Neutrinoless double beta decays from lattice QCD

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Neutrinos and β decays

- 1930: Proposed by Pauli to explain conservation of E, $\vec{p}$, L in β decay
  $\Rightarrow$ missing energy is carried by neutrino

- 1942: Ganchang Wang proposed to detect neutrino using β capture

- 1956: Cowan-Reines neutrino experiment detects $\bar{\nu}_e$ [Nobel prize 1995]

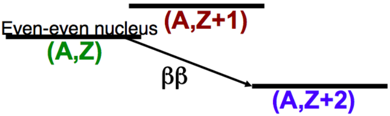
$$\bar{\nu}_e + p \rightarrow n + e^+$$

- 1962: Detection of muon neutrinos [Nobel prize 1988]

- 2000: Detection of tau neutrinos at Fermilab

Early in 1935, Goppert-Mayer propose to detect double beta decay

- Nuclear pairing: In some case even-even nucleus is more stable, e.g. Ge^{76}



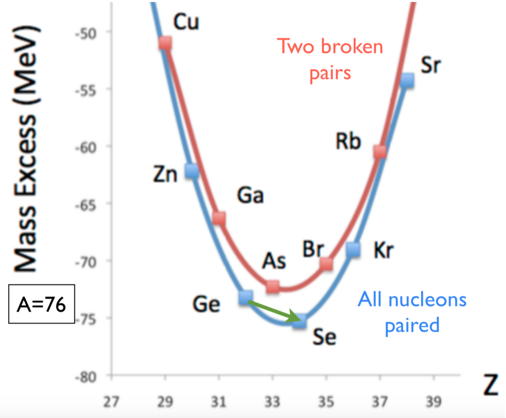
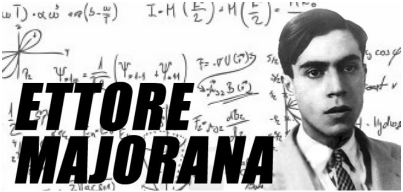


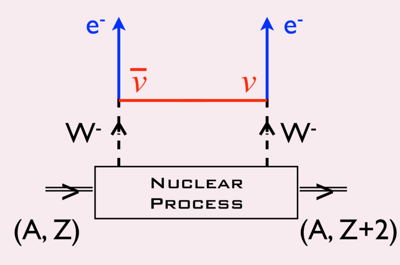
Figure by A. Nicholson

Majorana's proposal in 1937: $\nu = \bar{\nu}$?

$\Leftarrow$ This is allowed by symmetry properties of Dirac's theory

- In single beta decay, one cannot distinguish Dirac or Majorana neutrino
- 1939, Furry propose to search for neutrinoless double beta ($0\nu\beta\beta$) decays





- The process violates the lepton number by two units

Question: do we need the lepton number conservation?

Lepton number conservation

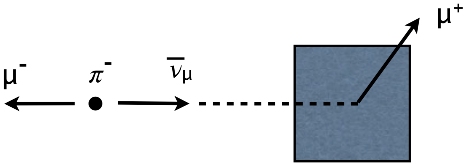
According to phase space factor, $0\nu\beta\beta$ mode is highly favored over $2\nu\beta\beta$

$$T_{1/2}^{2\nu 2\beta} \approx 10^{25} \text{ yr}, \quad T_{1/2}^{0\nu 2\beta} \approx 10^{19} \text{ yr}$$

However

- $2\nu\beta\beta$ has been detected in total of 10 nuclei: $^{48}\mathrm{Ca}$, $^{76}\mathrm{Ge}$, $\cdots$ $^{238}\mathrm{U}$
- No $0\nu\beta\beta$ detected yet

Also, in neutrino capture, $\bar{\nu}$ always produce positive charged lepton

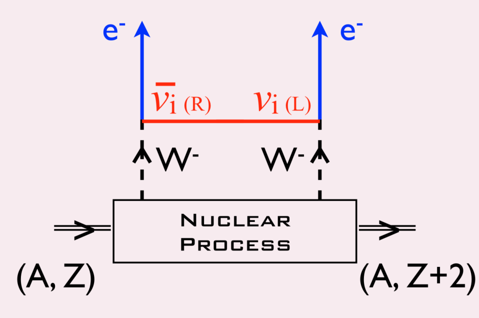


Consequence: Introduce lepton number conservation to explain experiments

Maximal Parity Violation

1956, Lee & Yang discover parity violation in weak decays [Nobel prize 1957]

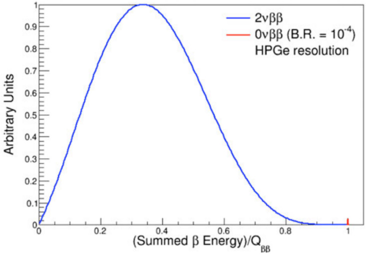
- Neutrino is left-handed, while anti-neutrino is right-handed
- Helicity exactly forbids the second vertex in $0\nu\beta\beta$ already
  - Lepton number conservation is no longer needed



ν oscillation discovered by Kajita (Super-K) and McDonald (SNO) [Nobel prize 2015]

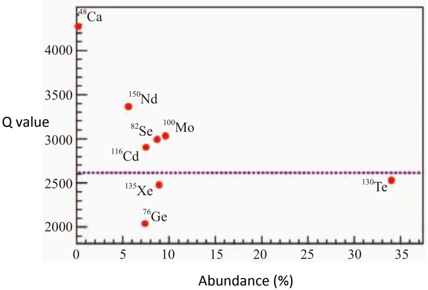
- New possibility for $0\nu\beta\beta$ search $\Rightarrow$ sensitive to neutrino's absolute mass

$0\nu\beta\beta$ vs $2\nu\beta\beta$ decay



$T_{1/2}^{0\nu} > 10^{26}$ yr $\Rightarrow$ Ton of isotopes $\sim 10^{28}$ nuclei

$\Rightarrow$ requires both large decay energy (Q value) and isotope abundance



More than 10 experiments underway

Collaboration	Isotope	Technique	Mass	Status
CAMEO	Cd-116	$CdWO_4$ crystals	1 t	
CANDLES	Ca-48	60 CaF_2 crystals in liq. scint	6 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	100 kg	
COBRA	Cd-116, Te-130	CdZnTe detectors	10 kg	R&D
CUROICINO	Te-130	TeO_2 Bolometer	11 kg	Operating
CUORE	Te-130	TeO_2 Bolometer	206 kg	Construction
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D
EXO200	Xe-136	Xe TPC	200 kg	Construction
EXO	Xe-136	Xe TPC	1-10t	R&D
GEM	Ge-76	Ge diodes in LN	1 t	
GERDA	Ge-76	Seg. and UnSeg. Ge in LAr	35-40 kg 1 t	Construction Future
GSO	Gd-160	Gd_2SiO_5:Ce crystal scint. in liquid scint	2t	
HPXeTPC	Xe-136	High Pressure TPC	1t	R&D
Majorana	Ge-76	Segmented Ge	60 kg 1 t	Proposed Future
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Operating
SuperNEMO	Se-82	Foils with tracking	100 kg	Proposed
MOON	Mo-100	Mo sheets	200 kg 1 t	R&D
SNO+ ββ	Nd-150	0.1% suspended in Scint.	56 kg	R&D
Xe	Xe-136	Xe in liq. Scint.	1.56 t	
XMASS ββ	Xe-136	Liquid Xe	10 kg	Feasibility

- 4 Exp. (Majorana, EXO, CUORE, GERDA) reached $T^{0\nu}_{1/2} > 10^{25}$ year
- 1 Exp. (KamLAND-Zen) exceeded the level of 1×10^{26} year

Jinping underground lab (China) can provide an ideal $0\nu 2\beta$ search

- Depth of the lab is $\sim$2,500 m, cosmic ray rate is 10^{-7}-10^{-8} times less
- PandaX reports the lower limit of $T^{0\nu}_{1/2} > 2.1 \times 10^{23}$ from Chinese experiments [Chin.Phys.C 43 (2019) 11, 113001]

Chinese Physics C

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Searching for neutrino-less double beta decay of ^{136}Xe with PandaX-II liquid xenon detector *

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Chinese Physics C, Volume 43, Number 11

Citation Kaixiang Ni *et al* 2019 *Chinese Phys. C* **43** 113001

Theoretical understanding

Majorana fermion vs Dirac fermion (I)

- Lagrangian density for a classical Dirac field

$$\mathcal{L}_{\mathrm{Dirac}} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$$

- One can construct self-charge-conjugate (Majorana) field N_1 and N_2

$$N_1 = \frac{\psi + \psi^c}{\sqrt{2}}, \quad N_2 = -i\frac{\psi - \psi^c}{\sqrt{2}}$$

with $\psi^c = C\bar{\psi}^T$ the charge-conjugate field of ψ

- Lagrangian density for Dirac field can also be expressed as

$$\mathcal{L}_{\mathrm{Dirac}} = \mathcal{L}_{\mathrm{Majorana}}(N_1) + \mathcal{L}_{\mathrm{Majorana}}(N_2)$$

with

$$\mathcal{L}_{\mathrm{Majorana}}(N_i) = \frac{1}{2}\overline{N_i}(i\gamma^\mu \partial_\mu - m)N_i, \quad i = 1, 2$$

  - Dirac fermion consists of a pair of mass degenerate Majorana fermion
  - Majorana fermion also satisfies Dirac equation

Majorana fermion vs Dirac fermion (II)

- Using Weyl representation of γ, one can write Dirac fermion field ψ as

$$\psi = \begin{pmatrix} \phi \\ \chi \end{pmatrix}, \quad \psi_L = \begin{pmatrix} 0 \\ \chi \end{pmatrix}, \quad \psi_R = \begin{pmatrix} \phi \\ 0 \end{pmatrix}$$

- Realizing that $\tilde{\phi} = i\sigma_2\phi^*$ behaves like a left-handed spinor, one can define

$$\text{Left hand: } \eta = \frac{\chi + \tilde{\phi}}{\sqrt{2}}, \quad \text{Right hand: } \xi = -i\frac{\tilde{\chi} + \phi}{\sqrt{2}}$$

- Majorana fermion field can be written as

$$N_1 = \begin{pmatrix} -\tilde{\eta} \\ \eta \end{pmatrix}, \quad N_2 = \begin{pmatrix} \xi \\ \tilde{\xi} \end{pmatrix}$$

- Under global phase transformation

$$\begin{aligned} \text{Dirac: } & \chi \to e^{i\alpha}\chi, \quad \phi \to e^{i\alpha}\phi \quad && \Rightarrow \quad \text{lepton number conservation} \\ \text{Majorana: } & \eta \to e^{i\alpha}\eta, \quad \tilde{\eta} \to e^{-i\alpha}\tilde{\eta} \quad && \Rightarrow \quad \text{lepton number violation} \end{aligned}$$

  - Electric charge conservation forces charged fermion to be Dirac type
  - Neutrino can be Dirac, Majorana or the mixed type

Light-neutrino exchange in $0\nu\beta\beta$ decay

Minimal extension of SM – exchange of three light Majorana neutrinos

- Effective Lagrangian for β decay

$$\mathcal{L}_{eff} = 2\sqrt{2} G_F V_{ud} (\overline{u}_L \gamma_\mu d_L)(\overline{e}_L \gamma_\mu \nu_{eL})$$

- Effective Hamlitonian for 2β decay

$$\mathcal{H}_{eff}^{2\beta} = \frac{1}{2!} \int d^4x \, \mathcal{L}_{eff}(x) \mathcal{L}_{eff}(0)$$

- Neutrino flavor eigenstate mixes with three mass eigenstates

$$\overline{e}_L \gamma_\mu \nu_{eL} \quad \rightarrow \quad \sum_k \overline{e}_L \gamma_\mu U_{ek} \nu_{kL}$$

  U_{ek} is the mixing matrix element.

- These neutrinos are very light

Long-distance contribution dominated

Light-neutrino exchange in $0\nu\beta\beta$ decay

Assume that $0\nu\beta\beta$ is mediated by exchange of light Majorana neutrinos

$$
\begin{aligned}
& \sum_k \overline{e}_L(x)\gamma_\mu U_{ek}\underbrace{\nu_{kL}(x)\,\overline{e}_L(0)\gamma_\nu U_{ek}\nu_{kL}}(0) \\
= \quad & -\sum_k \overline{e}_L(x)\gamma_\mu U_{ek}\underbrace{\nu_{kL}(x)\,\overline{\nu^c_k}_L}(0)\gamma_\nu U_{ek} e^c_L(0) \\
= \quad & -\sum_k \overline{e}_L(x)\gamma_\mu U_{ek} P_L \left(\int \frac{d^4q}{(2\pi)^4} \frac{-i\not{q} + m_k}{q^2 + m_k^2} e^{iqx} \right) P_L \gamma_\nu U_{ek} e^c_L(0) \\
\approx \quad & -m_{\beta\beta} \int \frac{d^4q}{(2\pi)^4} \frac{e^{iqx}}{q^2} \overline{e}_L(x)\gamma_\mu\gamma_\nu e^c_L(0)
\end{aligned}
$$

In the last step, $\not{q}$ vanishes and m_k enters into the effective mass $m_{\beta\beta}$

$$
m_{\beta\beta} = \sum_k m_k U_{ek}^2
$$

$0\nu2\beta$ decay amplitude is proportional to the absolute neutrino mass

Short summary

$0\nu\beta\beta$ decay

- The easiest way to determine whehter ν is a Majorana fermion
- Give the information on the absolute mass scale of ν
- Provide the evidence of lepton number violation

Introduction to lattice QCD

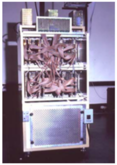
∼50 years for lattice QCD

- Invented by Kenneth G. Wilson in 1973
- 1^{st} numerical implementation by M. Creutz in 1979
- QCD computers 1983 – 2011 [credit by N. Christ]

Matrix Multiplier

1Mflops 1983

16-Node



256 Mflops 1985

64-Node

1.0 Gflops 1987

256-Node

16 Gflops 1989

QCDSP

600 Gflops 1998

QCDOC

20 Tflops 2005

LLNL Sequoia, IBM

20 Pflops 2011

QCD computers start to enter in the Eflops generation, 10^{18} floating point operation per second

Entering Eflops era

#1 Fugaku (Japan)
0.54 Eflops

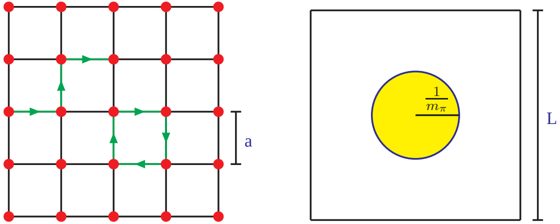
#4 Sunway TaihuLight (China)
0.13 Eflops

#5 Tianhe-2A (China)
0.05 Eflops

Three proptotypes of Eflops HPCs built in China ⇒ realistic Eflops HPCs

Lattice discretization

- quark fields live on the lattice sites, $\psi(x)$, $x_\mu = n_\mu a$
- gluons represented as links between lattice sites, $U_\mu(x) = e^{iagA_\mu(x)}$



With finite a and L, quarks and gluons can be simulated on supercomputer

Euclidean path integral:

- Minkowski time replaced by $x_0 \to -it \quad \Rightarrow \quad e^{-iHx_0} \to e^{-Ht} = e^{-S[\psi,\bar{\psi},A]}$
- Same Hamiltonian H for Minkowski space and Euclidean space

$$\langle O \rangle \sim \int [d\psi][d\bar{\psi}][dA] O \, e^{-S[\psi,\bar{\psi},A]}$$

Configuration simulation

Integrate out the quark fields using Grassmann Algebra

$$\langle O \rangle \sim \int [dU] O[U] \det(\not{D} + m) e^{-S_g[U]}$$

Importance sampling: generate gauge configurations with probability distribution

$$p[U] \propto \det(\not{D} + m) e^{-S_g[U]}$$

this can be achieved by Monte Carlo simulation

Integration is approximated by average over gauge configurations

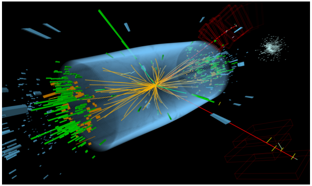
$$\int [dU] \det(\not{D} + m) e^{-S_g[U]} \quad \rightarrow \quad \frac{1}{N} \sum_{\{U\}}$$

statistical error is reduced by $1/\sqrt{N}$

Experiment vs Lattice QCD

HEP Experiment

BEPC collider(Energy、Luminosity)

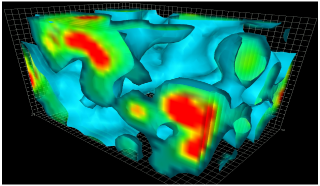


Collision， Events

BES III Detector, measurement

LQCD simulation

Super Computer(Performance、Memory)



Simulation, QCD vacuum

Lattice QCD calculation

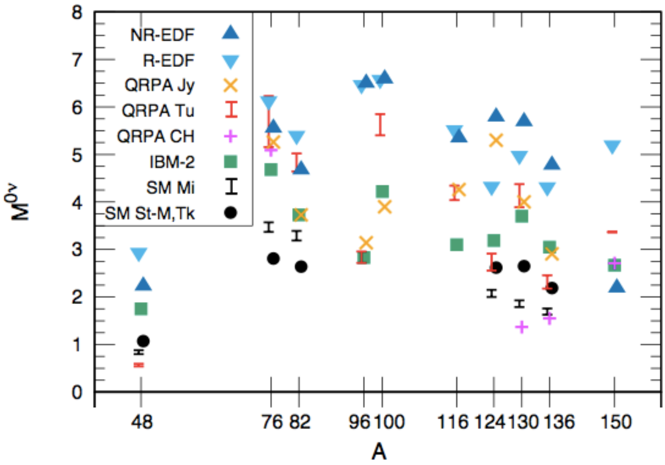
How can lattice QCD contribute?

Double β decay: generic difficulties

At present, lattice QCD mainly targets on light nuclei

- For nucleus A: $\frac{\text{signal}}{\text{noise}} \sim \exp\left[-A(M_N - 3/2m_\pi)t\right] \quad \Rightarrow \quad$ a sign problem!

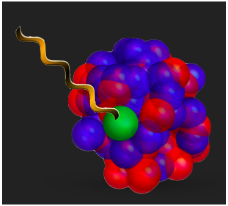
For nuclear matrix element, various models yield O(100%) discrepancies



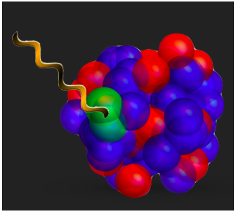
Single β decay of nuclei

Coupling of currents to nuclei in nuclear EFT [Detmold, talk at Lat18]

- One body coupling dominates



- Two nucleon contributions are subleading but non-negligible



A promising way to provide few-body inputs to ab initio many-body calculations

ECT* workshop on $0\nu 2\beta$

Progress and Challenges in Neutrinoless Double Beta Decay

ECT* workshop subscription

ECT*, Strada delle Tabarelle, 286, Villazzano, 38123 Trento, Italy

Monday, 15 July 2019 at 08:00 - Friday, 19 July 2019 at 18:00 (CEST)

organized by Menendez, Mereghetti, Nicholson, Pastore, Walker-loud

Summarize on recent advances in

- Lattice QCD
  $\Rightarrow$ Calculate $\langle ppee|H_W(x)H_W(0)|nn\rangle$ from first-principle theory, QCD
- Chiral effective field theory
  $\Rightarrow$ Match EFT with lattice amplitude to determine the two body operator
- Many-body nuclear theory
  $\Rightarrow$ Use two body operator as input for a many-body nuclear matrix element

Target on

- a seamless connection between the theory at quark and nuclear level
- reliable calculations of the nuclear matrix elements, with robust uncertainty

Double β decay of nuclei

Begin with the effective Lagrangian $\mathcal{L}_{\rm eff}$ for the single β decay

$$\mathcal{L}_{\rm eff} = 2\sqrt{2} G_F V_{ud} (\bar{u}_L \gamma_\mu d_L)(\bar{e}_L \gamma_\mu \nu_{eL})$$

Contributions are identified into three regions in EFT

- Hard region: $\Lambda \gg 1$ GeV

$$\int d^4x \, e^{i\Lambda x} \mathcal{L}_{\rm eff}(x) \mathcal{L}_{\rm eff}(0) \sim 8 G_F^2 V_{ud}^2 \frac{m_{\beta\beta}}{\Lambda^2} (\bar{u}_L \gamma_\mu d_L)(\bar{u}_L \gamma_\mu d_L) \bar{e}_L e_L^c.$$

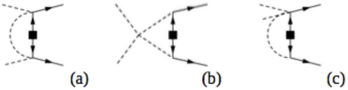
  In lattice QCD, a hard cutoff is introduced by $1/a \Rightarrow O(a^2)$ effects

- Soft region: $O(100$ MeV$)$ - $O(1$ GeV$)$
  - Few-body decay dominates
  - Nuclear potential mediated by pions: $\pi\pi \to ee$, $\pi n \to pee$, $nn \to ppee$, $\cdots$

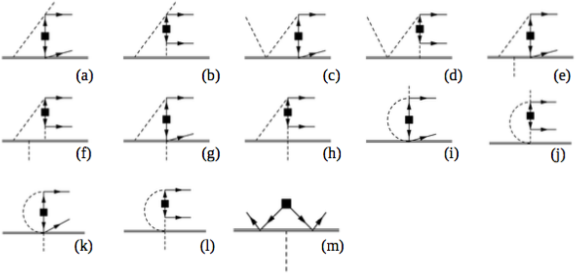
- Ultrasoft or radiative region: $\Lambda \ll 100$ MeV
  - Neutrinos feel the complete nucleus instead of just the nucleons

Loop diagrams in EFT

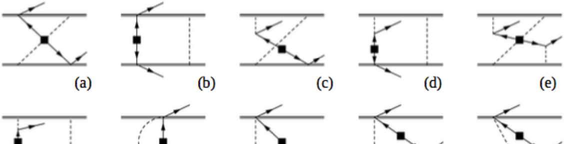
- $\pi\pi \to ee$



- $\pi n \to pee$



- $nn \to ppee$



Exploratory lattice QCD studies

Recent review - Lattice QCD Inputs for Nuclear Double Beta Decay
[Cirigliano, Detmold, Nicholson, Shanahan, 2003.08493]

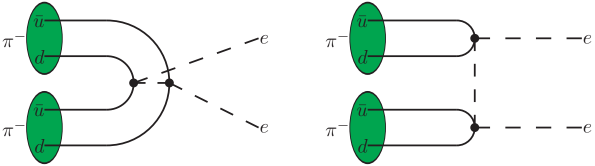
- $2\nu2\beta$ decay: $nn \to ppee\nu\nu$ @ $m_\pi = 800$ MeV
  [NPLQCD, PRD96 (2017) 054505, PRL119 (2017) 062003]

- $0\nu2\beta$ decays in the pion sector
  - SD contributions in $\langle\pi^+|O_i|\pi^-\rangle$, O_i the local four-quark operators
    [A. Nicholson et al., PRL121 (2018) 172501]
  - LD contributions in $\pi^-\pi^- \to ee$
    [XF, L. Jin, X. Tuo, S. Xia, PRL122 (2019) 022001]
  - LD contributions in $\pi^- \to \pi^+ ee$
    [X. Tuo, XF, L. Jin, PRD100 (2019) 094511]
    [W. Detmold, D. Murphy, arXiv:2004.07404]

Lattice QCD calculation on $0\nu 2\beta$ decays: $\pi^-\pi^- \to ee$ and $\pi^- \to \pi^+ ee$

$\pi^-\pi^- \to ee$: XF, L. Jin, X. Tuo, S. Xia, PRL122 (2019) 022001
$\pi^- \to \pi^+ ee$: XF, L. Jin, X. Tuo, PRD100 (2019) 094511

$\pi^-\pi^- \to ee$: standard procedure



Construct the correlation function

$$C(t_x, t_y, t_{\pi\pi}) = \frac{1}{2!}\langle e_1 e_2 | \mathcal{L}_{eff}(t_x)\, \mathcal{L}_{eff}(t_y)\, \phi_{\pi\pi}(t_{\pi\pi})|0\rangle$$

Massless neutrino propagator is implemented stochastically

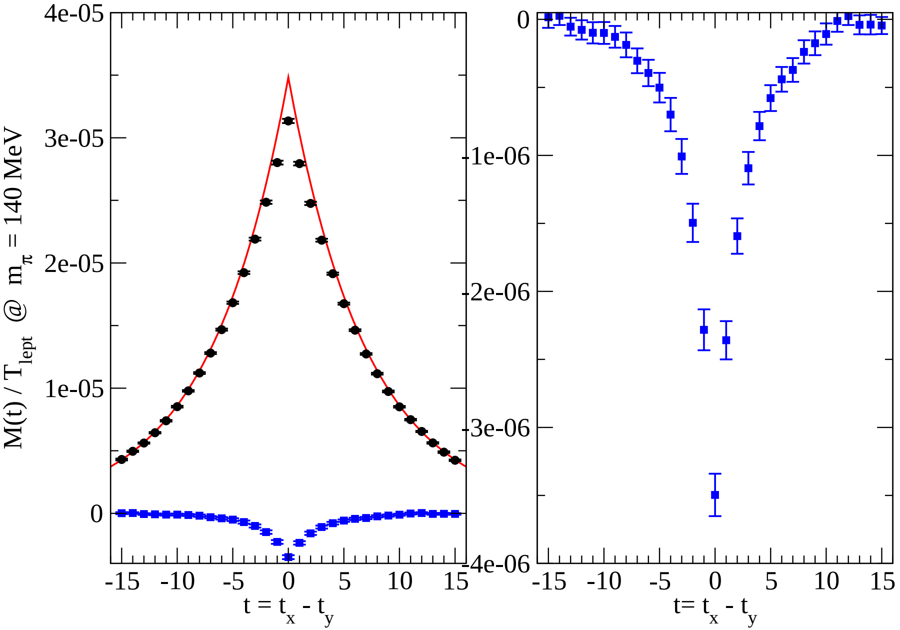
Define the amplitude $\mathcal{M}(t)$ with $t = t_x - t_y$:

$$\mathcal{M}(t) = C(t_x, t_y, t_{\pi\pi}) / \left(V \frac{N_{\pi\pi}}{2E_{\pi\pi}} e^{E_{\pi\pi} t_{\pi\pi}} \right)$$

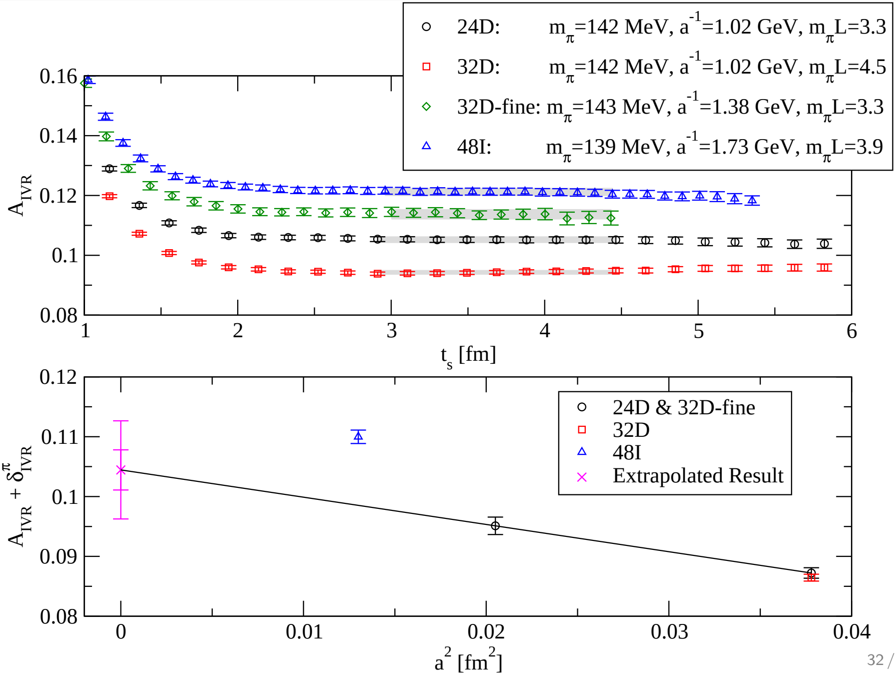
At large $|t|$, $\mathcal{M}(t)$ is saturated by ground intermediate state - $e\bar{\nu}\pi$

$$\mathcal{M}(t) \xrightarrow{|t|\gg 0} -T_{\rm lept} \frac{1}{V} \frac{2\langle 0|J_{\mu L}|\pi\rangle_{\rm V} \langle \pi|J_{\mu L}|\pi\pi\rangle_{\rm V}}{(2m_\pi)(2E_\nu)} e^{-m_\pi |t|}$$

$\pi\pi \to ee$ decay amplitude @ $m_\pi = 140$ MeV



$\pi^- \to \pi^+ ee$: infinite volume reconstruction



Summary of $\pi^-\pi^- \to ee$ and $\pi^- \to \pi^+ ee$

Chiral perturbation theory for $\pi^-\pi^- \to ee$

[Cirigliano, Dekens, Mereghetti, Walker-Loud, PRC97 (2018) 065501]

$$\frac{\mathcal{A}(\pi^-\pi^- \to ee)}{2F_\pi^2\, T_{\mathrm{lept}}} = 1 - \frac{m_\pi^2}{(4\pi F_\pi)^2}\left(3\log\frac{\mu^2}{m_\pi^2} + \frac{7}{2} + \frac{\pi^2}{4} + \frac{5}{6}g_\nu^{\pi\pi}(\mu)\right)$$

Lattice calculation yields (statistical error only)

[XF, L. Jin, X. Tuo, S. Xia, PRL122 (2019) 022001]

$$\frac{\mathcal{A}(\pi\pi \to ee)}{2F_\pi^2\, T_{\mathrm{lept}}} = 0.910(3) \quad \Rightarrow \quad g_\nu^{\pi\pi}(m_\rho) = -12.0(3)$$

Chiral perturbation theory for $\pi^- \to \pi^+ ee$

$$\frac{\mathcal{A}(\pi^- \to \pi^+ ee)}{2F_\pi^2\, T_{\mathrm{lept}}} = 1 + \frac{m_\pi^2}{(4\pi F_\pi)^2}\left(3\log\frac{\mu^2}{m_\pi^2} + 6 + \frac{5}{6}g_\nu^{\pi\pi}(\mu)\right)$$

Lattice calculation yields (statistical + systematical errors)

[X. Tuo, XF, L. Jin, PRD100 (2019) 094511]

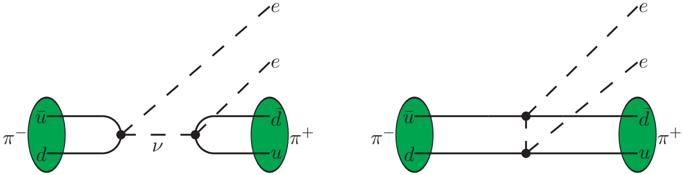
$$\frac{\mathcal{A}(\pi^- \to \pi^+ ee)}{2F_\pi^2\, T_{\mathrm{lept}}} = 1.105(3)(7) \quad \Rightarrow \quad g_\nu^{\pi\pi}(m_\rho) = -10.9(3)(7)$$

Also $g_\nu^{\pi\pi}(m_\rho) = -10.8(1)(5)$ [W. Detmold, D. Murphy, arXiv:2004.07404]

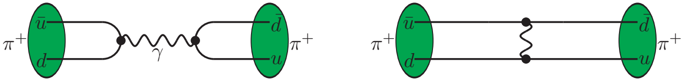
Side product: π^+-π^0 mass splitting

Similarity between $\pi^- \to \pi^+ ee$ and π^+-π^0 mass splitting

$\pi^- \to \pi^+ ee$:

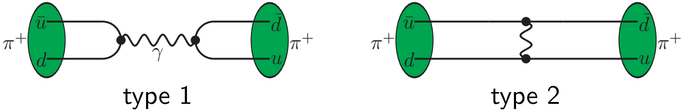


$m_{\pi^+} - m_{\pi^0}$:



Pion mass splitting

$m_{\pi^+} - m_{\pi^0}$:



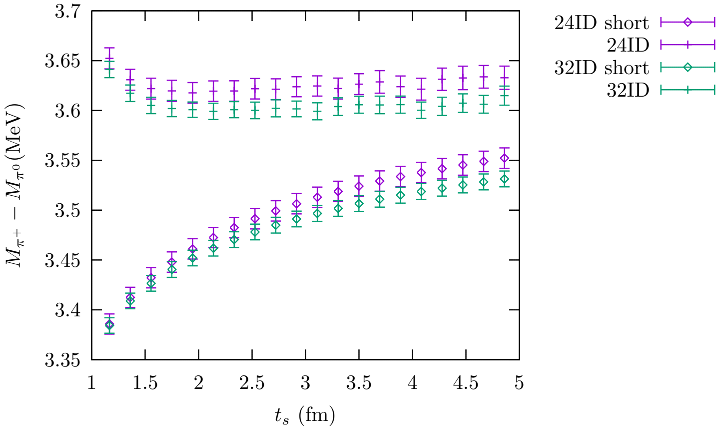
Isospin breaking effects: EM (α_e) + strong ($\frac{m_u - m_d}{\Lambda_{\mathrm{QCD}}}$) contributions

- Strong IB breaking appears at $O\left(\left(\frac{m_u - m_d}{\Lambda_{\mathrm{QCD}}}\right)^2\right)$ $\Rightarrow$ dominated by EM effect
- Previous calculation by [RM123, 2013]

$$M^2_{\pi^+} - M^2_{\pi^0} = 1.44(13)_{\mathrm{stat}}(16)_{\mathrm{chiral}} \times 10^3 \ \mathrm{MeV}^2$$

including type 2 diagram only

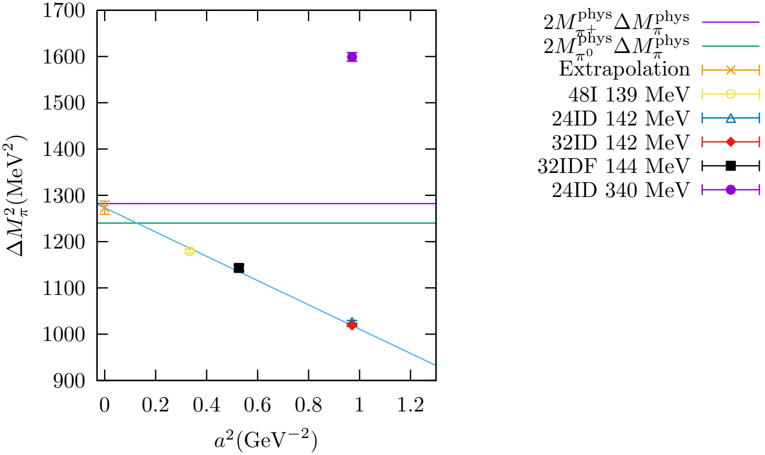
Using infinite-volume reconstruction



- 24ID: 142 MeV, a^{-1}=1.015 GeV, L=4.7 fm, $N_{\mathrm{conf}} = 91$
- 32ID: 142 MeV, a^{-1}=1.015 GeV, L=6.2 fm, $N_{\mathrm{conf}} = 56$
- ground state saturation at $t_s \gtrsim 1.5$ fm
- stat. error $\lesssim 0.3\%$, including both type 1 and type 2 diagrams
- residual FV effects $\Rightarrow$ $L = 4.7$ fm not large enough for phyiscal m_π

Pion mass splitting

$$\Delta M_\pi^2(a, M_\pi) = \Delta M_\pi^2(0, M_\pi^{\text{phys}}) + c_1 a^2 + c_2 \left(M_\pi^2 - (M_{\pi^+}^{\text{phys}})^2 \right)$$

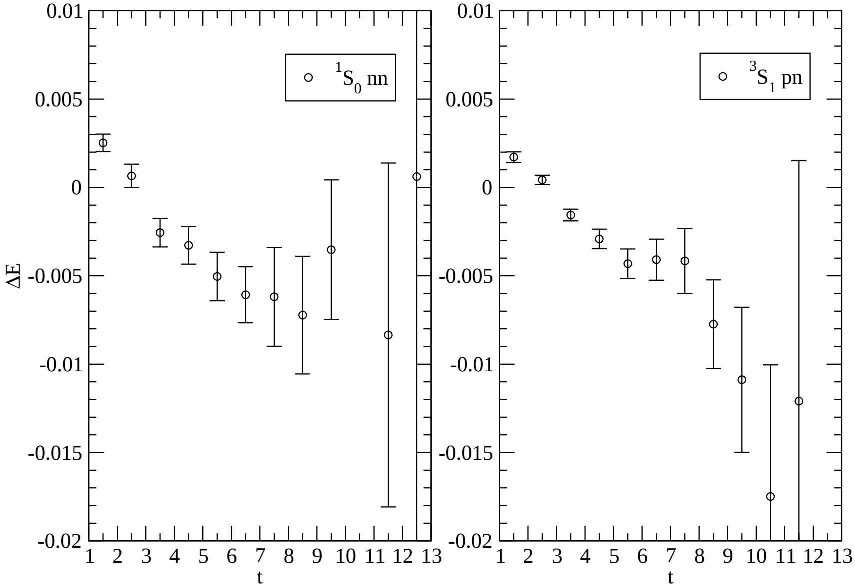


$$\Delta M_\pi^2(0, M_{\pi^+}^{\text{phys}}) = 1.275(15) \times 10^3 \text{ MeV}^2$$

10 times more accurate than previous

Move to dibaryon

Di-neutron vs deuteron



Relevant observables

2 point correlation function

- Bounding energy

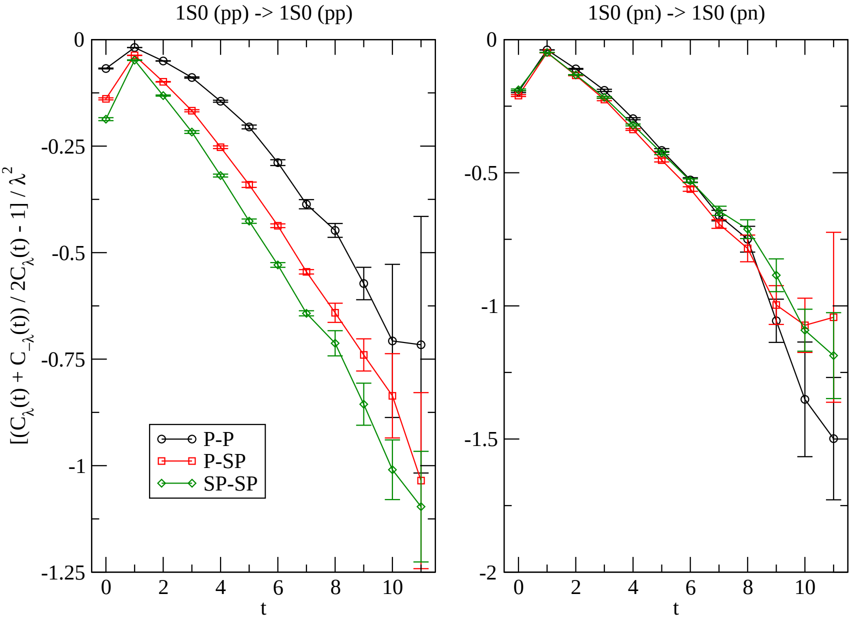
3 point correlation function

- g_A quenching effects
- proton-proton fusion $pp \to de^+\nu_e$

4 point correlation function

- $2\nu2\beta$ decay: $nn \to ppee\bar{\nu}\bar{\nu}$
- $0\nu2\beta$ decay: $nn \to ppee$

4 point correlation function for $0\nu2\beta$ decay



Outlook

- $0\nu\beta\beta$ is of fundamental interests $\Rightarrow$ Experimental search worldwide
- The interpretation of $0\nu\beta\beta$ experiments relies on
  - a seamless connection between the theory at quark and nuclear level
  - reliable calculations of the nuclear matrix elements, with robust uncertainty estimation
- Appealing to connect lattice QCD $\Rightarrow$ chiral EFT $\Rightarrow$ many-body nuclear theory
- We calculate decay amplitudes and LECs for $\pi^-\pi^- \to ee$ and $\pi^- \to \pi^+ ee$ decay channel $\Rightarrow$ move on to $nn \to ppee$