A direct probe of neutrino compositness

Borrello, Costa, Redigolo, *to appear*

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WiN 25

Neutrino masses: standard seesaw

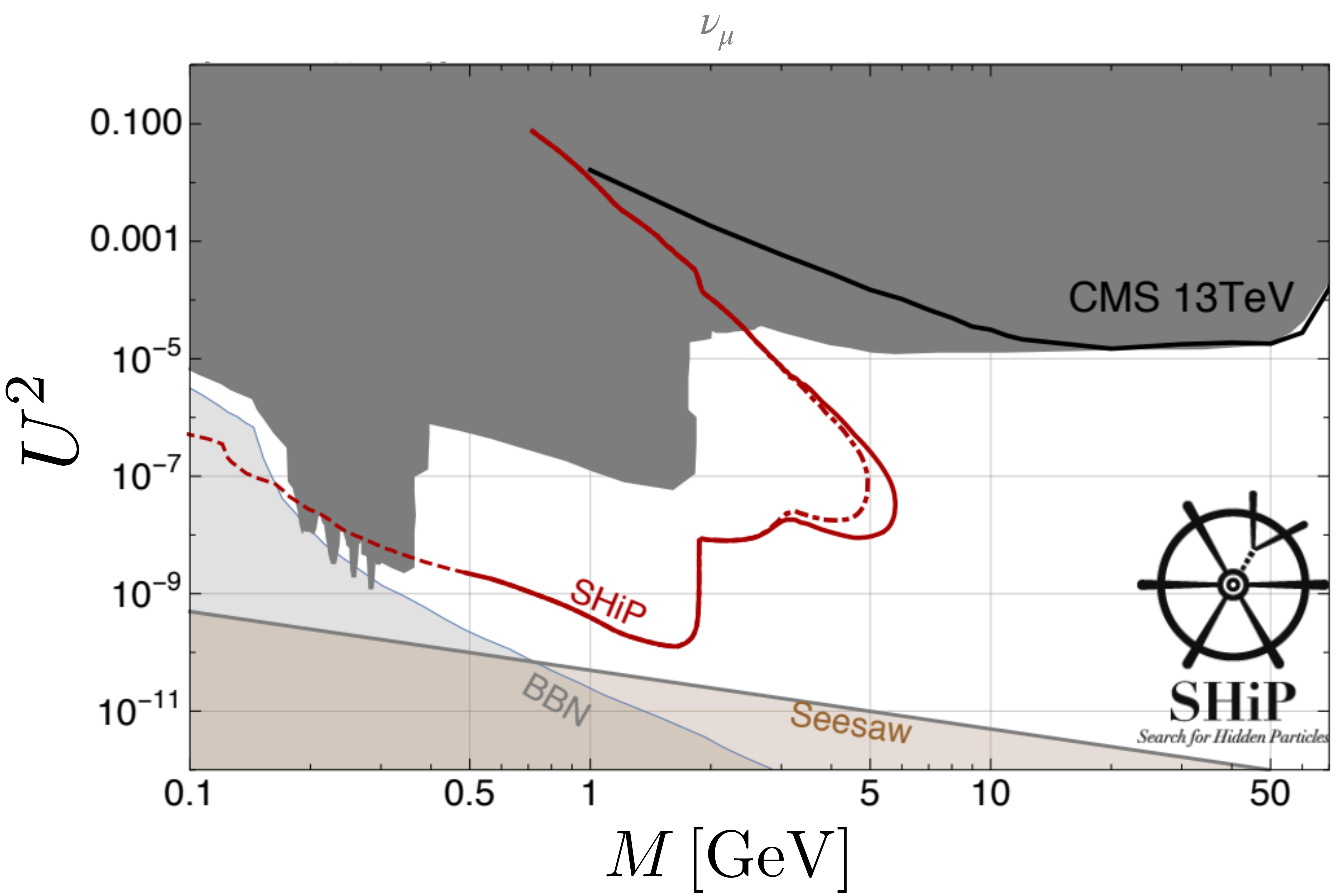
$$\mathcal{L} = y\overline{L}NH + \frac{1}{2}M\overline{N^c}N + \text{h.c.}$$

N SM singlet

active - sterile mixing

$$|U|^2 = \left(\frac{yv}{M}\right)^2 = \frac{m_\nu}{M}$$

Poor phenomenology: small mixing



SHIP collaboration[1811.00930v3]

Neutrino masses: inverse seesaw

$$|U|^2 = \left(\frac{yv}{M}\right)^2 = \frac{m_\nu}{M}$$

Standard seesaw

$$\mathcal{L} = y\overline{L}NH + M\overline{N}S + \frac{1}{2}\mu\overline{S^c}S + \text{h.c.}$$

Mohapatra and Valle, Phys. Rev. Lett. 44, 912 (1980)

active - sterile mixing

$$|U|^2 = \left(\frac{yv}{M}\right)^2 = \frac{m_\nu}{\mu}$$

N, S SM singlets

μ Majorana mass

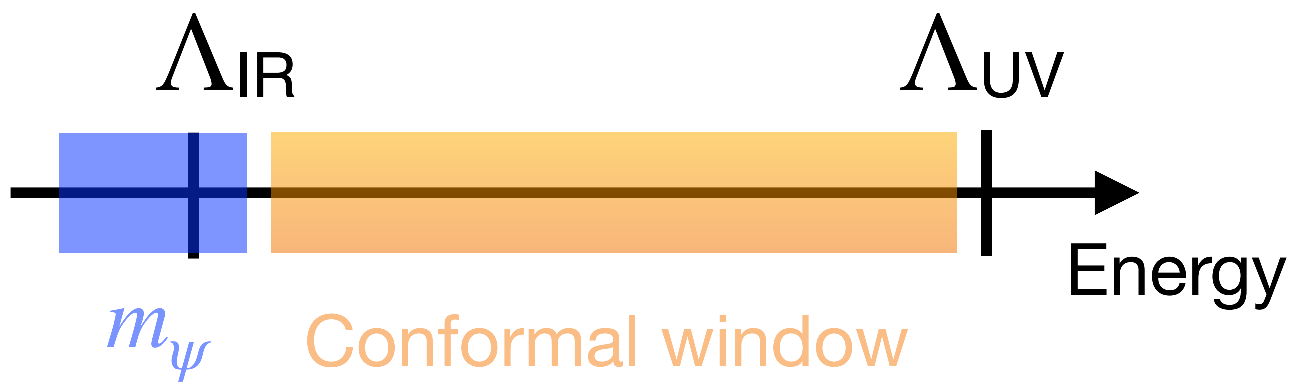
μ is very small $\Longrightarrow$ Much richer phenomenology

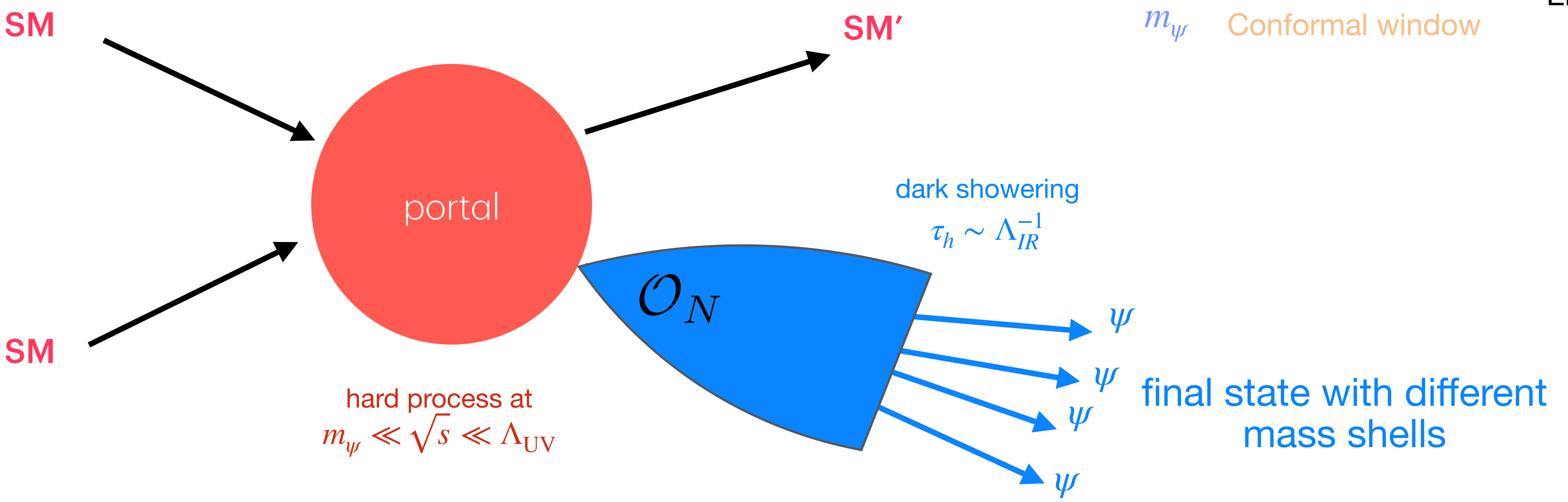
Strongly coupled sterile sectors

$$\Delta\mathcal{L}_N = \frac{y_\mu H L_\mu \mathcal{O}_N}{\Lambda_{\rm UV}^{\Delta_N - 3/2}}$$

Chacko at al. [2012.01443]

Large hierarchy $\Lambda_{\rm IR} \ll \Lambda_{\rm UV} \implies$ approximately **scale invariance**

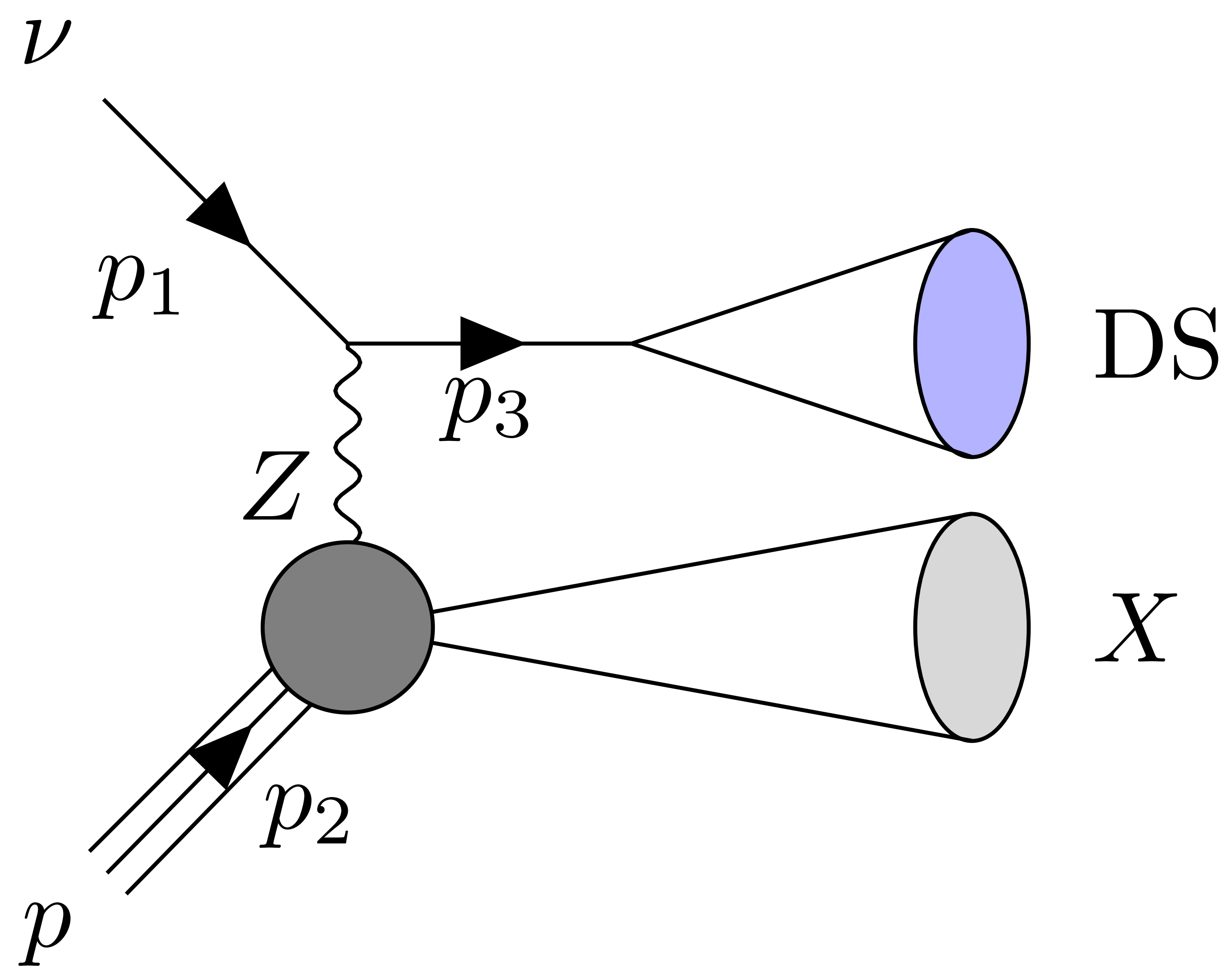




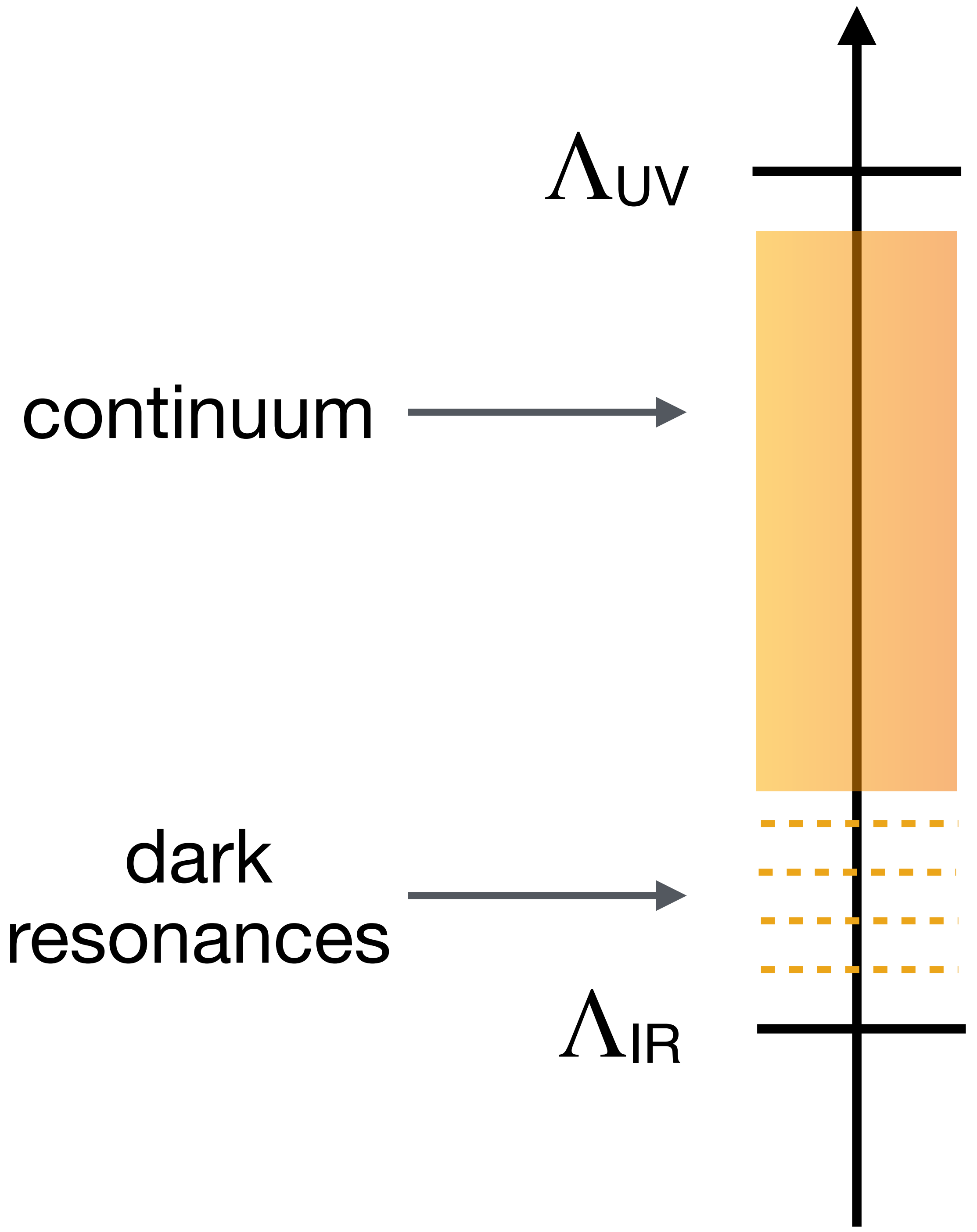
New signature: neutrino disintegration

$$\Delta\mathcal{L}_N = \frac{y_\mu H L_\mu \mathcal{O}_N}{\Lambda_{\rm UV}^{\Delta_N - 3/2}}$$

Neutrino disintegrates into dark particles in neutral currents scattering



$$\frac{d\sigma_S}{dm_N^2} \sim \left(\frac{m_N^2}{\Lambda_{\rm UV}^2}\right)^{\Delta_N - 7/2}$$



UV dominated for $\Delta_N \geq 7/2$

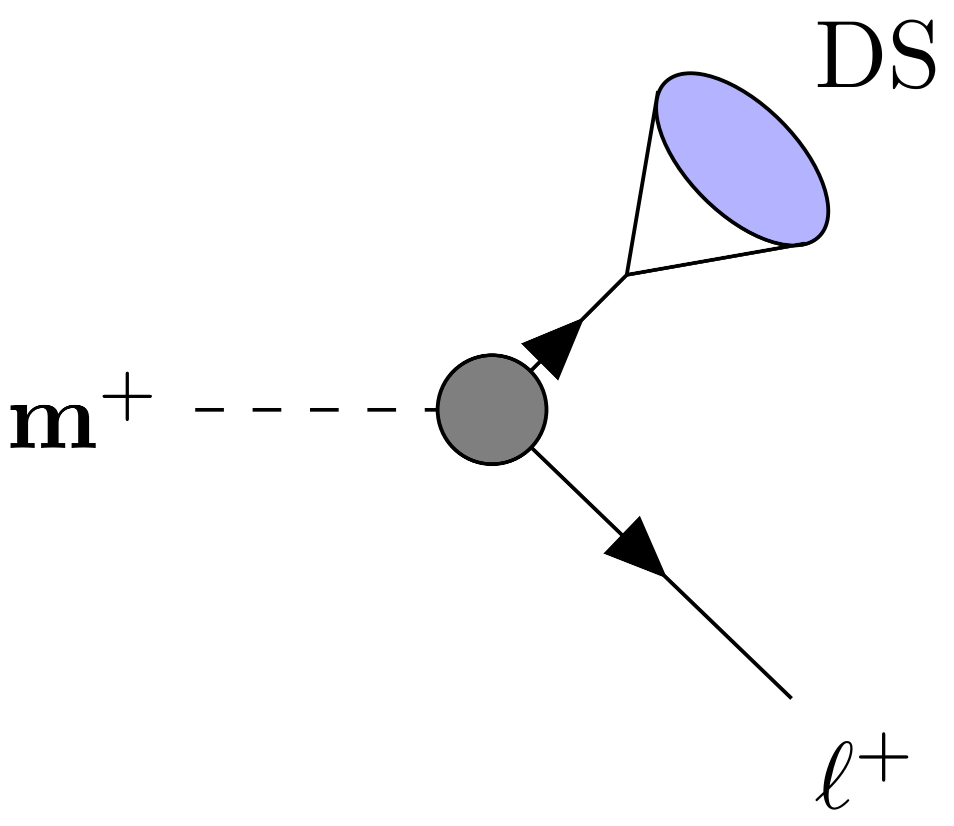
$\Longrightarrow$ Light dark particles are long lived

Invisible branching ratios

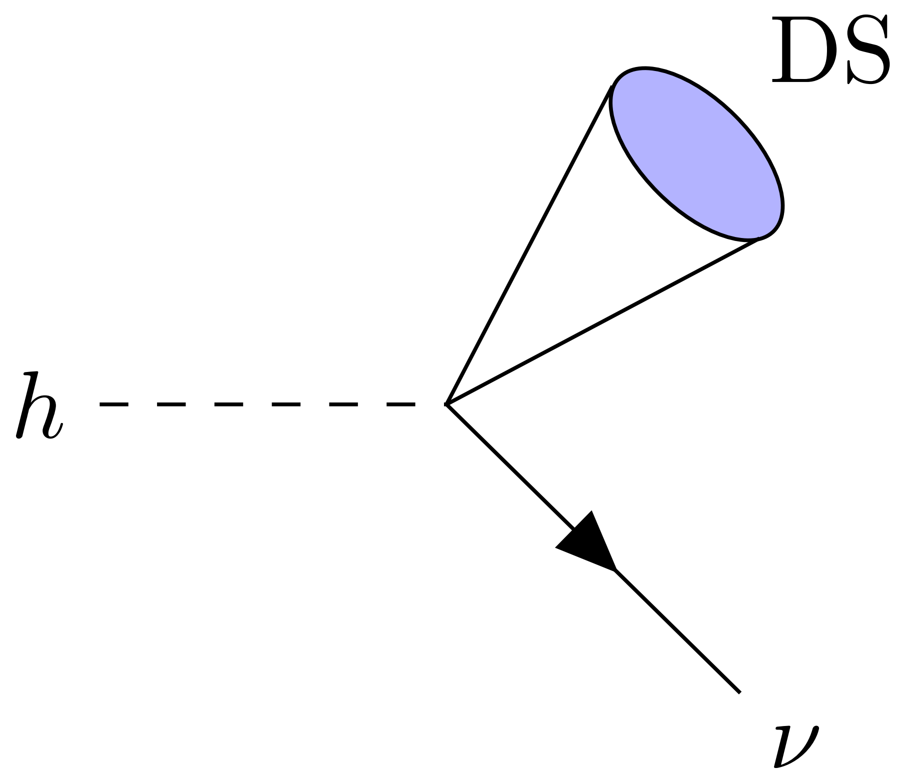
$$\Delta_N = \frac{7}{2}$$

$$\Delta\mathcal{L}_N = \frac{y_\mu H L_\mu \mathcal{O}_N}{\Lambda_{UV}^2}$$

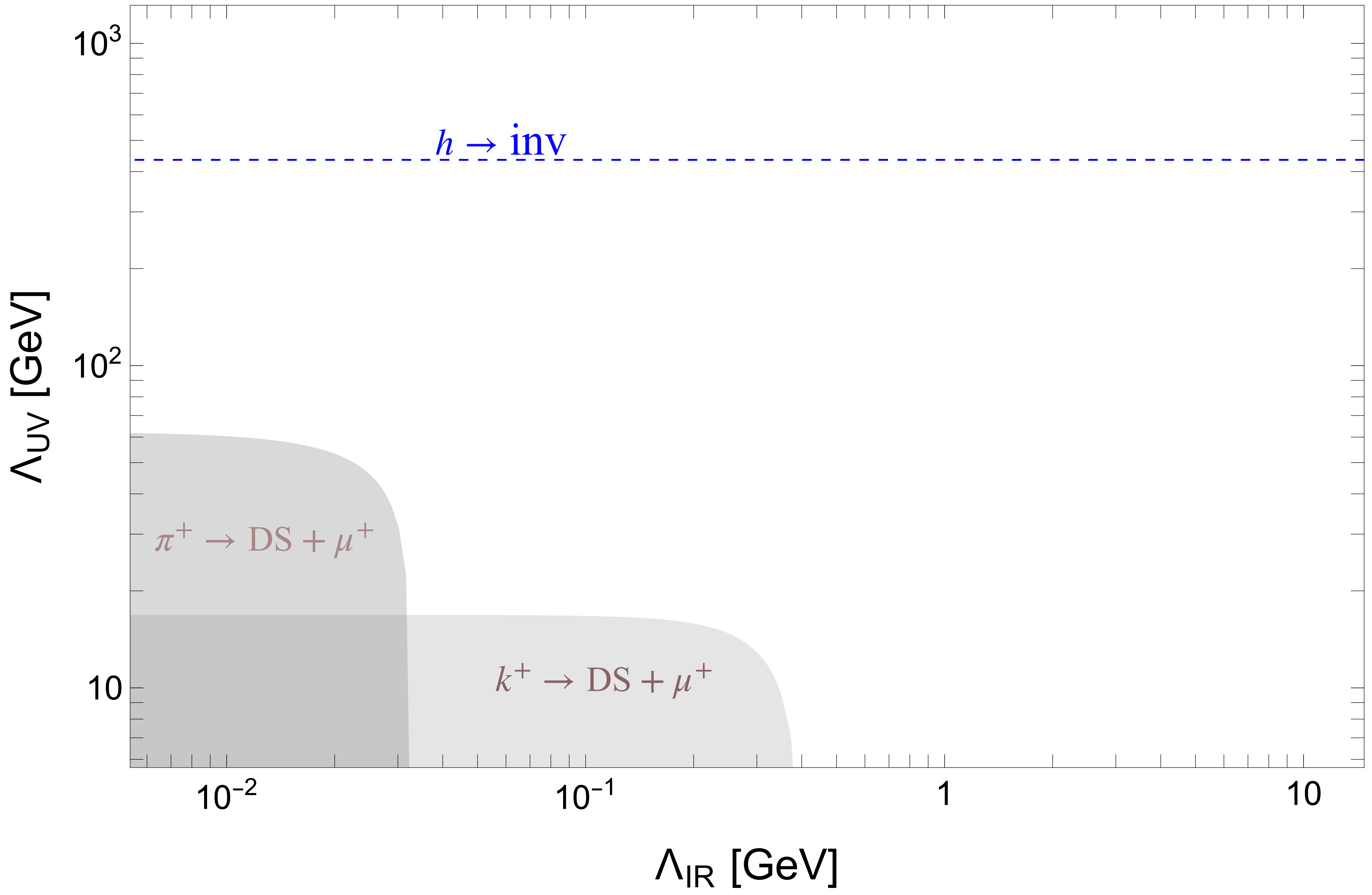
Charged mesons



Higgs

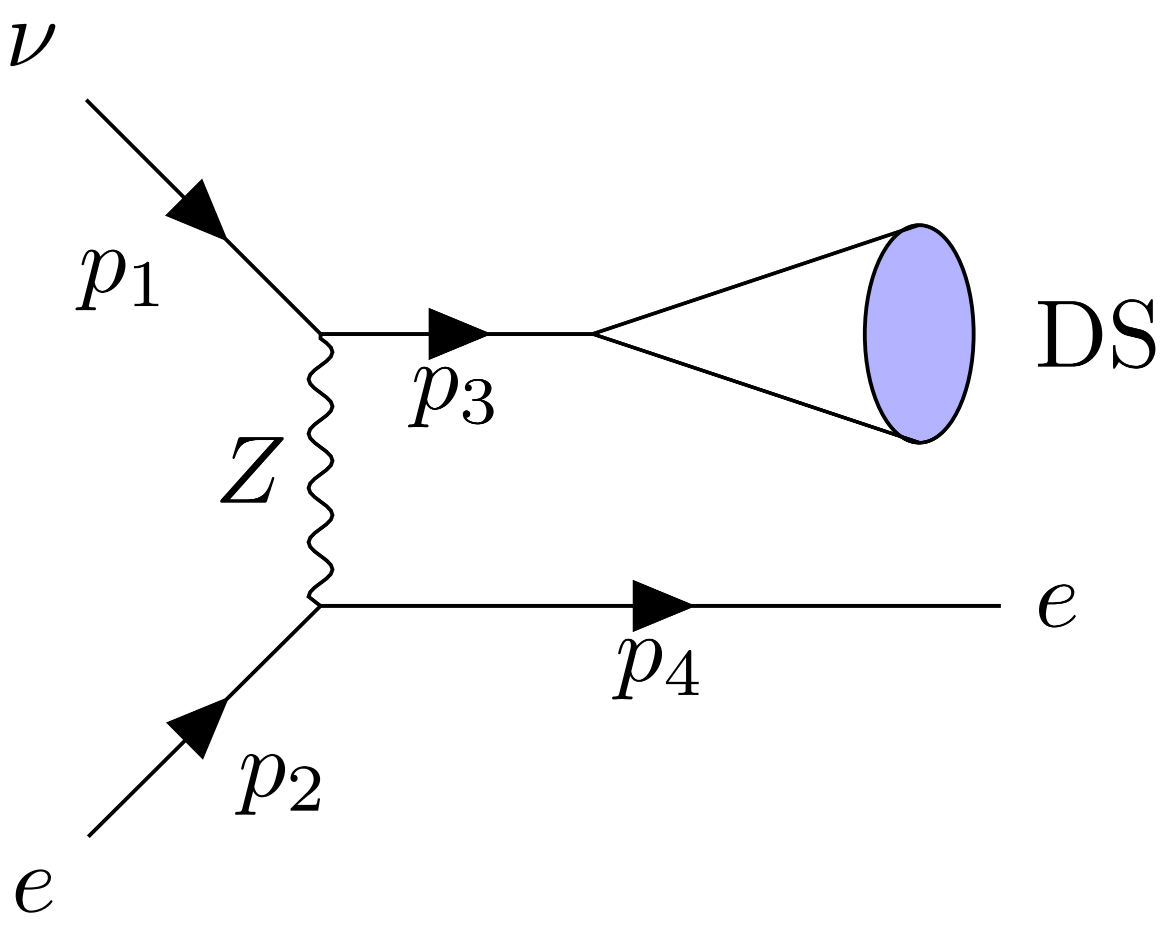


Stronger but UV dependent



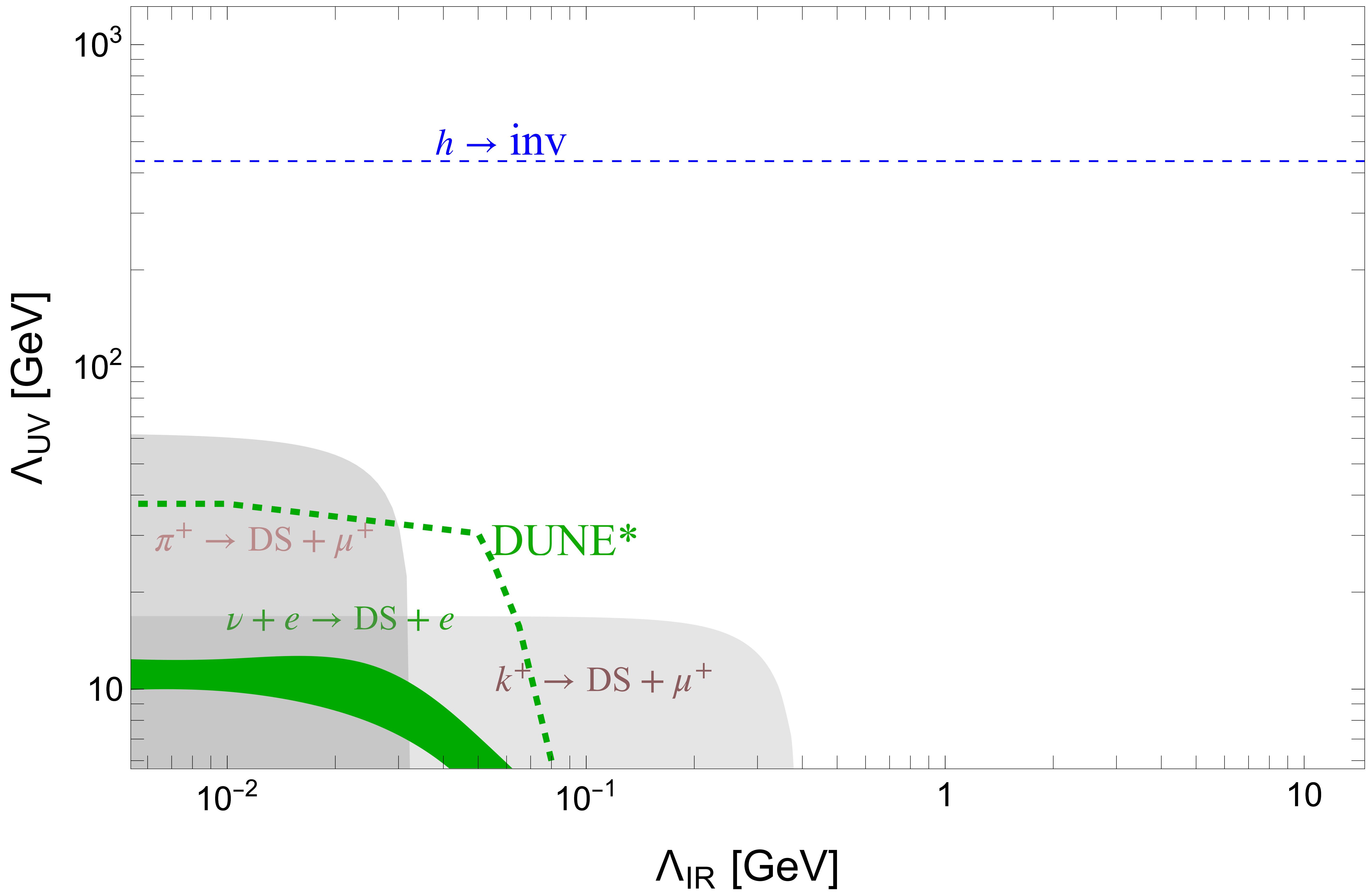
Scattering over electrons at DUNE

$$\Delta\mathcal{L}_N = \frac{y_\mu H L_\mu \mathcal{O}_N}{\Lambda_{UV}^2}$$



The reach is limited by small $\sqrt{s_e} = \sqrt{2m_e E_\nu}$

$$\sigma \sim \frac{s_e^2}{\Lambda_{UV}^4 v^2}$$

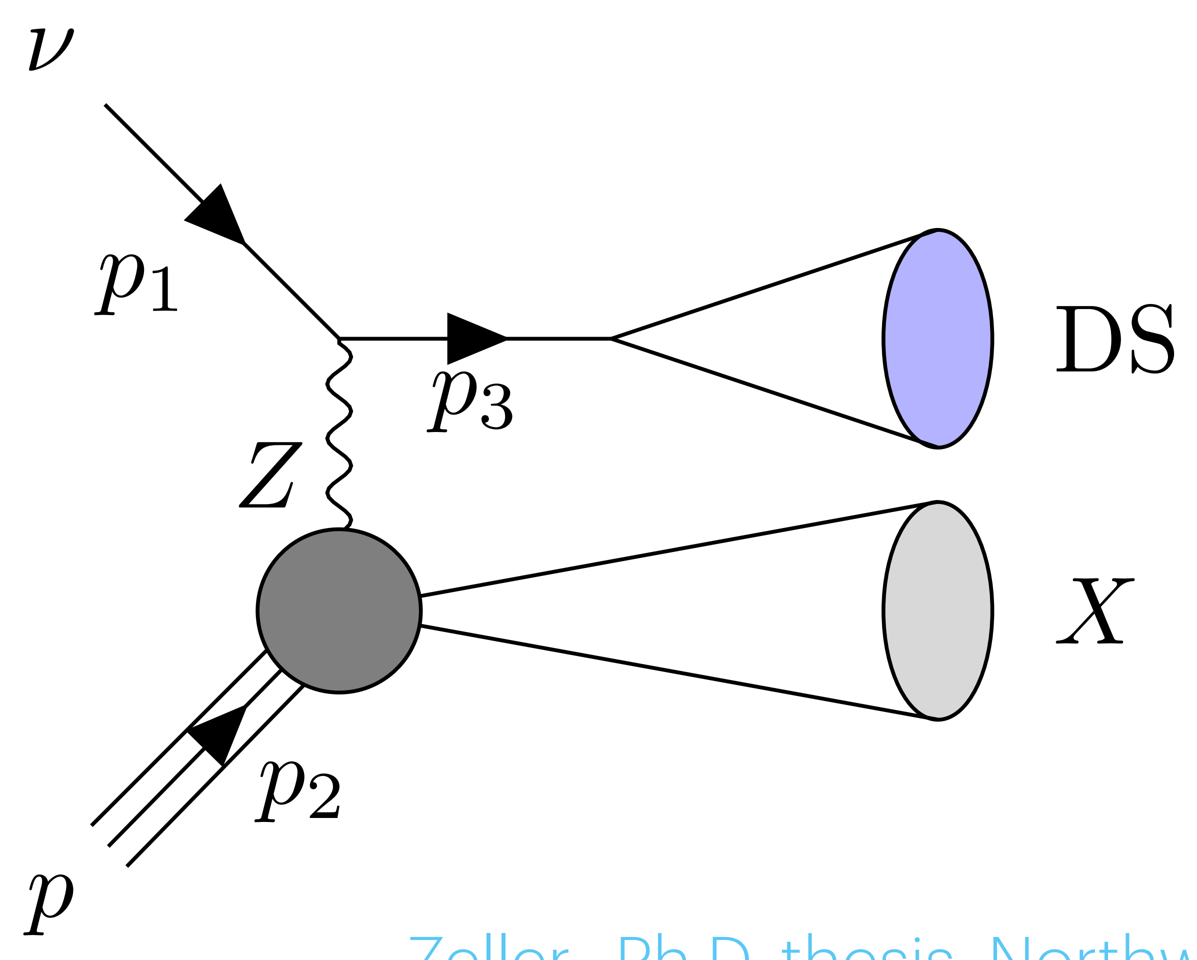


NuTeV: enhancing neutral currents

$$\Delta\mathcal{L}_N = \frac{y_\mu H L_\mu \mathcal{O}_N}{\Lambda_{UV}^2}$$

$$s_e/s_p = m_e/m_p$$

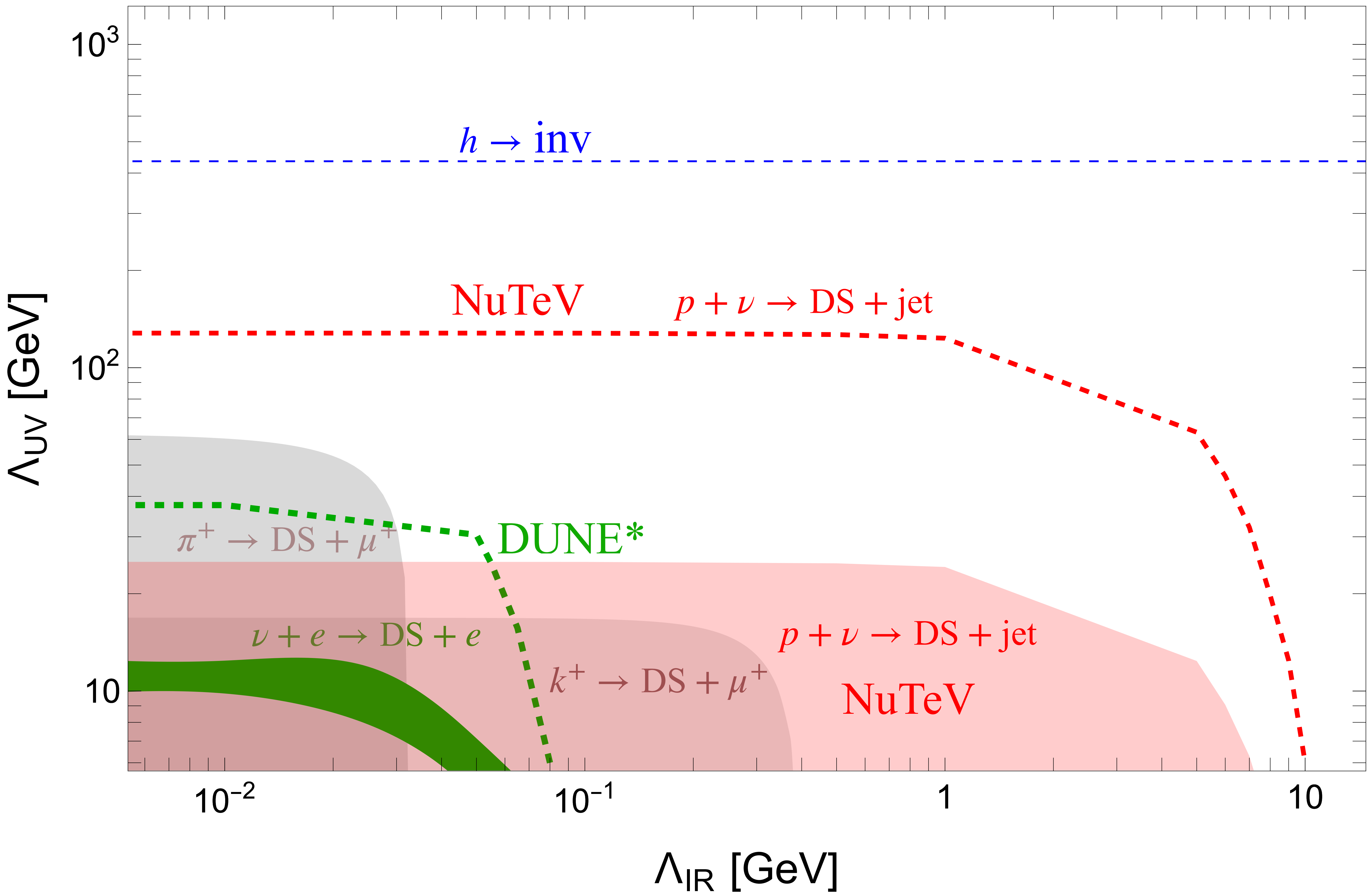
Deep inelastic scattering



Zeller, Ph.D. thesis, Northwestern U. (2002)

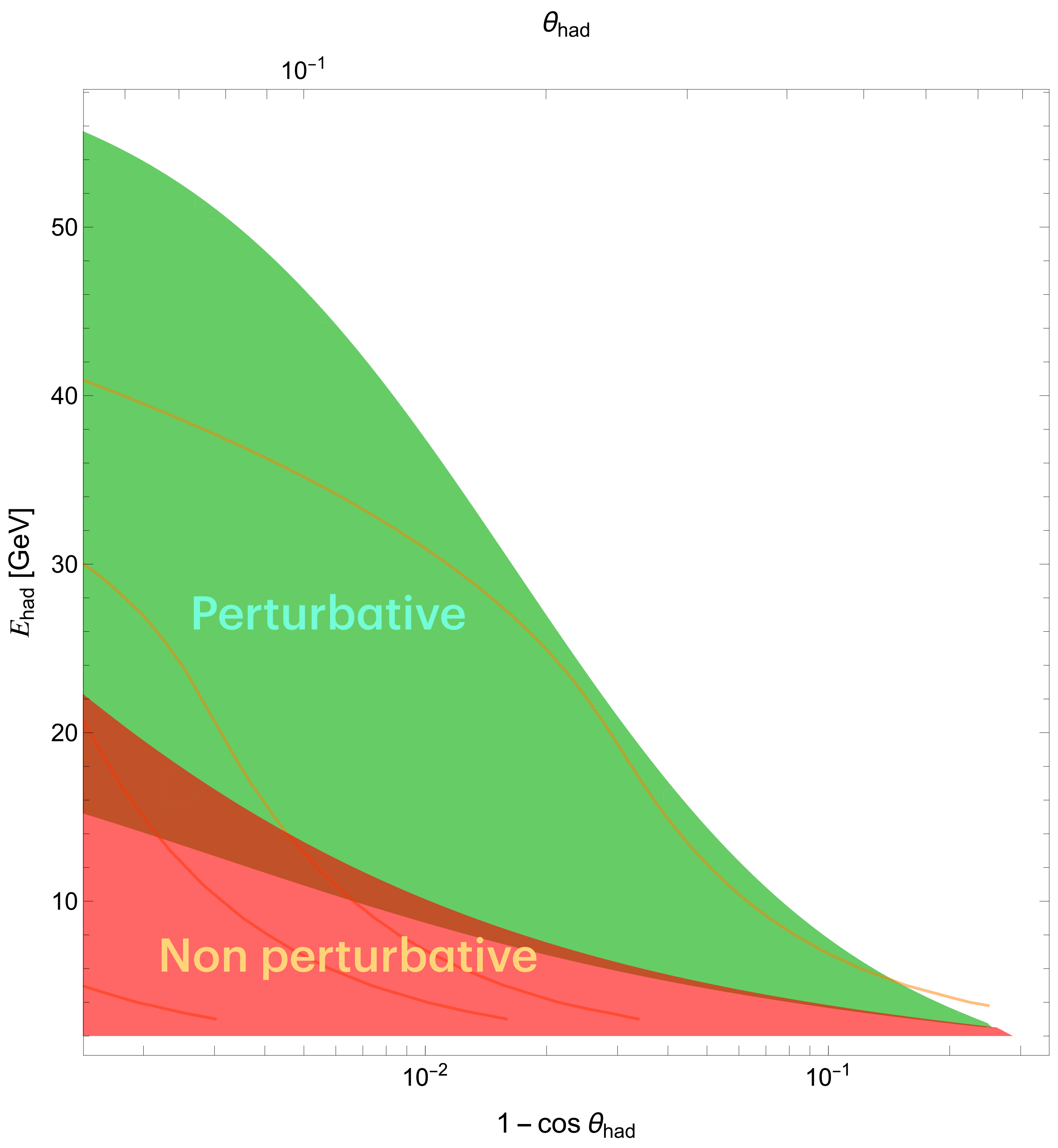
$S_{mis} > S_{bsm}$

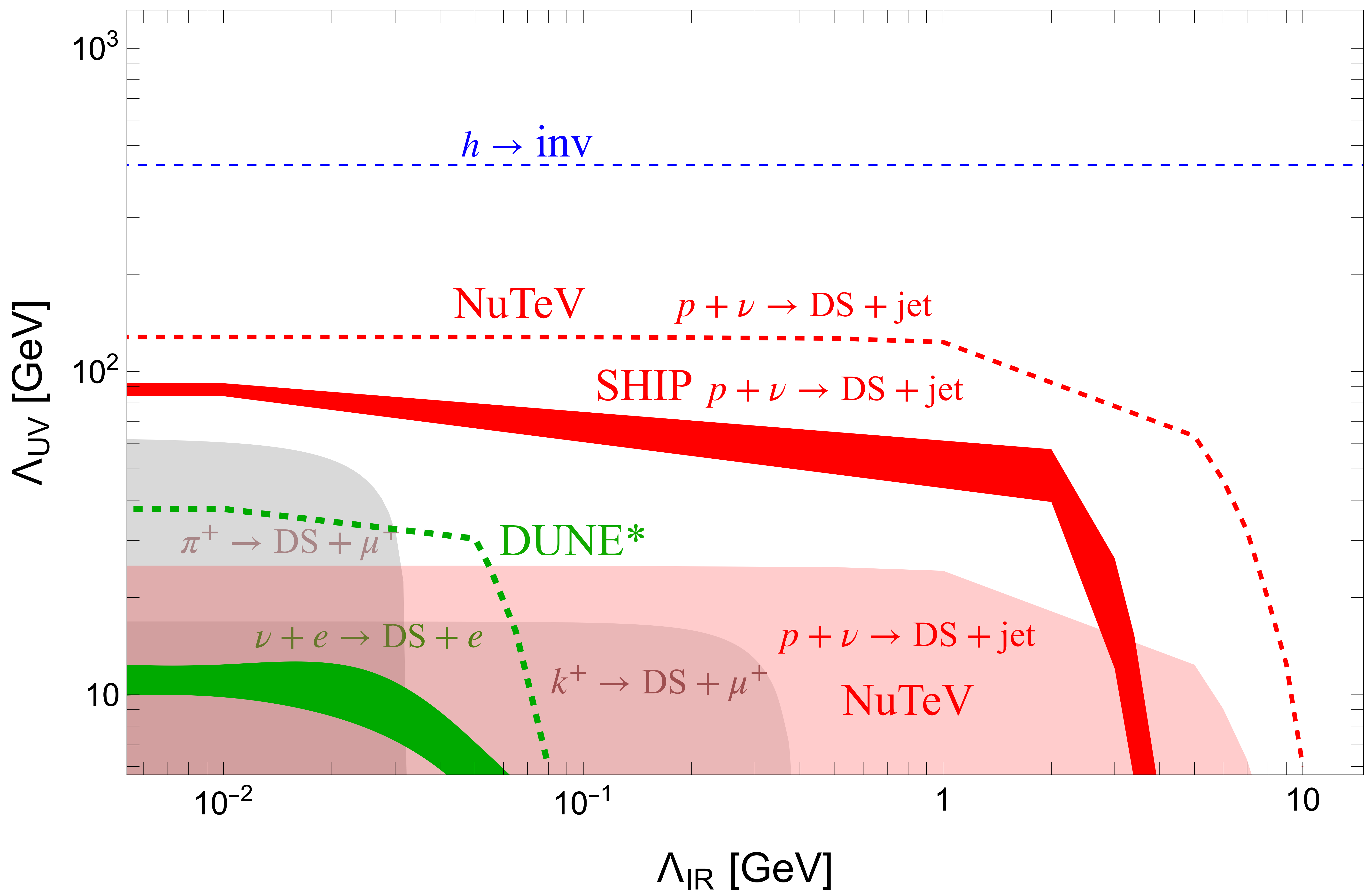
$\sqrt{S_{mis}} > S_{bsm}$



SHIP

$$\Delta\mathcal{L}_N = \frac{y_\mu H L_\mu \mathcal{O}_N}{\Lambda_{UV}^2}$$

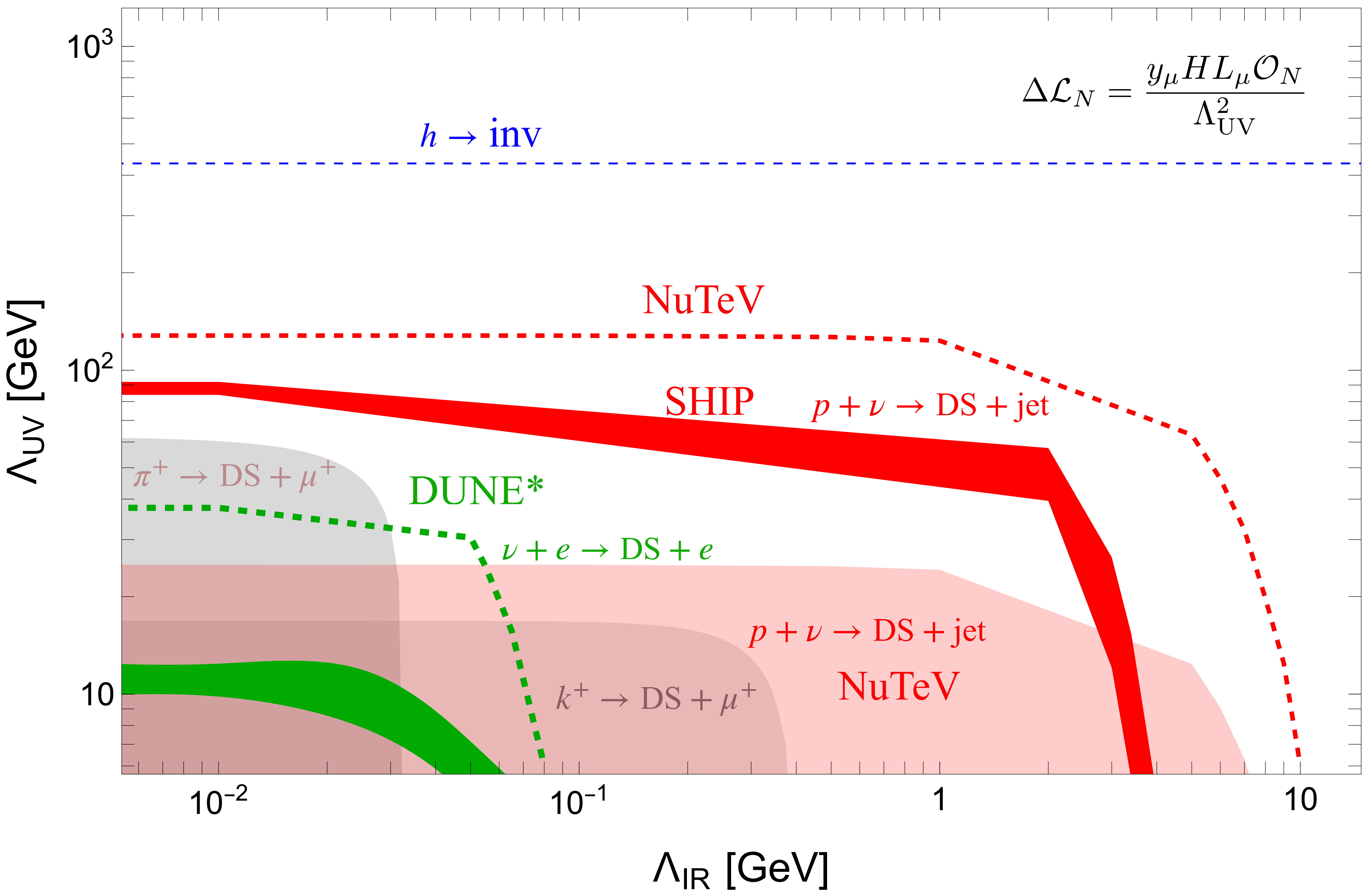




- Lower line: only perturbative $Q_{SM}^2 > 2\ \text{GeV}^2$
- Upper line: all events

Summary

- **Composite neutrino:** testable framework
  - ✓ Higgs decay: best prove but UV dependent
  - ✓ Scattering over electrons: limited by center of mass energy
  - ✓ Scattering over nucleons: enhancement of neutral to charge currents



What's next?

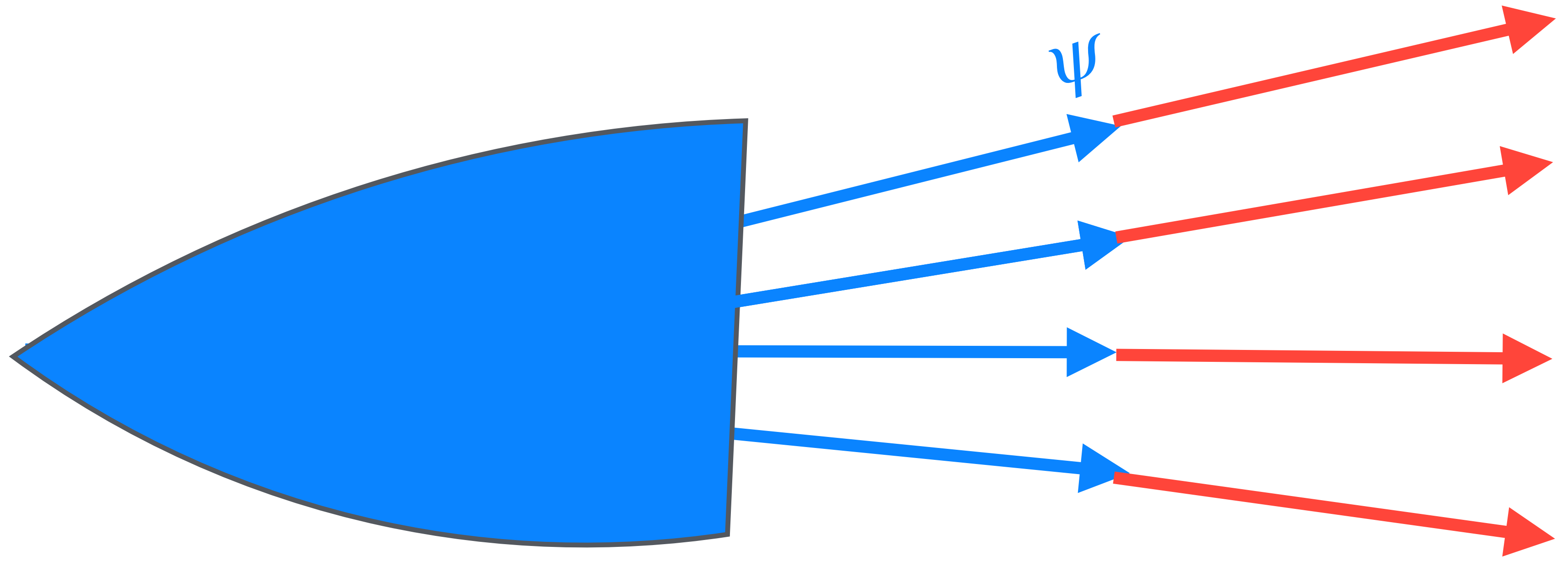
- FASERν: $\sqrt{s_{\rm FASER}} \sim 4\sqrt{s_{\rm SHIP}}$ but $L_{\rm FASER} \sim 10^{-4} L_{\rm SHIP}$

  ✘ Effective theory $\Delta_N = 7/2 \implies \sqrt{s_{\rm FASER}} > \Lambda_{\rm UV}$

  ? Lower dimensions → resonance modelling

- Background free signature: **emerging jets** at DUNE

  - For lower Δ_N ψs decay inside the detector



$$\tau_\psi \sim 10^{-10+4\Delta_N} \,\mathrm{km} \left(\frac{10\,\mathrm{MeV}}{\Lambda_{\rm IR}}\right)^{2\Delta_N} \left(\frac{\Lambda_{\rm UV}}{1\,\mathrm{GeV}}\right)^{2\Delta_N - 3}$$

Thank you for your attention and stay tuned!

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More on standard seesaw

In the **Standard Model**, neutrinos are massless: no ν_R hence no Dirac mass

Experimental observation: ν oscillations = flavor changes point to New Physics

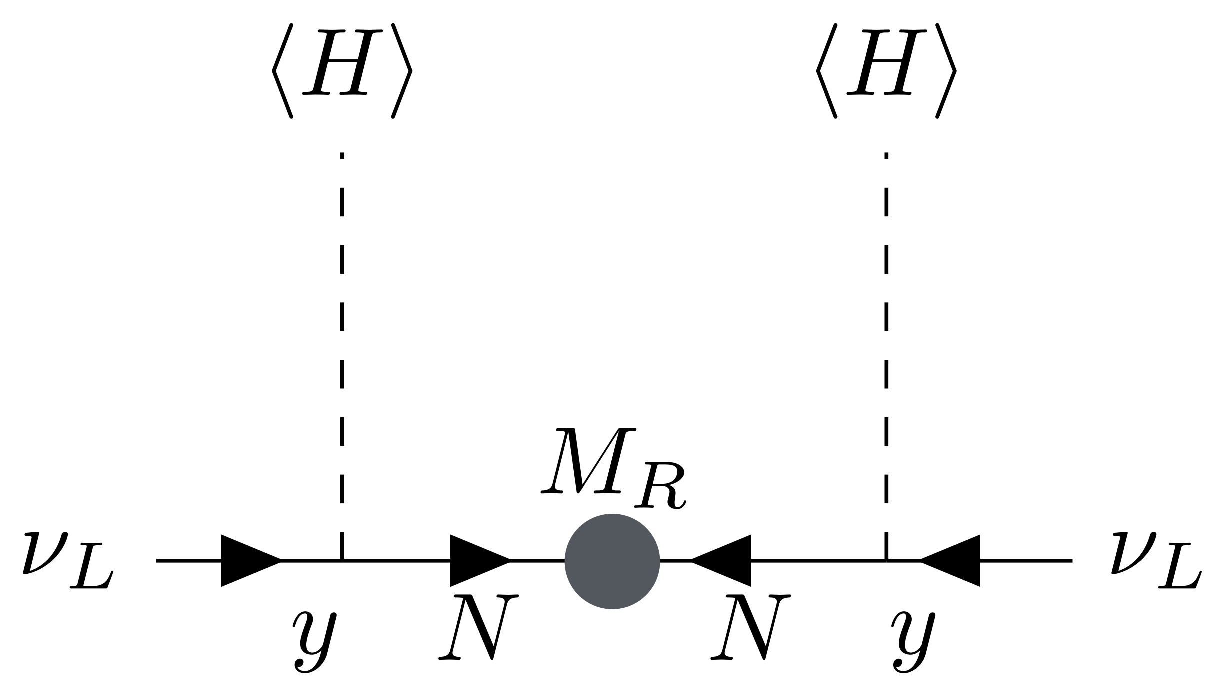
Standard seesaw mechanism

P. Minkowski

$$\mathcal{L} = y\bar{L}NH + \frac{1}{2}M_R\bar{N}^cN + \text{h.c.}$$

N SM singlet

(Type I)



If the Dirac mass from the Yukawa $m_D = yv \ll M_R \implies m_\nu \sim y^2 \frac{v^2}{M_R}$

very small for large New Physics scale $M_R = 10^{13} y^2$ GeV

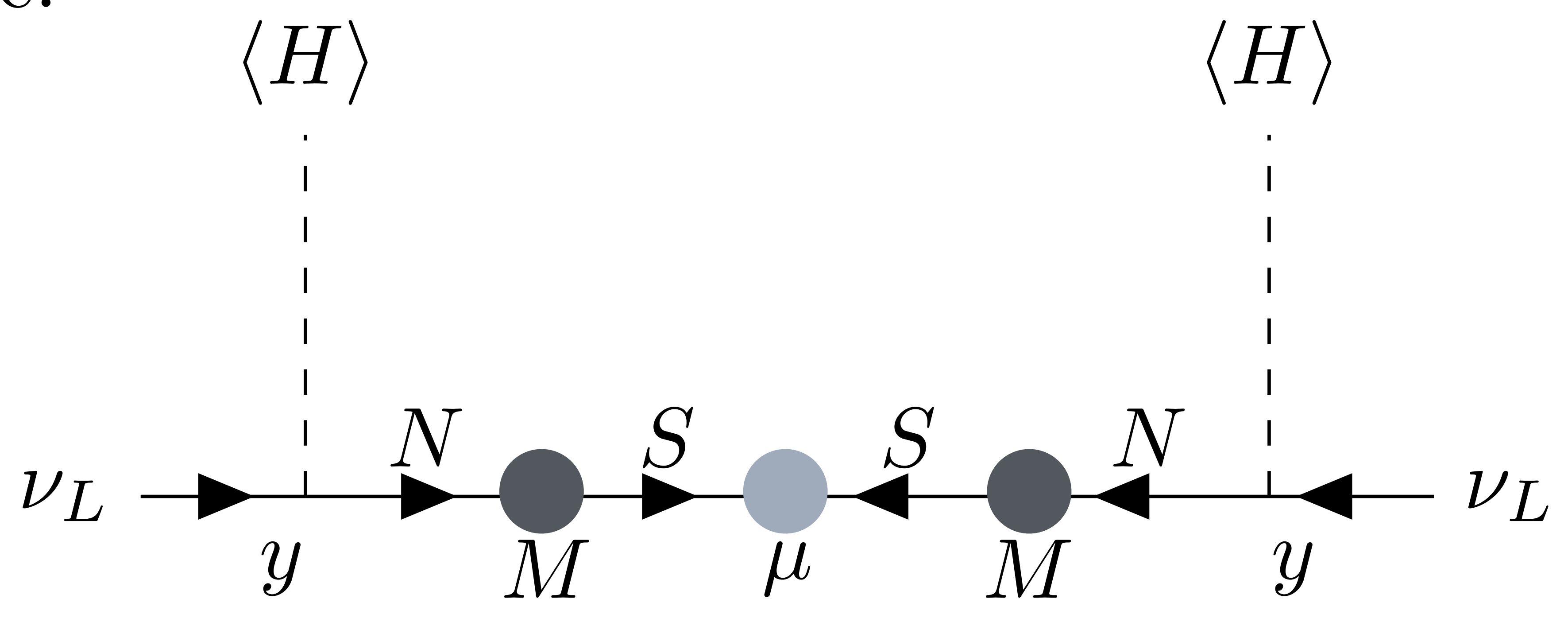
Poor phenomenology: N is very massive or weakly coupled to the **Standard Model**

More on inverse seesaw

Alternative framework: new fermions singlets N, S, a small lepton number violating Majorana mass μ and a Dirac mass term mixing them

Mohapatra and Valle

$$\mathcal{L} = y\bar{L}NH + M\bar{N}S + \frac{1}{2}\mu\bar{S^C}S + \text{h.c.}$$



If the Dirac mass from the Yukawa is such that $\mu \ll m_D = yv \ll M_R$

$$m_\nu \sim \frac{v^2}{M^2}\mu$$

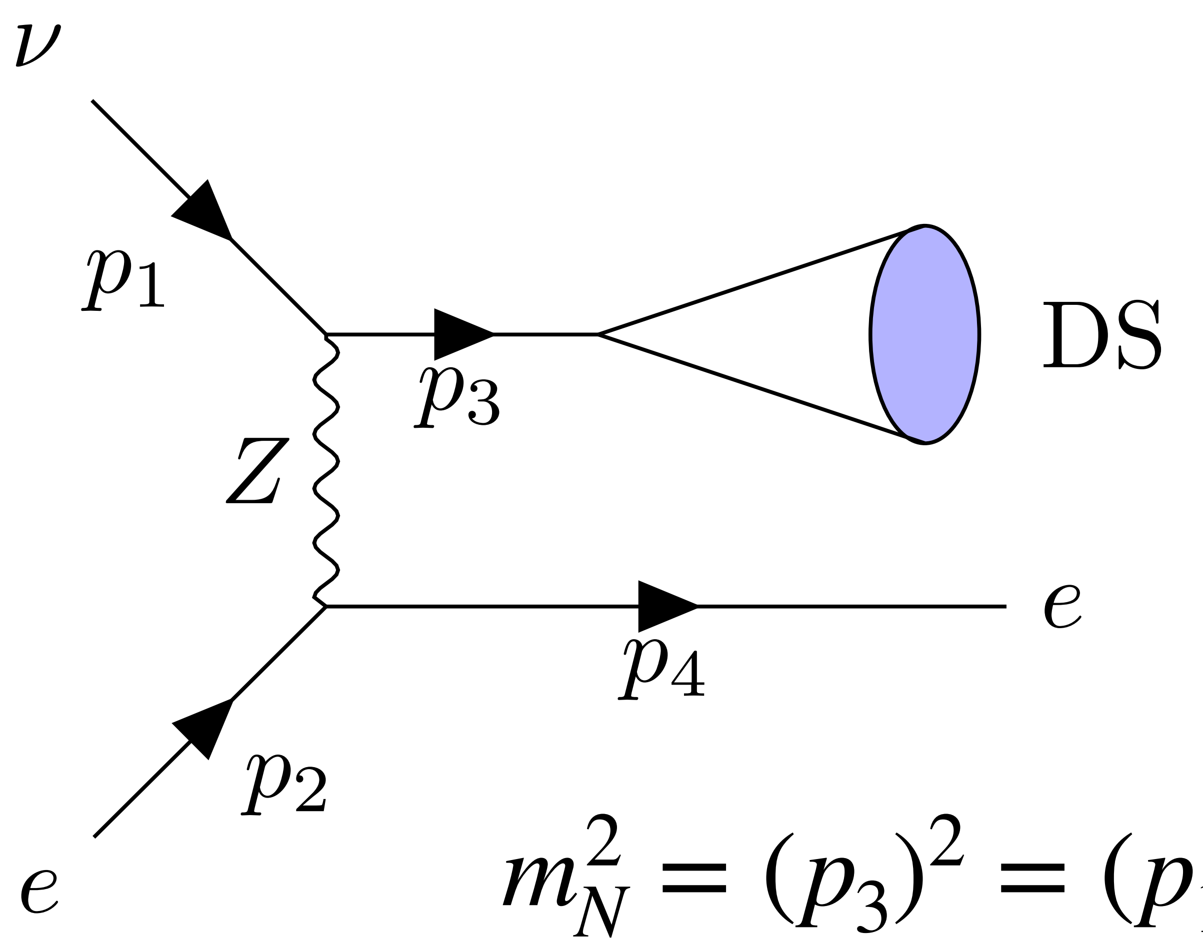
μ is very small $\Longrightarrow$ m_ν is naturally suppressed

Lowering the new physics scale: much richer phenomenology since M is not as big as in standard seesaw

$$y \sim 1,\ M \sim 1\ \text{TeV},\ m_\nu \sim 1\ \text{eV}, \mu \sim 40\ \text{eV} \ll M,\ v$$

Electron scattering

$$\Delta\mathcal{L}_N = \frac{y_\mu H L_\mu \mathcal{O}_N}{\Lambda_{\rm UV}^2}$$

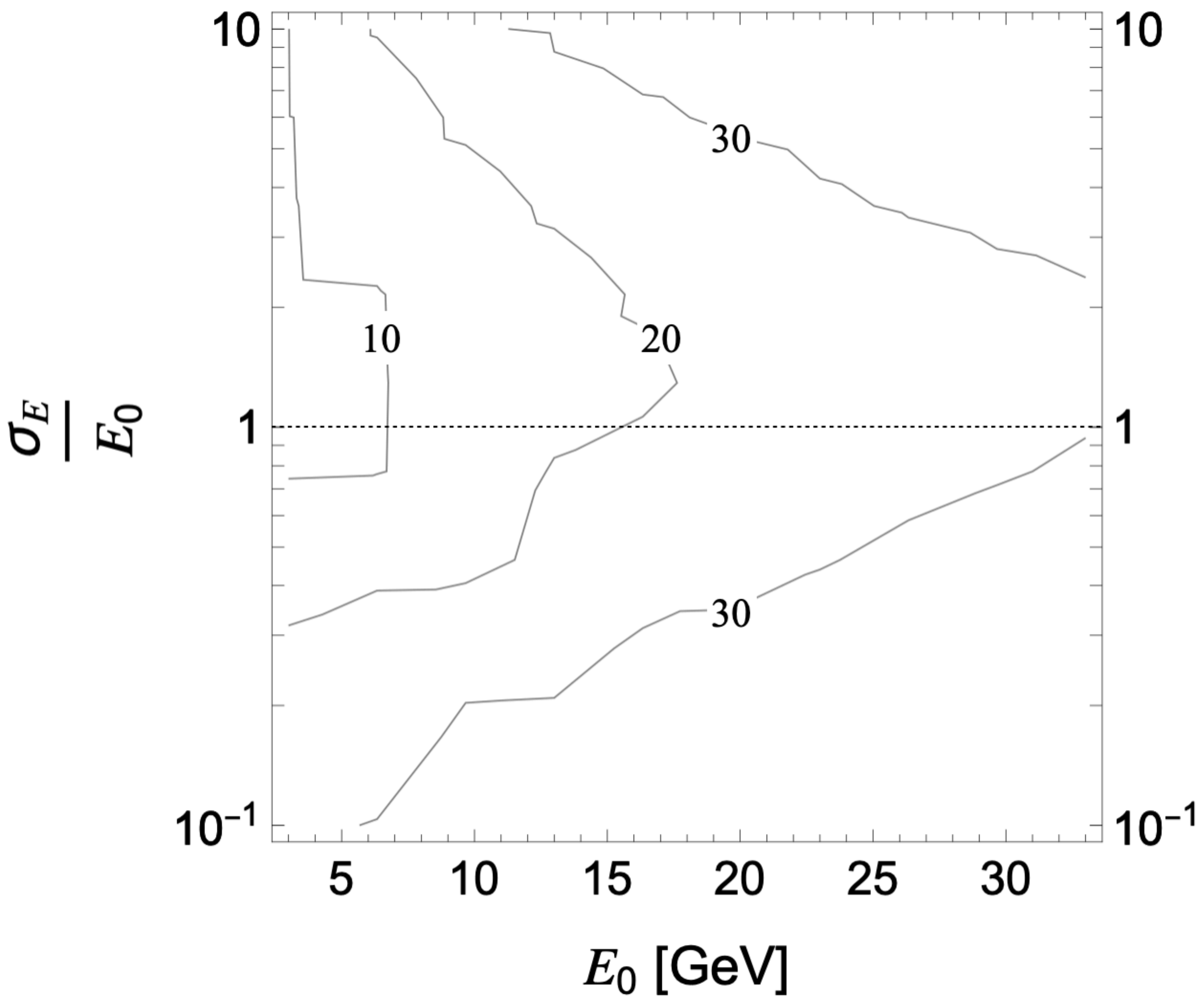


$$\frac{d\sigma_L}{dm_N^2} = \frac{A_N l_e^2 y_\mu^2}{96\pi^2}\frac{s_e}{v^2\Lambda_{\rm UV}^4}\left[\frac{m_N^2}{\Lambda_{\rm UV}^2}\right]^{\Delta_N-7/2}\left[1-\frac{m_N^2}{s_e}\right]^2$$

$$m_N^2 = (p_3)^2 = (p_1+p_2-p_4)^2$$

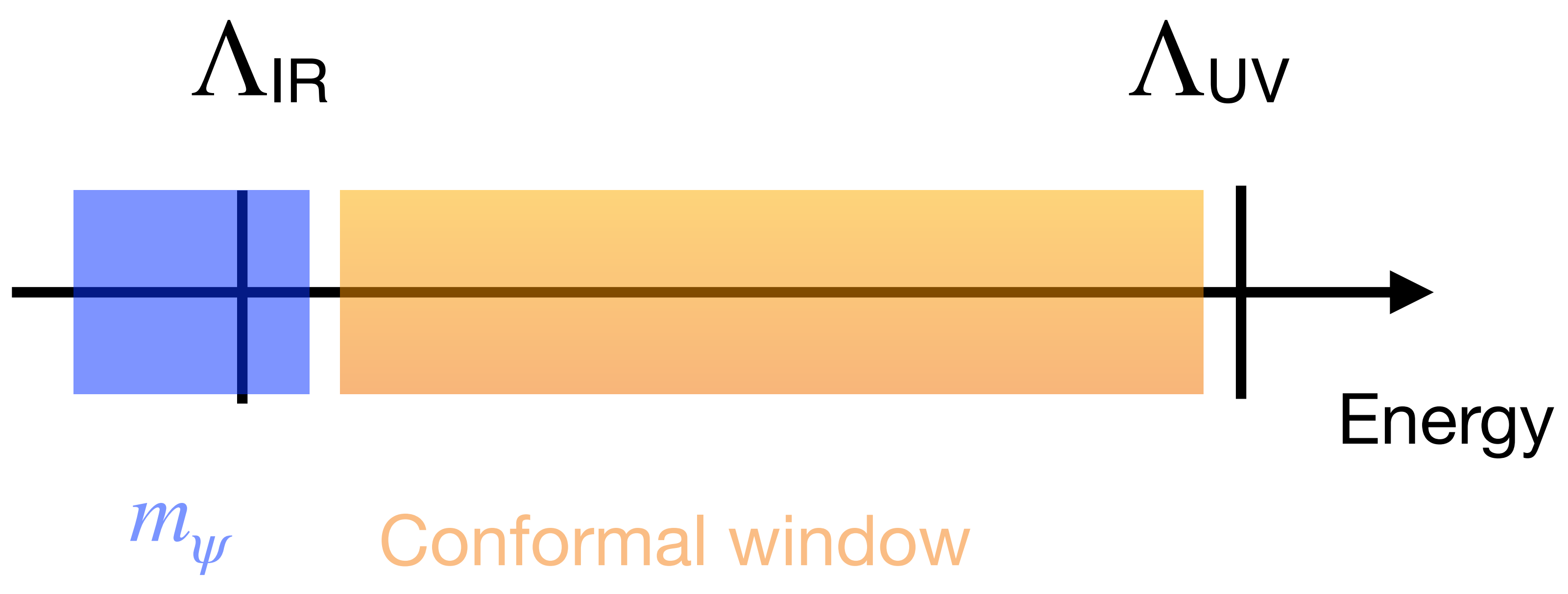
monochromatic neutrino beam sensitivity:

$$S_{m_N^2\geq 0} = 1$$

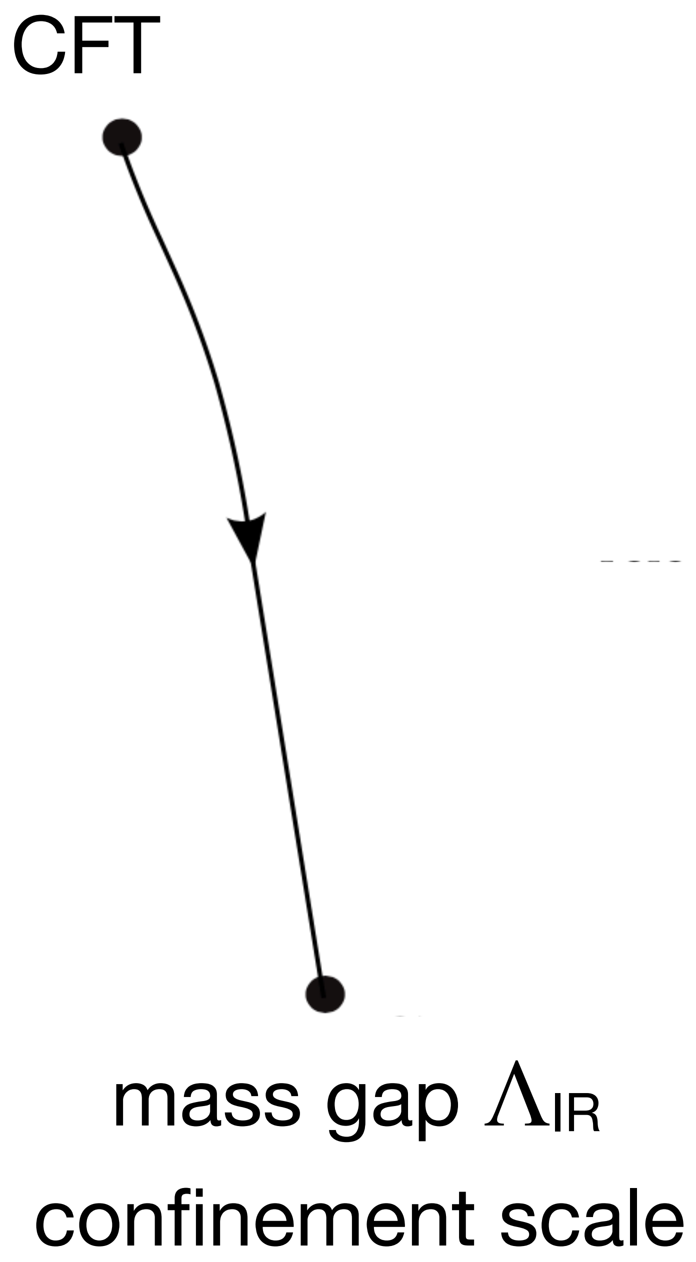


Strongly coupled sterile sectors

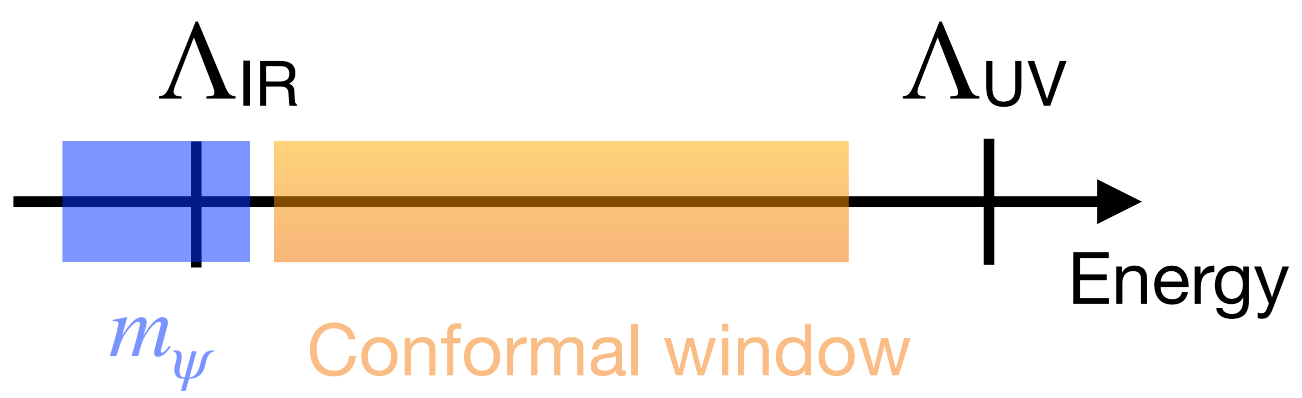
Explicit realization: CFT at high energy deformed by a marginal relevan operator ($\Delta_O = 4 + \epsilon$) driving in the infrared to a confined and gapped theory



$$\mathcal{L}_{\text{DS}} = \mathcal{L}_{\text{CFT}} + c_O \frac{O_{\text{DS}}}{\Lambda^{\Delta_O - 4}}$$



Strongly coupled sterile sectors



Large hierarchy $\Lambda_{\text{IR}} \ll \Lambda_{\text{UV}} \Longrightarrow$ approximately **scale invariance**

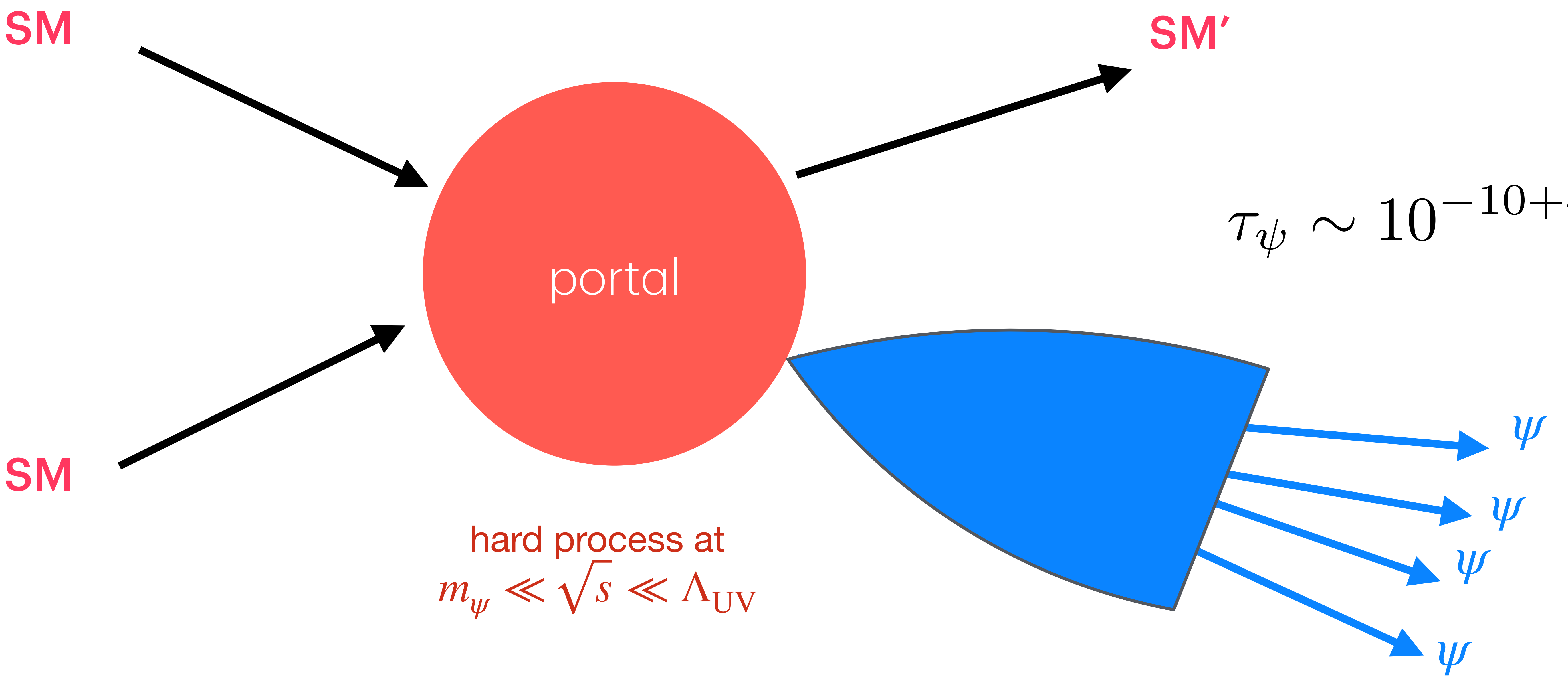
Conformal window: inclusive physics computed indepentently on **Dark Sector** spectrum

optical theorem

$$\text{Im}\left[i\langle T[\mathcal{O}_{\text{DS}}^{(\Delta_{\text{DS}})}(p)\bar{\mathcal{O}}_{\text{DS}}^{(\Delta_{\text{DS}})}(-p)]\rangle\right] = A_{\Delta_{\text{DS}}}(p^2)^{\Delta_{\text{DS}}-2}$$

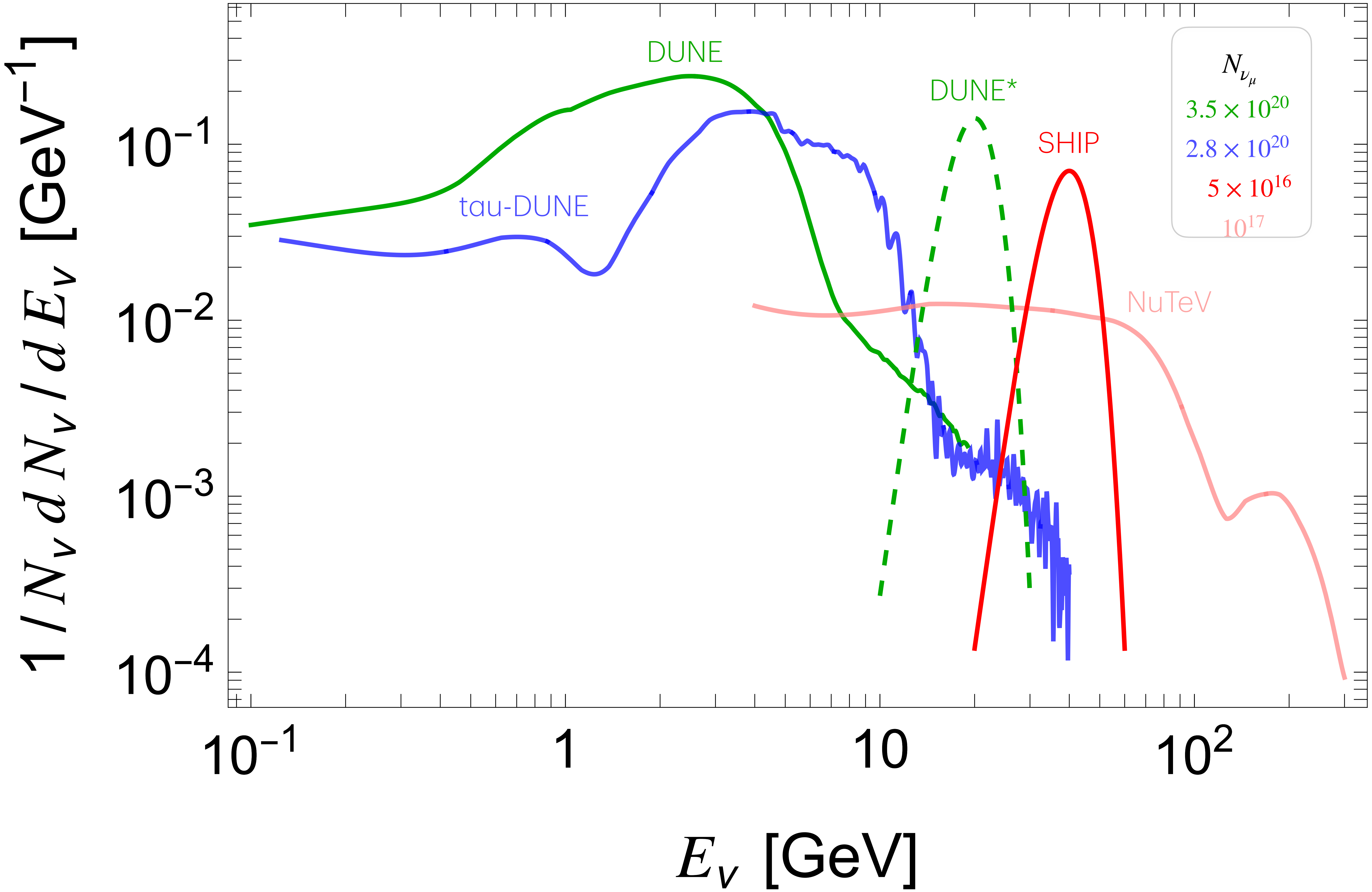
Lifetimes

$$\Delta\mathcal{L}_N = \frac{y_\mu H L_\mu \mathcal{O}_N}{\Lambda_{\rm UV}^{\Delta_N - 3/2}}$$



$$\tau_\psi \sim 10^{-10+4\Delta_N}\,{\rm km}\left(\frac{10\,{\rm MeV}}{\Lambda_{\rm IR}}\right)^{2\Delta_N}\left(\frac{\Lambda_{\rm UV}}{1\,{\rm GeV}}\right)^{2\Delta_N-3}$$

The role of fluxes



Scattering over nucleons

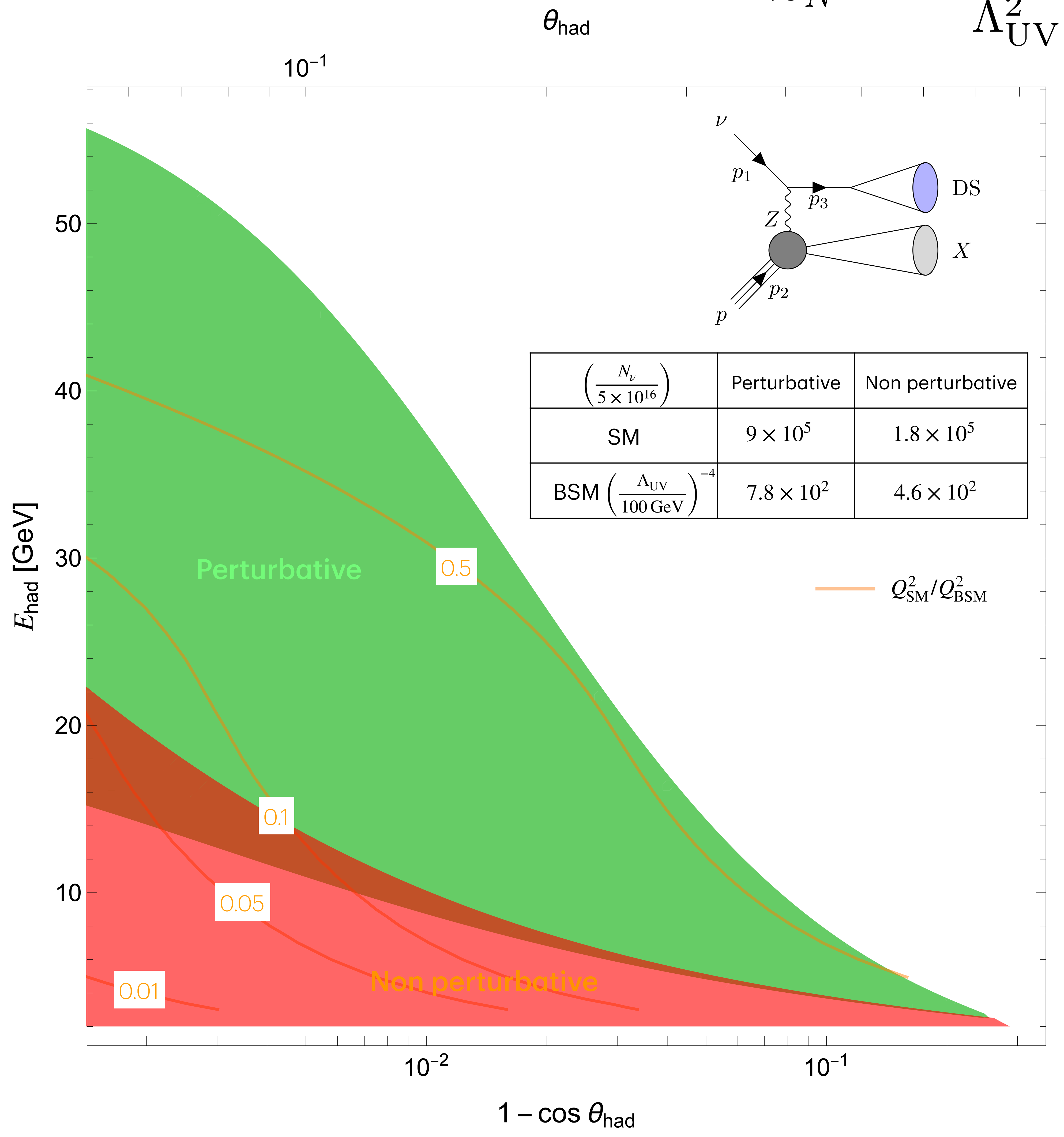
$$\Delta\mathcal{L}_N = \frac{y_\mu H L_\mu \mathcal{O}_N}{\Lambda_{\rm UV}^2}$$

Enhancement of exchange momentum

$$Q^2_{\rm BSM} \approx Q^2_{\rm SM} + m_N^2 \frac{E_{\rm had}}{E_\nu - E_{\rm had}}$$

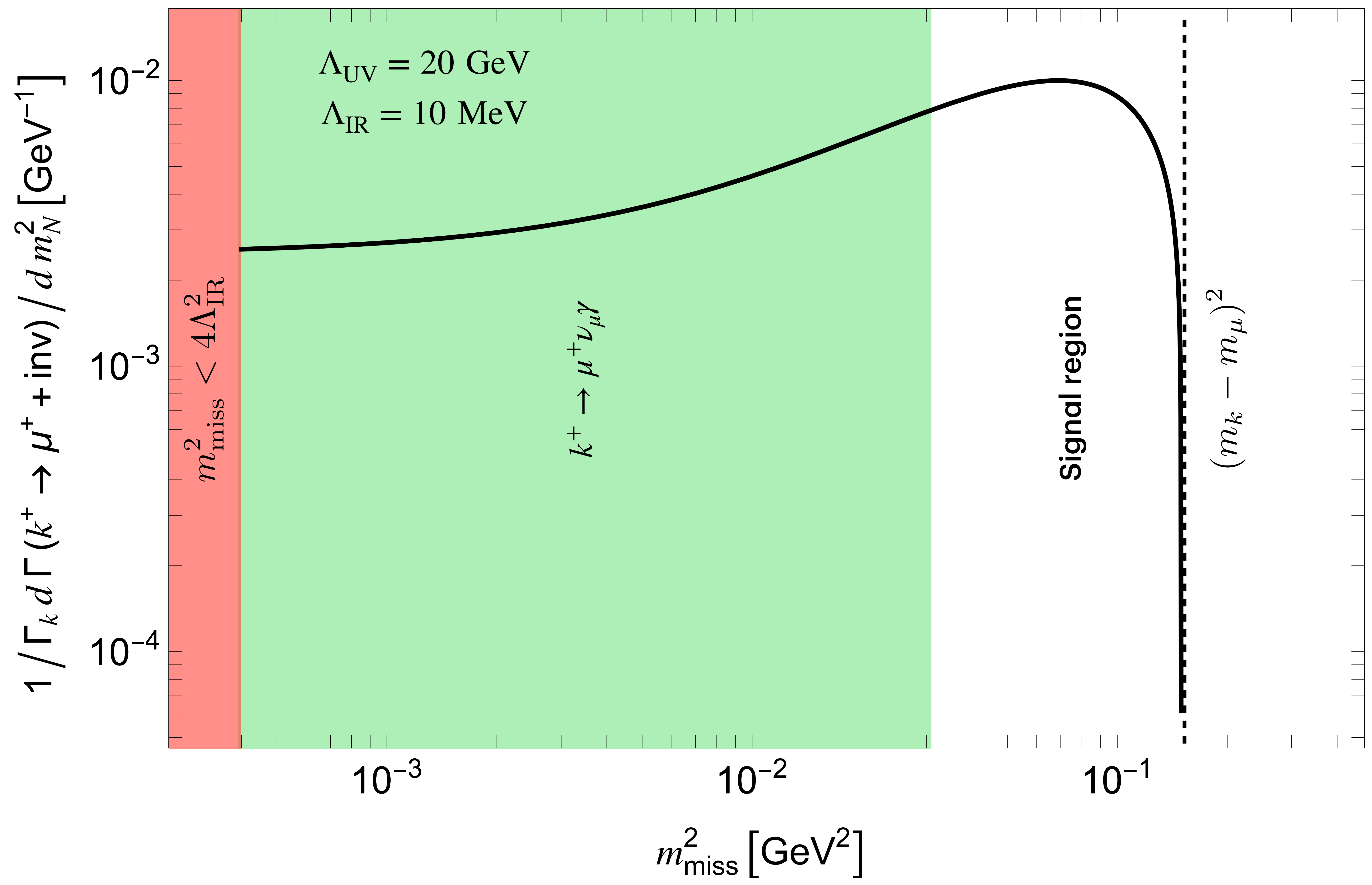
Less massive hadronic states

$$m^2_{\rm had,BSM} \approx m^2_{\rm had,SM} - m_N^2 \frac{E_{\rm had}}{E_\nu - E_{\rm had}}$$



$\left(\frac{N_\nu}{5\times10^{16}}\right)$	Perturbative	Non perturbative
SM	9×10^5	1.8×10^5
BSM $\left(\frac{\Lambda_{\rm UV}}{100\,{\rm GeV}}\right)^{-4}$	7.8×10^2	4.6×10^2

Kaon decays



$\Lambda_{UV} = 20$ GeV
$\Lambda_{IR} = 10$ MeV
$m^2_{miss} < 4\Lambda^2_{IR}$
$k^+ \to \mu^+ \nu_\mu \gamma$
Signal region
$(m_k - m_\mu)^2$
10^{-2}
10^{-3}
10^{-4}
$1 / \Gamma_k \, d\Gamma(k^+ \to \mu^+ + \text{inv}) / d\, m_N^2$ [GeV^{-1}]
10^{-3}
10^{-2}
10^{-1}
m^2_{miss} [GeV^2]

Pdfs uncertainties