Neutrinoless double-beta ($0\nu\beta\beta$) decay of light baryons

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Based on arXiv:2604.12535, LPH, Feng-Kun Guo, Ulf Meissner, De-Liang Yao, Xiao-Yu Zhang and Zhen-Hua Zhang
arXiv:2602.08453, Zi-Ying Zhao, Ze-Rui Liang, Feng-Kun Guo, LPH, and De-Liang Yao

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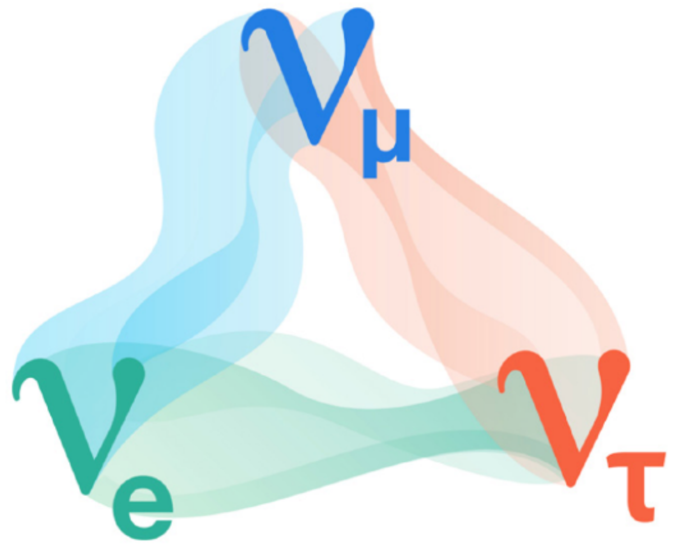
Outline

1. Introduction
2. $0\nu\beta\beta$ decay of Δ^- resonance
3. $0\nu\beta\beta$ decay of hyperons
4. Summary

Neutrino mass

- **Standard Model (SM)**: neutrinos are **massless.**
- Discovery of **neutrino oscillations:**
  → **neutrinos do have mass!**

$$P(\nu_e \to \nu_\alpha) \sim \sin^2 \frac{\Delta m^2 L}{4E}$$

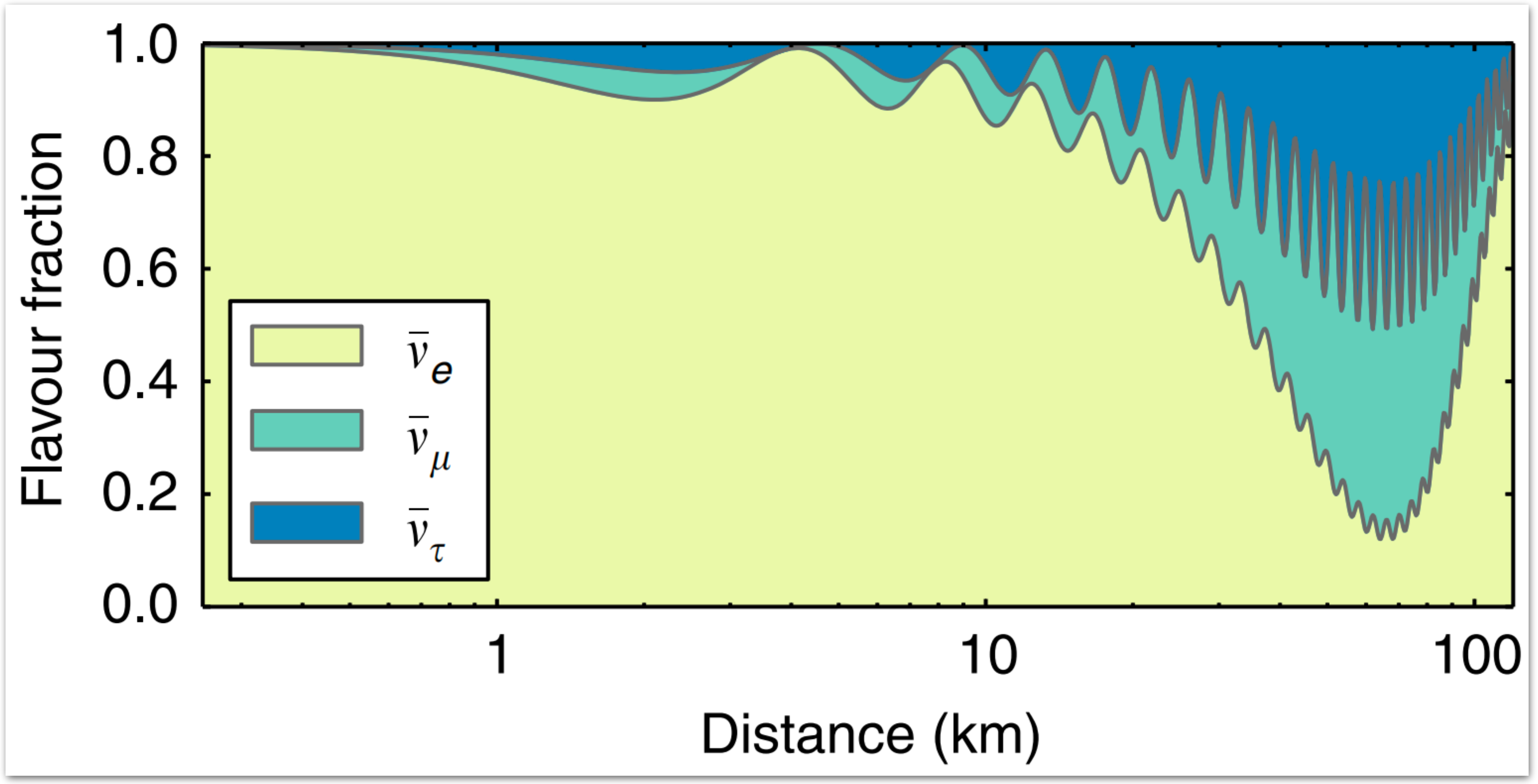


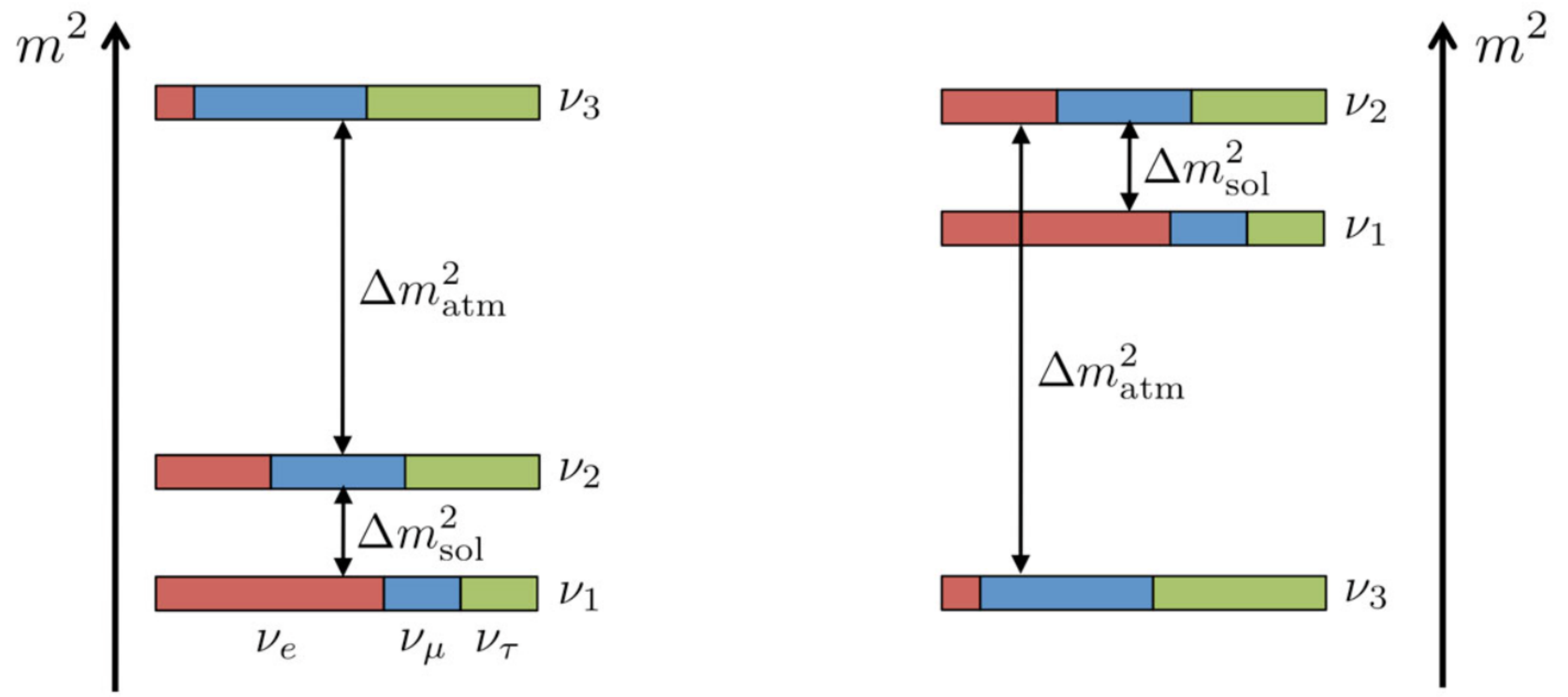
- **Neutrino oscillations cannot determine the absolute neutrino mass**

$$\Delta m_{21}^2 \equiv \Delta m_{\rm sol}^2 = 7 \times 10^{-5}\,({\rm eV})^2$$
$$\left|\Delta m_{31}^2\right| \approx \left|\Delta m_{32}^2\right| \equiv \Delta m_{\rm atm}^2 = 2 \times 10^{-3}\,({\rm eV})^2$$

(in the normal mass hierarchy)

Illustration of neutrino oscillations. *Nature Commun.* 6 (2015) 6935





Two potential mass orderings of neutrinos are the normal ordering (normal hierarchy) and the inverted ordering (inverted hierarchy). Credit: JUNO Collaboration / JGU-Mainz

Neutrino mass and $0\nu\beta\beta$ decay

Current constraints to absolute m_ν

- **Direct β decay**

  KATRIN (Tritium-decay):

  $m_\nu <$ 0.45 eV (90% C.L.)

- **Cosmology**
  - Planck: $\Sigma m_\nu <$ 0.12 eV
  - DESI: $\Sigma m_\nu <$ 0.072 eV

- **Neutrinoless double-beta ($0\nu\beta\beta$) decay**

  KamLAND-Zen (^{136}Xe):

  $m_\nu <$ 28-122 meV (90% C.L.)

Neutrino mass and $0\nu\beta\beta$ decay

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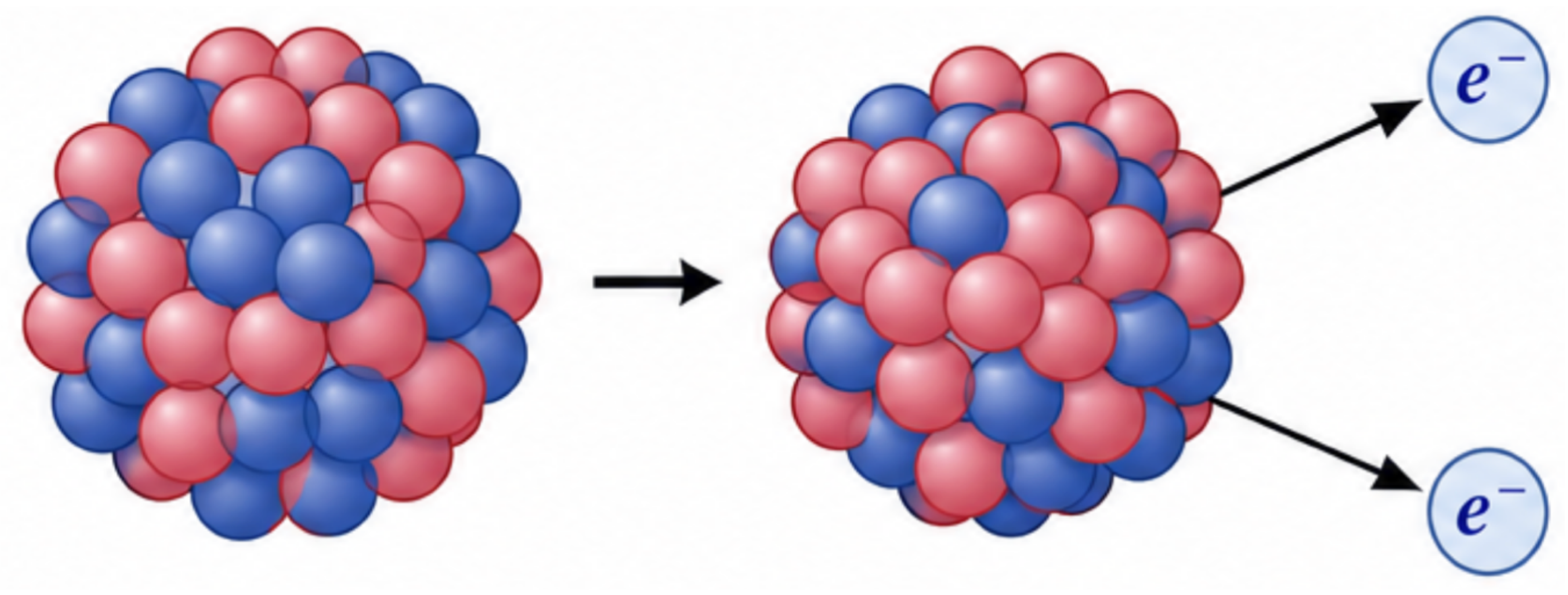
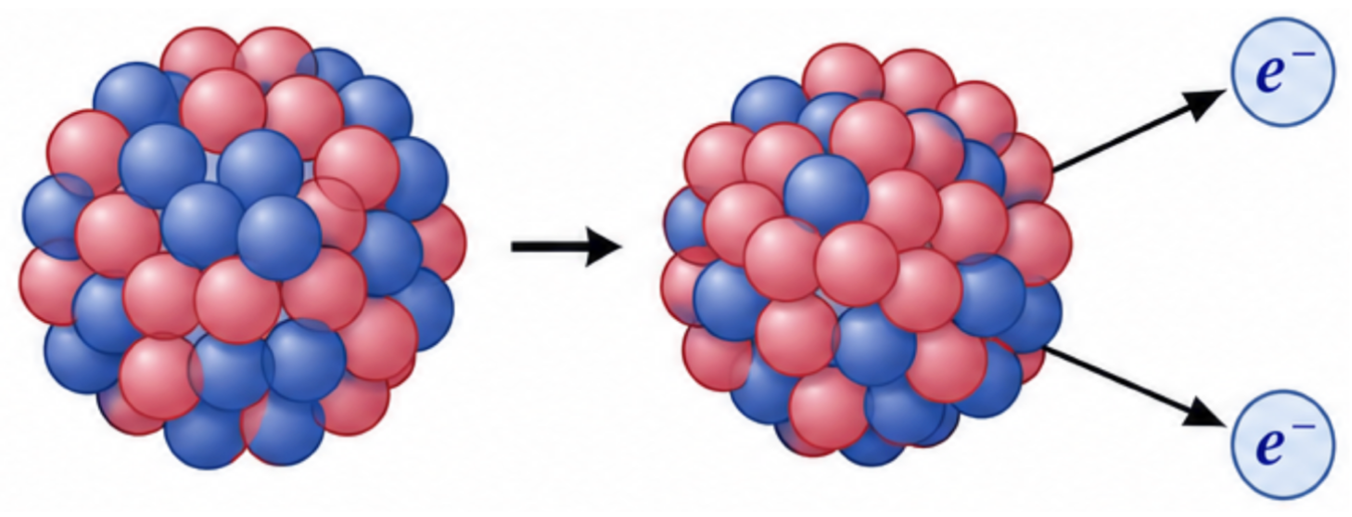


Double-beta decay without any neutrinos

- **Direct access to** m_ν
- **Observation would establish**
  - **Neutrino mass has Majorana component**
  - **lepton-number violation (LNV): ΔL = 2**

Experimental searches for 0νββ decays

- **Nucleus:** $(A,Z) \to (A,Z+2) + 2e^-$

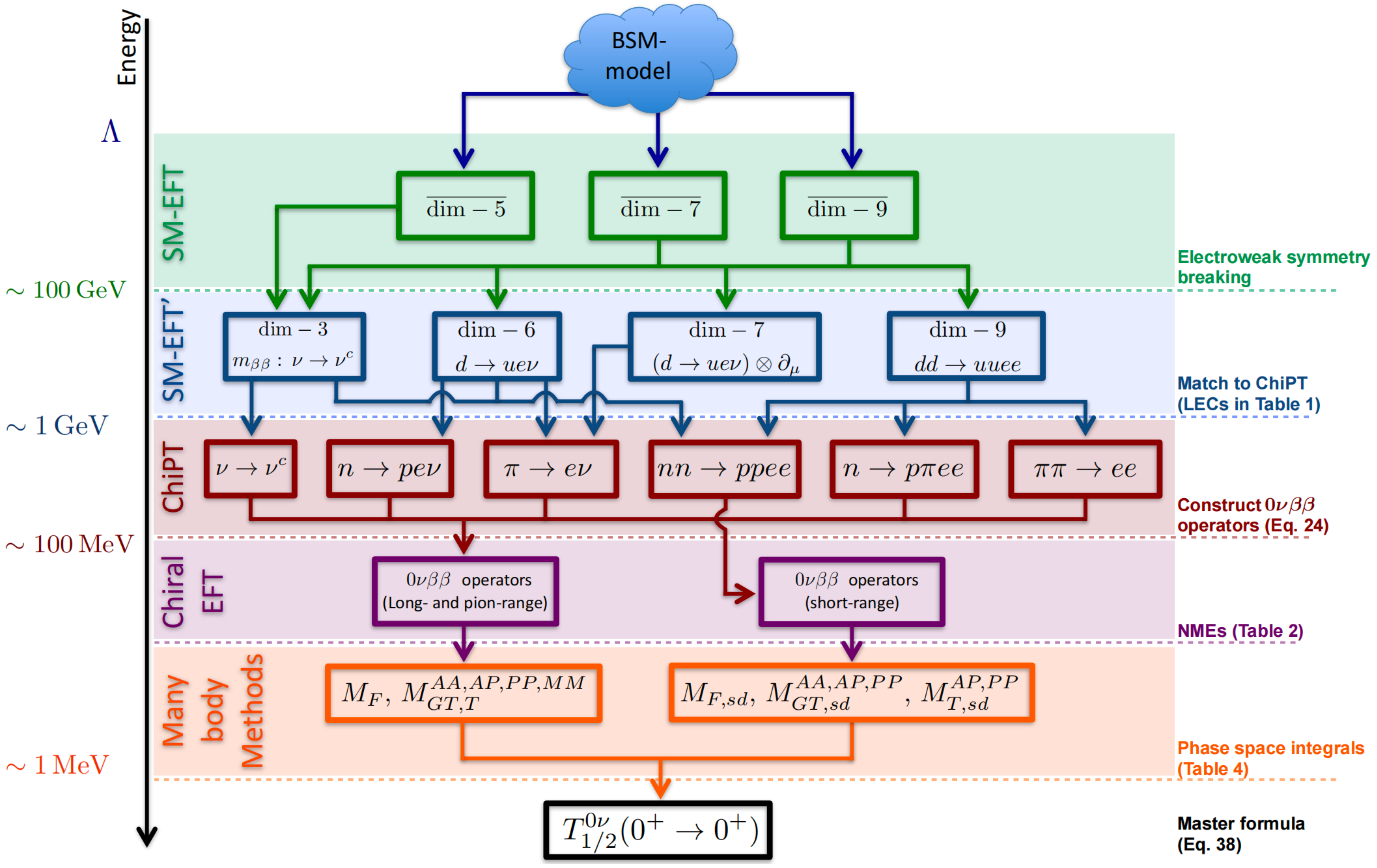


Experiment	Isotope	$\mathbf{T}^{0\nu}_{1/2}$ (yr)	$\mathbf{m}_{\beta\beta}$ (meV)
KamLAND-Zen	^{136}Xe	–	< 28–122
PandaX	^{136}Xe	$> 2.1 \times 10^{24}$	< 400–1600
EXO-200	^{136}Xe	$> 3.5 \times 10^{25}$	< 93–286
GERDA	^{76}Ge	–	< 79–180
MAJORANA	^{76}Ge	$> 8.3 \times 10^{25}$	< 113–269
LEGEND-200	^{76}Ge	$> \mathbf{1.9} \times \mathbf{10^{26}}$	< 75–200
CUORE	^{130}Te	$> 2.2 \times 10^{25}$	–
CUPID	^{82}Se	$> 4.6 \times 10^{24}$	< 263–545
CUPID	^{100}Mo	$> 1.6 \times 10^{27}$	< 9.6–16.3

- **Hadrons:** $H_1 \to H_2 + 2l$
  - **NA62:** $K^+ \to \pi^- l^+ l^+$
  - **HyperCP:** $\Xi^- \to p\mu^-\mu^-$
  - **LHCb:**
    - ☑ $B^- \to D^{(*)}\mu^-\mu^-$
    - ☑ $D \to \pi\mu^+\mu^+$,...
  - **BESIII**
    - ☑ $\Sigma^- \to pe^-e^-$
    - ☑ $\Xi^- \to \Sigma^+ e^- e^-$, ...
  - ...

No evidence for 0νββ has been observed. Experimental limits continue to improve.

BSM theories for ΔL=2

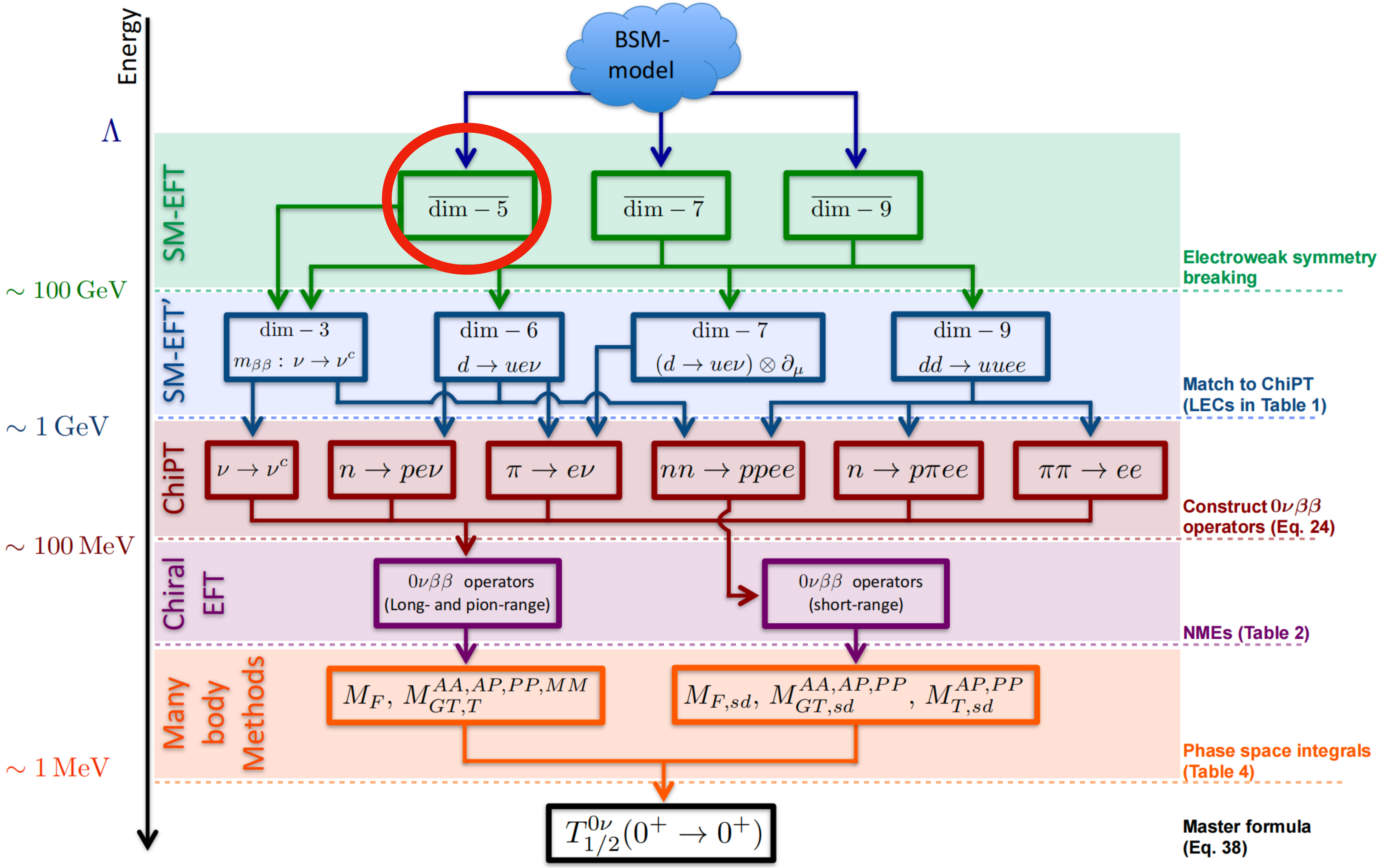


Cirigliano et al, JHEP 12(2018),097

Lepton-Number Violation (LNV)

- very high scales: $\Lambda_{LNV} \gg \Lambda_{EW}$
- higher-dimensional operators
- $0\nu\beta\beta$: odd dimension [Kobach, PLB (2016)]
- suppressed by powers of Λ_{LNV}
  - Dim-5: $1/\Lambda_{LNV}$
  - Dim-7: $1/\Lambda_{LNV}^3$
  - Dim-9: $1/\Lambda_{LNV}^5$
  - ...

BSM theories for ΔL=2



Cirigliano et al, JHEP 12(2018),097

Low energy realization from dim-5 Weinberg operator

$$\mathcal{L}^{\text{eff}} = -\frac{1}{\Lambda_{\text{LNV}}}(\bar{\psi}_L\tilde{H})YC(\bar{\psi}_L\tilde{H})^T + \text{H.c.}$$

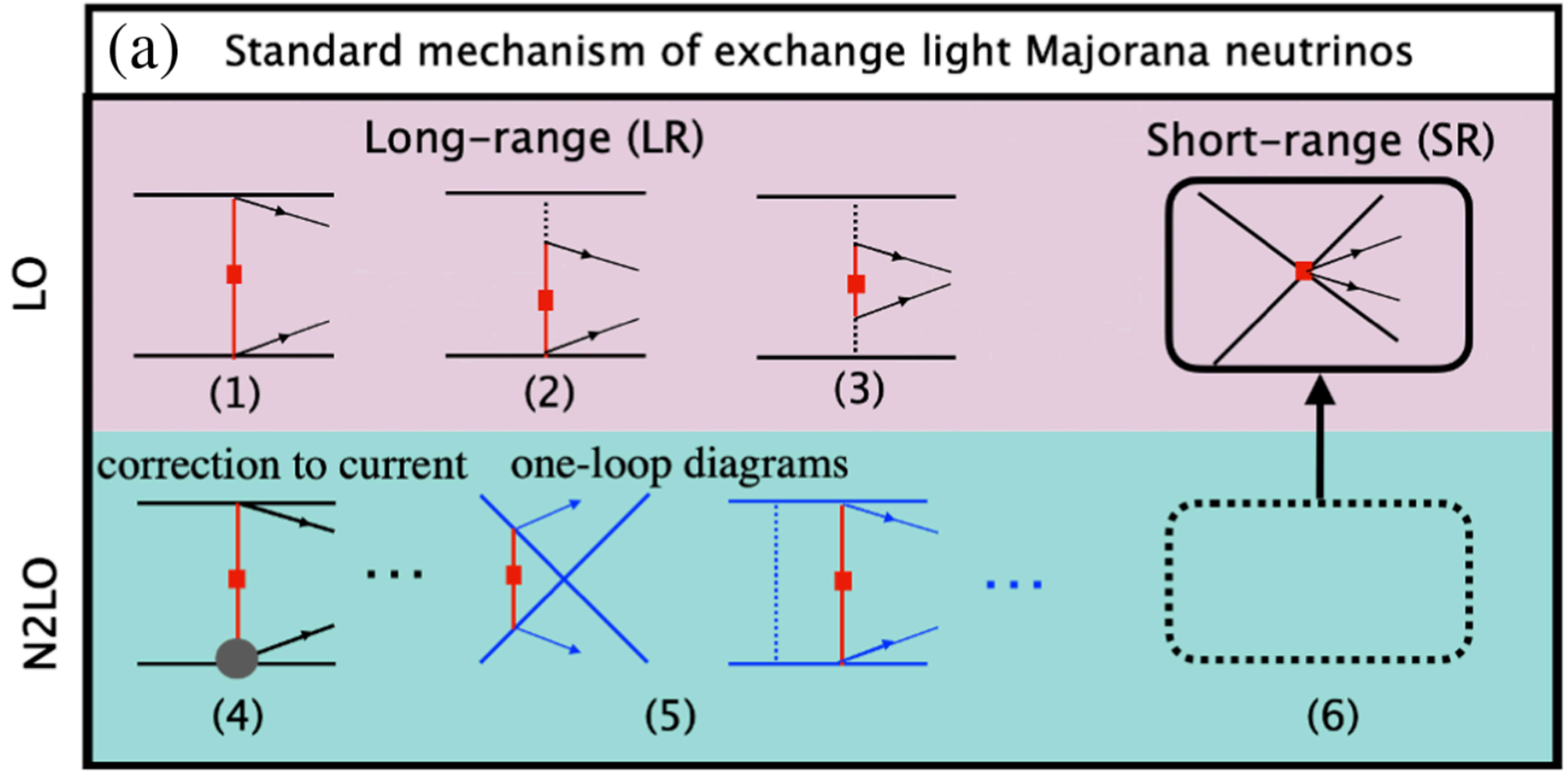
Majorana mass term

$$\mathcal{L}_{\text{M}}^{\text{eff}} = -\frac{1}{2}\frac{v^2}{\Lambda_{\text{LNV}}}\bar{\nu}_L Y C\bar{\nu}_L^T + \text{H.c.}$$

$$m \sim v^2/\Lambda_{LNV}$$

$0\nu\beta\beta$ transition of $nn \to pp$

Elementary transition for $(A,Z) \to (A,Z+2) + e^-e^-$ **:** $nn \to ppe^-e^-$



Belley et al, PRL132, 182502 (2024)

ChiEFT studies

- Cirigliano et al, PRL 120, 202001 (2018)
- Wirth et al, PRL 127, 242502(2024)
- Yang & Zhao, PLB 855, 138782(2024)
- Gofferier, PRD 111,055033(2025)
- …..

- Cirigliano et al, PRC 97, 065501 (2018)
- ……

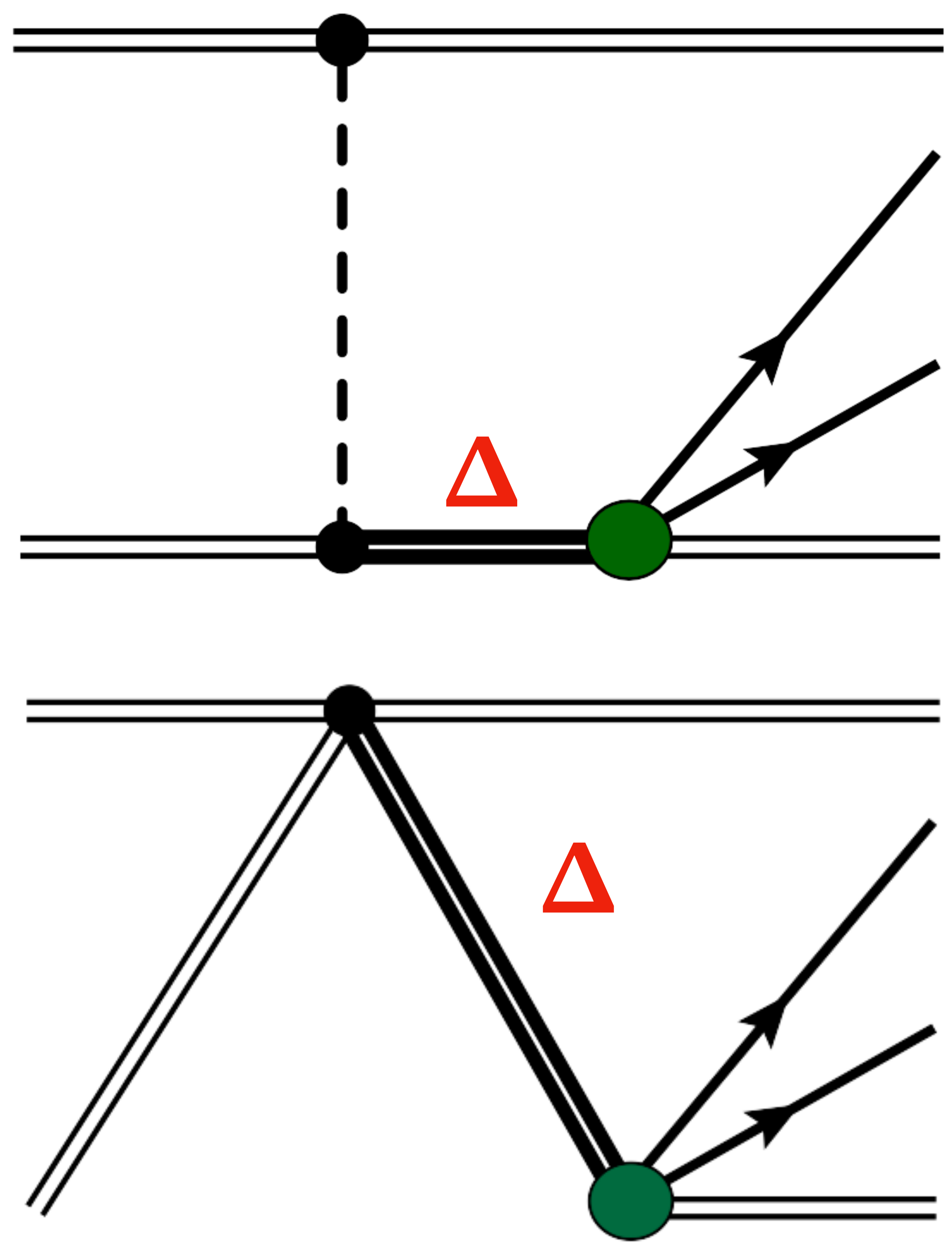
NLO: Yang & Zhao, PRL 134, 242502 (2025)

$0\nu\beta\beta$ transition of $nn \to pp$

Elementary transition for $(A,Z) \to (A,Z+2) + e^- e^-$: $nn \to ppe^-e^-$

Additional contribution at NNLO

- Δ(1232) resonance couples strongly to πN
- more accuracy in a Δ-full theory
  [Hemmert et al, J. Phys. G 24, 1831 (1998), Yao et al, JHEP 05(2016), 038]
- more natural LECs
  [Epelbaum et al, Rev. Mod. Phys (2009), Machleidt&Entem, Phys. Rept (2011), …]

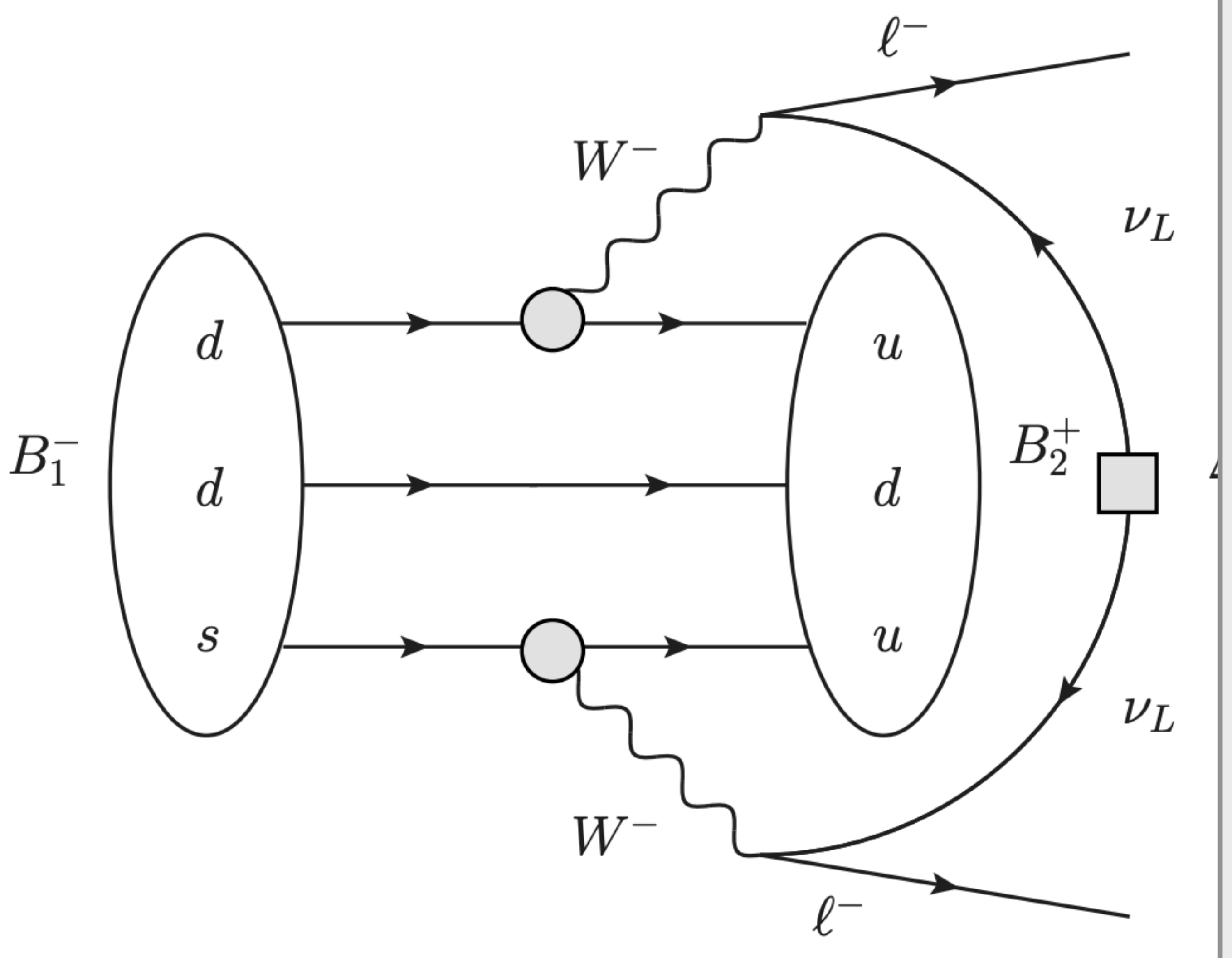


LQCD accessible to $\Delta^- \to pe^-e^-$ with large pion mass

- pion-mass dependence of the decay amplitude

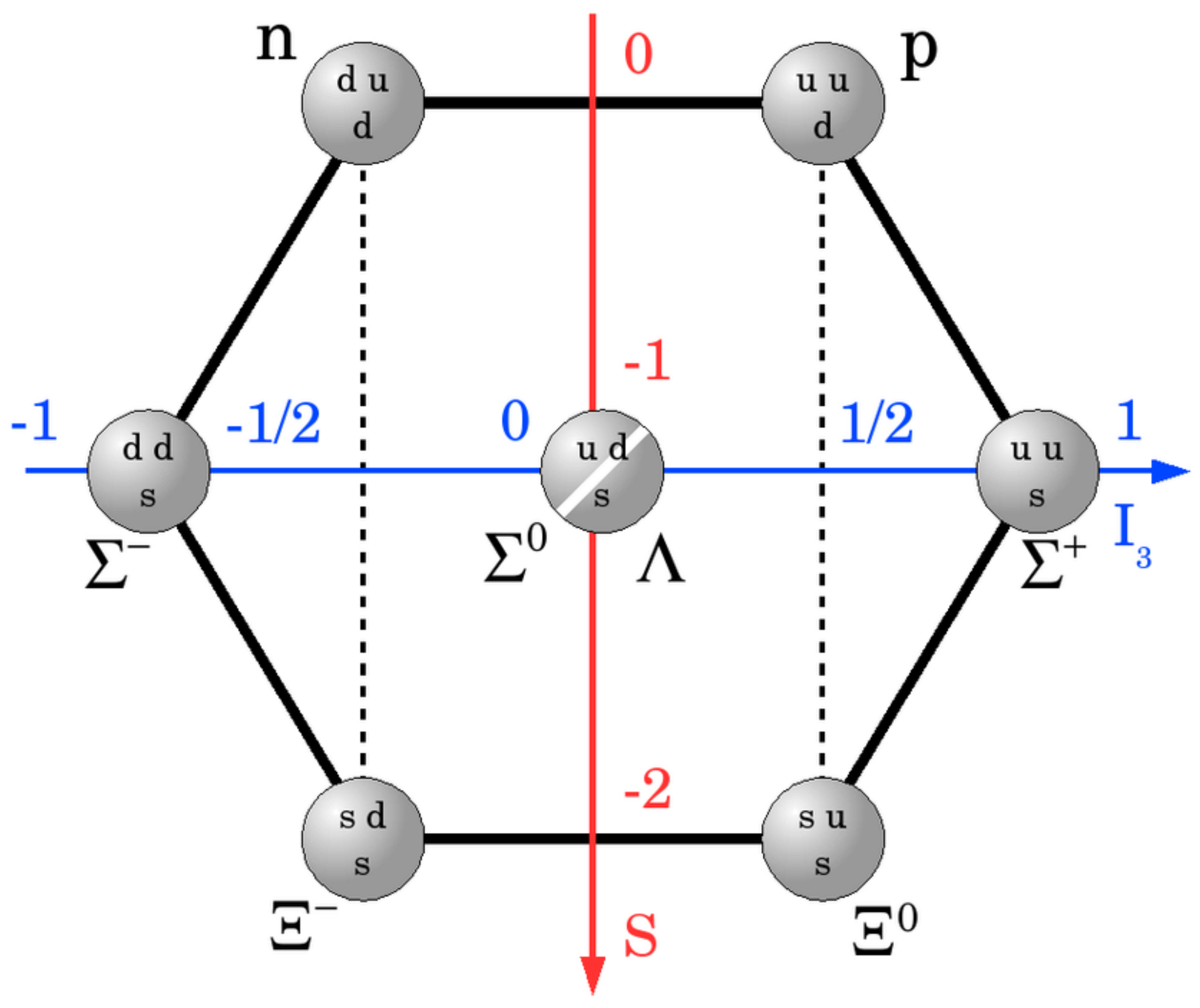
$0\nu\beta\beta$ decay of light baryons in χEFT

Ground states of light baryons: baryon octet (stable against strong decays)



$0\nu\beta\beta$ transitions:

Quark level	hadronic level
∘ dd $\Rightarrow$ uu ($\Delta S = 0$):	$\Sigma^- \to \Sigma^+$
∘ ds $\Rightarrow$ uu ($\Delta S = 1$):	$\Sigma^- \to p, \Xi^- \to \Sigma^+$
∘ ss $\Rightarrow$ uu ($\Delta S = 2$):	$\Xi^- \to p$



χEFT : low energy realization of QCD with hadronic degrees of freedom

- approximate chiral symmetry
- spontaneous symmetry breaking
- systematic description order by order with power counting p/Λ_χ

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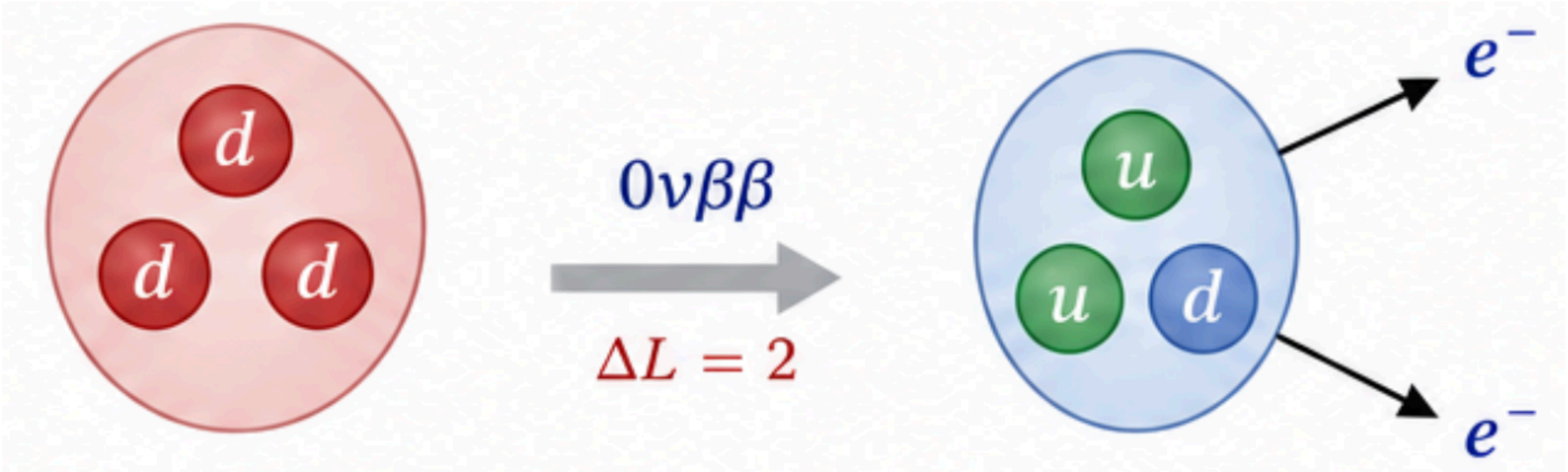
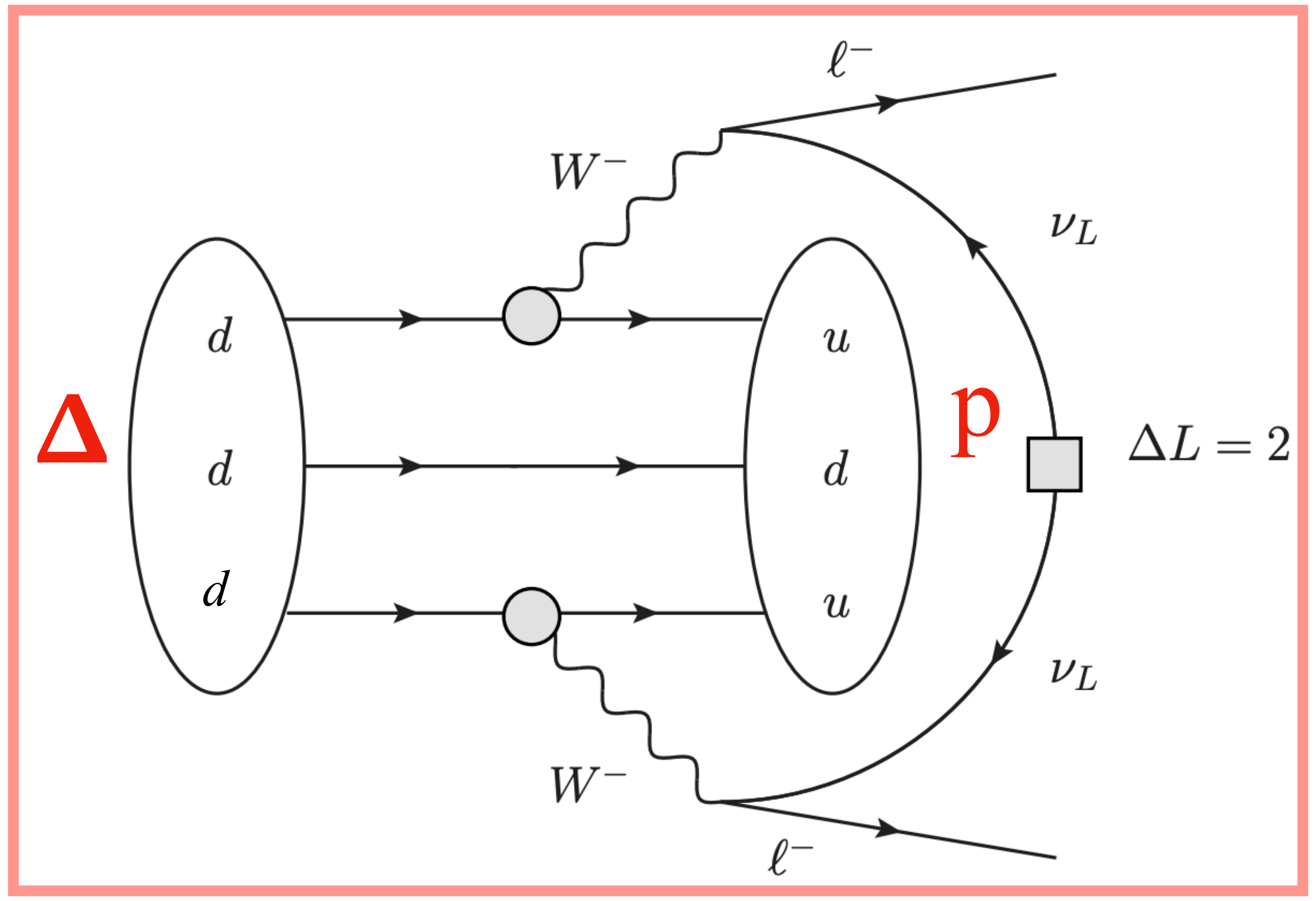
$0\nu\beta\beta$ decay of Δ^- resonance

arXiv:2604.12535, LPH, Feng-Kun Guo, Ulf Meissner, De-Liang Yao, Xiao-Yu Zhang and Zhen-Hua Zhang

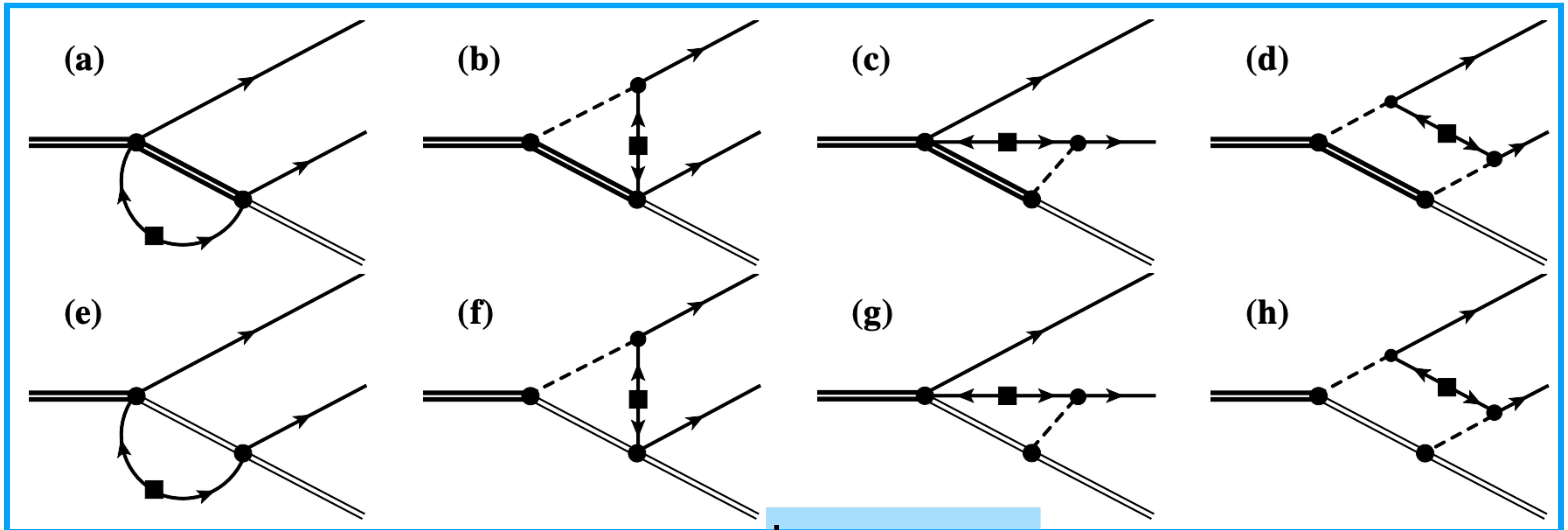
$0\nu\beta\beta$ decay of $\Delta^- \to p$

$\Delta^- \to p e^- e^-$

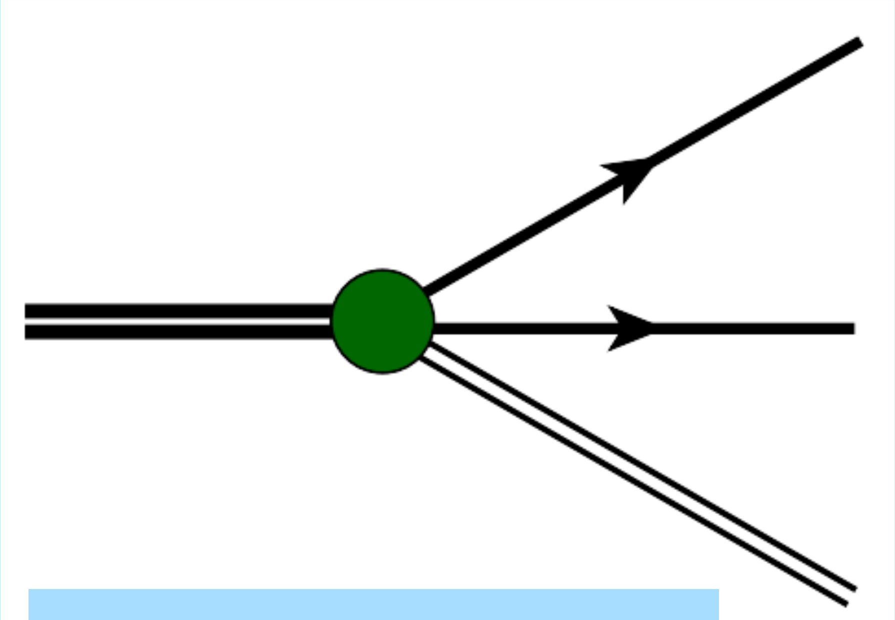




Quark level



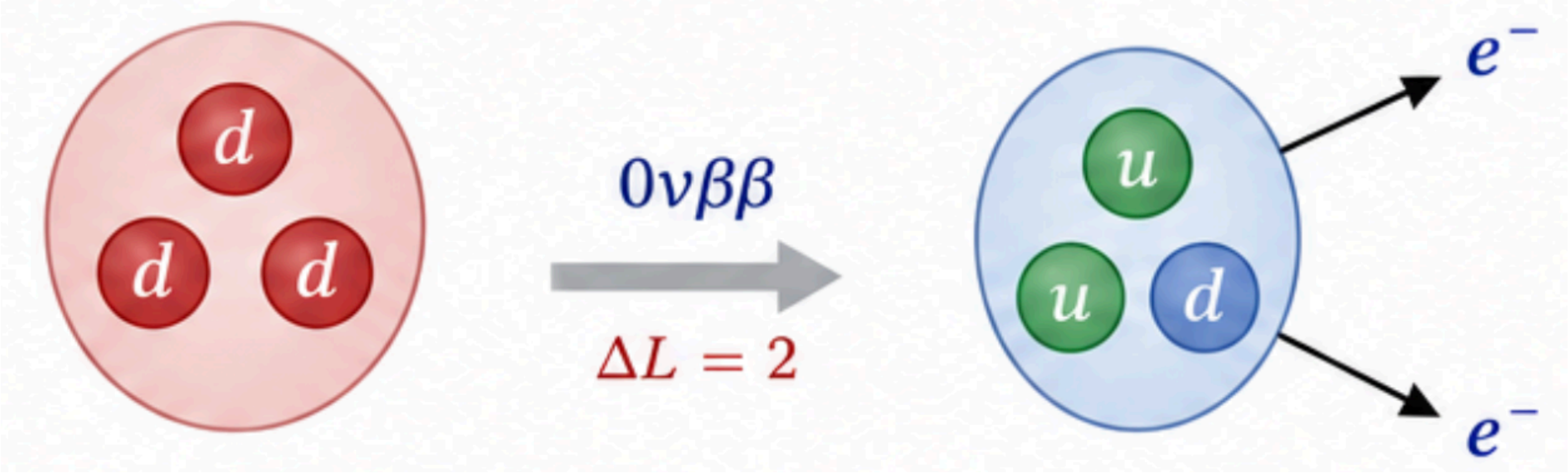
Hadronic level
(χEFT at $\mathcal{O}(p^3)$)

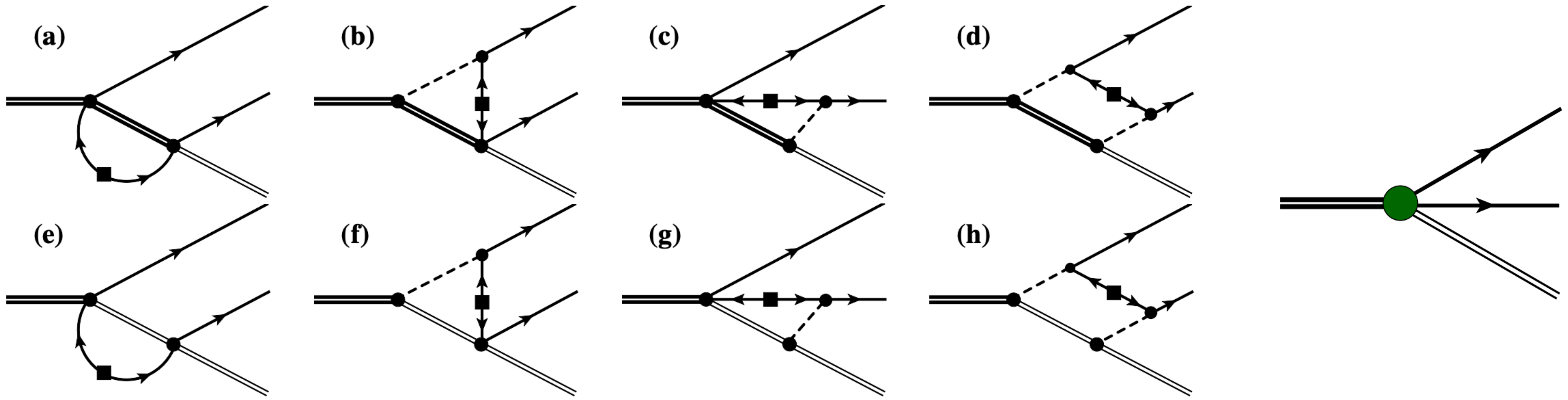


long-range

short-range

$0\nu\beta\beta$ decay of $\Delta^- \to p$





transition amplitude $\mathcal{M} = G\,\bar{u}_N(p_2)\left[T_S^{\alpha}\bar{u}_L(q_1)C\bar{u}_L^T(q_2) - iT_A^{\alpha,\mu\nu}\bar{u}_L(q_1)\sigma_{\mu\nu}C\bar{u}_L^T(q_2)\right]u_\alpha(p_1)$

$G \equiv (2\sqrt{2}G_F V_{ud})^2 m_{\beta\beta}h$ and $\sigma_{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$

Symmetric T:

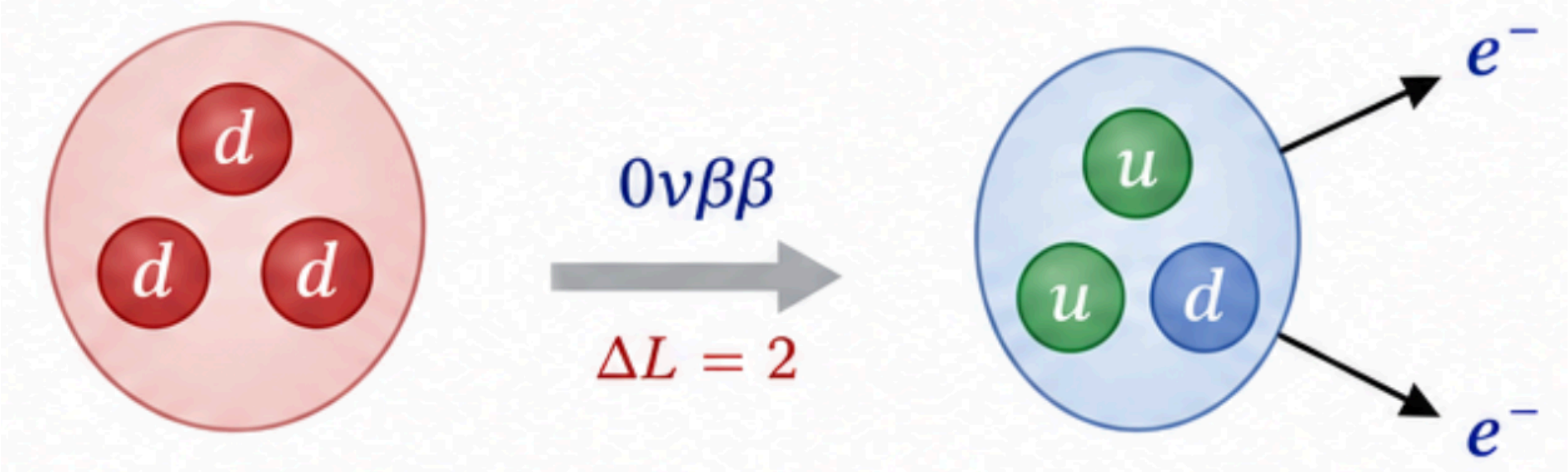
Antisymmetric T:

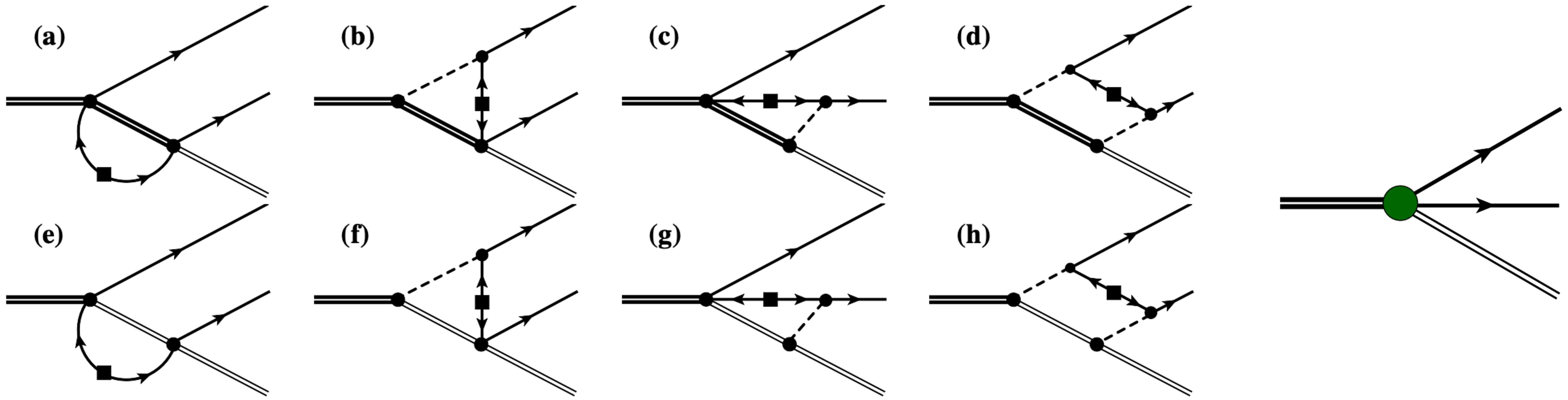
$$\begin{aligned} T_S^{\alpha} &= (T_t^{\alpha,\mu\nu} + T_u^{\alpha,\mu\nu})g_{\mu\nu} \\ T_A^{\alpha,\mu\nu} &= T_t^{\alpha,\mu\nu} - T_u^{\alpha,\mu\nu}, \end{aligned}$$

Power counting: $M \sim \mathcal{O}(p^3), T \sim \mathcal{O}(p)$

simple case: $q_1 = q_2 = q$: $\begin{cases} T_S^{\alpha}(q) = T\,q^{\alpha} + T'\,q^{\alpha}\gamma_5 \\ T_A^{\alpha,\mu\nu}(q) = 0 \end{cases}$

$0\nu\beta\beta$ decay of $\Delta^- \to p$





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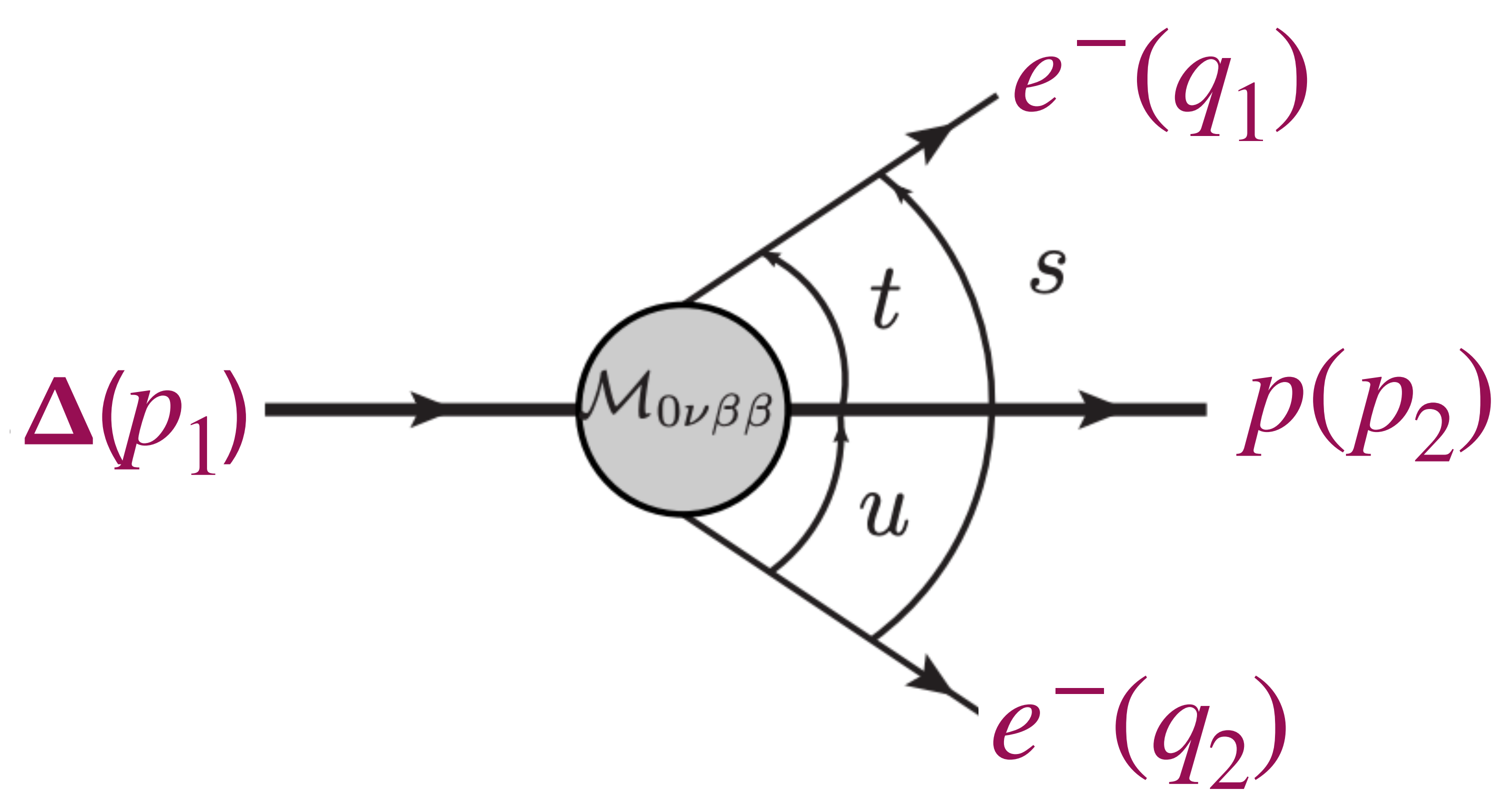
$0\nu\beta\beta$ transition form factors

Pion mass dependence of the $0\nu\beta\beta$ decay of $\Delta^- \to p$

Mandelstam variables

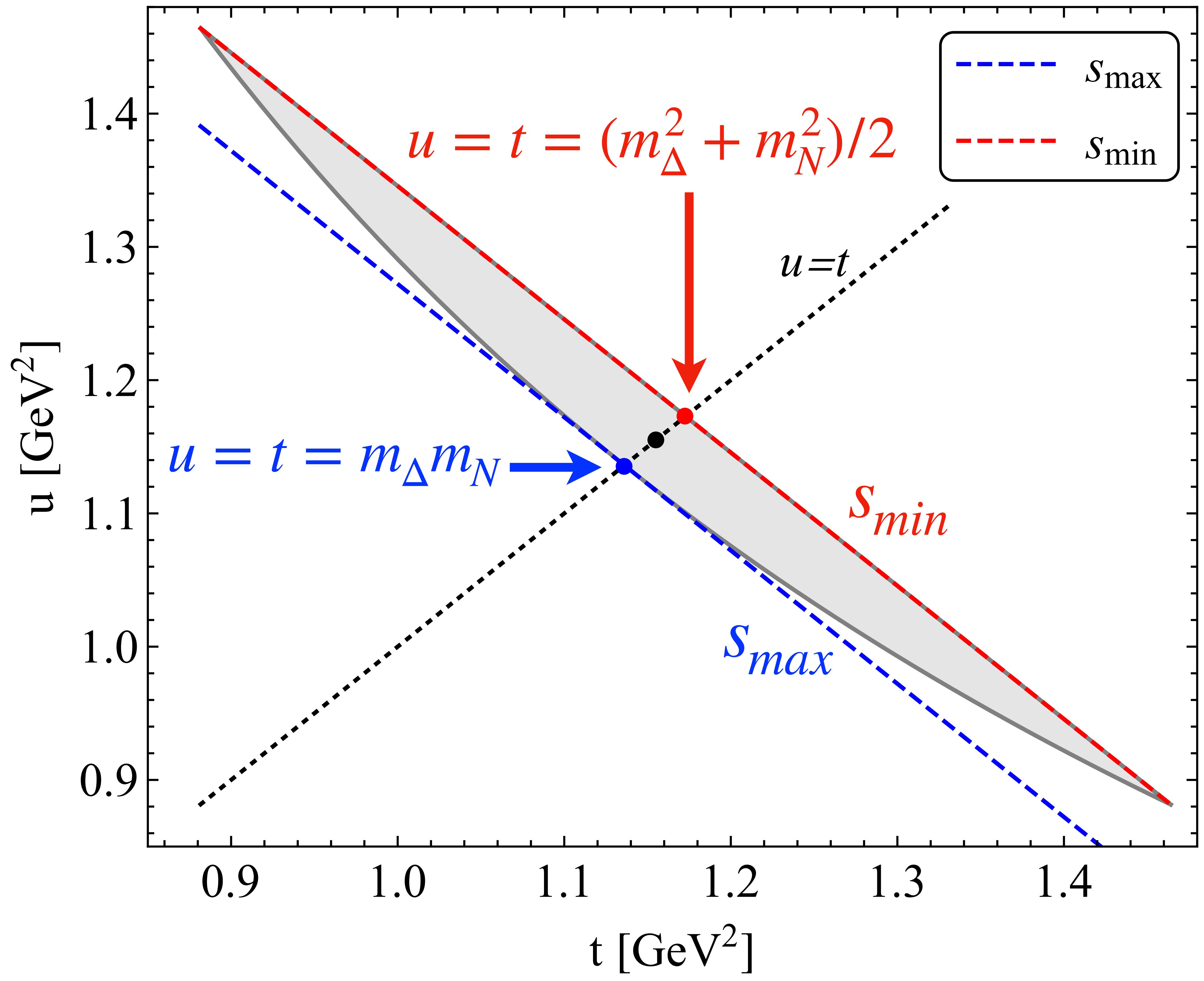


$$0 = s_{min} \leq s \leq s_{max} = (m_\Delta - m_N)^2$$

$$m_N^2 = t_{min} \leq t, u \leq t_{max} = m_\Delta^2$$

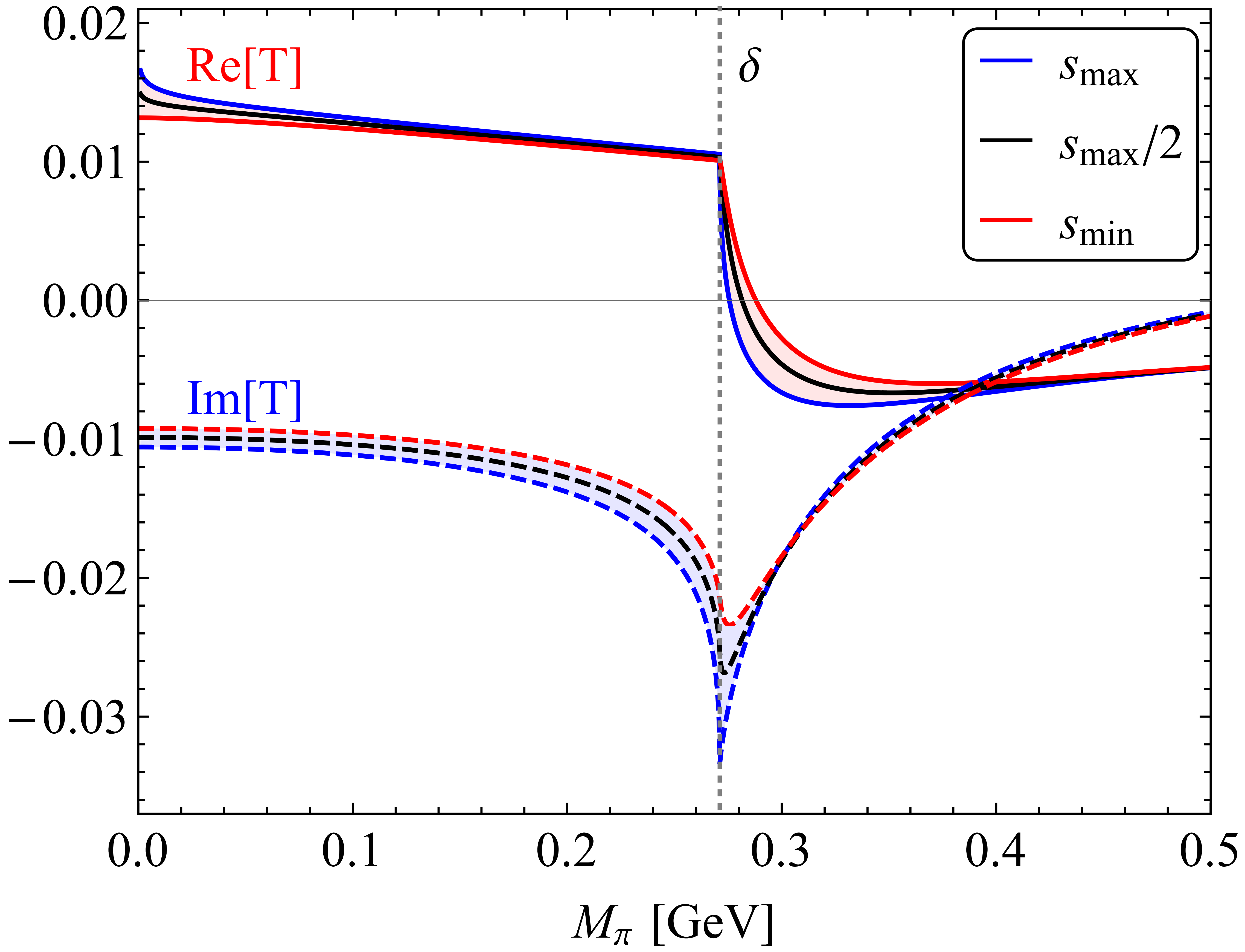
simple case: $q_1 = q_2 = q : u = t$

Dalitz plot region



Pion mass dependence of the $0\nu\beta\beta$ decay of $\Delta^- \to p$

$$q_1 = q_2 = q: \qquad \mathcal{M} \sim \bar{u}_N(p_2)\,(Tq^\alpha + T'q^\alpha\gamma_5)\,u_\alpha(p_1)\bar{u}_L(q_1)C\bar{u}_L(q_2)$$



- LECs independent
- Chiral limit: $\propto \log M_\pi$
- Imaginary part

Pion mass dependence of the 0νββ decay of $\Delta^- \to p$

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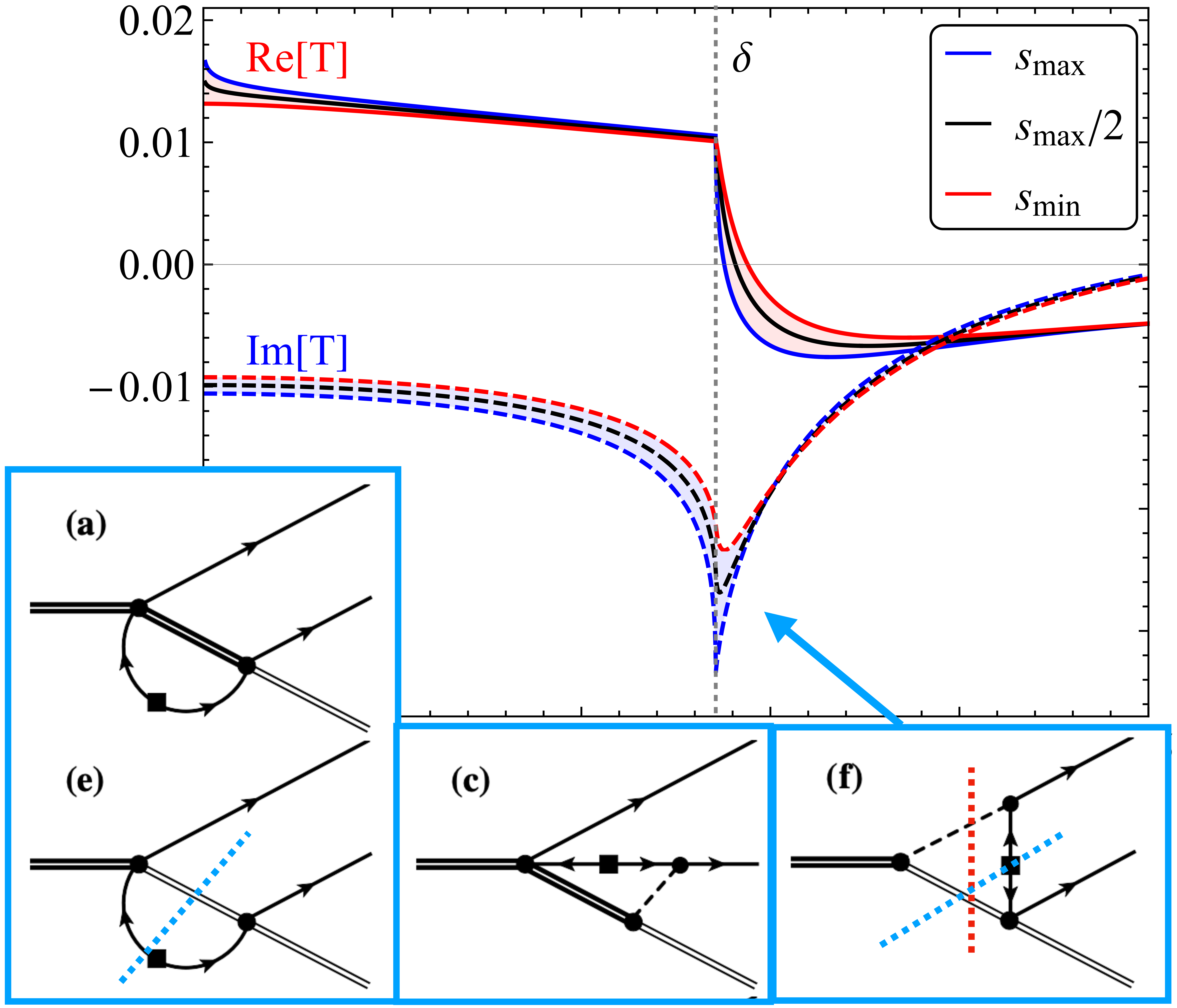

- LECs independent
- Chiral limit: $\propto \log M_\pi$
- Imaginary part from (e,f)
- Contributions from (a,c,e,f)

$$T_{(a)} \simeq -0.003\,,$$
$$T_{(e)} \simeq 0.010 + 0.006i$$

- Landau singularities [cusp & triangle singularity in (f)] ➡ sensitivity to M_π and s

Pion mass dependence of the $0\nu\beta\beta$ decay of $\Delta^- \to p$

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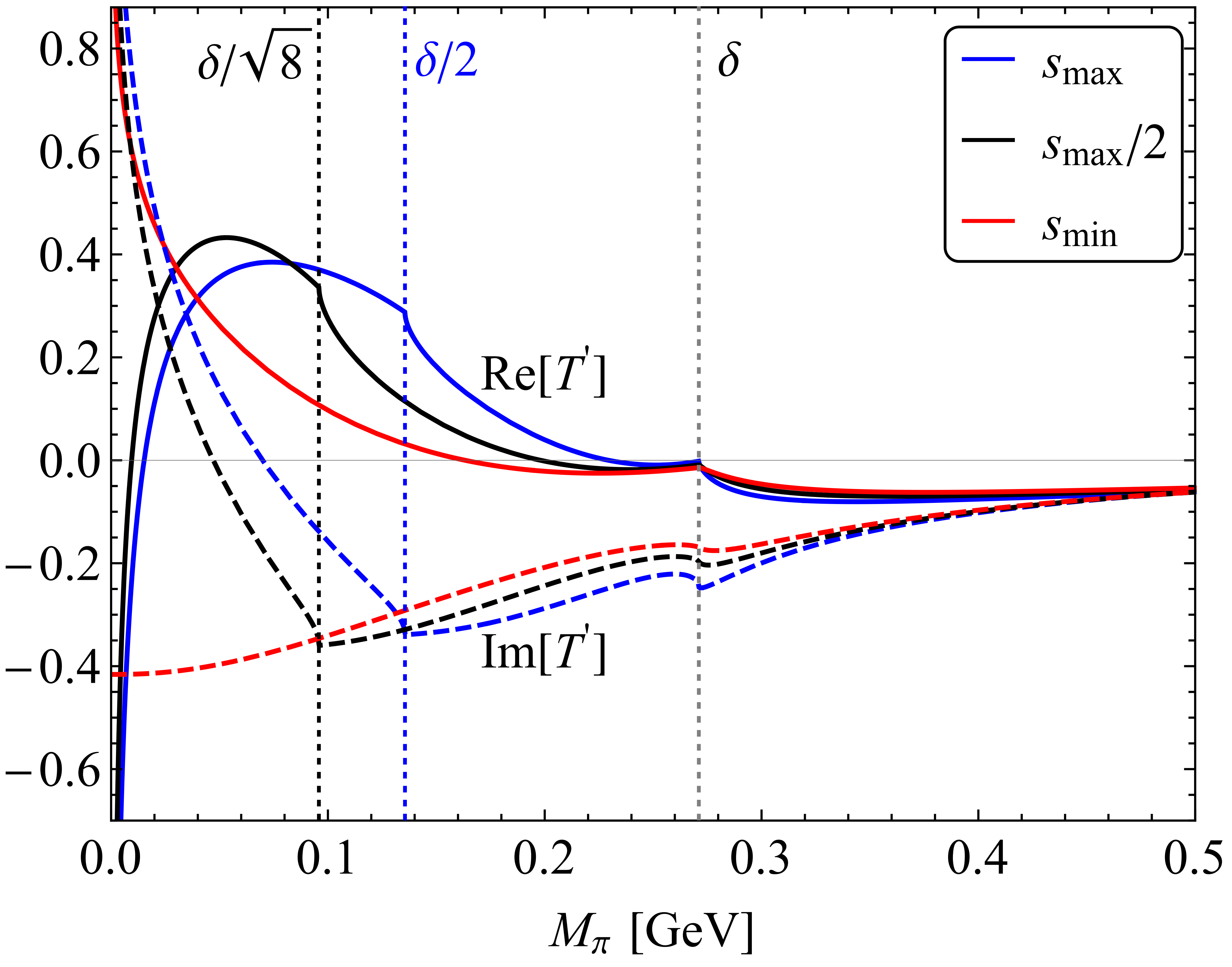
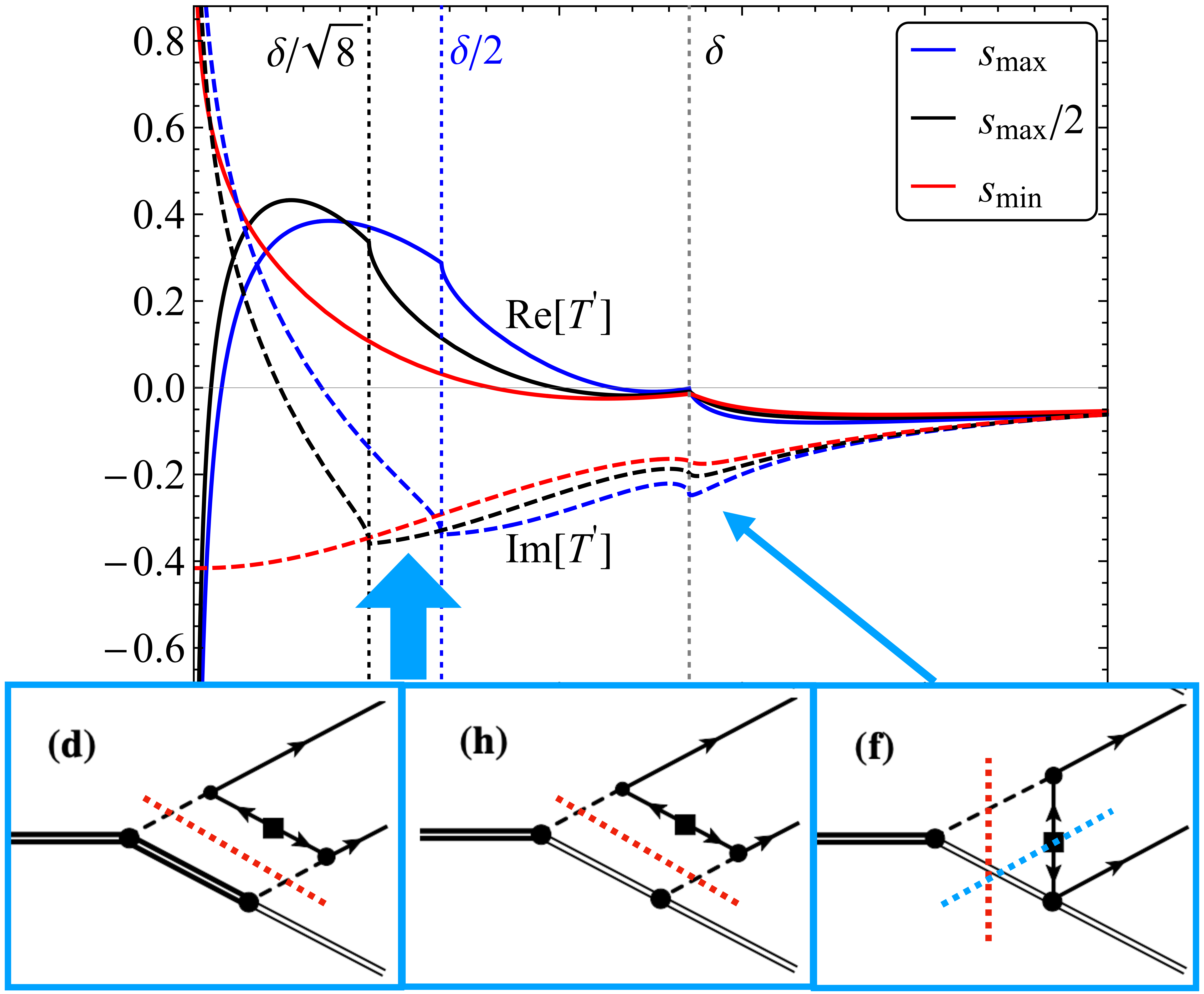


- LECs dependent (g_A, g_1)
- Chiral limit: $\propto \log M_\pi$
- Imaginary part

Pion mass dependence of the 0$\nu\beta\beta$ decay of $\Delta^- \to p$

$$q_1 = q_2 = q: \qquad \mathscr{M} \sim \bar{u}_N(p_2)\,(Tq^\alpha + T'q^\alpha\gamma_5)\,u_\alpha(p_1)\bar{u}_L(q_1)C\bar{u}_L(q_2)$$



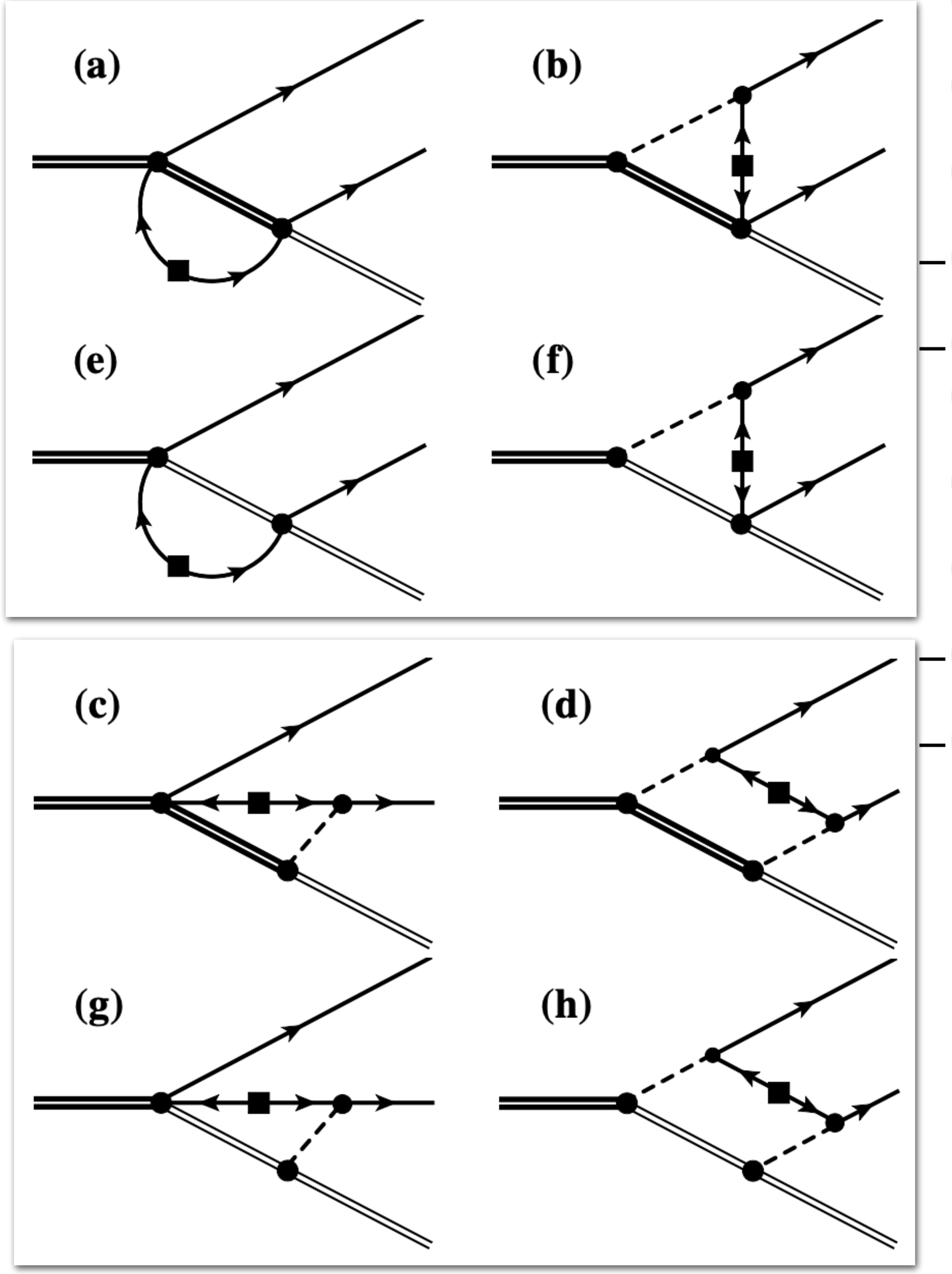
- LECs dependent (g_A, g_1)
- Chiral limit: $\propto \log M_\pi$
- Imaginary part from (d,e,f,g,h)
- Contributions from all diagrams

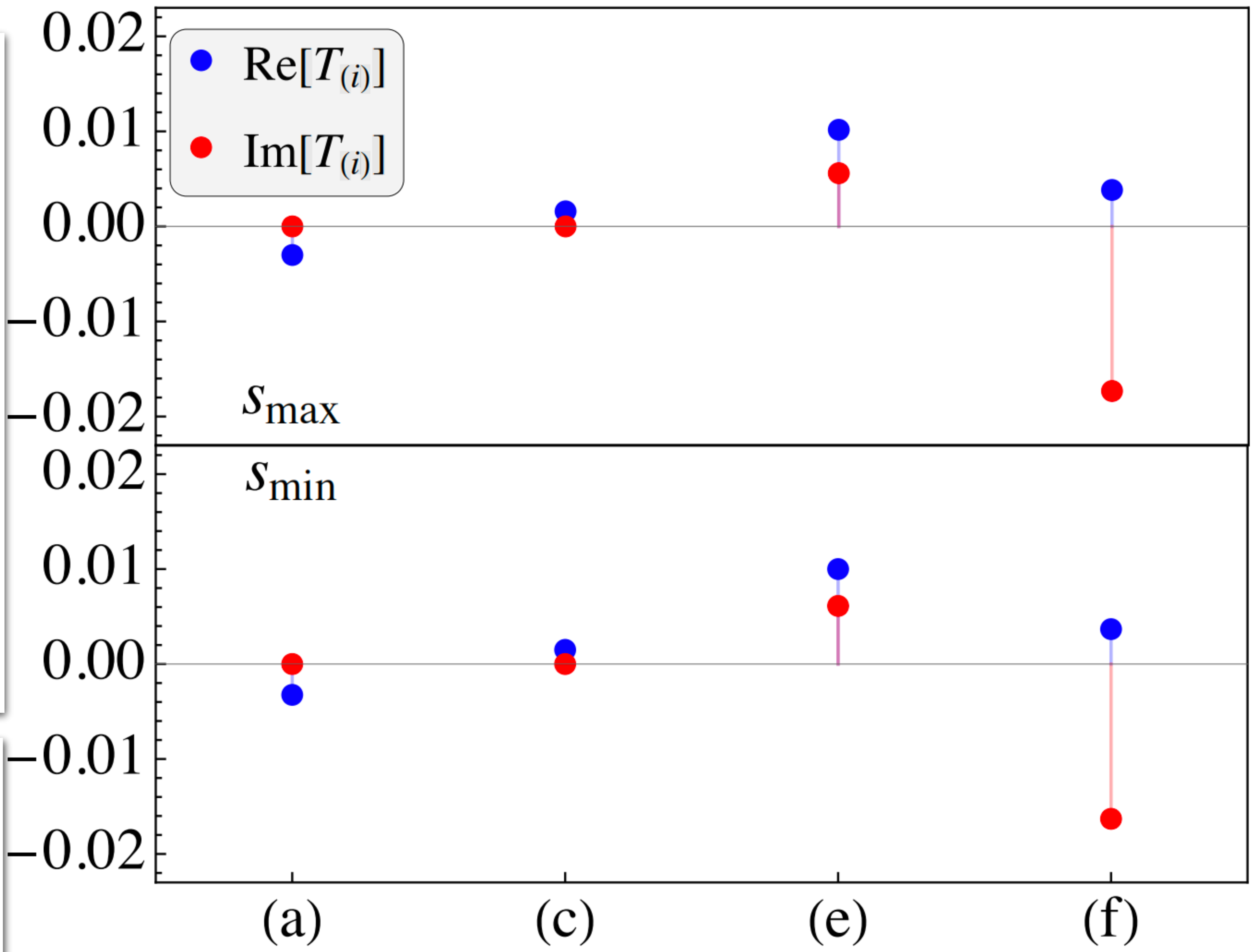
$$T'_{(a)} \simeq -0.005\,,$$
$$T'_{(e)} \simeq 0.013 + 0.0075i$$

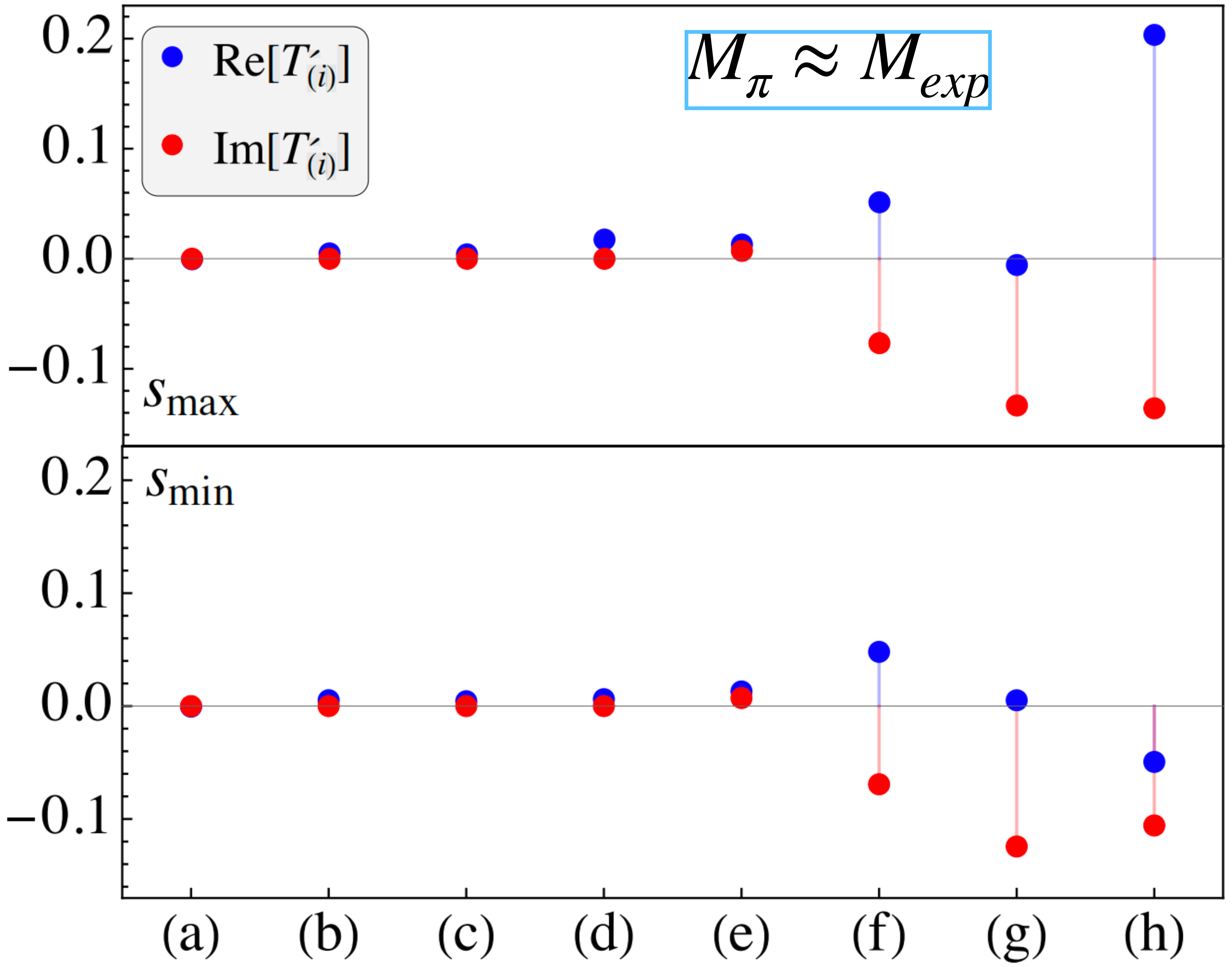
- Landau singularities [cusp & triangle singularity] ➡ sensitivity to M_π and s

Contributions from each diagram

$$q_1 = q_2 = q: \qquad \mathcal{M} \sim \bar{u}_N(p_2)\,(Tq^\alpha + T'q^\alpha\gamma_5)\,u_\alpha(p_1)\bar{u}_L(q_1)C\bar{u}_L(q_2)$$





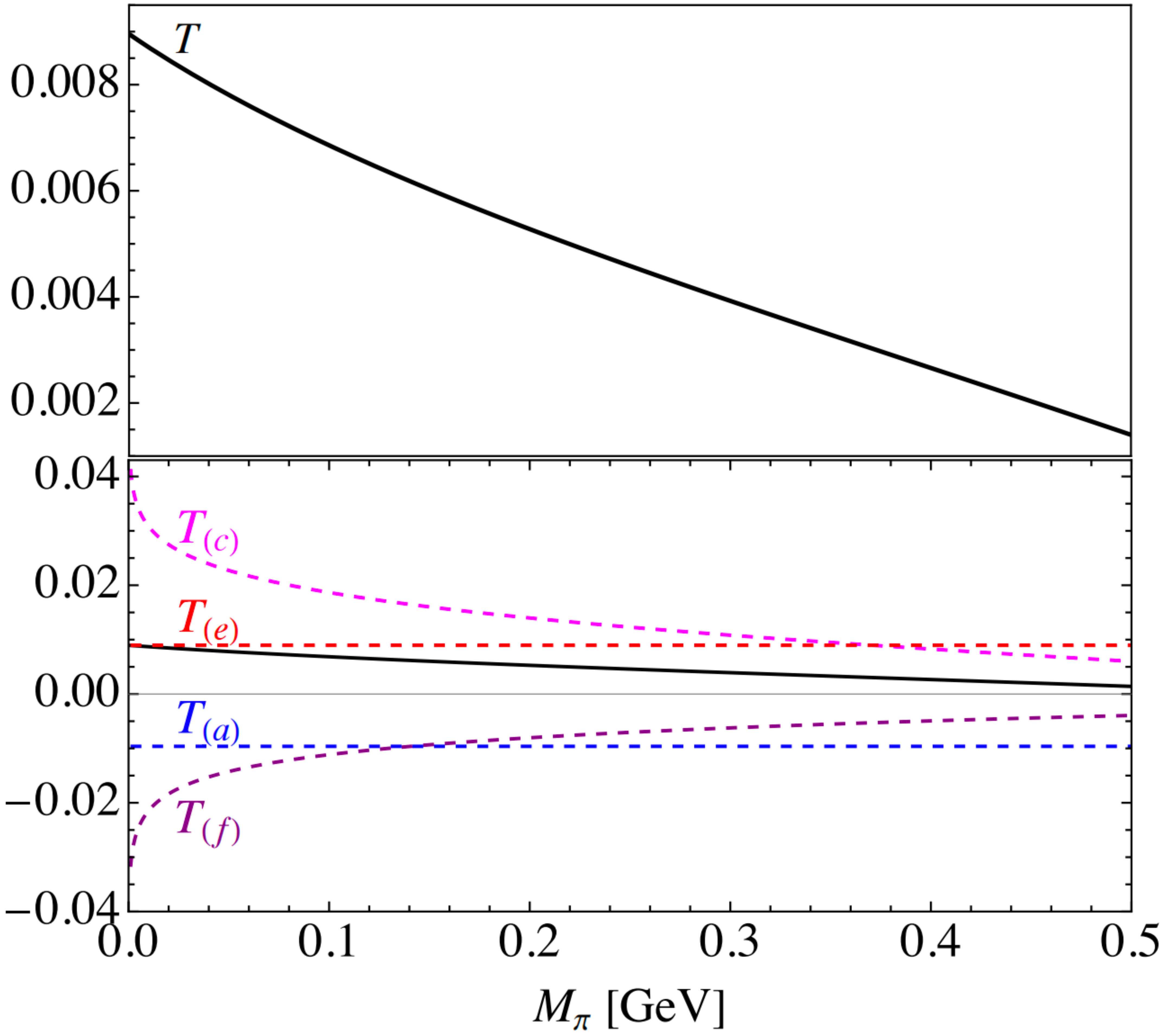


- Contributions with a Δ propagator is suppressed
- Additional suppression from $m_\Delta - m_N \sim \mathcal{O}(p)$

Real decay amplitude in the limit $m_\Delta = m_N$

$$q_1 = q_2 = q: \qquad \mathcal{M} \sim \bar{u}_N(p_2)\,(Tq^\alpha + T'q^\alpha\gamma_5)\,u_\alpha(p_1)\bar{u}_L(q_1)C\bar{u}_L(q_2)$$

$$\boxed{q_1 = q_2 = q: \qquad \mathcal{M} \sim \bar{u}_N(p_2)\,T\,q^\alpha\,u_\alpha(p_1)\bar{u}_L(q_1)C\bar{u}_L(q_2)}$$



$$T_{\rm SR} = 4\sqrt{2}ih_1^R\,,$$

$$T_{\rm LR} = \frac{1}{288\sqrt{2}\pi^2 m_N^6}\Big[\left(10M_\pi^4 m_N^2 - 30M_\pi^2 m_N^4 - M_\pi^6 + 18m_N^6\right)\log\frac{M_\pi^2}{m_N^2} + 6m_N^4\left(2M_\pi^2 + 3m_N^2\right)\log\frac{\mu^2}{M_\pi^2} + m_N^2\left(3m_N^2 - 2M_\pi^2\right)\left(12m_N^2 - M_\pi^2\right) - 2M_\pi(4m_N^2 - M_\pi^2)^{5/2}\log\frac{\sqrt{M_\pi^2 - 4m_N^2} + M_\pi}{2m_N}\Big]\,,$$

- contributions from (a,c) enhanced
- logarithmic $\log M_\pi$ cancels
- chiral limit:

$$T = 4\sqrt{2}ih_1^R + \frac{1}{16\sqrt{2}\pi^2}\left(\log\frac{\mu^2}{m_N^2} + 2\right)$$

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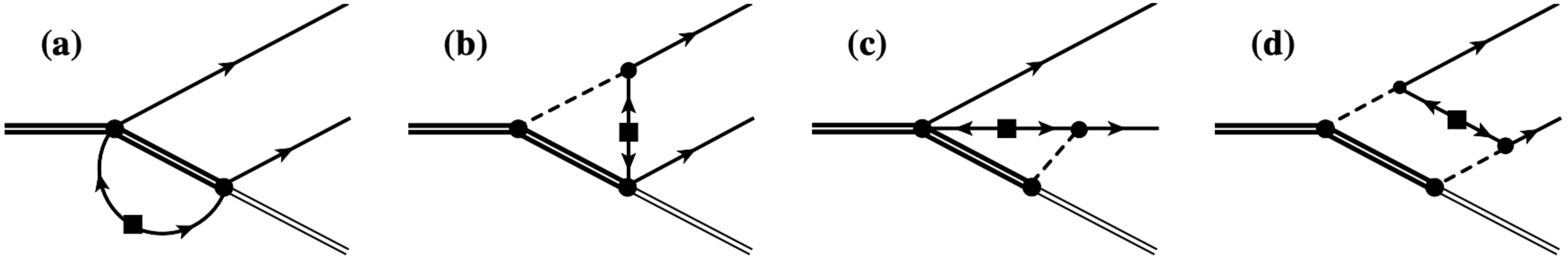
$0\nu\beta\beta$ decay of hyperons

arXiv:2602.08453, Zi-Ying Zhao, Ze-Rui Liang, Feng-Kun Guo, LPH, and De-Liang Yao

$0\nu\beta\beta$ decay of hyperons

Ground states of light baryons: baryon octet (stable against strong decays)

long-range:



$0\nu\beta\beta$ transitions:

- $\Delta S = 0$: $\Sigma^- \to \Sigma^+$
- $\Delta S = 1$: $\Sigma^- \to p, \Xi^- \to \Sigma^+$
- $\Delta S = 2$: $\Xi^- \to p$

$m_\nu \sim 100$ meV

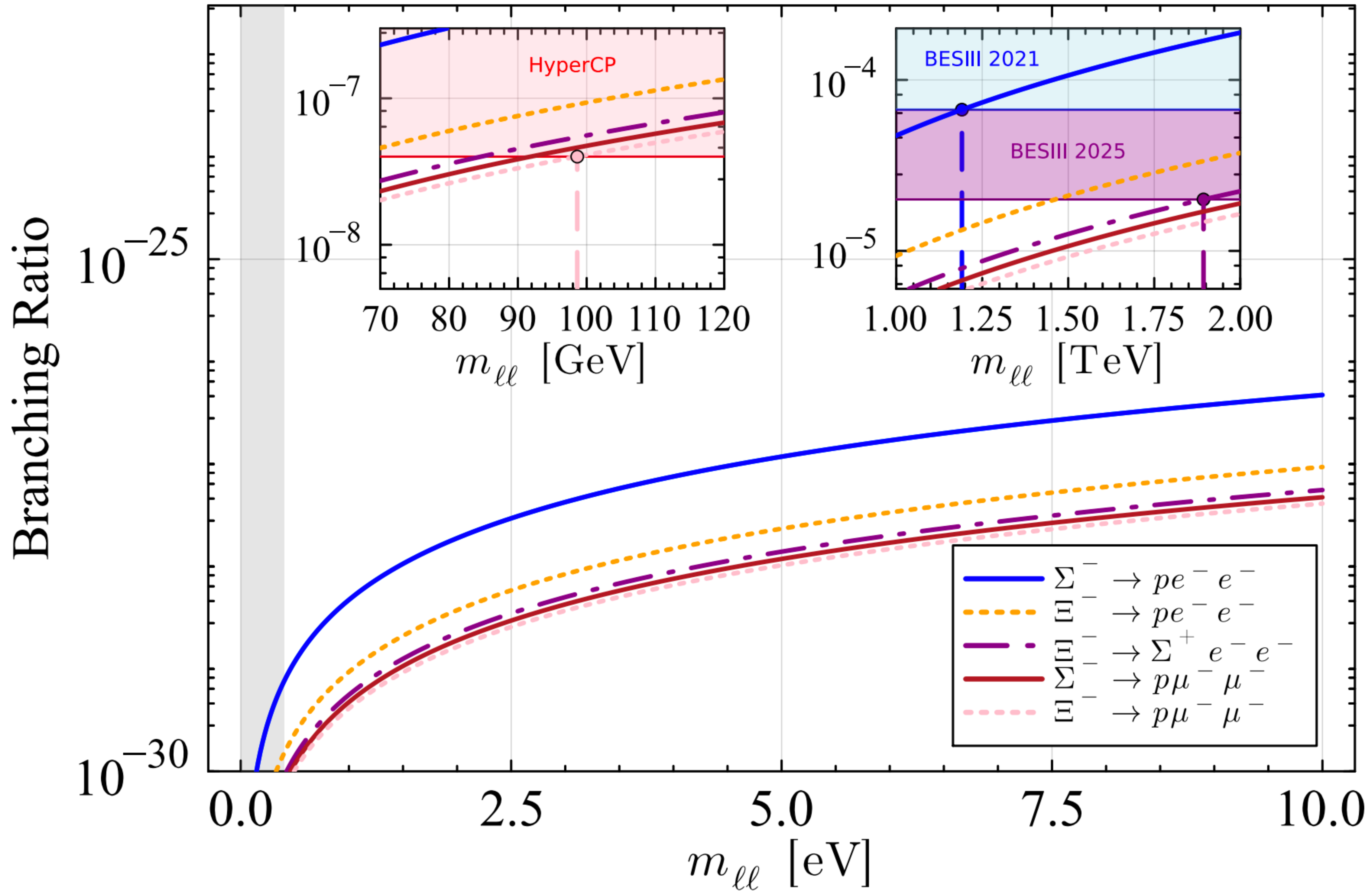
Process	$\mathcal{B}_{\text{Theory}}$	Experiment	
$\Sigma^- \to p\, e^- e^-$	4.7×10^{-31}	$< 6.7 \times 10^{-5}$ [BESIII]	2021
$\Sigma^- \to \Sigma^+ e^- e^-$	5.8×10^{-38}	—	
$\Sigma^- \to p\, e^- \mu^-$	1.9×10^{-31}	—	
$\Sigma^- \to p\, \mu^- \mu^-$	3.9×10^{-32}	—	
$\Xi^- \to \Sigma^+ e^- e^-$	5.6×10^{-32}	$< 2.0 \times 10^{-5}$ [BESIII]	2025
$\Xi^- \to \Sigma^+ e^- \mu^-$	1.2×10^{-33}	—	
$\Xi^- \to p\, e^- e^-$	9.4×10^{-32}	—	
$\Xi^- \to p\, e^- \mu^-$	6.2×10^{-32}	—	
$\Xi^- \to p\, \mu^- \mu^-$	4.1×10^{-32}	$< 4.0 \times 10^{-8}$ [HyperCP]	2005

arXiv:2602.08453, ZY Zhao et al

0νββ decay of hyperons

Ground states of light baryons: baryon octet (stable against strong decays)

long-range:



short-range:

$$\mathcal{L}_C^{(2)} = 4 m_{\ell\ell'} G_F^2 g_1 \mathrm{Tr}[\bar{B}\mathcal{Q}_L^{\mathrm{w}}] g_{\mu\nu} \mathrm{Tr}[\mathcal{Q}_L^{\mathrm{w}} B] \bar{\ell}_L \gamma^\mu \gamma^\nu C \bar{\ell}_L'^T + \mathrm{h.c.}$$

one order higher

Extremely small branching fractions.

Hyperon 0νββ decays are not expected to be observable at current colliders

Other mechanisms: higher-dim operators?

heavy sterile neutrino?

arXiv:2602.08453, ZY Zhao et al

Summary

- Neutrinoless double beta ($0\nu\beta\beta$) decay
  - determine if neutrinos are Majorana particles
  - constrain the effective neutrino mass
- $0\nu\beta\beta$ decay of $\Delta^- \to pee$
  - long-range from loop diagrams (light-ν exchange)
  - short-range from counter term (to be estimated)
  - transition form factor (accessible by LQCD)
- $0\nu\beta\beta$ decay of hyperons:
  - tiny branching fractions: $< 10^{-30}$ with $m_\nu \sim 0.1$ eV

Thank you for your attention!