Universidad Autónoma de Madrid

Instituto de Física Teórica UAM-CSIC

SUSY 2024
Theory meets Experiment

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EXCELENCIA SEVERO OCHOA

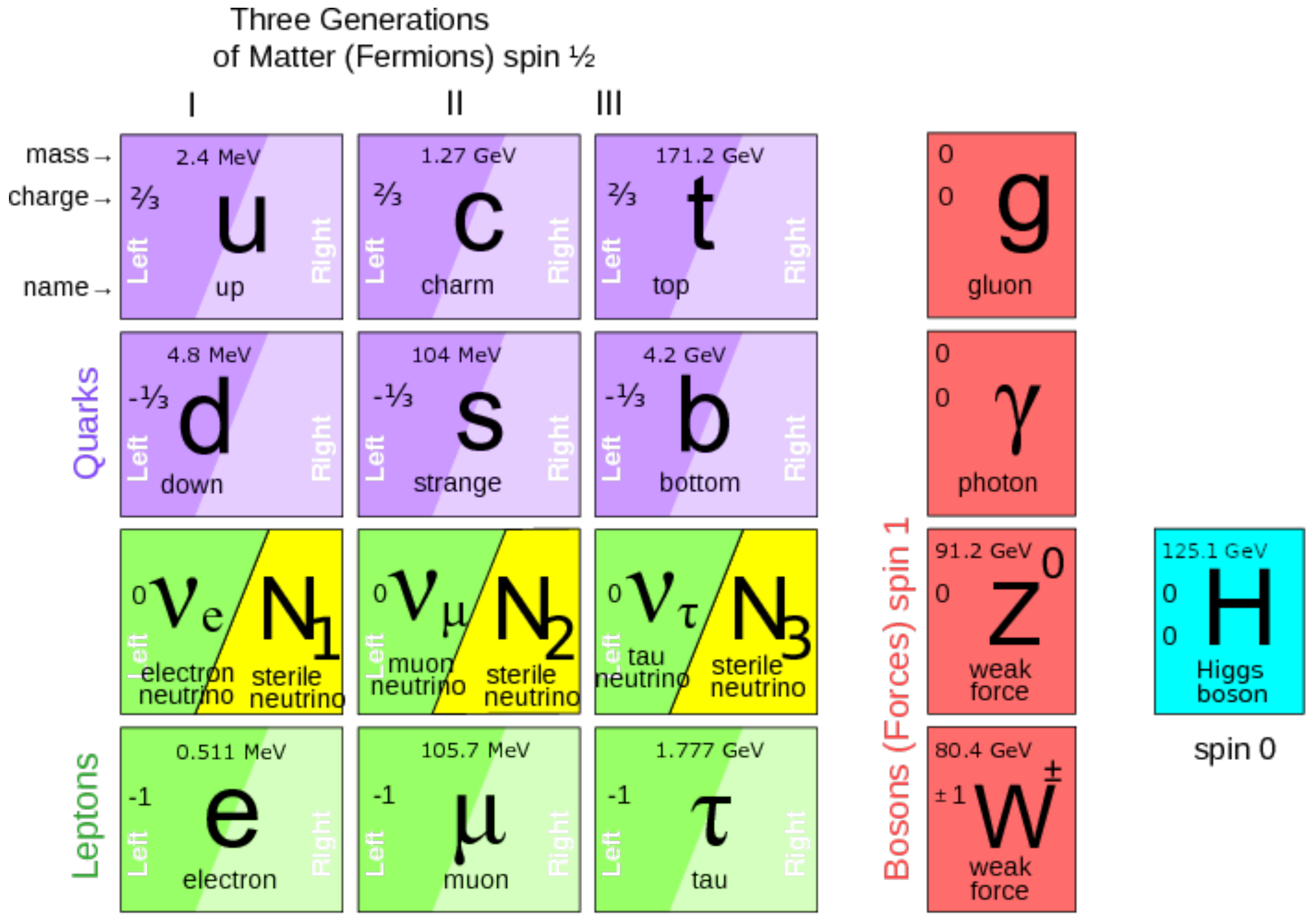
ALPs or HNLs? Pick two!

Based on [2212.11290] and [24XX.YYYY] (to appear soon)
by Marta Burgos Marcos, Arturo de Giorgi, Luca Merlo and Jean-Loup Tastet

Jean-Loup Tastet <jean-loup.tastet@uam.es> · SUSY24 · Madrid · 2024-06-14

Heavy neutral leptons (HNLs)

Or heavy right-handed neutrinos



- The missing $SU(2)_L$ singlet neutrinos
- Completely neutral under SM gauge, allowing both:
  - Yukawa term (EWSB → Dirac mass)

    $$-(Y^{\nu}_{\alpha I})^*(L_\alpha \cdot \tilde{\phi}^\dagger)N_{R,I} \longrightarrow (m_D)_{\alpha I}\nu_{L,\alpha}N_{R,I}$$

  - Majorana mass

    $$-\frac{M_I}{2}(N_{R,I}N_{R,I} + N^\dagger_{R,I}N^\dagger_{R,I})$$

Type-I see-saw mechanism

- Combining both mass terms: $-\frac{1}{2}\begin{pmatrix}\nu_L^T & N_R^T\end{pmatrix}\begin{pmatrix}0 & m_D^T \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L \\ N_R\end{pmatrix} + \mathrm{h.c.}$

- Mass diagonalisation leads to mixing: $\nu_{L,\alpha} \cong U^{\mathrm{PMNS}}_{\alpha,i}\nu_i + \Theta_{\alpha,I}N_{R,I}$

- Neutrinos are light if HNLs are heavy, i.e. $M_R \gg m_D$ (or $\Theta \ll 1$)
  Their masses are given by the see-saw formula:

$$m^{\mathrm{light}}_{\alpha\beta} \approx -\sum_I \frac{(m_D)_{\alpha I}(m_D)_{\beta I}}{M_I} \approx -\sum_I M_I \Theta_{\alpha I}\Theta_{\beta I}$$

Low-scale see-saw(s)

- Original see-saw: $Y^{\nu} \sim 1$ and $M_N \sim 10^{15}\,\mathrm{GeV}$
  $\rightarrow$ inaccessible in the foreseeable future

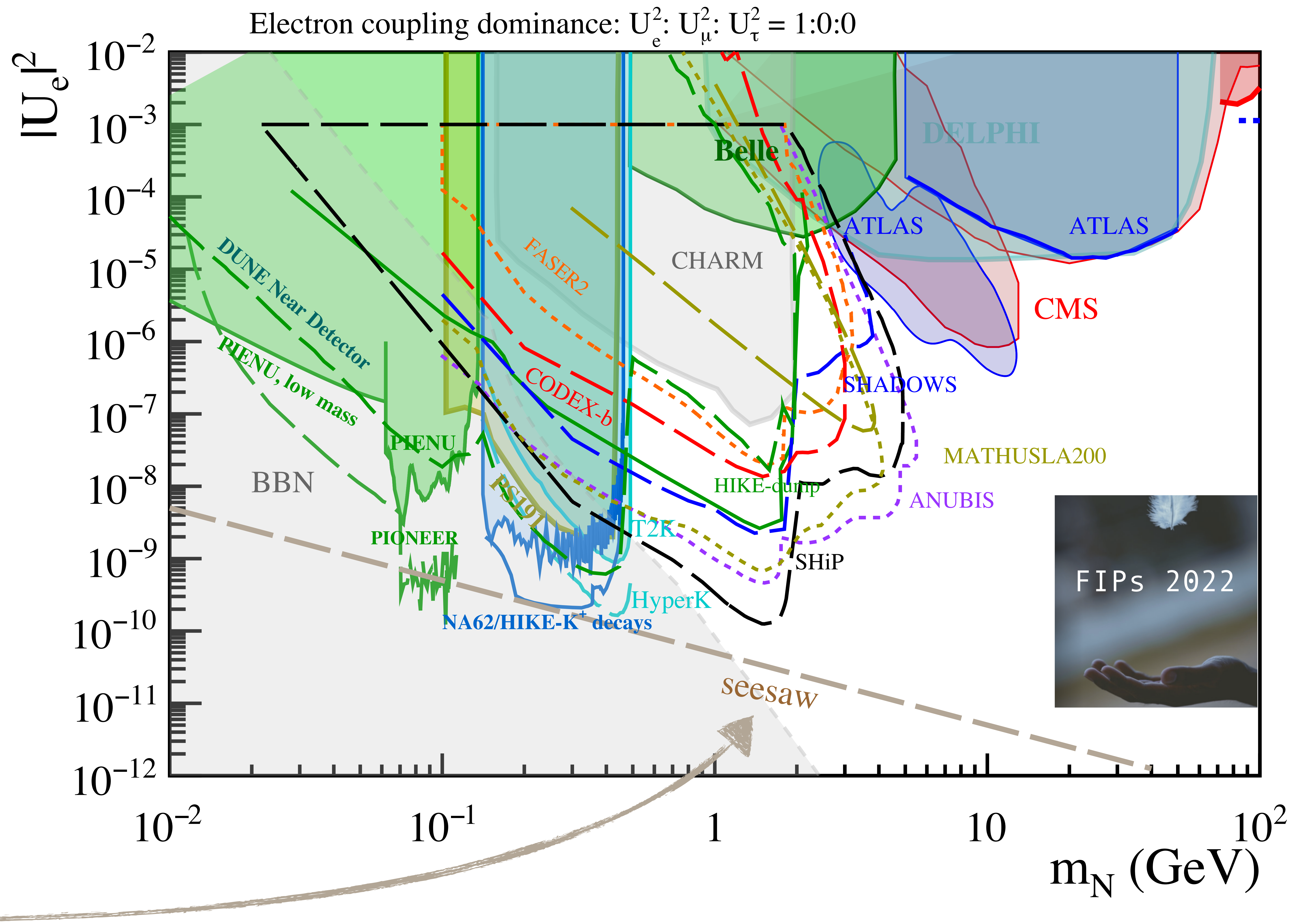
- Smaller Yukawas: $Y^{\nu} \sim 10^{-6} \sim Y^{e}$ and $M_N \sim \mathrm{TeV}$
  $\rightarrow$ still inaccessible to most experiments (on the "see-saw line") (unless an ALP is present!)

- Symmetry-protected (e.g. linear or inverse see-saw)
  $\rightarrow$ near-cancellation between contributions of two HNLs to m^{light}

Focus of most current experiments

HNL searches

- Many existing & proposed searches for HNLs
- Feebly interacting & possibly long-lived
- Colliders, beam dumps, kaon decays in flight, etc.
- Small mixing angle vs. HNL mass
- "See-saw line" hard to reach, especially at large masses!



From [2305.01715], but see [2305.13383] for caveats

Axion-like particles (ALPs)

~ pseudo-Nambu-Goldstone bosons (pNGBs)

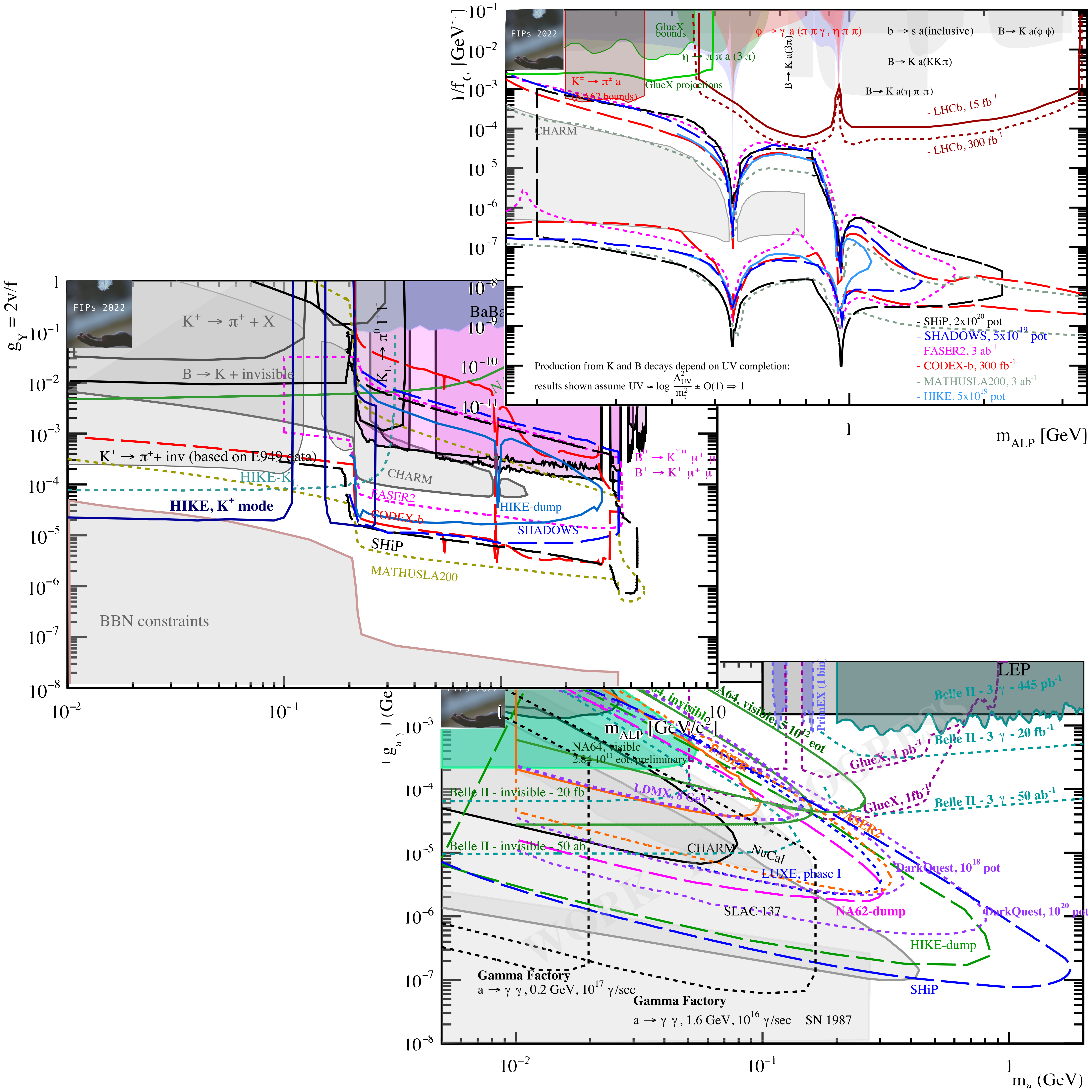
See Víctor Enguita's talk for more details

- Generated whenever an approximate global symmetry is broken
- Abundantly present in BSM models (incl. string theories)
- Shift-symmetric interactions implemented by derivative terms ∂a...
  ... but broken by a mass term and anomalous couplings $aX\tilde{X}$
- Derivative coupling to fermions lead to interaction $\propto$ fermion masses
  $\rightarrow$ potentially **enhanced coupling** to TeV-scale HNLs!

«Just give me an ALP!»
- Someone at a recent lunch

ALP searches

- Many current or proposed searches at colliders, beam dumps, kaon decay-in-flight and pion decays
- Feebly interacting and often long-lived
- Constraints on various effective couplings (c/f_a vs. m_a)



ALPs & HNLs

ALPs and HNLs address largely **orthogonal** problems:

- ALPs cannot explain neutrino masses → still need *something* more
- The presence of HNLs does not affect the motivation for ALPs

Why not have both?

Joint limits

A model containing HNLs and ALPs will be constrained by:

- Limits on HNLs alone
- Limits on ALPs alone
- **Joint limits** that only apply if you have both HNLs and ALPs
  $\rightarrow$ New, unique processes that would not occur otherwise

Motivation of the present study

Effective Lagrangian

ALP kinetic term

HNL kinetic term

$$\mathscr{L}_a = \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \overline{N_R} i \not{\partial} N_R - \frac{1}{2} M_N \overline{N_R^c} N_R + \mathscr{L}_a^X + \mathscr{L}_{\partial a}^\psi$$

ALP anomalous couplings

$$\mathscr{L}_a^X = -\frac{1}{4} c_{\tilde{B}} \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu} - \frac{1}{4} c_{\tilde{W}} \frac{a}{f_a} W^i_{\mu\nu} \tilde{W}^{i\mu\nu} - \frac{1}{4} c_{\tilde{G}} \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

ALP derivative couplings

$$\mathscr{L}_{\partial a}^\psi = \frac{\partial_\mu a}{f_a} \sum_\psi c_\psi \bar{\psi} \gamma^\mu \psi, \qquad \psi = Q_L, L_L, u_R, d_R, e_R, N_R$$

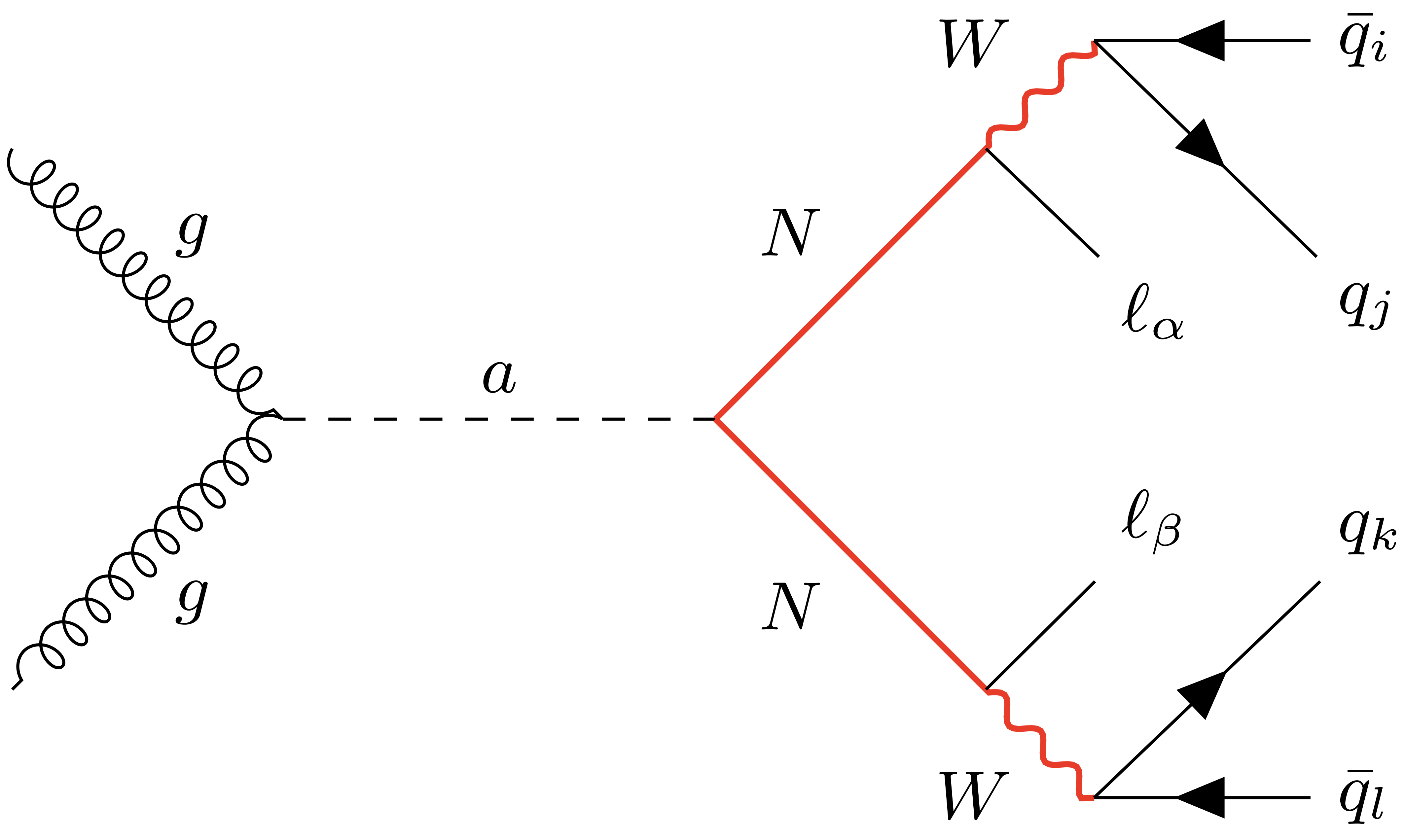
(flavour indices suppressed)

A new production mechanism

1 HNL, non-cascade case

- $\frac{c_N}{f_a}\partial_\mu a \overline{N}_R \gamma^\mu N_R$ enables *new production mechanism*, from off-shell ALP $a^* \to 2N$
- HNL $\gtrsim 100\,\mathrm{GeV}$ above the see-saw line would decay promptly through mixing with SM ν's (→ sensitivity *down to the see-saw line*)
- Focus on reconstructible decays ($N \to W_\mathrm{h}\ell$, hadronic $W_\mathrm{h} \to jj$)
- 4 *simultaneous* invariant mass peaks

red = on-shell



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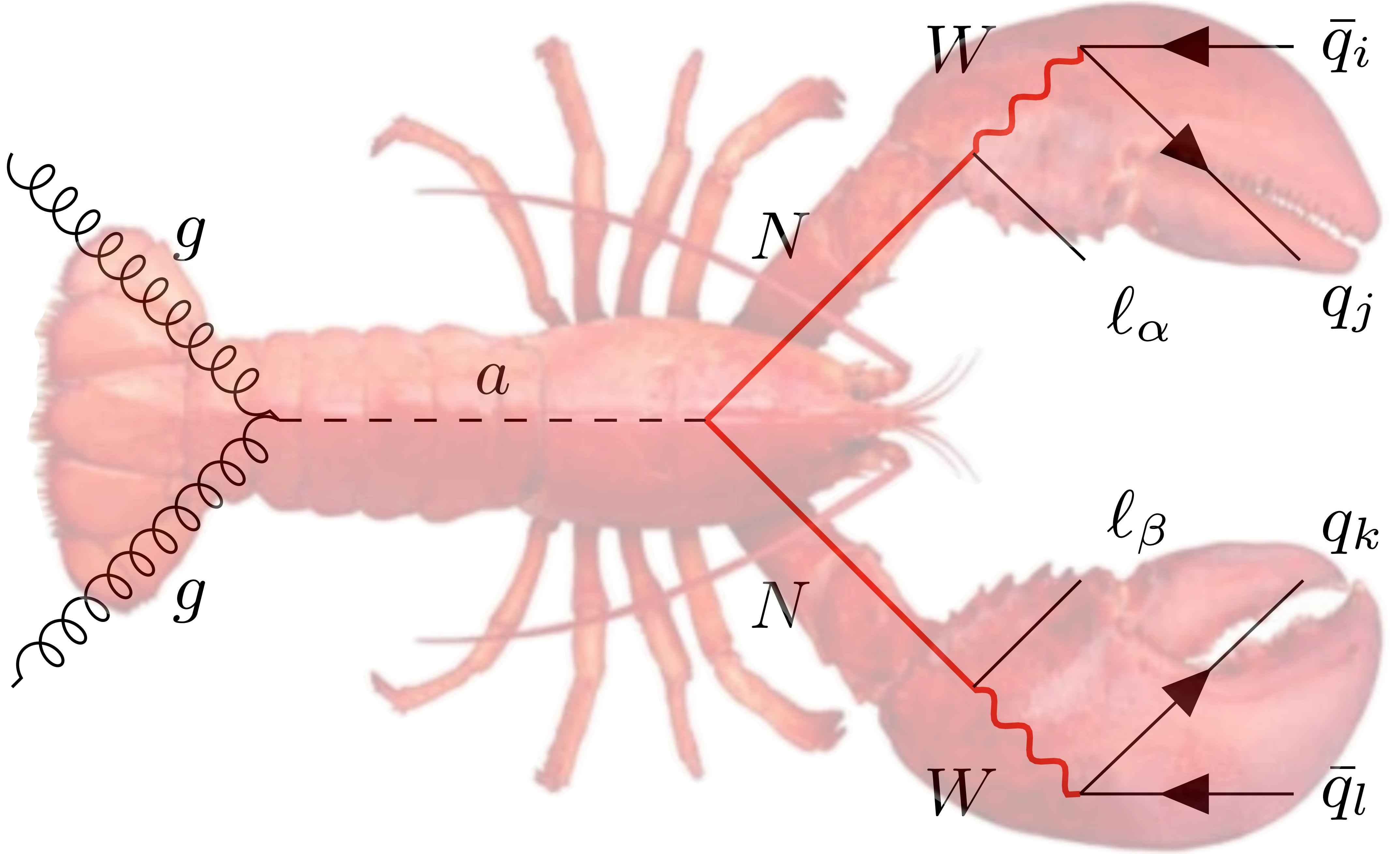
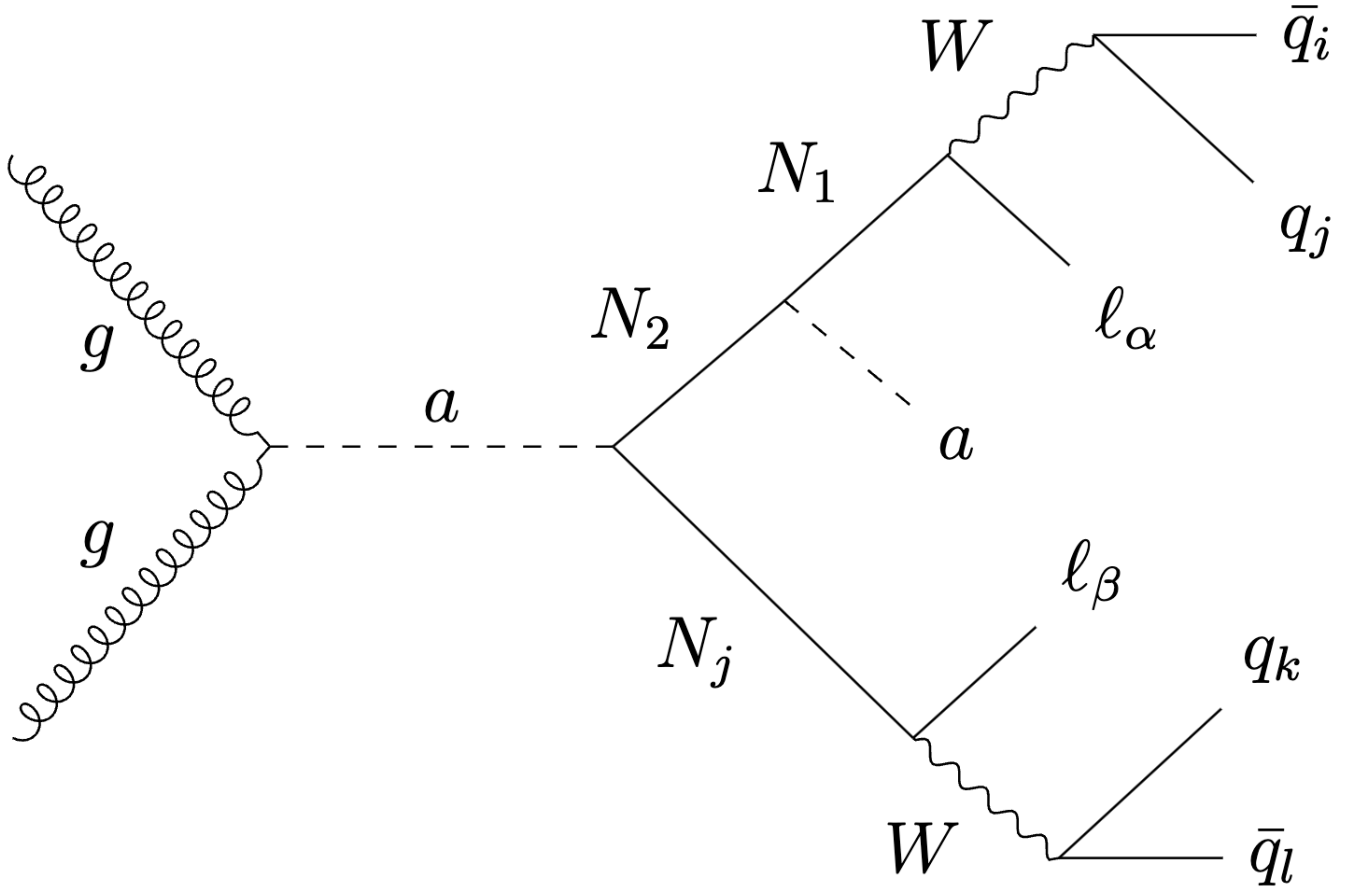


A new production mechanism

2 HNLs, cascade decay

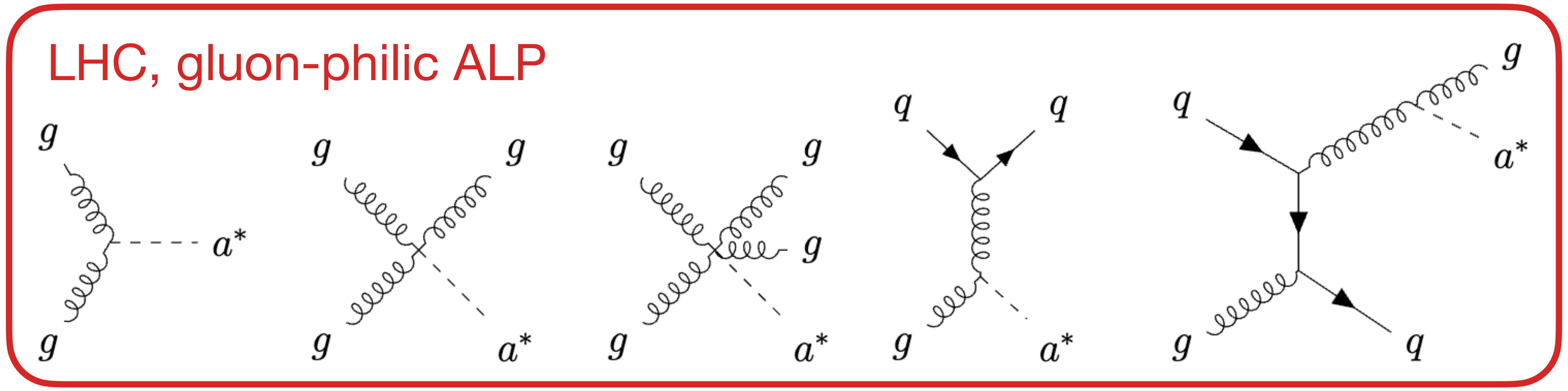
Work in progress...

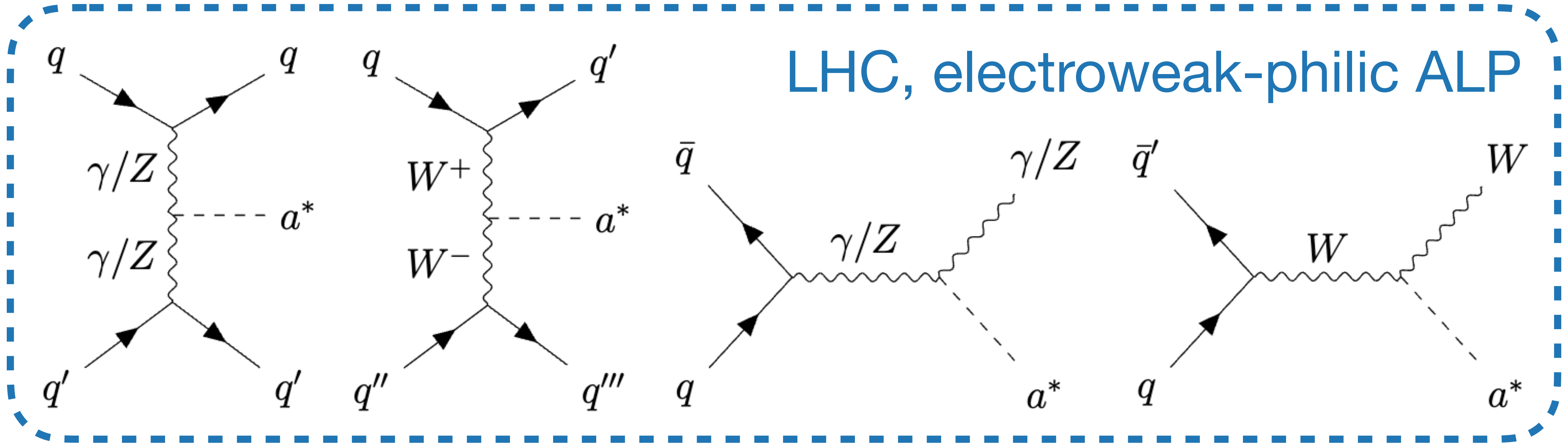
- 2+ HNLs required to explain the observed neutrino masses
- $\frac{c_N}{f_a}\partial_\mu a \overline{N}_R \gamma^\mu N_R \rightarrow \frac{c_{N,ij}}{f_a}\partial_\mu a \overline{N}_{R,i} \gamma^\mu N_{R,j}$
- When the lighter HNL N_1 is produced → same process
- Heaviest HNL N_2 decays primarily though ALP coupling → *cascade*

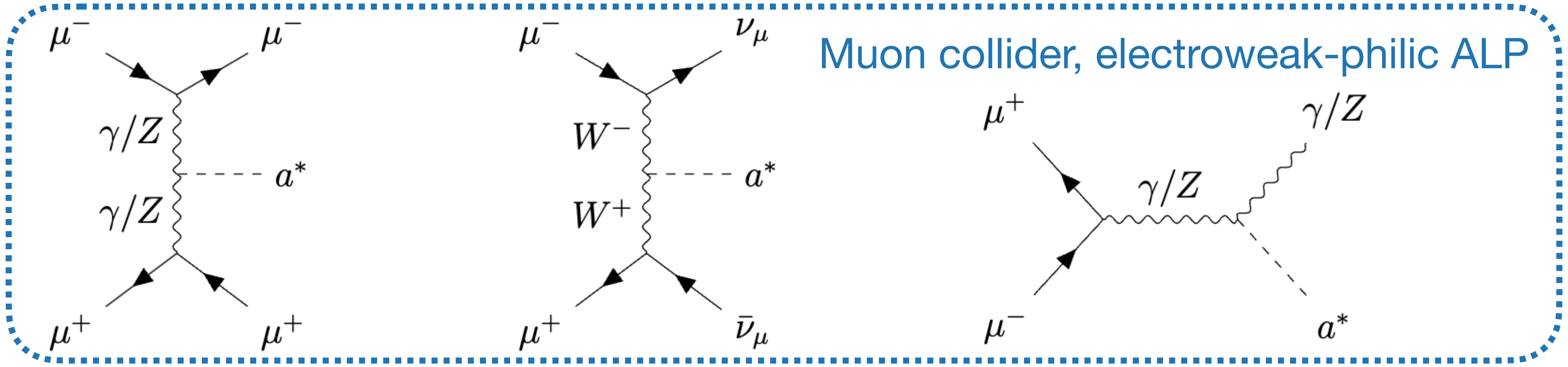


Signal at HL-LHC and 10TeV muon collider

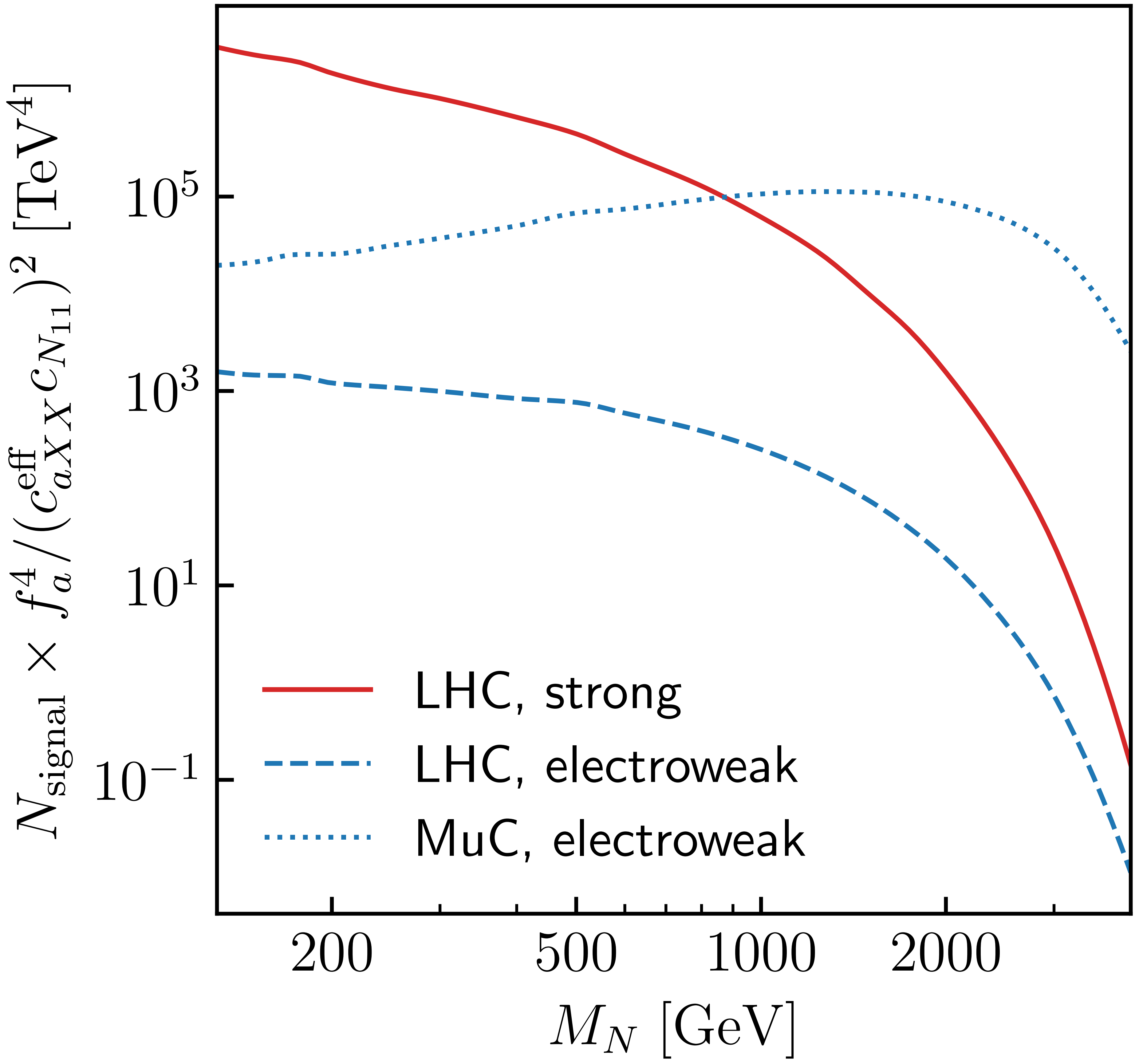
Varied production mechanisms for a^*, but same decays







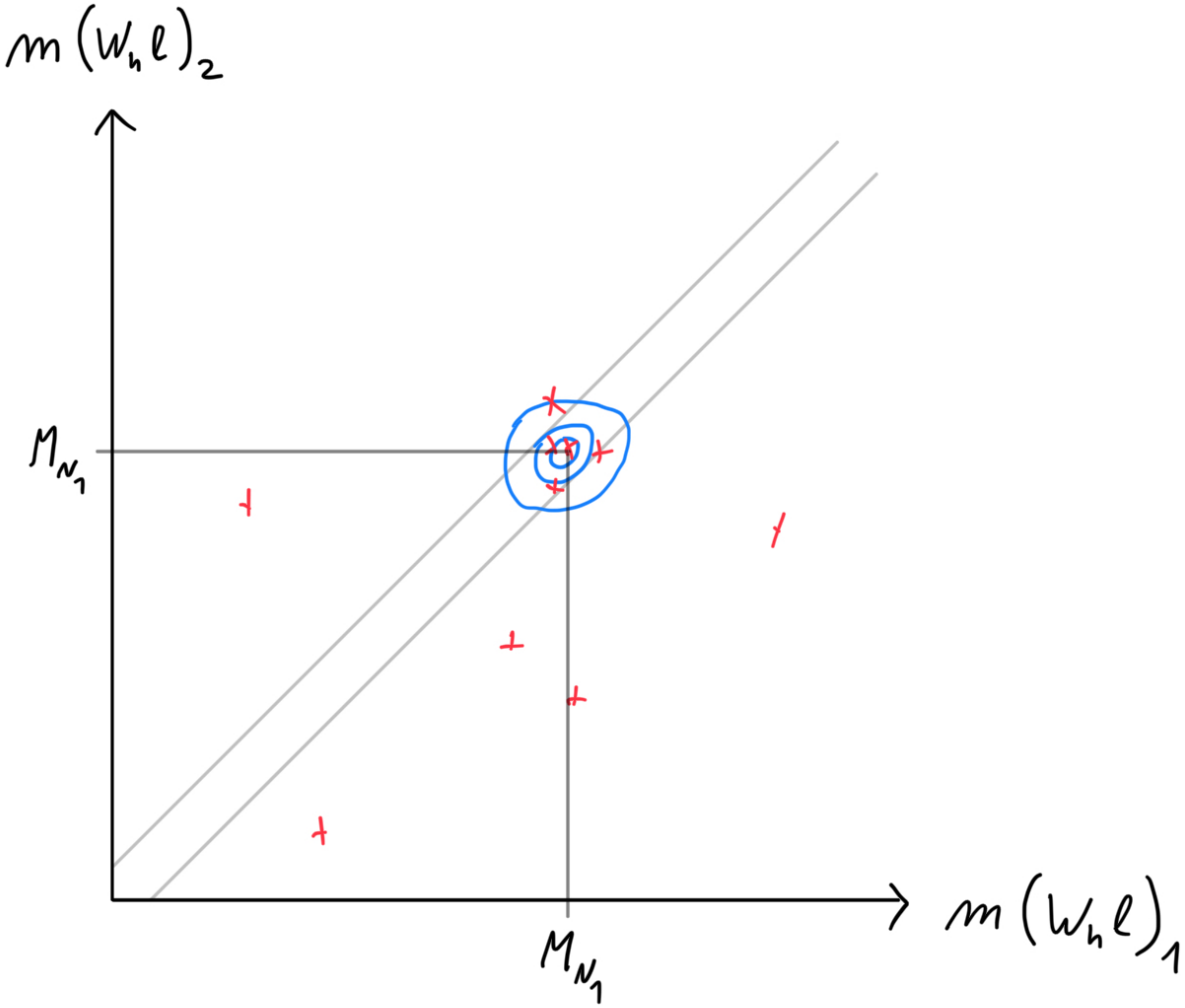
Signal yields for 1 HNL



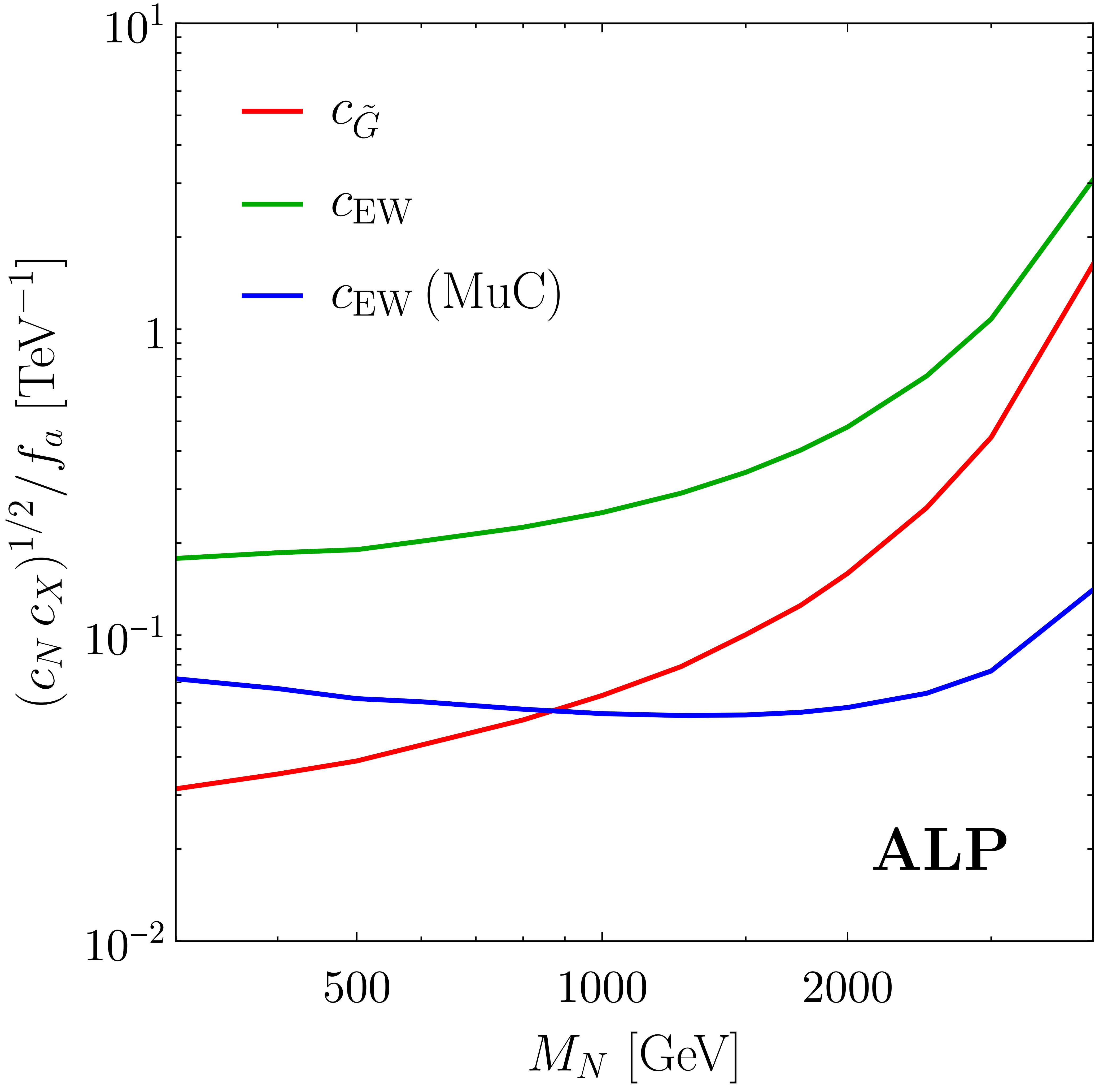
Possible search strategy

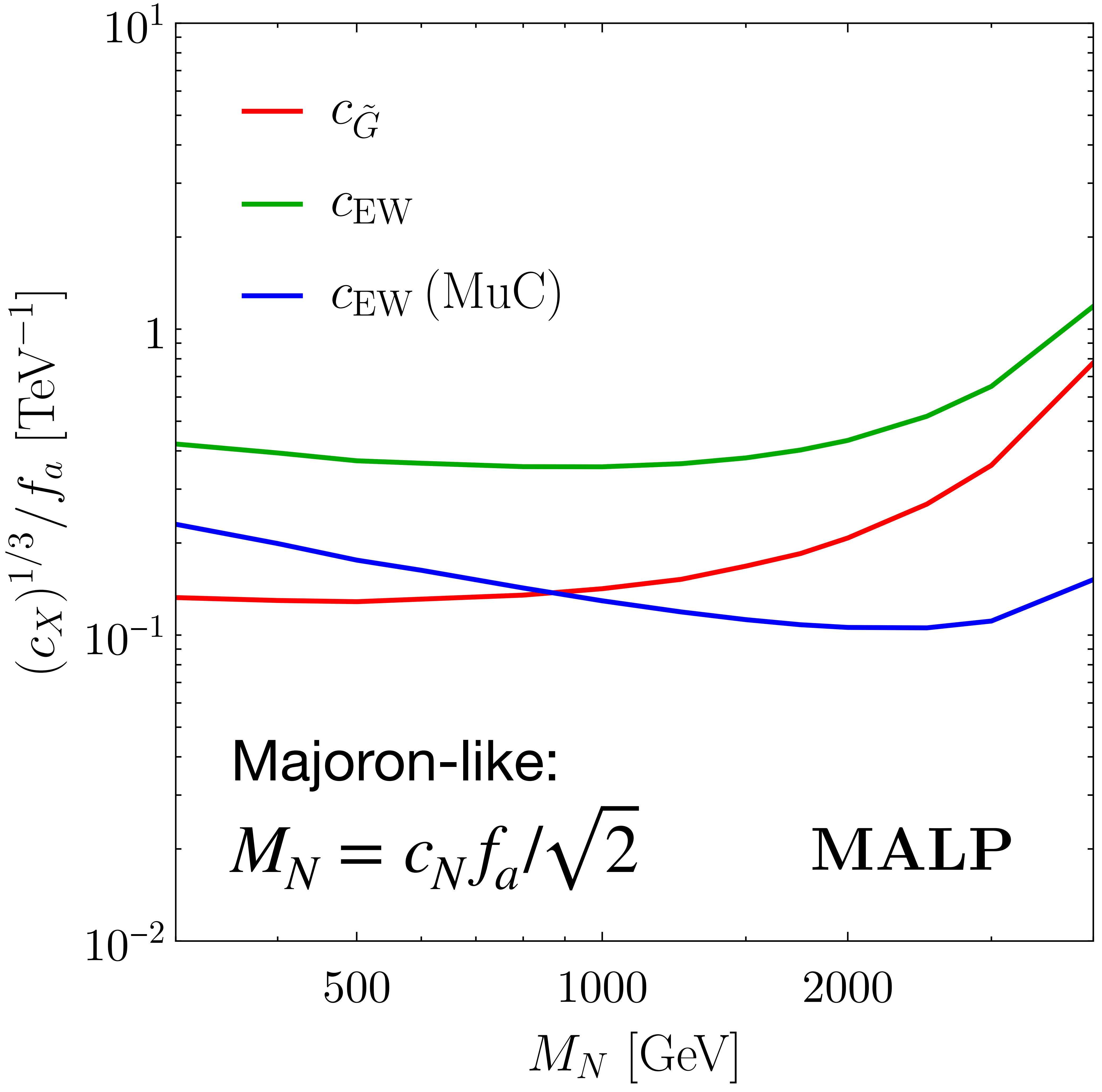
Similar to the search in María Cepeda's talk!

- Identify hadronically decaying $W_h \to jj$, pair them with all leptons
- Select events with exactly 2 $W\ell$ pairs
- Plot the invariant masses, with 1st pair on x-axis & 2nd on y-axis
- Bump search along the diagonal
- Off-diagonal entries used to estimate background (notably combinatorial)



Expected joint limits

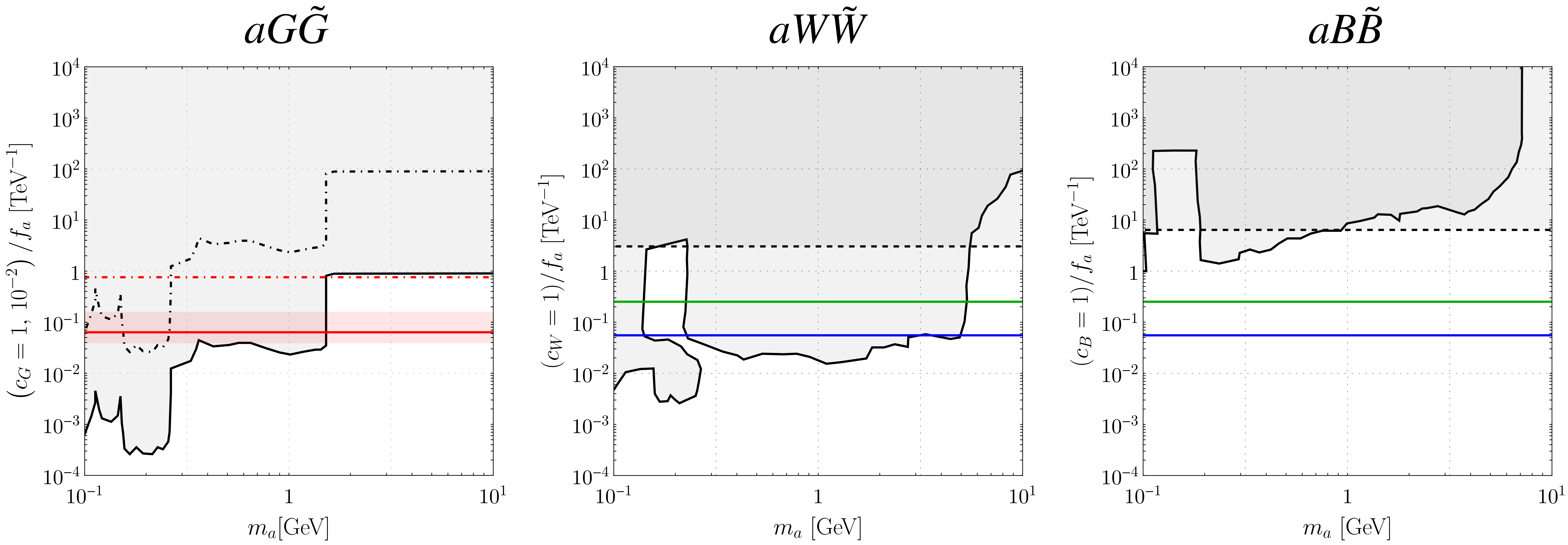




Comparison with existing limits

Limits from [2110.10698] and [2203.01734]

Expected limits from the proposed search



LHC only

LHC / muon collider @ $M_N = 1\,\text{TeV}$

Conclusion

- ALPs and HNLs address largely orthogonal problems → complementary?
- Some models may want both
- New processes, involving ALP-HNL interactions, may become dominant
- Places joint limits on ALPs and HNLs that are stronger than individual limits
- We outlined a proposed search strategy
- We computed projected limits for searches at the LHC and muon collider

Any questions?

Backup slides

Production at HL-LHC & 10TeV MuC