



# Neutrinoless double beta decay of light hadrons

## —Hyperons & Deltas—

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湖南大学

[Z.-Y. Zhao, Z.-R. Liang, F.-K. Guo, L.-P. He and **DLY**, arXiv:2602.08453 [hep-ph]]

[L.-P. He, F.-K. Guo, Ulf-G. Meissner, **DLY**, X.-Y. Zhang & Z.-H. Zhang, arXiv:2604.12535 [hep-ph]]

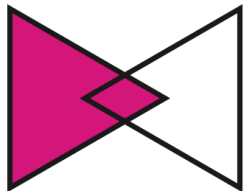
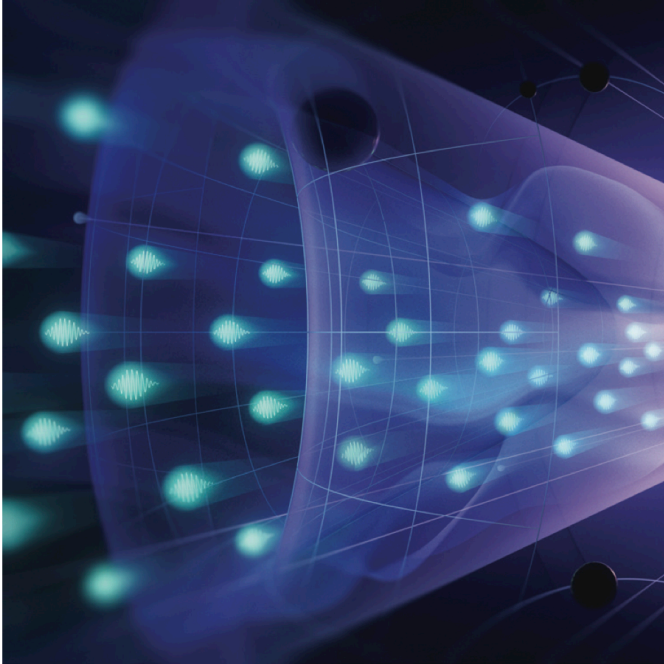
2026轻强子专题研讨会

河南商丘，商丘师范学院，14-18 May 2026

- Introduction
- Hyperon  $0\nu\beta\beta$  decays in SU(3) BChPT
- $\Delta^- \rightarrow pe^-e^-$  in  $\Delta$ -full  $\chi$ EFT
- Summary and outlook

# Neutrino Physics

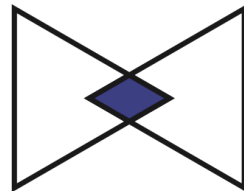
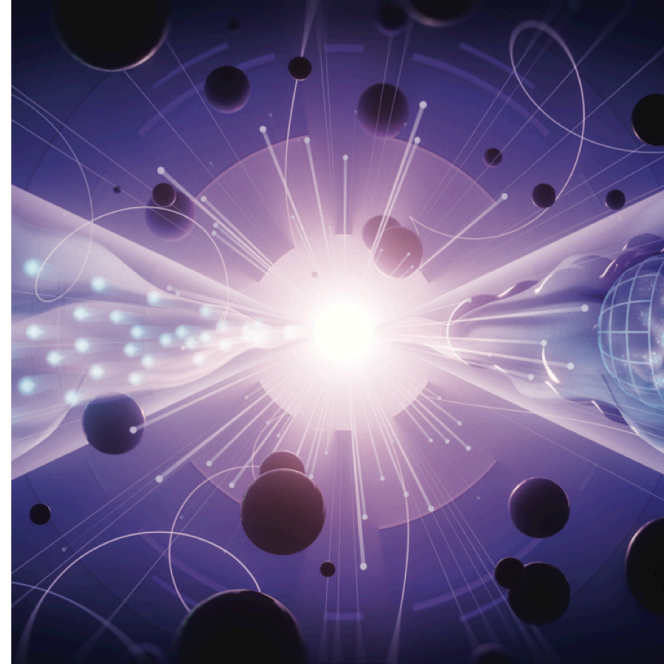
- Report of the 2023 P5



Decipher  
the  
Quantum  
Realm

Elucidate the Mysteries  
of Neutrinos

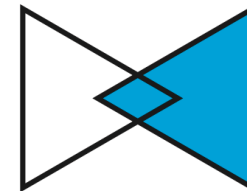
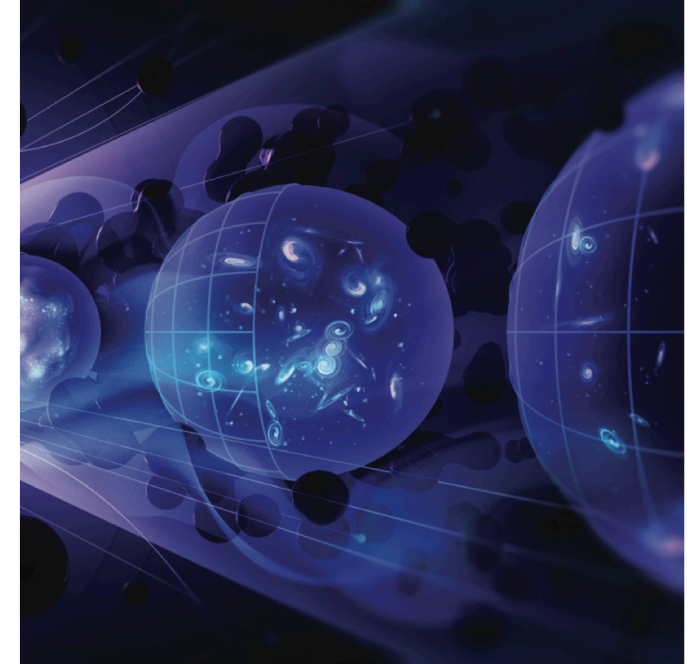
Reveal the Secrets of  
the Higgs Boson



Explore  
New  
Paradigms  
in Physics

Search for Direct Evidence  
of New Particles

Pursue Quantum Imprints  
of New Phenomena



Illuminate  
the  
Hidden  
Universe

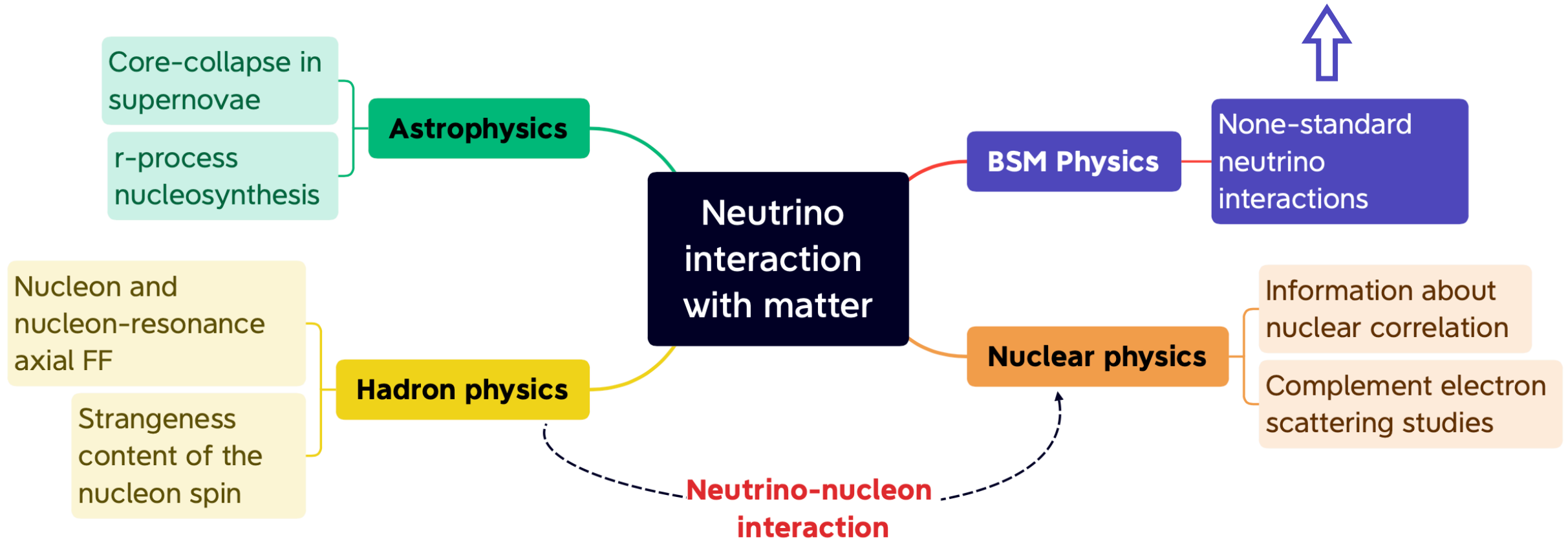
Determine the Nature  
of Dark Matter

Understand What Drives  
Cosmic Evolution

# Neutrino interaction with matter

- At the heart of many interesting and relevant physical phenomena

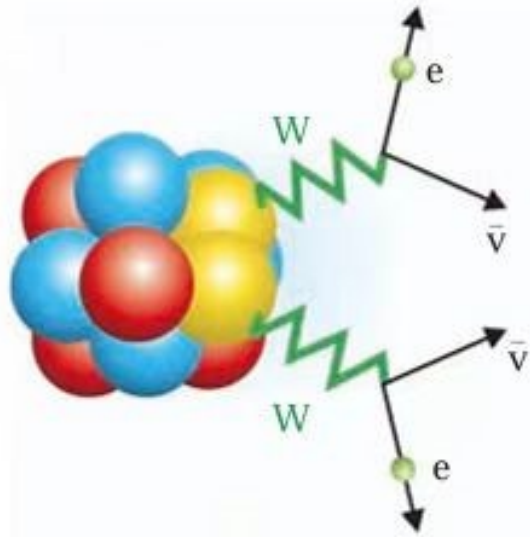
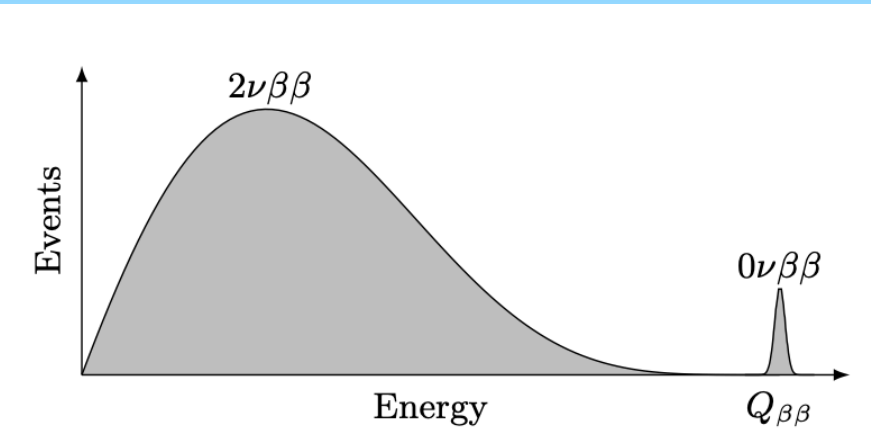
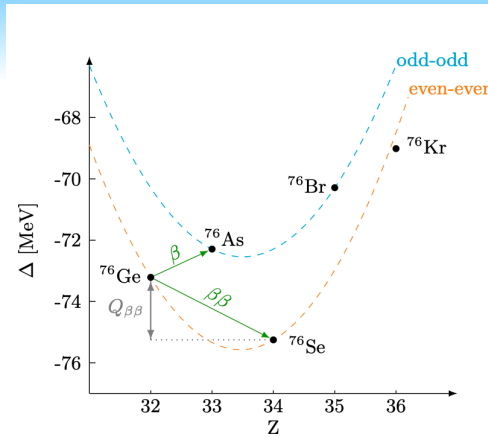
One of the most important ones:  $0\nu\beta\beta$  decay!



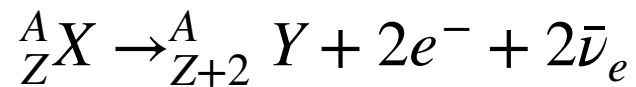
# Neutrinoless double beta decay

- **Nuclear  $0\nu\beta\beta$  decay**

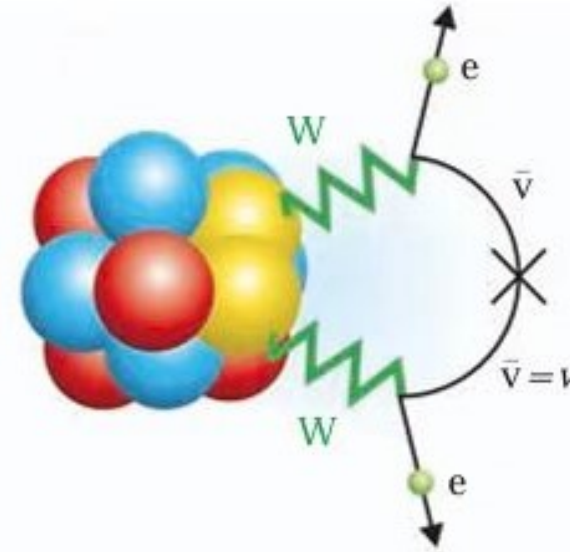
- ▶ Lepton number violation  $\Delta L = 2$
- ▶ **Majorana nature of neutrinos**
- ▶ Neutrino mass scale and hierarchy



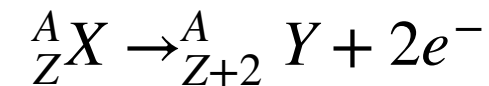
$2\nu\beta\beta$  decay



[M. G. Mayer, Phys.Rev.48,512(1935)]



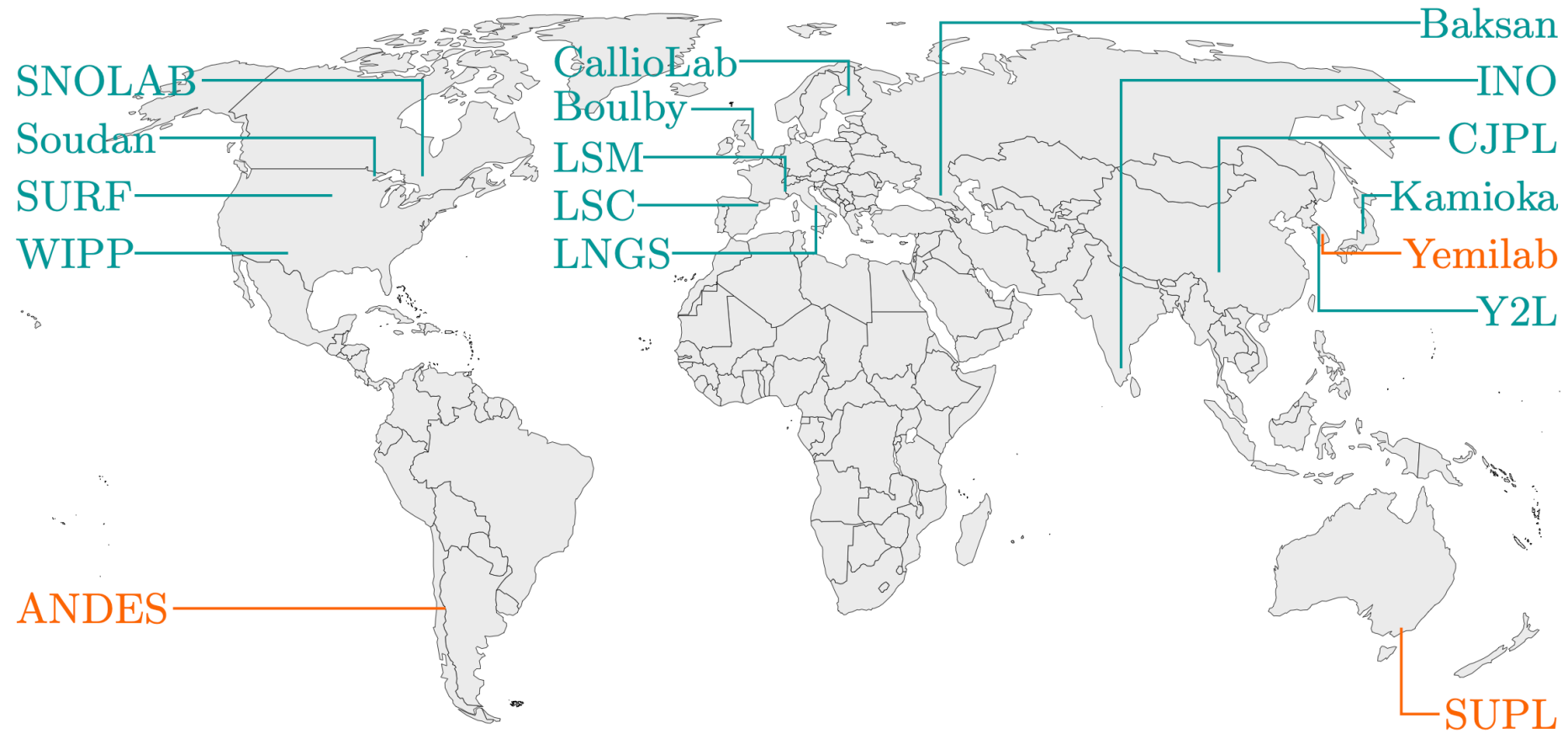
$0\nu\beta\beta$  decay



[Furry, Phys.Rev.56,1184(1939)]

# Neutrinoless double beta decay

- **Experimental  $0\nu\beta\beta$  searches:**
  - ▶ worldwide map of deep underground laboratories



# Nuclear $0\nu\beta\beta$ decays

- Large uncertainty in nuclear matrix elements

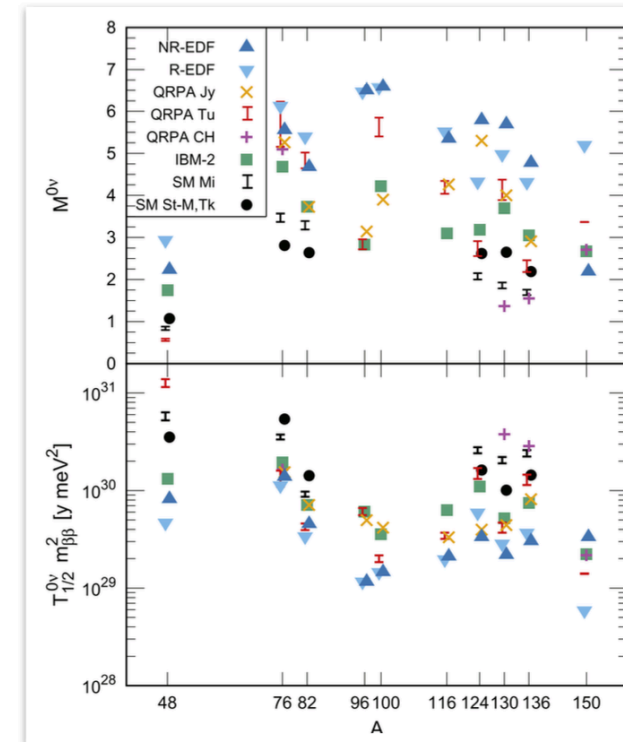
**Nuclear matrix elements** encode the impact of the nuclear structure on the **decay half-life**, crucial to interpreting the  $0\nu\beta\beta$  experimental limits on the **effective neutrino mass**.

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

## Nuclear matrix element

$$M^{0\nu} = \langle \Psi_f | \hat{O}^{0\nu} | \Psi_i \rangle$$

- Different **nuclear models** for  $\Psi_{f,i}$
- Large uncertainty ....

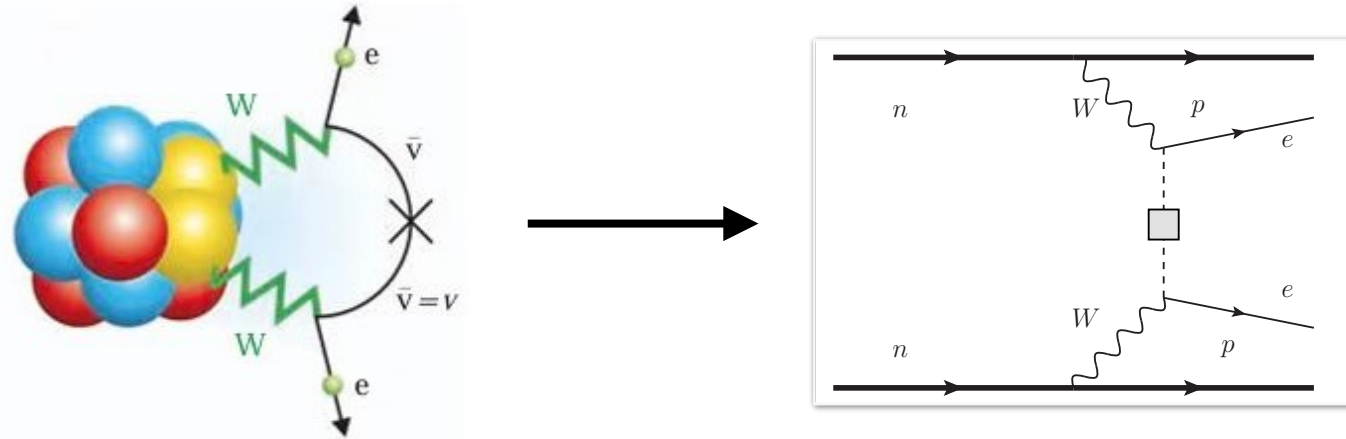


Courtesy of P.-W. Zhao

Engel and Menéndez, Rep. Prog. Phys. 80, 046301 (2017)

# Hadronic neutrinoless double beta decay

- Nuclear  $0\nu 2\beta$



- Hadronic  $0\nu 2\beta$ ?

- ▶ Kaons:  $K^\pm \rightarrow \pi^\mp l_\alpha^\pm l_\beta^\pm$  [Liao, Ma and Wang, JHEP03(2020) ]

- ▶ Hyperons, Deltas, ...

- $\Delta S = 0$ :  $\Sigma^- [dds] \rightarrow \Sigma^+ [uus] e^- e^-$ ;
- $\Delta S = 1$ :  $\Sigma^- [dds] \rightarrow p [duu] l^- l^-$ ,  $\Xi^- [dss] \rightarrow \Sigma^+ [uus] e^- e^-$ ;
- $\Delta S = 2$ :  $\Xi^- [dss] \rightarrow p [duu] l^- l^-$ .

$\Delta^- [ddd] \rightarrow p [uud] e^- e^-$

# Experimental status

- **Meson sector**

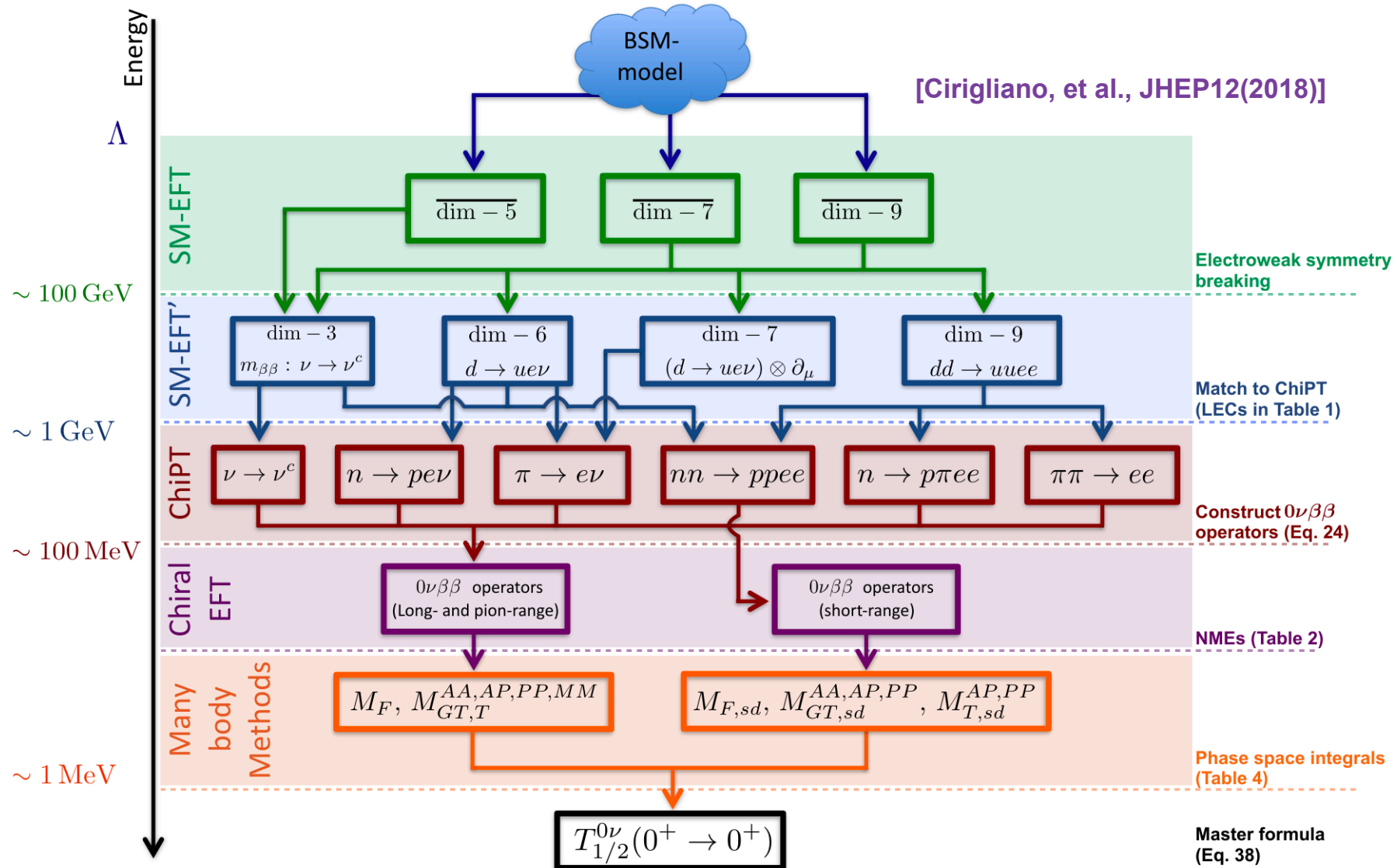
- ▶ 1976, CERN:  $K^+ \rightarrow \pi^- e^+ e^+$ , BR < 2.9e-9;
- ▶ 2000, BNL-ARSE865:  $K^+ \rightarrow \pi^- \ell^+ \ell^+$ , BR < 6.4e-10;  $K^+ \rightarrow \pi^- \mu^+ \mu^+$ , BR < 3.0e-9;
- ▶ CERN NA48/2 & NA62: BR < 5.0e-11;
- ▶ NA62:  $K^+ \rightarrow \pi^0 \pi^- e^+ e^+$ , BR < 8.5e-11;
- ▶ BESIII, LHCb:  $0\nu\beta\beta$  of  $D$  and  $B$ .
- ▶ ...

- **Baryon sector**

- ▶ 2005, Fermilab HyperCP:  $\Xi^- \rightarrow p e^- e^-$ , BR <  $4.0 \times 10^{-8}$ ;
- ▶ 2021, BESIII:  $\Sigma^- \rightarrow p e^- e^-$ , BR <  $6.7 \times 10^{-5}$ ;
- ▶ 2025, BESIII:  $\Xi^- \rightarrow \Sigma^+ e^- e^-$ , BR <  $2.0 \times 10^{-5}$ ;
- ▶ Future STCF: ...

# ChEFT and BSM physics

- EFT at various scalars (e.g. Lepton number violation)



# Mass mechanism

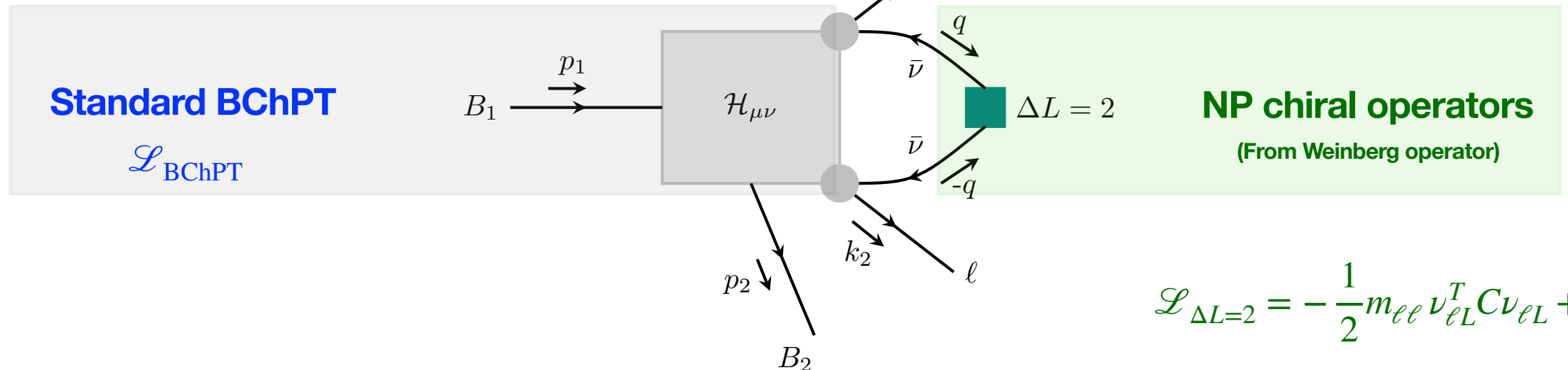
- **Standard BChPT augmented by dim-5 Weinberg operator**

▶ EW scale:

$$\mathcal{L}_{eff}^{EW} = \mathcal{L}_{SM} + \underbrace{\sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_j \frac{c_j^{(6)}}{\Lambda^2} \mathcal{O}_j^{(6)} + \sum_k \frac{c_k^{(7)}}{\Lambda^3} \mathcal{O}_k^{(7)} + \dots}_{\text{SMEFT}}$$

$$\mathcal{O}_{\text{Weinberg}}^{(5)} = \frac{y_{\ell\ell'}}{\Lambda_{\text{LNV}}} \bar{L}_{\ell L} \widetilde{H} \widetilde{H}^T L_{\ell' L}^c + \text{h.c.}$$

▶ Chiral symmetry breaking scale:



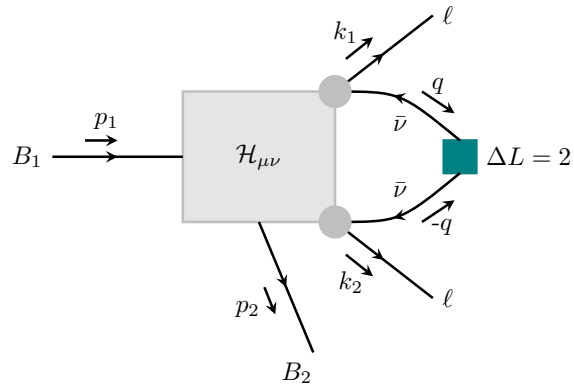
$$\mathcal{L}_{\Delta L=2} = -\frac{1}{2} m_{\ell\ell'} \nu_{\ell L}^T C \nu_{\ell' L} + \text{h.c.}$$

# Hyperon $0\nu 2\beta$ in BChPT

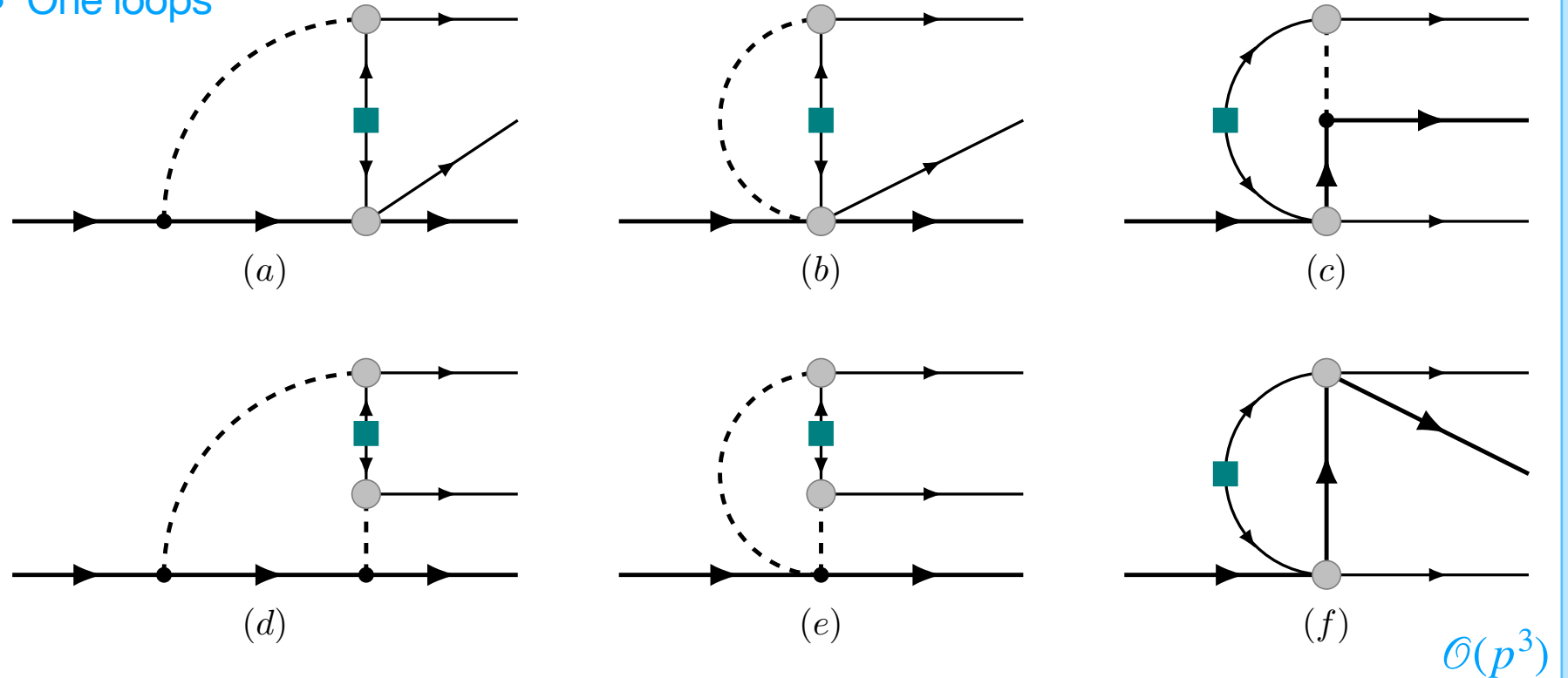
- Mass mechanism begins to contribute at one-loop level

► Amplitude is separable:

$$\mathcal{M}_{0\nu\beta\beta} = C_{\text{Lept}} H_{\mu\nu}(p_1, p_2; k_1, k_2) L^{\mu\nu}(k_1, k_2)$$



• One loops



# Hyperon $0\nu 2\beta$ in BChPT

- **Renormalization:** Dimensional regularisation + EOMS scheme

► UV divergence

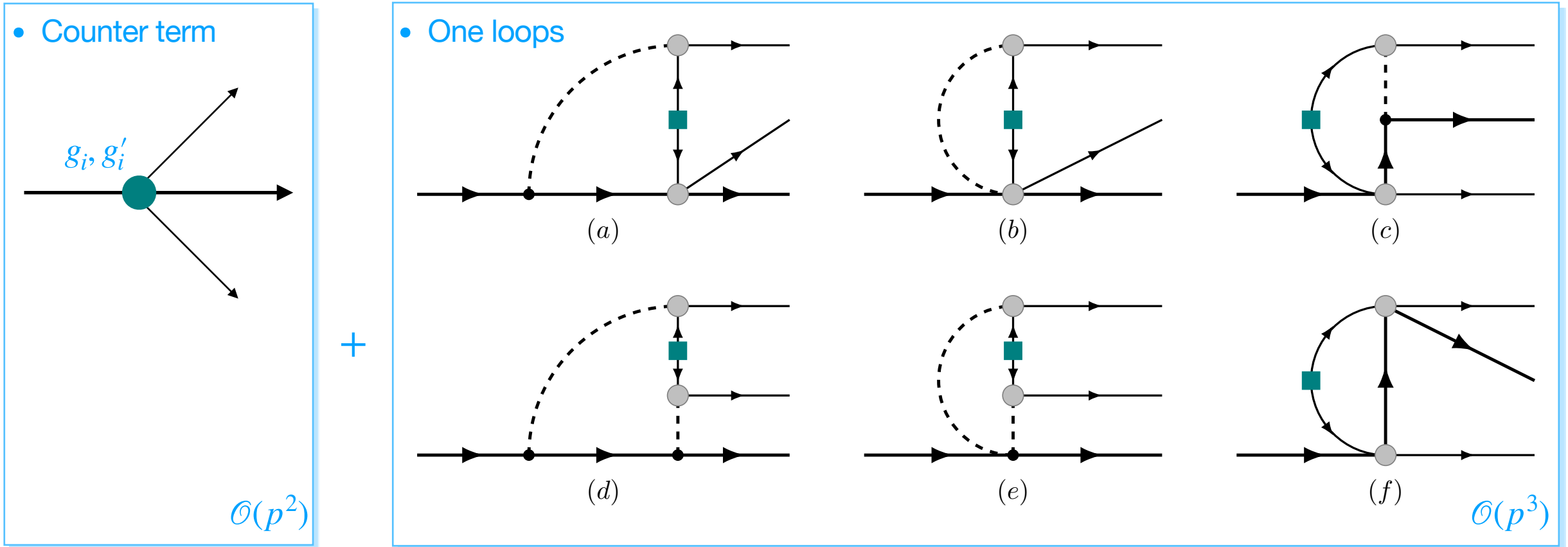
$$H_{\mu\nu}^{\text{UV}} = \left[ \frac{1}{2}m(2D^2 - 6F^2 + 1)\mathcal{O}_V^1 + \frac{1}{6}(D^2 - 3F^2 - 3)\left(-\frac{3}{2}\mathcal{O}_V^2 + \mathcal{O}_V^3 - 2\mathcal{O}_V^{23} + 3\mathcal{O}_V^{25} + \mathcal{O}_V^{26}\right) + F\left(m\mathcal{O}_A^1 + \frac{3}{2}\mathcal{O}_A^2 - \mathcal{O}_A^3 - m\mathcal{O}_A^4 + 2\mathcal{O}_A^{23} - 3\mathcal{O}_A^{25} - \mathcal{O}_A^{26}\right) \right] R, \quad R = \frac{2}{d-4} + \gamma_E - 1 - \ln(4\pi)$$

► PCB term

$$H_{\mu\nu}^{\text{PCB}} = \left[ \frac{-(D^2 - 3F^2)(d^2 + 5d - 10) + 3d(3 - d)}{6d(d - 3)m} \mathcal{O}_V^1 + \frac{2D^2 - 6F^2 - 3}{3(d - 3)m^2} \mathcal{O}_V^{23} + \frac{F}{(d - 3)m} \mathcal{O}_A^4 - \frac{2F}{(d - 3)m^2} \mathcal{O}_A^{23} \right] A_0(m^2)$$

# Hyperon $0\nu 2\beta$ in BChPT

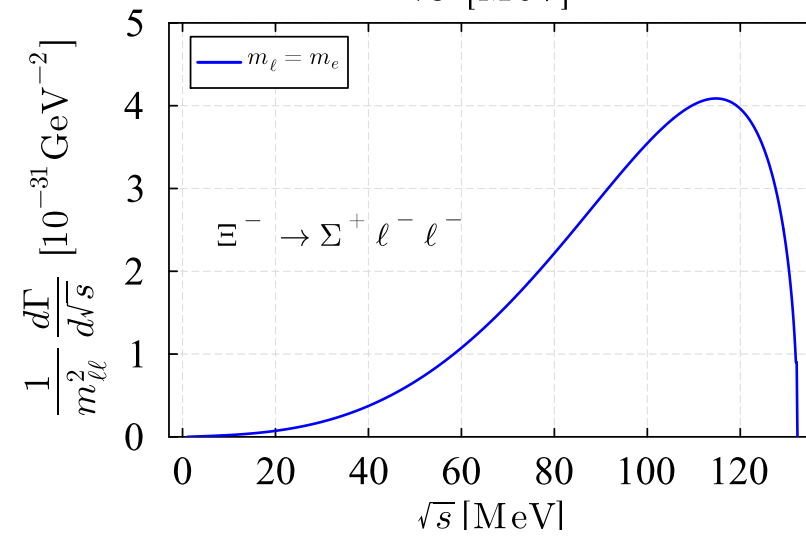
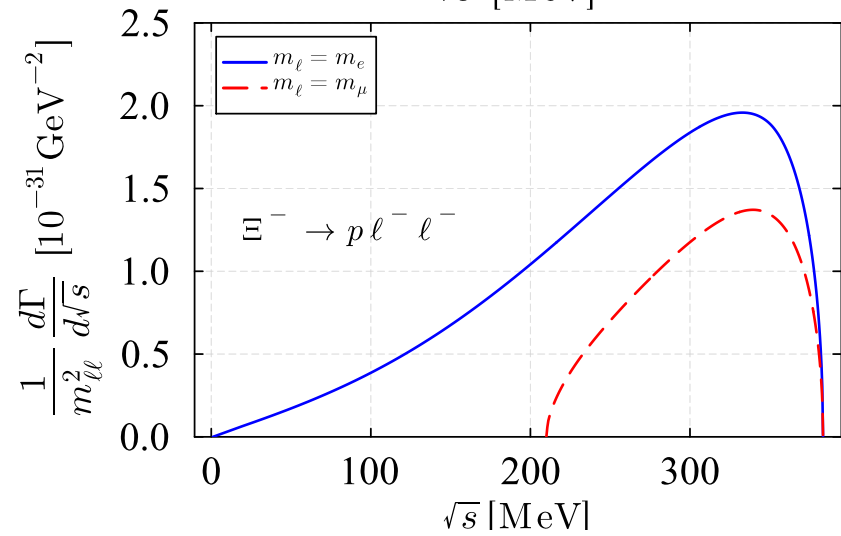
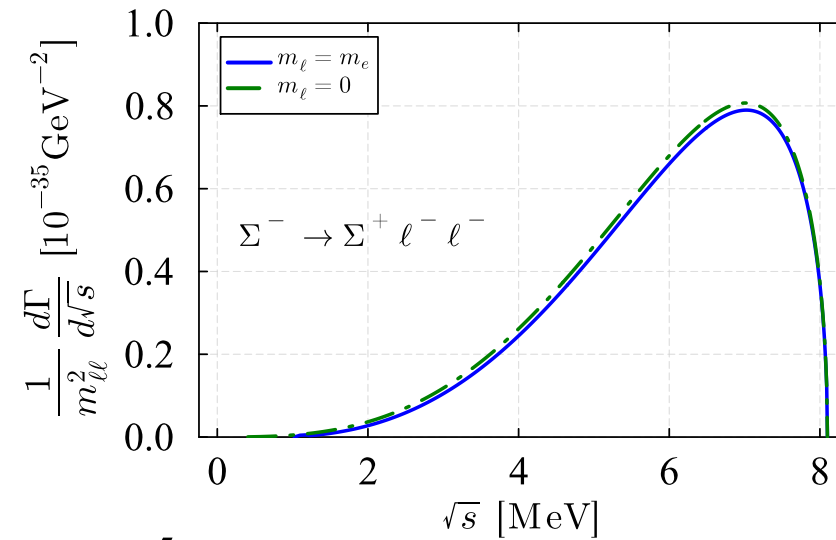
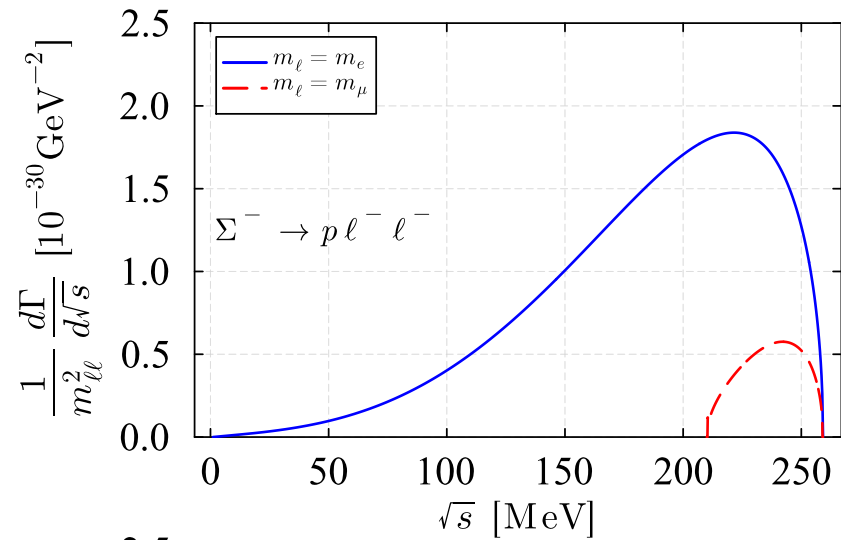
- **Renormalization:** Dimensional regularisation + EOMS scheme
  - ▶ Counterterms constructed using bottom-up approach



Short range contribution is needed by renormalization requirement!

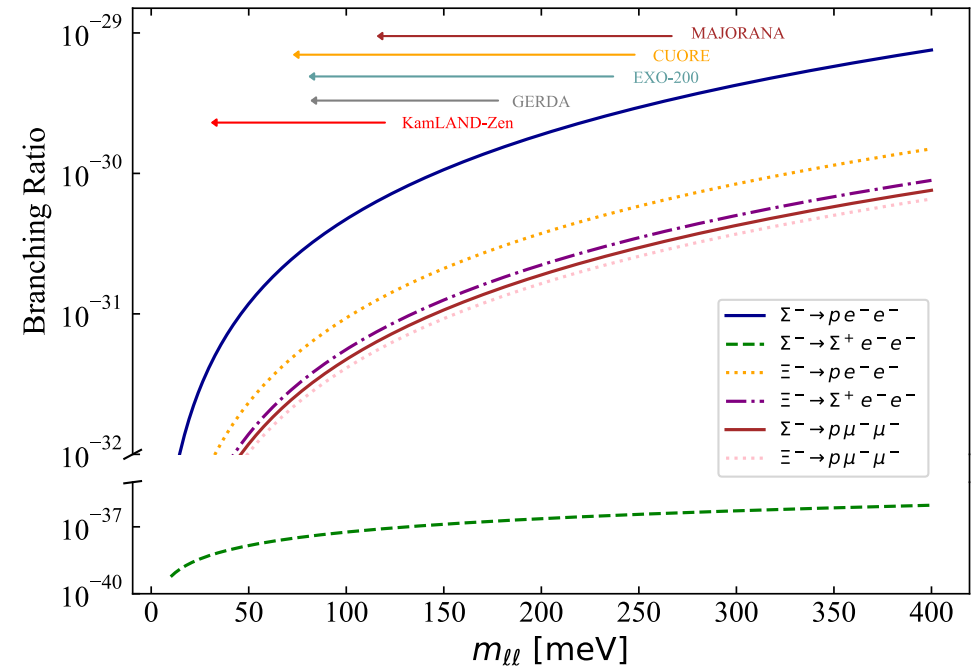
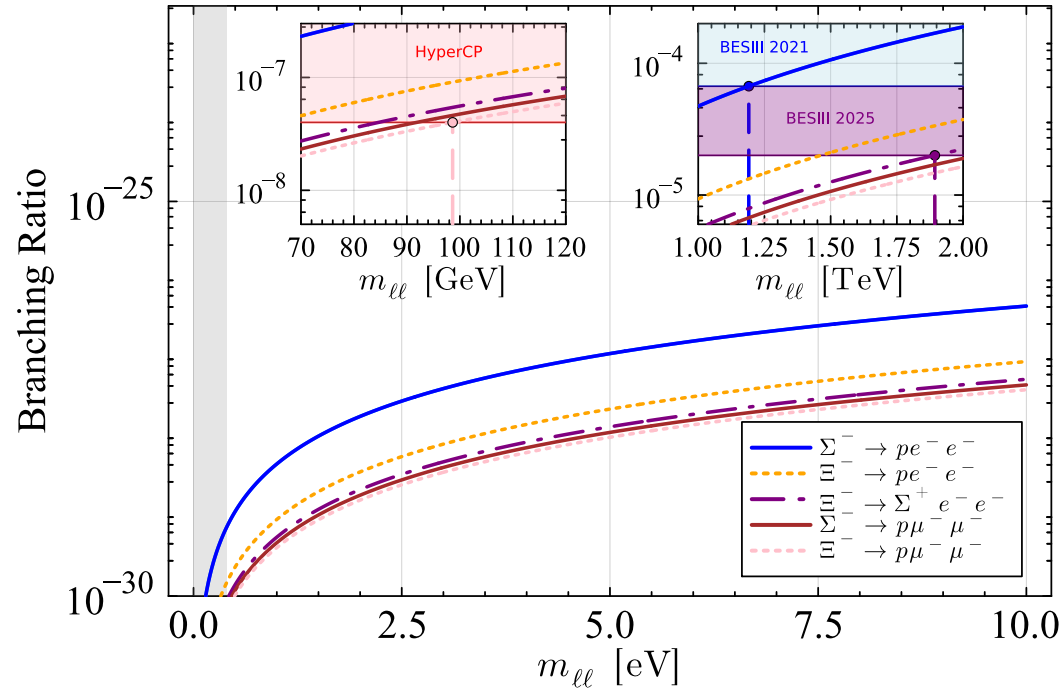
# Hyperon $0\nu 2\beta$ in BChPT

- Differential decay rates



# Hyperon $0\nu 2\beta$ in BChPT

- Branching ratios

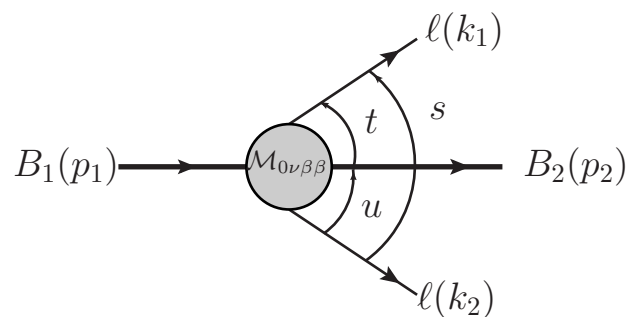


- Complementary to nuclear  $0\nu 2\beta$
- Future hyperon factory

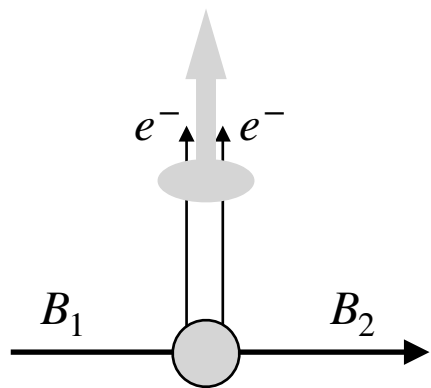
Process	$\frac{\Gamma_{0\nu}}{m_{\ell\ell}^2}$ [sec <sup>-1</sup> /MeV <sup>2</sup> ]	$\mathcal{B}(B_1 \rightarrow B_2 \ell^- \ell^-)$	
		This work	Experiments
$\Sigma^- \rightarrow p e^- e^-$	$3.194 \times 10^{-7}$	$4.7 \times 10^{-31}$	$< 6.7 \times 10^{-5}$ [26]
$\Sigma^- \rightarrow \Sigma^+ e^- e^-$	$3.925 \times 10^{-14}$	$5.8 \times 10^{-38}$	-
$\Sigma^- \rightarrow p \mu^- \mu^-$	$3.202 \times 10^{-8}$	$4.7 \times 10^{-28}$	-
$\Xi^- \rightarrow \Sigma^+ e^- e^-$	$3.404 \times 10^{-8}$	$5.6 \times 10^{-32}$	$< 2.0 \times 10^{-5}$ [27]
$\Xi^- \rightarrow p e^- e^-$	$5.706 \times 10^{-8}$	$9.4 \times 10^{-32}$	-
$\Xi^- \rightarrow p \mu^- \mu^-$	$2.509 \times 10^{-8}$	$4.1 \times 10^{-28}$	$< 4.0 \times 10^{-8}$ [25]

# How to determine the counterterm

- **Neutrinoless transition form factors (NTFFs)**



An effective  $0\nu\beta\beta$  current



Colinear leptons ( $k_1 = k_2$ )

- Decomposition of the leptonic tensor

$$L^{\mu\nu} = \underbrace{\bar{u}_{\ell L}(k_1) g^{\mu\nu} C \bar{u}_{\ell L}^T(k_2)}_{L_S^{\mu\nu}} - i \underbrace{\bar{u}_{\ell L}(k_1) \sigma^{\mu\nu} C \bar{u}_{\ell L}^T(k_2)}_{L_A^{\mu\nu}}$$

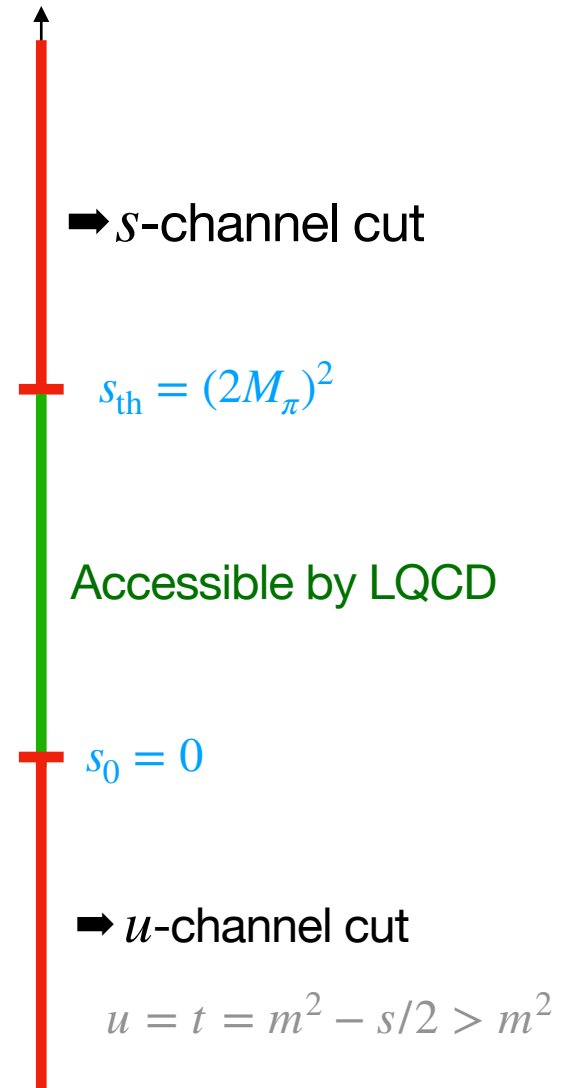
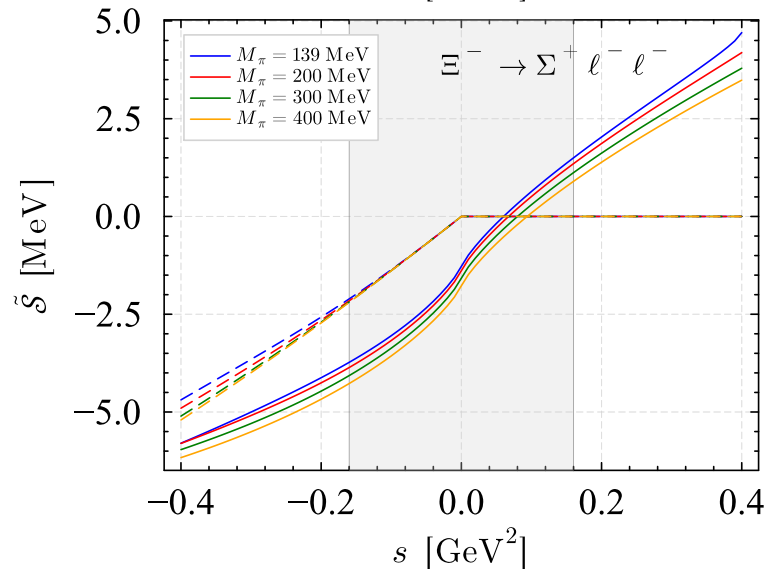
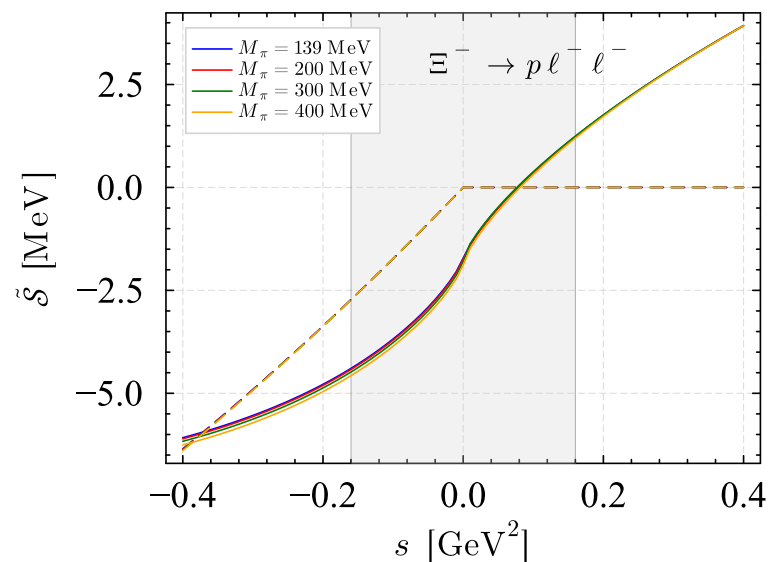
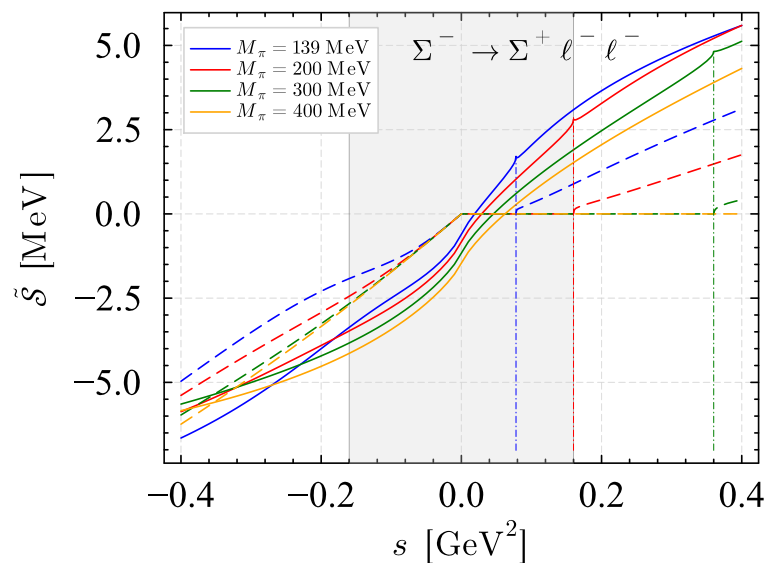
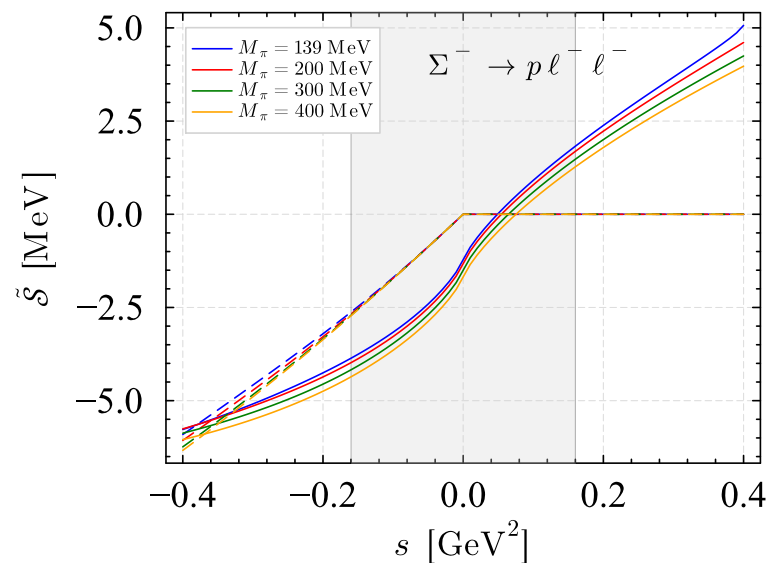
- Amplitude in terms of NTFFs

$$\begin{aligned} \mathcal{M}_{0\nu\beta\beta} &= C_{\text{Lept}} H_{\mu\nu} L_S^{\mu\nu} \\ &= C_{\text{Lept}} \left\{ \bar{u}(p_2) [\mathcal{S}(s) + \gamma_5 \mathcal{P}(s)] u(p_1) \right\} \left\{ \bar{u}_{\ell L}(k) C \bar{u}_{\ell L}^T(k) \right\} \end{aligned}$$

**Chiral expression:**  $\mathcal{S}(s) = 8\tilde{g}_1 + \widetilde{\mathcal{S}}(s)^{\text{loop}}$   
 $\mathcal{P}(s) = 0$  (Degenerate baryon mass case)

# Neutrinoless transition form factors

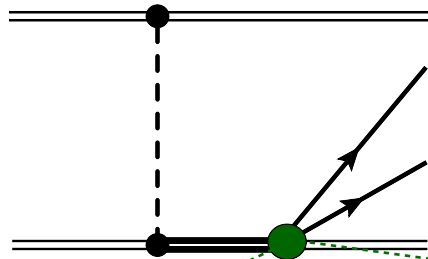
- $s$  dependence at different pion masses (solid: real part; dashed: imaginary part)



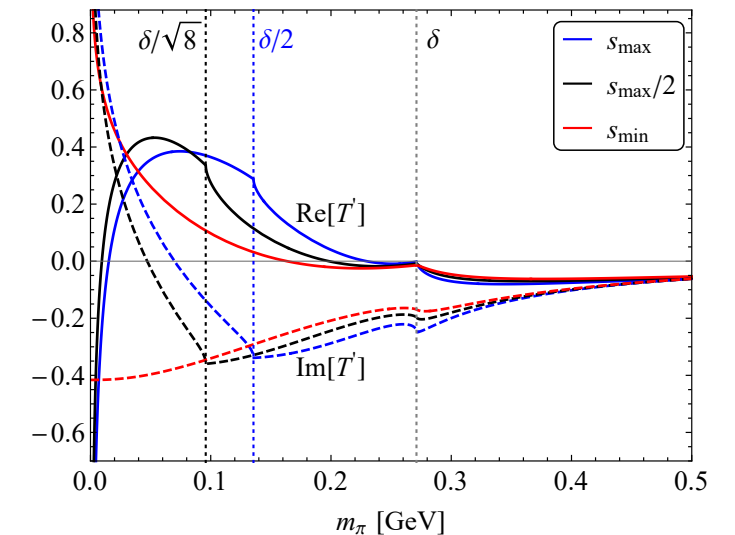
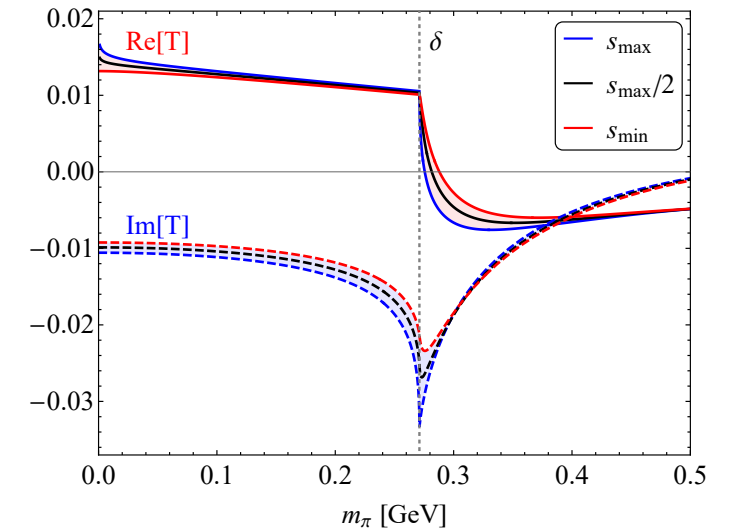
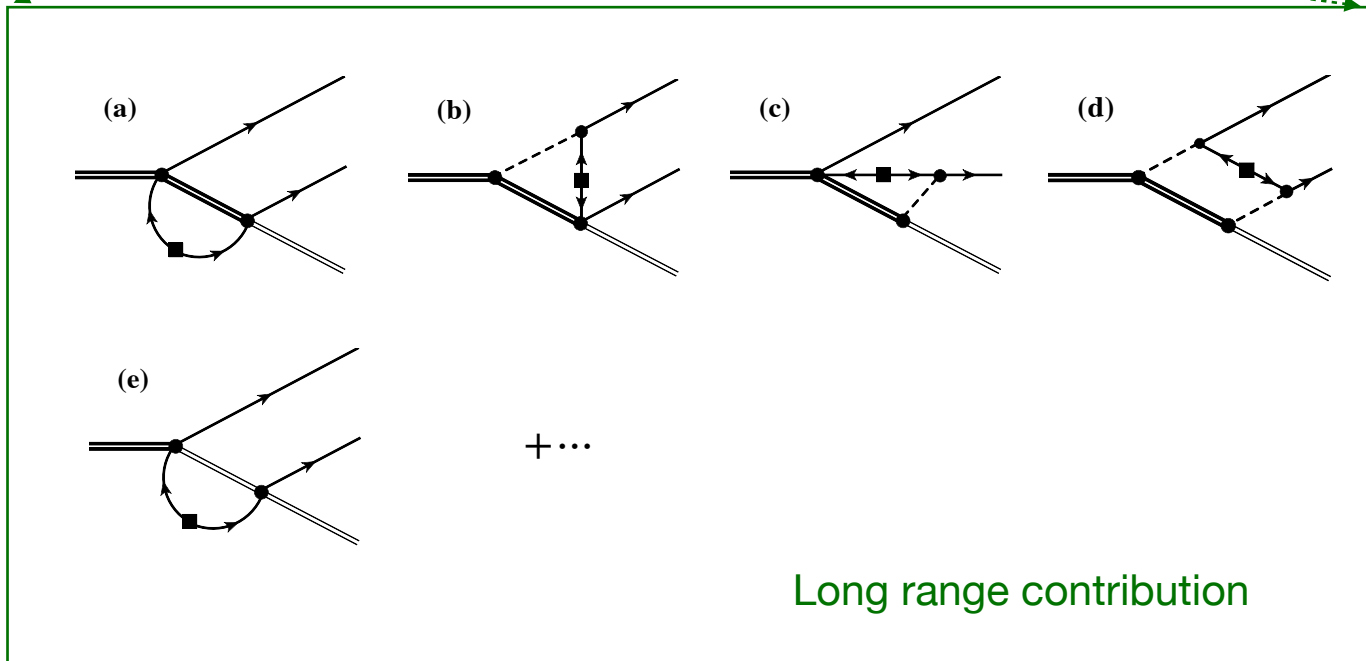
# Deutrinoleless double beta decay of $\Delta$

- Delta  $0\nu 2\beta$  in BChPT**

[He, Guo, Meissner, **DLY**, Zhang & Zhang, arXiv:2604.12535 [hep-ph]]



- Towards a deltafull description of  $nn \rightarrow ppee$
- Pion mass dependence





# Summary and outlook

- Hyperon  $0\nu\beta\beta$  decays in covariant BChPT augmented by a  $\Delta L = 2$  operator
  - ▶ **Long-range contribution:** emerge at one-loop level within mass mechanism
  - ▶ **Short-range operators:** leading contribution to the decay amplitude
  - ▶ **Branching ratios:** more than 20 orders of magnitude smaller than the current experimental upper bounds
  - ▶ **Neutrinoless transition form factors:** accessible by future LQCD simulation
- Delta  $0\nu\beta\beta$  decay:
  - ▶ **Singularities (threshold cusp, triangle singularities)** are studied with varying pion masses
- Outlook:
  - ▶ Extension to spin-3/2 decuplet, D/B mesons, ...
  - ▶ Top-down construction of short-range chiral operators with dim.-7/9 SMEFT operators, ....

**Thank you very much!**