Double Beta Decay:
Status and connections to lattice QCD

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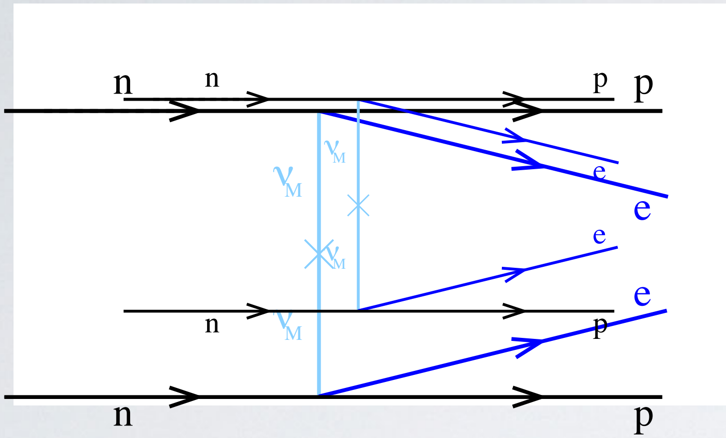
Weak interactions and nuclear physics:

- introduction to double beta decay
- single nucleon g_A and form factor
- two nucleons: neutrino scattering from deuteron
- light ($A \lesssim 10$) and heavy nucleon beta decay
- light nuclei and heavy nuclei: neutrino scattering
- double beta decay

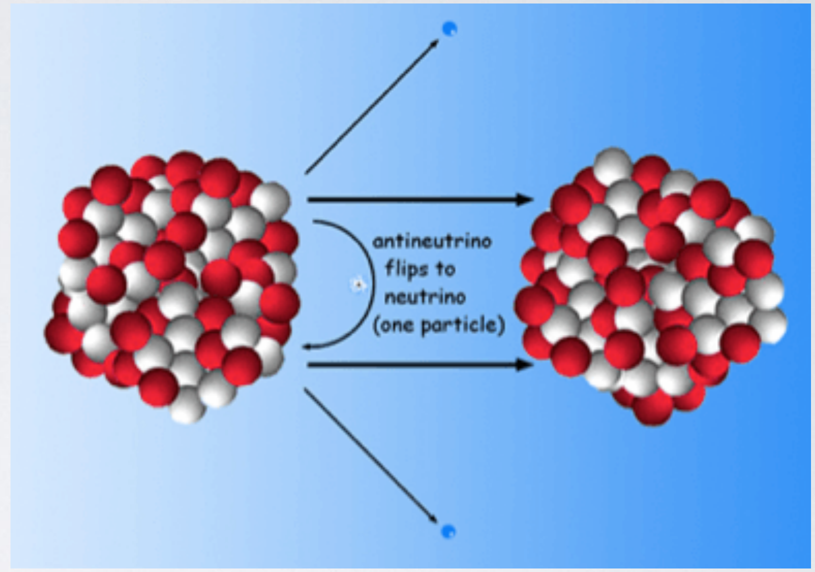
Intersections between lattice QCD and many-body
Summary and outlook

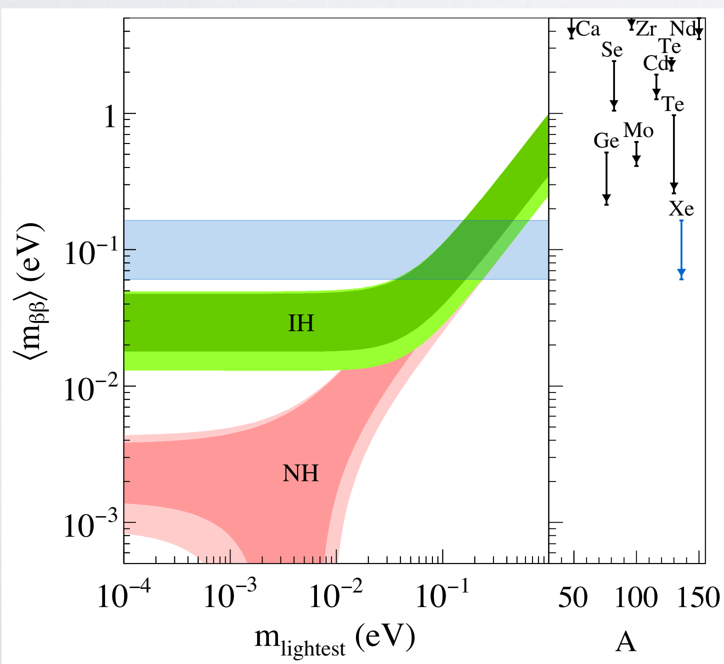
Nucleon Level



from Engel and Menendez
Reports on Progress in Physics 2017

Nuclear Level (neutrinoless)





$$[T_{1/2}^{0\nu}]^{-1} = \sum_{\text{spins}} \int |Z_{0\nu}|^2 \delta(E_{e1}+E_{e2}+E_f-E_i) \frac{d^3\boldsymbol{p}_1}{2\pi^3} \frac{d^3\boldsymbol{p}_2}{2\pi^3} \, ,$$

rate

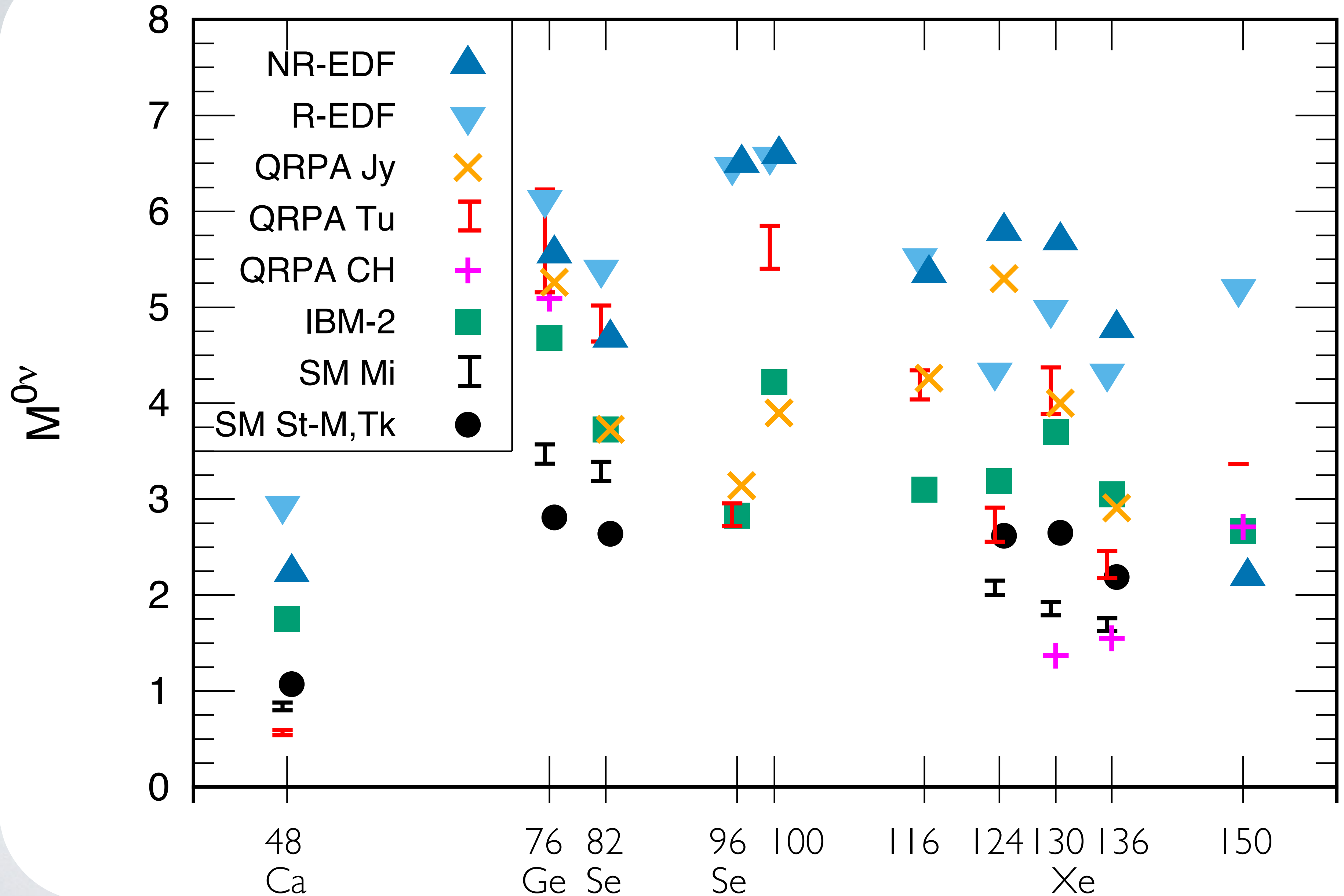
$$m_{\beta\beta} \equiv \left| \sum_k m_k U_{ek}^2 \right| \tag{5}$$
$$= \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i(\alpha_2-\alpha_1)} + m_3 |U_{e3}|^2 e^{i(-\alpha_1-2\delta)} \right| .$$

neutrino mass

$$\sum_n \left[\frac{\langle f|J_L^\mu(\boldsymbol{q})|n\rangle\langle n|J_L^\nu(-\boldsymbol{q})|i\rangle}{|\boldsymbol{q}|(E_n+|\boldsymbol{q}|+E_{e2}-E_i)} + \frac{\langle f|J_L^\nu(\boldsymbol{q})|n\rangle\langle n|J_L^\mu(-\boldsymbol{q})|i\rangle}{|\boldsymbol{q}|(E_n+|\boldsymbol{q}|+E_{e1}-E_i)} \right]$$
$$\times 2\pi\delta(E_f+E_{e1}+E_{e2}-E_i) \, , \tag{7}$$

nuclear matrix element

Nuclear Matrix Element



from Engel and Menendez
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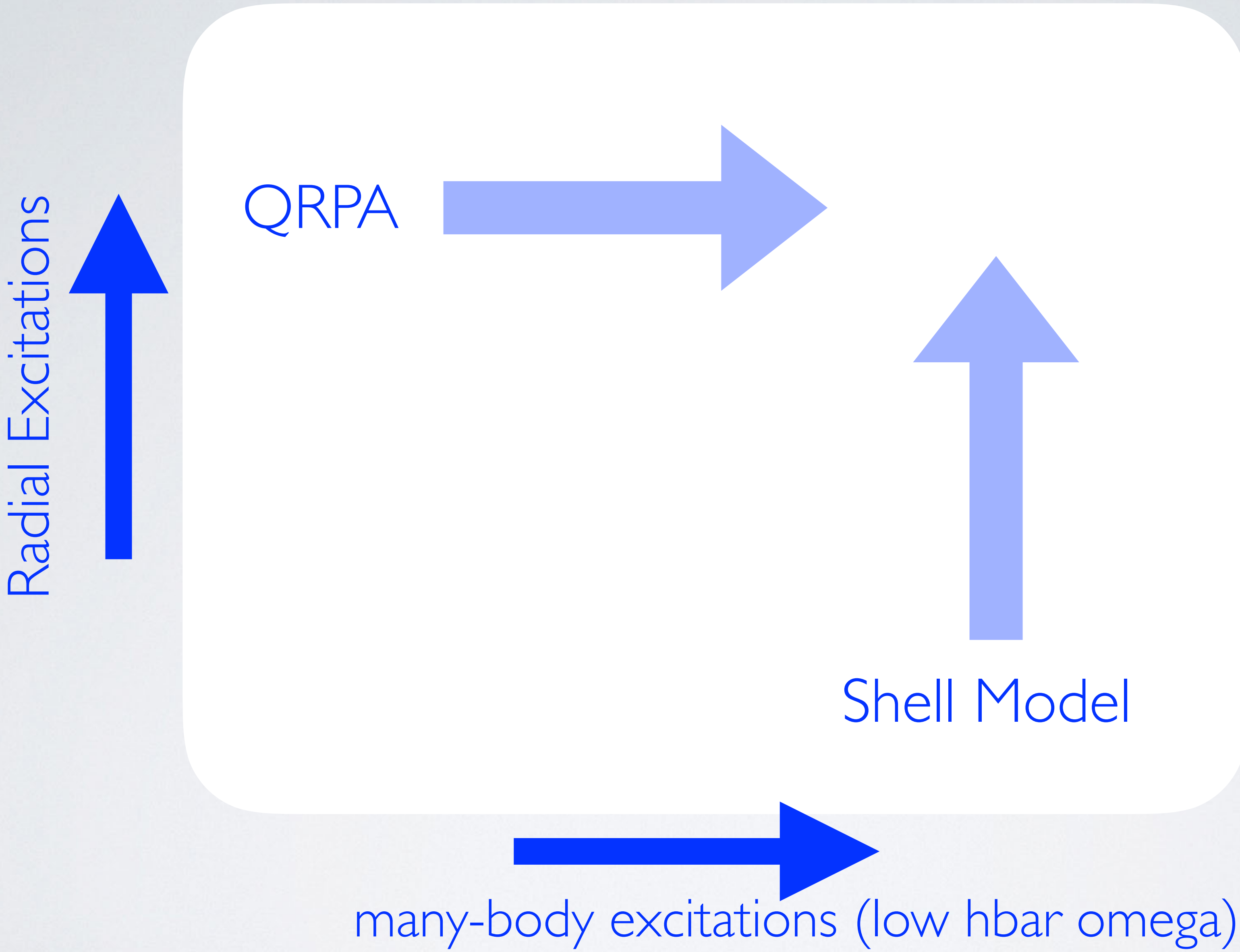
Theory Methods:

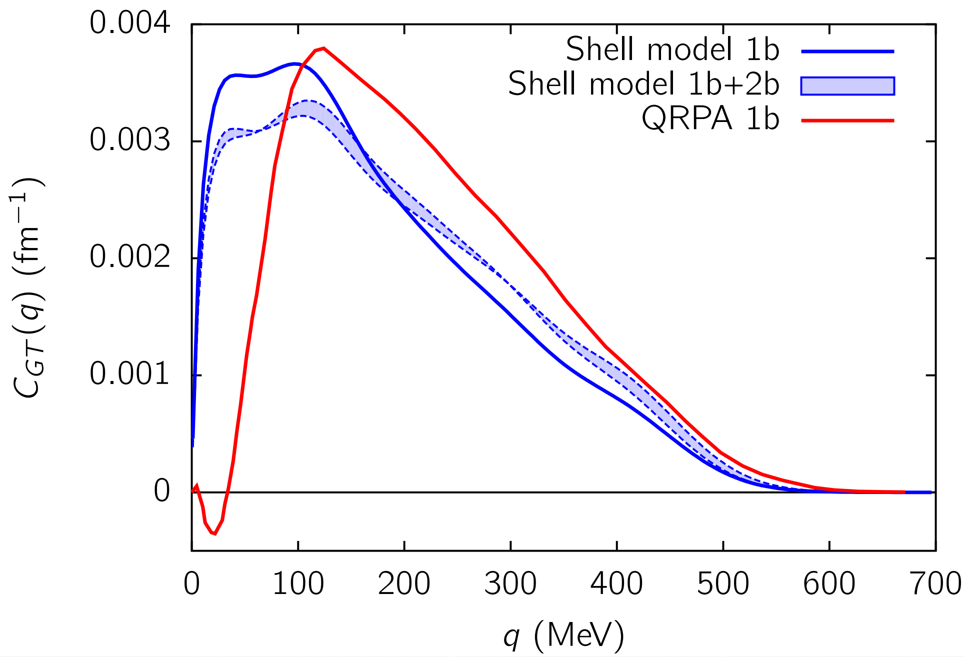


Everything seems to matter: deformation, n-p pairing, …

Combining methods should be very valuable

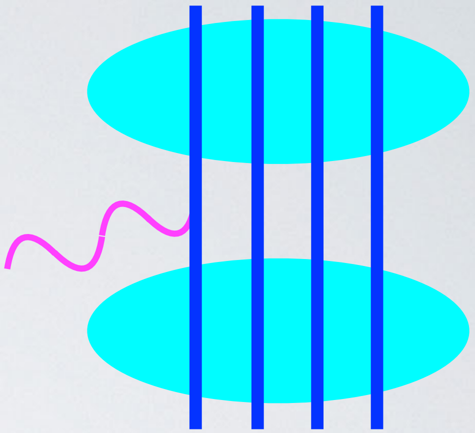
Why is this difficult?

- momentum dependence (light neutrino):
  Fermi matrix element: $(\tau_i^+ \tau_j^+ / r_{ij})$
  Gamow-Teller: $(\sigma_i \cdot \sigma_j \tau_i^+ \tau_j^+ / r_{ij})$



- low-energy transition to/from explicit states with moderate momentum transfer
- low-energy modes (deformation, etc.) important
- very small fraction (<< 1%) of the relevant sum rules

First look at a single weak vertex:



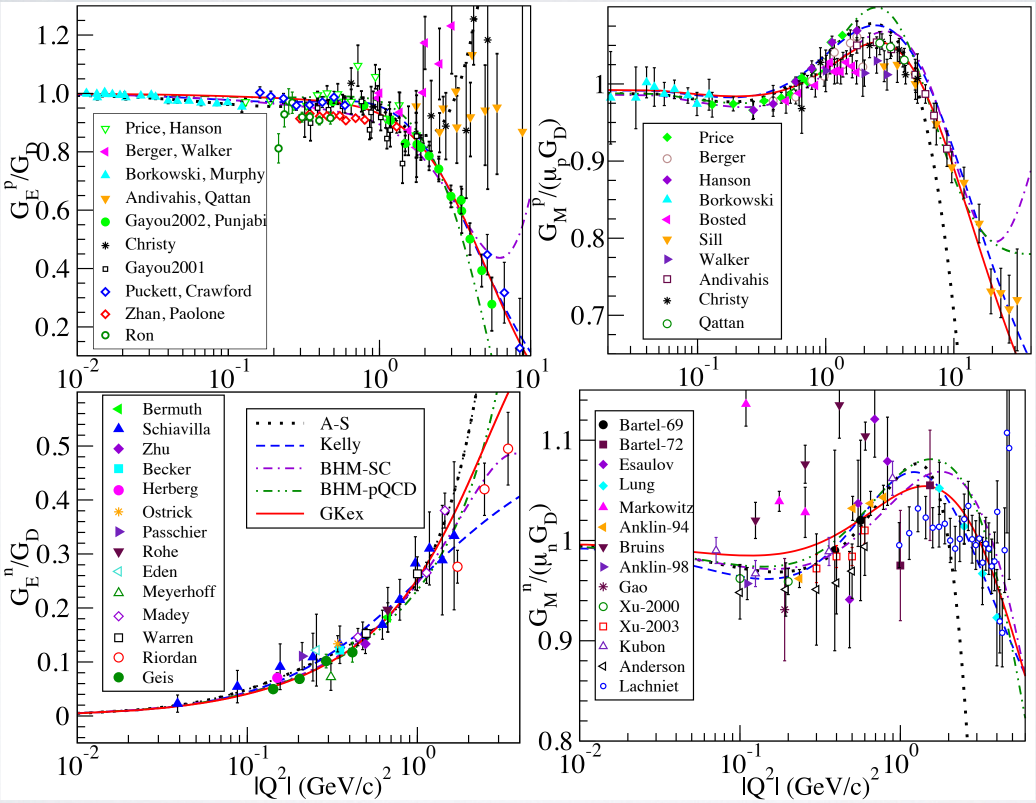
- neutrino-nucleon scattering
- nuclear beta decay
- muon capture
- low-energy neutrino scattering
- quasi-elastic neutrino scattering

Not a lot of data on weak interactions at moderate q

- LSND (stopped pions) on Carbon
- muon capture
- more data would be very valuable

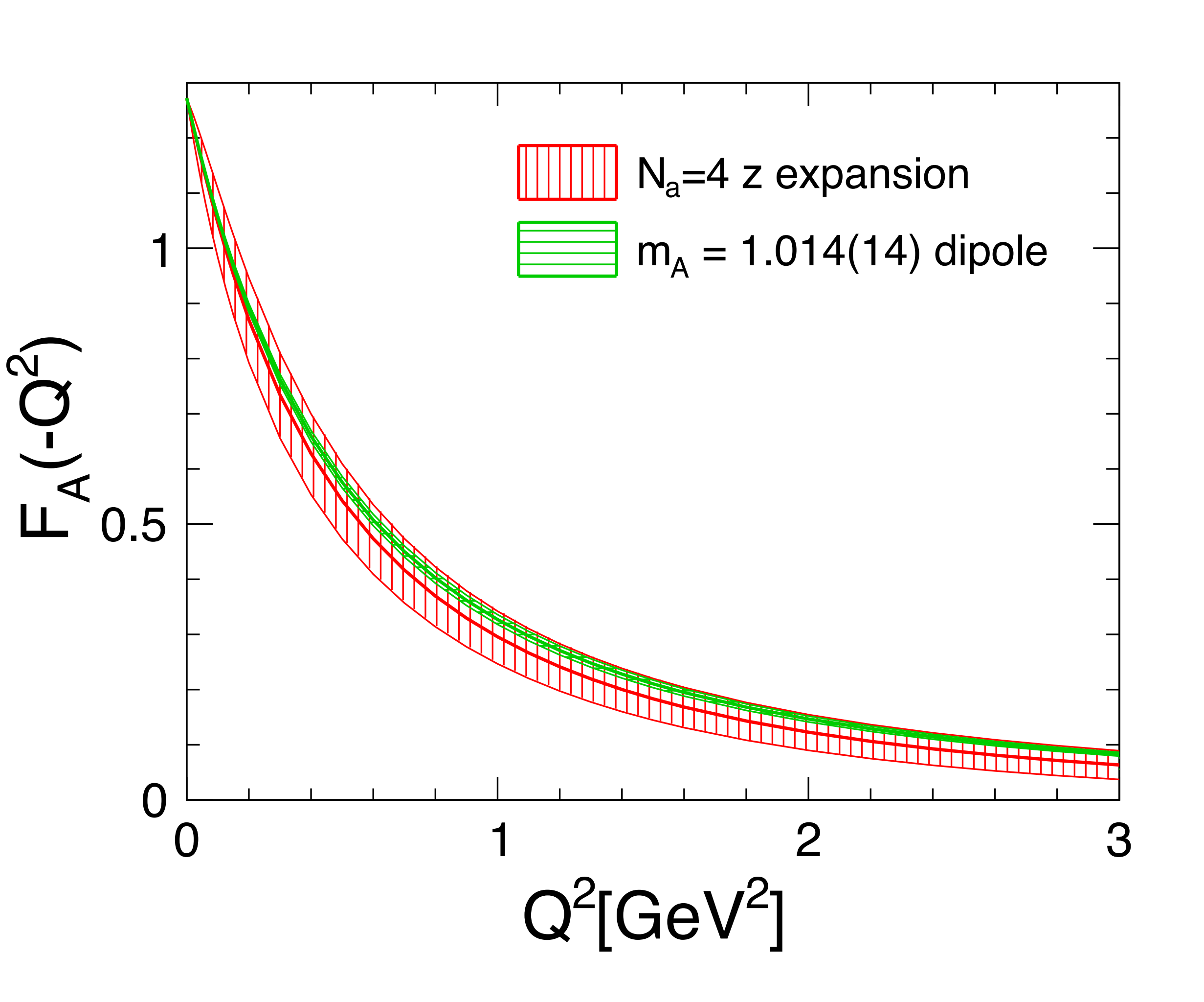
Scattering from a single nucleon

EM (vector) Nucleon Form Factors



Gonzalex-Jiminez, Caballero, Donnelly, Phys. Reports 2013

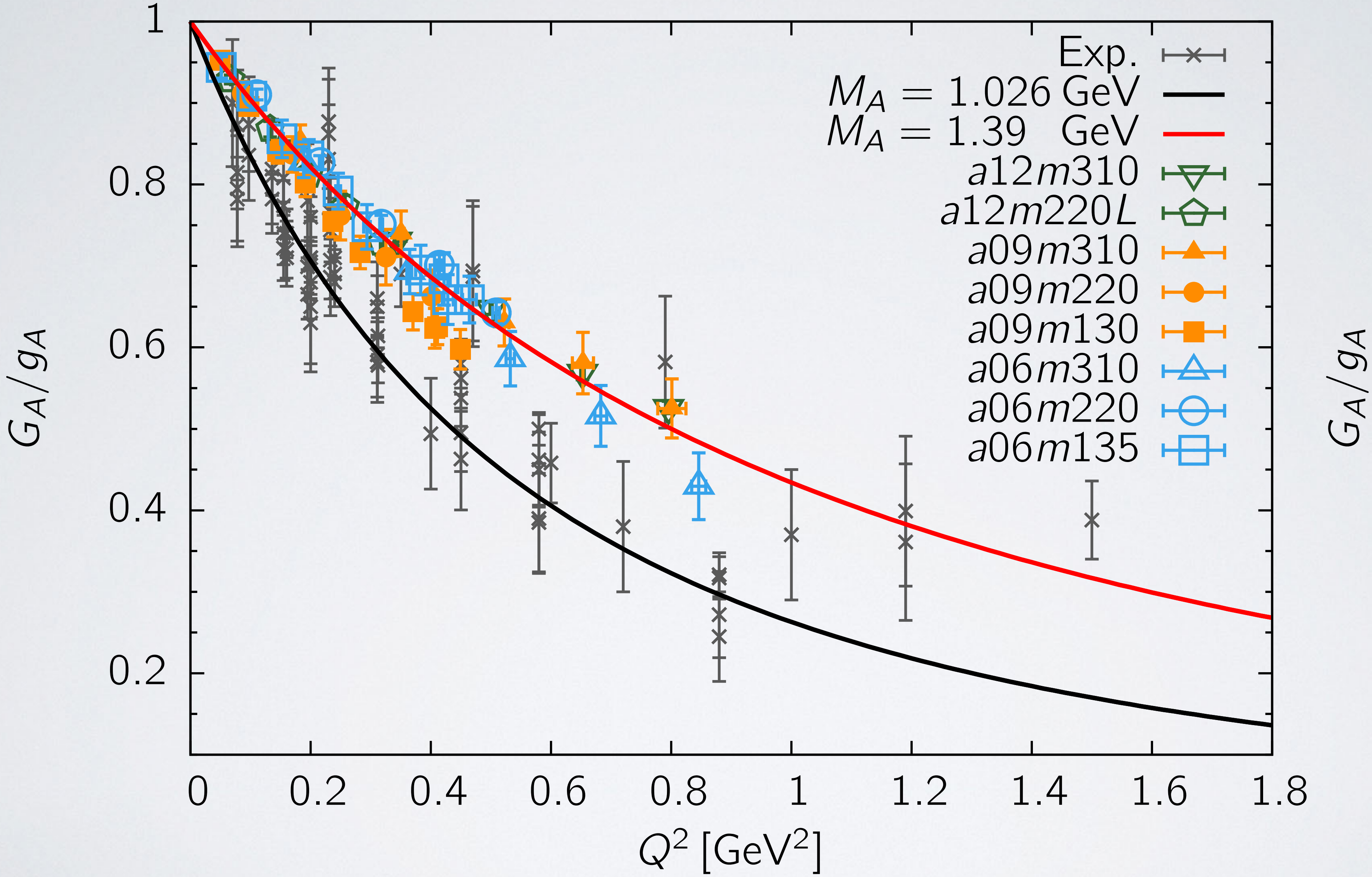
Axial Form Factor: Deuterium analysis



$$r_A^2 \;=\; 0.46\;(0.22)\;\mathrm{fm}^2$$

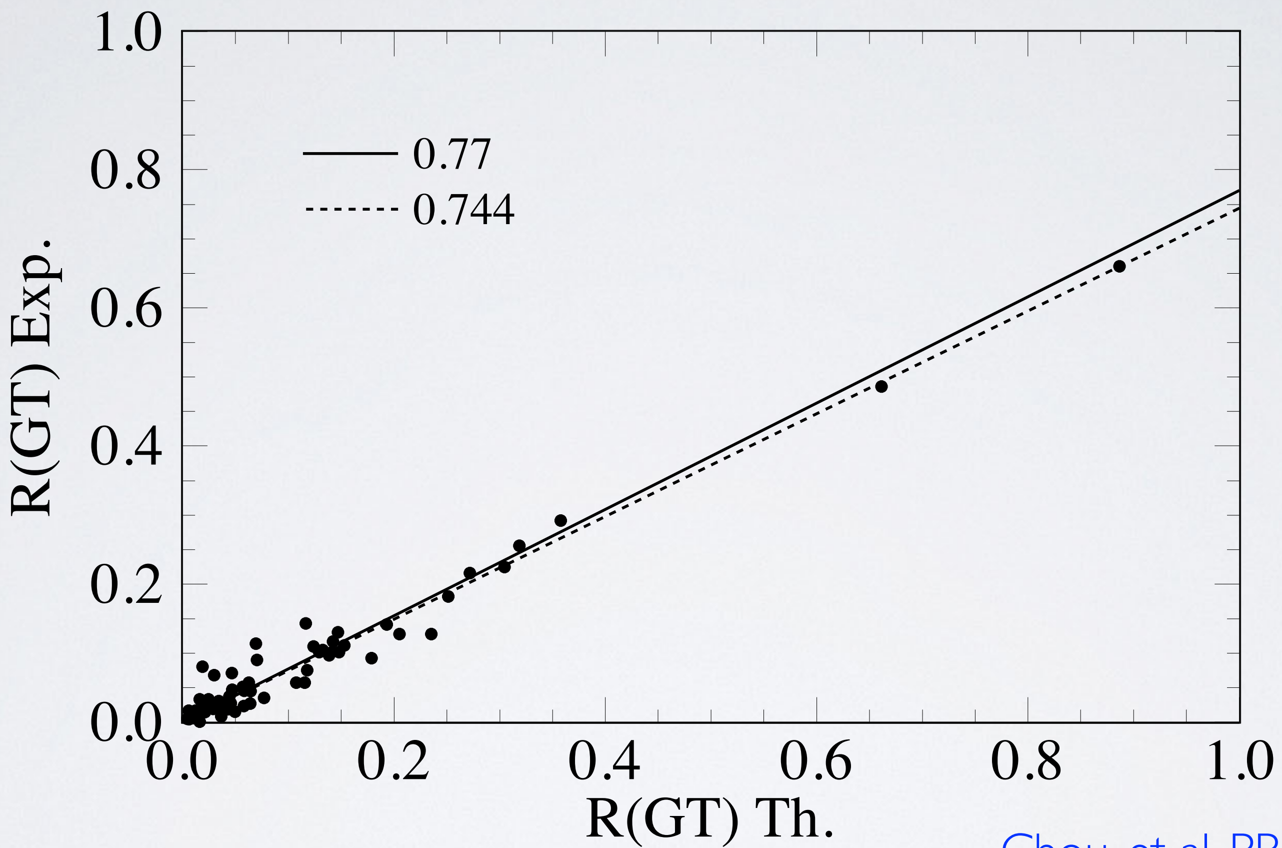
Axial form factor from analysis of deuterium data
Meyer, Betancourt, Gran, Hill (2016)

Nucleon axial form factor in lattice QCD



Gupta et al 2017

Nuclear Beta Decay
Calculations vs. Experiment

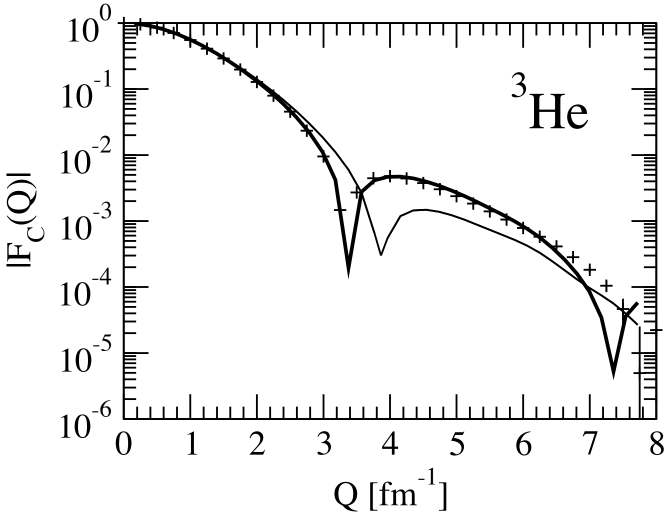


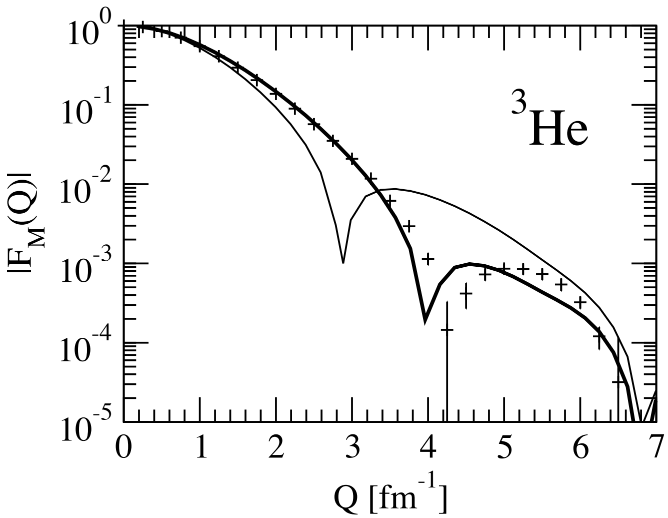
Chou, et al, PRC (1993)

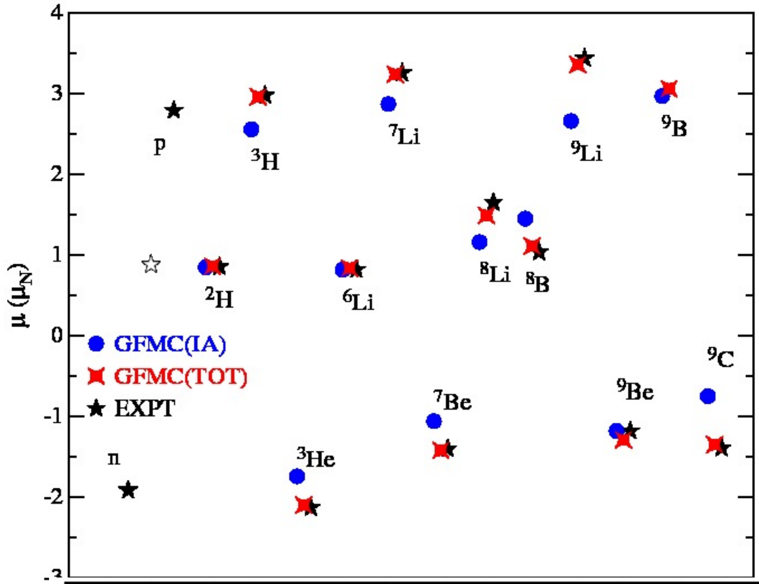
Quenching enters as 4th power in ββ decay:
up to a factor of $(1/1.27)^4 \sim 0.38$

2-Nucleon Currents critical to describe EM data

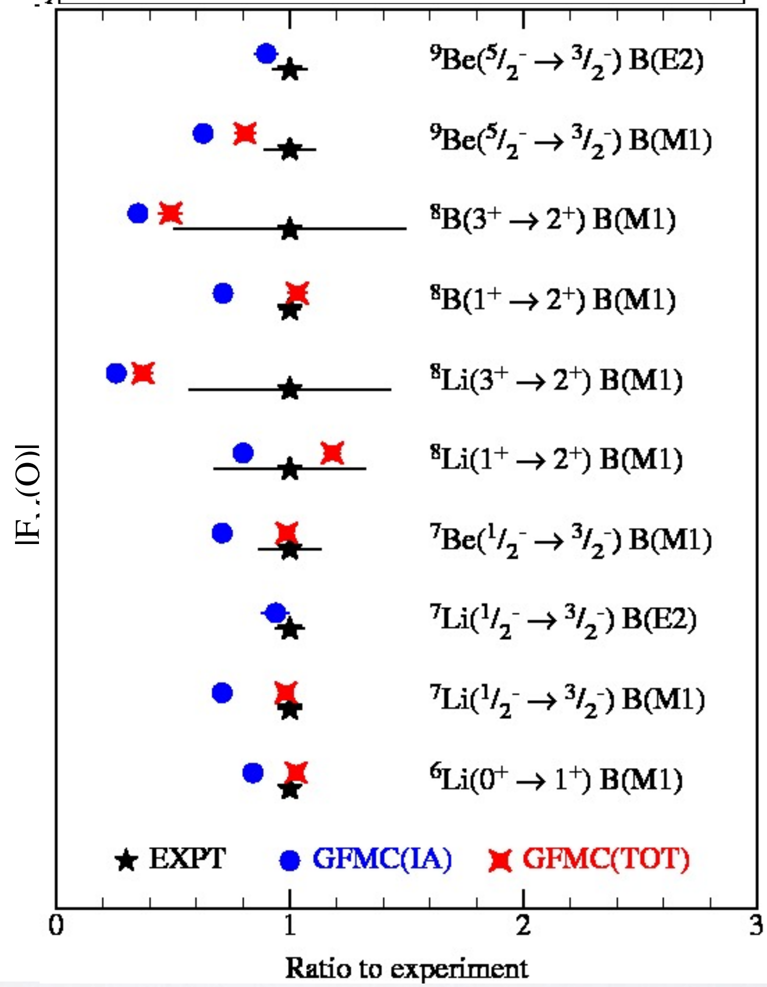
Form Factors







Magnetic Moments



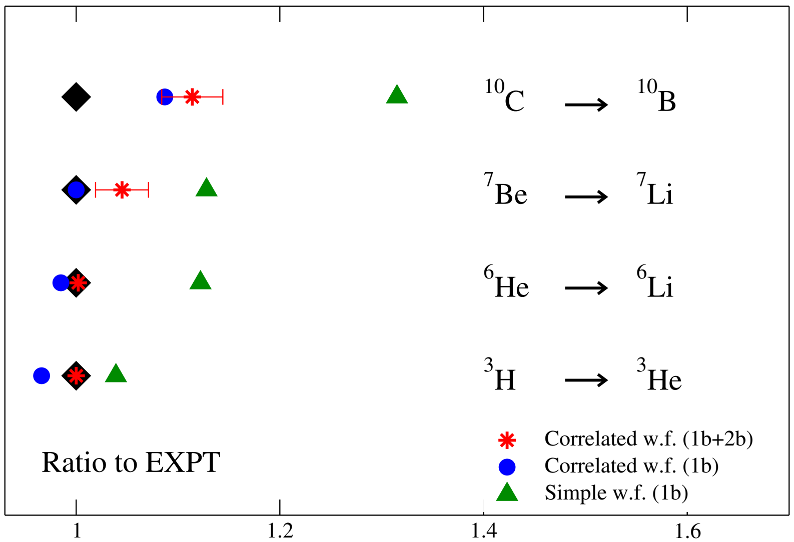
EM Transitions

Wiringa, Pastore, Schiavilla, et al

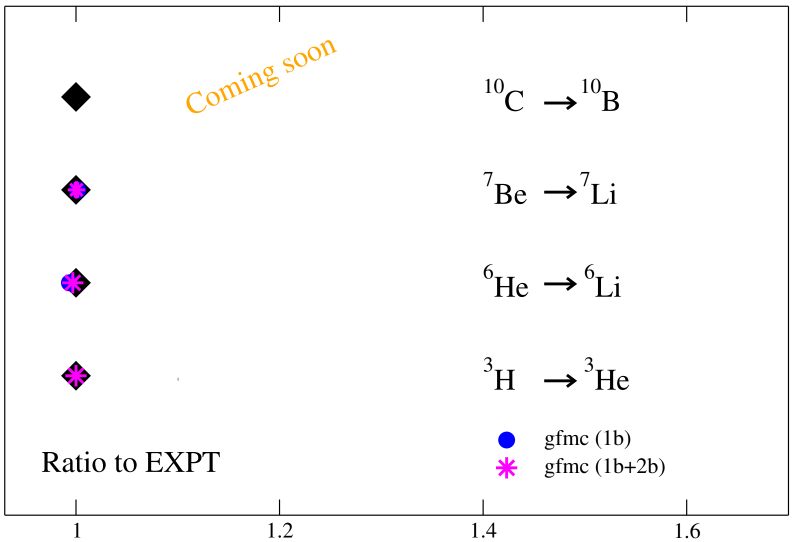
NUCLEI
Nuclear Computational Low-Energy Initiative

Nuclear Beta Decay: Light Nuclei

‘SNPA’ currents



chiral EFT currents

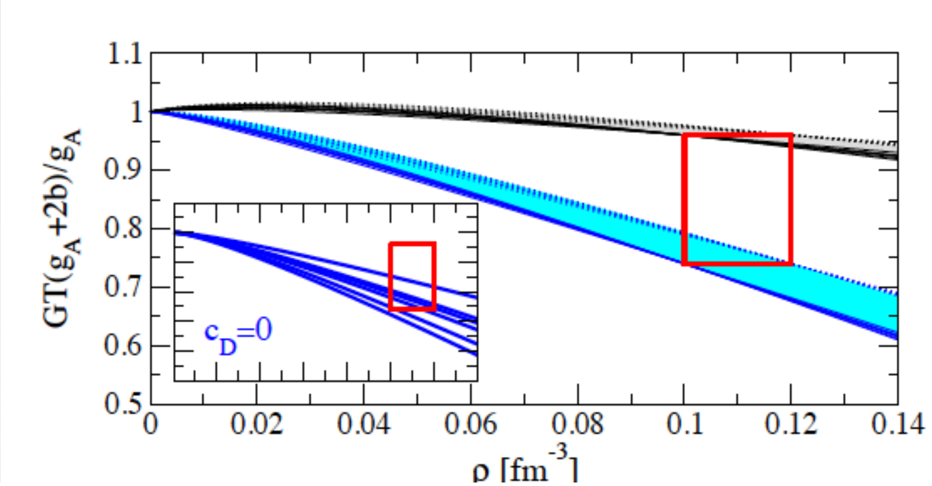


from S. Pastore’s talk at this program

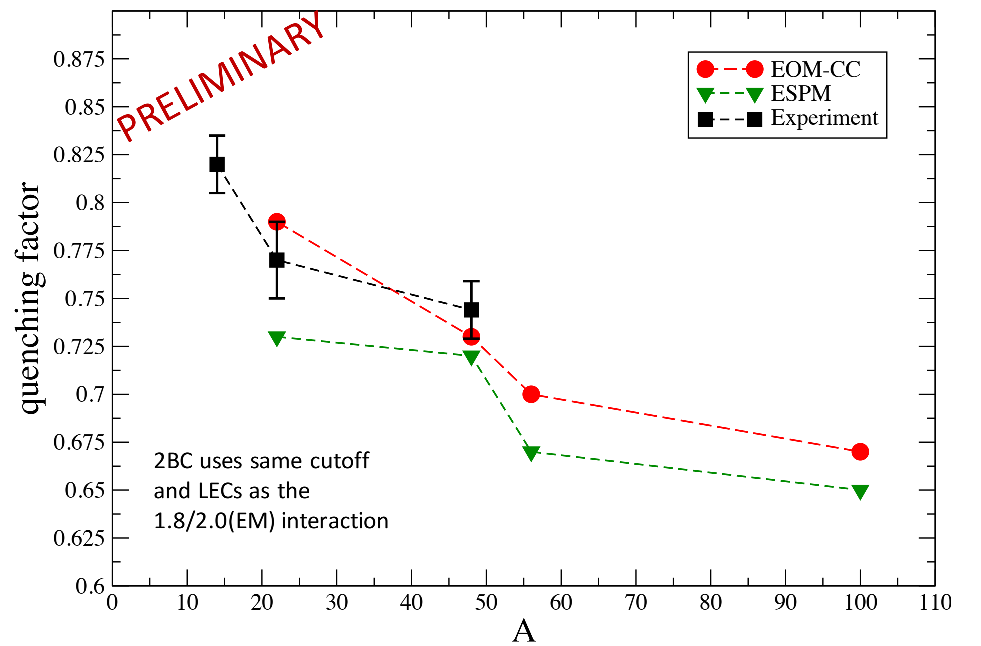
- moderate quenching in light nuclei: 10-25%
- significant reduction from correlations
- modest enhancement from 2N currents

  much smaller effects than magnetic moments, transitions
- good reproduction of experimental results

Nuclear Beta Decay: Heavy Nuclei



Infinite Matter:
Menendez, Gazit, Schwenk, PRL (2011)



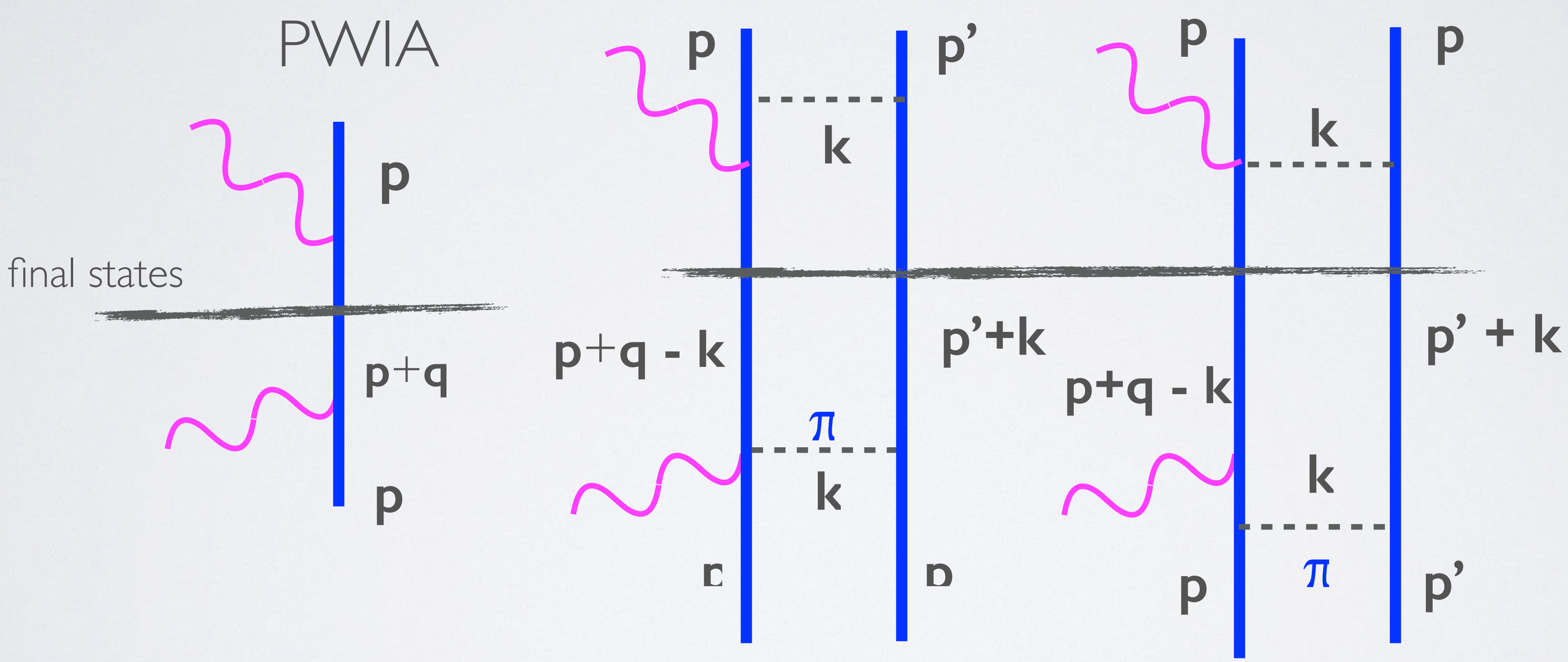
Coupled cluster:
G. Hagen (talk at this program)

- significant quenching from 2N currents (different resolution in calculation)
- normal-ordering approximation (effective 1-body operator)
- need a consistent picture across momentum, A

Higher momentum transfer: neutrino scattering

Quasielastic Scattering: Sum Rules

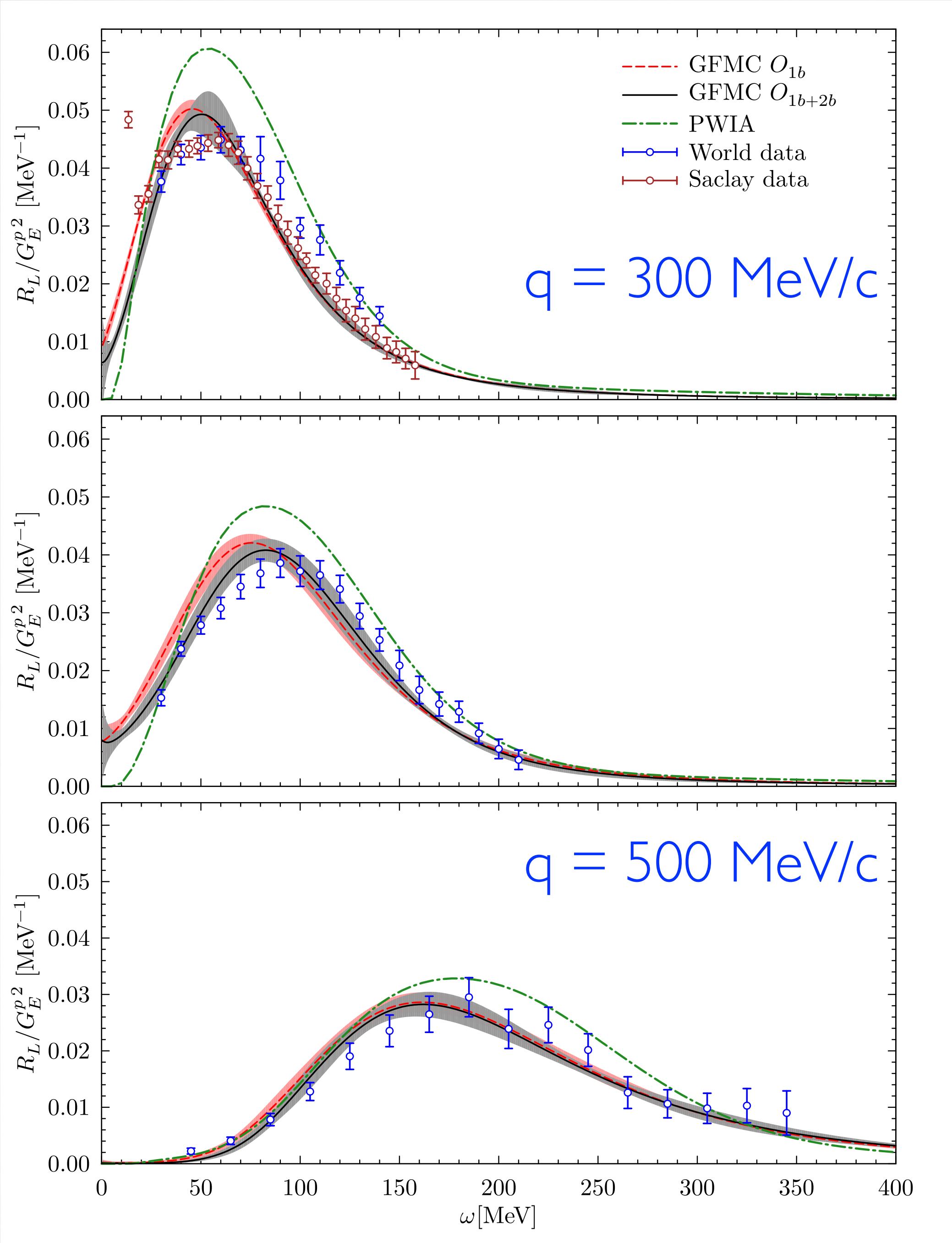
Constructive Interference
between 1- and 2-body



Large enhancement from combination of initial state

$$\propto\ \sigma_i \cdot \mathbf{k}\ \sigma_i \cdot \mathbf{q}\ (\sigma_j \cdot \mathbf{k})^2\ (\tau_i \cdot \tau_j)^2\ v_\pi^2(k)$$

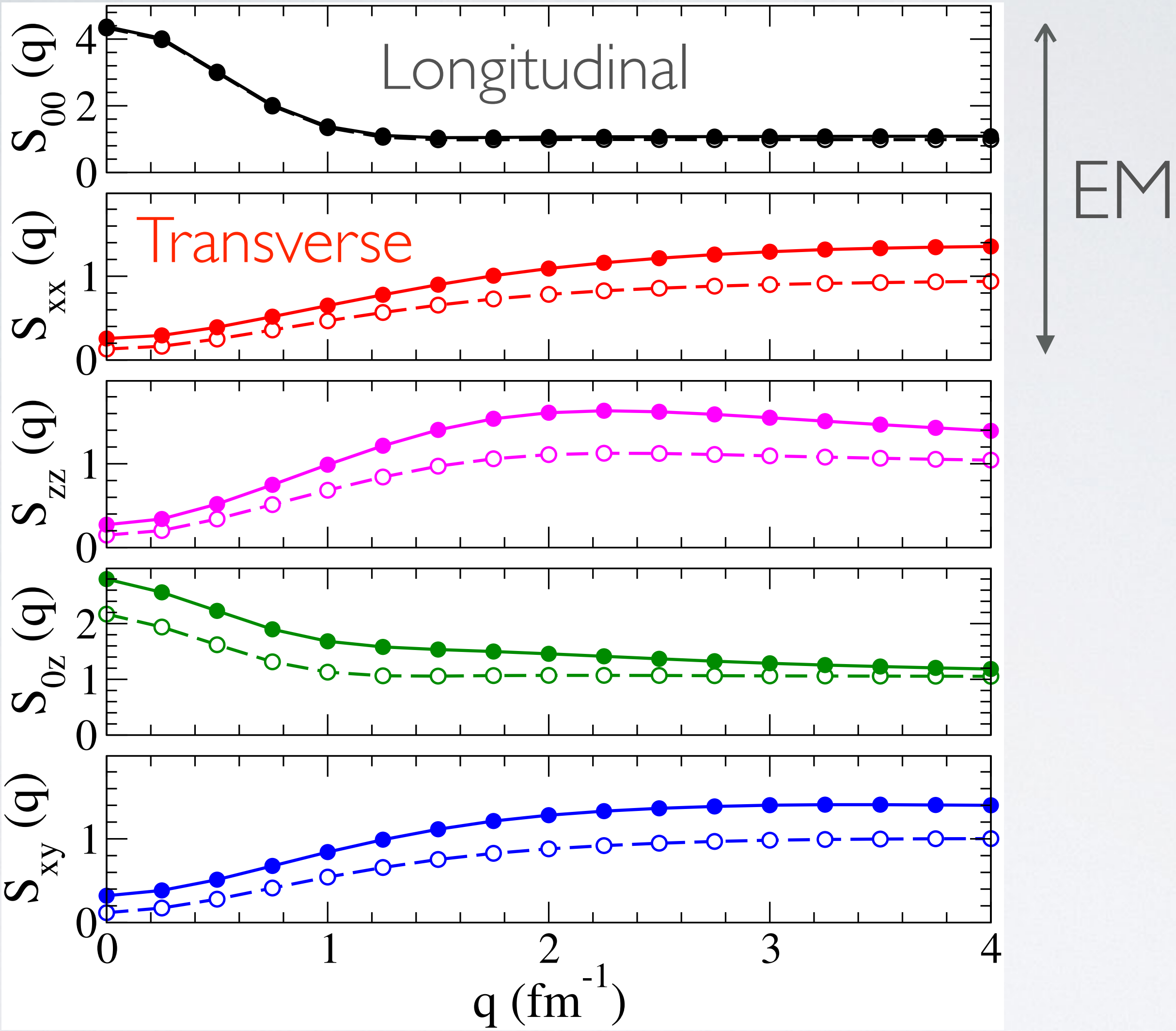
Transverse response



Quasi-elastic electron scattering: 12C

Lovato, et al, PRL 2016

Neutral current: sum rules in ^{12}C

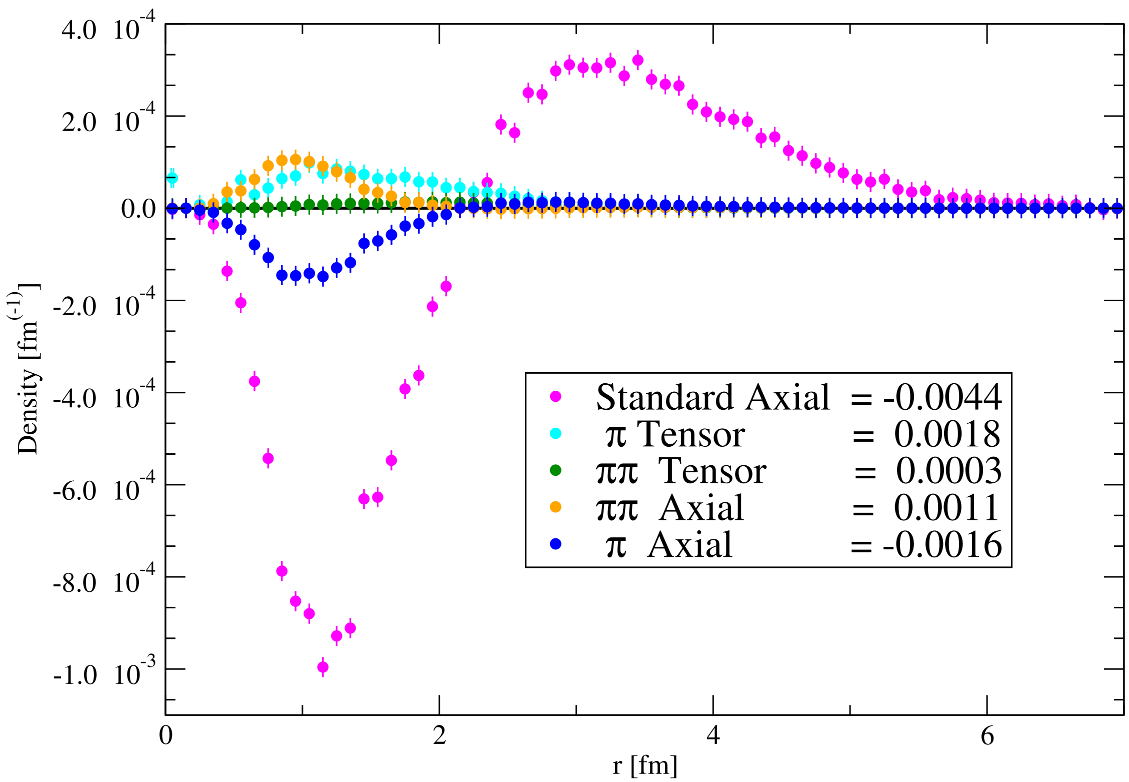


Note enhancement in axial charge; expected from non-relativistic nature of 2N currents (as opposed to V)

Lovato, et. al PRL 2014

Single Nucleon currents (open symbols) versus Full currents (filled symbols)

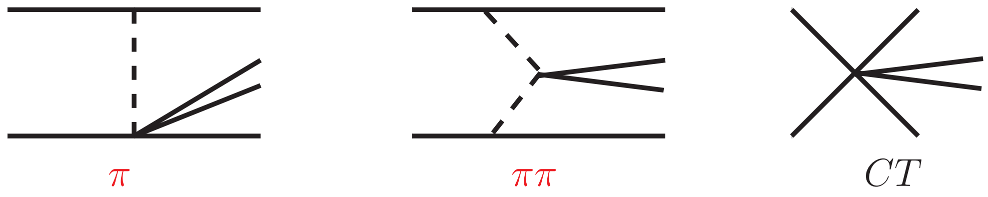
Double Beta Decay:
test cases in light nuclei



Axial $\propto \tau_1^+ \tau_2^+ \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$

Tensor $\propto \tau_1^+ \tau_2^+ S_{12}$

* Preliminary *



- Standard light neutrino plus other possible mechanisms
- note large cancellations in standard axial matrix element

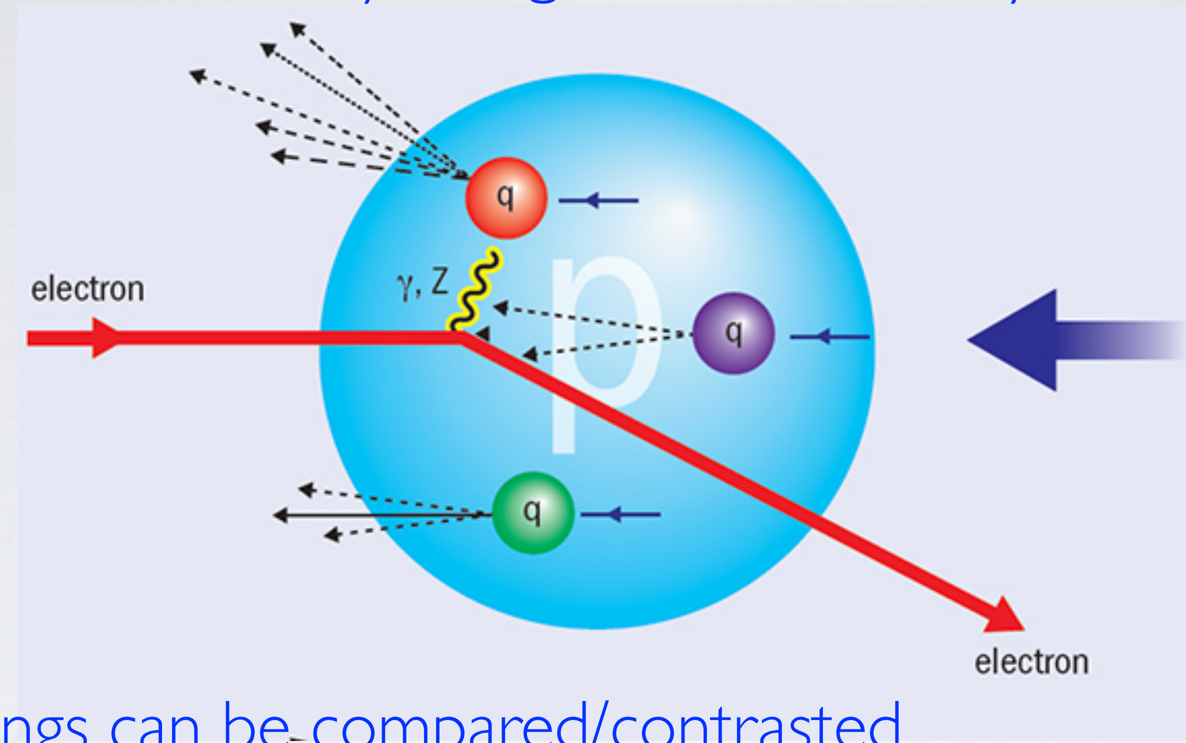
Double Beta Decay: Heavy Nuclei

- compute effective operators in restricted spaces
- extending shell model spaces
- add correlations to DFT and QRPA approaches
- compare to calculations in light nuclei

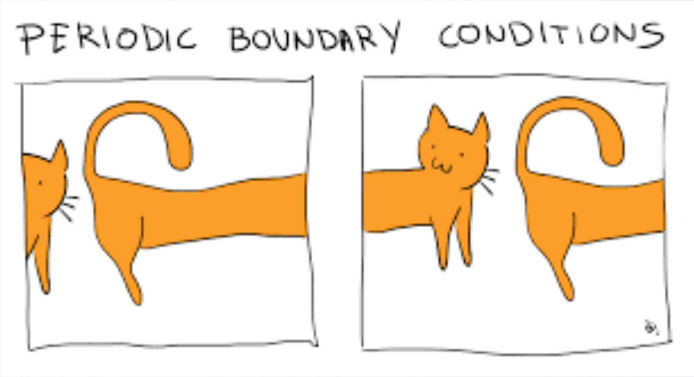
Improved inputs at higher scale from lattice QCD

Lattice QCD / Nuclear Physics interface

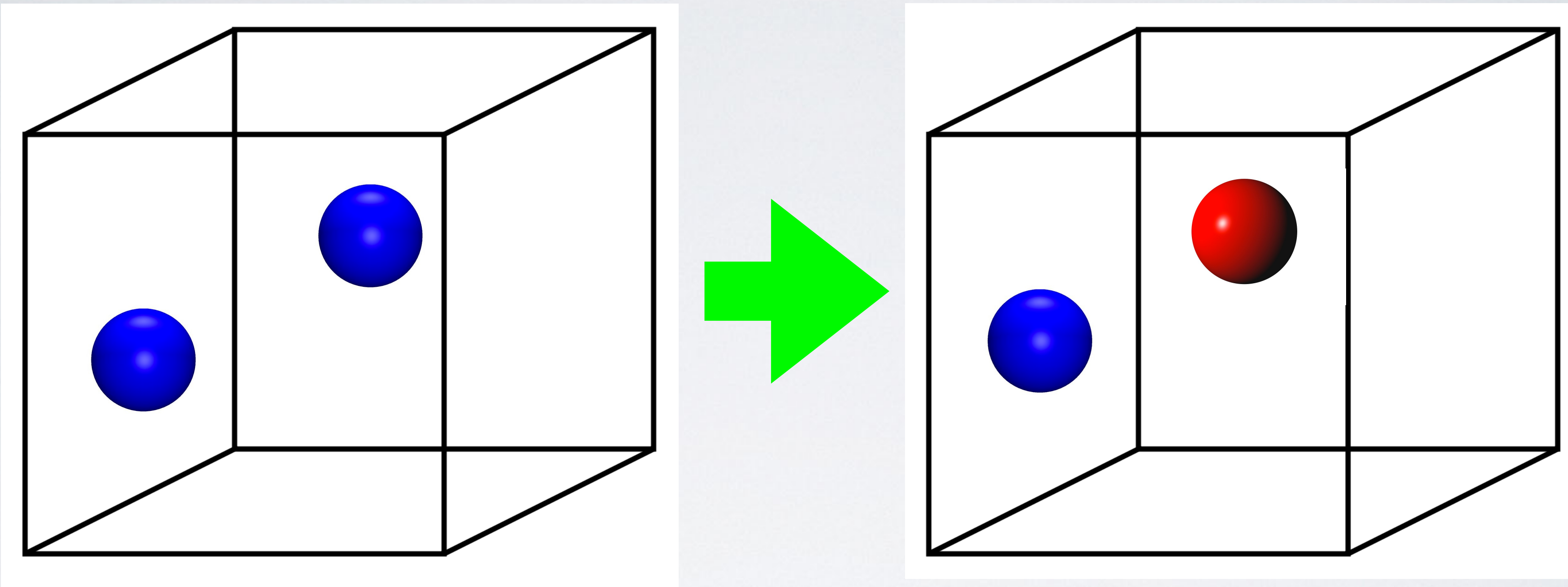
many things well underway



- many things can be compared/contrasted
- strong interactions w/ 2- and 3-nucleons
- electroweak form factors of the nucleon
- inelastic scattering (**π** production, …)



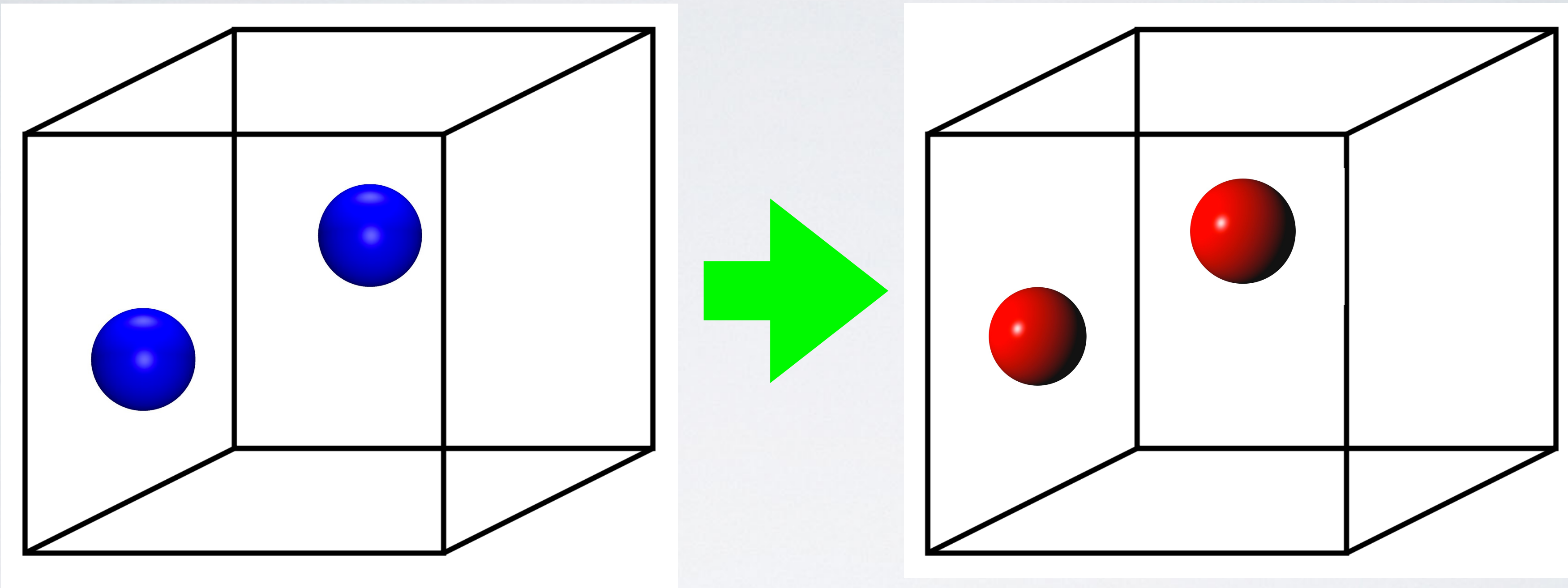
Two Nucleons: beta decay



pion mass dependence may be important:

- binding (momentum) of the system
- D-state in the deuteron (analogous to tritium beta decay)

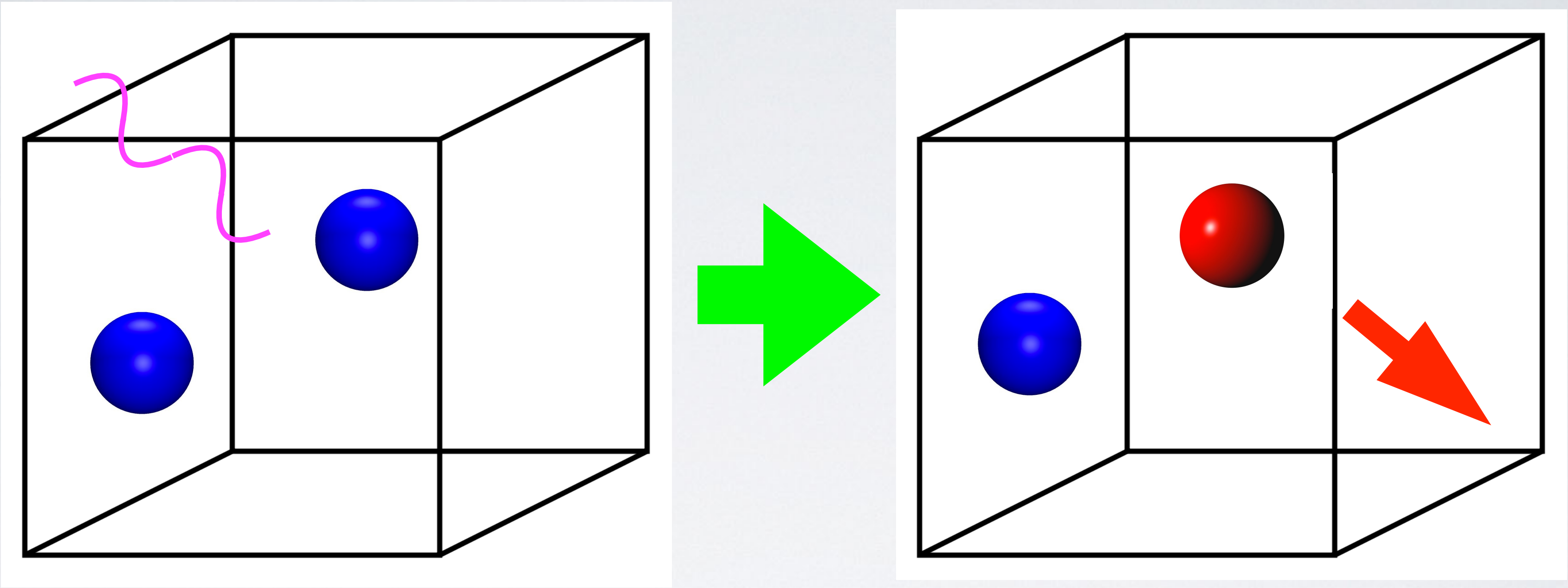
Two Nucleons: double beta decay (2-neutrino)



pion mass dependence nuclear interaction less important

- binding (momentum) of the system
- nn & pp states essentially s-wave

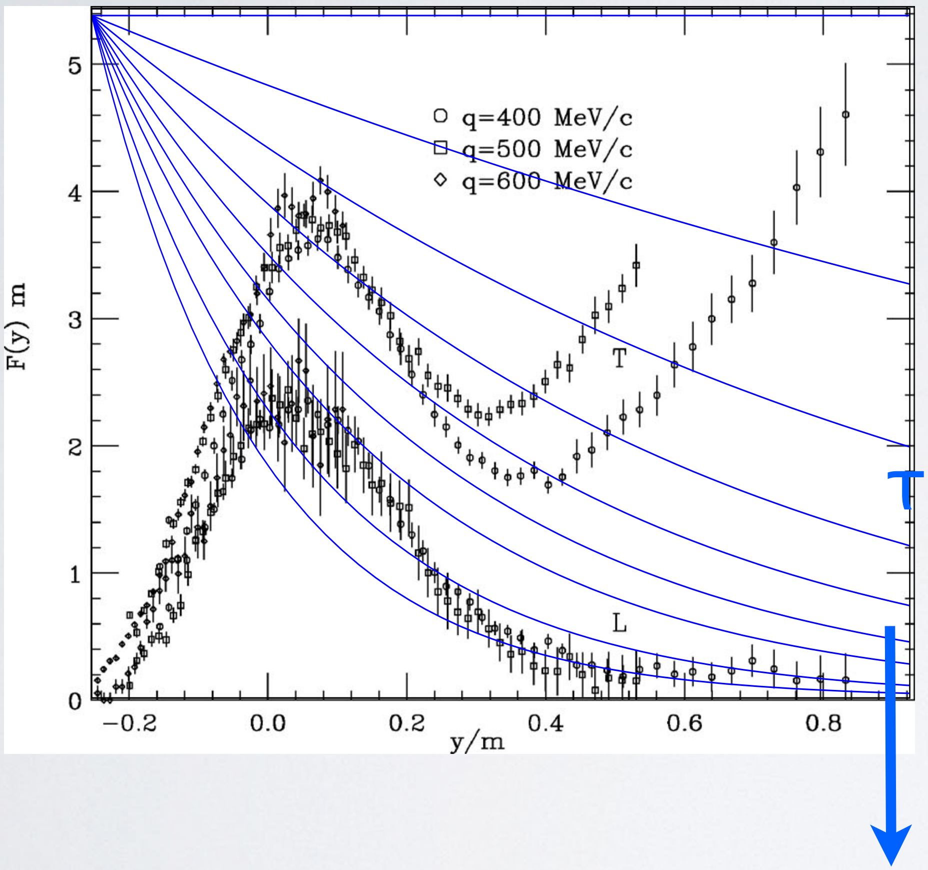
Inject momentum (neutrino scattering)

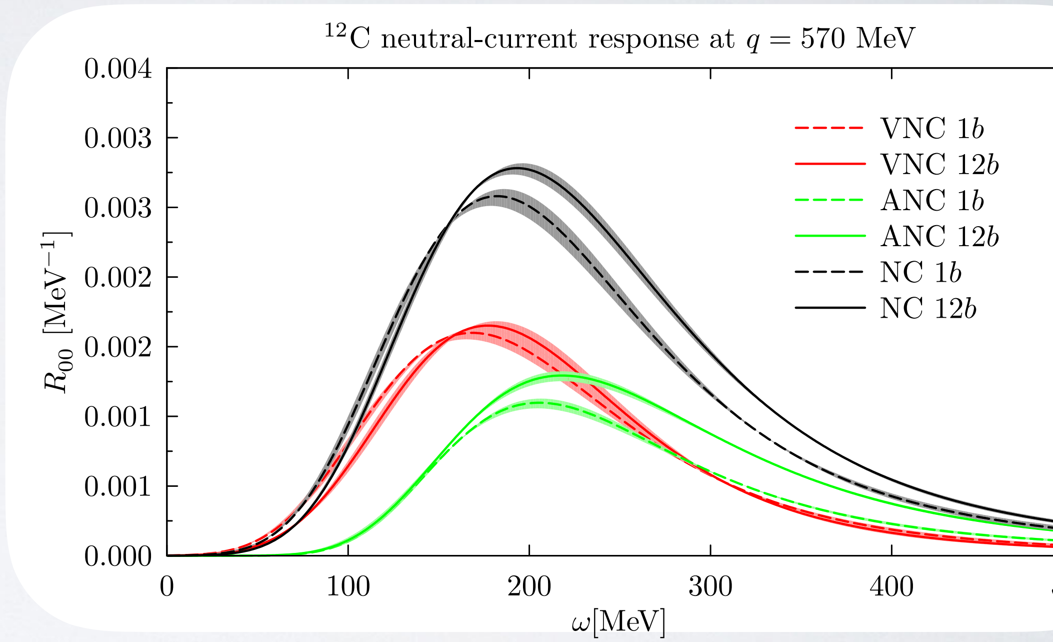


- charge and neutral current processes
- moderate momentum transfers (1 to 2 lattice units)
- exclusive final states (?)
- inclusive final states (?)

LQCD analogue of Euclidean response ?

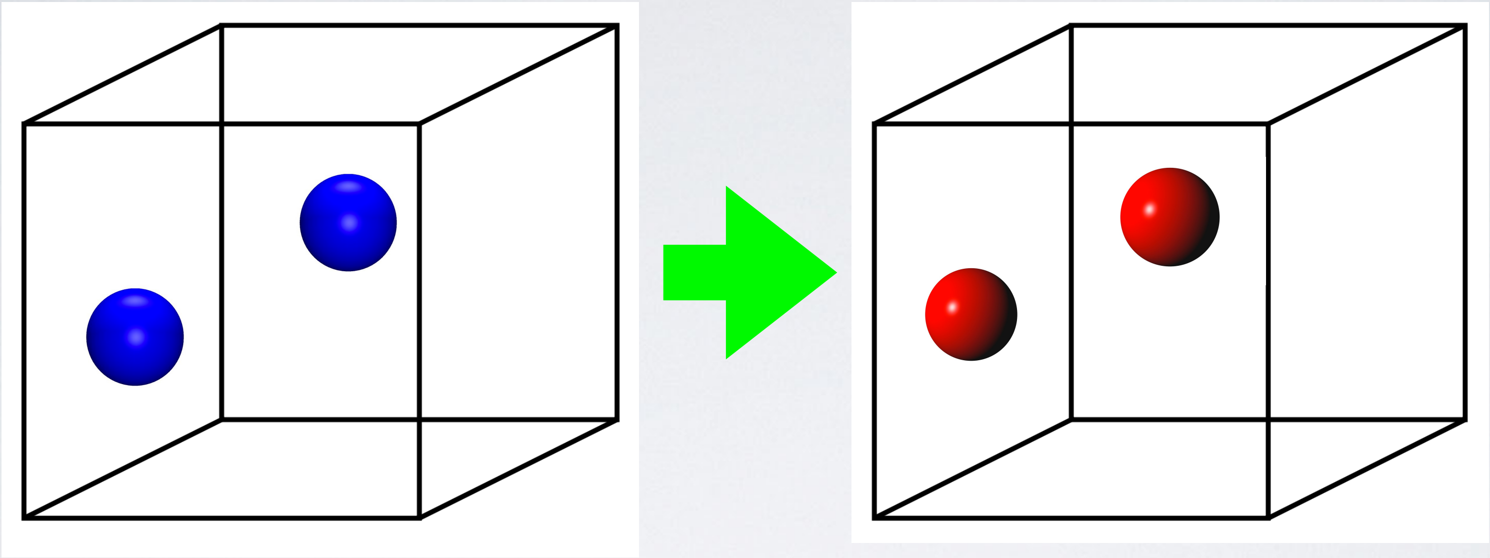
$$\tilde{R}(q,\tau) \;=\; \langle 0|\; \mathbf{j}^{\dagger}\;\; \exp[-(\mathbf{H}-\mathbf{E_0}-\mathbf{q^2}/(\mathbf{2m}))\tau]\;\; \mathbf{j}\;|\mathbf{0}\rangle >$$



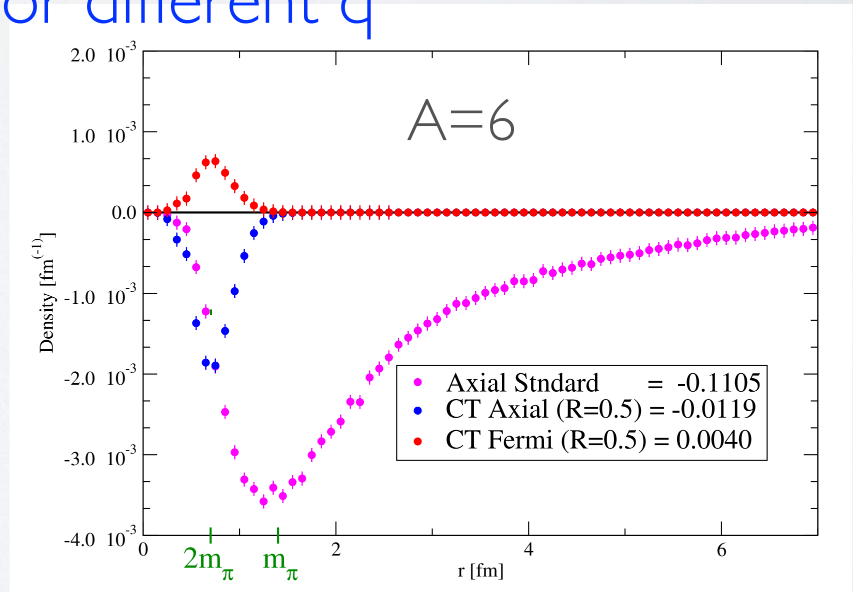


Lovato, et al, preliminary

Double beta decay



- nn to pp different than for real case
- useful to have the matrix element for different q
- want to understand pion - light neutrino matrix elements



Summary and Outlook

- g_A quenching should be quantitatively understood
- g_A enhancement (quasi-elastic) is solvable
- requires consistent treatment of interactions & currents
  and reliable matching to experiment and LQCD

- neutrinoless double beta decay more difficult
- involves multiple length scales that interfere
- quenching likely different in 0 and 2 neutrino cases
- more information needed from theory/lattice
  (2 weak vertices at NN level)
- more information at different q required
- significant progress by refining and combining methods