Precision test of Standard Model and search for New Physics using lattice QCD

Xu Feng (冯旭)

北京大學
PEKING UNIVERSITY

Frontier of QCD: Opportunities and Challenges @ PKU，2019/11/10

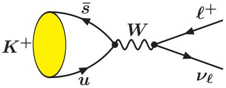
云山苍苍，江水泱泱，先生之风，山高水长

恭祝赵老师八十华诞

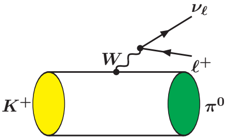
桃李天下，松柏常青

Role of lattice QCD in flavor physics

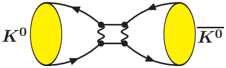
Lattice QCD is powerful for observables such as



$K_{\ell 2} \to f_K$



$K_{\ell 3} \to f_+(0)$



K^0-$\overline{K^0}$ mixing $\to B_K$

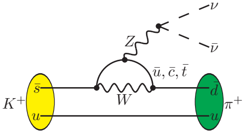
Flavor Lattice Averaging Group (FLAG) average 2019

	N_f	FLAG average	Frac. Err.
f_K/f_π	$2+1+1$	1.1932(19)	0.16%
$f_+(0)$	$2+1+1$	0.9706(27)	0.28%
f_{D_s}/f_D	$2+1+1$	1.1783(16)	0.13%
$\hat{B}_K$	$2+1$	0.7625(97)	1.27%

lattice QCD calculations play important role in precision flavor physics

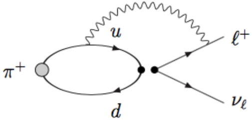
Search for New Physics in rare processes / high-intensity frontiers

2^{nd} order electroweak interaction



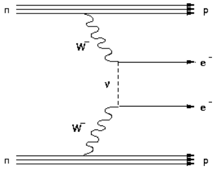
$\mathrm{Br}[K^+ \to \pi^+ \nu\bar{\nu}] = 1.73^{+1.15}_{-1.05} \times 10^{-10}$

Electromagnetic correction



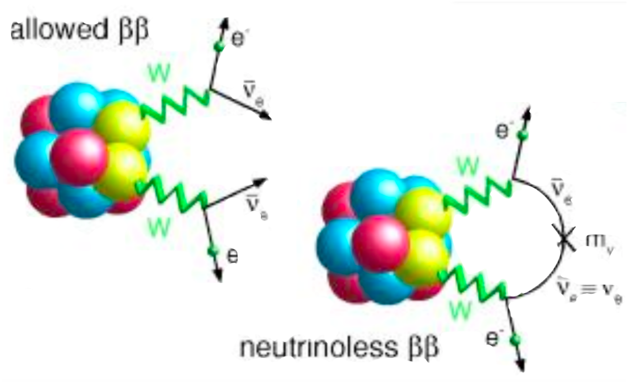
$f_K/f_\pi = 1.1932(19) \Rightarrow 0.16\%$ uncertainty

Neutrinoless double beta decay



$T^{0\nu}_{1/2} > 10^{25}$ year

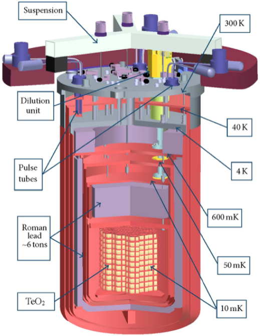
$0\nu 2\beta$ decays

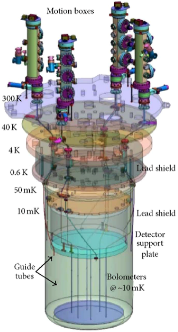


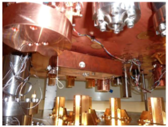
Inspired by a talk given by Prof. HuanZhong Huang

Majorana Neutrinos
&
Recent CUORE Result on Neutrinoless Double Beta Decay

Huan Zhong Huang (黄焕中)

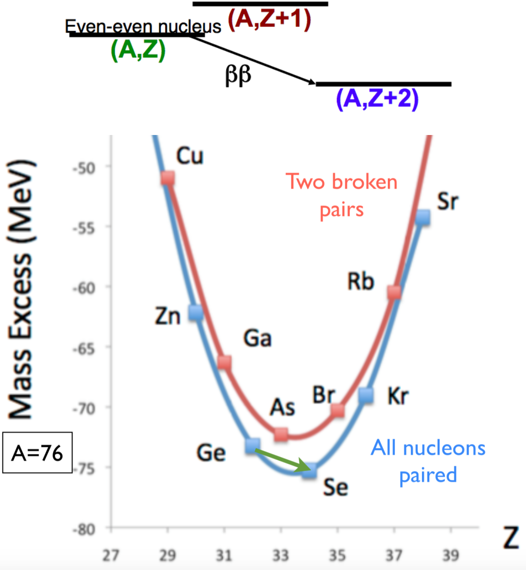






Early in 1935, Goppert-Mayer propose to detect double beta decay

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

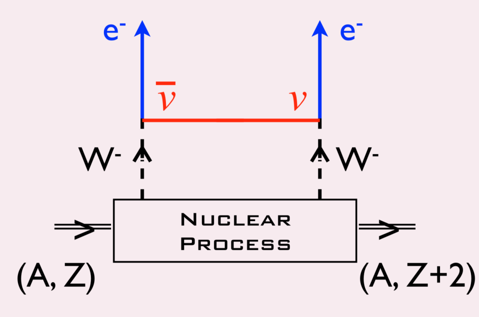


Majorana neutrinos

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?

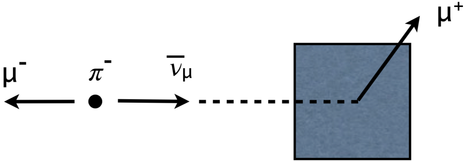
According to phase space factor, $0\nu\beta\beta$ mode is highly favored over $2\nu\beta\beta$

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

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

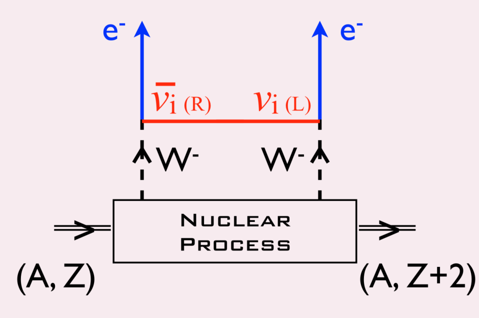


Consequence: Introduce lepton number conservation to explain experiments

Maximal Parity Violation

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

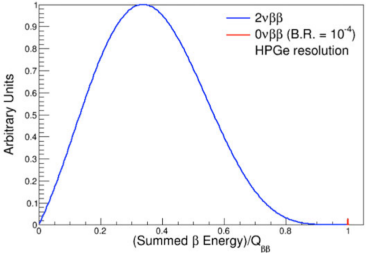
- Neutrino is left-handed, while anti-neutrino is right-handed
- Helicity exactly forbids the second vertex in $0\nu\beta\beta$ already
  - Lepton number conservation is no longer needed



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

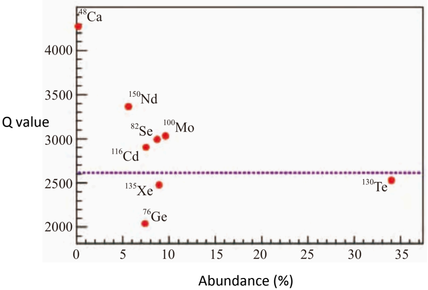
- New possibility for $0\nu\beta\beta$ search $\Rightarrow$ sensitive to neutrino's absolute mass

$0\nu\beta\beta$ 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



Experiments underway

$0\nu\beta\beta$ 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

More than 10 experiments underway

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	35-40 kg	Construction

- 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

PandaX reports the lower limit of $T^{0\nu}_{1/2} > 2.1 \times 10^{23}$ from Chinese experiments

PandaX 实验组发表首个寻找马约拉纳中微子结果

上海交通大学物理与天文学院 1周前

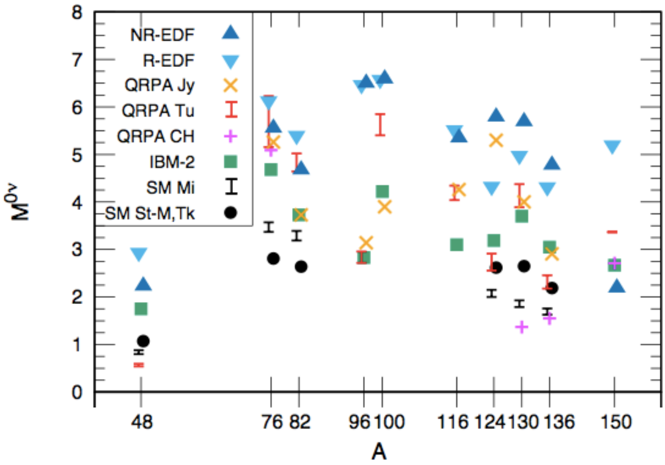
上海交通大学牵头的PandaX合作组近期在“中国物理C”杂志（IF=5.86）以“编辑推荐”的形式发表了首个利用液氙探测器寻找马约拉纳中微子的实验结果。他们的实验表明，核同位素136Xe通过马约拉纳中微子而产生的衰变寿命大于2.1x1023年， 即两千一百万亿亿年，比宇宙的年龄长了约15万亿倍。这是在中国本土物理实验中探测到最长的核素衰变寿命下限。该结果也能解释为马约拉纳电子中微子有效质量的上限，mee < 1.4~3.7eV/c2(电子伏特)。

Double β decay: generic difficulties

At present, lattice QCD mainly targets on light nuclei

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

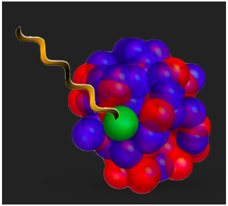
For nuclear matrix element, various models yield O(100%) discrepancies



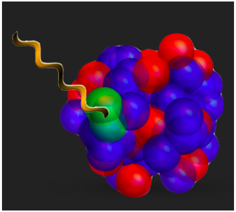
Single β decay of nuclei

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 $0\nu2\beta$

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)

Summarize on recent advances in

- Lattice QCD
- Chiral effective field theory
- Many-body nuclear theory

Target on

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

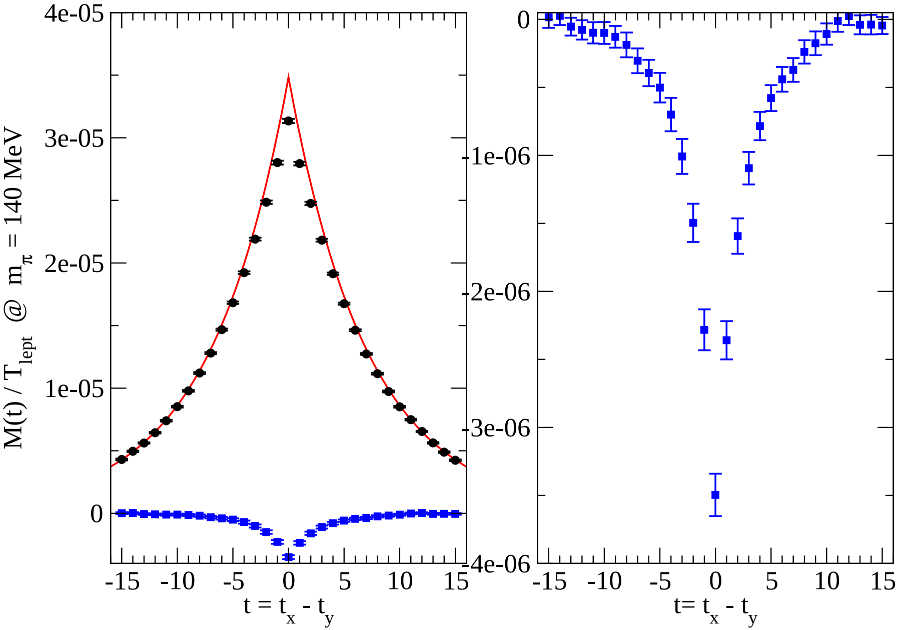
If neutrinoless double beta decays exist ...

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

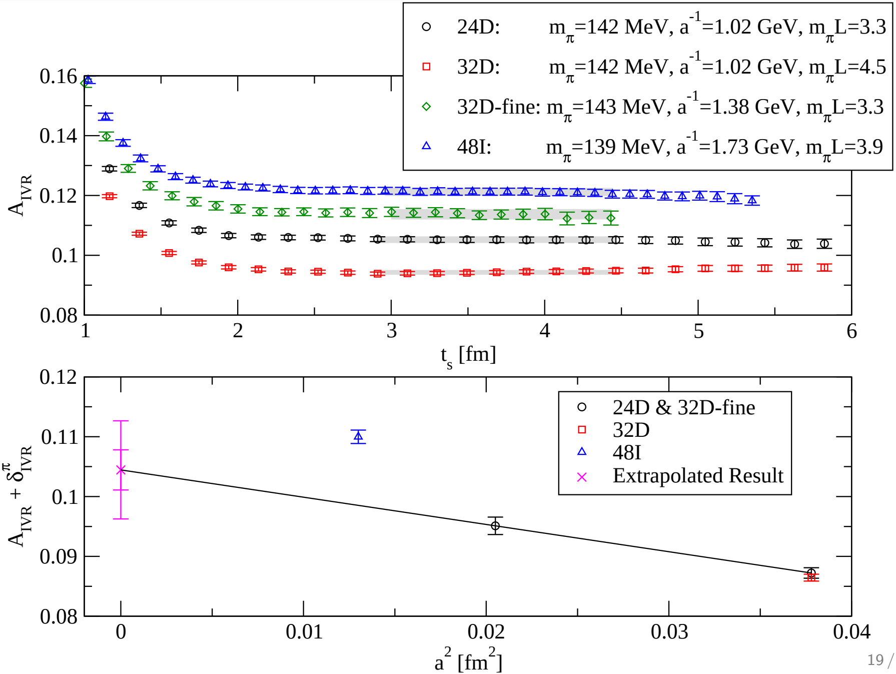
Lattice QCD starts with simplest decays

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

$\pi^- \to \pi^+ ee$: X. Tuo, XF, L. Jin, arXiv:1909.13525, accepted by PRD


M(t) / T_lept @ m_π = 140 MeV
4e-05
3e-05
2e-05
1e-05
0
-15 -10 -5 0 5 10 15
t = t_x - t_y
0
-1e-06
-2e-06
-3e-06
-4e-06
-15 -10 -5 0 5 10 15
t= t_x - t_y

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

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

Lattice calculation yields (statistical error only)

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

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

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

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

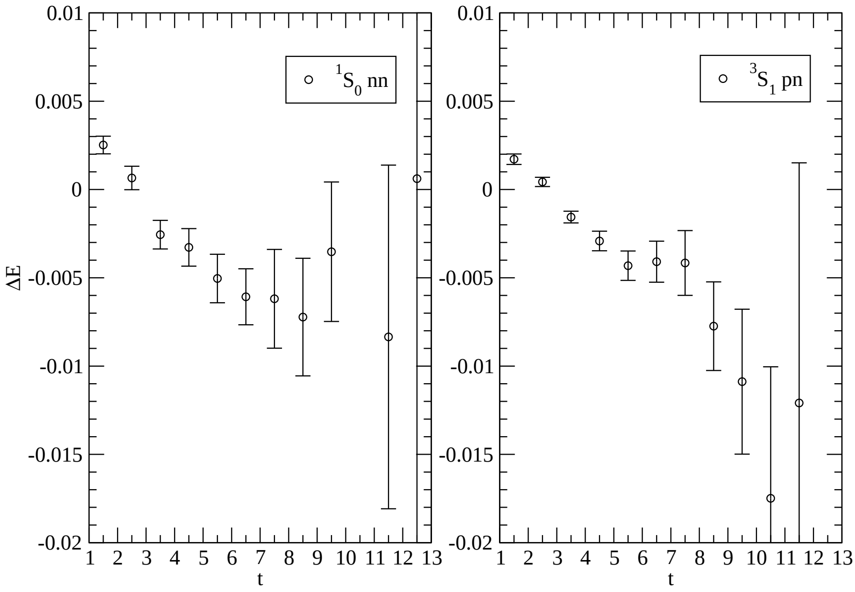
Lattice calculation yields (statistical + systematical errors)

[X. Tuo, XF, L. Jin, accepted by PRD]

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

Move to dibaryon

Di-neutron vs deuteron



Relevant observables

2 point correlation function

- Bounding energy

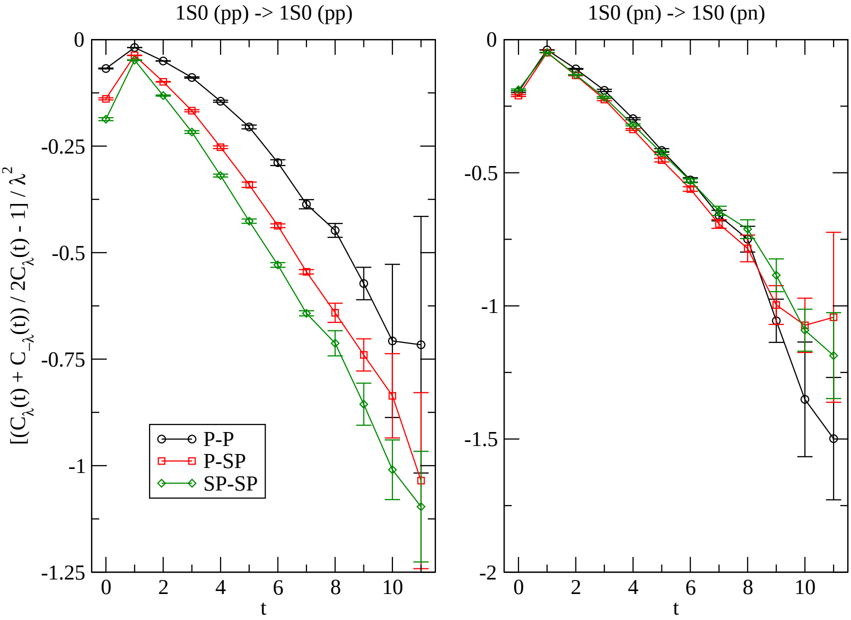
3 point correlation function

- 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

With developments of supercomputers, computational technologies and novel ideas and methods

- the precision of lattice QCD calculation has been improved significantly and have great potential to further improve

For flavor physics:

- lattice QCD provides useful low-energy QCD information
- plays important role in high-precision frontier

The techniques developed in flavor physics can be used in nuclear physics

- help to study the rare processes related to nuclear matter
- Can one day, nuclear physics become a new flavor physics?


寿比南山
寿
福如东海

Double β decay of nuclei

Cirigliano, Dekens, Mereghetti, Walker-loud, PRC97 (2018) 065501

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

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

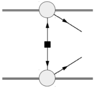
  In lattice QCD, a hard cutoff is introduced by $1/a \Rightarrow O(a^2)$ effects

- 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

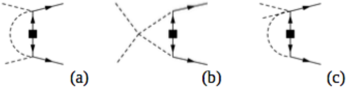
Diagrams in chiral perturbation theory

LO diagrams (tree level)

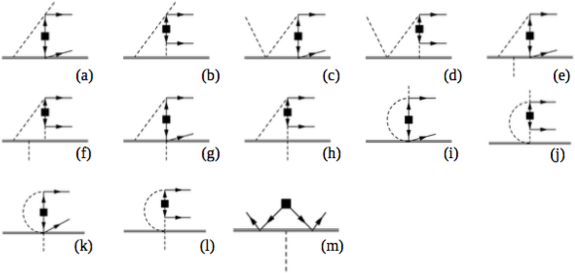


NLO diagrams (one loop)

- $\pi\pi \to ee$

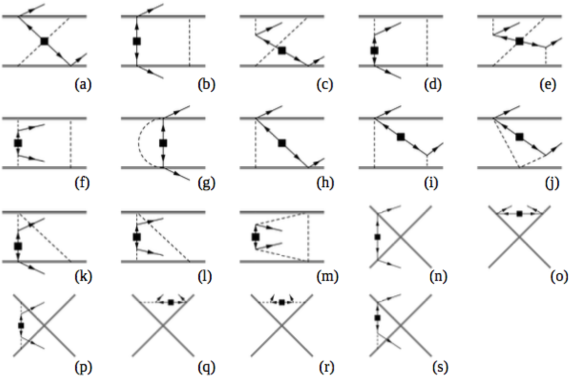


- $\pi n \to pee$



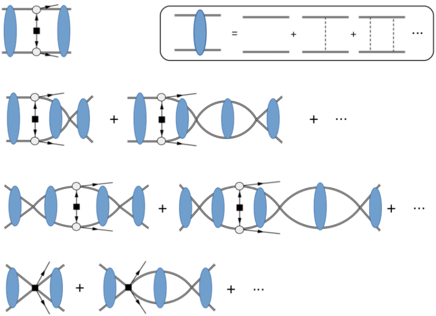
NLO diagrams (one loop)

- $nn \to ppee$



Logarithmic divergence at NNLO

Cirigliano, Dekens, De Vries, et.al. PRL120 (2018) 202001



Transition amplitude from EFT

$$A_\nu = \langle pp, \mathrm{out}|V_\nu|nn, \mathrm{in}\rangle = -\int d^3\mathbf{r}\,\psi^-_{\mathbf{p}'}(\mathbf{r})^* V_\nu(\mathbf{r})\psi^+_{\mathbf{p}}(\mathbf{r})$$

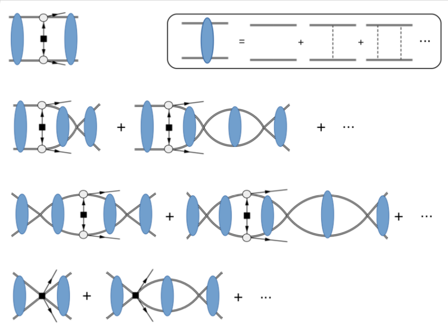
Wave function

$$\psi^\pm_{\mathbf{p}}(\mathbf{r}) = \chi^\pm_{\mathbf{p}}(\mathbf{r}) + \chi^\pm_{\mathbf{p}}(\mathbf{0}) K_E G^\pm_E(\mathbf{r}, \mathbf{0})$$

where

$$G^\pm_E(\mathbf{r}, \mathbf{r}') = \langle \mathbf{r}| \frac{1}{E - H_0 - V_\pi \pm i\varepsilon} |\mathbf{r}'\rangle, \quad K_E = \frac{C}{1 - C G^+_E \mathbf{0}, \mathbf{0}}$$

Logarithmic divergence at NNLO



Transition amplitude from EFT

$$A_\nu = \langle pp, \mathrm{out}|V_\nu|nn, \mathrm{in}\rangle = -\int d^3\mathbf{r}\, \psi^-_{\mathbf{p}'}(\mathbf{r})^* V_\nu(\mathbf{r}) \psi^+_{\mathbf{p}}(\mathbf{r})$$

For $\mathbf{r} \to 0$

$$V_\nu(\mathbf{r}) \to 1/r, \quad \text{Neutrino potential}$$
$$\chi^+_{\mathbf{p}}(\mathbf{r}) \to \text{constant}, \quad \text{Yukawa wave function}$$
$$G^\pm_E(\mathbf{r}, \mathbf{0}) \to \frac{m_N}{4\pi r} + \cdots, \quad \text{Propagator}$$

Need lattice QCD to confirm it

How much chance to obseve $0\nu\beta\beta$?

- The two mass eigenstates that mix most strongly with electron flavor are lighter than the third (normal hierarchy) or heavier (inverted hierarchy)