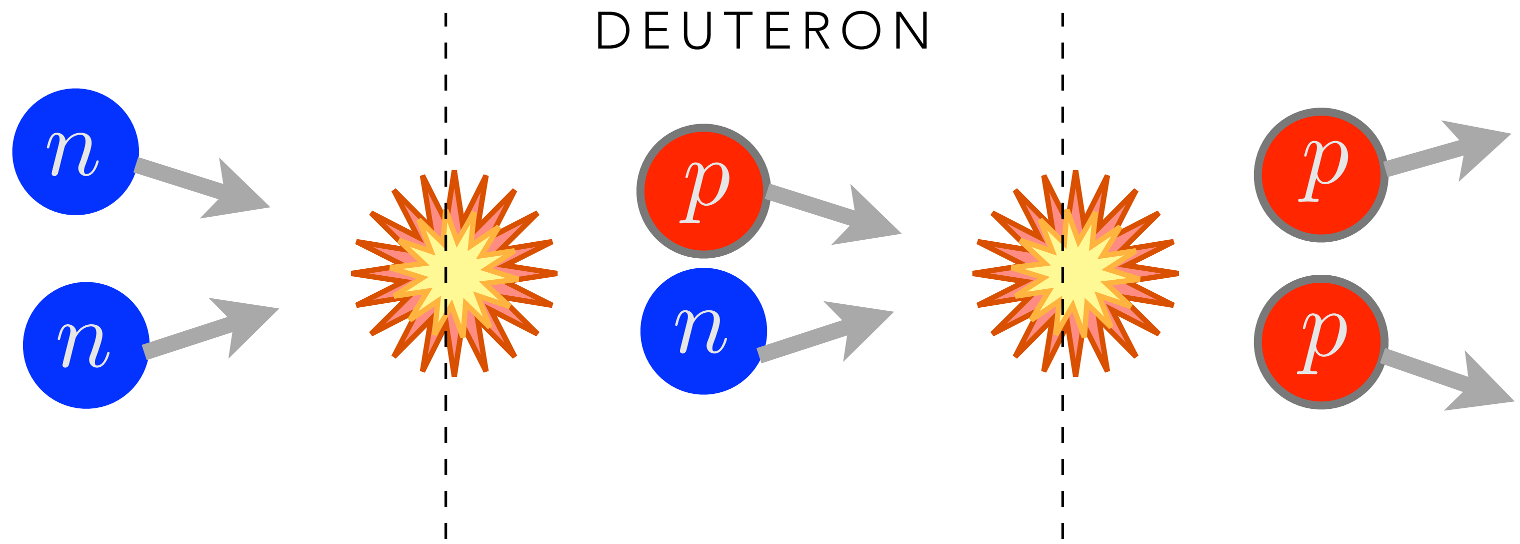
$$L_{1,A} \approx 3.9(0.2)(1.0)(0.4)(0.9)\ \text{fm}^3 \ \text{@}\ \ \mu = m_\pi^{\text{phys.}} = 140\ \text{MeV}$$

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

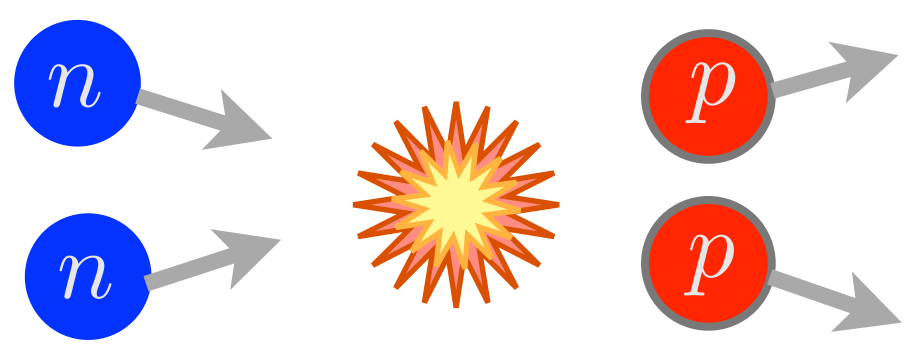
NEUTRINOFUL DOUBLE-BETA DECAY

$$n + n \rightarrow p + p + e + e + \bar{\nu}_e + \bar{\nu}_e$$





LONG-DISTANCE PIECE

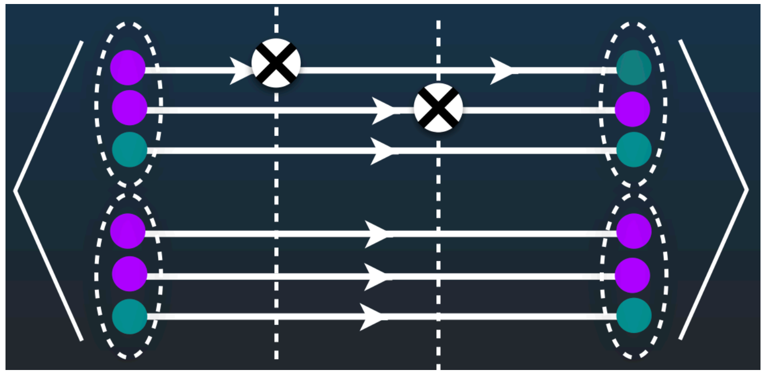


SHORT-DISTANCE PIECE

SECOND-ORDER RESPONSE TO AN AXIAL BACKGROUND FIELD

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

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

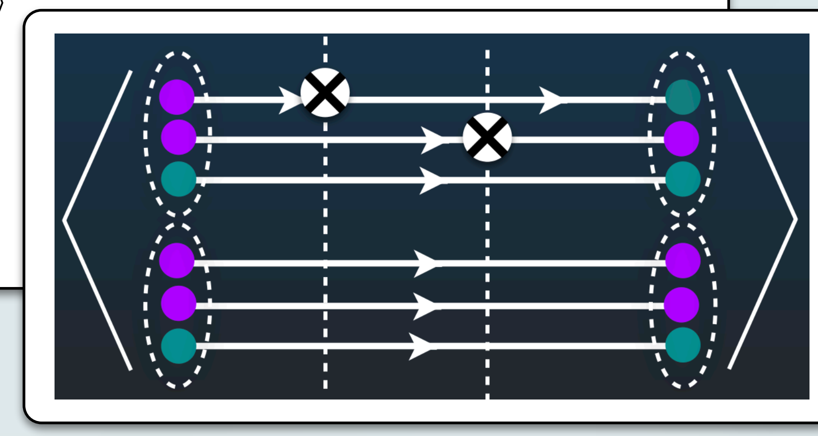


SECOND-ORDER RESPONSE TO AN AXIAL BACKGROUND FIELD

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

$$\downarrow$$

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



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!

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

MATRIX ELEMENT FROM QCD

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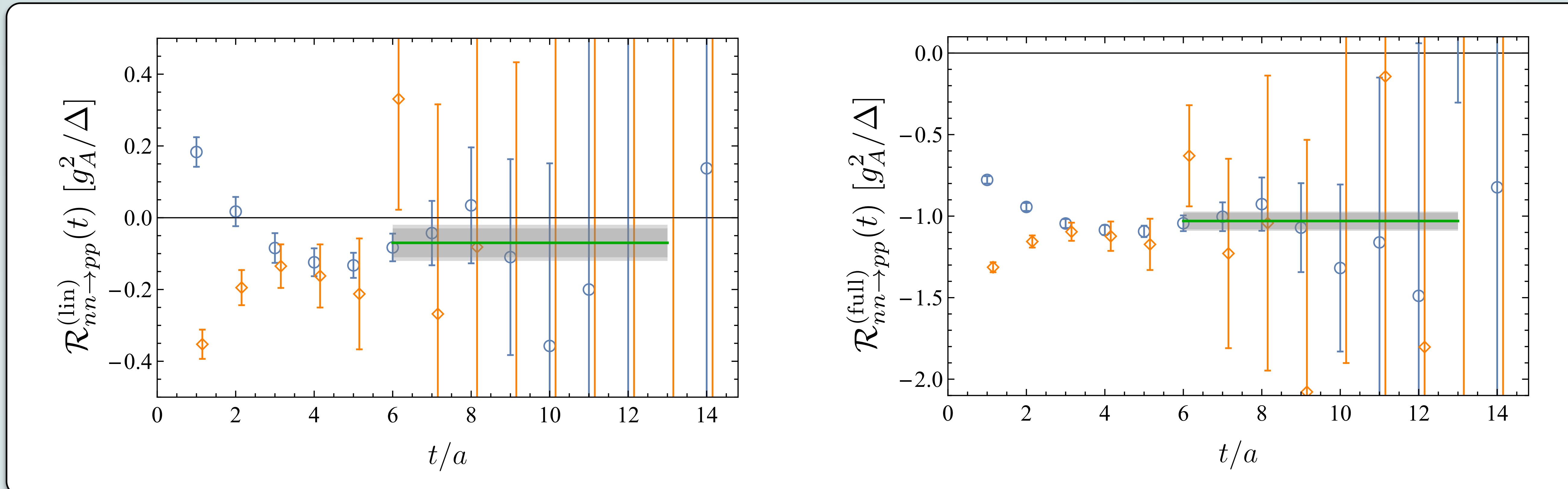
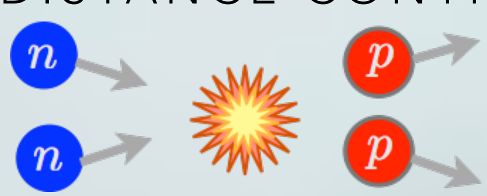
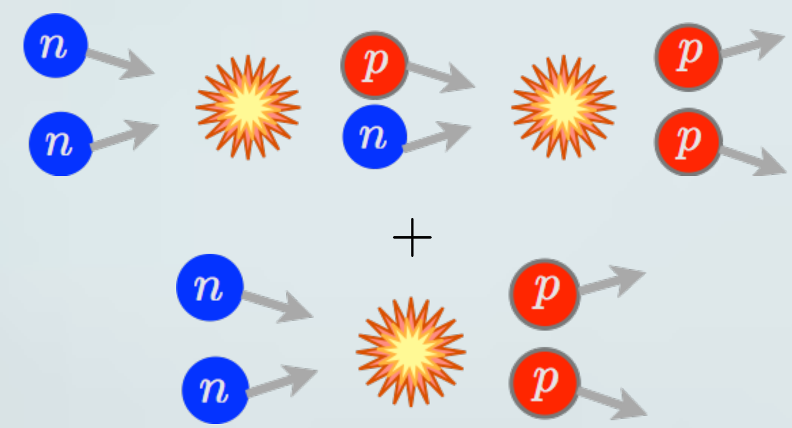


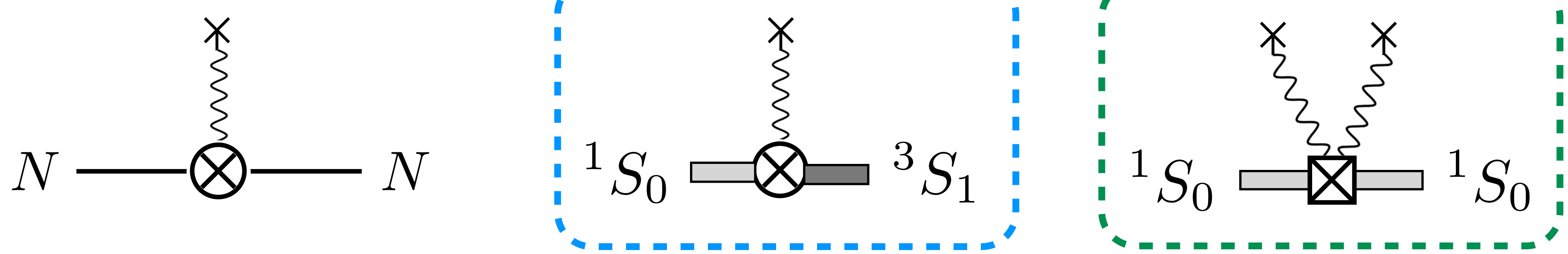
SHORT-DISTANCE CONTRIBUTION

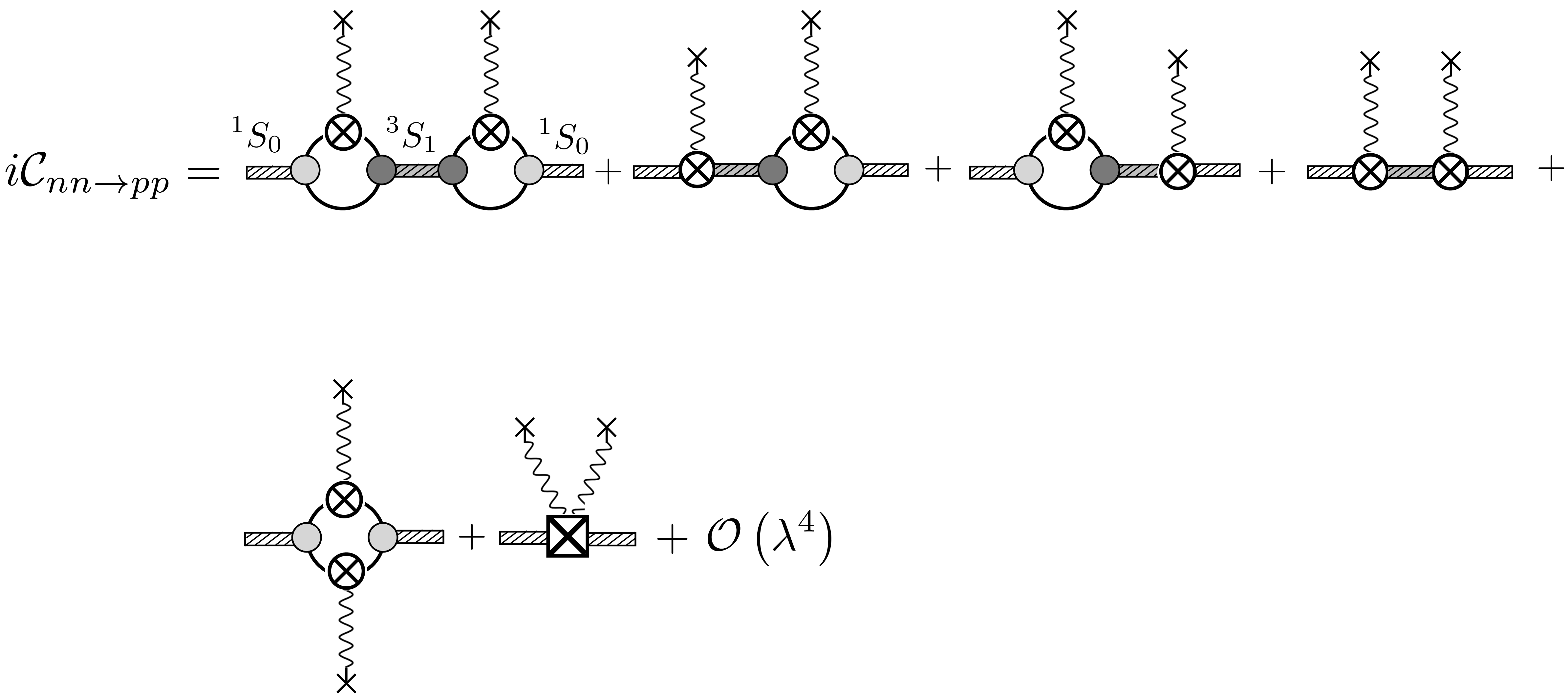


FULL CONTRIBUTION



EFT VERTICES AND CORRELATION FUNCTIONS USING DIBARYONS





Tiburzi et al (NPLQCD), Phys. Rev.D96,054505(2017)
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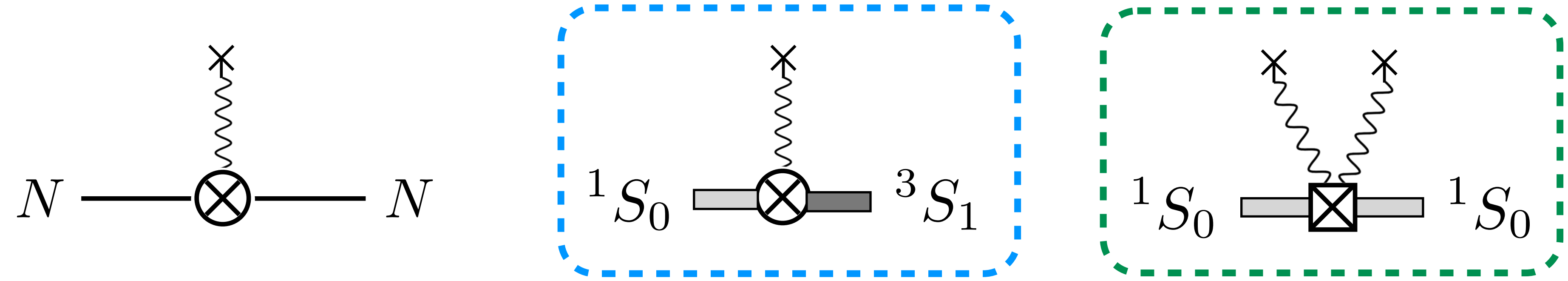
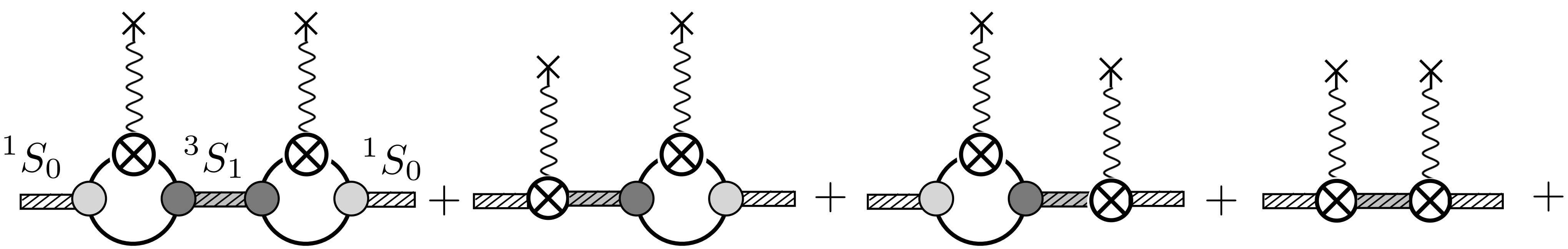
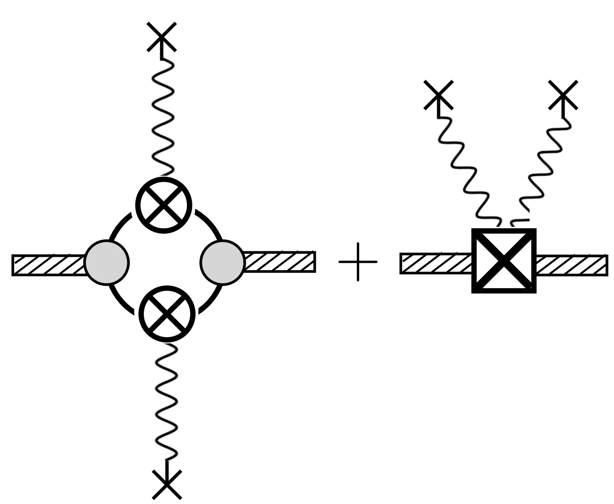


$i\mathcal{C}_{nn\to pp} =$



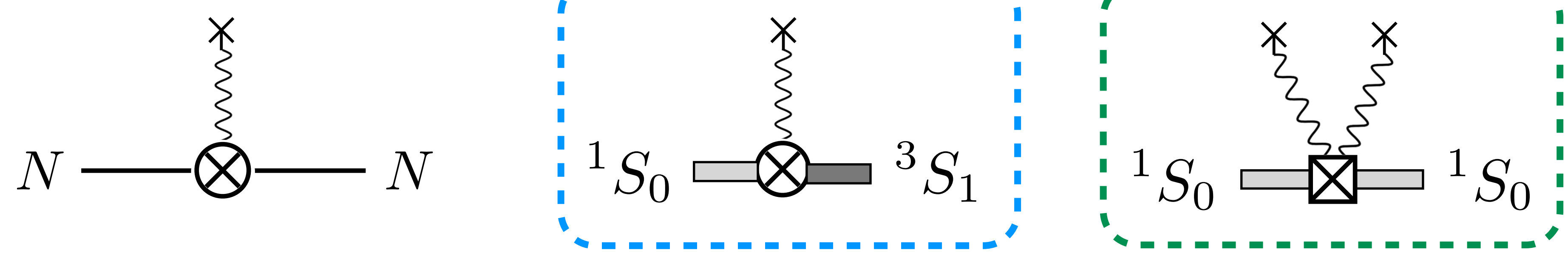
Give partly the dominant long-range contribution

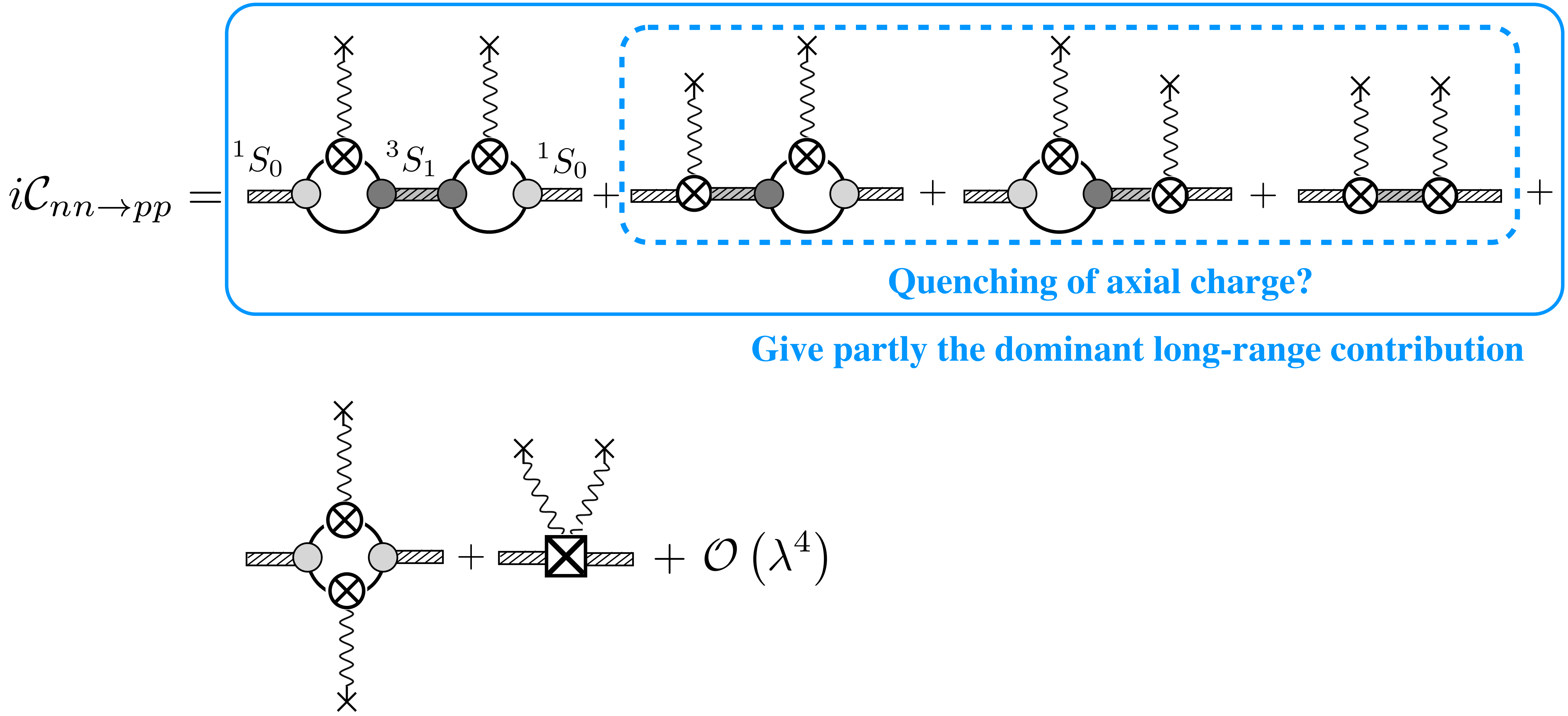


$+\ \mathcal{O}\left(\lambda^4\right)$

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

EFT VERTICES AND CORRELATION FUNCTIONS USING DIBARYONS





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

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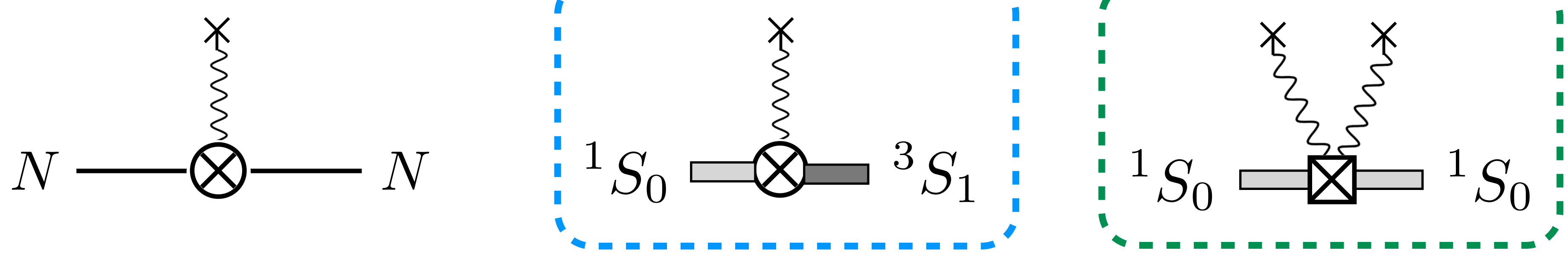
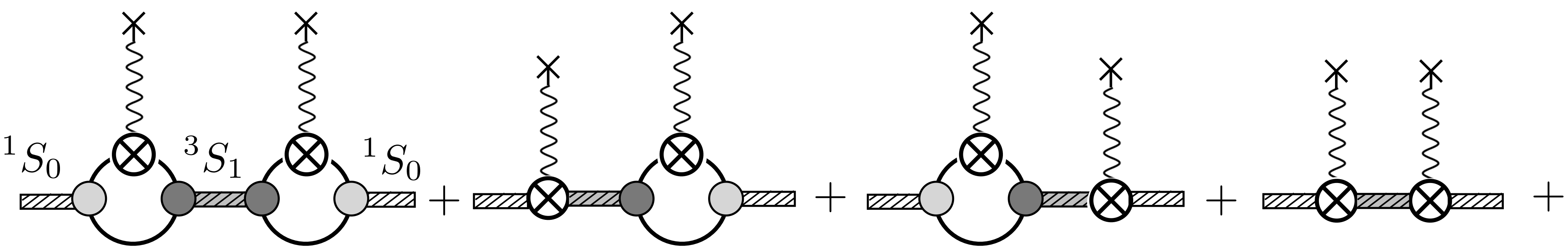
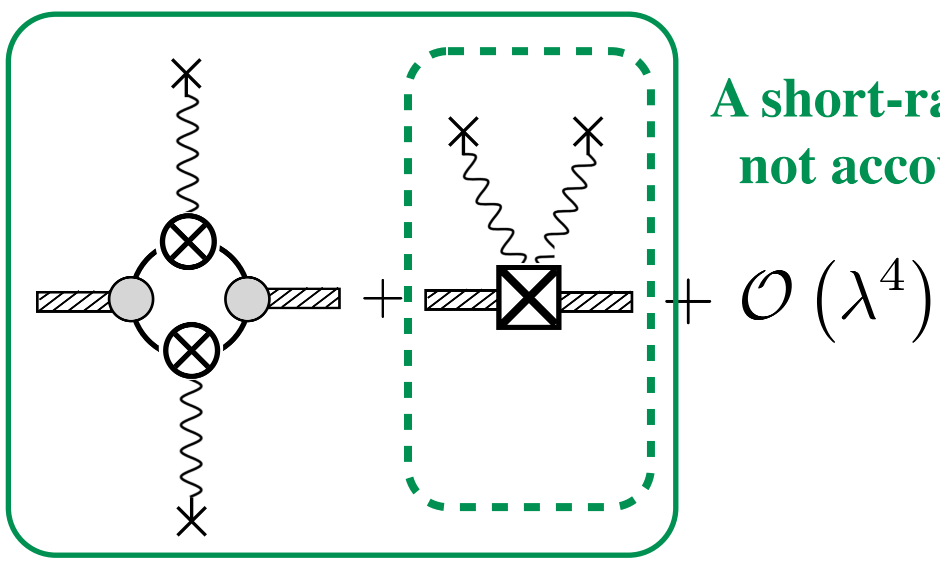


$i\mathcal{C}_{nn\to pp} =$

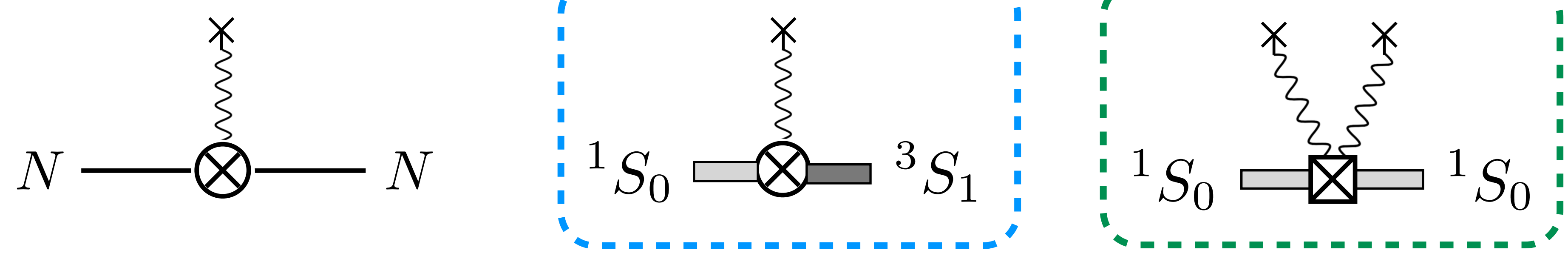


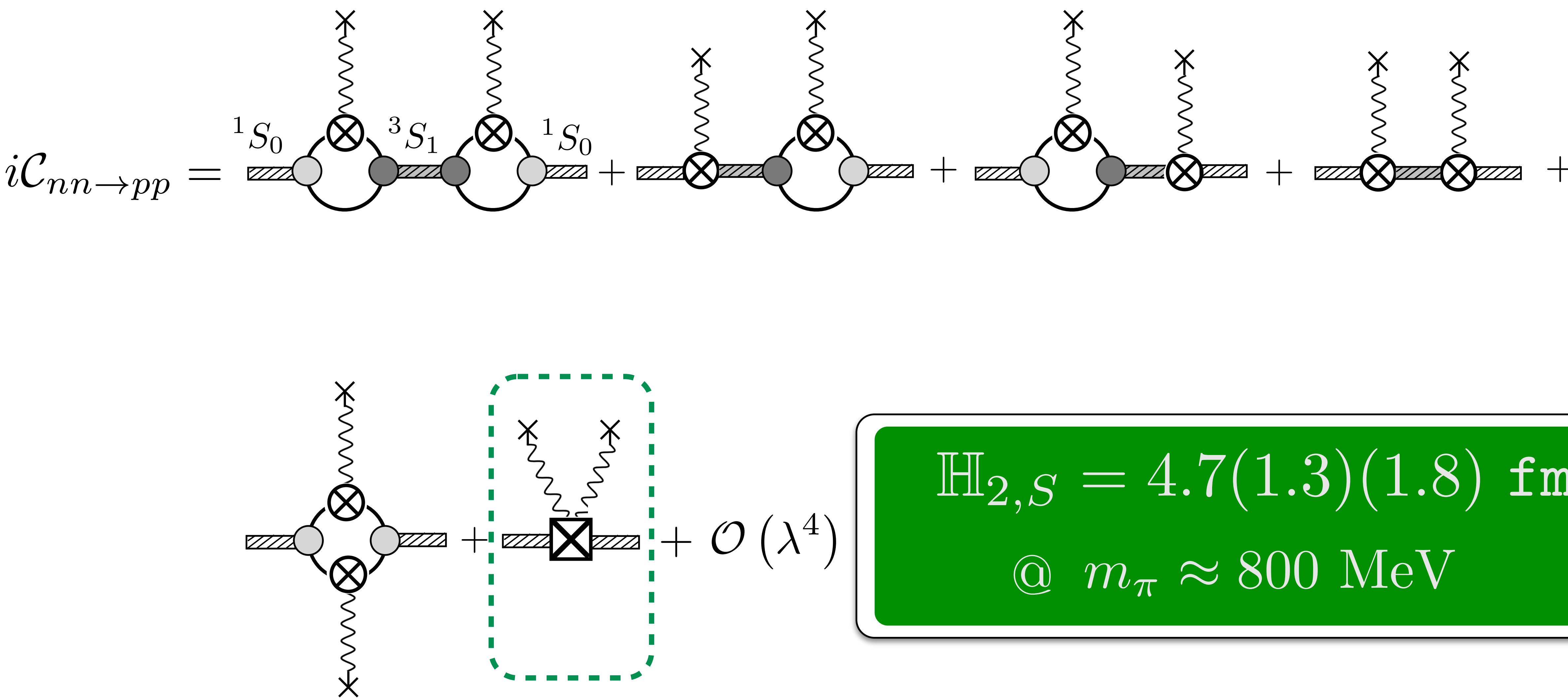


A short-range contribution not accounted for before

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

EFT VERTICES AND CORRELATION FUNCTIONS USING DIBARYONS



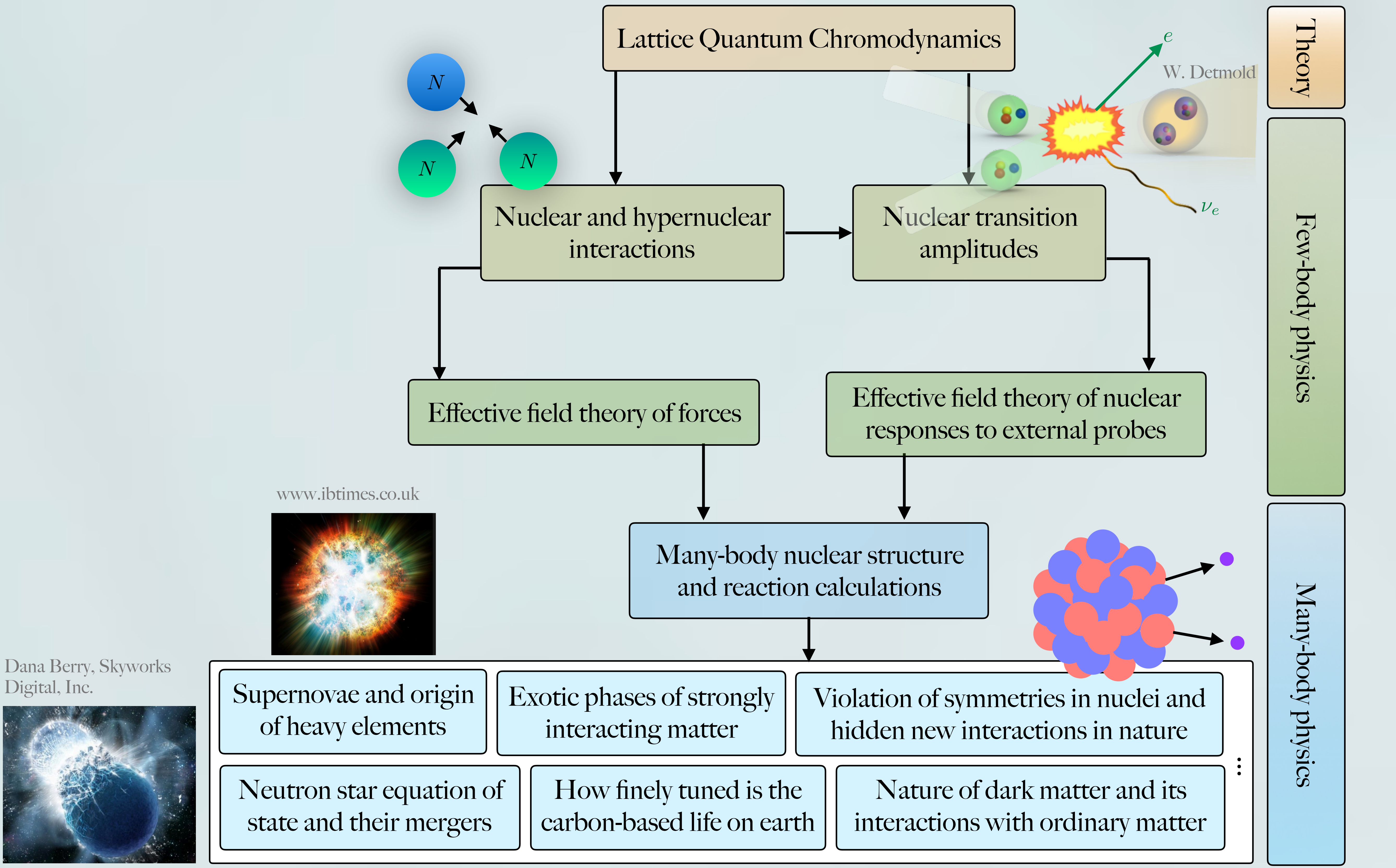


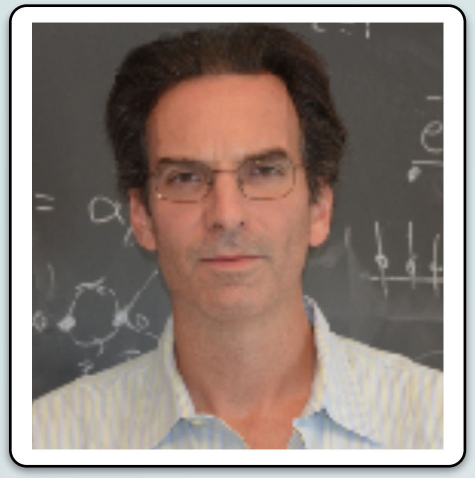
$$\mathbb{H}_{2,S} = 4.7(1.3)(1.8)\ \mathtt{fm}$$

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

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

NUCLEAR PHYSICS FROM FIRST-PRINCIPLES ROADMAP





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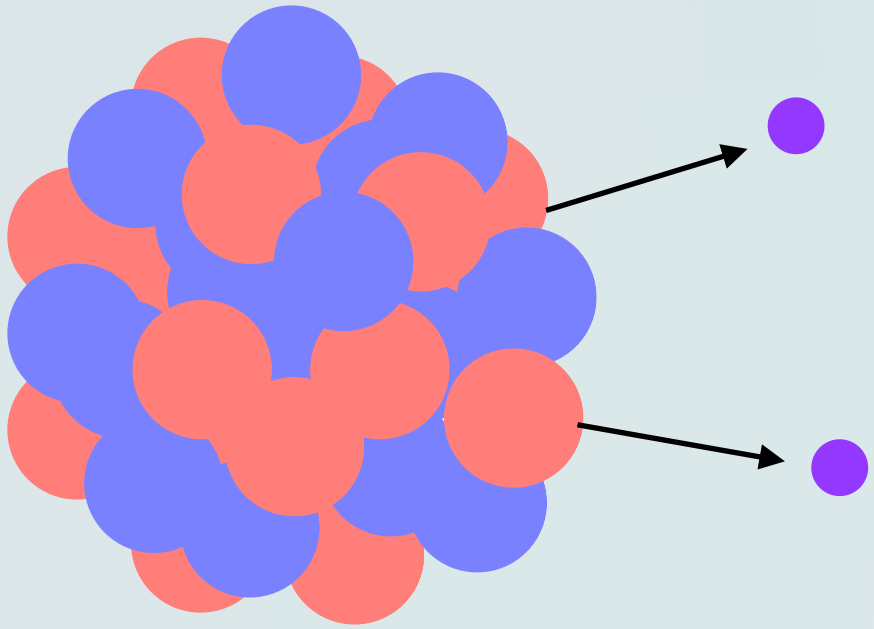

THANK YOU