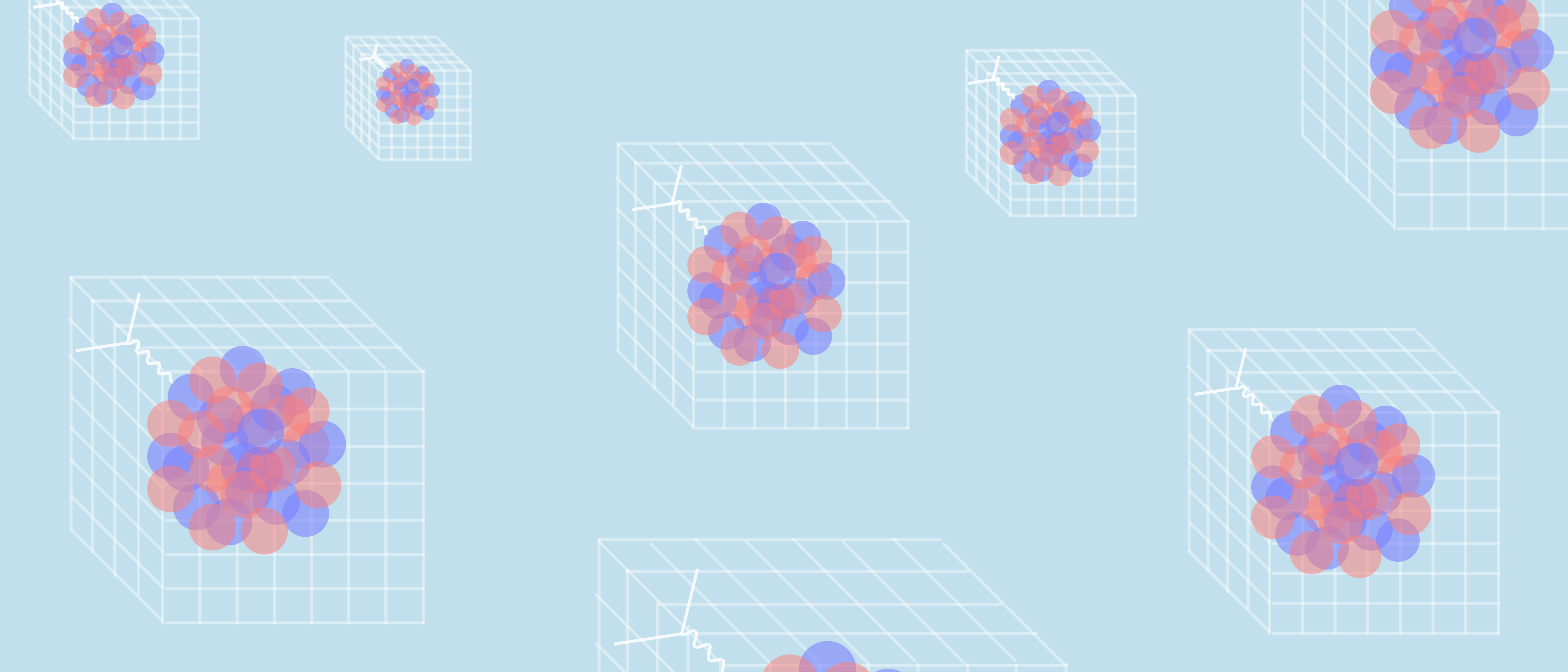

THE 2021 RDP SCHOOL & WORKSHOP ON
“ASPECTS OF SYMMETRY”

Lattice QCD, Fundamental Symmetries, and Neutrinoless Double Beta Decay

ZOHREH DAVOUDI
UNIVERSITY OF MARYLAND

THREE USQCD WHITEPAPERS FROM 2019 SET THE GUIDELINES IN FUNDAMENTAL SYMMETRY PROGRAM:

Springer Link

Regular Article - Theoretical Physics | Published: 14 November 2019

Lattice QCD and neutrino-nucleus scattering

Andreas S. Kronfeld, David G. Richards, William Detmold, Rajan Gupta, Huey-Wen Lin, Keh-Fei Liu, Aaron S. Meyer, Raza Sufian & Sergey Syritsyn

The European Physical Journal A **55**, Article number: 196 (2019) | Cite this article

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Review | Published: 14 November 2019

The role of Lattice QCD in searches for violations of fundamental symmetries and signals for new physics

USQCD Collaboration, Vincenzo Cirigliano, Zohreh Davoudi, Tanmoy Bhattacharya, Taku Izubuchi, Phiala E. Shanahan, Sergey Syritsyn & Michael L. Wagman

The European Physical Journal A **55**, Article number: 197 (2019) | Cite this article

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Review | Published: 14 November 2019

Opportunities for Lattice QCD in quark and lepton flavor physics

USQCD Collaboration, Christoph Lehner, Stefan Meinel, Tom Blum, Norman H. Christ, Aida X. El-Khadra, Maxwell T. Hansen, Andreas S. Kronfeld, Jack Laiho, Ethan T. Neil, Stephen R. Sharpe & Ruth S. Van de Water

The European Physical Journal A **55**, Article number: 195 (2019) | Cite this article

I WILL DISCUSS AT LEAST TWO EXAMPLES…

Computing matrix elements of currents from lattice QCD

Lattice QCD, Fundamental Symmetries, and Neutrino Physics

Example: Nucleon axial charge and form factors for neutrino-nucleus scattering

Example: Neutrinofull and neutrinoless double beta decays

Computing matrix elements of currents from lattice QCD

T. Luu's talk!

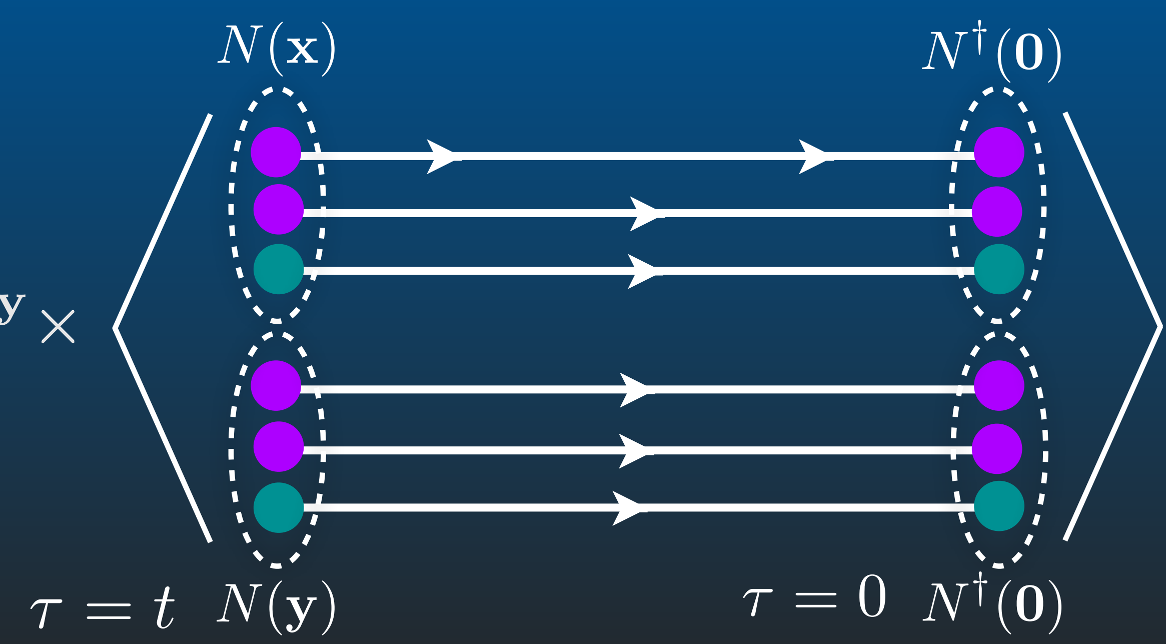
Lattice QCD, Fundamental Symmetries, and Neutrino Physics

Example: Nucleon axial charge and form factors for neutrino-nucleus scattering

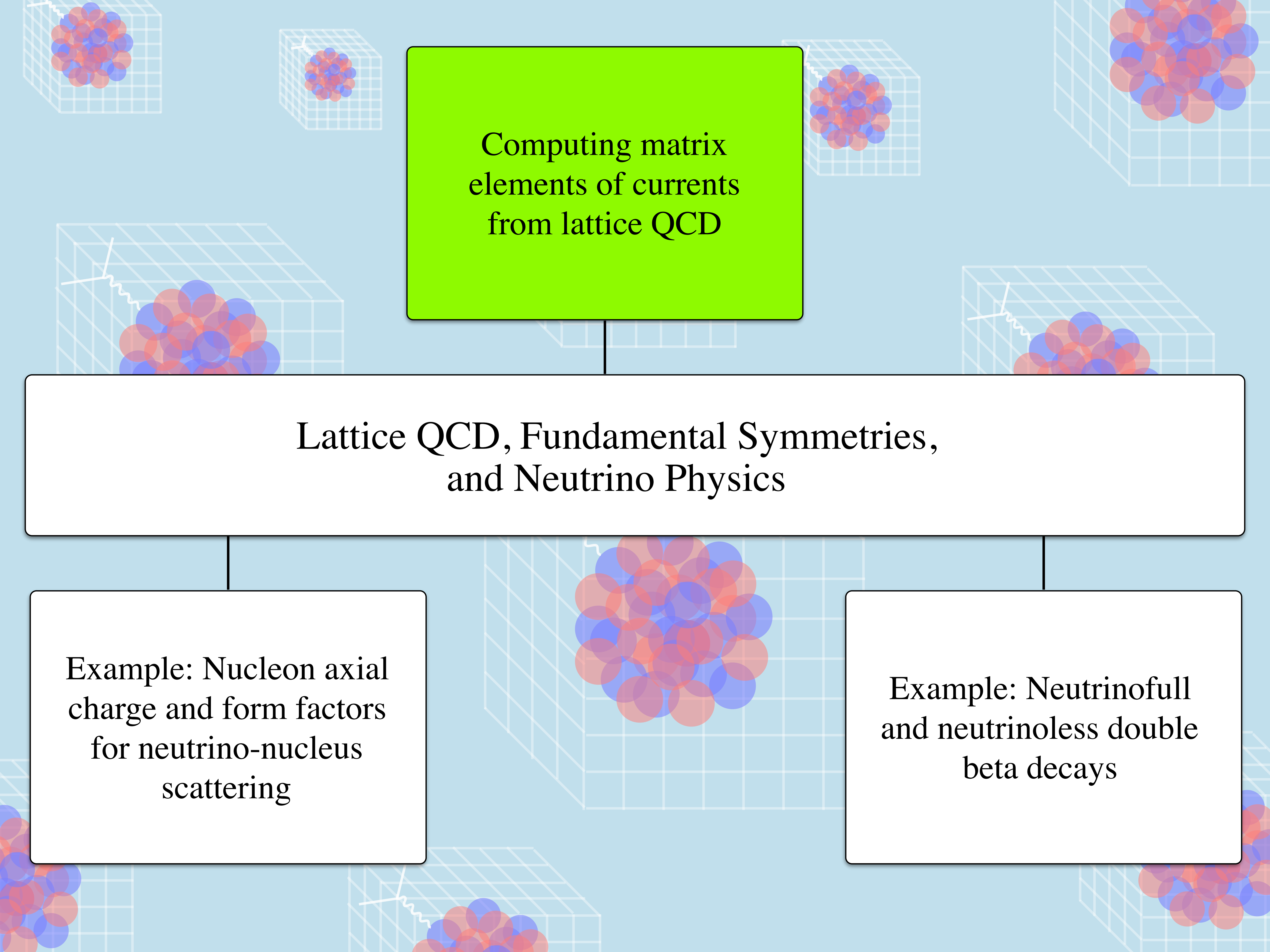
Example: Neutrinofull and neutrinoless double beta decays

The simplest objects to calculate using the lattice QCD method are two-point correlation functions…they give access to energy spectrum and more.

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



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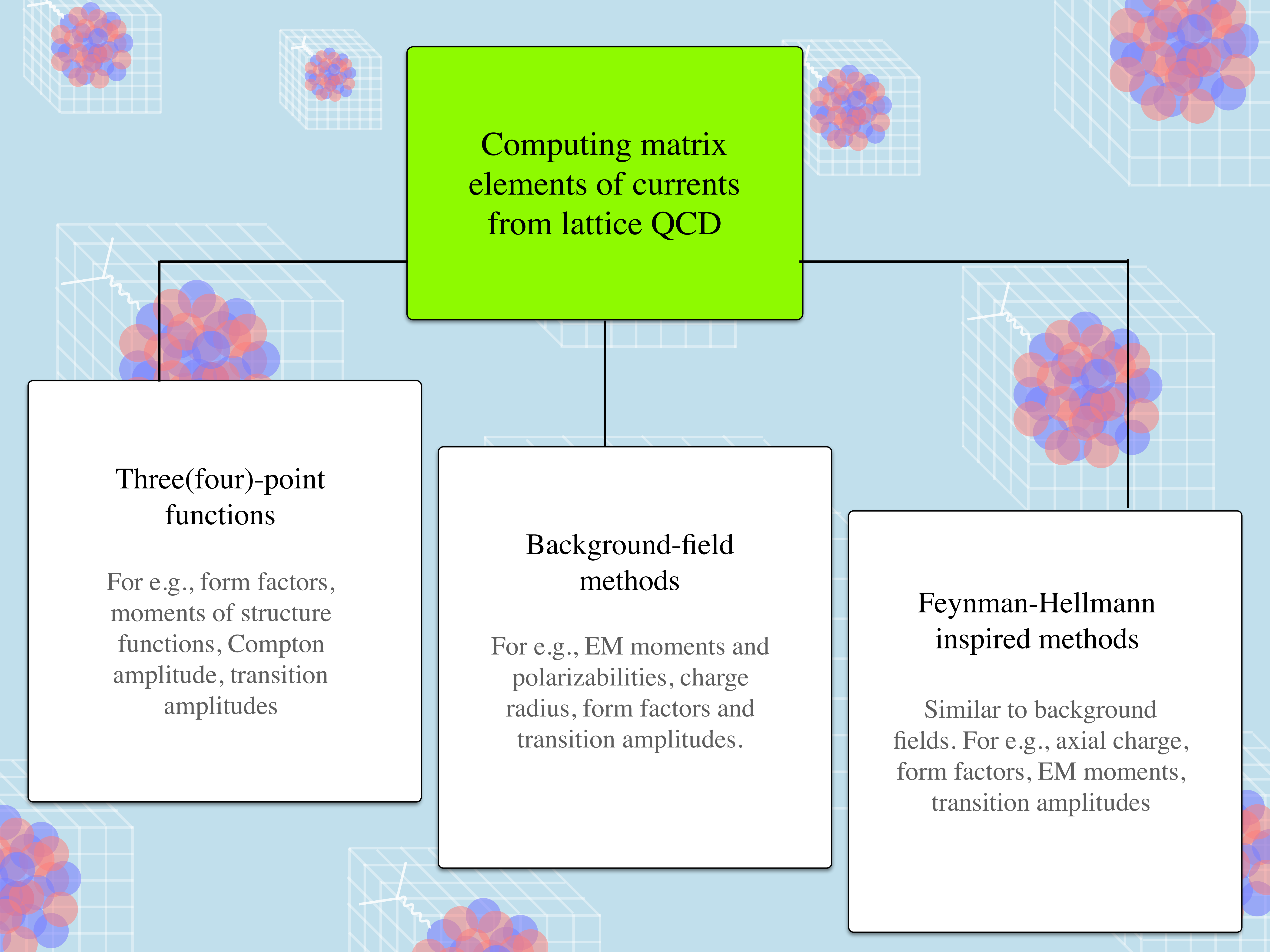
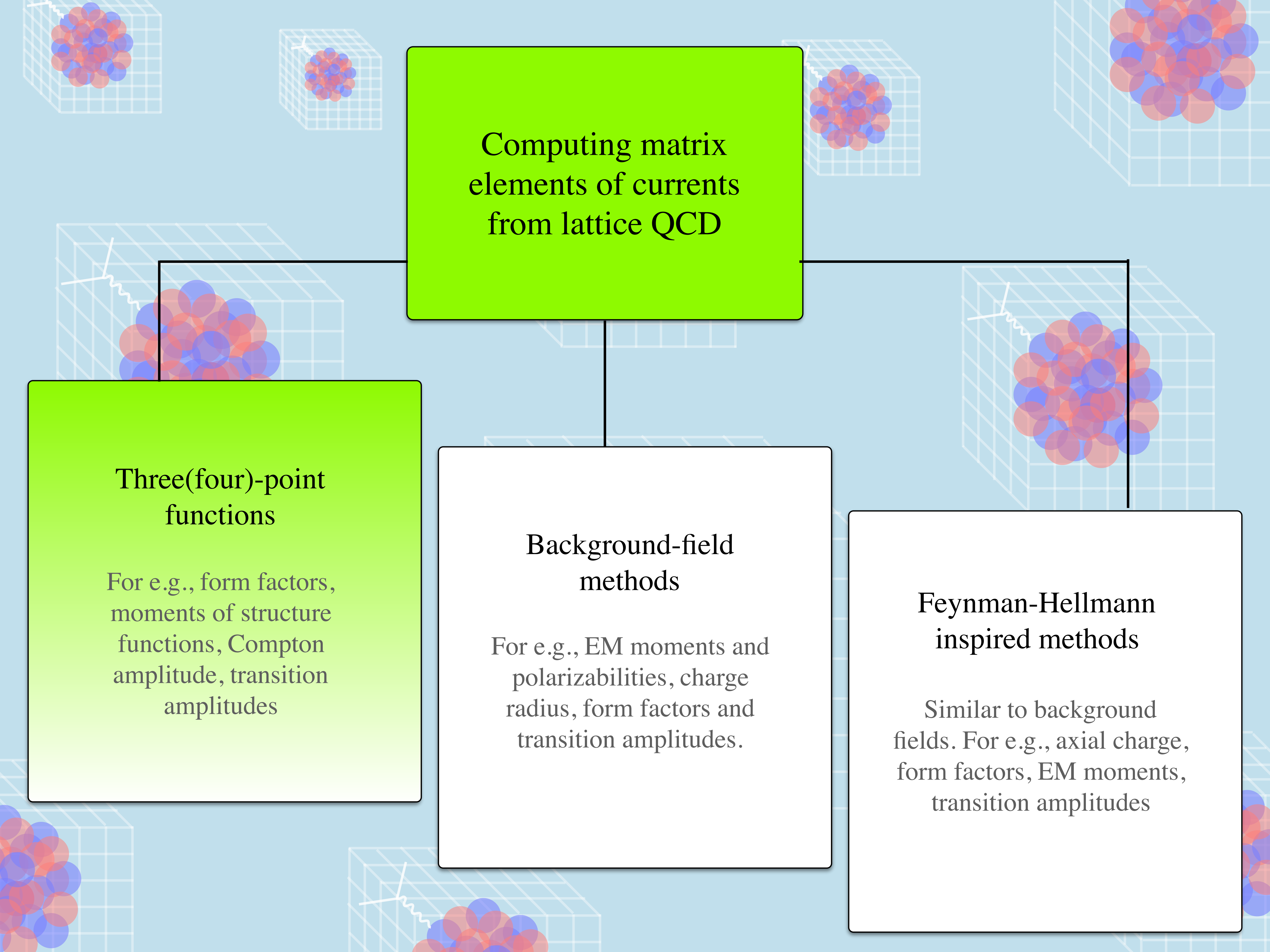

Computing matrix elements of currents from lattice QCD
Three(four)-point functions
For e.g., form factors, moments of structure functions, Compton amplitude, transition amplitudes
Background-field methods
For e.g., EM moments and polarizabilities, charge radius, form factors and transition amplitudes.
Feynman-Hellmann inspired methods
Similar to background fields. For e.g., axial charge, form factors, EM moments, transition amplitudes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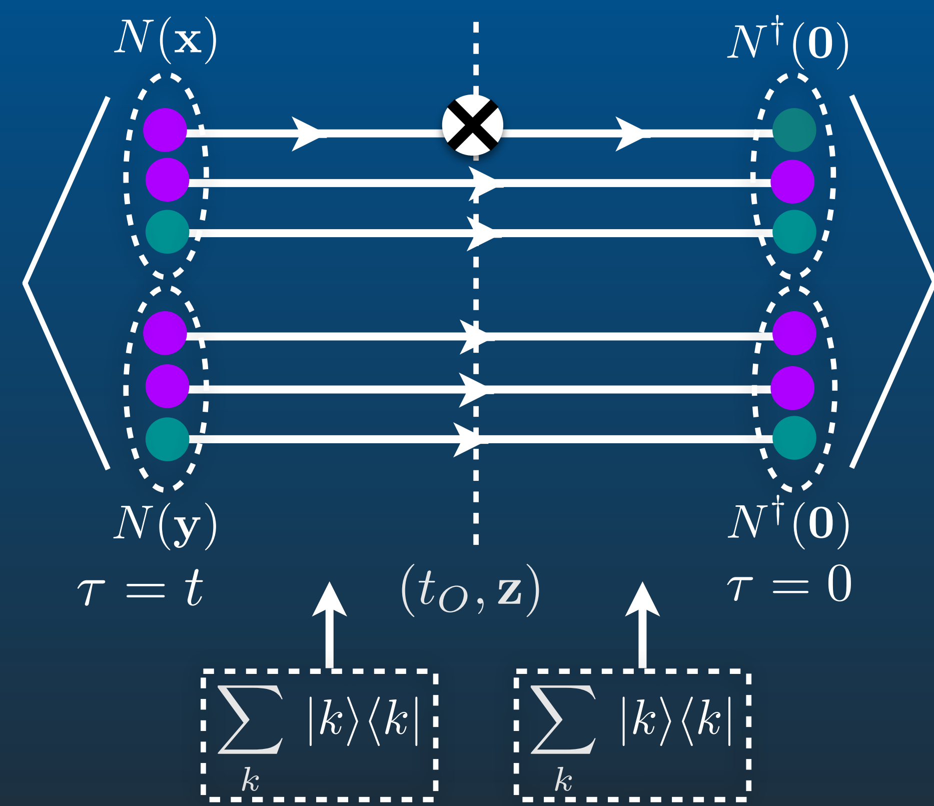
Pictorially a three-point function looks like…

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



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

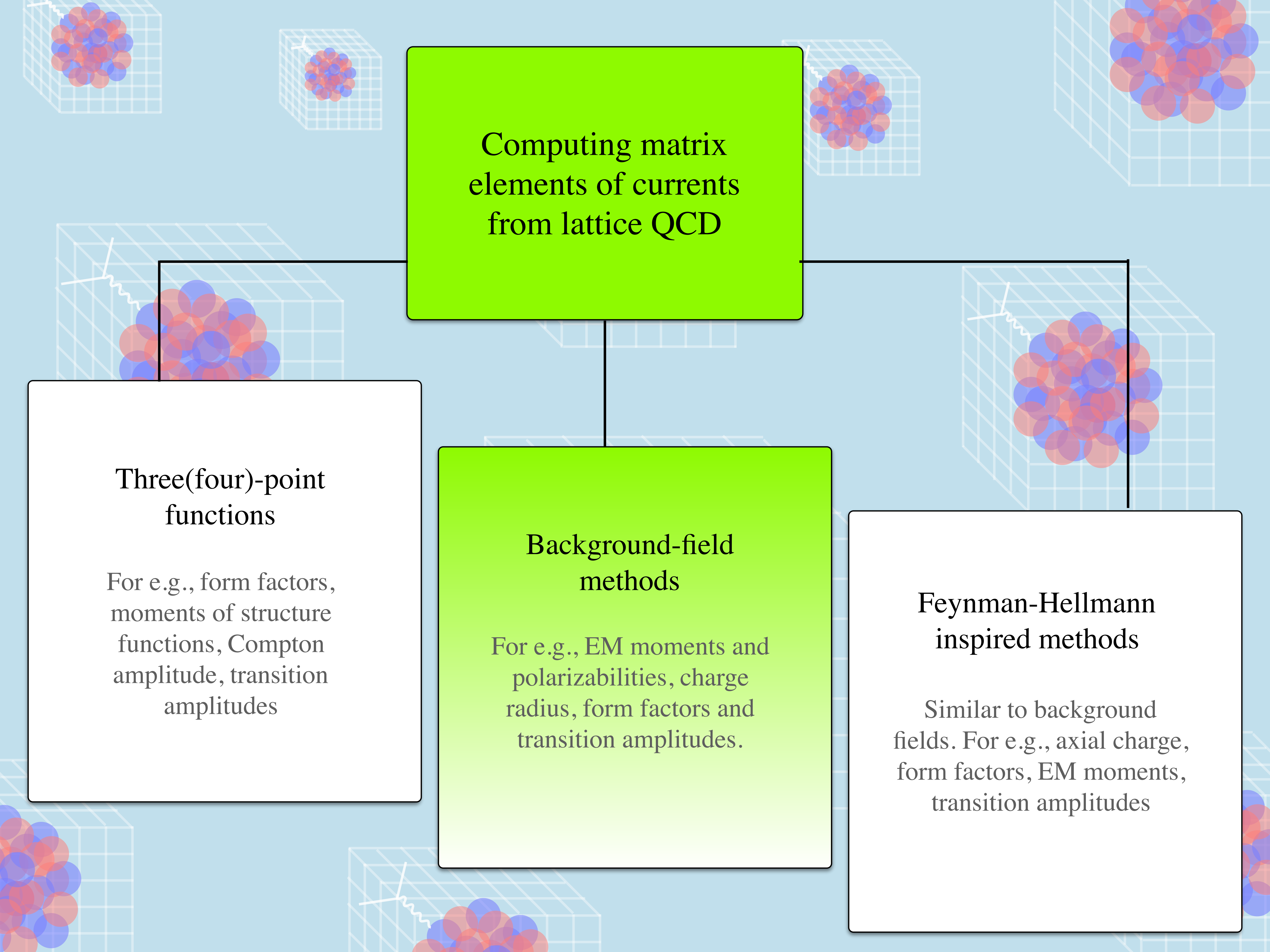
Three points:

i) Need to divide by appropriate two-point functions to cancel out unphysical overlap factors.

ii) Need to renormalize the operator from lattice scheme to continuum scheme.

iii) Need to turn the finite-volume matrix element to a physical transition amplitude.

Not essential for bound states!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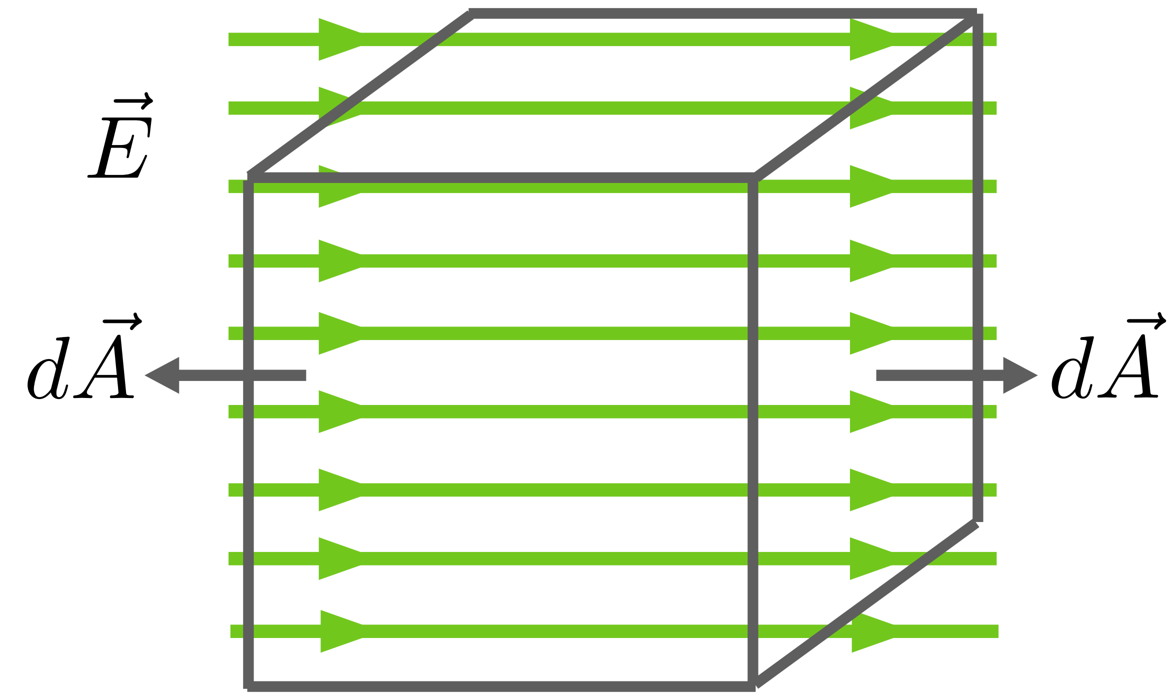
Background fields are non-dynamical, i.e., there will be no pair creation and annihilation in vacuum with a classical EM background field. This mean the photon zero mode is no problem: it is absent from the calculation!

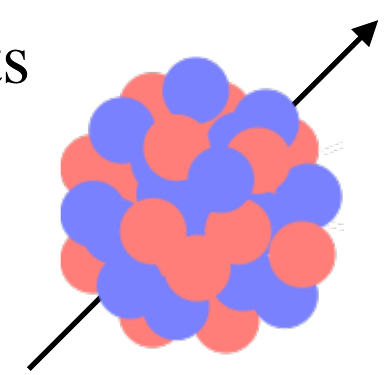


$$U^{(\mathrm{QCD})} \to U^{(\mathrm{QCD})} \times U^{(\mathrm{QED})}$$

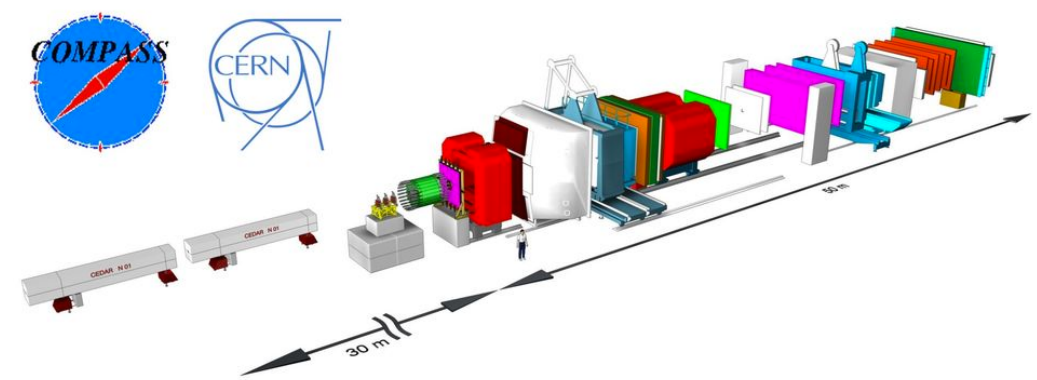
Modify the links when forming the quark propagators (quench approx).

Traditionally they are used for constraining the response of hadrons/nuclei to external probes:

Magnetic moments



Electric and magnetic polarizabilities



See e.g., BEANE et al (NPLQCD), Phys.Rev.Lett. 113 (2014) 25, 252001 and Phys.Rev. D92 (2015) 11, 114502. for nuclear-physics calculations.

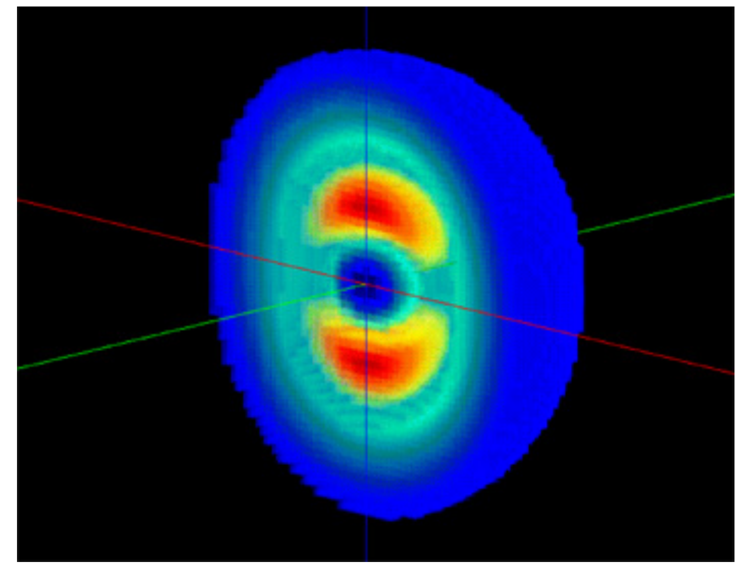
Various other structure properties of hadrons and nuclei, as well as their transitions, can be studied using more complex background fields…just a two-point function calculation!

1) EM charge radius

ZD and Detmold, Phys. Rev. D 93, 014509 (2016).

2) Electric quadrupole moment

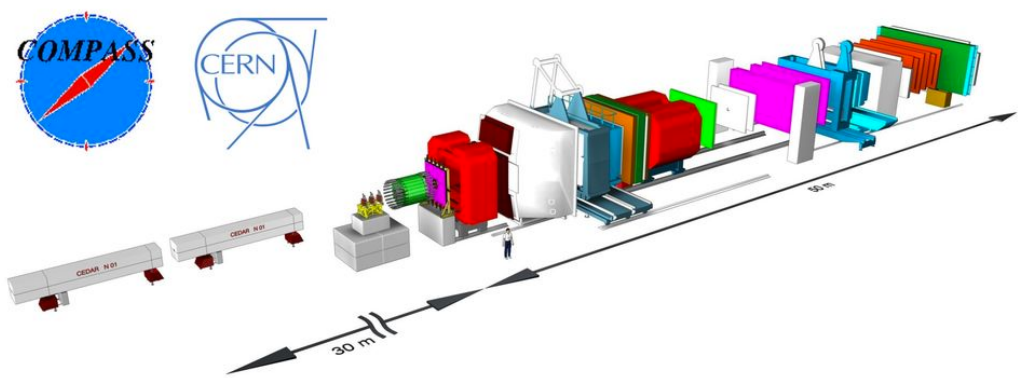
ZD and Detmold, Phys. Rev. D 93, 014509 (2016).



3) Form factors

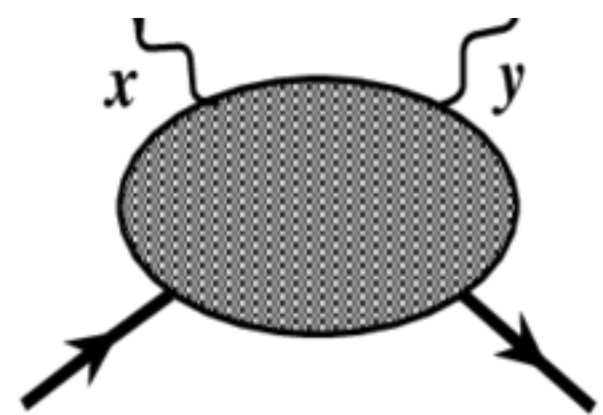
Detmold, Phys.Rev. D71, 054506 (2005).

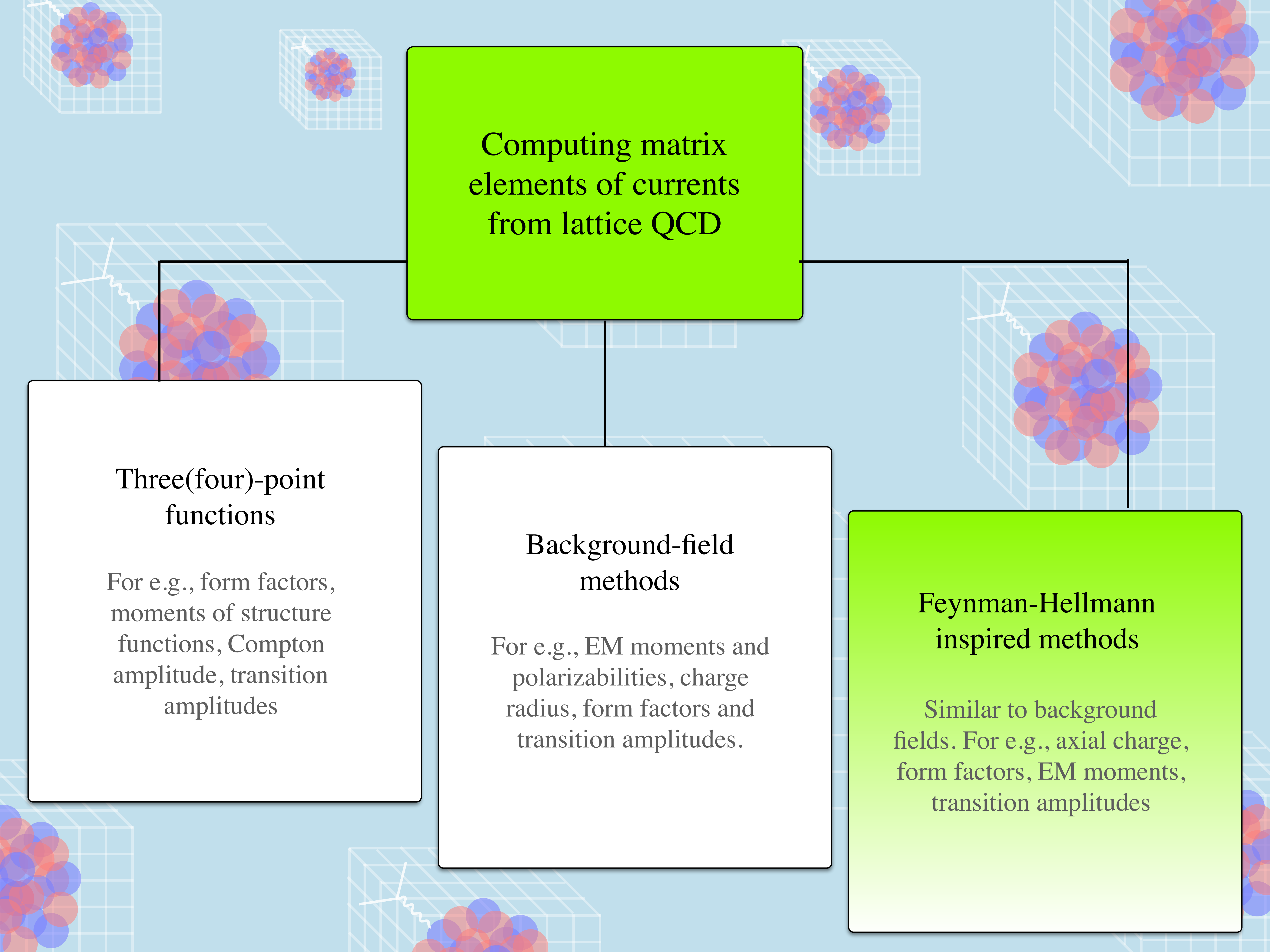
COMPASS CERN



4) Compton amplitude

Agadjanov, Meißner, Rusetsky, Phys. Rev. D 95, 031502 (2017).

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Hamiltonian as a function of a variable parameter

$$\hat{H}(\lambda) = \hat{H} + \lambda\hat{V}$$

Energy eigenvalue

$$\frac{\mathrm{d}E_n}{\mathrm{d}\lambda} = \frac{\langle\psi_n|\frac{\mathrm{d}\hat{H}}{\mathrm{d}\lambda}|\psi_n\rangle}{\langle\psi_n|\psi_n\rangle}$$

Energy eigenstate

Example: sigma term

$$m_q \frac{\partial m_N}{\partial m_q}\bigg|_{m_q=m_q^{\mathrm{phy}}} = \langle\mathcal{N}|m_q\bar{q}q|\mathcal{N}\rangle$$

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Energy eigenstate

Example: sigma term $$m_q \frac{\partial m_N}{\partial m_q}\bigg|_{m_q = m_q^{\text{phy}}} = \langle \mathcal{N} | m_q \bar{q} q | \mathcal{N} \rangle$$

Generalization to correlation functions

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

Just a 2pt function

$$S_\lambda = \lambda \int d^4x j(x)$$

Integrated matrix element

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

$$\mathcal{J}(t) = \int d^3x j(t, \vec{x})$$

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

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$$\mathcal{J}(t) = \int d^3x j(t, \vec{x})$$

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

One way to implement this is to modify the usual quark propagators:

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

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

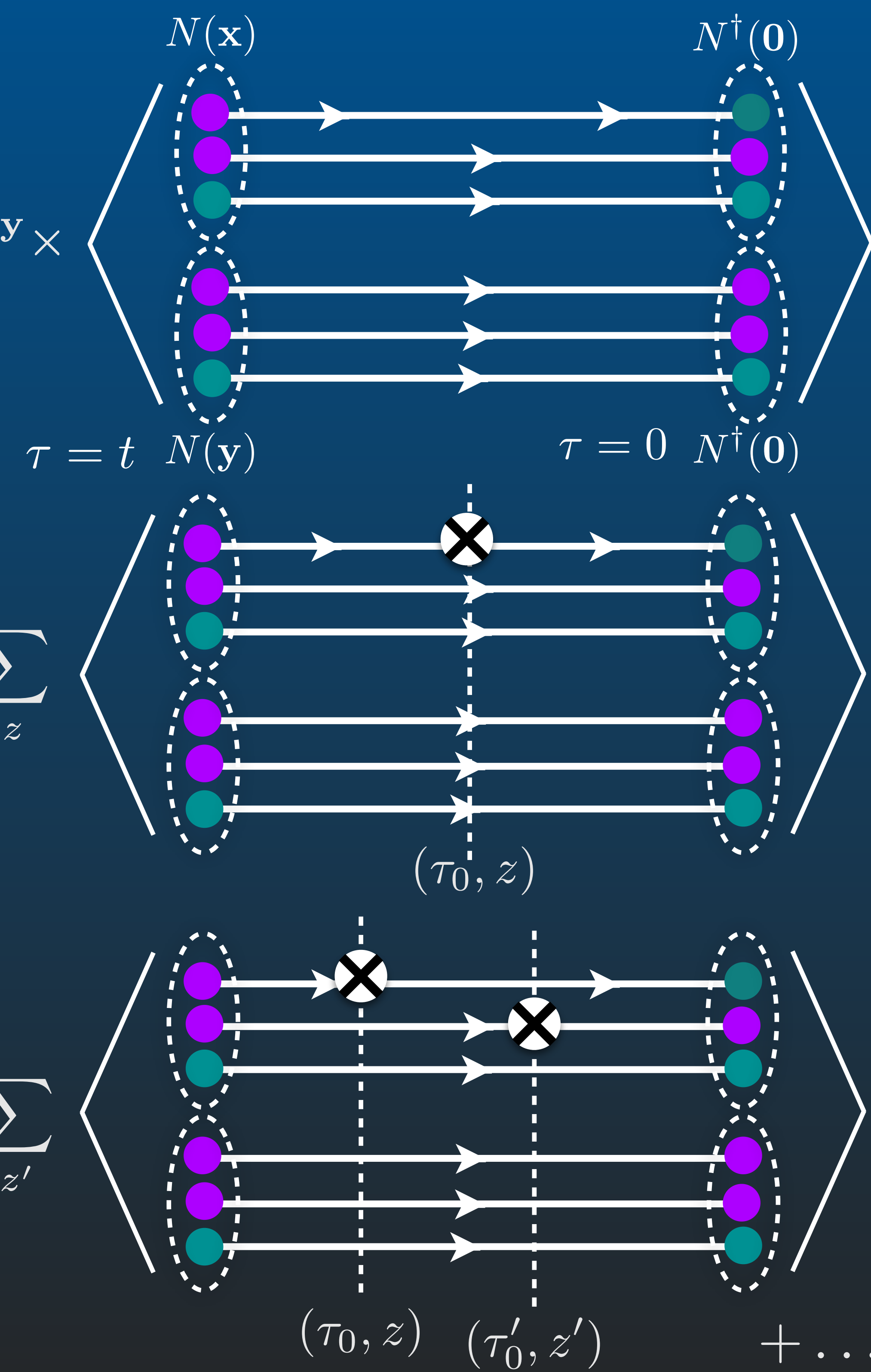
Let's look at an example:

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

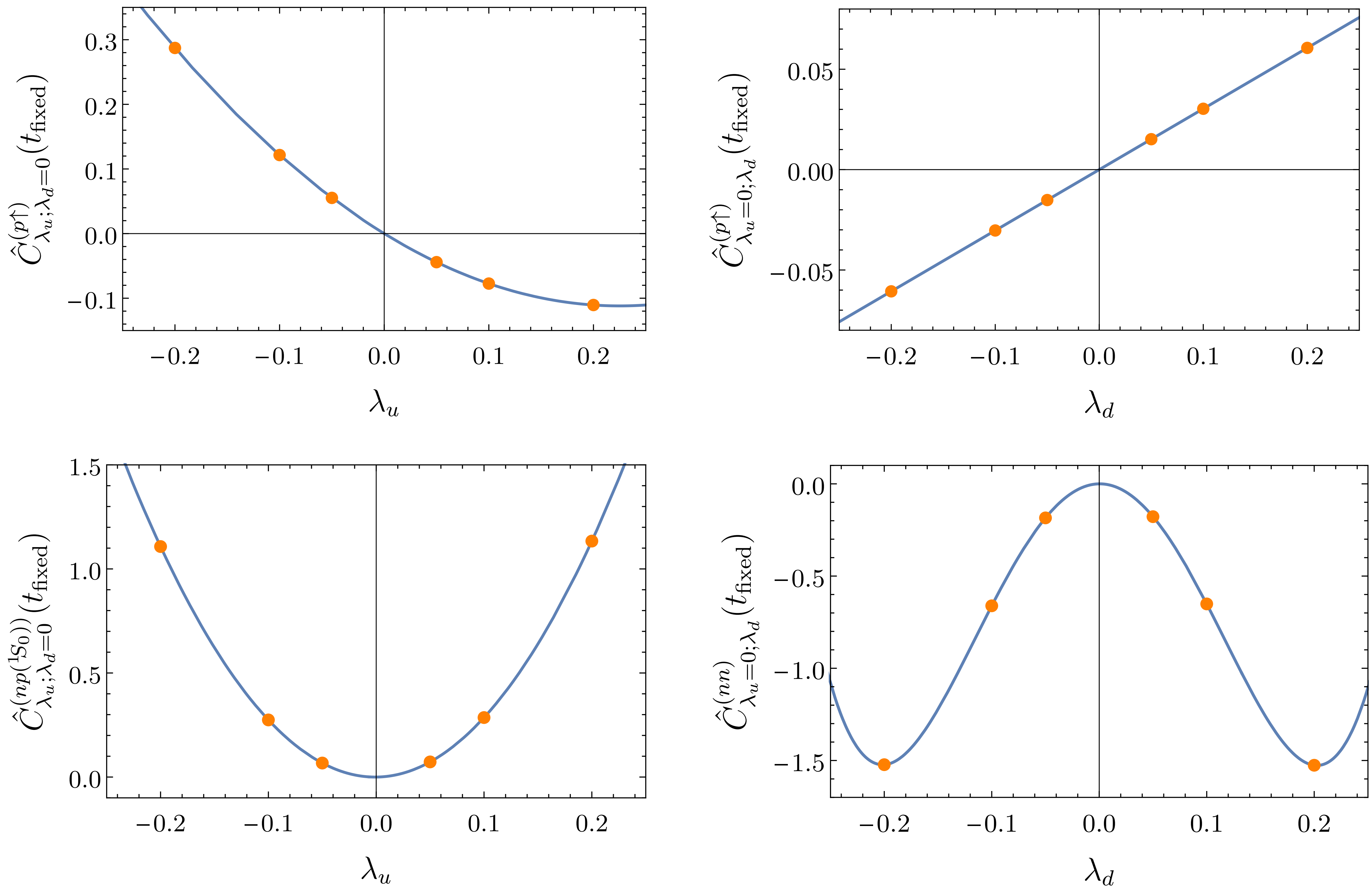
All possibilities $\longrightarrow$ $+\lambda \sum_{\tau_0=0}^{T} \sum_{z}$

time-ordered producT $\downarrow$

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



Matrix elements from a compound propagator/background field



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

Computing matrix elements of currents from lattice QCD

Lattice QCD, Fundamental Symmetries, and Neutrino Physics

Example: Nucleon axial charge and form factors for neutrino-nucleus scattering

Example: Neutrinofull and neutrinoless double beta decays

Why neutrino-nucleus scattering?

Search for CP violation in neutrino oscillation experiment is entering a new era with the next generation experiments such as DUNE in the U.S. and HyperK in Japan.

Probability of muon neutrino to electron neutrino conversion, that holds information about CP violation, depends on the neutrino energy:

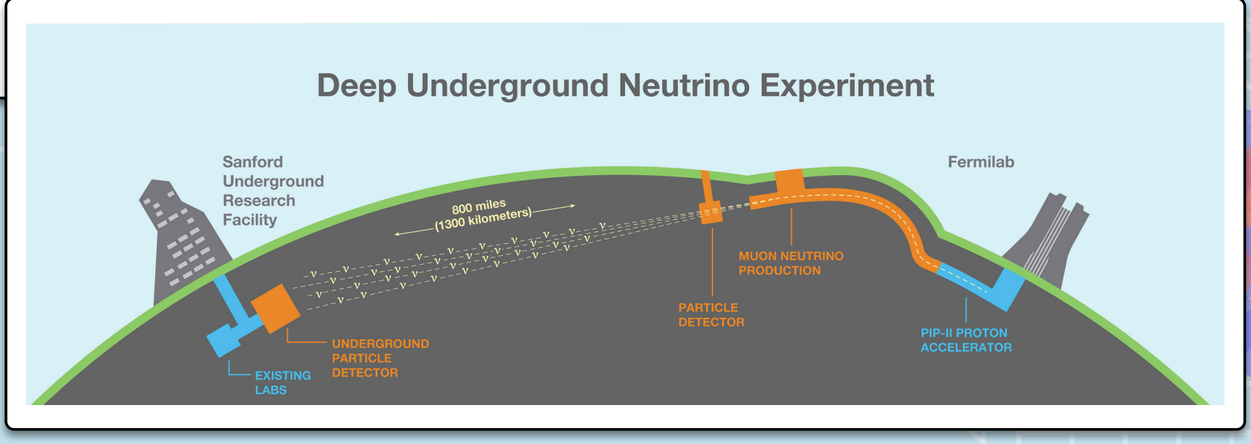
Desired CP-violating phase

$$P(\nu_\mu \to \nu_e) \cong \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2[\Delta(A-1)]}{(A-1)^2} + \alpha J \sin\delta_{CP}\sin\Delta\frac{\sin(A\Delta)\sin[(1-A)\Delta]}{A(1-A)} +$$
$$\alpha J\cos\delta_{CP}\cos\Delta\frac{\sin(A\Delta)\sin[(1-A)\Delta]}{A(1-A)} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(A\Delta)}{A^2}$$

Quantities that depend on neutrino energy

De Romeri et al, *JHEP* 09 (2016) 030.

Unfortunately the neutrino energy is undetermined a priori and must be reconstructed from its collision with target nuclear isotopes such as Argon: A very complex problem!



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Desired CP-violating phase

$$\ldots \alpha J \sin\delta_{CP} \sin\Delta \frac{\sin(A\Delta)\sin[(1-A)\Delta]}{A(1-A)} +$$

$$\ldots \frac{\ldots)\Delta]}{\ldots} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(A\Delta)}{A^2}$$

De Romeri et al, *JHEP* 09 (2016) 030.

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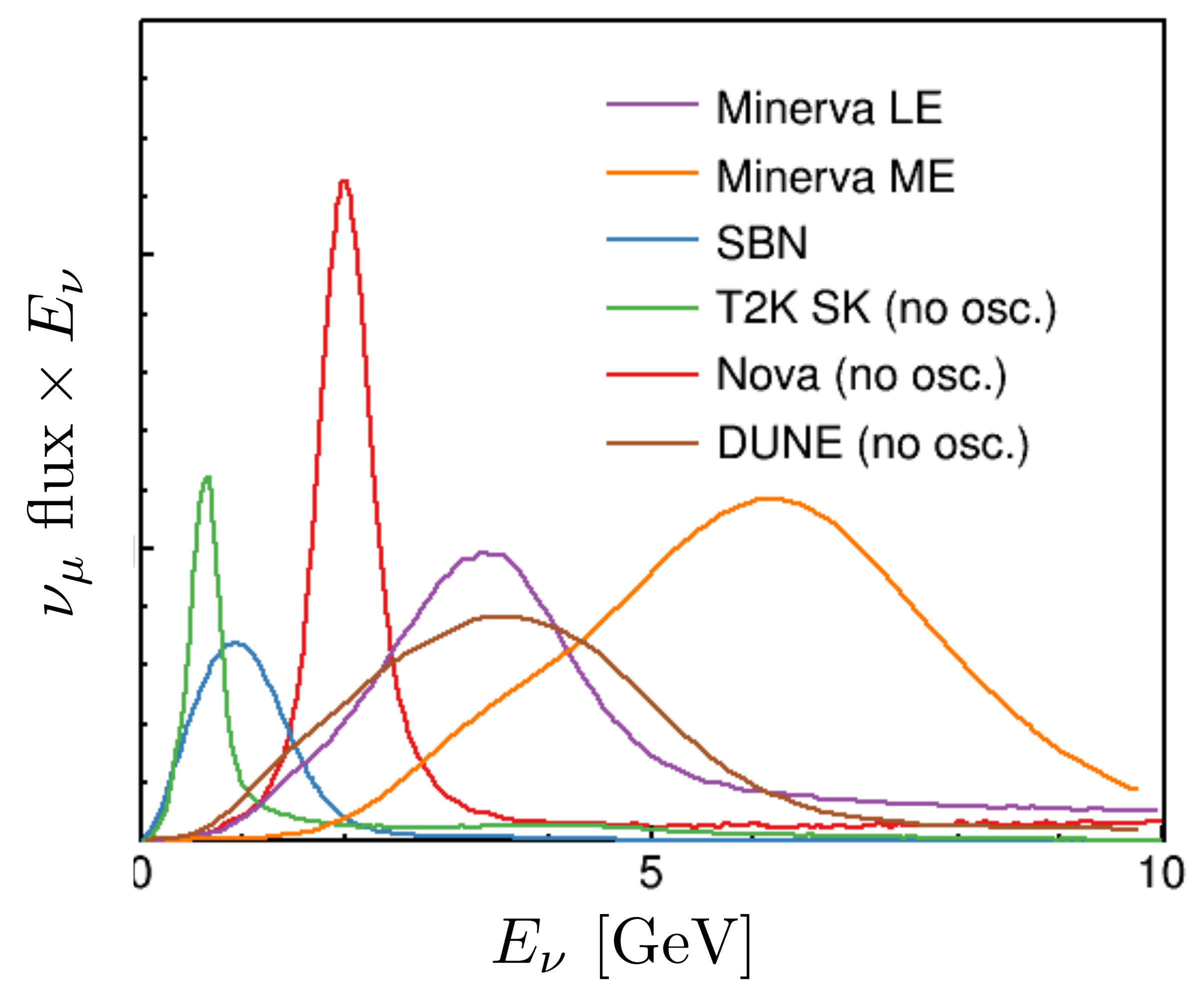
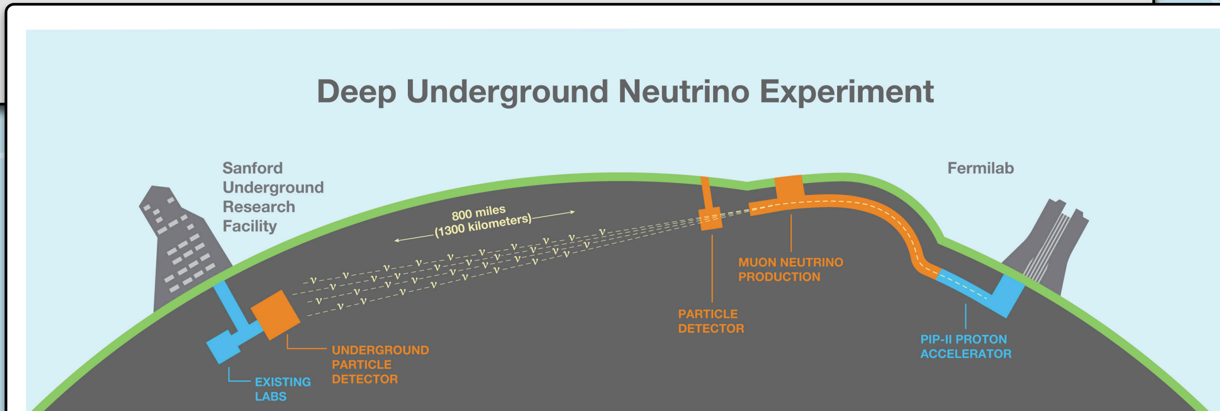
Kronfeld et al (USQCD collaboration), Eur.Phys.J.A 55 (2019)+Laura Fields.

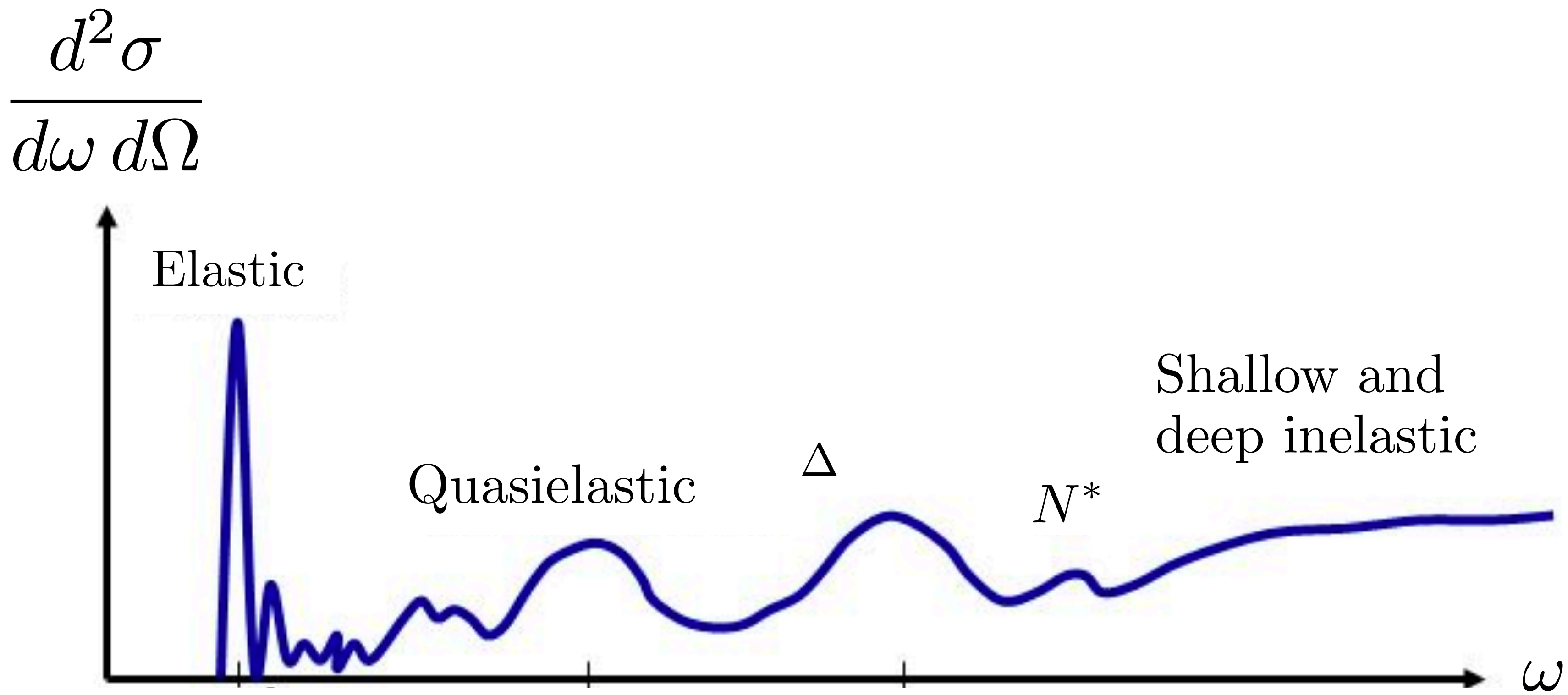




One needs to constrain nuclear response to incoming neutrino of various energy. How can lattice QCD help?

ν-nucleus scattering at a fixed momentum transferred

$\nu_\ell A \rightarrow \ell^- X$



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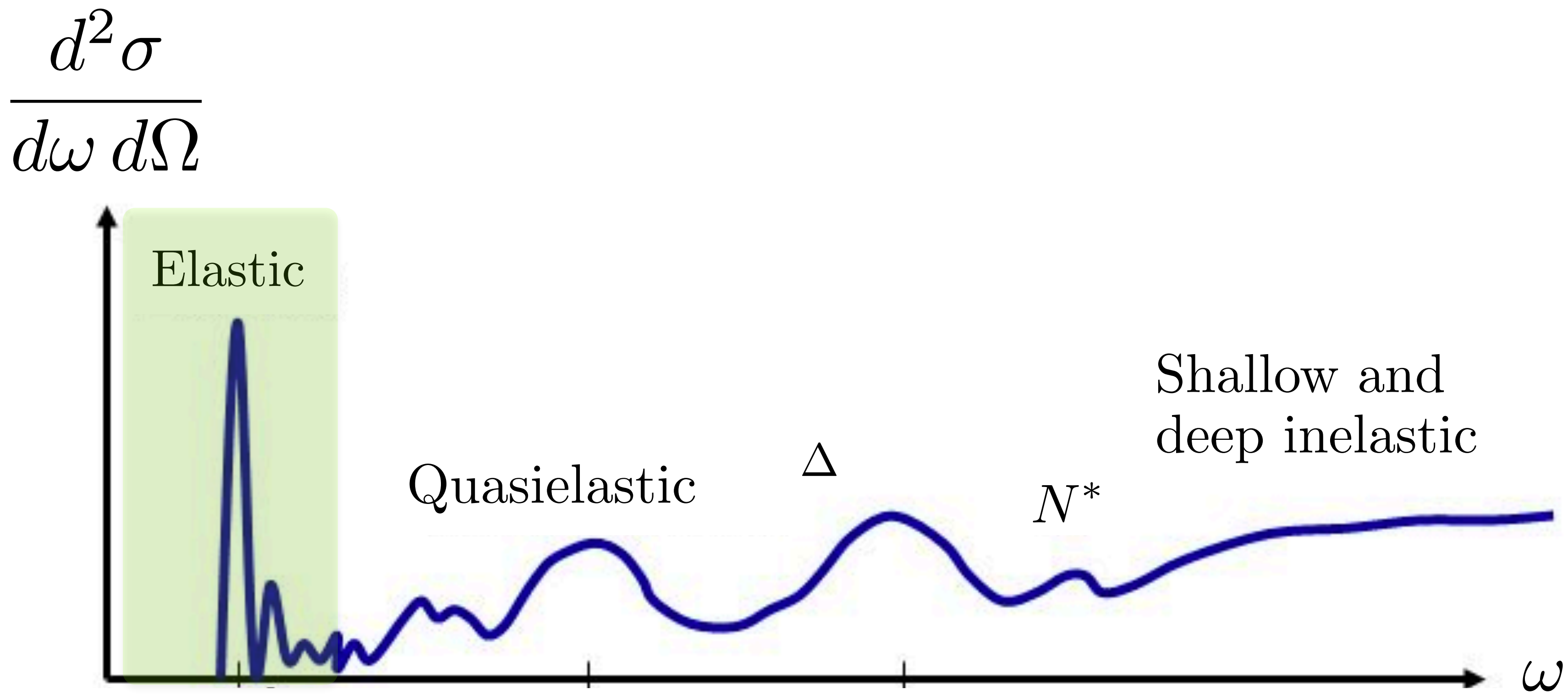

Forward form factors, radii

Kronfeld et al (USQCD collaboration), Eur.Phys.J.A 55 (2019).

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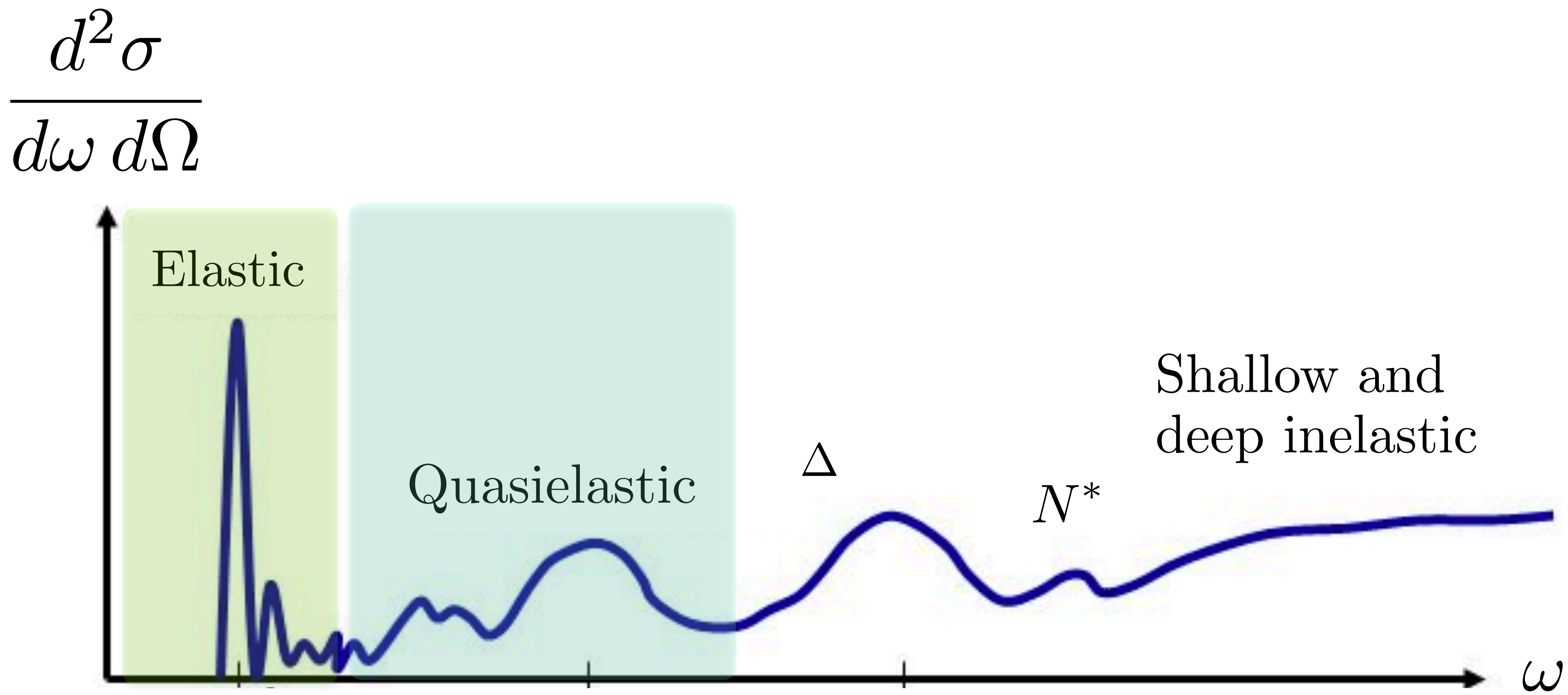

Forward form factors, radii

Off-forward form factors

Kronfeld et al (USQCD collaboration), Eur.Phys.J.A 55 (2019).

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ν-nucleus scattering at a fixed momentum transfer

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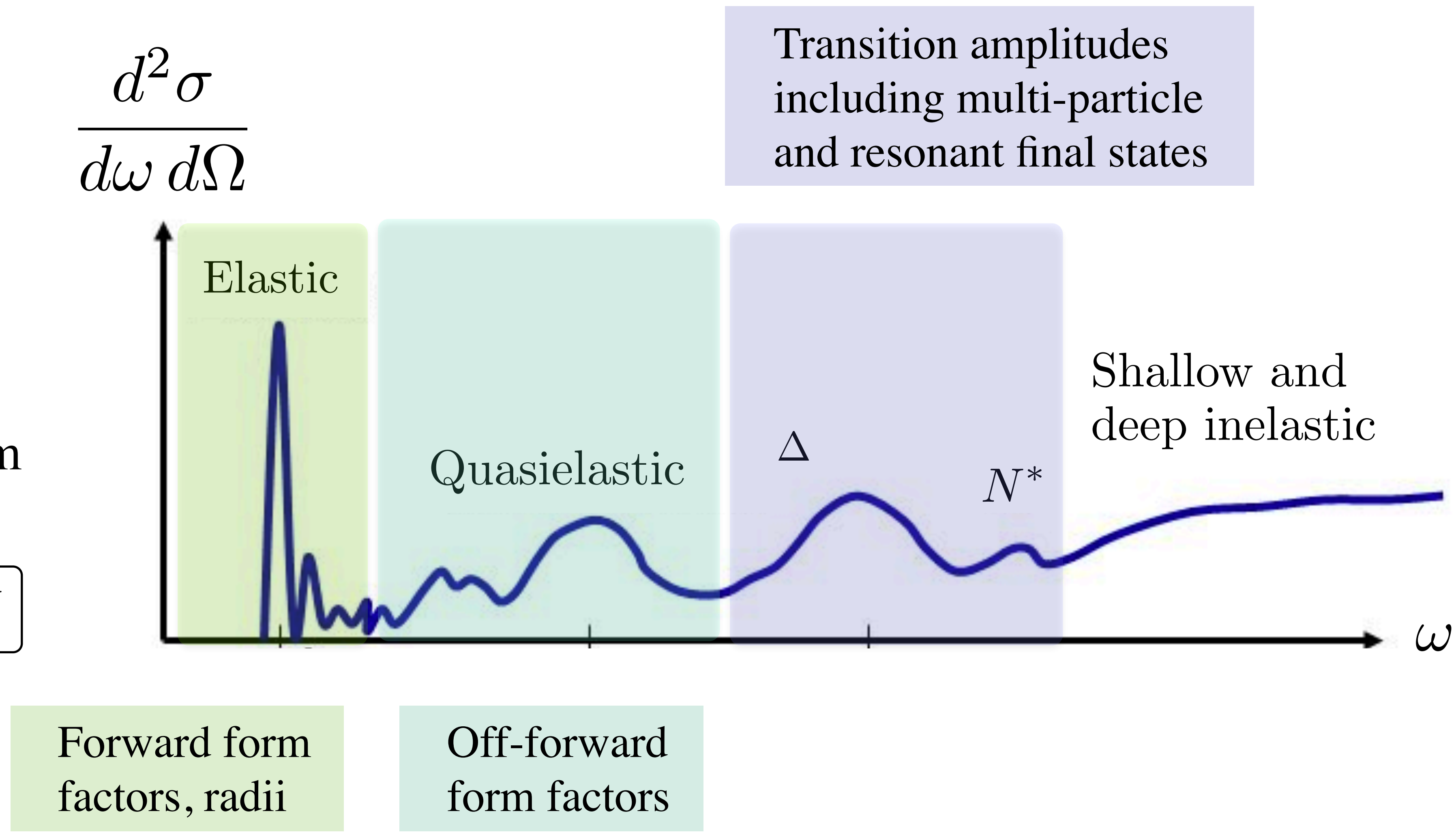

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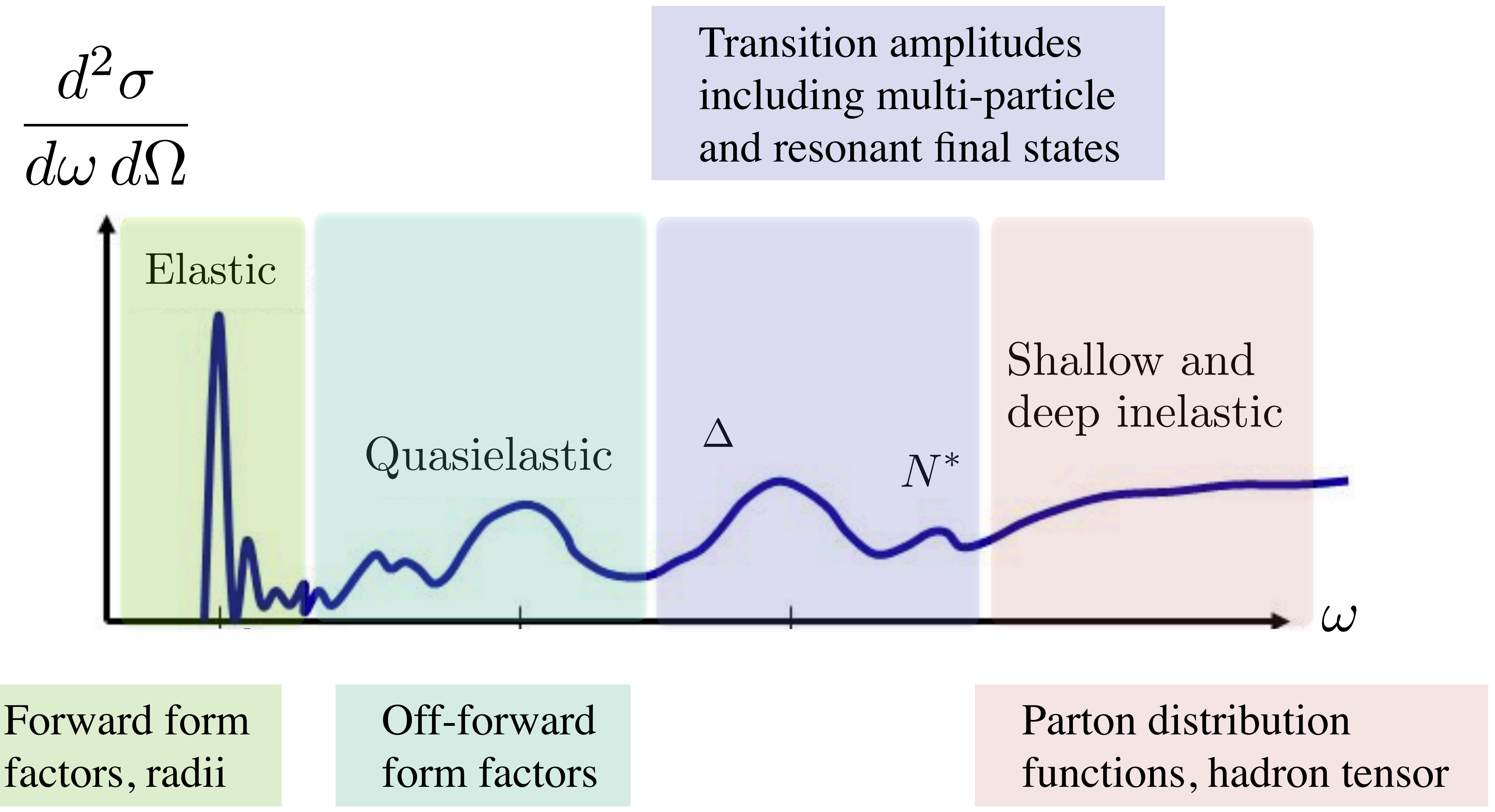

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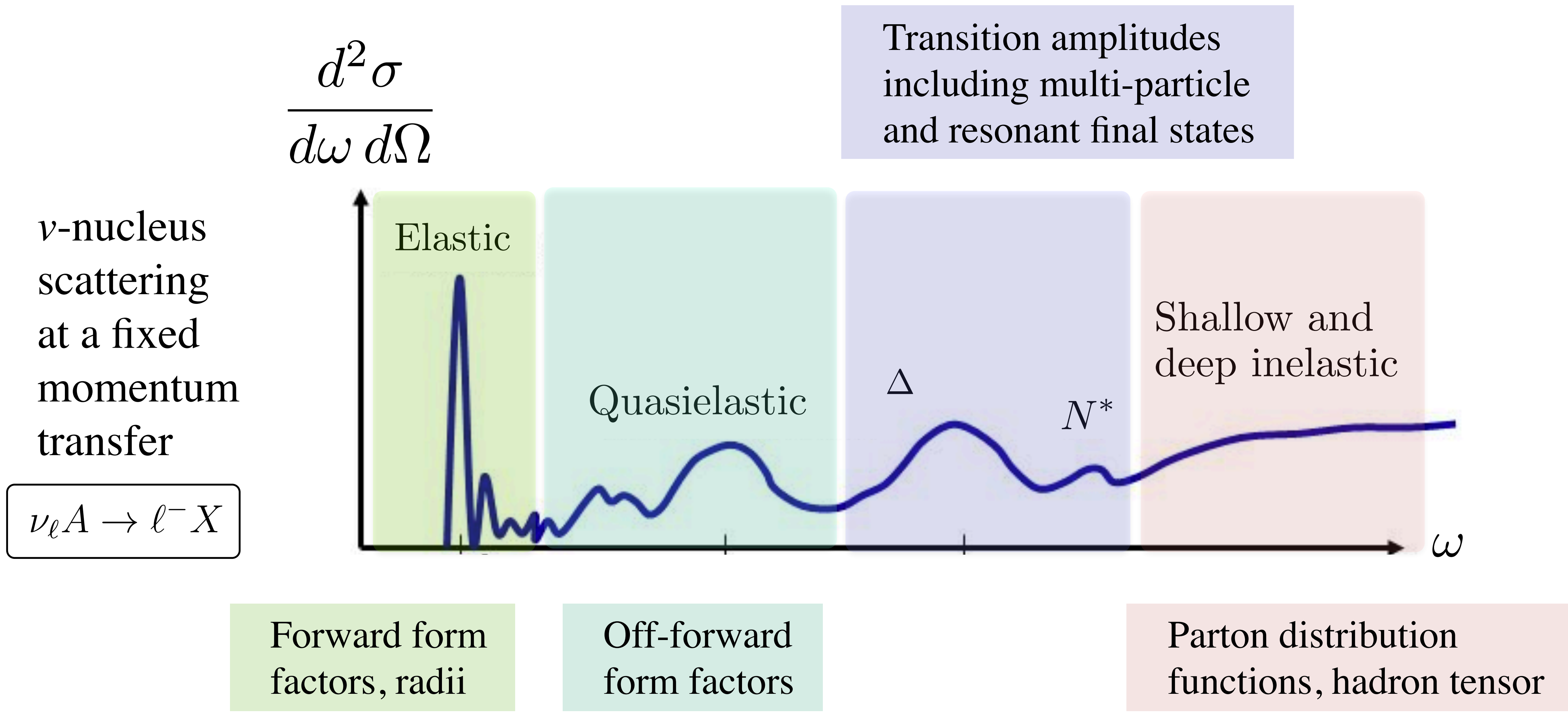


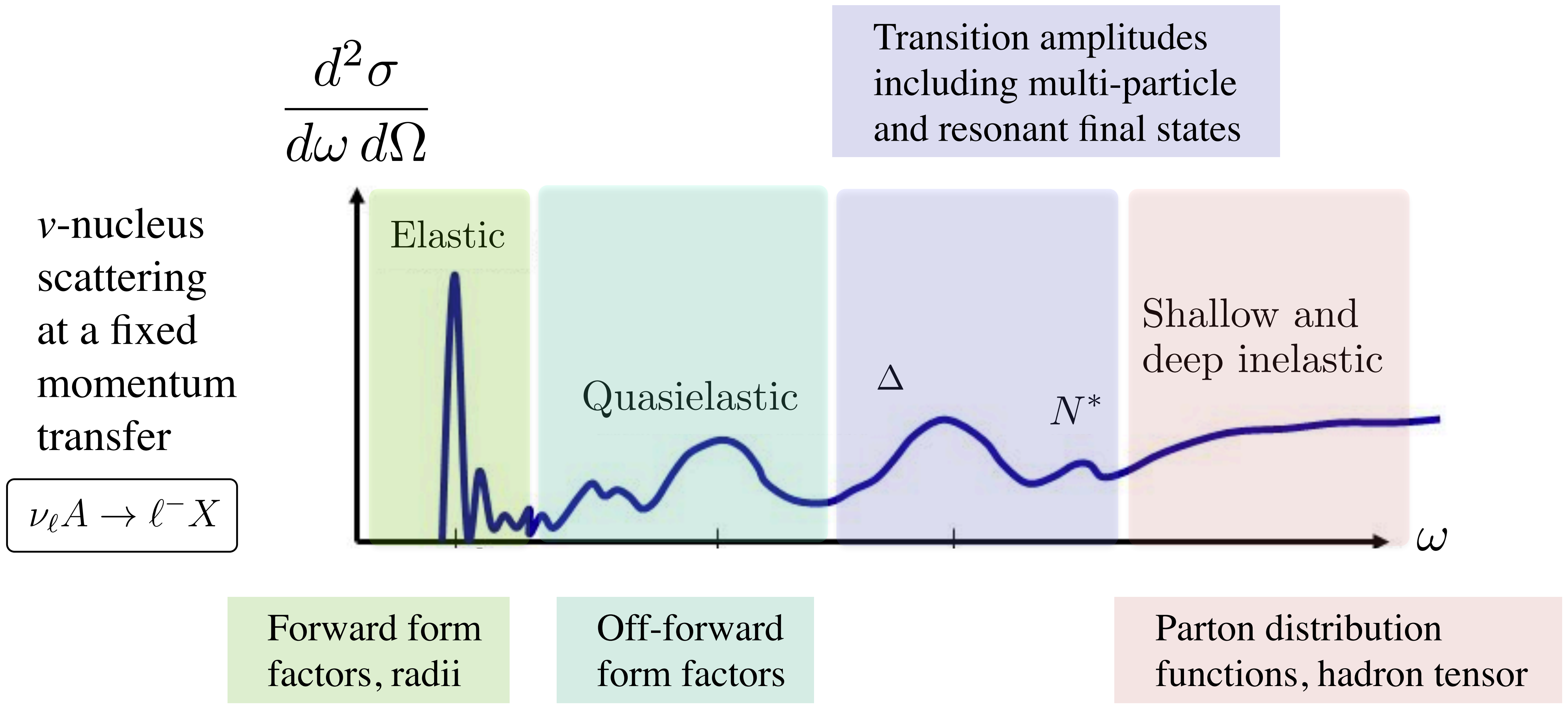
Need to compute various matrix elements in nucleon, multi-hadron states, and (light) nuclei:

$$\langle f|J_\nu|i\rangle, \qquad \langle f|J^\dagger_\mu J_\nu|i\rangle, \qquad \langle f|\mathcal{O}|i\rangle$$

and resort to EFTs to connect to large isotopes in experiments.

Kronfeld et al (USQCD collaboration), Eur.Phys.J.A 55 (2019).

One needs to constrain nuclear response to incoming neutrino of various energy. How can lattice QCD help?



I will not be able to tell you about the complete story, but I give you an example of a quantity lattice QCD can obtain well: the (nucleon) axial charge and form factors.

Kronfeld et al (USQCD collaboration), Eur.Phys.J.A 55 (2019).

Example: The application of 3pt function method to obtain the axial charge/form factors of the nucleon

Constantinou, arXiv:1411.0078 [hep-lat].

$$\langle N(p',s')|\bar{\psi}(x)\,\gamma_\mu\,\gamma_5\,\psi(x)|N(p,s)\rangle = i\left(\frac{m_N^2}{E_N(\mathbf{p}')E_N(\mathbf{p})}\right)^{1/2} \bar{u}_N(p',s')\left[G_A(q^2)\gamma_\mu\gamma_5 + \frac{q_\mu\gamma_5}{2m_N}G_p(q^2)\right]u_N(p,s)$$

Axial-vector current

Nucleon spinor

Axial and pseudo scalar form factors

$G_A(0) = g_A$

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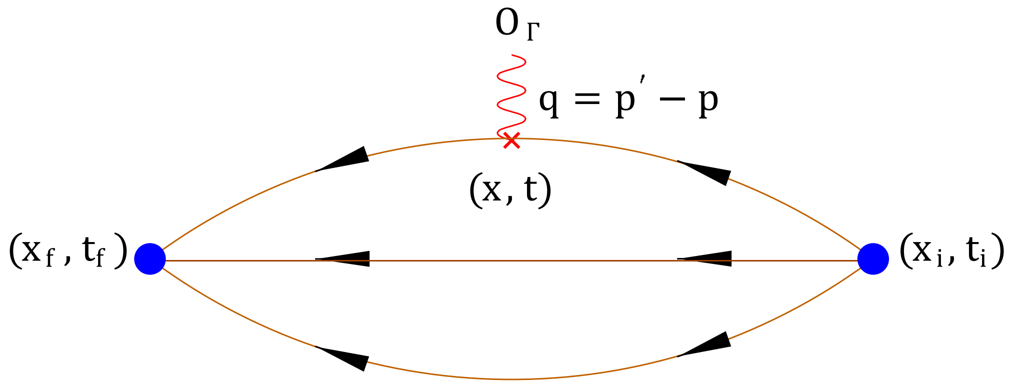
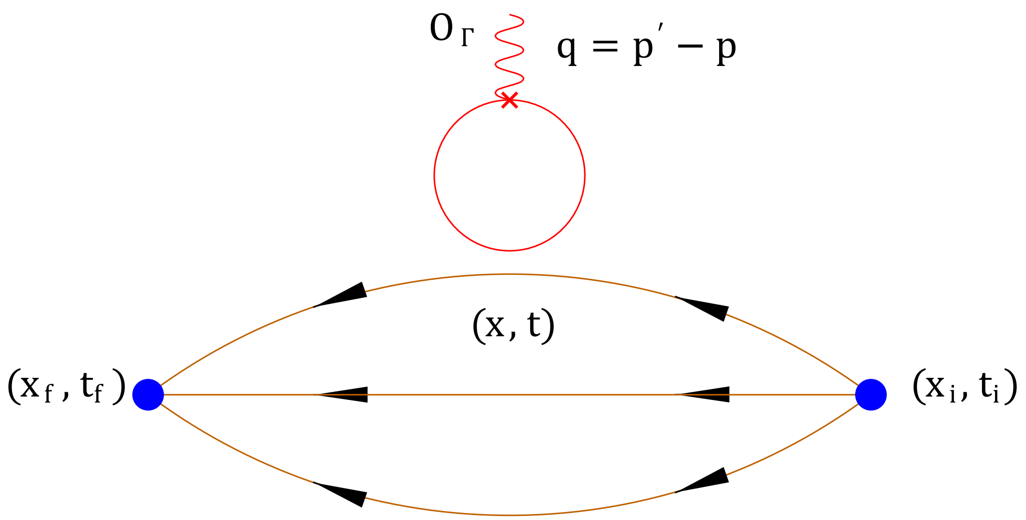
Axial-vector current

Nucleon spinor

Axial and pseudo scalar form factors $G_A(0) = g_A$



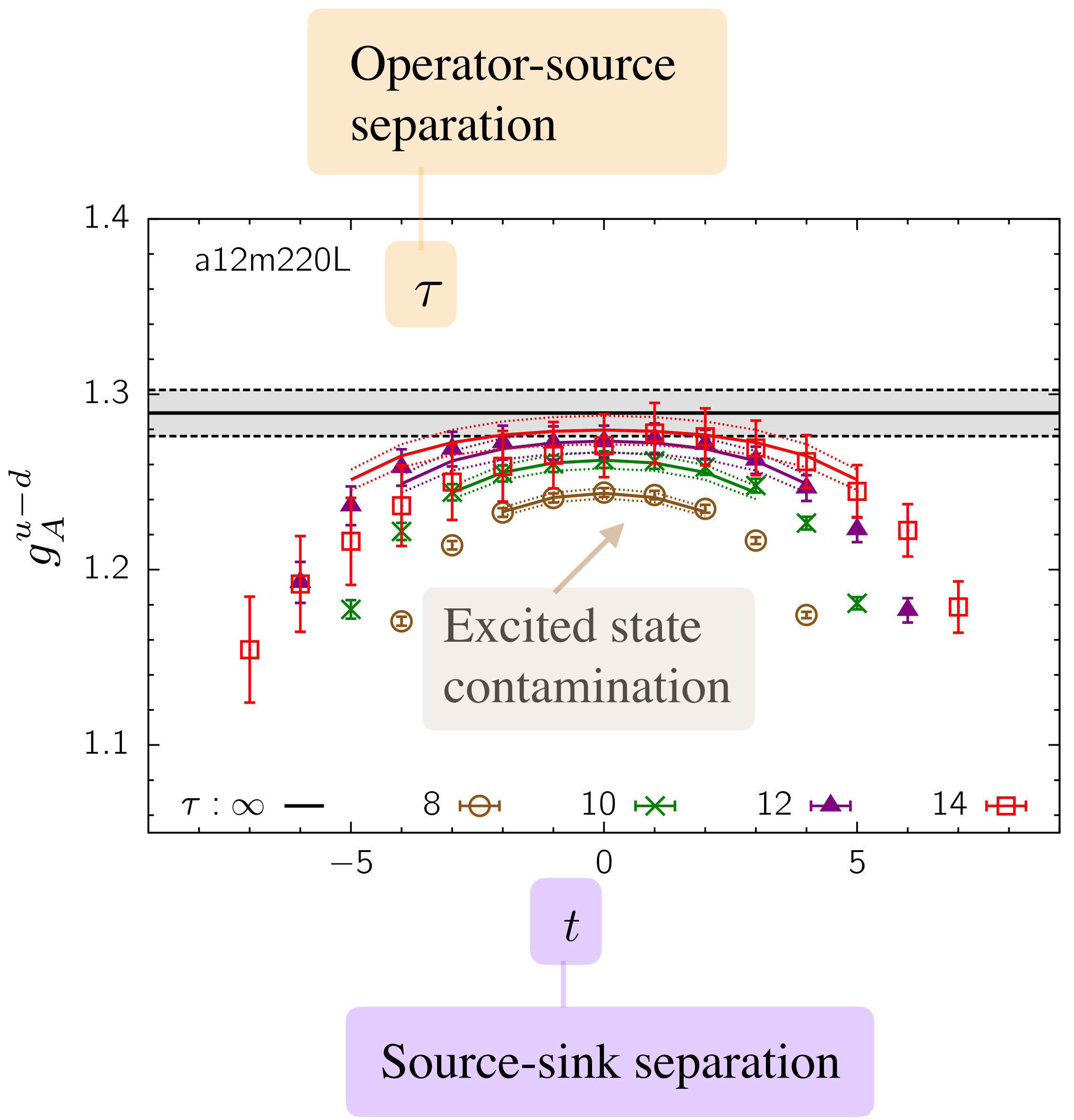
Connected contribution



Disconnected contribution
(vanishes at isospin limit for isovector quantities)

Example: The application of 3pt function method to obtain the axial charge/form factors of the nucleon

Gupta et al (PNDME), Phys. Rev. D 98, 034503 (2018)



3pt function for a single lattice spacing, volume and quark masses

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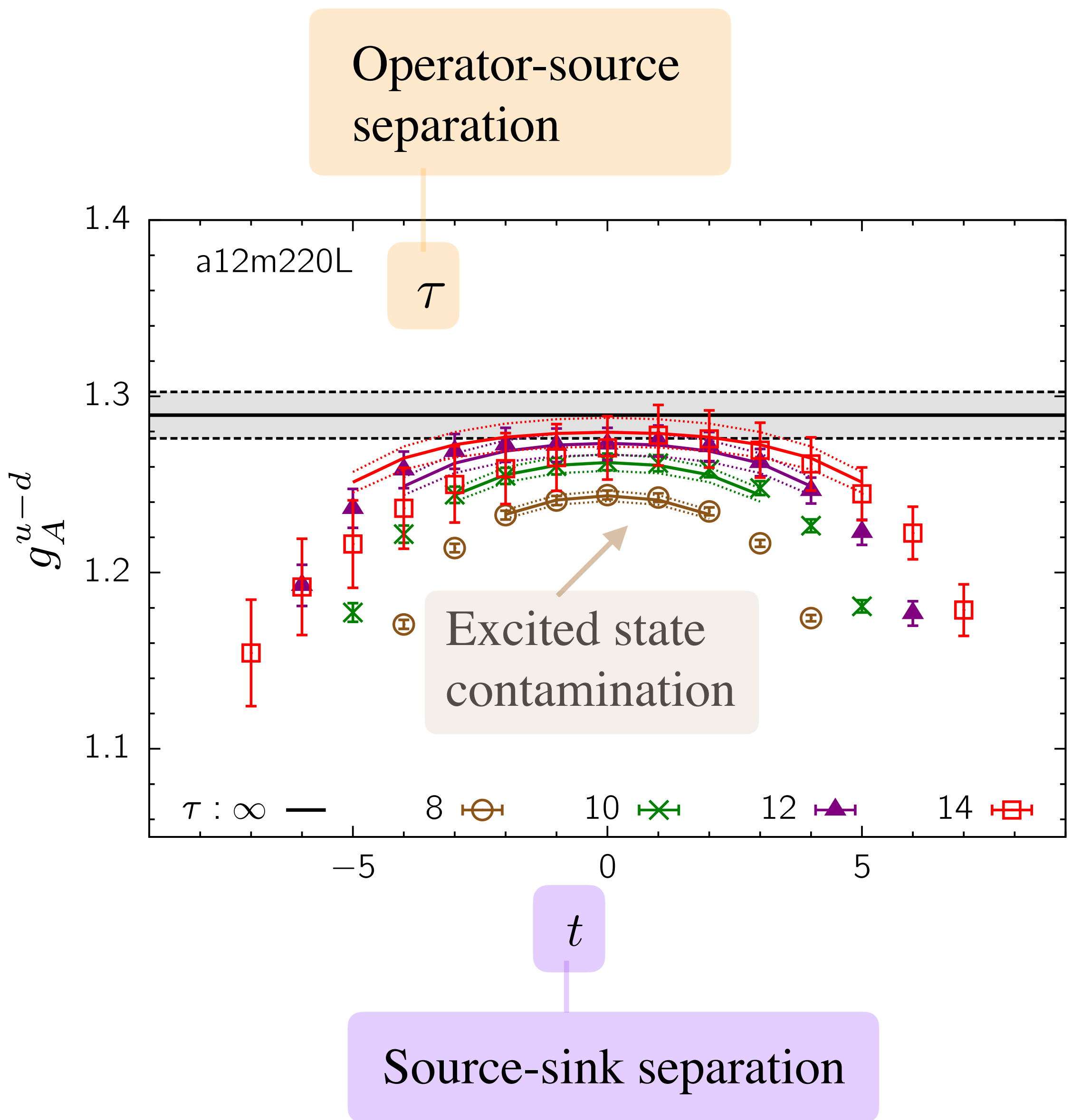
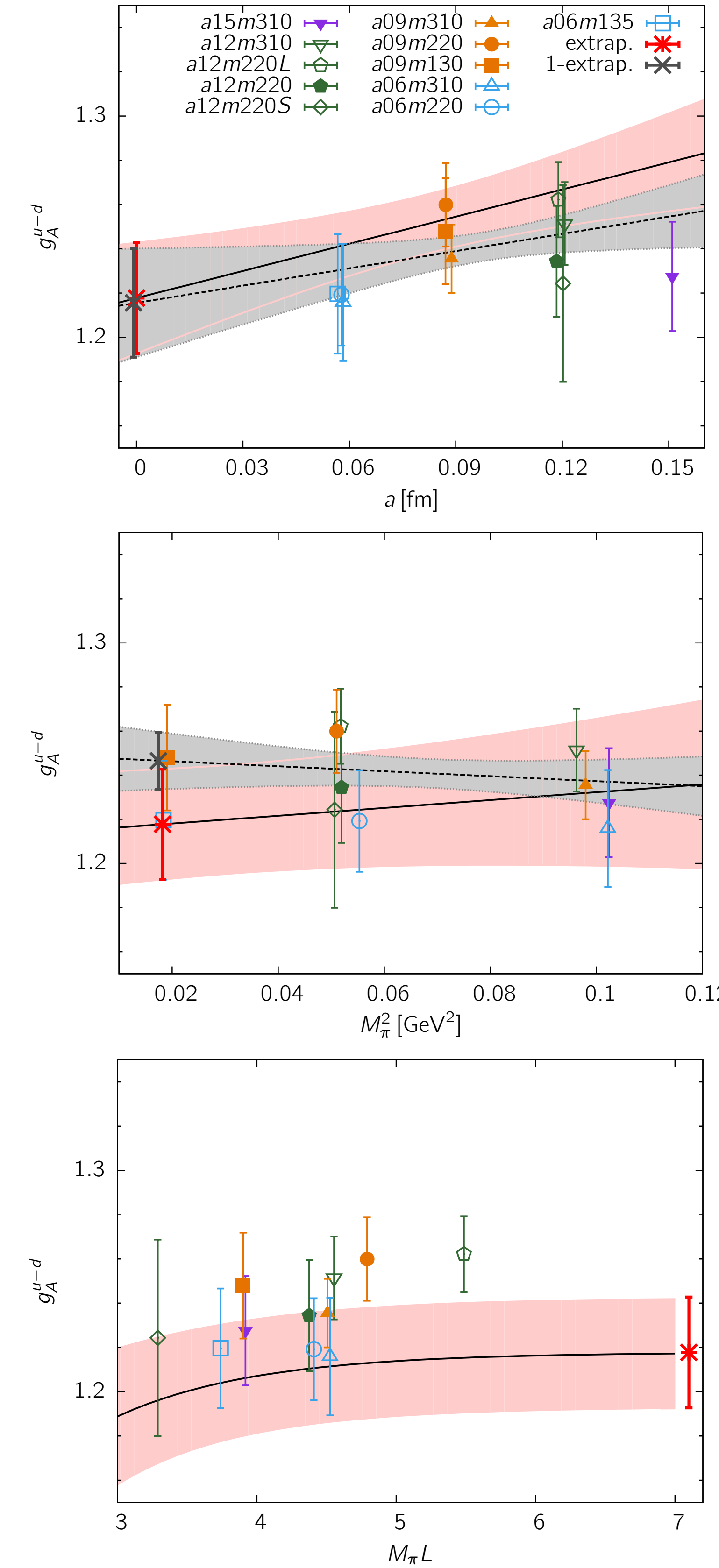
Gupta et al (PNDME), Phys. Rev. D 98, 034503 (2018)



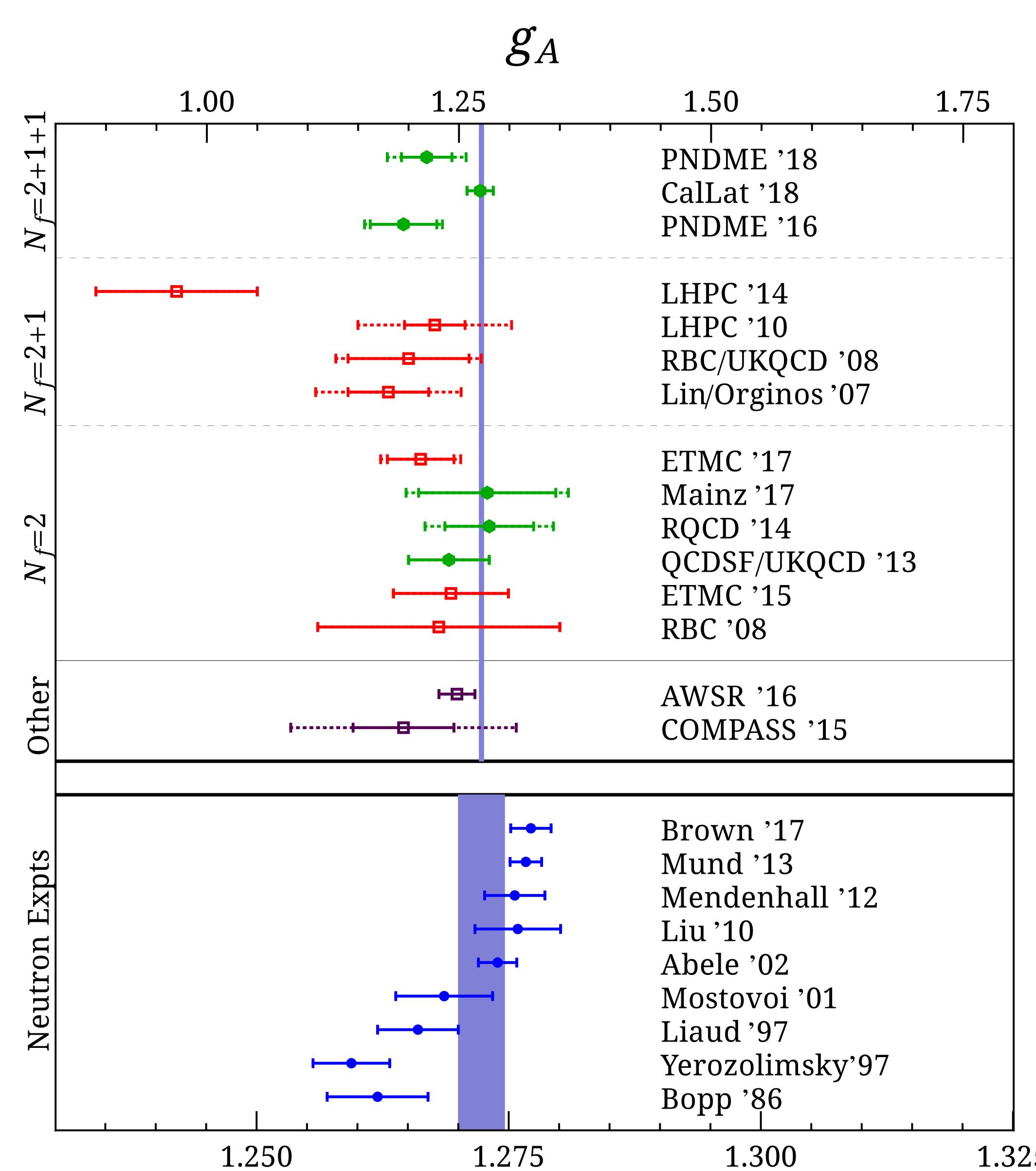
3pt function for a single lattice spacing, volume and quark masses



Extrapolation to continuum, infinite volume, and physical quark masses

Example: The application of 3pt function method to obtain the axial charge/form factors of the nucleon

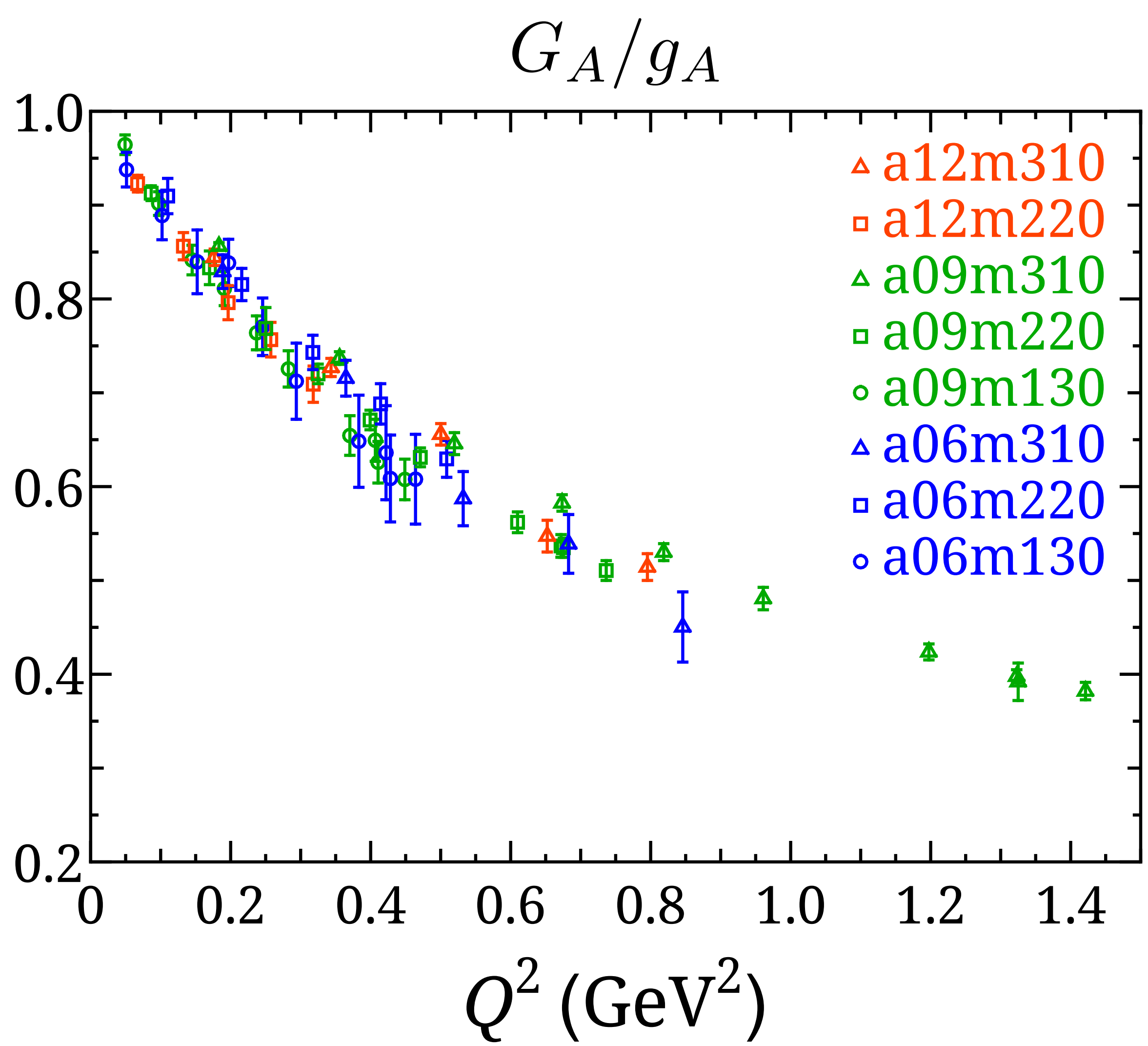
FLAG Review (2019), EPJC 80, 113 (2020).



Compilation of results

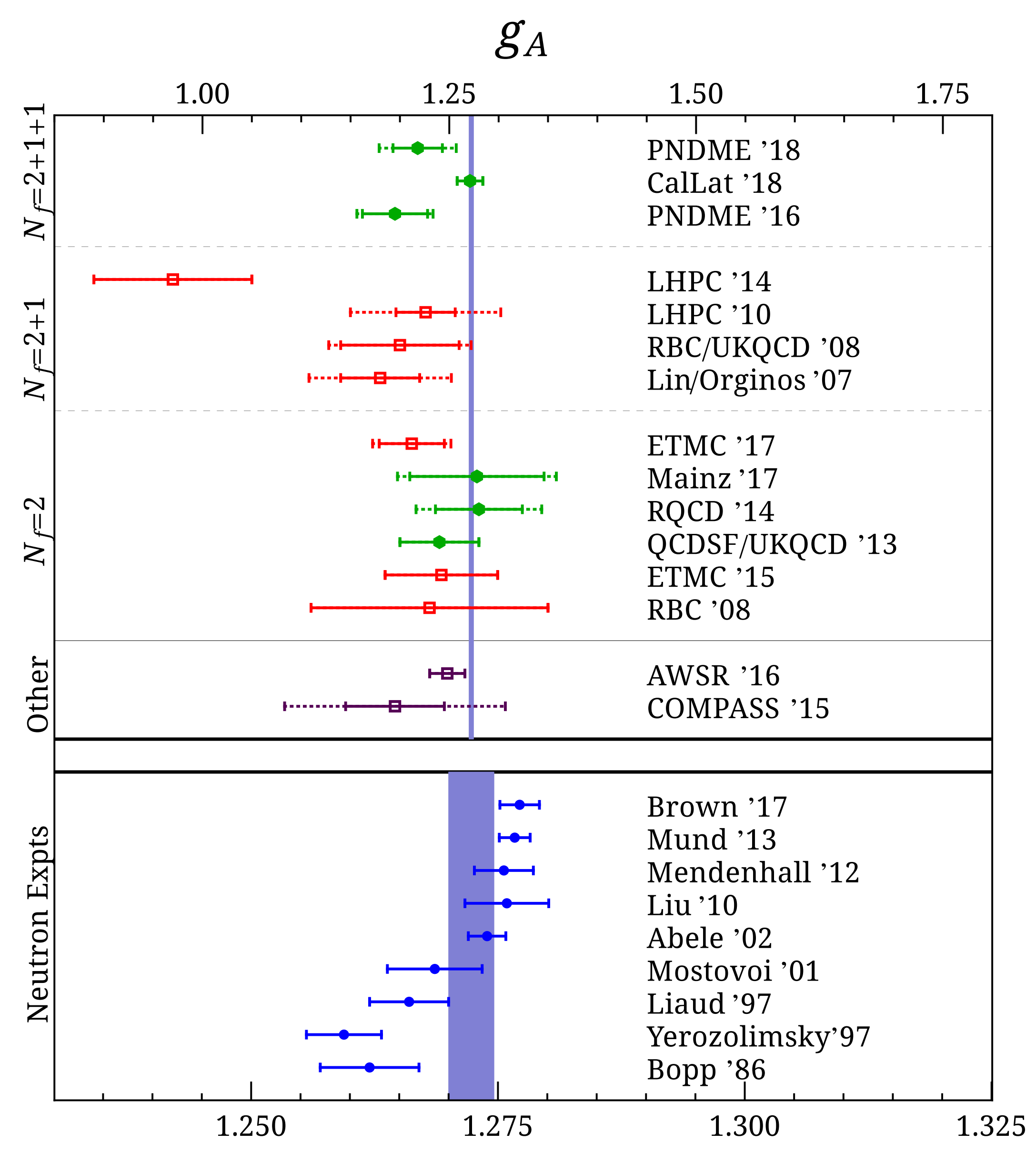
Example: The application of 3pt function method to obtain the axial charge/form factors of the nucleon

Jang et al, EPJ Web Conf. 175, 06033 (2018)

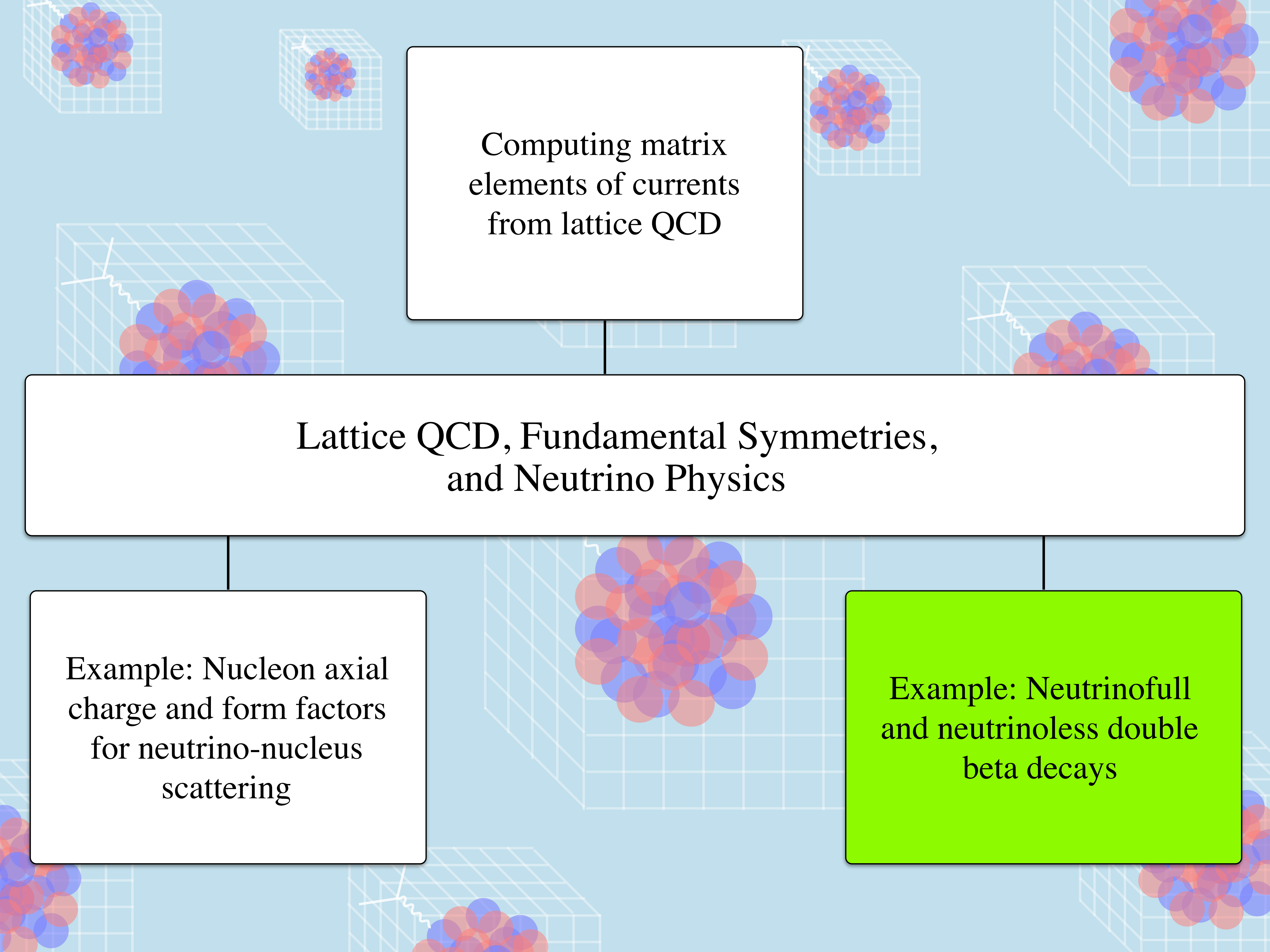


Axial form factor results

FLAG Review (2019), EPJC 80, 113 (2020).

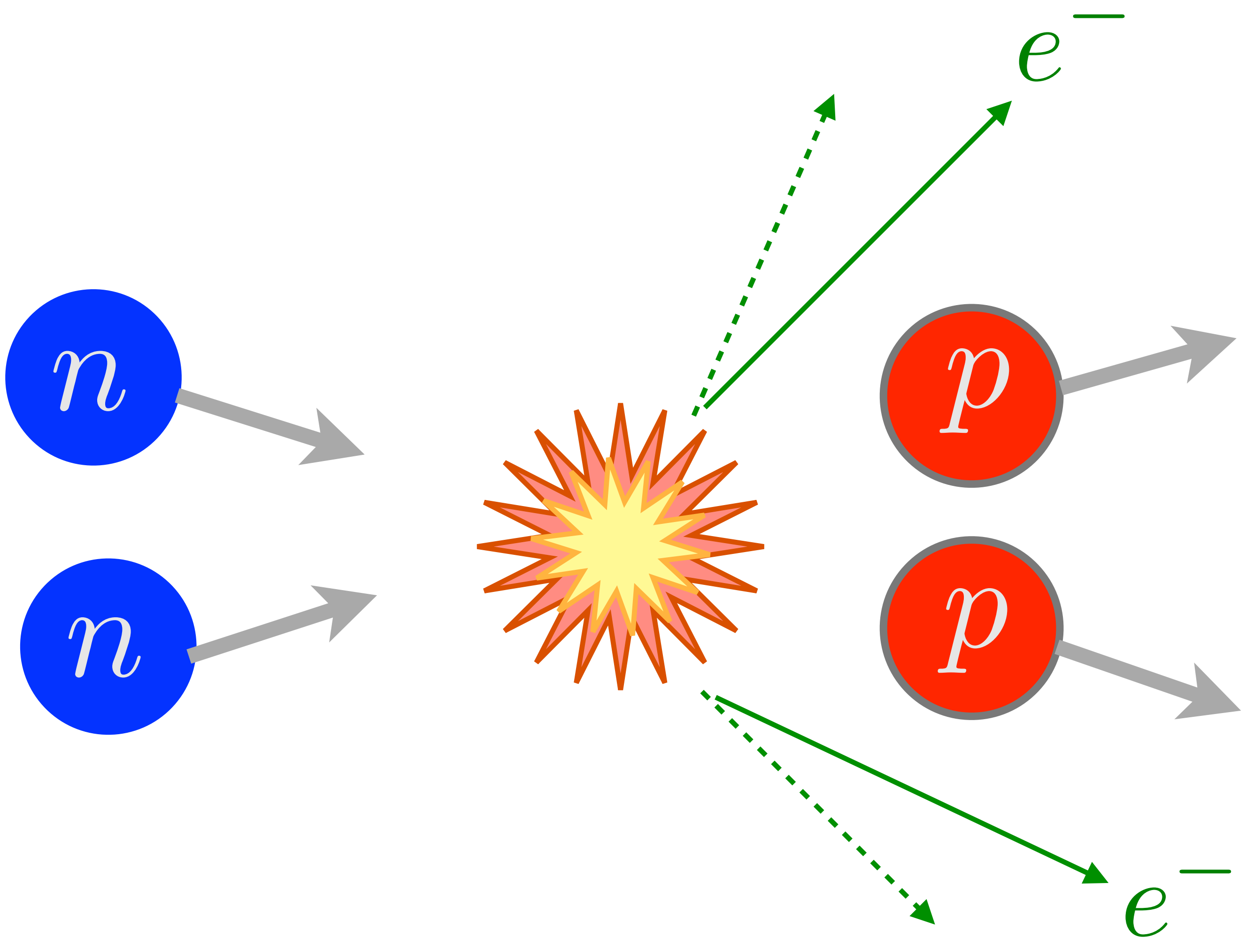


Compilation of results

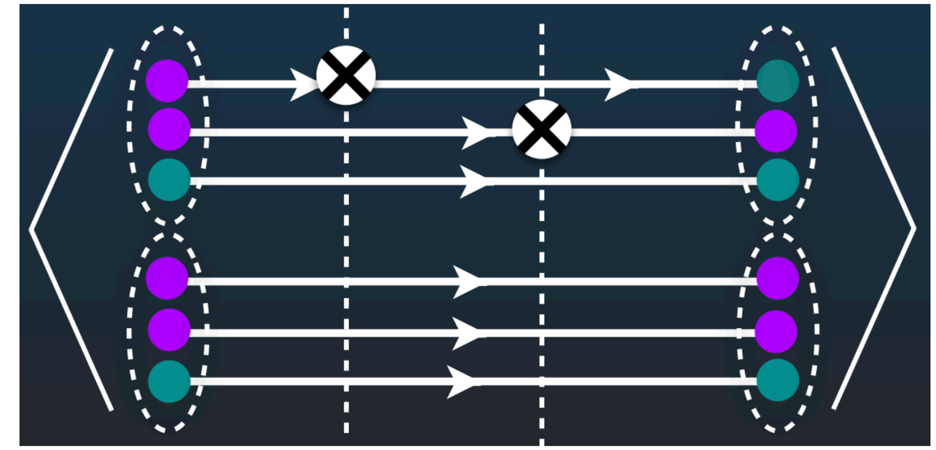

Computing matrix elements of currents from lattice QCD
Lattice QCD, Fundamental Symmetries, and Neutrino Physics
Example: Nucleon axial charge and form factors for neutrino-nucleus scattering
Example: Neutrinofull and neutrinoless double beta decays

NEUTRINOFUL DOUBLE-BETA DECAY

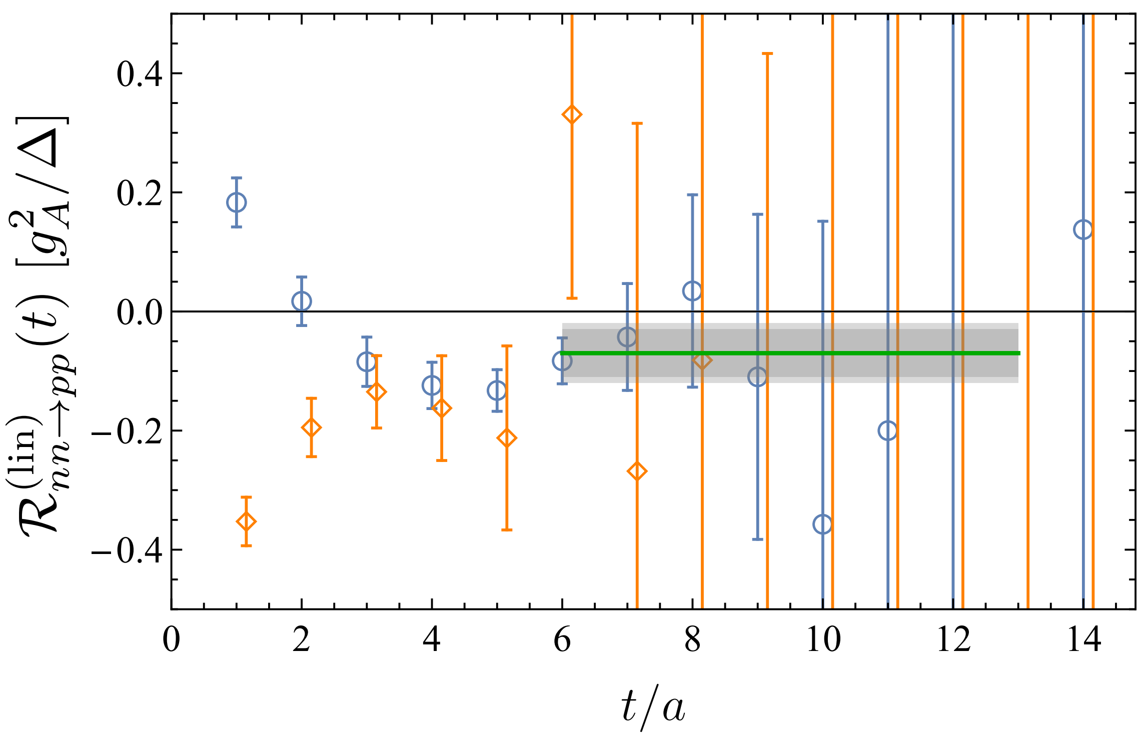
$$n + n \to p + p + e + e + \bar{\nu}_e + \bar{\nu}_e$$

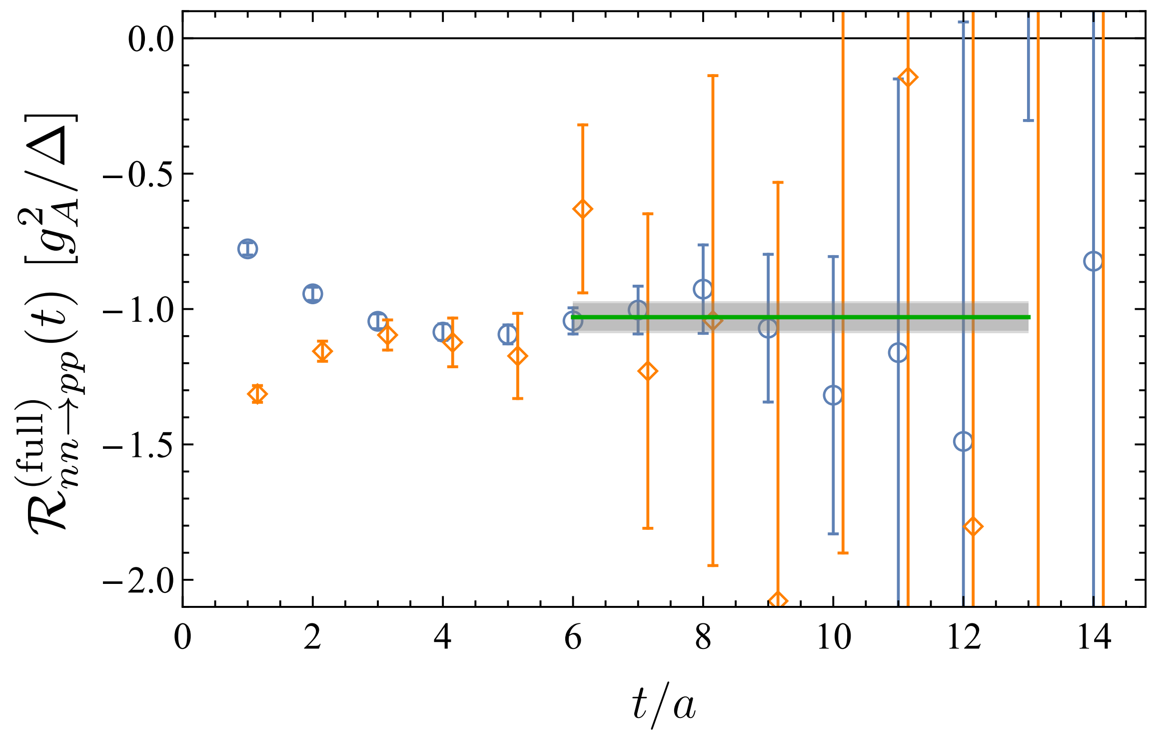


Matrix element from QCD using the Feynman-Hellmann (modified propagator) method (hiding all technicalities):



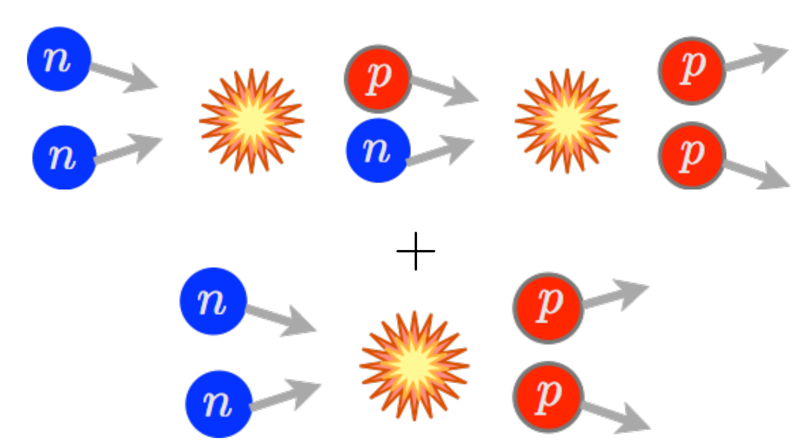
$N_f = 3, \; m_\pi = 0.806 \text{ GeV}, \; a = 0.145(2) \text{ fm}$





SHORT-DISTANCE CONTRIBUTION

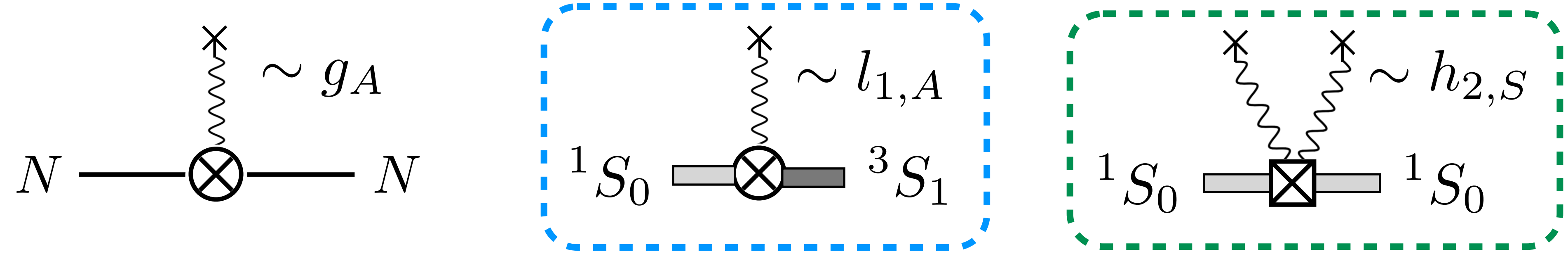
FULL CONTRIBUTION



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

Let’s see how we can match this result to a low-energy EFT and constrain unknown LECs

* Note “dibaryon” fields are used.



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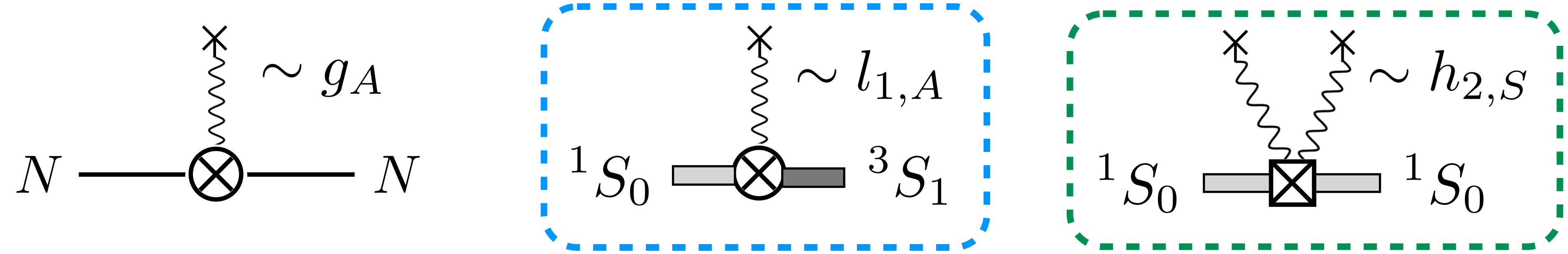
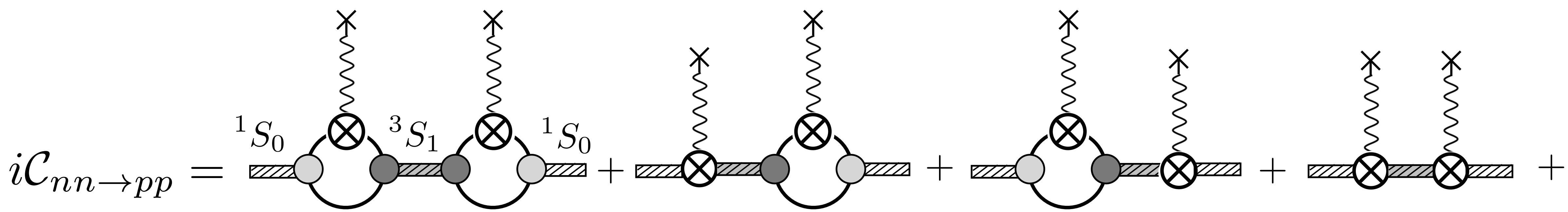
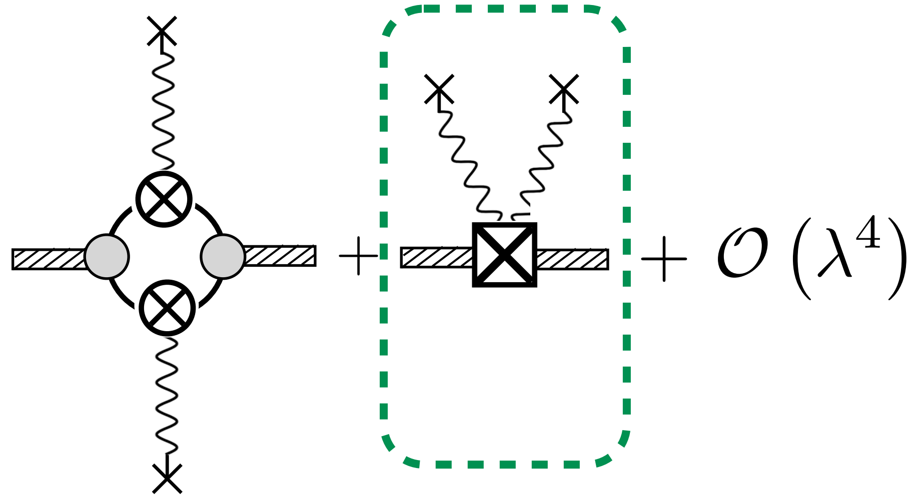






A coupling related to $\sim h_{2,S}$ above.

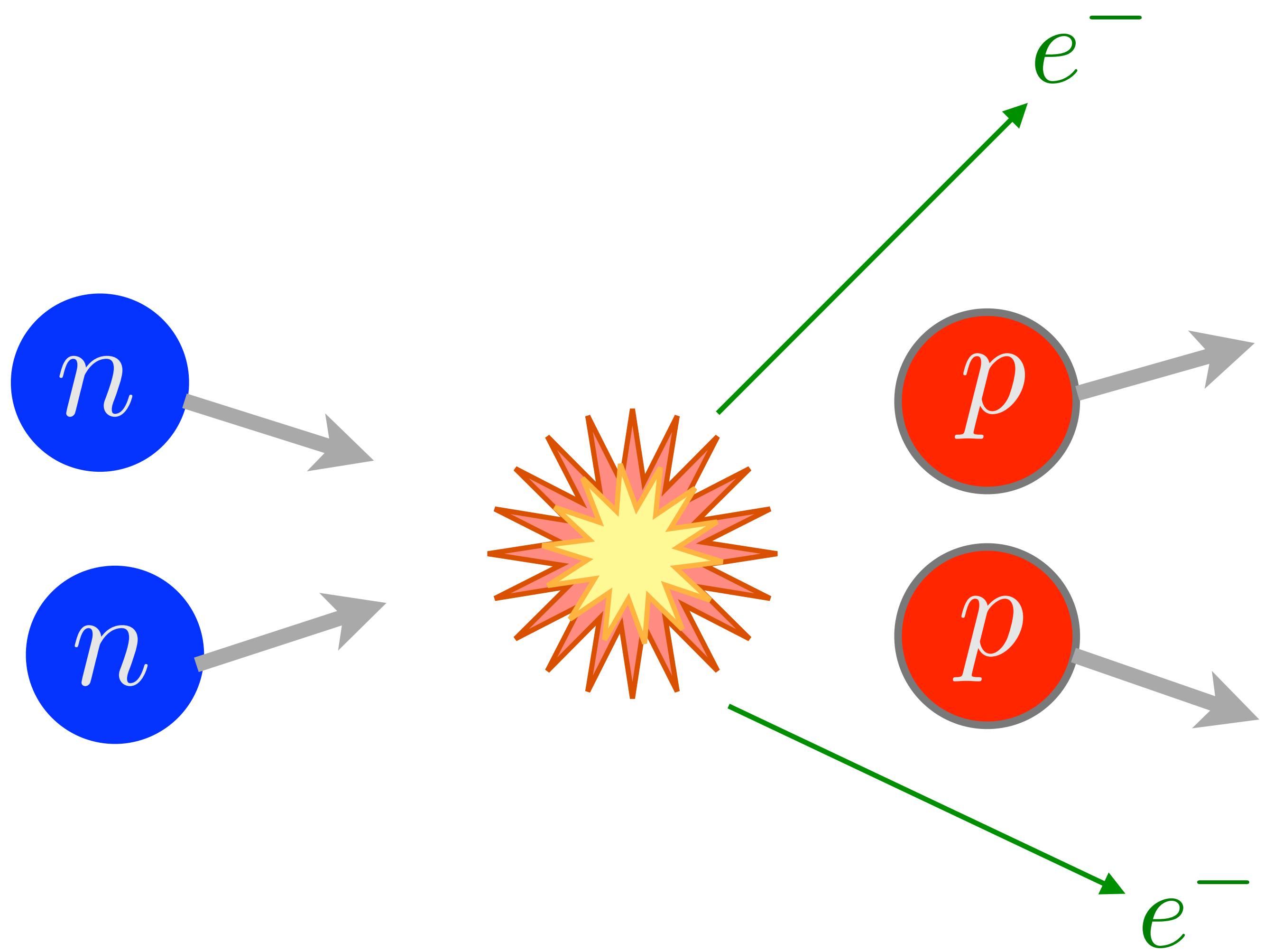
$$\mathbb{H}_{2,S} = 4.7(1.3)(1.8)\ \mathtt{fm}$$

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

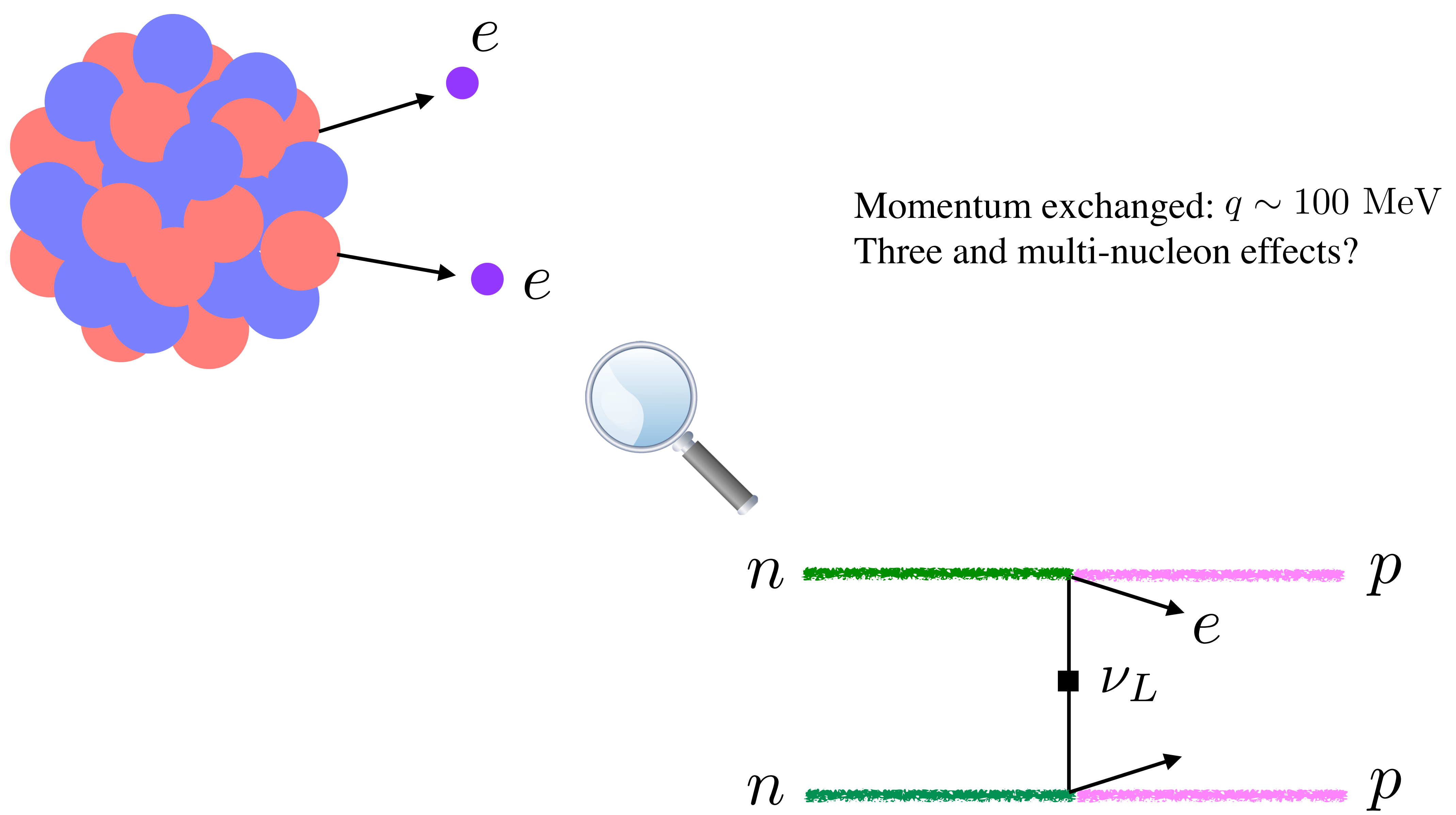
Tiburzi et al (NPLQCD), Phys. Rev.D96,054505(2017)
Shanahan et al (NPLQCD), Phys. Rev. Lett.119,062003(2017).

NEUTRINOLESS DOUBLE-BETA DECAY

$$n + n \rightarrow p + p + e + e$$



We cannot study the matrix elements of Germanium or other experimentally relevant isotopes directly, but lattice QCD combined with EFT can help improve nucelar structure predictions of the rates.



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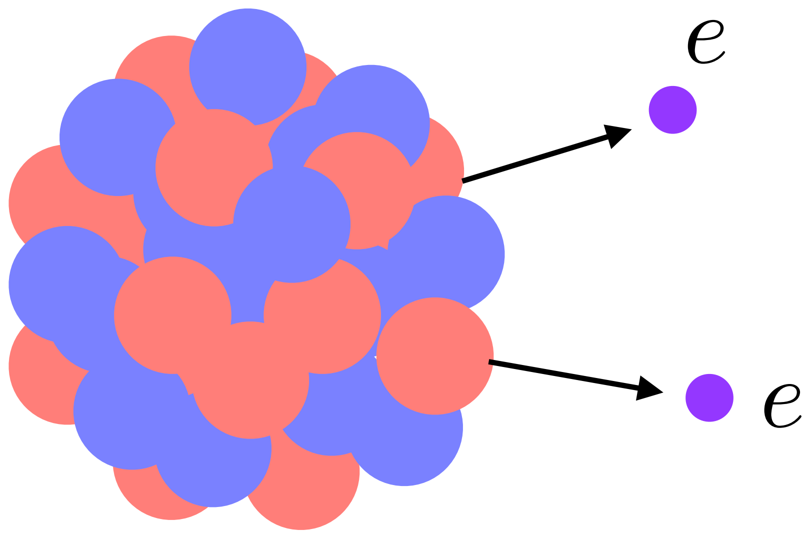
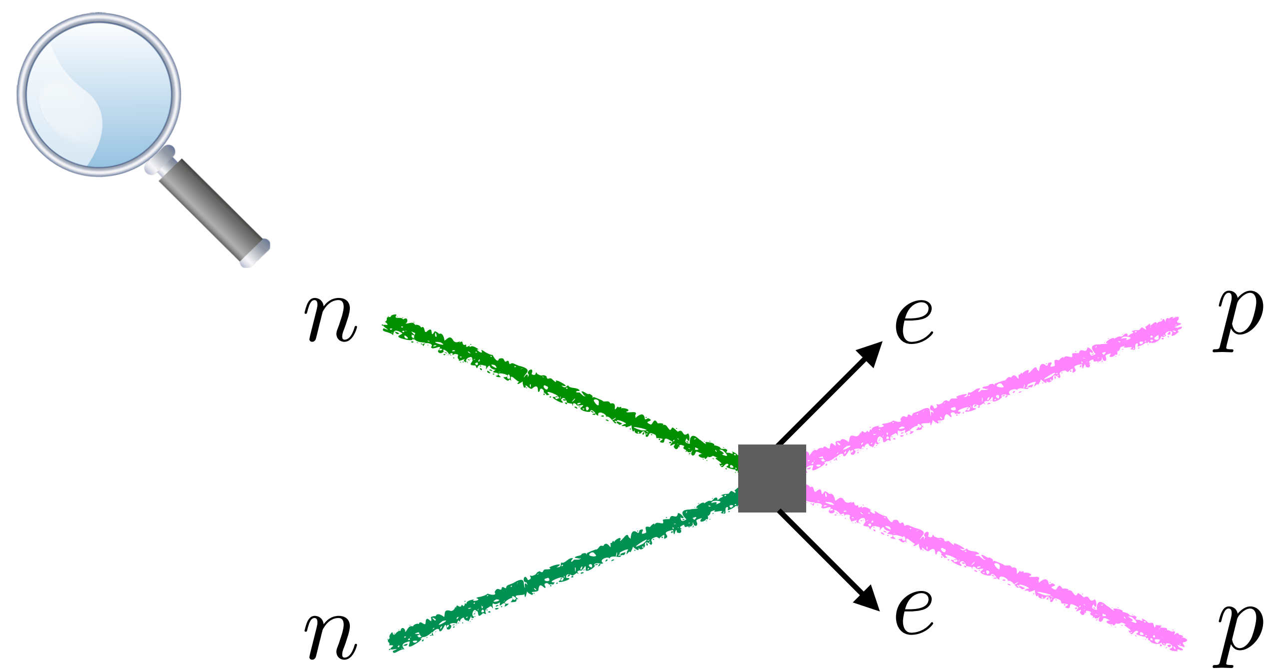


Momentum exchanged: $q \sim 100$ MeV
Three and multi-nucleon effects?

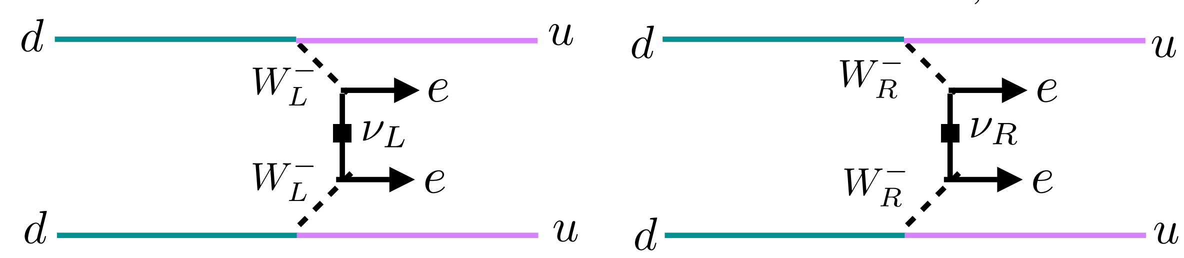


Ask Jordy all about it!

Matching high scale to low scale for $0\nu BB$ decay

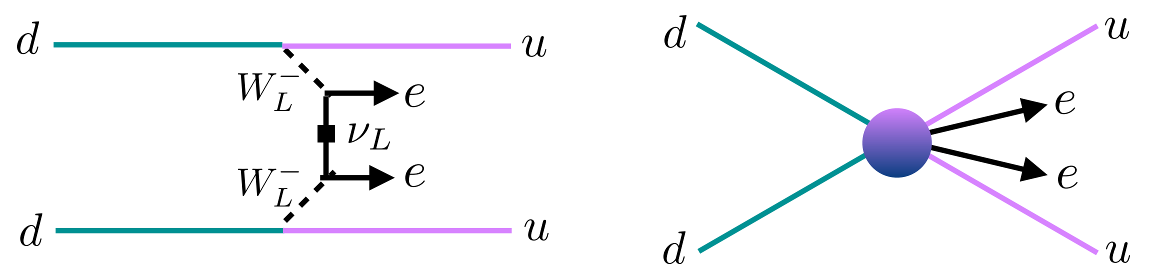
$\Lambda > \text{TeV}$

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



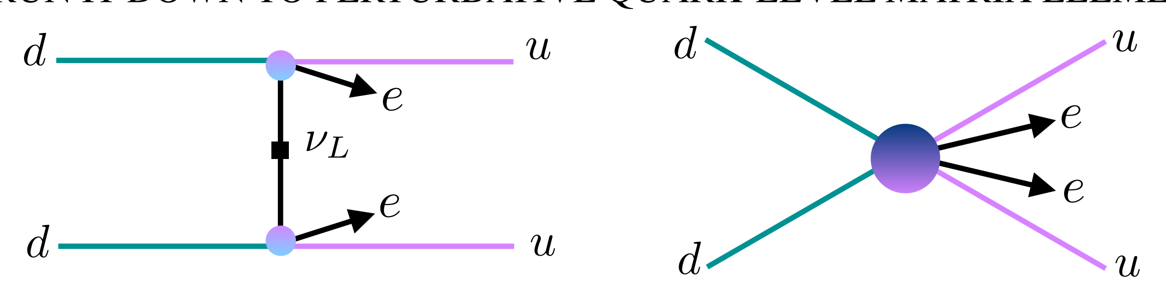
$\Lambda \sim 10^2\ \text{GeV}$

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



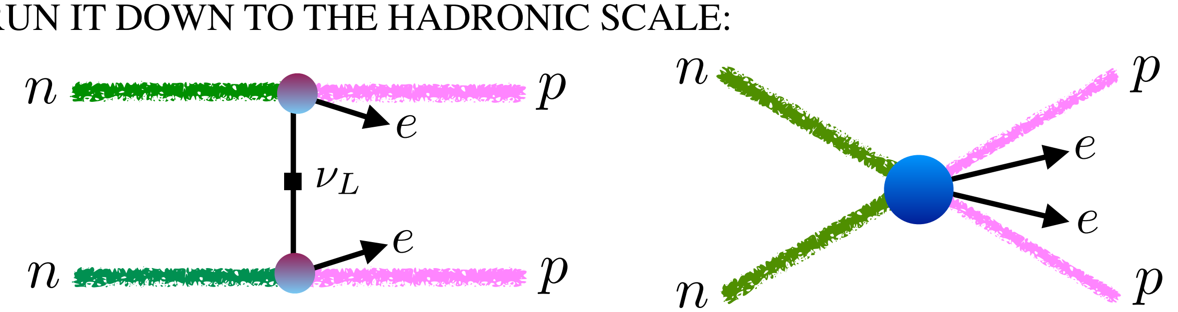
$\Lambda \sim 2\ \text{GeV}$

RUN IT DOWN TO PERTURBATIVE QUARK-LEVEL MATRIX ELEMENTS:



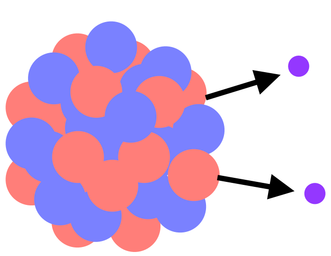
$\Lambda < \text{GeV}$

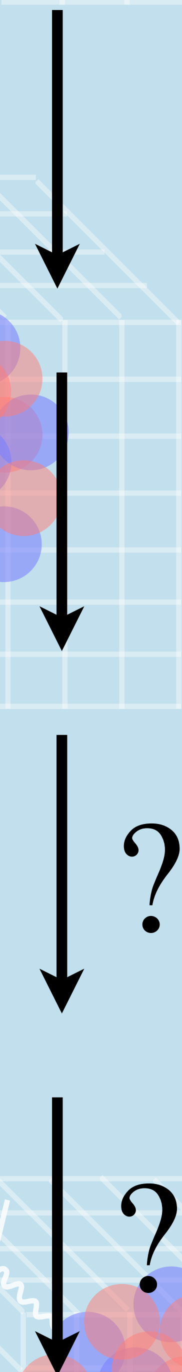
RUN IT DOWN TO THE HADRONIC SCALE:



$\Lambda < \text{MeV}$

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





Two scenarios

NON-LOCAL MATRIX ELEMENTS OF TWO DIMENSION-6 FOUR-FERMION STANDARD MODEL 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.

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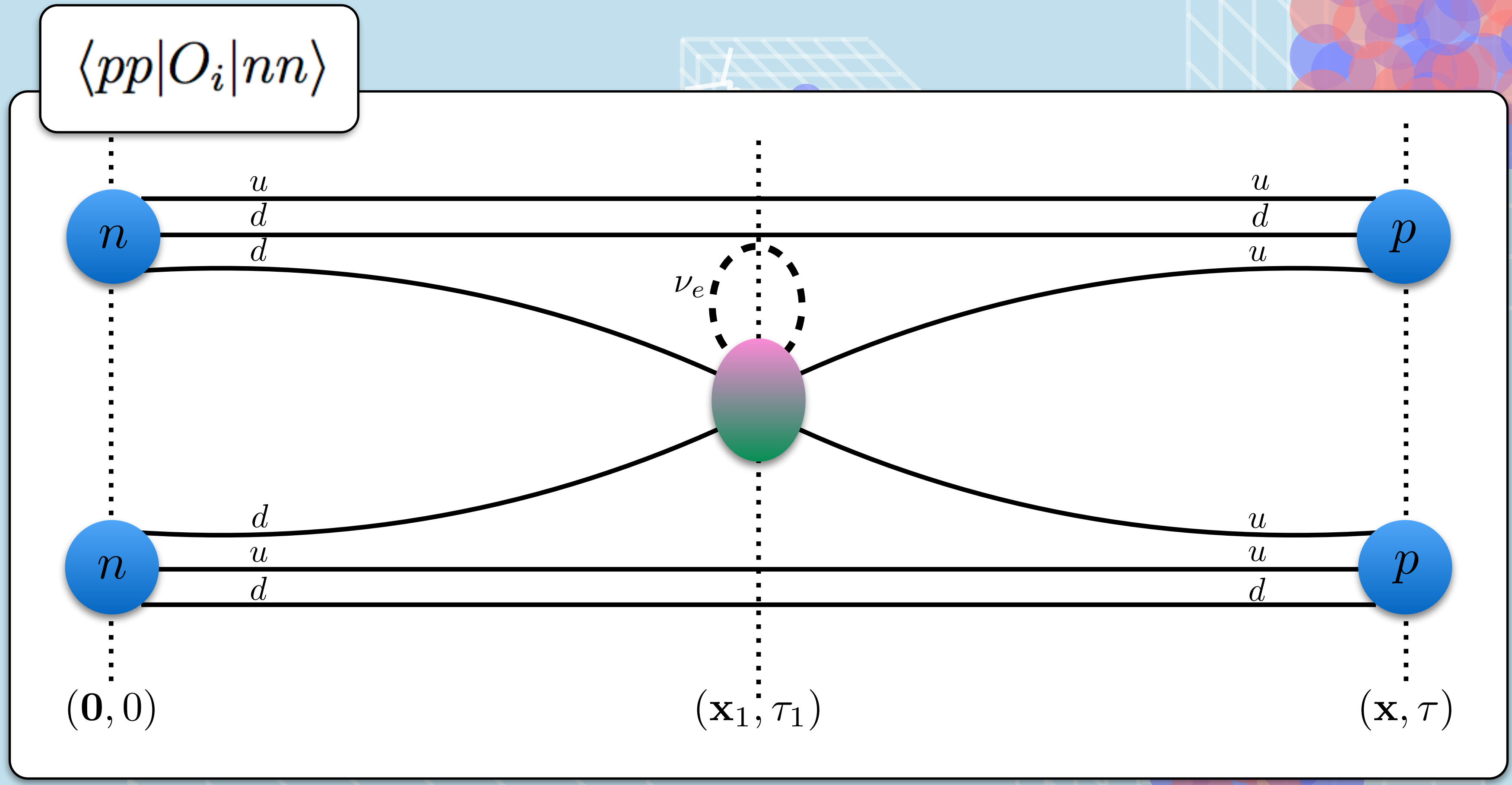
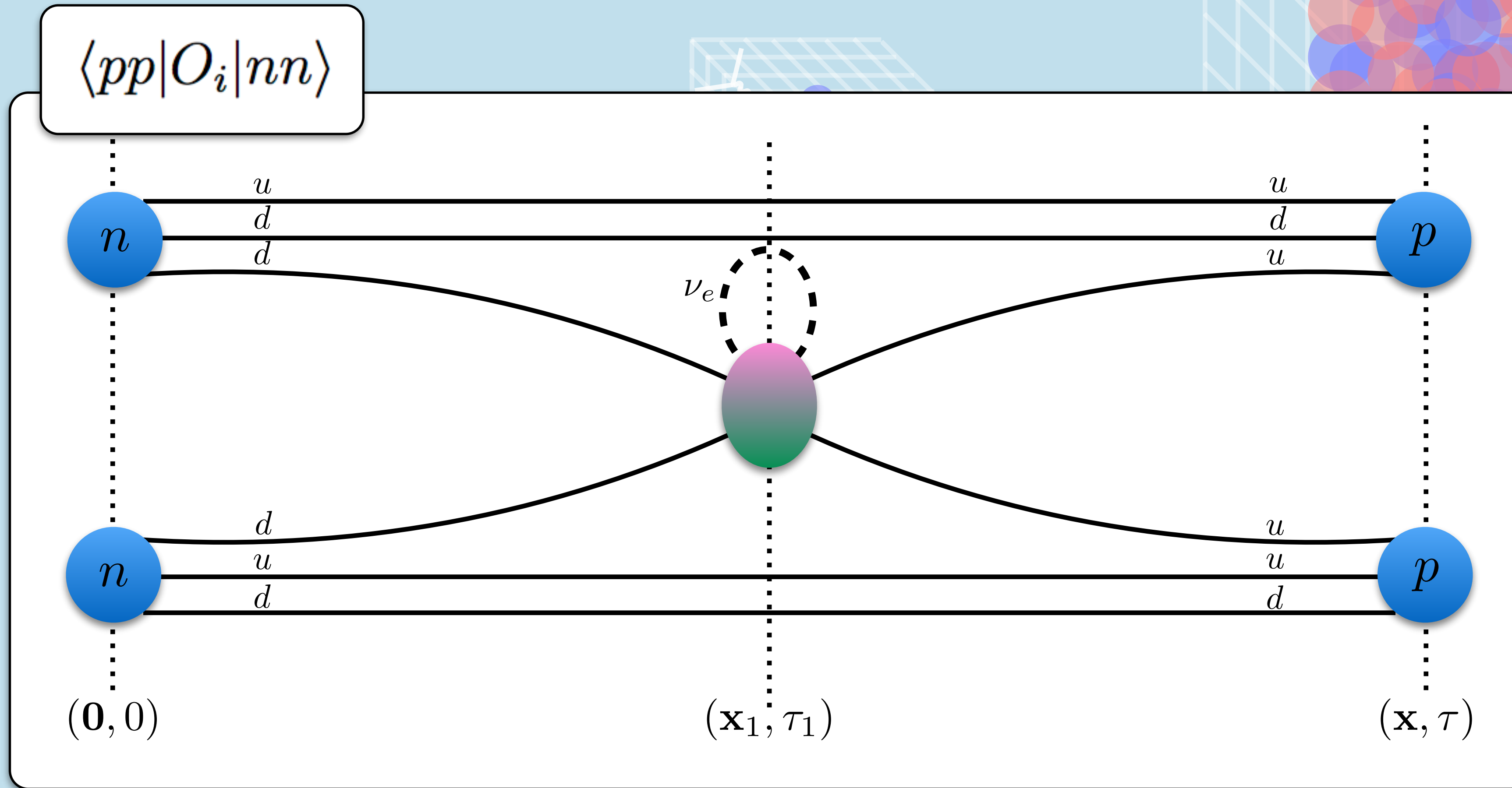
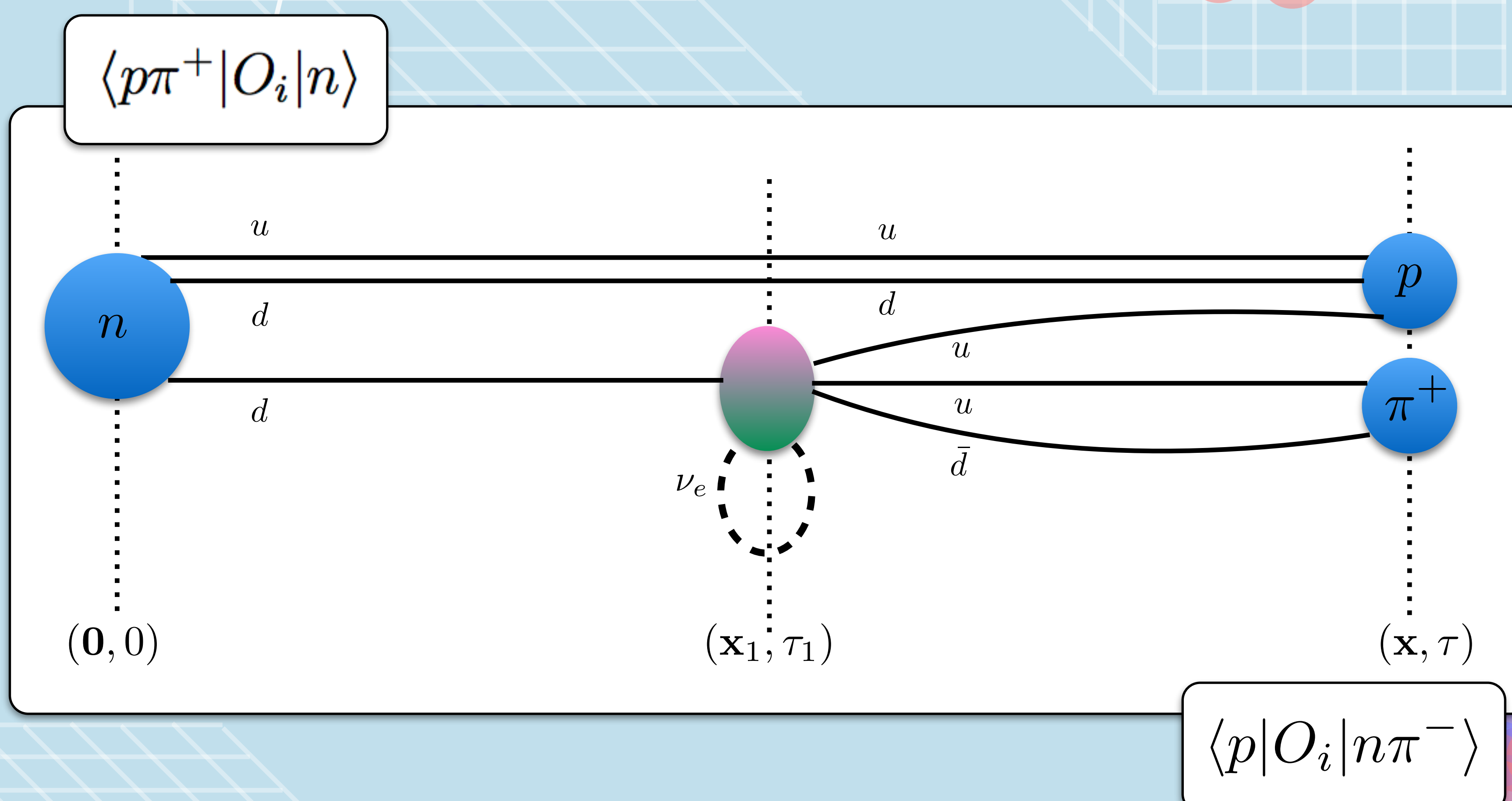
MATRIX ELEMENTS OF **LOCAL** FOUR-QUARK OPERATORS

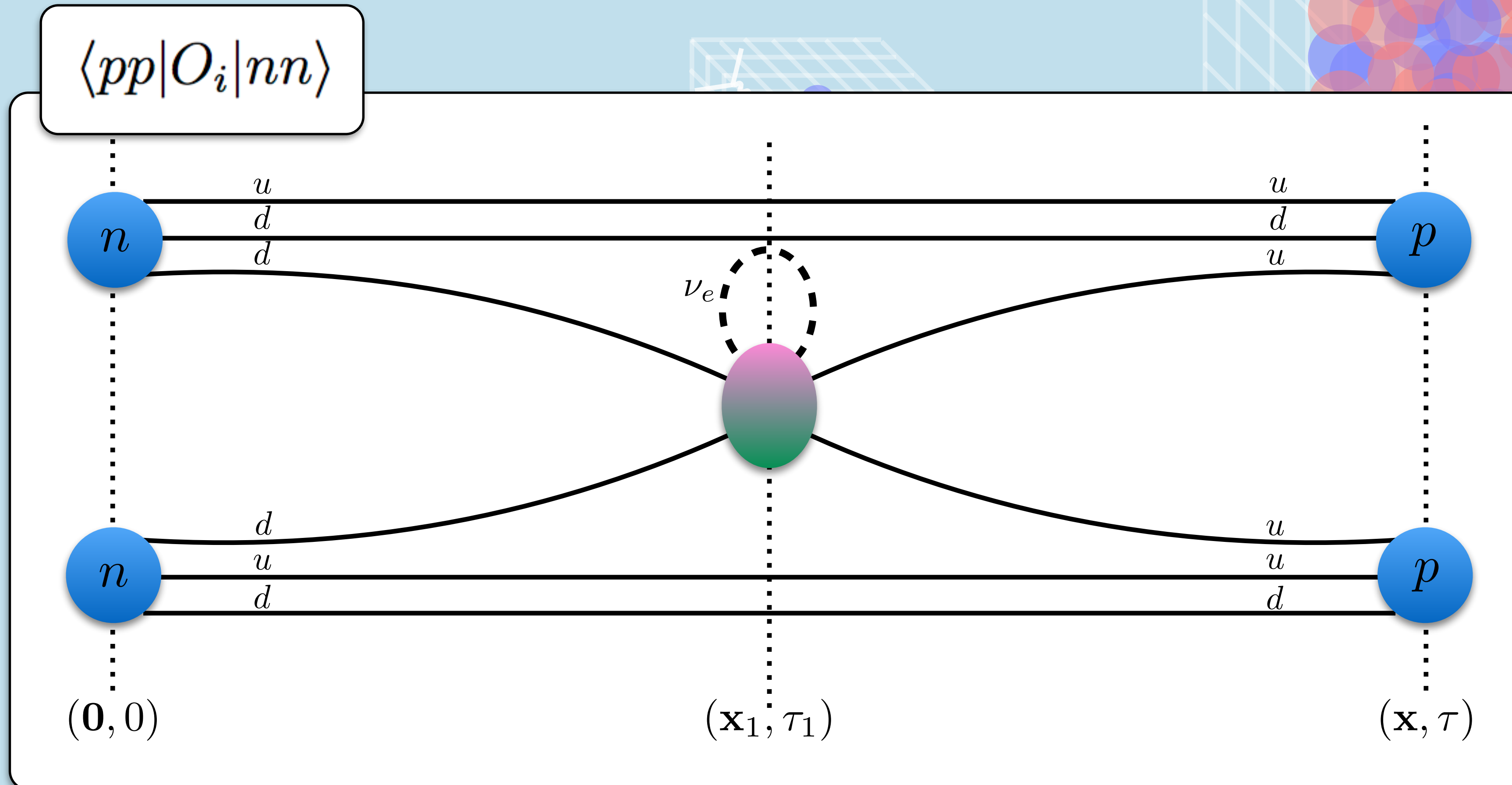


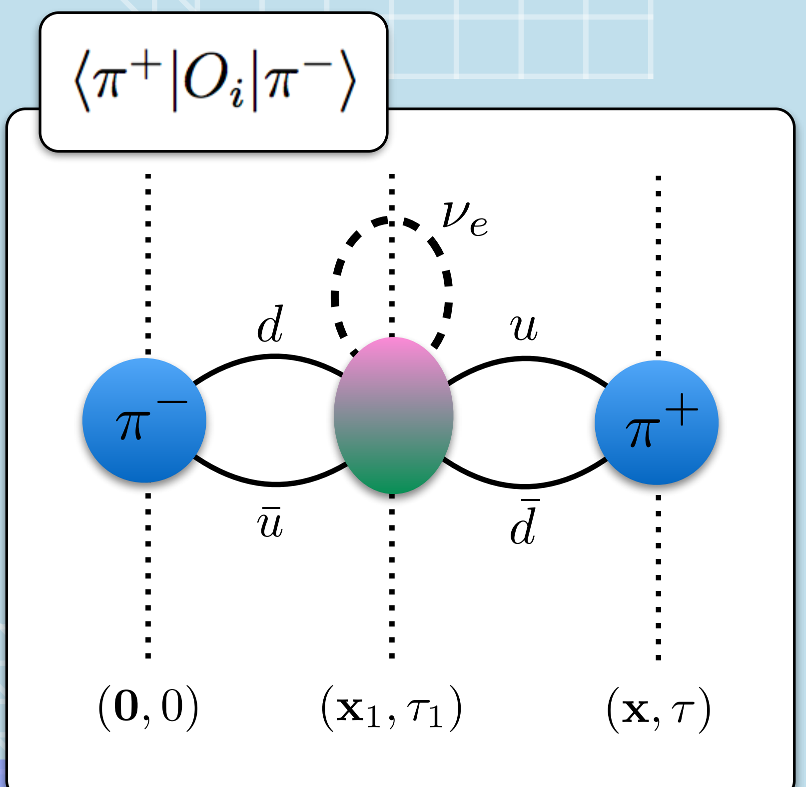
MATRIX ELEMENTS OF **LOCAL**
FOUR-QUARK OPERATORS

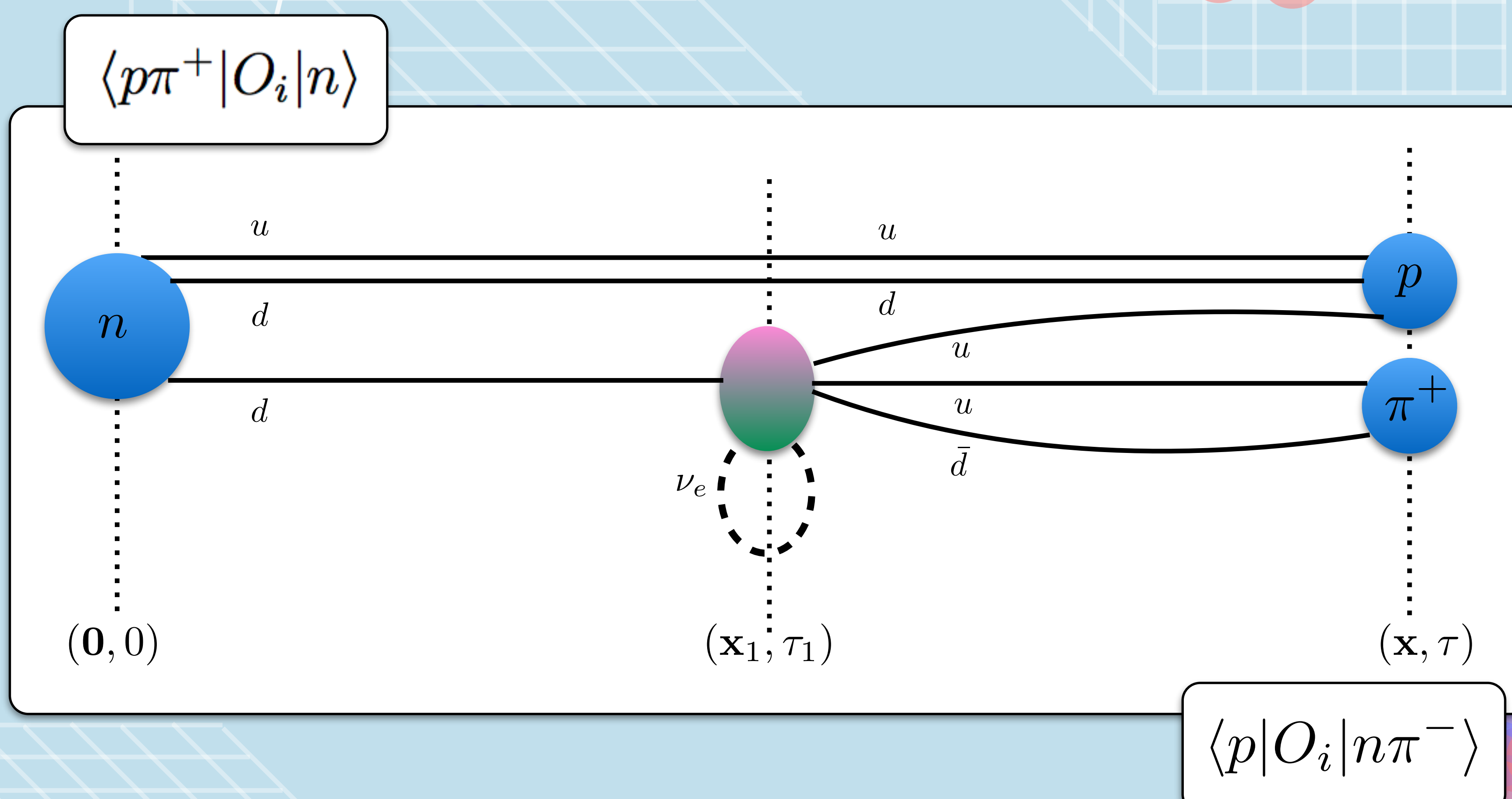




MATRIX ELEMENTS OF **LOCAL** FOUR-QUARK OPERATORS

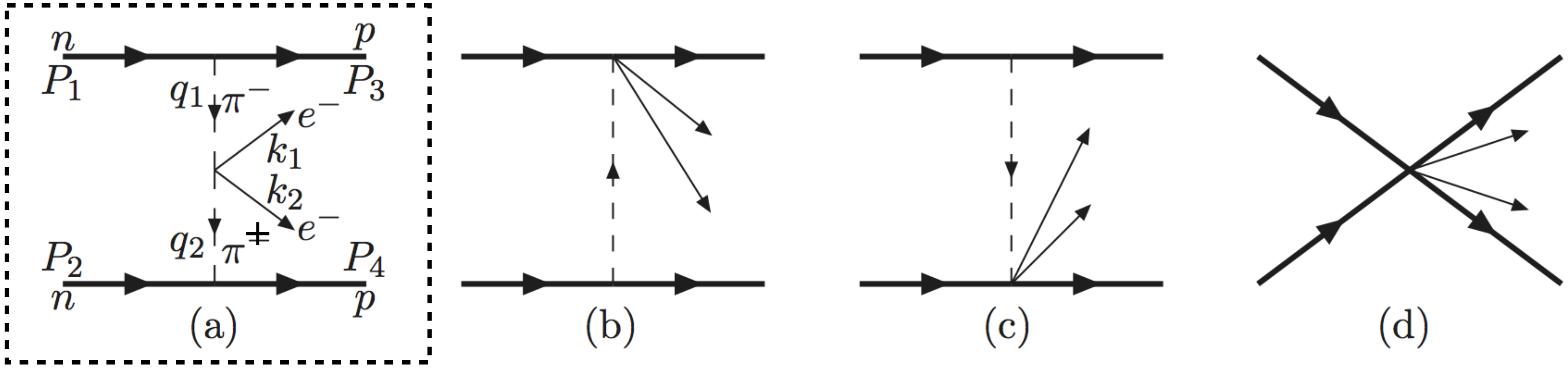




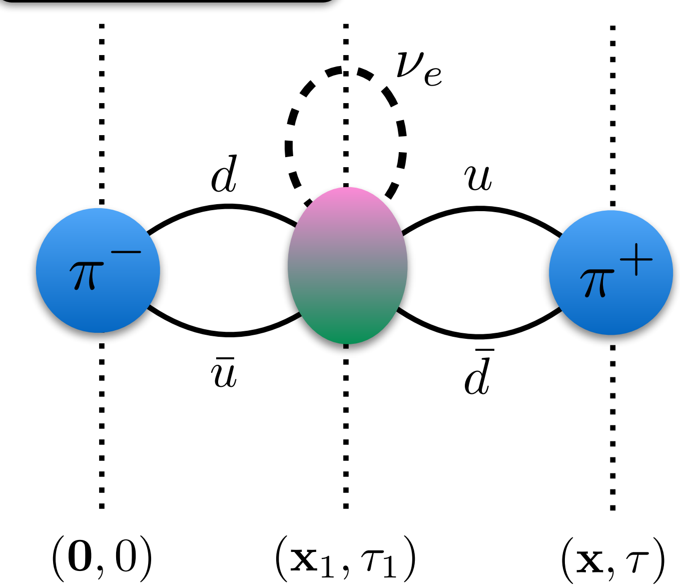


MATRIX ELEMENTS OF **LOCAL** FOUR-QUARK OPERATORS

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



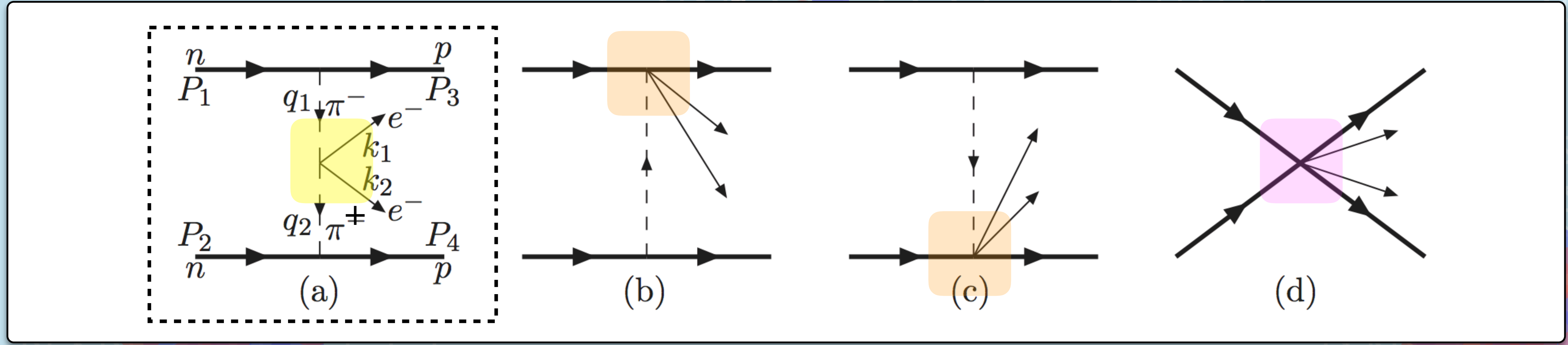
$\langle \pi^+ | O_i | \pi^- \rangle$

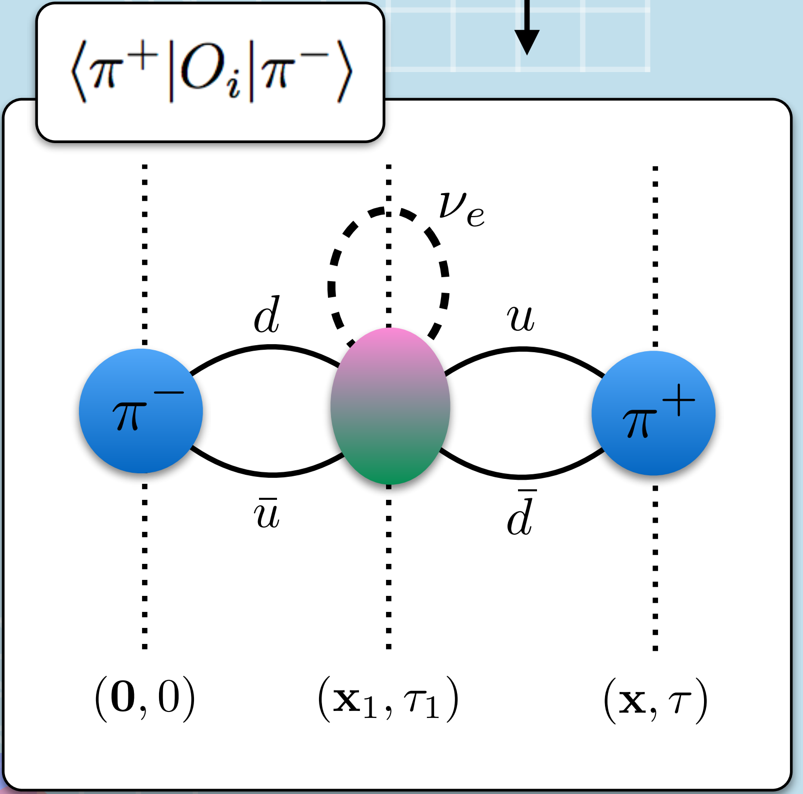


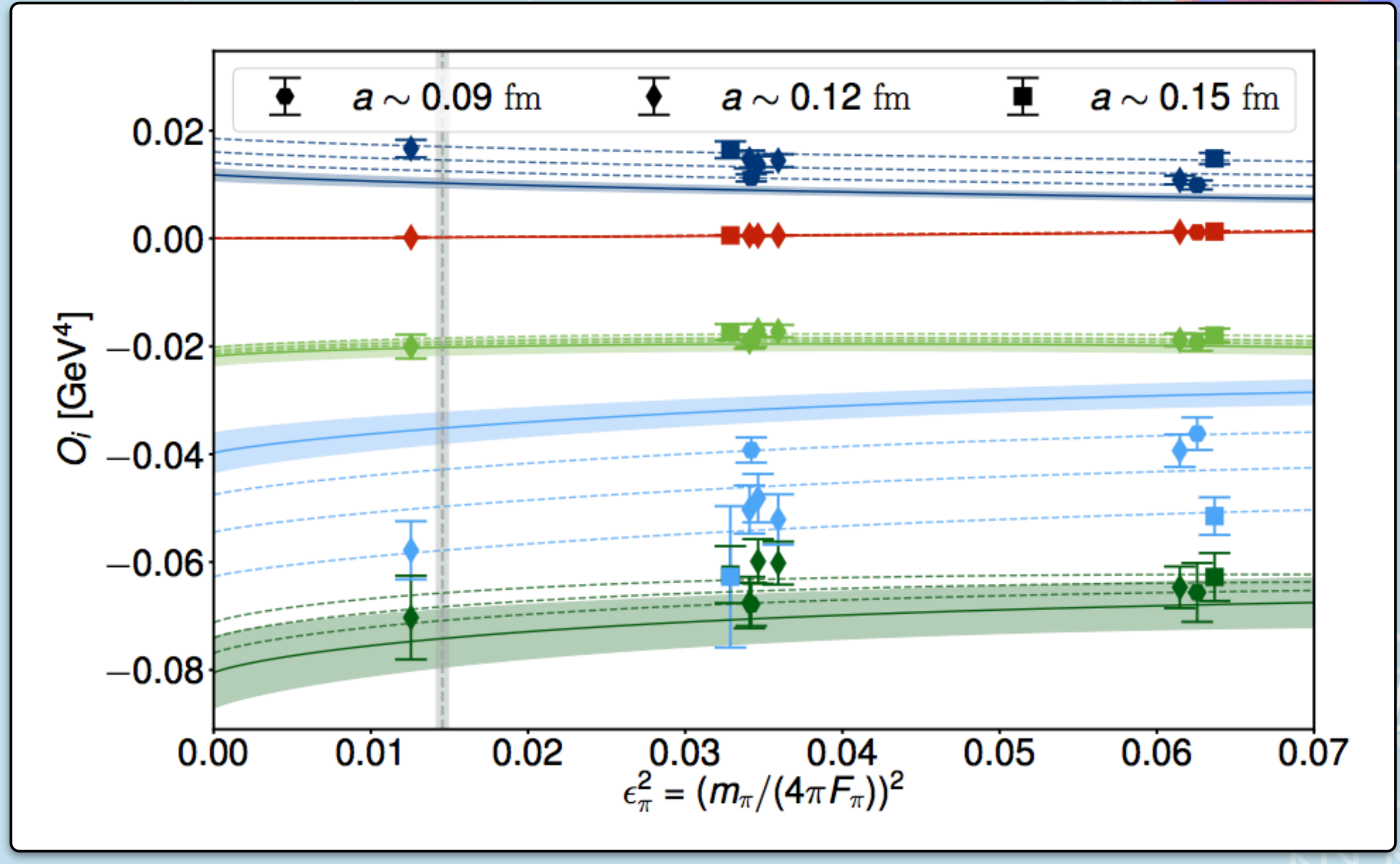
MATRIX ELEMENTS OF **LOCAL** FOUR-QUARK OPERATORS

Indirect methods to constrain the same LECs:
Savage, Phys. Rev. C59, 2293 (1999).
Cirigliano, Dekens, Graesser and Mereghetti, PLB Volume 769, 2017, 460-464.

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







A lattice QCD determination:
Nicholson et al (CALLATT collaboration),
Phys. Rev. Lett. 121, 172501 (2018).

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

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

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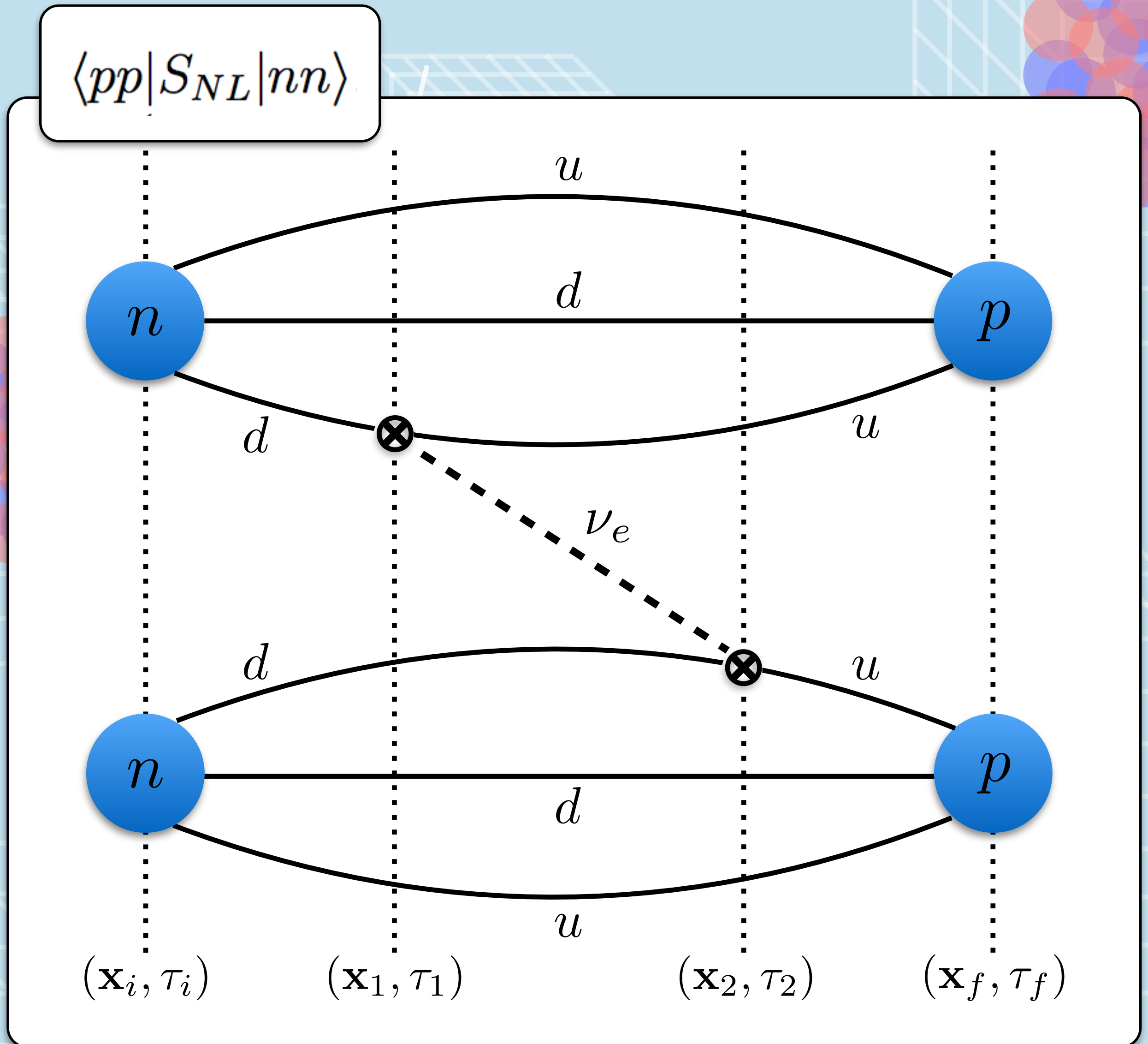
EFT approach makes the case for LQCD even stronger, see e.g., Cirigliano, Dekens, De Vries, Graesser, Mereghetti, Pastore, and Van Kolck, Phys. Rev. Lett. 120, 202001 (2018), arXiv:1802.10097 [hep-ph].



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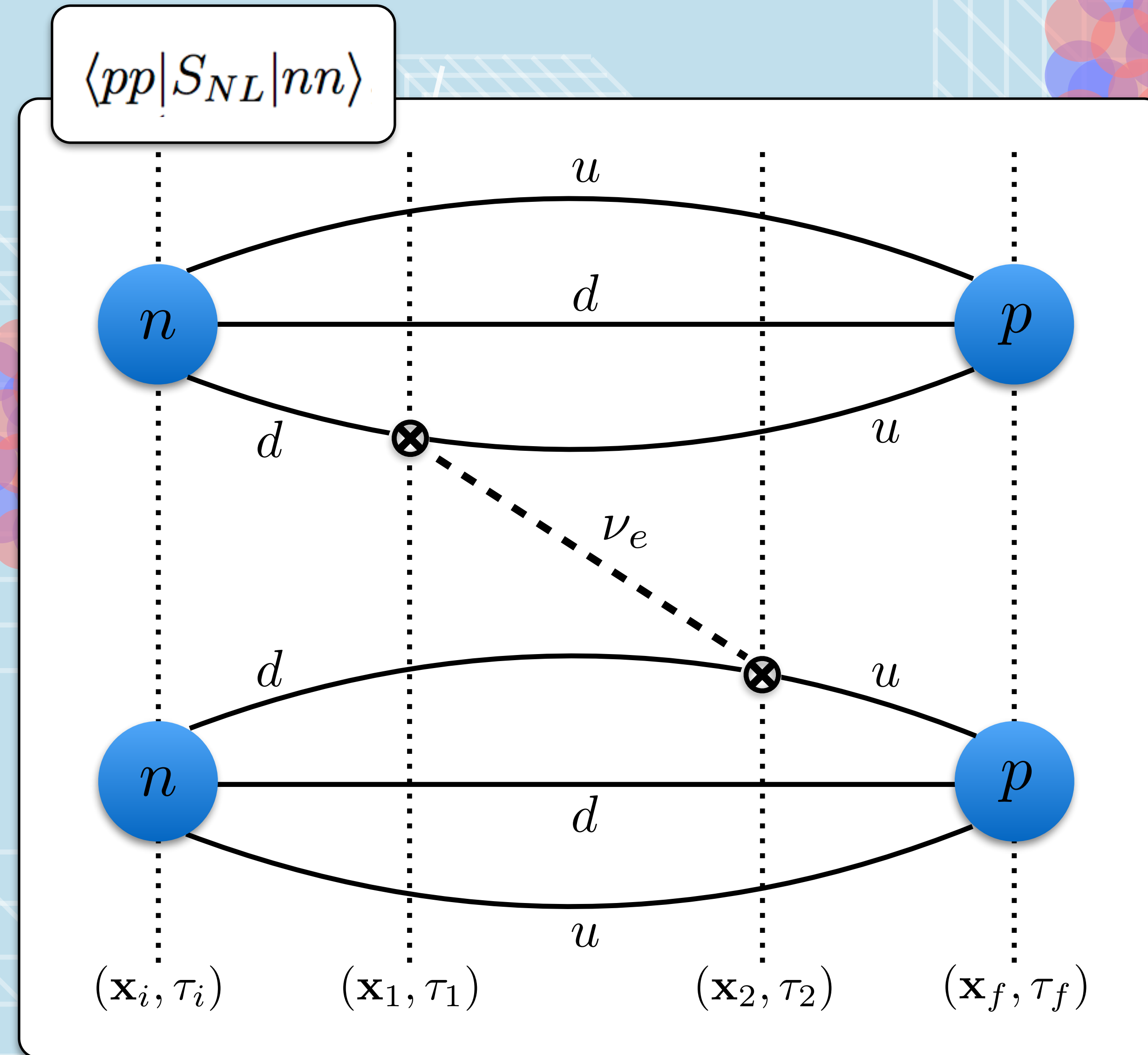

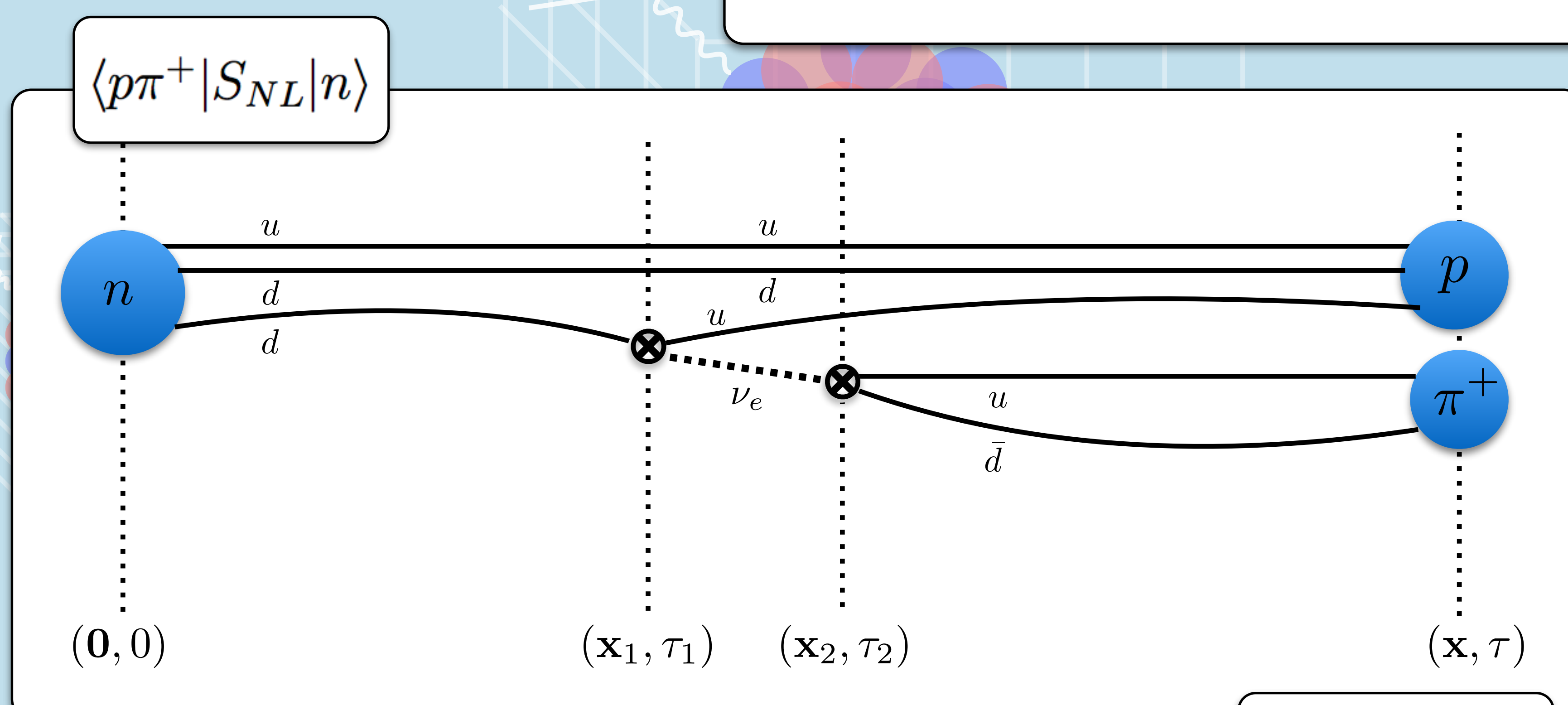

$\langle p|S_{NL}|n\pi^-\rangle$

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

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

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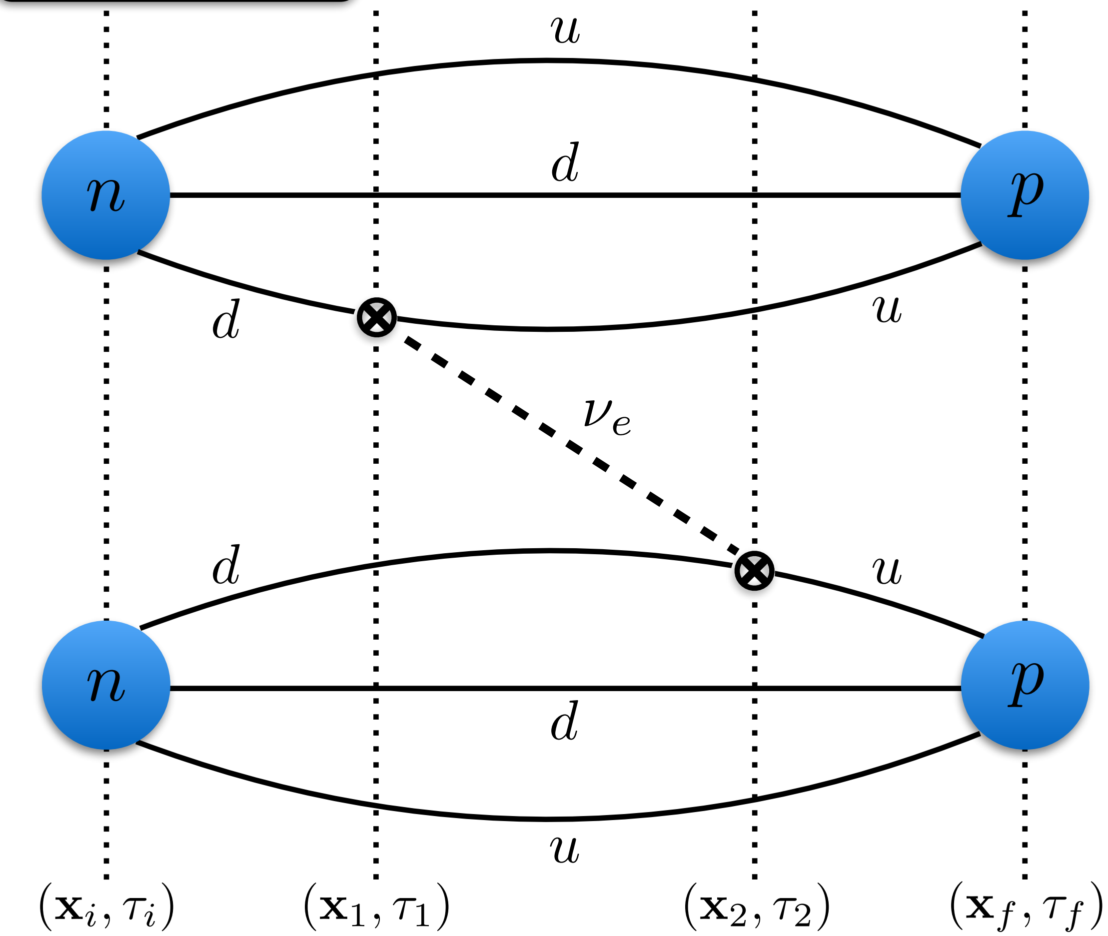
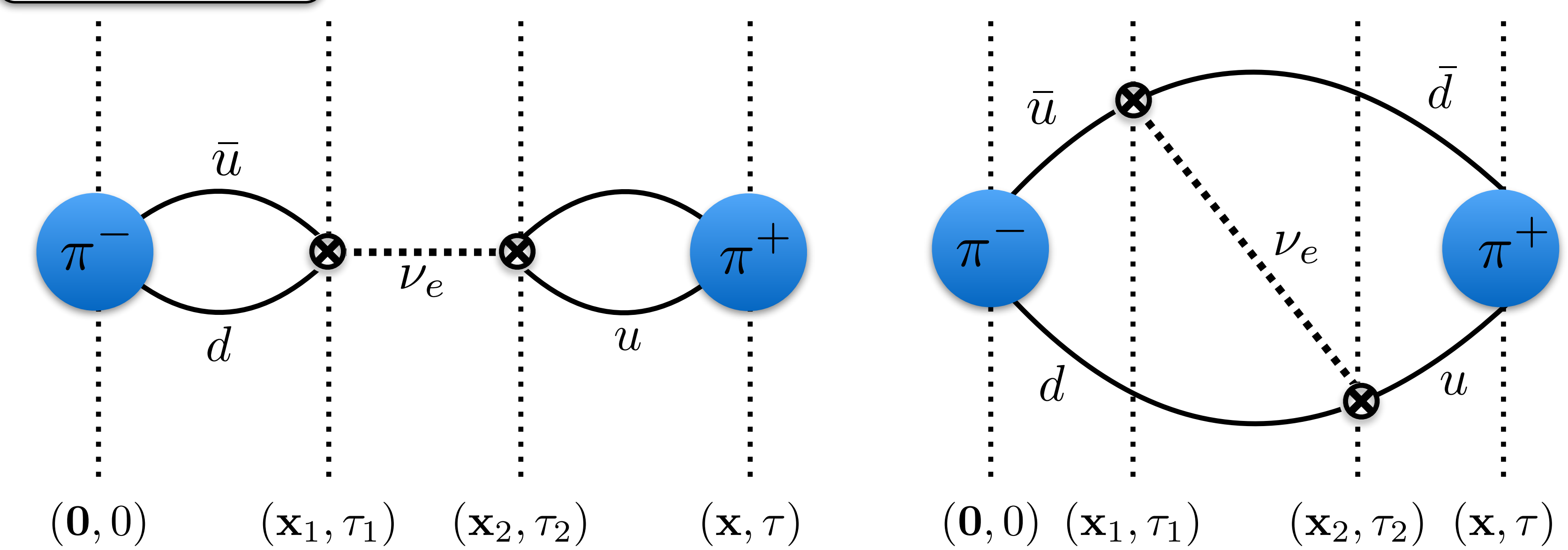
$\langle pp|S_{NL}|nn\rangle$



$\langle \pi^+|S_{NL}|\pi^-\rangle$



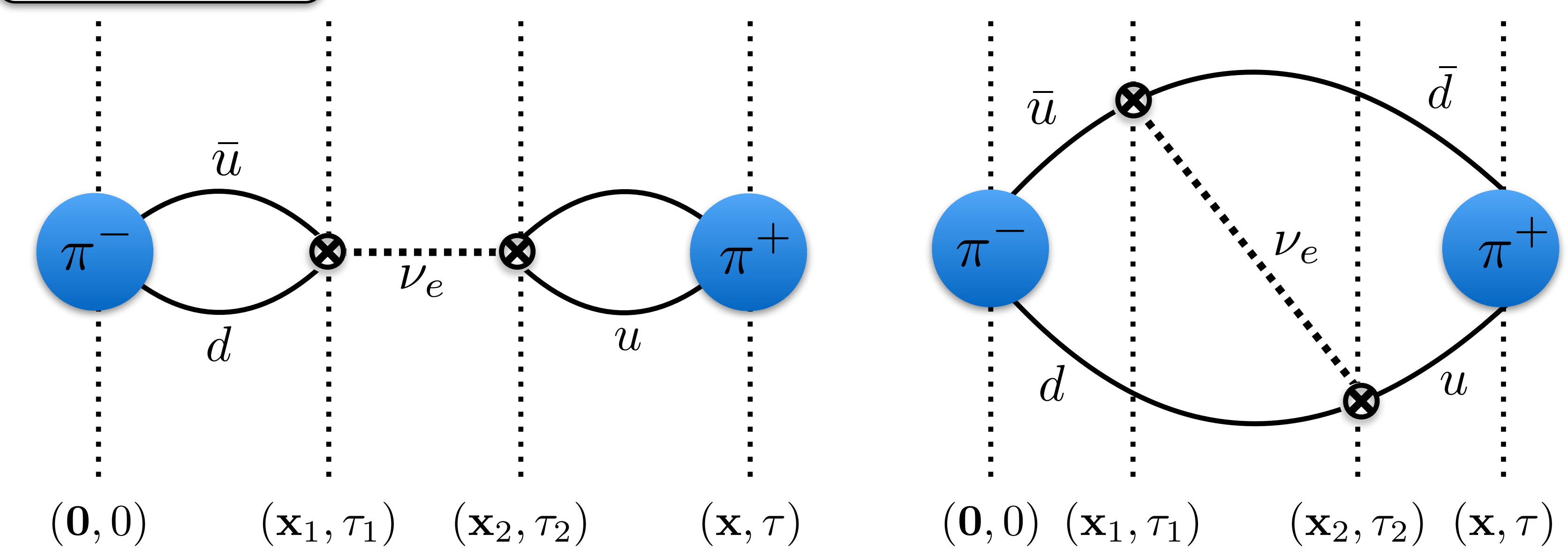
MATRIX ELEMENTS OF **NON-LOCAL** TWO-QUARK SM WEAK OPERATORS

Ratio of next-to-leading to leading order amplitude in chiral perturbation theory:

$$\mathcal{S}_{\pi\pi} = 1 + \frac{m_\pi^2}{8\pi^2 f_\pi^2}\left(3\log\left(\frac{\mu^2}{m_\pi^2}\right) + 6 + \frac{5}{6} g_\nu^{\pi\pi}(\mu)\right)$$

The unknown ChiPT LEC to be determined with lattice QCD.

$\langle \pi^+ | S_{NL} | \pi^- \rangle$

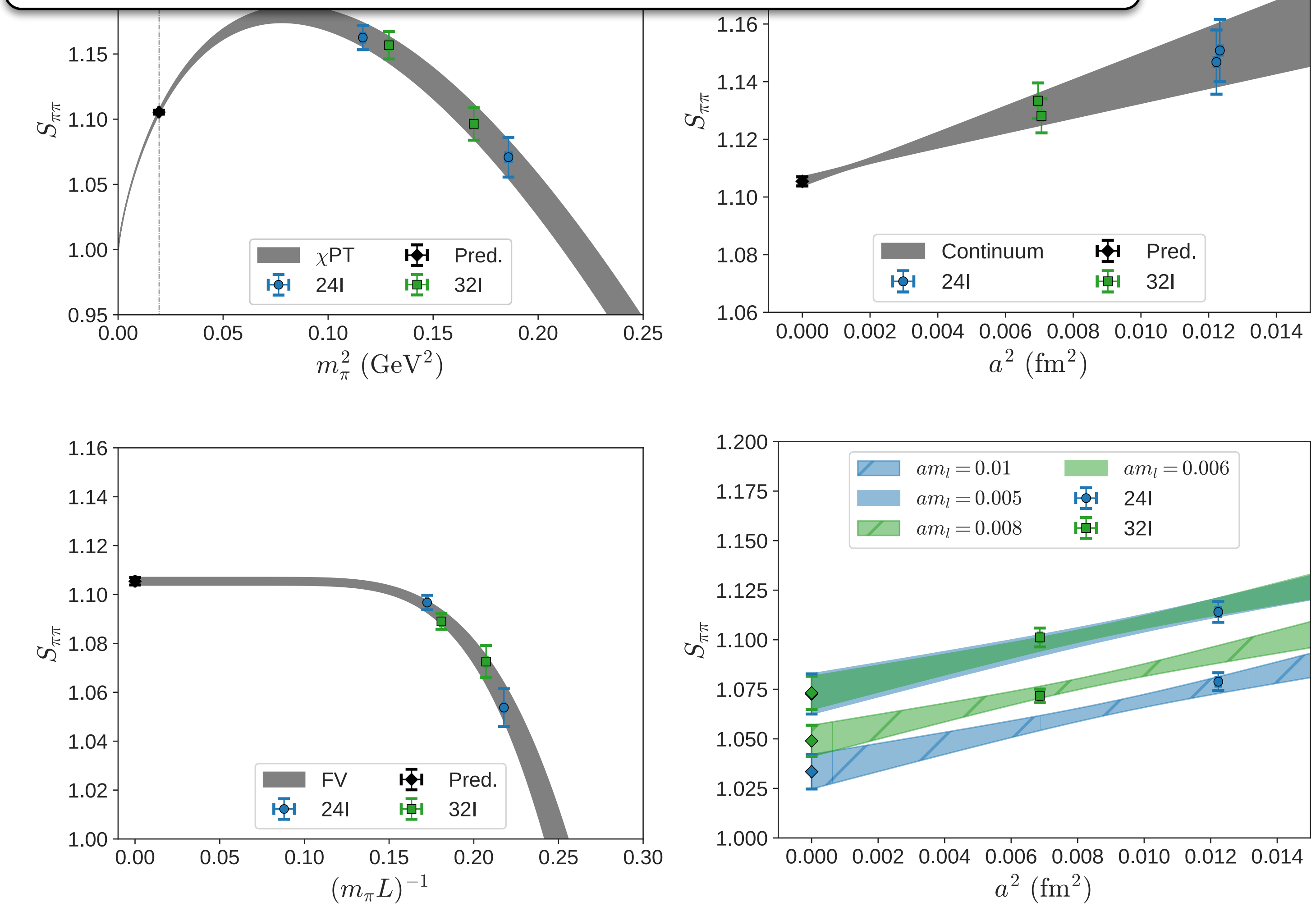


Detmold and Murphy, 2004.07404 [hep-lat].

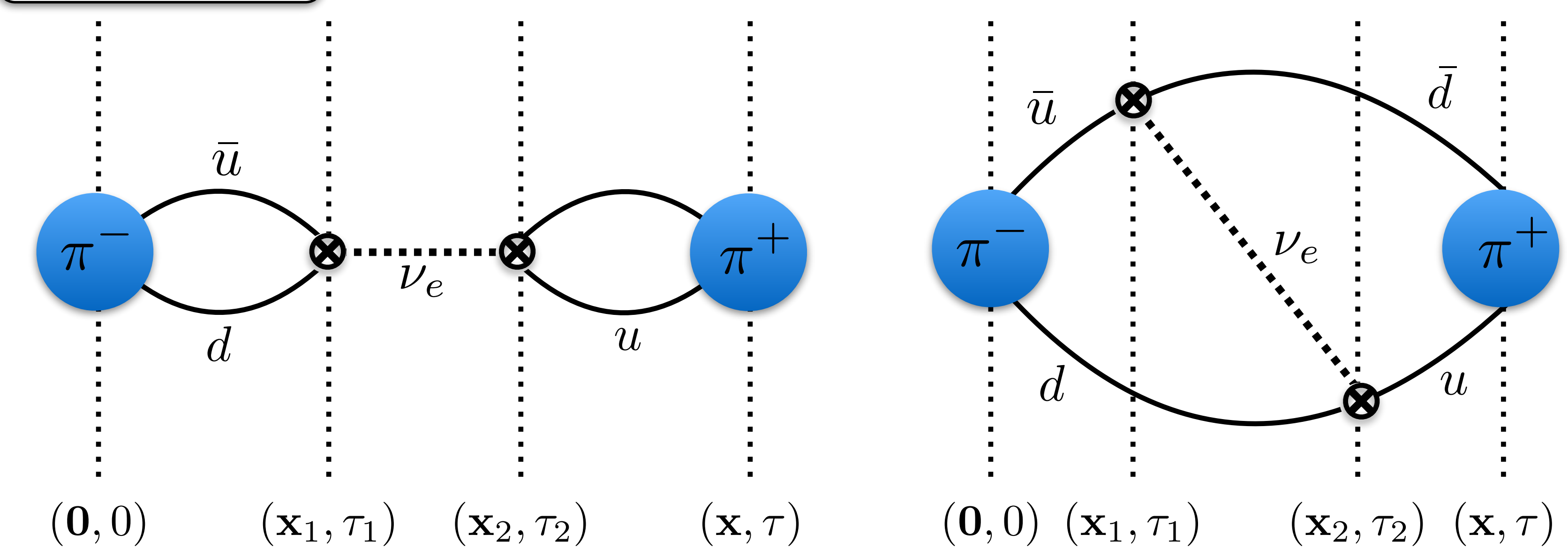
MATRIX ELEMENTS OF **NON-LOCAL** TWO-QUARK SM WEAK OPERATORS

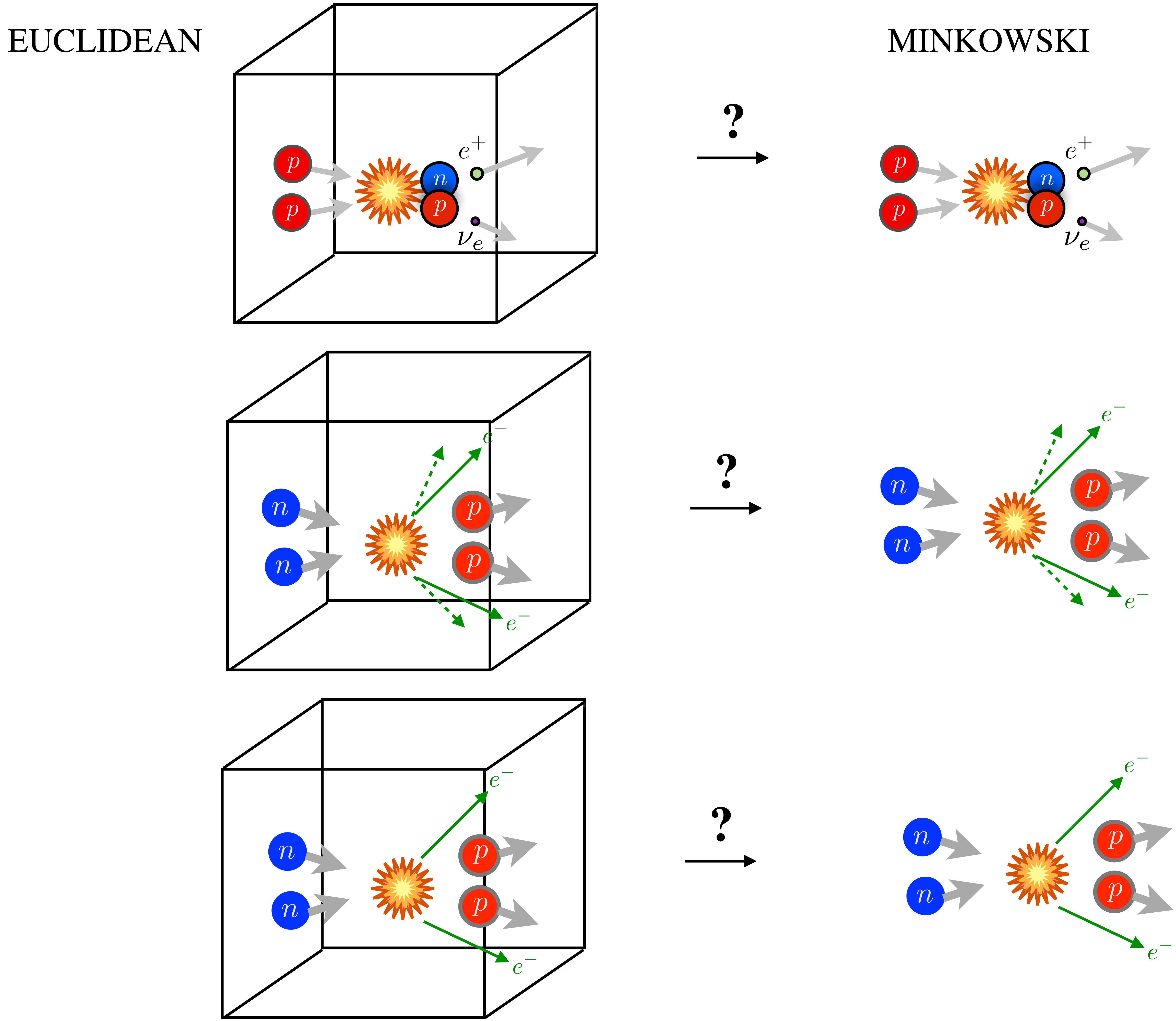
See also: Tuo, Feng, Jin, *phys.Rev.D* 100 (2019) 9, 094511.

$$g_\nu^{\pi\pi}(770\text{ MeV}) = -10.78(12)_{\text{stat}}(4)_{\text{fit}}(50)_{\text{FV}}(9)_{\chi\text{PT}}$$



$\langle\pi^+|S_{NL}|\pi^-\rangle$





EUCLIDEAN
MINKOWSKI
?
?
?

The **finite-volume technology** for electroweak matrix elements is crucial for the success of the program and builds upon many valuable developments of the past, to mention a few…

Weak transition matrix elements from finite volume correlation functions

Lellouch and Luescher, Commun. Math. Phys. 219, 31–44 (2001).

Finite-volume effects for two-hadron states in moving frames

Kim, Sachrajda, and Sharpe, Nucl. Phys. B 727, 218–243 (2005).

Electroweak matrix elements in the two-nucleon sector from lattice QCD

Detmold and Savage, Nucl.Phys.A743 170-193(2004).

Matrix elements of unstable states

Bernard, Hoja, Meißner, Rusetsky JHEP, Vol 2012, 23 (2012) .

Multichannel one-to-two transition form factors in a finite volume

Briceno, Hansen, and Walker-Loud, Phys. Rev. D 91, 034501 (2015).

Moving Multi-Channel Systems in a Finite Volume with Application to Proton-Proton Fusion

Briceno and Davoudi, Phys. Rev. D 88, 094507 (2013).

Relativistic, model-independent, multichannel 2 → 2 transition amplitudes in a finite volume

Briceno and Hansen, Phys. Rev. D 94, 013008 (2016).

Effects of finite volume on the KL-KS mass difference

Christ, Feng, Martinelli, and Sachrajda, Phys. Rev. D 91, 114510 (2015).

Long-range electroweak amplitudes of single hadrons from Euclidean finite-volume correlation

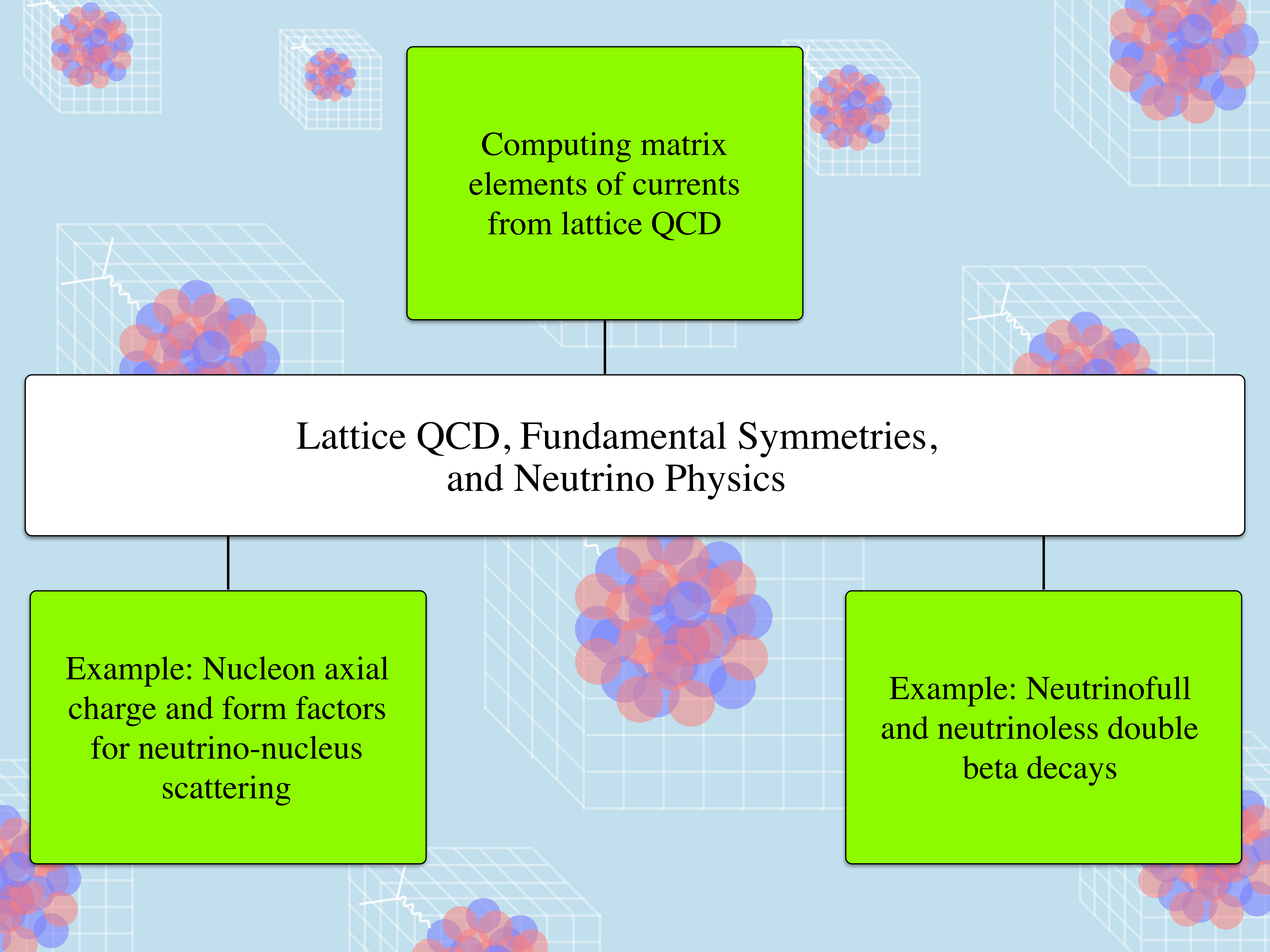
Briceno, Davoudi, Hansen, Schindler, and Baroni, Phys. Rev. D101, 14509 (2020).

Two-neutrino double-beta decay in pionless effective field theory from a Euclidean finite-volume correlation function

Davoudi and Kadam et al, Phys. Rev. D 102, 114521 (2020)

The path from lattice QCD to the short distance contribution to 0*vBB* decay with a light Majorana neutrino

Davoudi and Kadam et al, Phys. Rev. Lett. 126, 152003 (2021).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A few more examples where lattice QCD can have an impact…

Physics	Target Quantity	Experiments
Baryon Number Violation and Grand Unified Theories	Proton Decay Matrix Elements	DUNE, Hyper-Kamiokande
Baryon Number minus Lepton Number Violation	Neutron-antineutron Matrix Elements	ILL, ESS Super-K, DUNE and other reactors
Lepton Flavor Violation	Nucleon and Nuclei Form Factors	Mu2e, COMET
Lepton Number Violation	$0\nu\beta\beta$ Matrix Elements	EXO, Tonne-scale $0\nu\beta\beta$
CP Violation and Baryon Asymmetry in Universe	Electric Dipole Moment	Hg, Ra, *n* EDM at SNS and LANL
Dark Matter and New Physics Searches	Nucleon and Nuclei Form Factors	Dark Matter Experiments, Precision Measurements

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Physics	Target Quantity	Experiments
Baryon Number Violation and Grand Unified Theories	Proton Decay Matrix Elements	DUNE, Hyper-Kamiokande
Baryon Number minus Lepton Number Violation	Neutron-antineutron Matrix Elements	ILL, ESS Super-K, DUNE and other reactors
Lepton Flavor Violation	Nucleon and Nuclei Form Factors	Mu2e, COMET
Lepton Number Violation	$0\nu\beta\beta$ Matrix Elements	EXO, Tonne-scale $0\nu\beta\beta$
CP Violation and Baryon Asymmetry in Universe	Electric Dipole Moment	Hg, Ra, *n* EDM at SNS and LANL
Dark Matter and New Physics Searches	Nucleon and Nuclei Form Factors	Dark Matter Experiments, Precision Measurements

T. Luu's talk!

[Concluding remark] Lattice QCD (combined with EFTs and finite-volume methods) can be extremely useful in constraining important quantities in nuclear physics, particularly in support of the program in searches for new physics and violation of fundamental symmetries.

THANK YOU