Axial structure of light nuclei from lattice QCD


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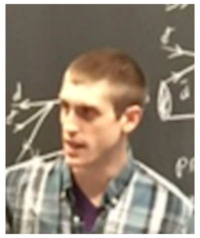
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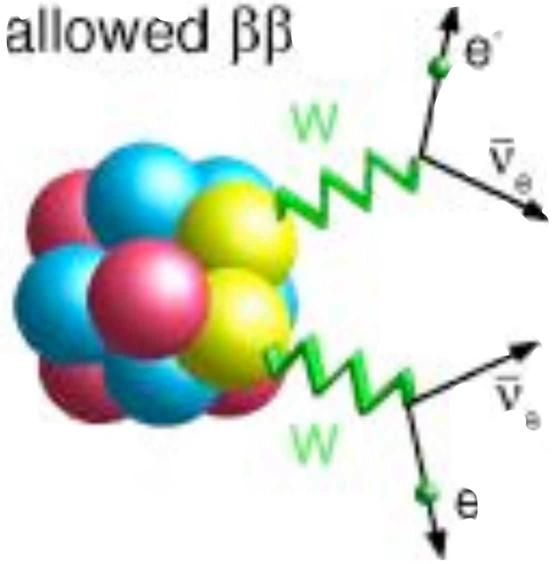
The intensity frontier

- Seek new physics through quantum effects
- Precise experiments
  - Sensitivity to probe the rarest interactions of the SM
  - Search for effects where there is no SM contribution
- Important focus of experimental programs
  - Dark matter direct detection
  - Neutrino physics
  - Charged lepton flavour violation, ββ-decay, proton decay, neutron-antineutron oscillations…
- **Major component is nuclear targets**



Outline

Weak nuclear processes

1. Matrix element determining
$$pp \rightarrow de^{+}\nu$$
fusion cross-section

2. Gamow-Teller matrix element in tritium

3. Two-neutrino double-beta decay matrix element

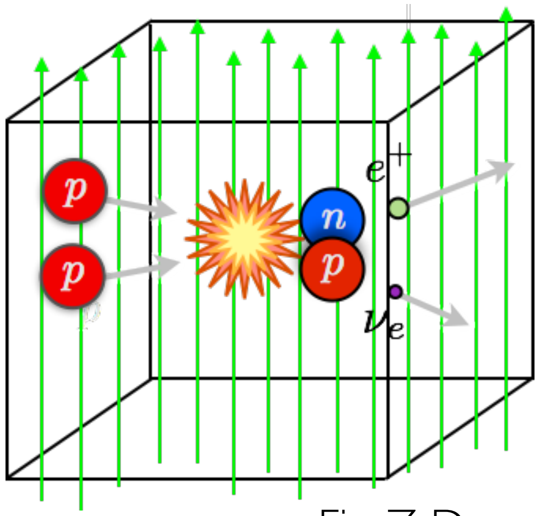
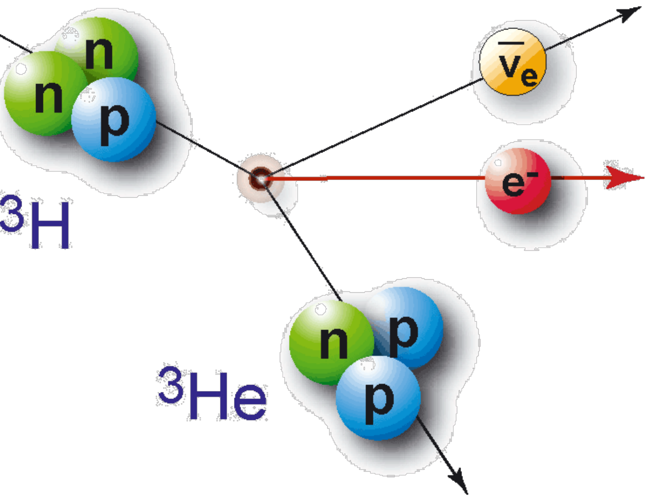
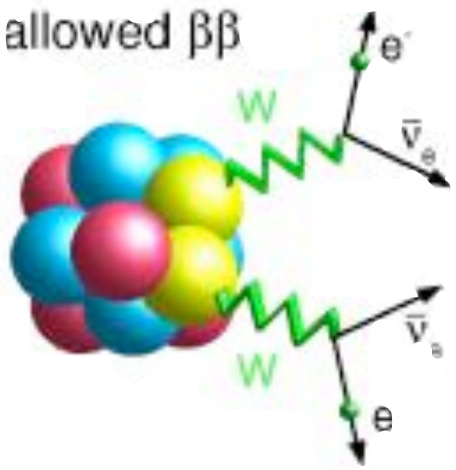


Fig: Z Davoudi





Proton-proton fusion

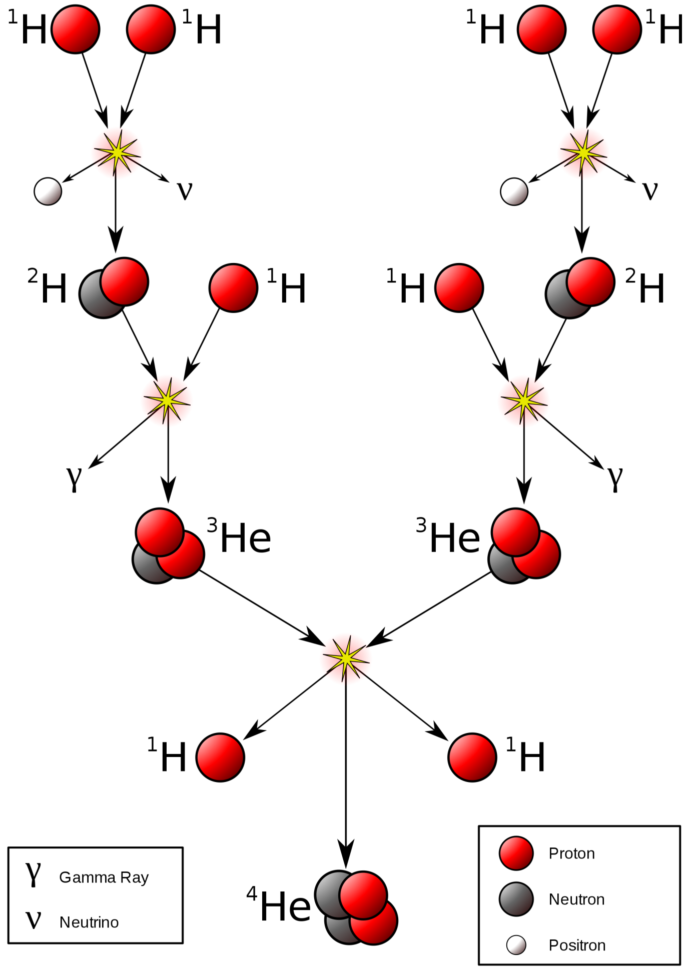
- Stars emit heat/light from conversion of H to He
- Sun + cooler stars: proton-proton fusion chain reaction

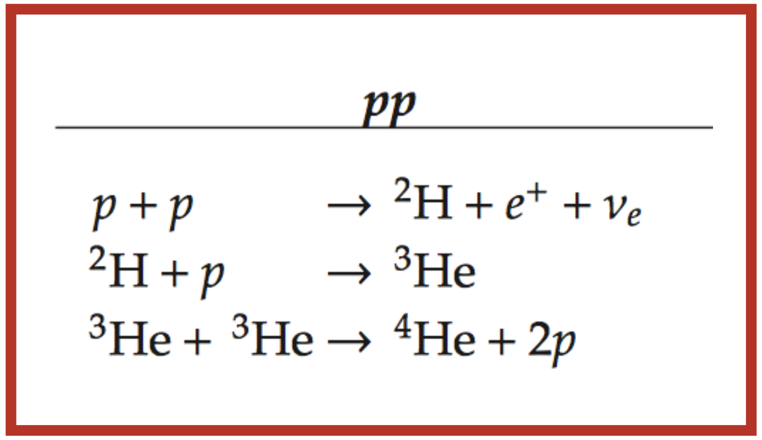
We calculate $\langle d;3|A_3^3|pp\rangle$

→ $L_{1,A},\ \ell_{1,A},\ \overline{L}_{1,A},\ldots$

$pp \rightarrow de^{+}\nu$ cross-section

- Related to:
  - Neutrino breakup reaction (SNO)
  - Muon capture reaction (MuSun)




pp

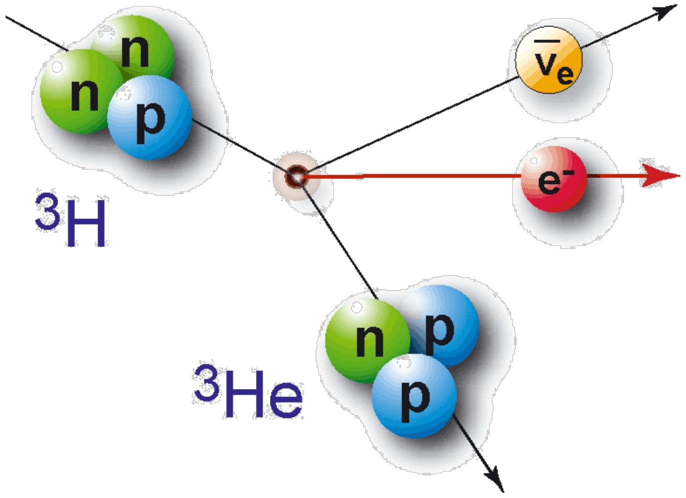
$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He}$

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

Tritium β-decay

- Simplest semileptonic weak decay of a nuclear system

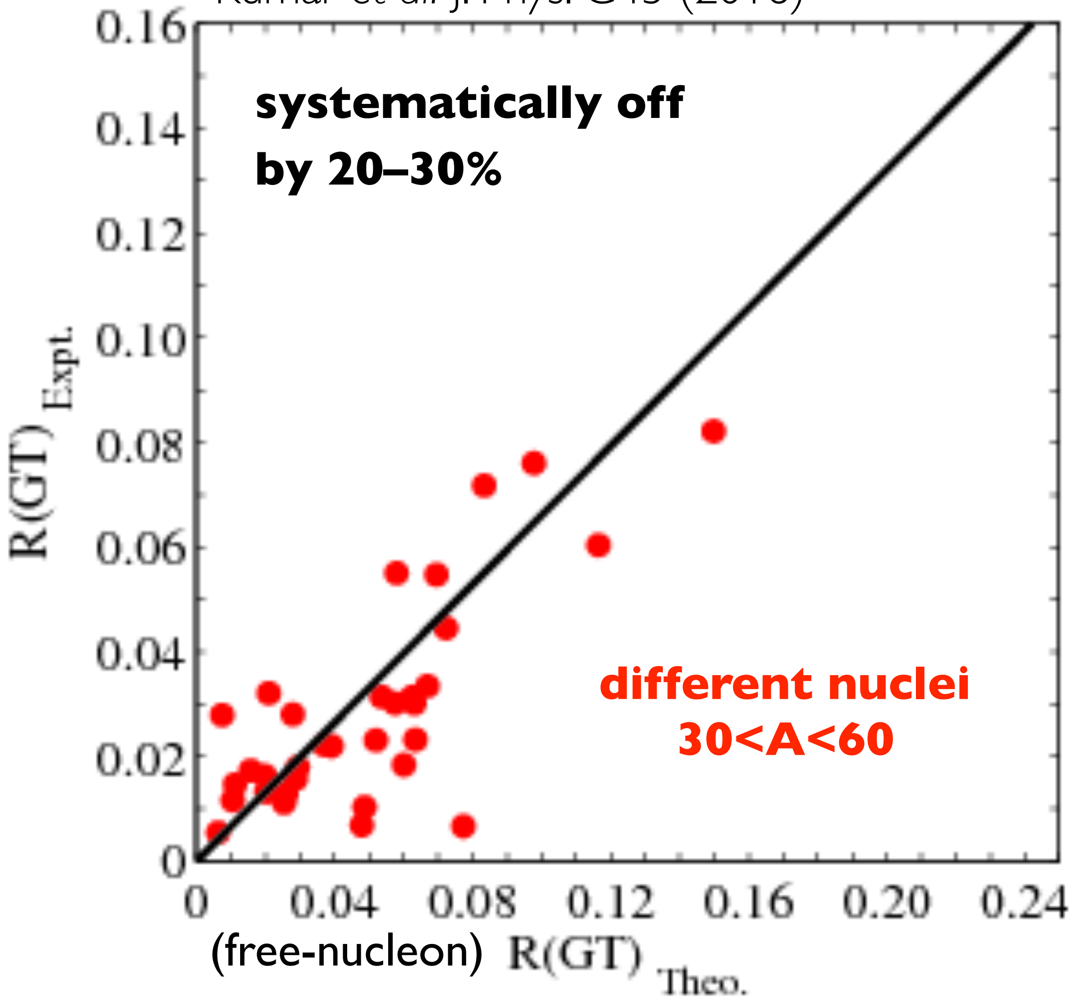


- Gamow-Teller (axial current) contribution to decays of nuclei not well-known from theory
- Understand multi-body contributions to $\langle \mathbf{GT} \rangle$ → better predictions for decay rates of larger nuclei

We calculate

$$g_A \langle \mathbf{GT} \rangle = \langle {}^{\mathbf{3}}\mathrm{He} | \overline{\mathbf{q}} \gamma_{\mathbf{k}} \gamma_{\mathbf{5}} \tau^- \mathbf{q} | {}^{\mathbf{3}}\mathrm{H} \rangle$$

Kumar *et al.* J. Phys. G43 (2016)

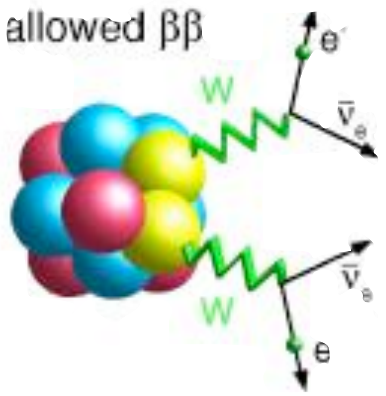


systematically off by 20–30%

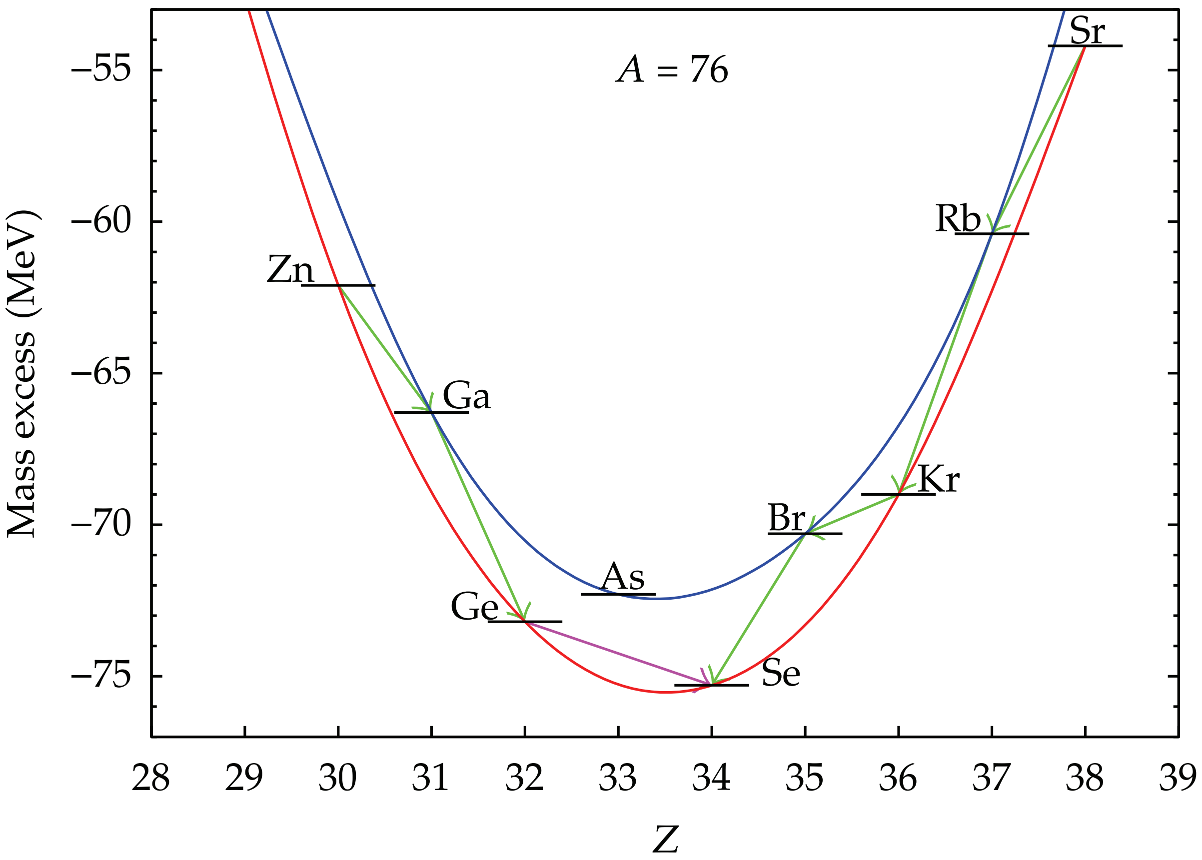
different nuclei 30<A<60

Double β-decay

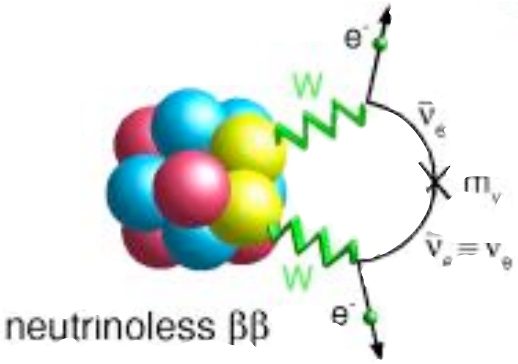
- Certain nuclei allow observable ββ decay



$T_{1/2}^{2\nu\beta\beta} \gtrsim 10^{19}$ y



- If neutrinos are massive Majorana fermions 0νββ decay is possible



$T_{1/2}^{0\nu\beta\beta} > 10^{25}$ y

We calculate two-current nuclear matrix elements
→ dictate half-life

Unphysical nuclei

NPLQCD collaboration

- QCD with unphysical quark masses

  m_π~800 MeV, m_N~1,600 MeV

  m_π~450 MeV, m_N~1,200 MeV

- Proton-proton fusion and tritium β-decay
- Double β-decay

  m_π~800 MeV, m_N~1,600 MeV

- Spectrum of light nuclei (A<5)

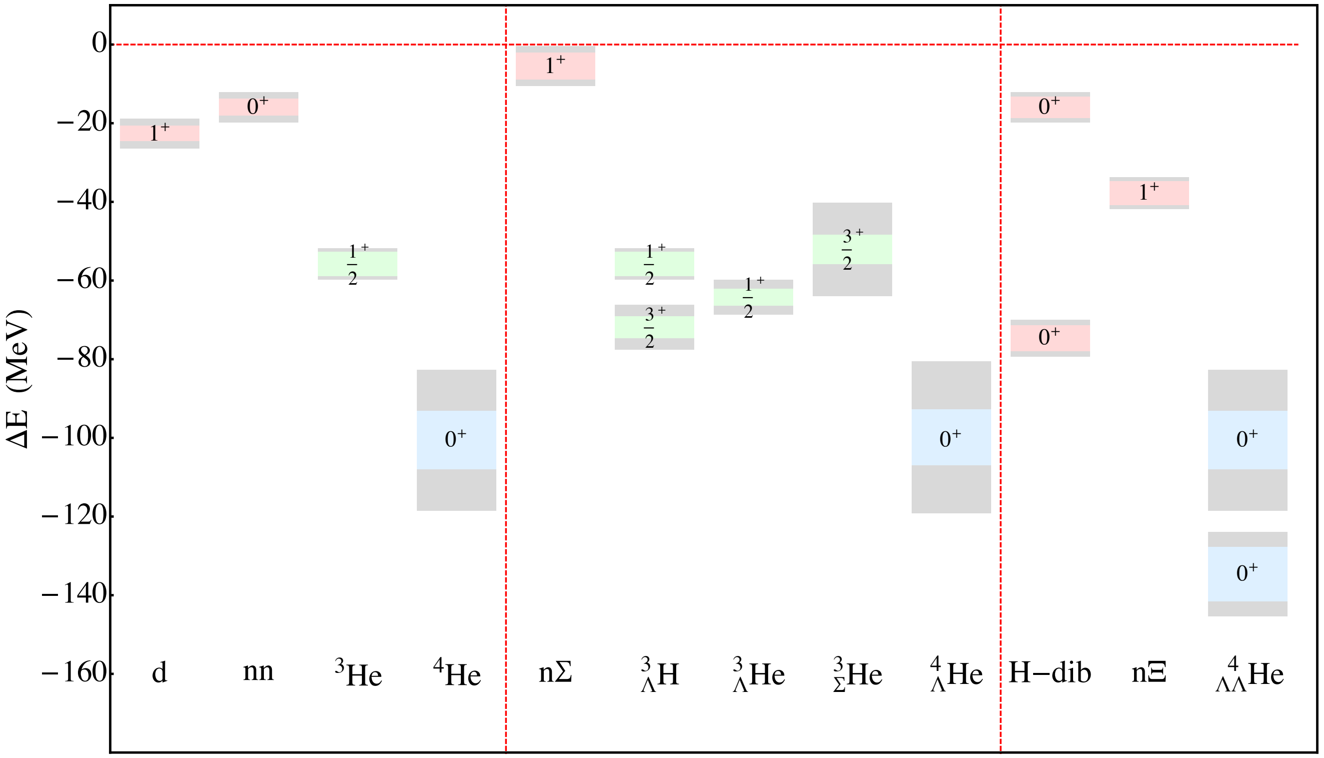
  [PRD **87** (2013), 034506]

- Nuclear structure: magnetic moments, polarisabilities (A<5)

  [PRL **113**, 252001 (2014), PRD 92, 114502 (2015)]

- First nuclear reaction: np⟶dγ

  [PRL **115**, 132001 (2015)]



Background field method

Hadron/nuclear energies are modified by presence of fixed/ constant external fields

Example: fixed magnetic field

landau level

mag. mmt

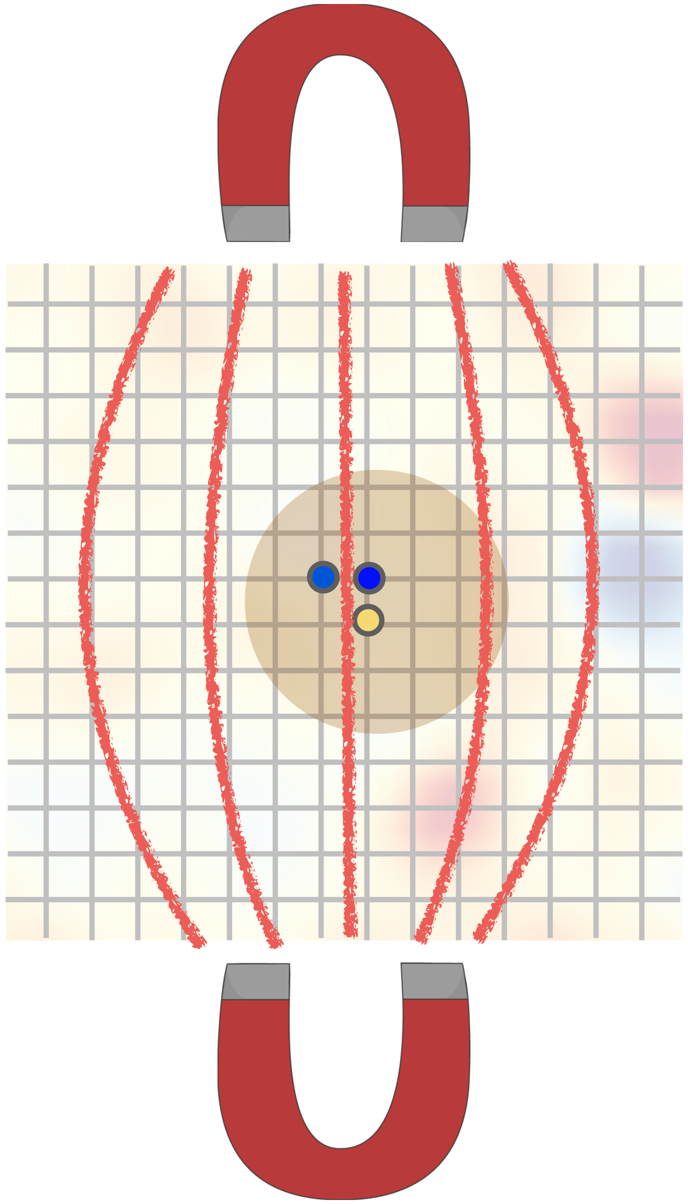
$$E(\vec{B}) = \sqrt{M^2 + (2\boxed{n}+1)|Qe\vec{B}|} - \boxed{\vec{\mu}}\cdot \vec{B}$$
$$-2\pi\boxed{\beta_{M0}}|\vec{B}|^2 - 2\pi\boxed{\beta_{M2}}\boxed{T_{ij}}B_i B_j + \ldots$$

polarisabilities

traceless,
sym tensor

- Calculations with multiple fields
  → extract coefficients of response
  e.g., magnetic moments, polarisabilities, …

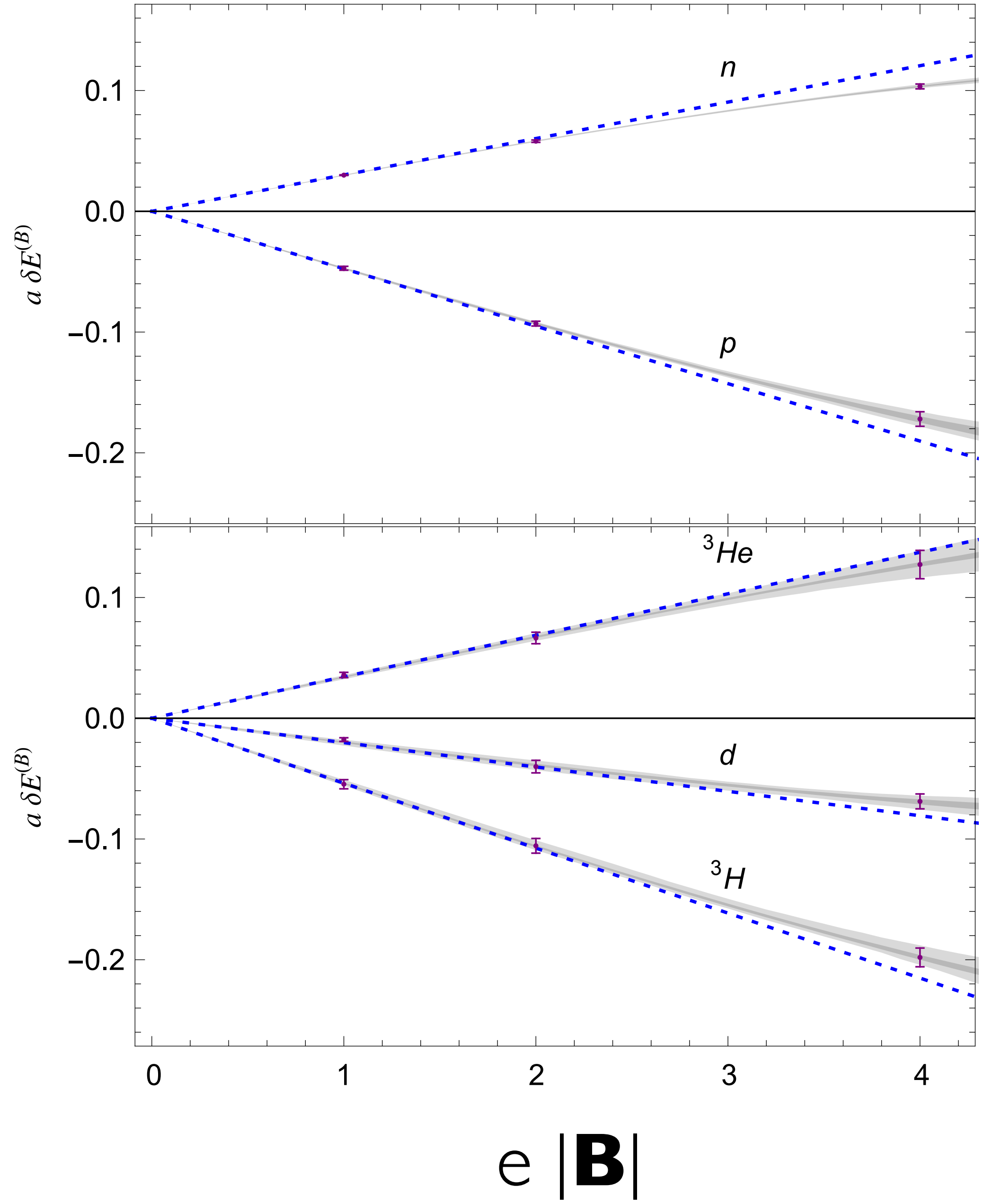
- Not restricted to simple EM fields
  This work: uniform axial background field



[NPLQCD PRL **113**, 252001 (2014)]

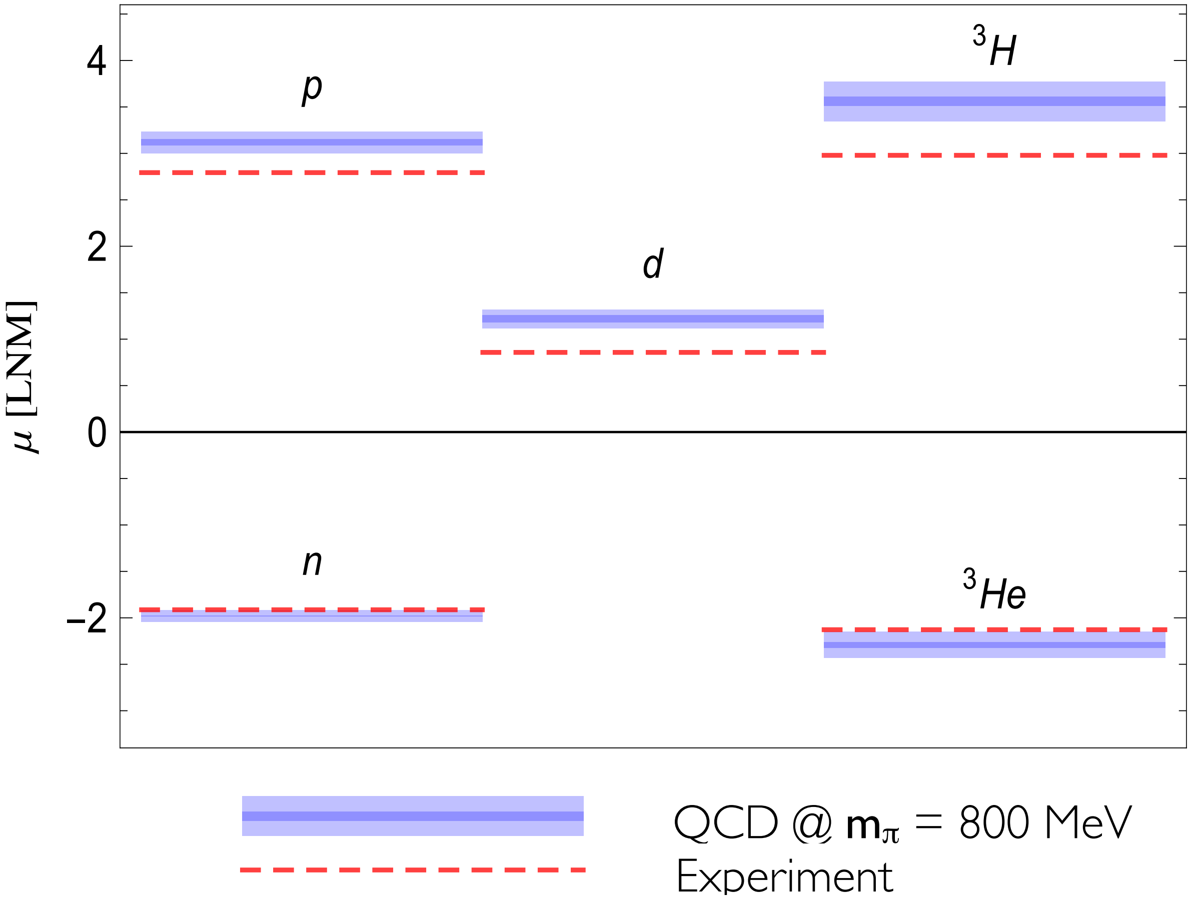
Magnetic moments

Energy shift between ground states
spin-aligned/anti-aligned with B



linear term

Magnetic moments



[NPLQCD PRL **113**, 252001 (2014)]

Axial background field

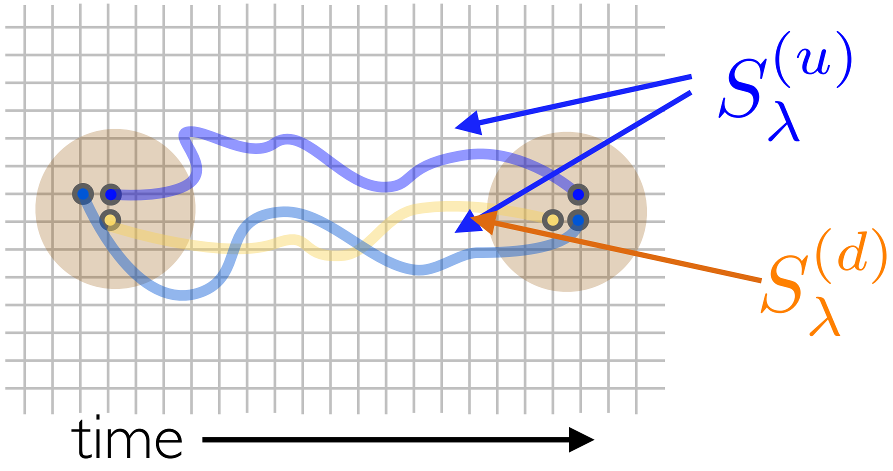
Example: fixed magnetic field → moments, polarisabilities
This work: fixed axial background field → axial charges, other matrix elts.

Construct correlation functions from propagators modified in axial field

compound propagator **constant**

$$\boxed{S_\lambda^{(q)}(x,y)} = S^{(q)}(x,y) + \boxed{\lambda_q} \int dz\, S^{(q)}(x,z)\, \gamma_3\gamma_5\, S^{(q)}(z,y)$$

$C_{\lambda_u;\lambda_d}(t) =$

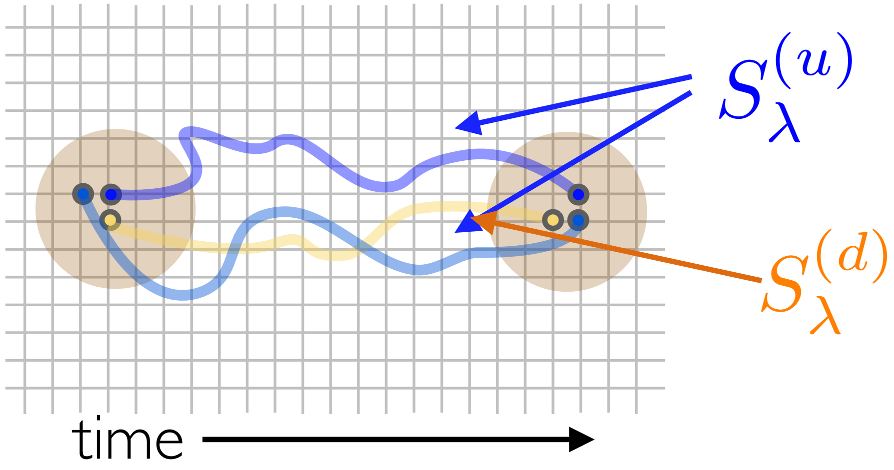


Linear response ↔ axial matrix element

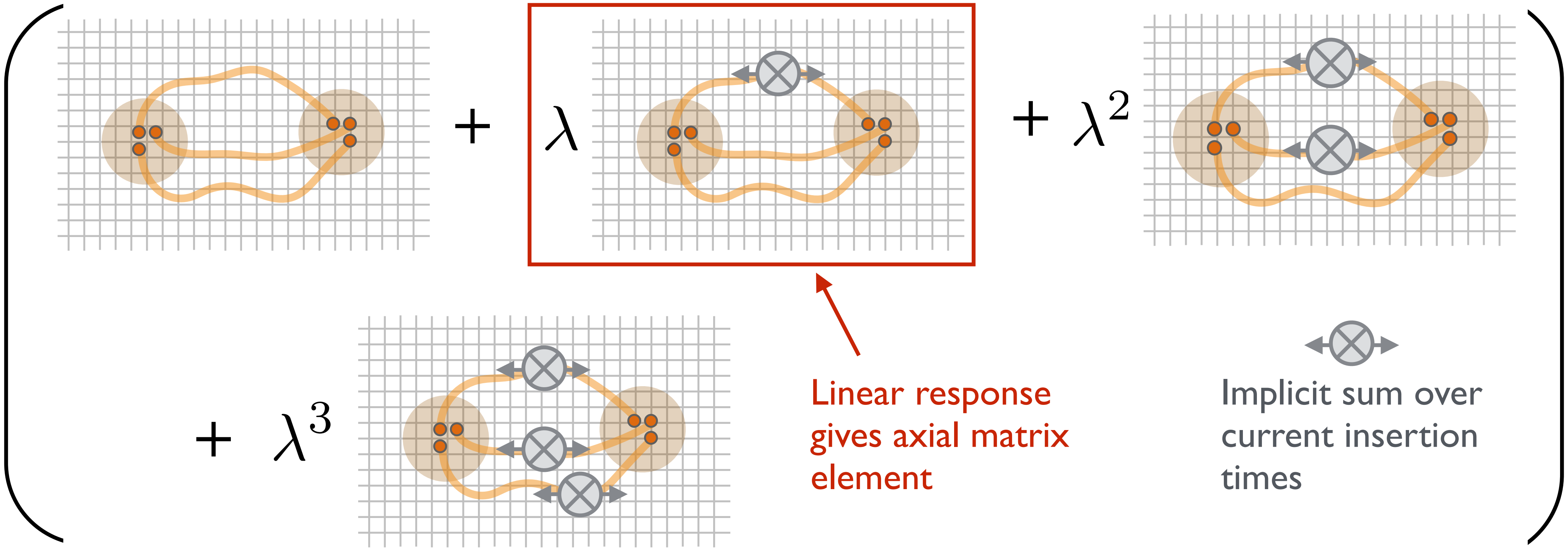
[NPLQCD Nucl. Phys. **A743**, 170 (2004)]

Axial background field

$$C_{\lambda_u;\lambda_d}(t) =$$



$$C_{\lambda_u;\lambda_d}(t) = \Big(\cdots + \lambda \cdots + \lambda^2 \cdots + \lambda^3 \cdots \Big)$$



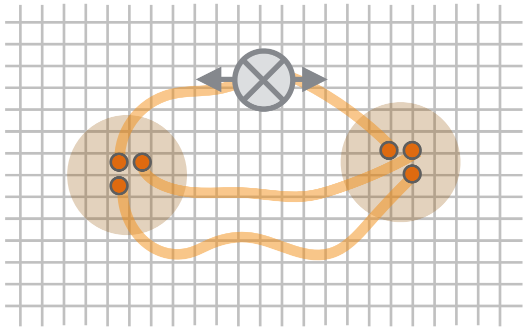
Linear response gives axial matrix element

Implicit sum over current insertion times

Axial background field

Example: determination of the proton axial charge

$$C_{\lambda_u;\lambda_d}(t)\Big|_{\mathcal{O}(\lambda)} =$$



⊗ Implicit sum over current insertion times

Time difference isolates matrix element part

$$\begin{aligned} C_{\lambda_u;\lambda_d}(t)\Big|_{\mathcal{O}(\lambda)} &= \sum_{\tau=0}^{t} \langle 0|\chi^\dagger(t)J(\tau)\chi(0)|0\rangle \\ &= \ldots \\ &= Z_0 e^{-M_p t}\left[C + t\,\langle p|A_3^{(u)}(0)|p\rangle + \mathcal{O}(e^{-\delta t})\right] \end{aligned}$$

Excited states

Irrelevant constants

Matrix element

$$\left(C_{\lambda_u;\lambda_d}(t+1) - C_{\lambda_u;\lambda_d}(t)\right)\Big|_{\mathcal{O}(\lambda)} = Z_0 e^{-M_p t}\langle p|A_3^{(u)}(0)|p\rangle + \mathcal{O}(e^{-\delta t})$$

Proton axial charge

Form ratios to cancel leading time-dependence

- Extract matrix element through linear response of correlators to the background field
- Form ratios to cancel leading time-dependence

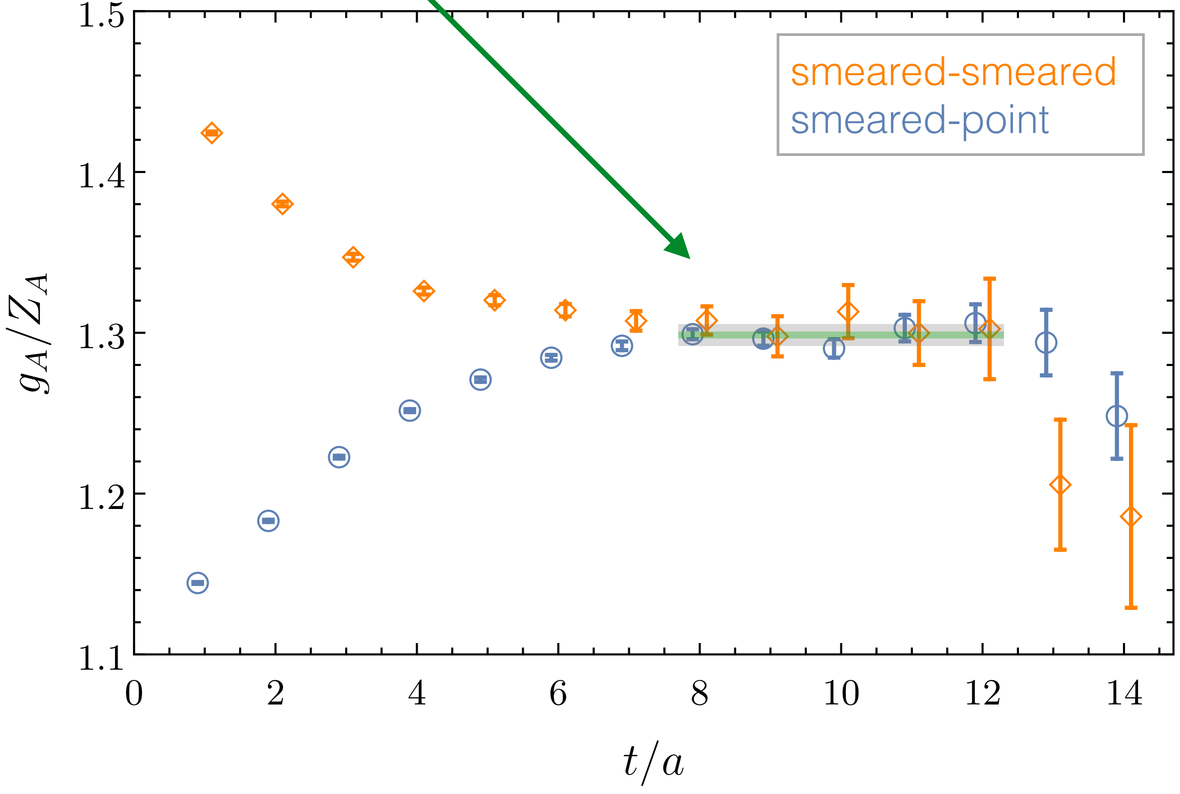
$$R_p(t) = \frac{\left(C^{(p)}_{\lambda_u;\lambda_d=0}(t) - C^{(p)}_{\lambda_u=0;\lambda_d}(t)\right)\Big|_{\mathcal{O}(\lambda)}}{C^{(p)}_{\lambda_u=0;\lambda_d=0}(t)}$$

At late times:

$$R_p(t+1) - R_p(t) \xrightarrow{t\to\infty} \frac{g_A}{Z_A}$$

- Matrix element revealed through "effective matrix elt. plot"

constant fit to plateau region



Tritium β-decay

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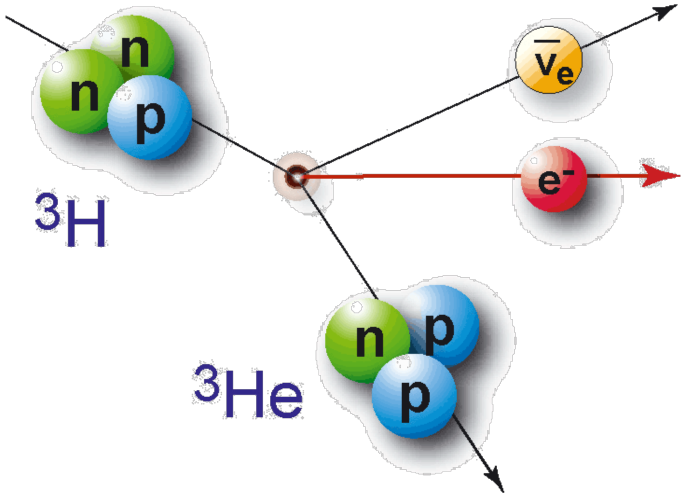

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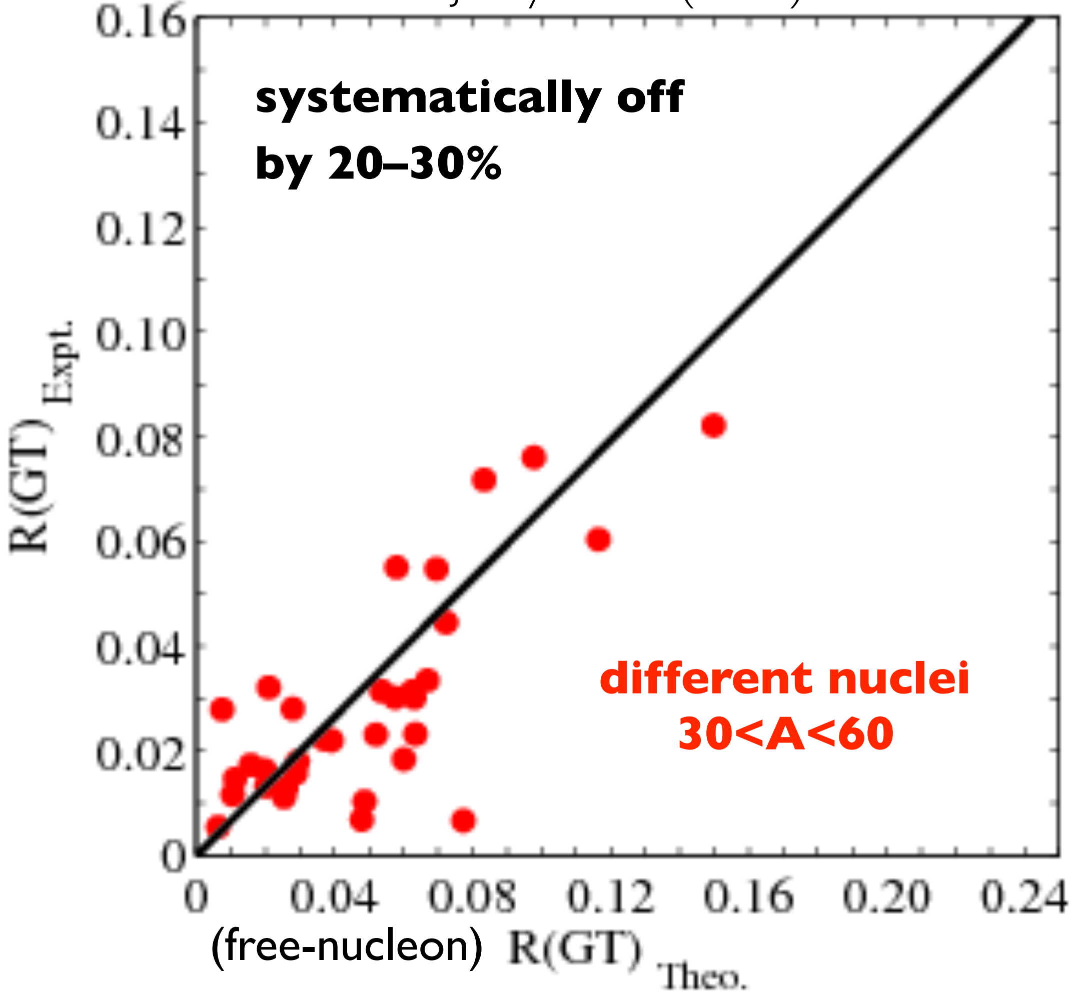
Kumar *et al.* J. Phys. G43 (2016)



systematically off by 20–30%

different nuclei 30<A<60

Tritium β-decay

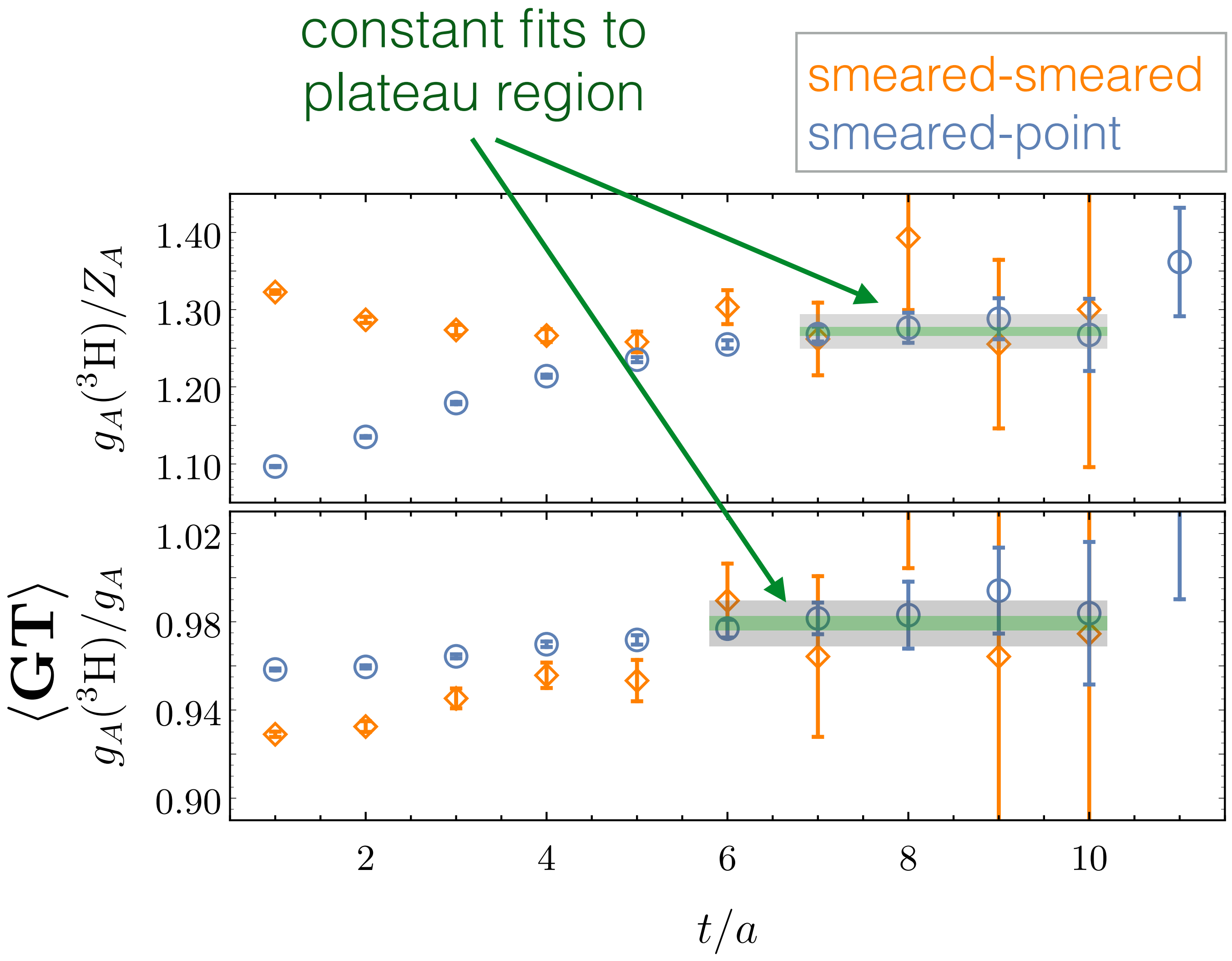
$$\underset{\text{known from theory or expt.}}{\boxed{\frac{(1+\delta_R)f_V}{K/G_V^2}}}\overset{\text{half-life}}{\boxed{t_{1/2}}} = \frac{1}{\overset{\text{vector ME}}{\boxed{\langle \mathbf{F}\rangle^2}} + f_A/f_V\, g_A^2 \overset{\text{axial ME}}{\boxed{\langle \mathbf{GT}\rangle^2}}}$$

- Form ratios of compound correlators to cancel leading time-dependence:

$$\frac{\overline{R}_{^3\mathrm{H}}(t)}{\overline{R}_p(t)} \xrightarrow{t\to\infty} \frac{g_A(^3\mathrm{H})}{g_A} = \langle \mathbf{GT}\rangle$$

- Ground state ME revealed through "effective ME plot"
- Experiment (physical point)

$$\langle \mathbf{GT}\rangle = 0.9511(13)$$



Proton-proton fusion

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$pp \to de^+\nu$ cross-section

- Related to:
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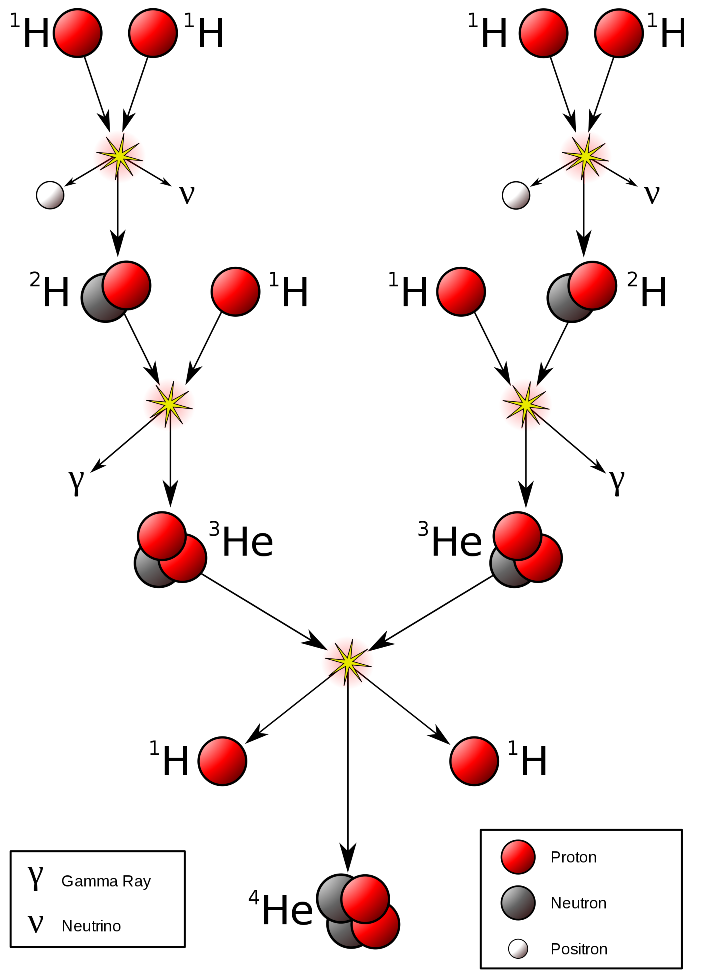


pp

$$
\begin{aligned}
p+p &\to {}^2\mathrm{H}+e^+ + \nu_e \\
{}^2\mathrm{H}+p &\to {}^3\mathrm{He} \\
{}^3\mathrm{He}+{}^3\mathrm{He} &\to {}^4\mathrm{He}+2p
\end{aligned}
$$

Proton-proton fusion

- Extract matrix element through linear response of correlators to the background field

matrix elt. is linear in Λ

$$\boxed{C^{({}^3S_1,{}^1S_0)}_{\lambda_u;\lambda_d=0}(t)} = \boxed{\lambda_u \sum_{\tau=0}^{t} \sum_{\mathbf{x}} \langle 0|\chi^3_{{}^3S_1}(\mathbf{x},t) A^u_3(\tau) \chi^\dagger_{{}^1S_0}(0)|0\rangle} \boxed{+ c_2\lambda_u^2 + c_3\lambda_u^3,}$$

correlator formed with background field coupling to u quark

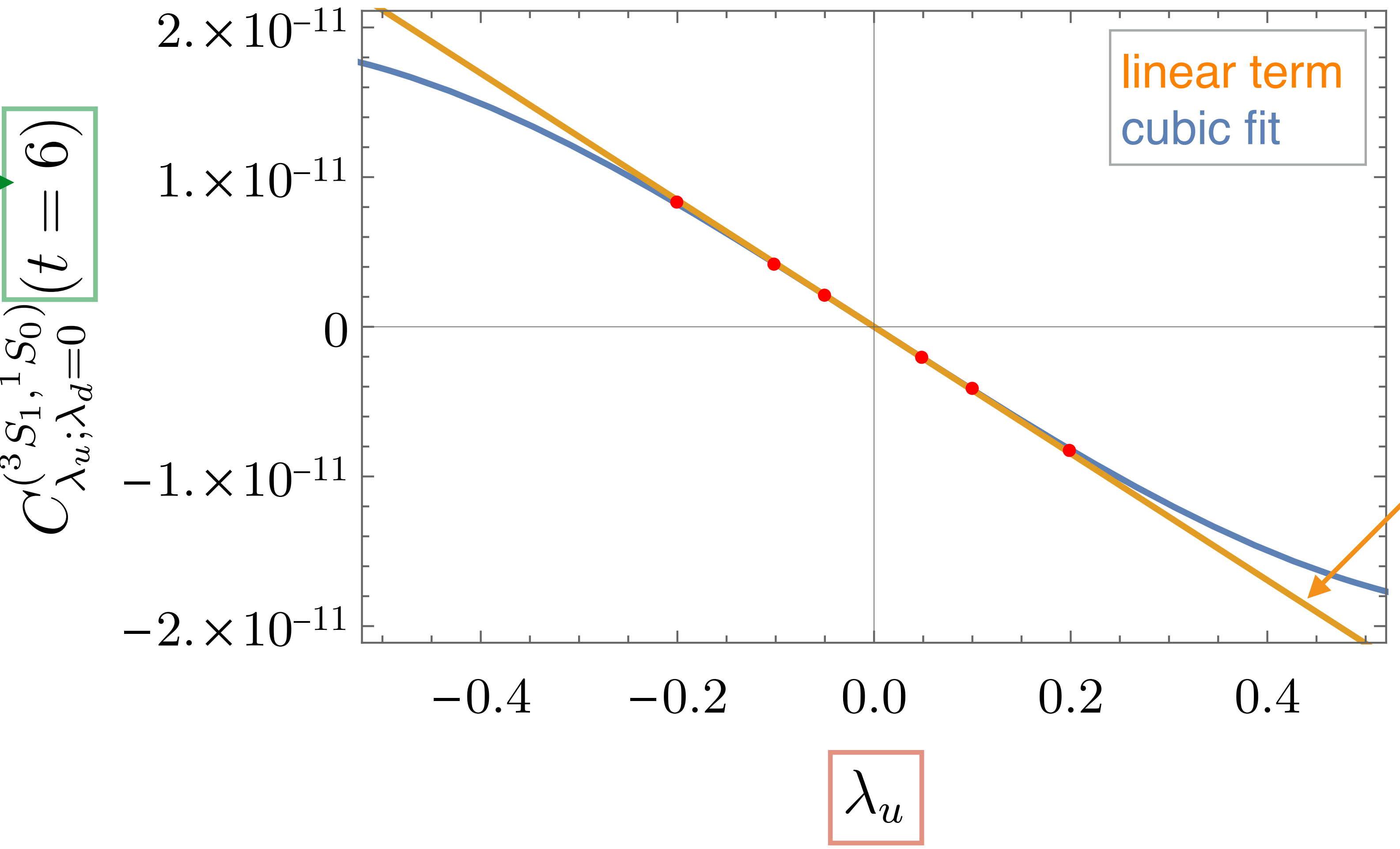
irrelevant consts.

- Calculate correlators at multiple values of $\lambda_u,\ \lambda_d$

  → extract matrix element pieces

Proton-proton fusion

- Example: correlator formed with background field coupling to u quark



time chosen for example

linear term gives ME

six choices of field strength: can fit up to λ^6

Proton-proton fusion

- Form ratios of compound correlators to cancel leading time-dependence

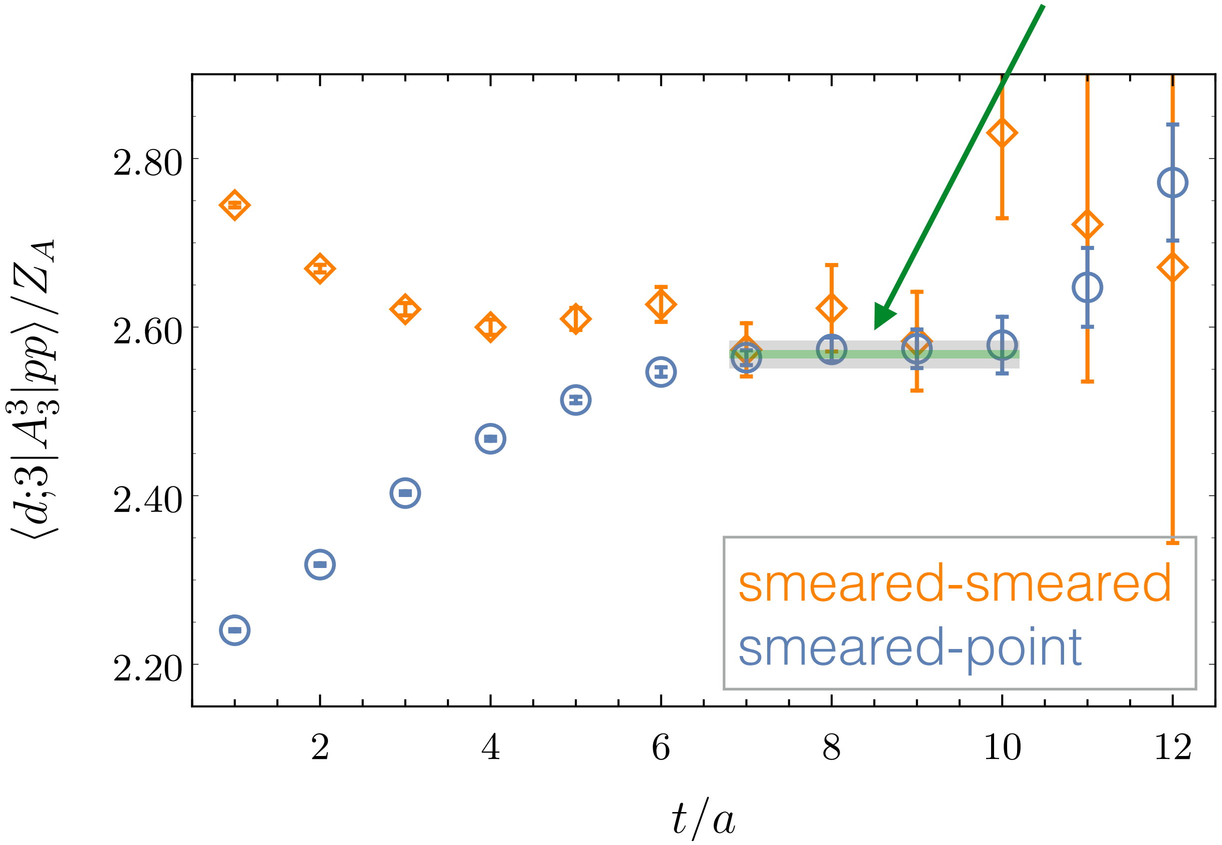
transition pieces linear in Λ

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

diagonal pieces with no field

- Fit a constant to the 'effective matrix element plot' at late times

$$R_{^3S_1,^1S_0}(t+1) - R_{^3S_1,^1S_0}(t) \xrightarrow{t\to\infty} \frac{\langle ^3S_1; J_z=0|A_3^3|^1S_0; I_z=0\rangle}{Z_A} = \frac{\langle d;3|A_3^3|pp\rangle}{Z_A}$$



constant fit to plateau region

Proton-proton fusion

Treatment of uncertainties: MEs at $m_\pi \sim$ 800MeV

- Statistical

  bootstrap/jackknife over configs.

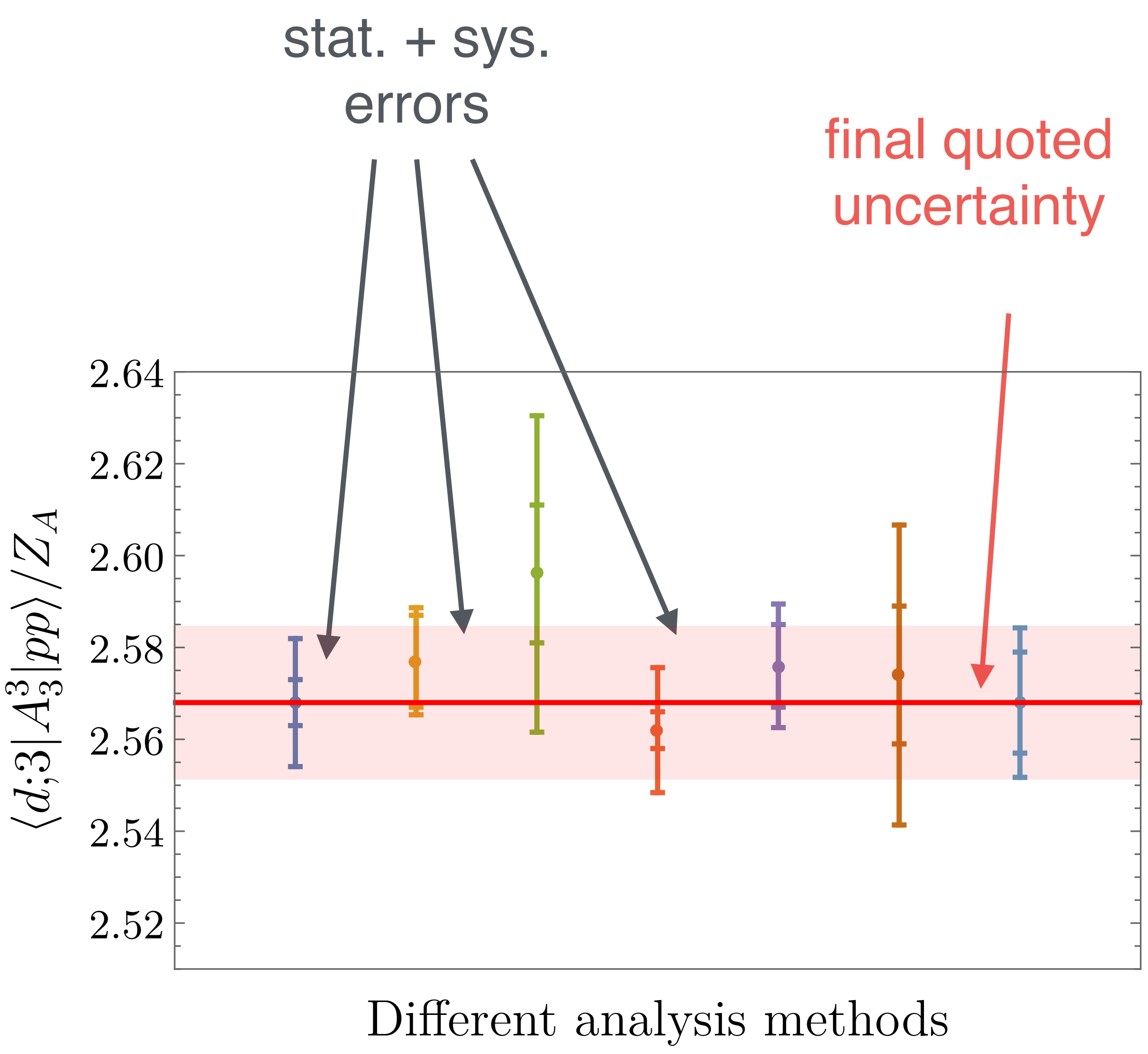
  correlated ratios of correlation functions

- Systematics in fit

  range of field strengths in fit
  t-range of plateau fit to ratio

- Systematic in analysis method

  range of analysis procedures chosen
  by different collaboration members


stat. + sys. errors

final quoted uncertainty

Proton-proton fusion

Want to relate lattice QCD ME to

- LECs of EFTs
- pp-fusion cross section

- Finite-volume quantisation condition: relate $\langle d;3|A_3^3|pp\rangle$ to scale-indep. LECs
  - Pionless EFT: $\overline{L}_{1,A}$
  - Dibaryon formalism: $\overline{\ell}_{1,A}$
- Define a new related quantity, $L_{1,A}^{sd-2b}$, which should have mild pion-mass dependence (remove effective range terms in $\overline{L}_{1,A}$)
- Extrapolate $L_{1,A}^{sd-2b}$ to the physical point

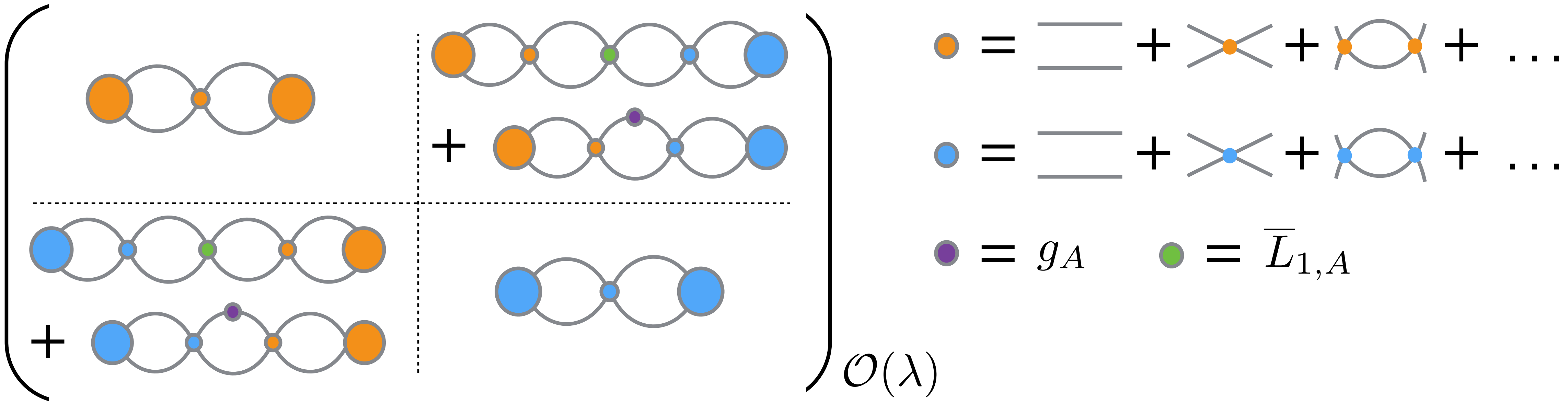
→ Prediction for $\overline{L}_{1,A}$, $\overline{\ell}_{1,A}$ at the physical point

→ Prediction for physical cross-section

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

Finite-volume quantisation

- Axial field splits degeneracy of the nucleon doublet
- ${}^3S_1$ and ${}^1S_0$ channels mix
- Construct 2x2 inverse scattering amplitude matrix in background field

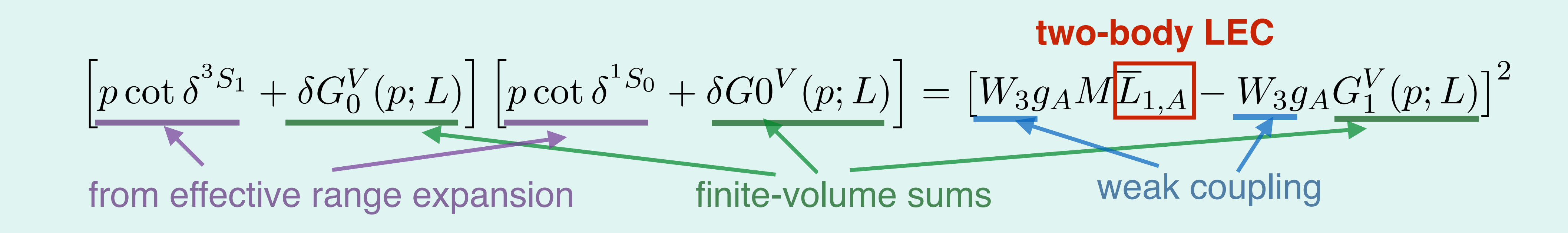


- Continuum integrals from bubble diagrams → discrete sums
- Det = 0 ↔ poles of scattering amplitude ↔ eigenenergies

Briceno, Davoudi ,Phys.Rev. D88 (2013) 094507

Finite-volume quantisation

- Det of inverse scattering matrix = 0 ⟷ eigenenergies are solutions of



two-body LEC

$$\left[\underline{p\cot\delta^{^3S_1}} + \underline{\delta G_0^V(p;L)}\right]\left[\underline{p\cot\delta^{^1S_0}} + \underline{\delta G0^V(p;L)}\right] = \left[\underline{W_3 g_A} M \boxed{\overline{L}_{1,A}} - \underline{W_3 g_A}\,\underline{G_1^V(p;L)}\right]^2$$

from effective range expansion

finite-volume sums

weak coupling

→ Matrix element related to scale-indep. LEC

$$|\delta E^{^3S_1 - ^1S_0}|/W_3 = |\langle ^3S_1\,| A_3^3 |^1S_0\rangle| = Z_d^2(4g_A\gamma\overline{L}_{1,A} + 2g_A)$$

- Define combination that characterises two-nucleon contribution
  Expect mild pion-mass dependence → can extrapolate

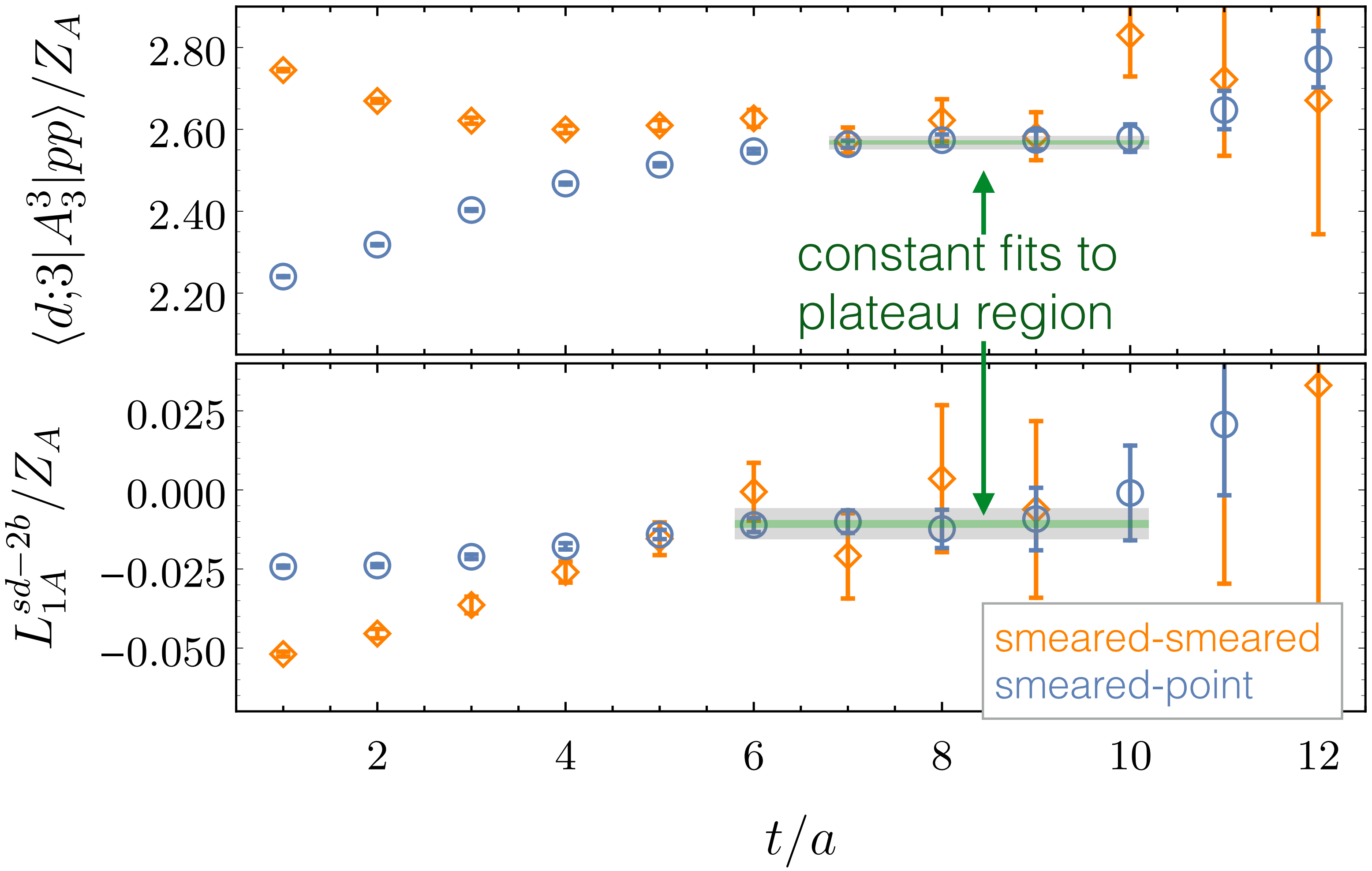
experience from
$np \to d\gamma$

$$\boxed{L_{1,A}^{sd-2b} \equiv (\langle d;3|A_3^3|pp\rangle - 2g_A)/2}$$

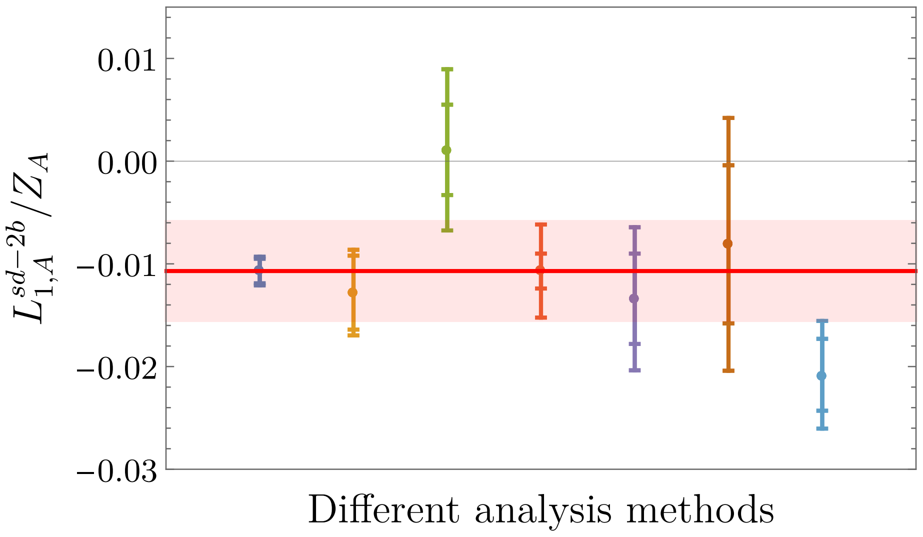
$$Z_d = 1/\sqrt{1-\rho\gamma}$$

Briceno, Davoudi ,Phys.Rev. D88 (2013) 094507

Proton-proton fusion



constant fits to plateau region



$$\frac{L_{1,A}^{sd-2b}}{Z_A} = -0.0107(12)(49) \longrightarrow$$

Extrapolate,
predict physical
cross-section

Proton-proton fusion

Low-energy cross section for $pp \rightarrow de^+\nu$ dictated by the matrix element

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

Relate $\Lambda(0)$ to extrapolated LEC using EFT

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

extrapolated lattice value

C_η	Sommerfield factor
γ	Deuteron binding mtm
$r_1,\ \rho$	Effective ranges
a_{pp}	pp scattering length
$\Gamma(0,\chi)$	Incomplete gamma func.

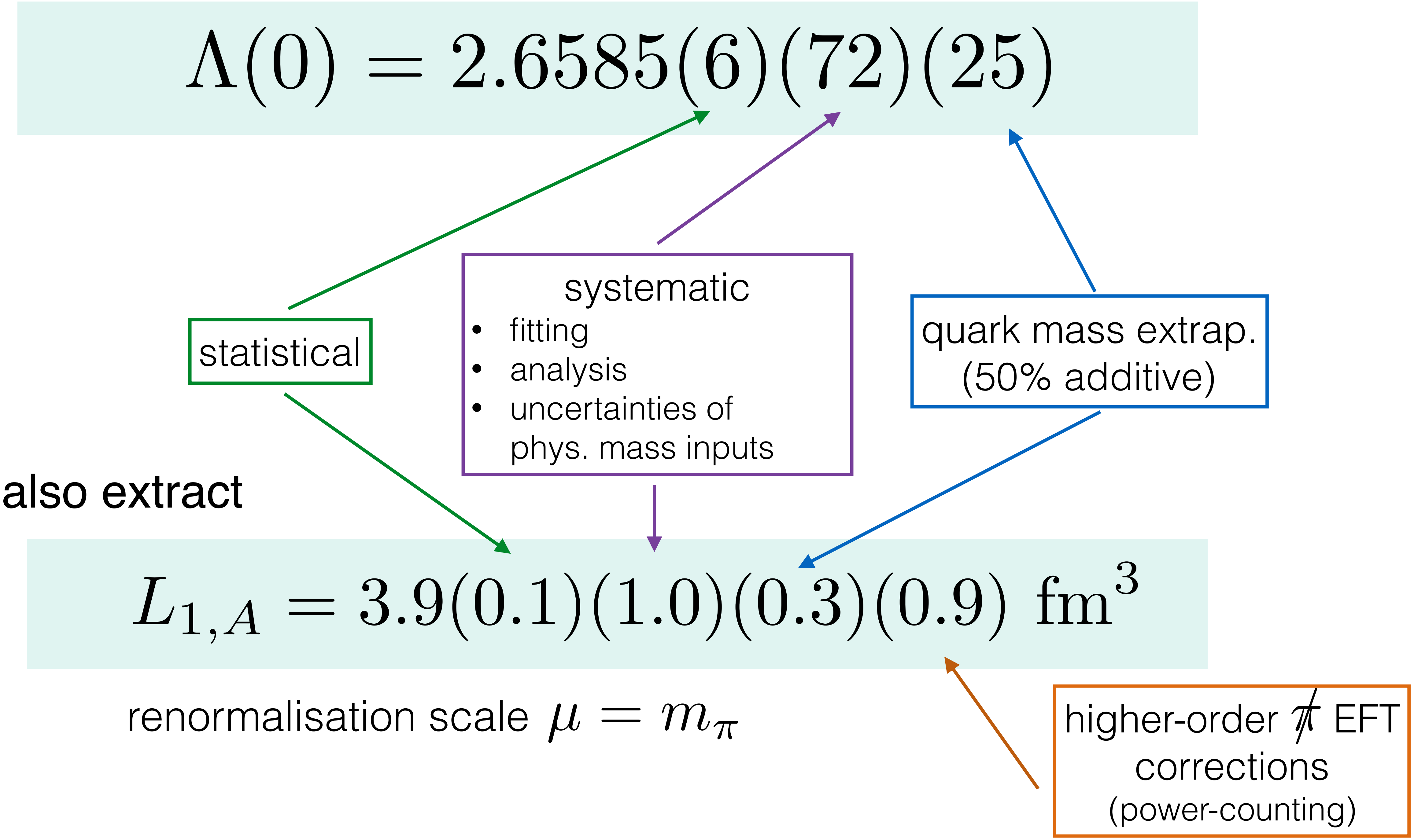
$\chi = \alpha M_p/\gamma$

N^{2}LO $\not\pi$EFT with effective range contributions resummed using the dibaryon approach

Butler and Chen, Phys. Lett. B520, 87 (2001)
Detmold and Savage, Nucl. Phys. A743, 170 (2004).

Proton-proton fusion

Physical cross-section dictated by



$$\Lambda(0) = 2.6585(6)(72)(25)$$

statistical

systematic
- fitting
- analysis
- uncertainties of phys. mass inputs

quark mass extrap. (50% additive)

Can also extract

$$L_{1,A} = 3.9(0.1)(1.0)(0.3)(0.9)\ \mathrm{fm}^3$$

renormalisation scale $\mu = m_\pi$

higher-order $\not\pi$ EFT corrections (power-counting)

Proton-proton fusion

Physical cross-section dictated by

$$\Lambda(0) = 2.6585(6)(72)(25)$$

$$\Lambda(0) = 2.652(2)$$ (models/EFT)

E. G. Adelberger et al., Rev. Mod. Phys. 83, 195 (2011)

Can also extract

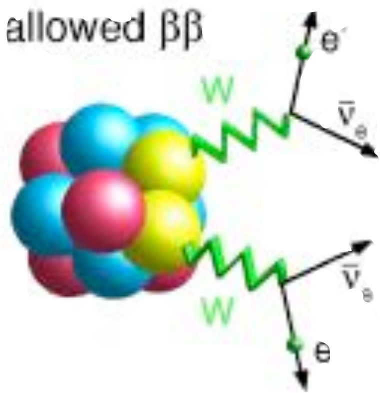
$$L_{1,A} = 3.9(0.1)(1.0)(0.3)(0.9)\ \mathrm{fm}^3$$

$$L_{1,A} = 3.6(5.5)\ \mathrm{fm}^3$$ (reactor expts.)

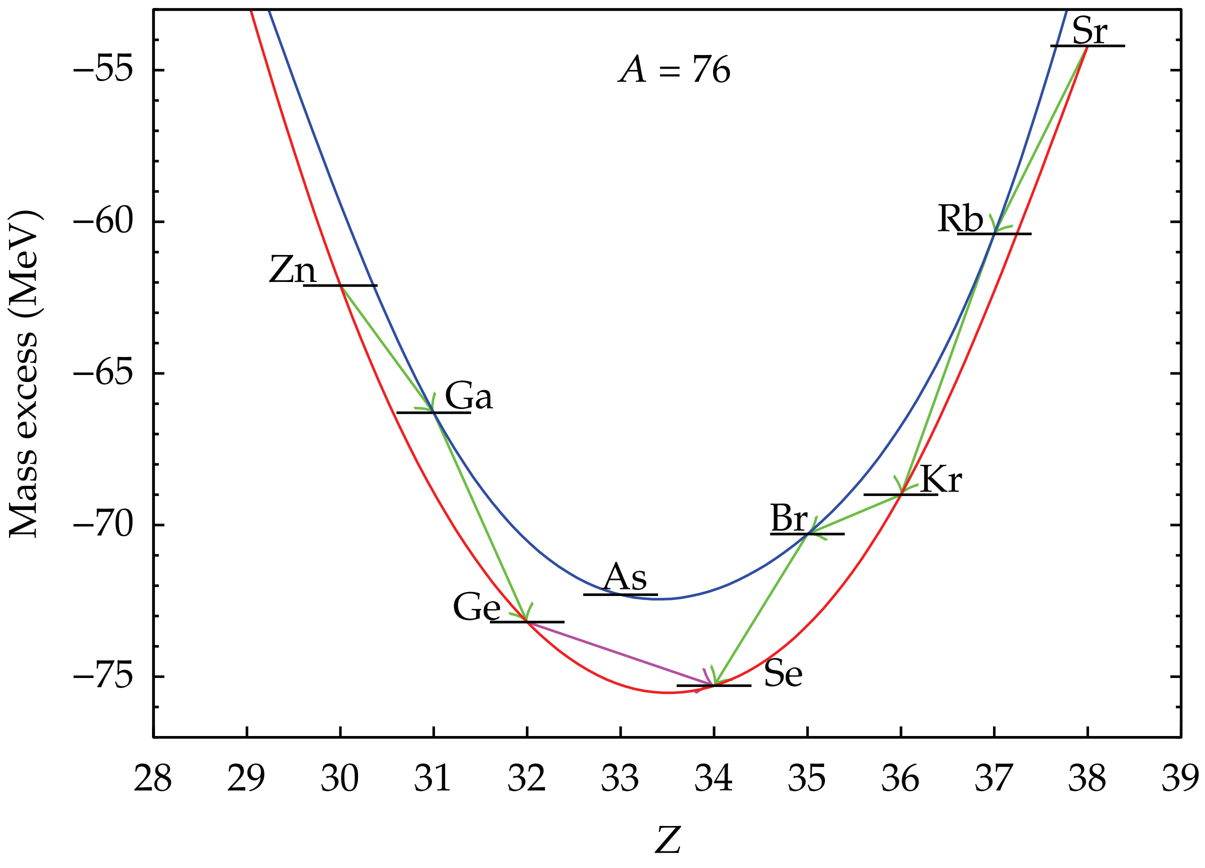
M. Butler, J.-W. Chen, and P. Vogel, Phys. Lett. B549

Double β-decay

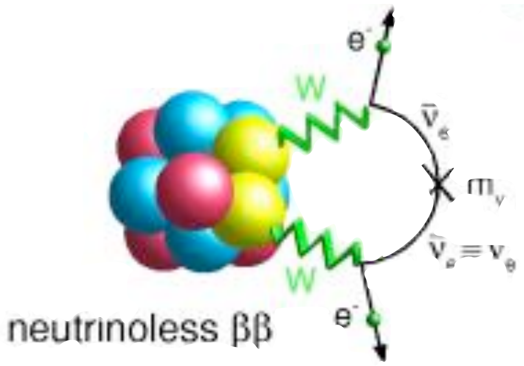
- Certain nuclei allow observable ββ decay



$T_{1/2}^{2\nu\beta\beta} \gtrsim 10^{19}$ y



- If neutrinos are massive Majorana fermions 0νββ decay is possible

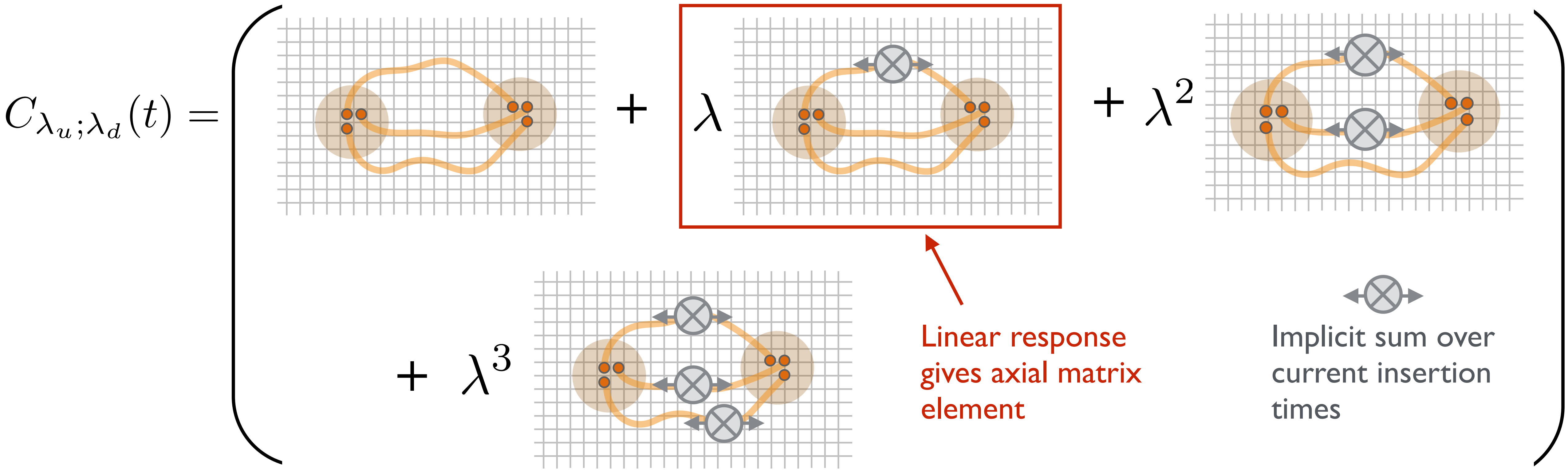


$T_{1/2}^{0\nu\beta\beta} > 10^{25}$ y

We calculate two-current nuclear matrix elements
→ dictate half-life

Higher-order insertions

- Can access terms with more current insertions from same calculations
- Recall: background field correlation function

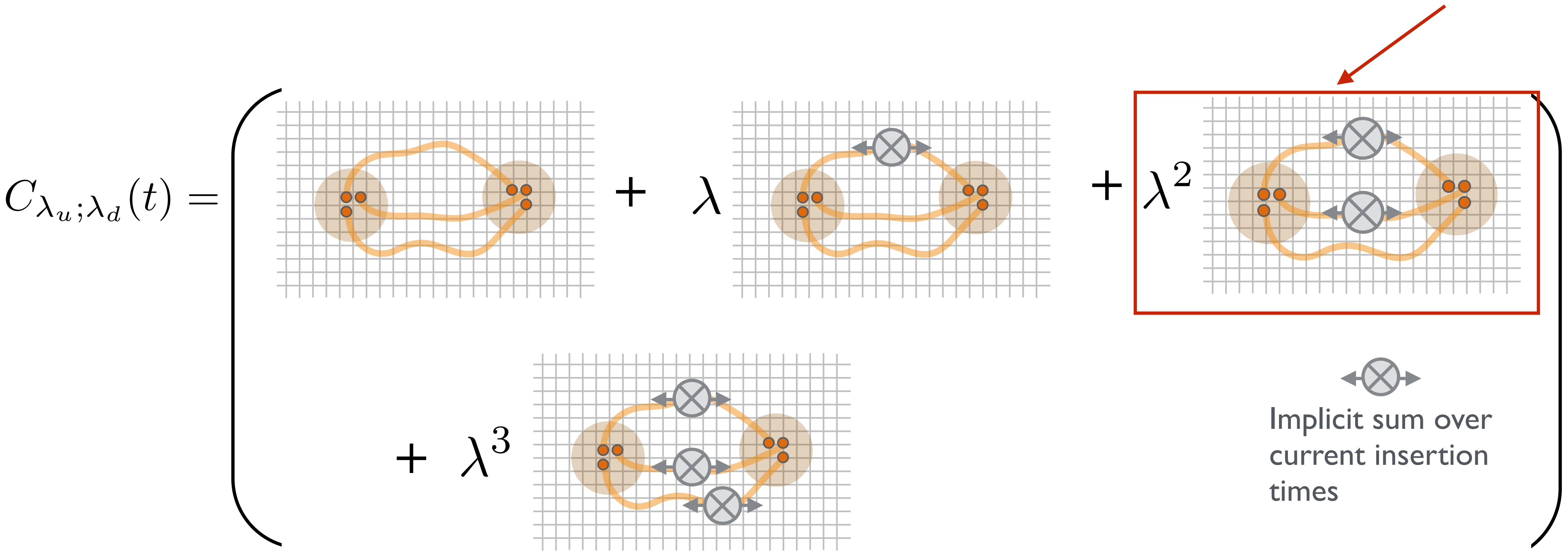


Linear response gives axial matrix element

Implicit sum over current insertion times

Higher-order insertions

- Can access terms with more current insertions from same calculations
- Recall: background field correlation function



Quadratic response from two insertions on different quark lines

Implicit sum over current insertion times

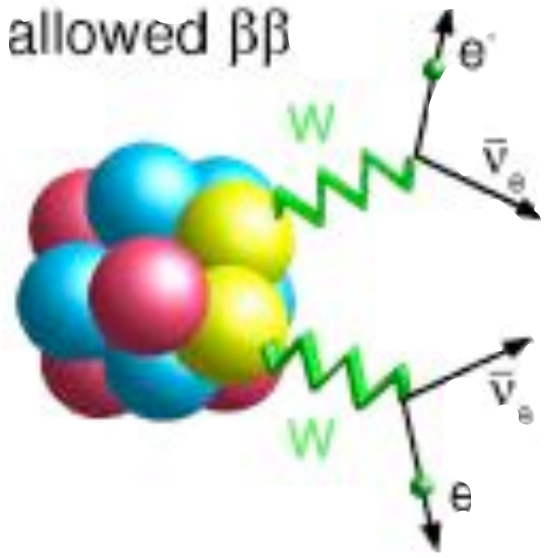
Second order weak interactions

NPLQCD arXiv:1701.03456, 1702.02929

- Background axial field to second order

  ➡ nn→pp transition matrix element

$$M^{2\nu}_{GT} = 6 \int d^4x d^4y \langle pp|T\left[J_3^+(x) J_3^+(y)\right]|nn\rangle$$



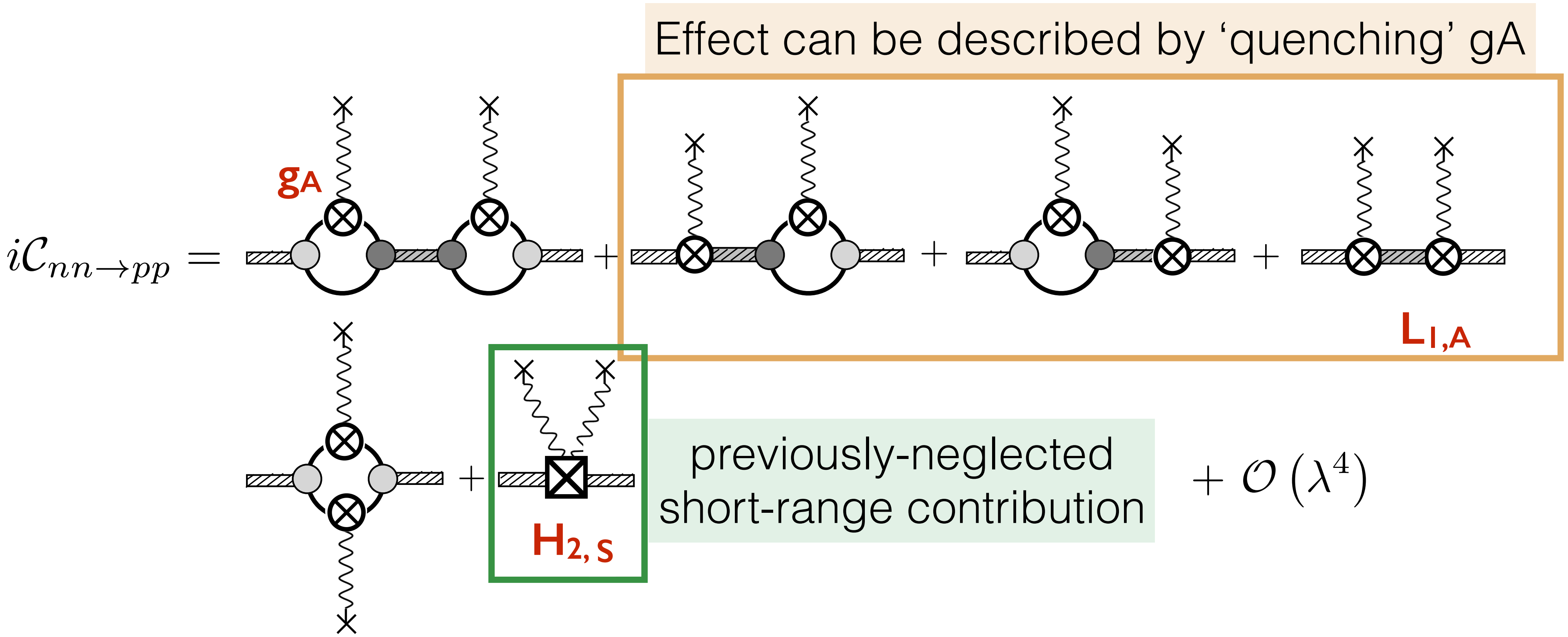
- $nn \rightarrow ppee\overline{\nu}_e\overline{\nu}_e$ decay not observed in nature because the dinucleon is not bound

BUT

- Nuclear matrix element well-defined and an important subprocess in double-beta decays of large nuclei

Second order weak interactions

- In effective field theory



Effect can be described by ‘quenching’ gA

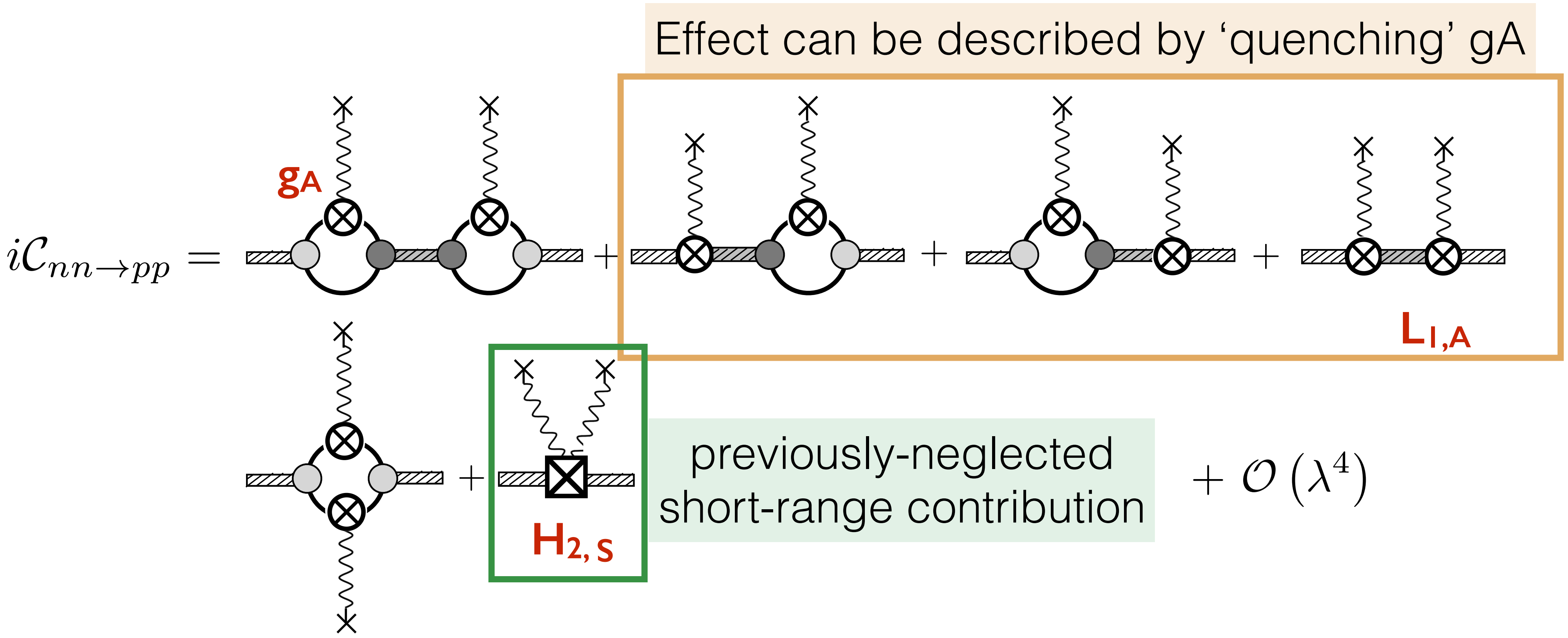
previously-neglected short-range contribution

One body (**g_A**), two body single-weak current (**L_{1A}**), two-body second order weak (**H_{2S}**)

H_{2S} ~ ***isotensor axial polarisability*** ignored in all phenomenological analyses (unconstrained except by DBD)

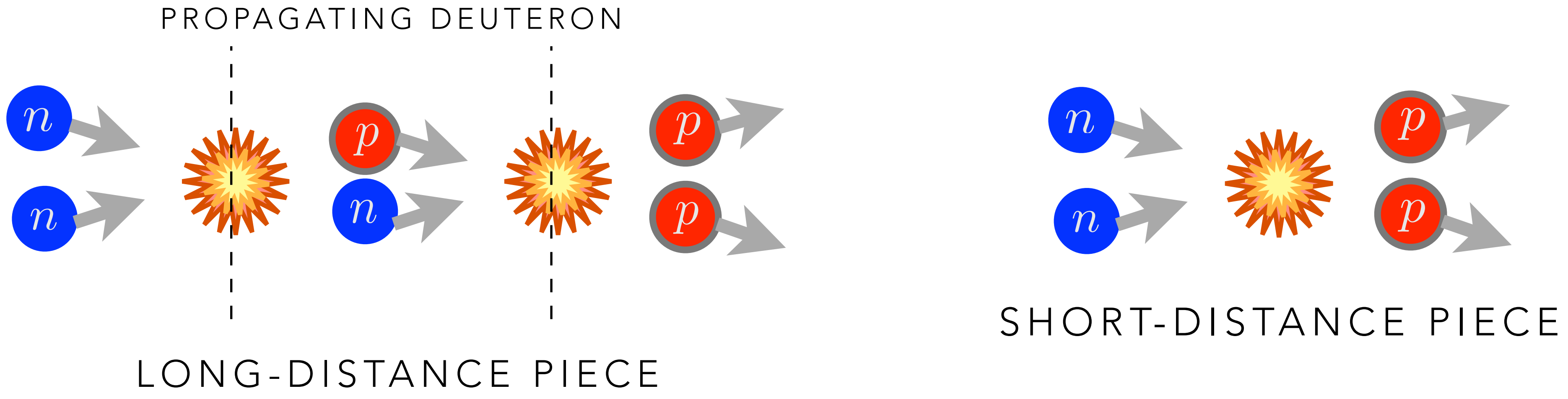
Second order weak interactions

- In effective field theory



Effect can be described by ‘quenching’ gA

previously-neglected short-range contribution



LONG-DISTANCE PIECE

SHORT-DISTANCE PIECE

Second order weak interactions

From lattice calculations: differentiate terms by their distinct time-dependences in correlation function

Expand contributions to the correlation function

$$\begin{aligned}
a^2 C_{nn\to pp}(t) = 2 Z_{pp} Z_{nn}^{\dagger} e^{-E_{nn}t} \Bigg\{ & \left[\frac{e^{\Delta t}-1}{\Delta^2} - \frac{t}{\Delta}\right] \langle pp|\tilde{J}_3^+|d\rangle\langle d|\tilde{J}_3^+|nn\rangle \\
& + \sum_{\mathfrak{l}'\neq d} \left[\frac{t}{\delta_{\mathfrak{l}'}} - \frac{1}{\delta_{\mathfrak{l}'}^2}\right] \langle pp|\tilde{J}_3^+|\mathfrak{l}'\rangle\langle \mathfrak{l}'|\tilde{J}_3^+|nn\rangle \\
& + \sum_{\mathfrak{n}\neq nn,pp} \left[\frac{e^{\Delta t}}{\Delta(\Delta+\delta_{\mathfrak{n}})} - \frac{1}{\Delta\delta_{\mathfrak{n}}}\right] \left(\frac{Z_{\mathfrak{n}}}{Z_{pp}} \langle \mathfrak{n}|\tilde{J}_3^+|d\rangle\langle d|\tilde{J}_3^+|nn\rangle + \frac{Z_{\mathfrak{n}}^{\dagger}}{Z_{nn}^{\dagger}} \langle pp|\tilde{J}_3^+|d\rangle\langle d|\tilde{J}_3^+|\mathfrak{n}\rangle\right) \\
& + \sum_{\mathfrak{n}\neq nn,pp} \sum_{\mathfrak{l}'\neq d} \frac{1}{\delta_{\mathfrak{l}'}\delta_{\mathfrak{n}}} \left(\frac{Z_{\mathfrak{n}}}{Z_{pp}} \langle \mathfrak{n}|\tilde{J}_3^+|\mathfrak{l}'\rangle\langle \mathfrak{l}'|\tilde{J}_3^+|nn\rangle + \frac{Z_{\mathfrak{n}}^{\dagger}}{Z_{nn}^{\dagger}} \langle pp|\tilde{J}_3^+|\mathfrak{l}'\rangle\langle \mathfrak{l}'|\tilde{J}_3^+|\mathfrak{n}\rangle\right) \\
& + \sum_{\mathfrak{n},\mathfrak{m}\neq nn,pp} \frac{e^{\Delta t}}{(\Delta+\delta_{\mathfrak{n}})(\Delta+\delta_{\mathfrak{m}})} \frac{Z_{\mathfrak{n}}}{Z_{pp}} \frac{Z_{\mathfrak{m}}^{\dagger}}{Z_{nn}^{\dagger}} \langle \mathfrak{n}|\tilde{J}_3^+|d\rangle\langle d|\tilde{J}_3^+|\mathfrak{m}\rangle + \mathcal{O}(e^{-\delta t}, e^{-\delta' t}) \Bigg\}.
\end{aligned}$$

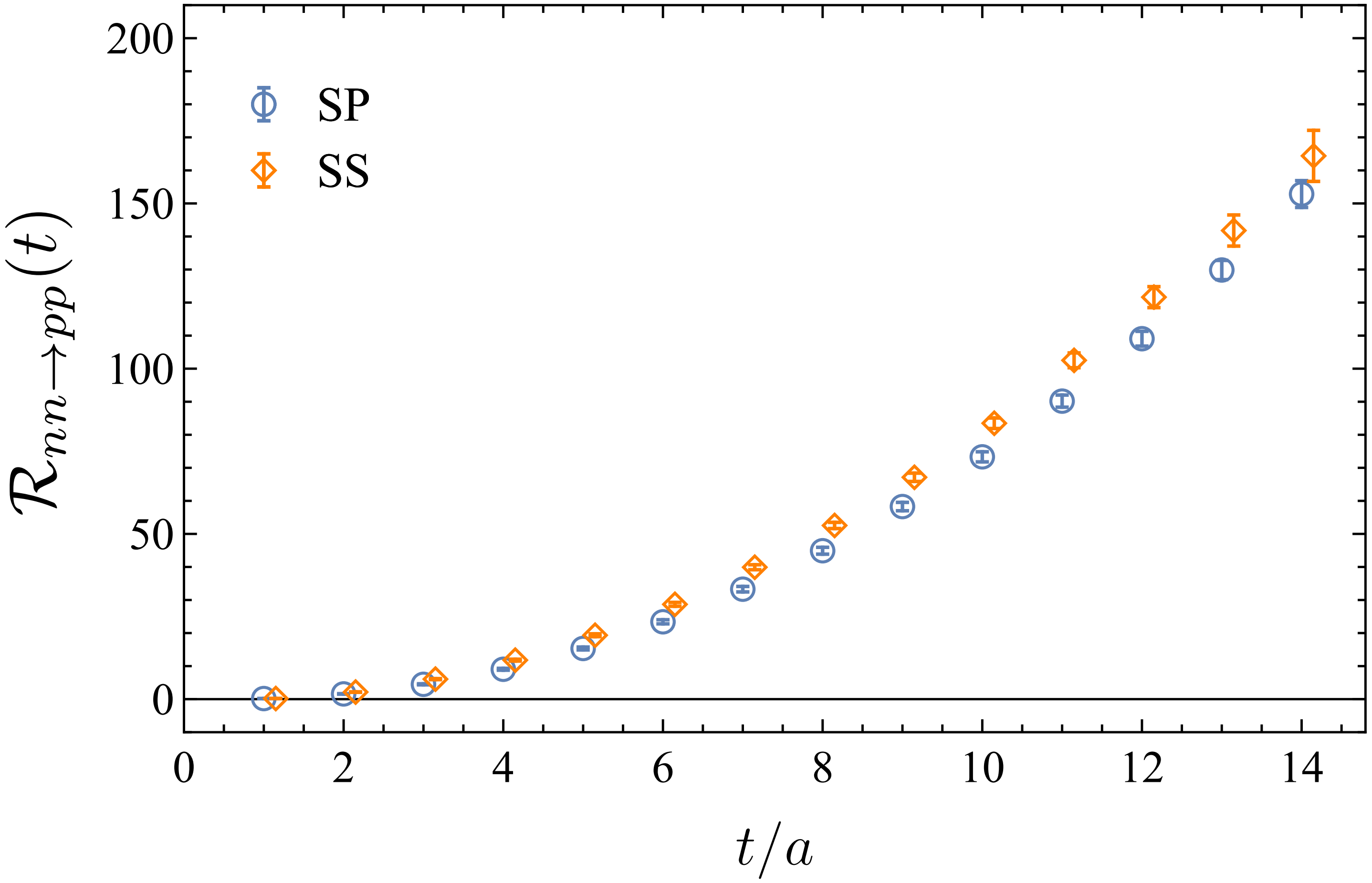
$$\begin{aligned}
\mathcal{R}_{nn\to pp}(t) = \frac{C_{nn\to pp}(t)}{2C_{0;0}^{(nn)}(t)} = \left[-t + \frac{e^{\Delta t}-1}{\Delta}\right] \frac{\langle pp|\tilde{J}_3^+|d\rangle\langle d|\tilde{J}_3^+|nn\rangle}{\Delta} \; + \; t \sum_{\mathfrak{l}'\neq d} \frac{\langle pp|\tilde{J}_3^+|\mathfrak{l}'\rangle\langle \mathfrak{l}'|\tilde{J}_3^+|nn\rangle}{\delta_{\mathfrak{l}'}} \\
+ \; C \; + \; D\, e^{\Delta t} + \mathcal{O}(e^{-\delta t}, e^{-\delta' t})
\end{aligned}$$

C,D irrelevant constants

Second order weak interactions

Challenging!

- Correlation function ratio clearly dominated by exponential
- BUT: Deuteron contribution well-determined by calculations with single axial current insertions



Second order weak interactions

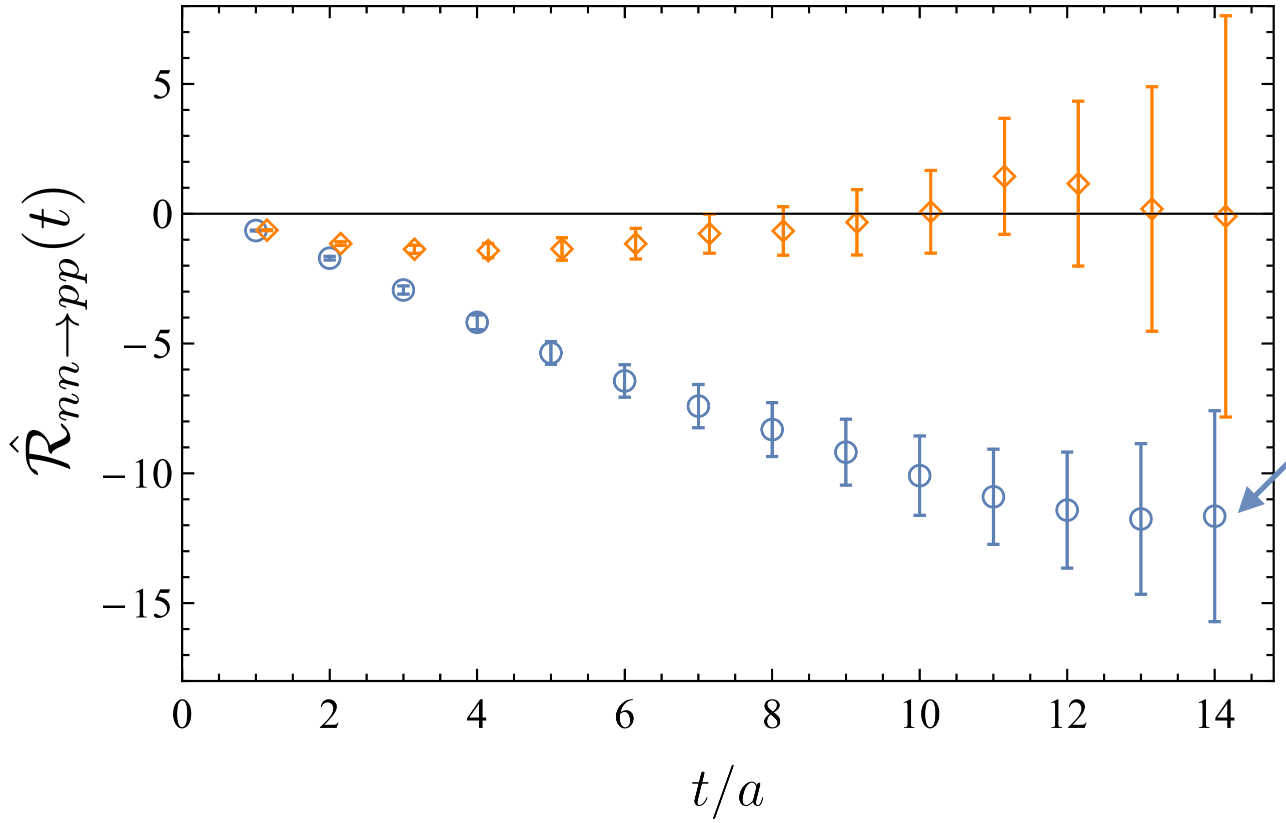
Subtract deuteron pole term determined from (correlated) single-insertion calculations

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

c,d irrelevant constants

$\Delta = E_{nn} - E_d$

determined from ratios of two-point functions



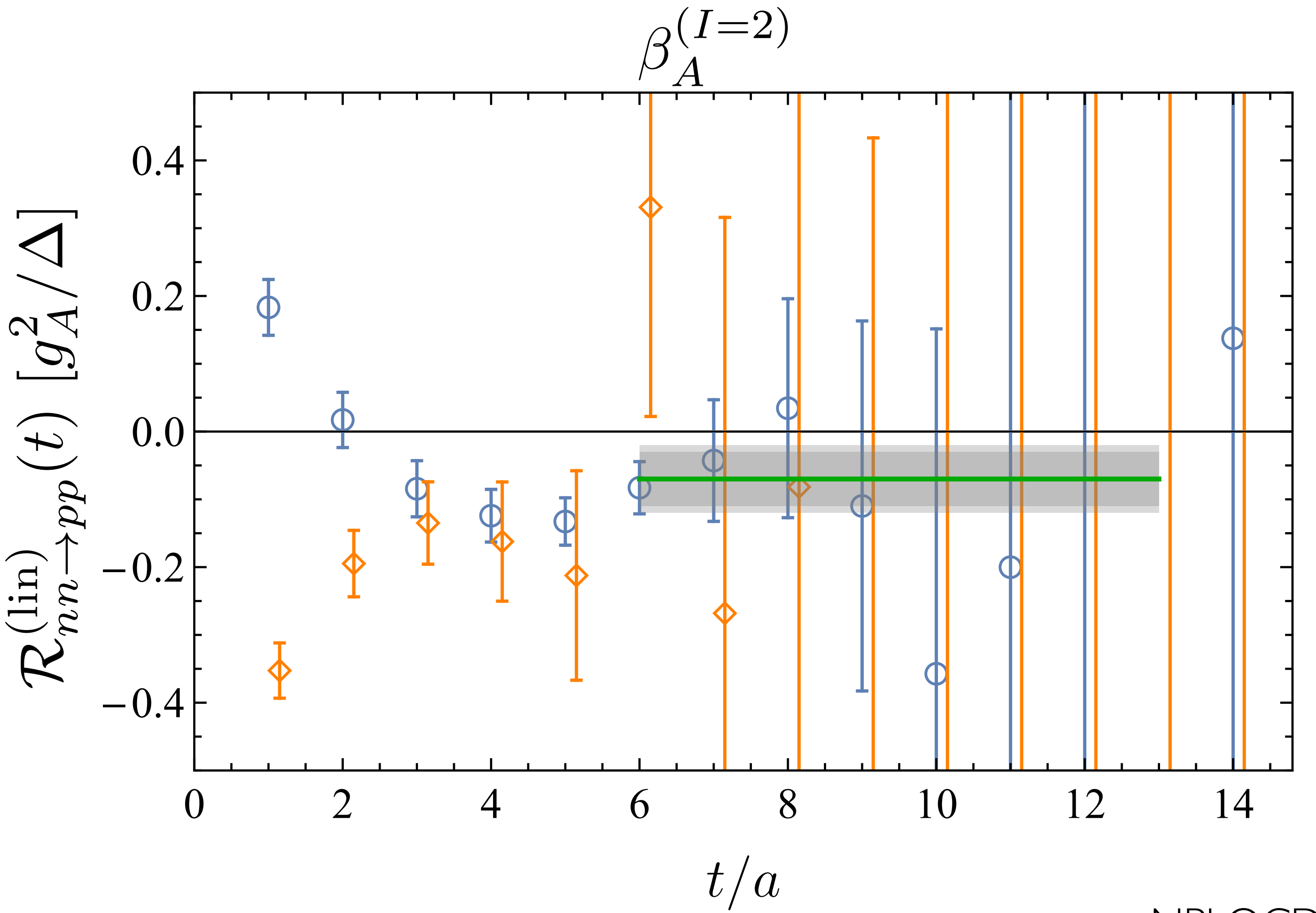
Linear in t:
SP sink has a highly suppressed overlap onto the nn scattering states

NPLQCD arXiv:1701.03456, 1702.02929

Second order weak interactions

Form ratios to extract **isotensor axial polarisability**

$$\mathcal{R}^{(\mathrm{lin})}_{nn\to pp}(t) = \frac{(e^{a\Delta}+1)\hat{\mathcal{R}}_{nn\to pp}(t+a) - \hat{\mathcal{R}}_{nn\to pp}(t+2a) - e^{a\Delta}\hat{\mathcal{R}}_{nn\to pp}(t)}{e^{a\Delta}-1} \xrightarrow{t\to\infty} \frac{1}{aZ_A^2}\frac{\beta_A^{(2)}}{6}$$

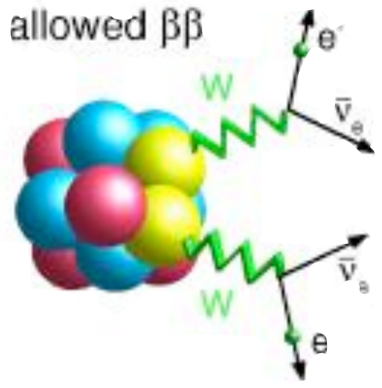


NPLQCD arXiv:1701.03456, 1702.02929

Second order weak interactions

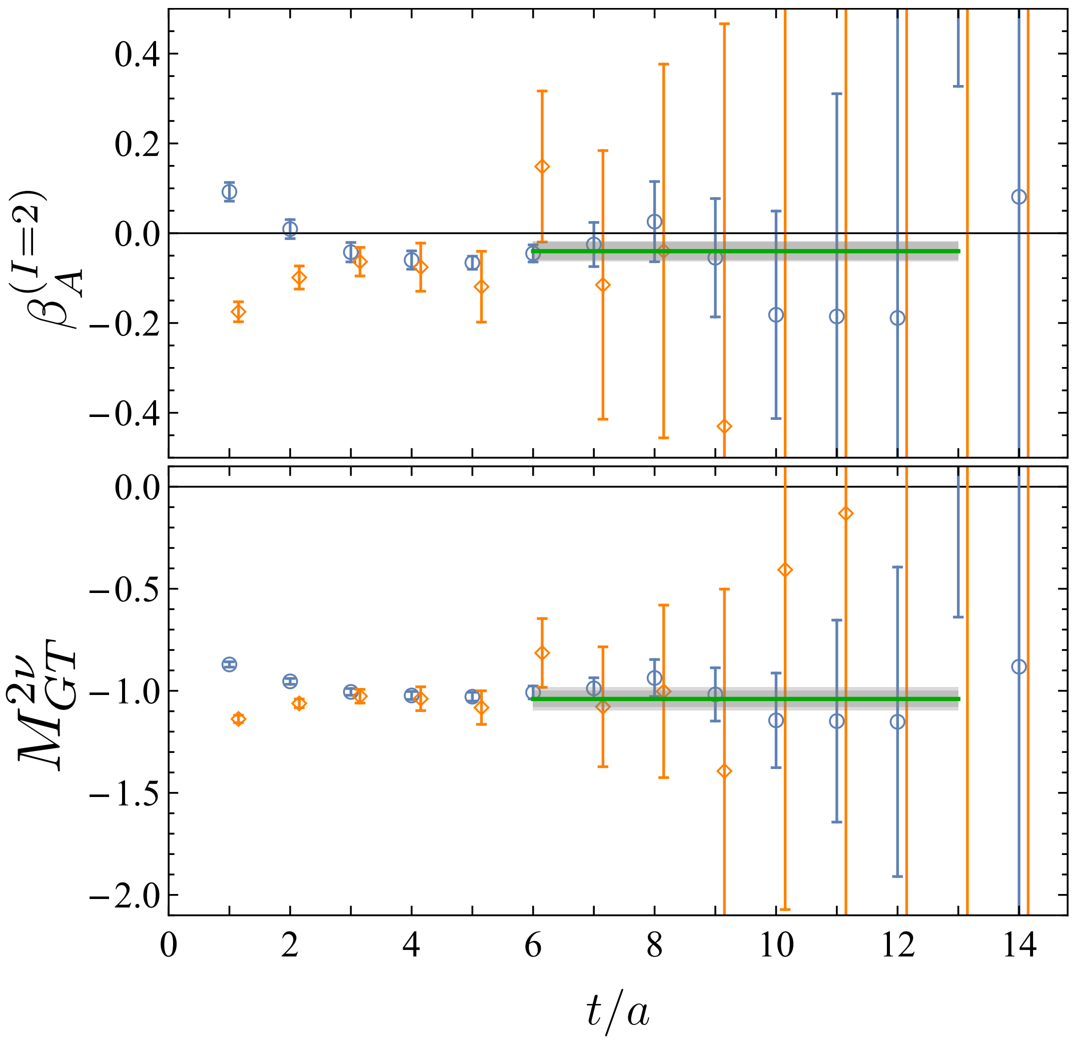
NPLQCD arXiv:1701.03456, 1702.02929

- Non-negligible deviation from long distance deuteron intermediate state contribution



Isotensor axial polarisability

$$M_{GT}^{2\nu} = -\frac{|M_{pp\to d}|^2}{E_{pp}-E_d} + \beta_A^{(I=2)}$$



Quenching of g_A in nuclei is insufficient!

- Connect to EFT for larger systems

Second order weak interactions

NPLQCD arXiv:1701.03456, 1702.02929

- Match QCD matrix element to low-energy constants of pionless EFT

  Correlation function matrix in coupled $nn, np(^3S_1), pp$ channel space

$$\mathcal{C}_{NN\to NN} \equiv \begin{pmatrix} \mathcal{C}_{nn\to nn} & \mathcal{C}_{nn\to np(^3S_1)} & \mathcal{C}_{nn\to pp} \\ \mathcal{C}_{np(^3S_1)\to nn} & \mathcal{C}_{np(^3S_1)\to np(^3S_1)} & \mathcal{C}_{np(^3S_1)\to pp} \\ \mathcal{C}_{pp\to nn} & \mathcal{C}_{pp\to np(^3S_1)} & \mathcal{C}_{pp\to pp} \end{pmatrix}$$

axial background field changes both spin and isospin
→ no coupling of $np(^1S_0)$

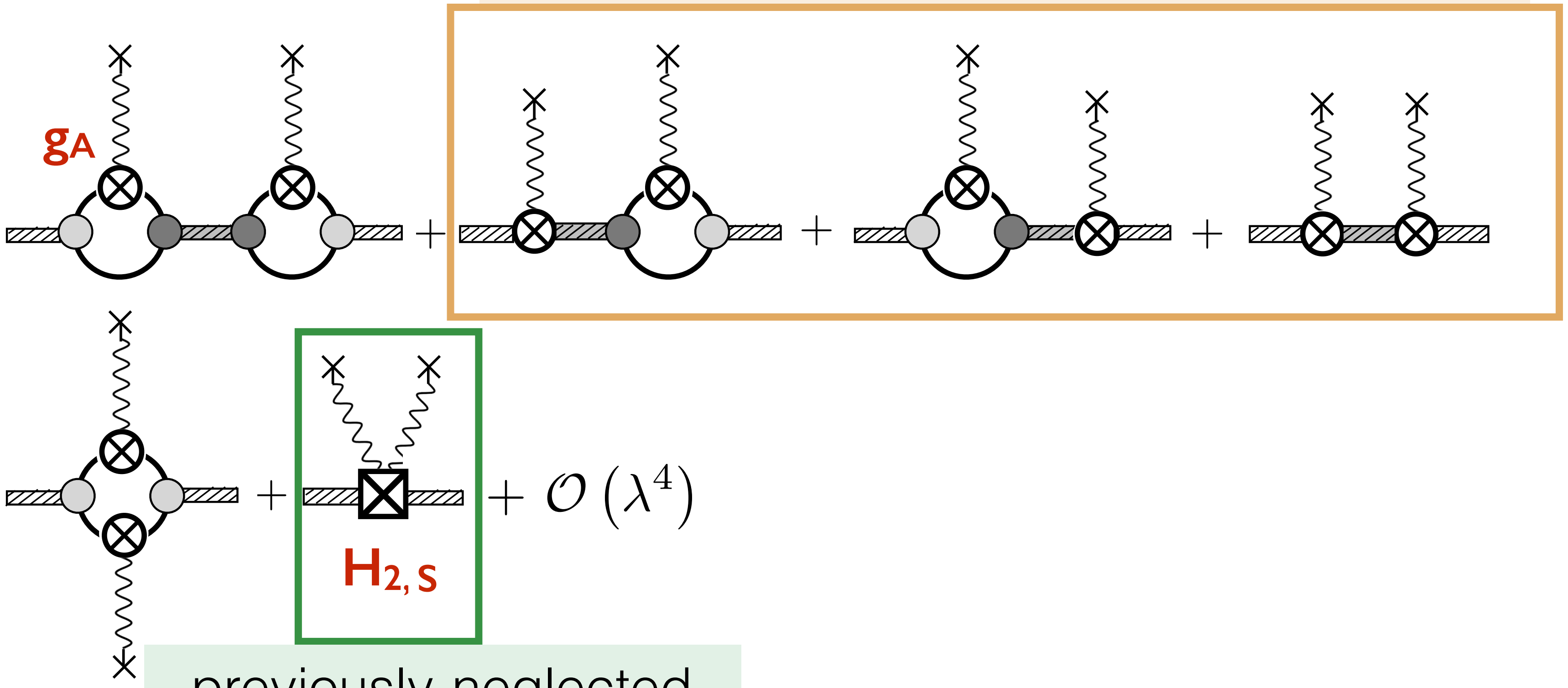
Second order weak interactions

NPLQCD arXiv:1701.03456, 1702.02929

- Match QCD matrix element to low-energy constants of pionless EFT

Effect can be described by ‘quenching’ gA

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



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

previously-neglected short-range contribution

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

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

$m_\pi = 806$ MeV

Second order weak interactions

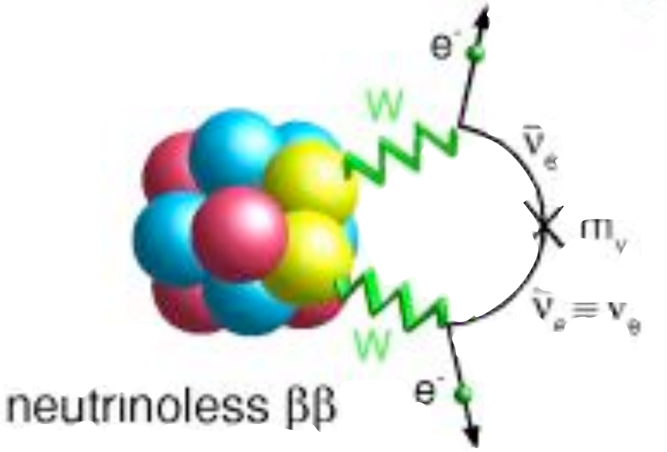
Future challenges:

- Lighter quark masses
  - Hierarchy between dinucleon-deuteron mass splitting and gap to excitations of dinucleon changes

    → Transition matrix elements of excited states not negligible
  - Need new techniques
    e.g., separate source and sink from background field region
  - Initial, intermediate, final states no longer bound
    → need multi-particle finite-volume formalism

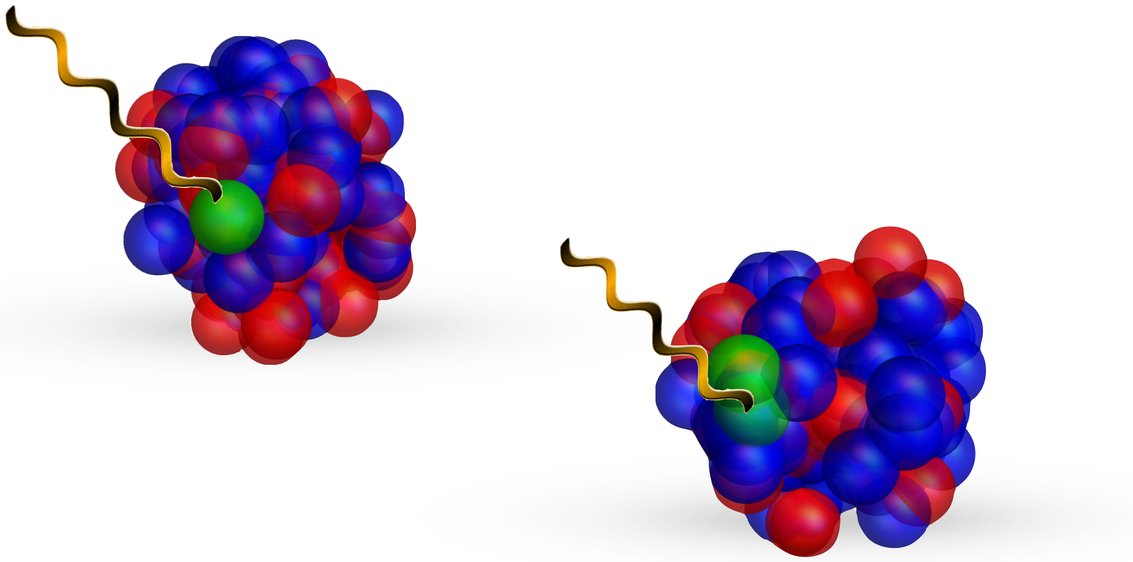
Detmold + Savage, Nucl. Phys A743 170 (2004)
Briceno + Davoudi, PRD88 94507 (2013)
Briceno + Hansen PRD94 13008 (2016)
Christ et al. PRD91 114510 (2015)

- Neutrinoless double-beta decay
  - Contraction of nuclear matrix element with leptonic tensor → integration over the intermediate neutrino momentum in ME
  - Both axial and vector currents important



Larger nuclei

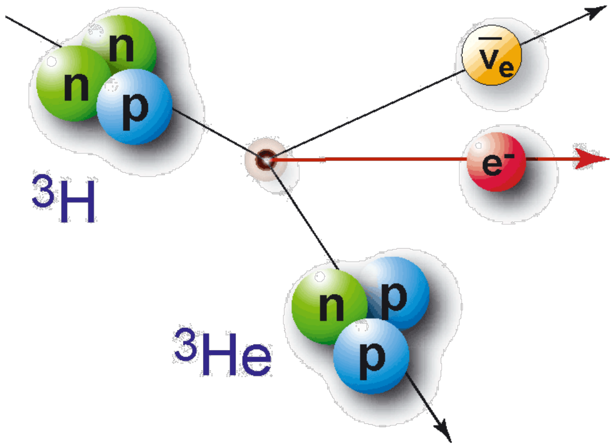
- Move to larger (phenomenologically-relevant) nuclei?
- Nuclear effective field theory:
  - 1-body currents are dominant
  - 2-body currents are sub-leading *but non-negligible*



- Determine one body contributions from single nucleon
- Determine few-body contributions from A=2,3,4...
- Match EFT and many body methods to LQCD to make predictions for larger nuclei

Summary

- Current state-of-the-art: significant systematics but phenomenologically interesting at current precision
  - Spectroscopy of nuclei
  - Structure, i.e., magnetic moments, polarisabilities
  - **Electroweak interactions**



- Nuclear matrix elements important to experimental programs e.g,
  - Neutrino breakup reaction (SNO)
  - Muon capture reaction (MuSun)
  - Double-beta decay