Constraining Neutrinophilic Scalars from Electroweak Precision

Drona Vatsyayan

29th July 2026, Light Dark World 2026, Ottawa

Based on:

arXiv: 2606.02704 [Saeid Foroughi-Abari, Camila Mupo, DV, Yue Zhang]

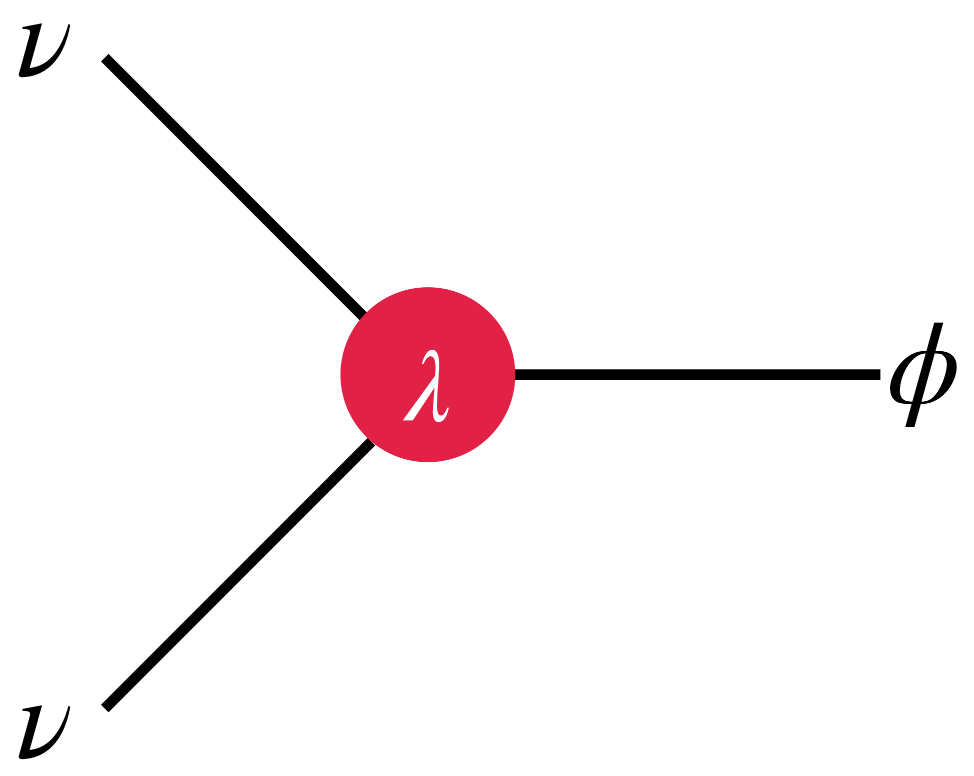
Carleton University | McDonald Institute

~ 14 mins

Neutrino Self Interactions

Overview

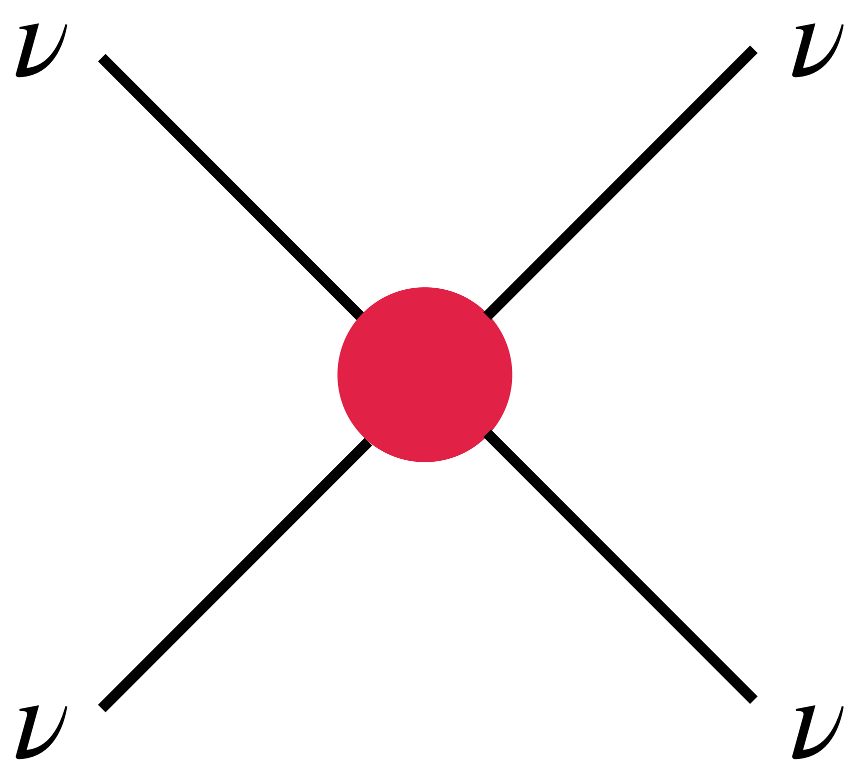
Indirect measurements from Z invisible decay width (LEP) → Self-interaction among active neutrinos (SIν) in the SM are extremely weak



Novel SIν mediated by a BSM scalar/vector bosons
→ Can be significantly large compared to SM

$$\boxed{G_{\text{eff}} \equiv \lambda^2/m_\phi^2}$$

Light mediators → Larger G_{eff}

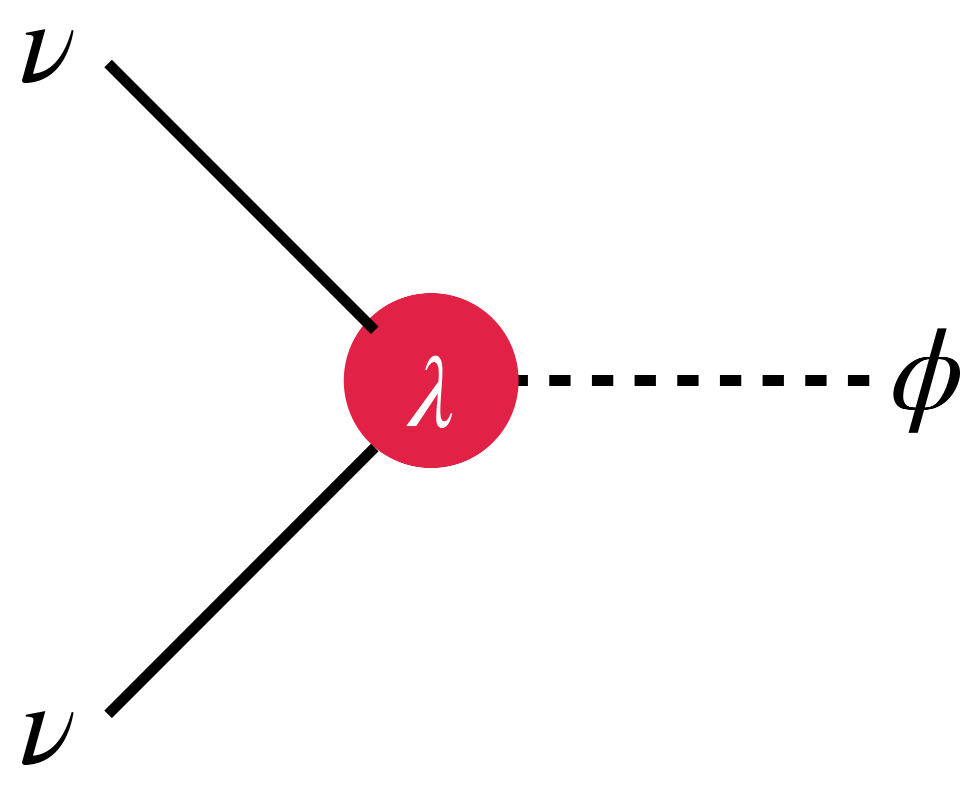


Well motivated from both theory and cosmology → Neutrino mass, connections to sterile neutrino DM, Hubble and S8 tensions, Muon g-2, relaxation of cosmological m_ν bound

Berryman et. al. (2022)

Neutrino Self Interactions

Neutrinophilic Scalar



$$\mathscr{L} = \sum_{\alpha,\beta=e,\mu,\tau} \frac{\lambda_{\alpha\beta}}{2} \bar{\nu}_\alpha \mathbb{P}_R \nu^c_\beta \phi + \mathrm{h.c.}$$

Simplified model at low-energies

Make ϕ neutrinophilic $\rightarrow$ Avoid charged lepton flavour constraints

Stronger constraints on vector mediators, more room with scalar mediators for strong neutrino self-interactions

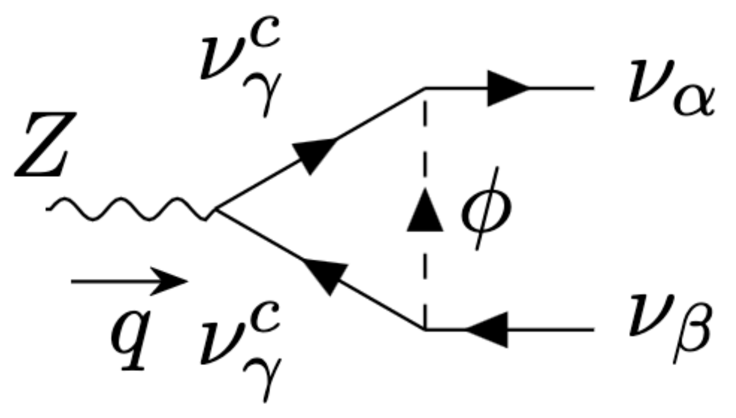
Tied to neutrino mass theories $\rightarrow \mathscr{L} = \frac{1}{\Lambda^2}(LH)^2\phi$

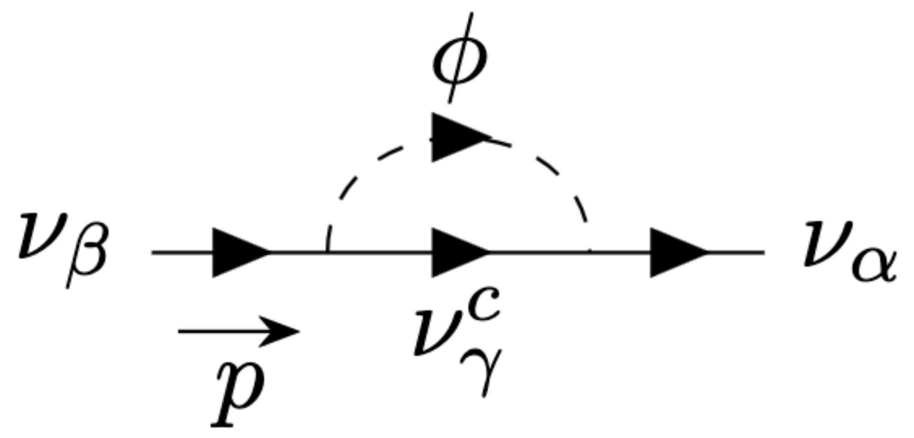
Simplified model: Singlet scalar ϕ solely mediates SIν, no VEV to avoid constraints from m_ν

Impact on Electroweak Precision

Neutrino EW Couplings

$$\mathscr{L} = -(g_Z)_{\alpha\beta}\,\bar{\nu}_\alpha\,\gamma^\mu \mathbb{P}_L\,\nu_\beta\,Z_\mu$$
$$-\left\{(g_W)_{\alpha\beta}\,\bar{\ell}_\alpha\,\gamma^\mu \mathbb{P}_L\,\nu_\beta\,W^-_\mu + \mathrm{h.c.}\right\}$$





Self-interaction among neutrinos→ Radiative corrections to neutrino EW couplings

Simplified SIν Lagrangian→ Not gauge-invariant, has UV divergences → Need a UV complete model

$$(\delta g_Z)_{\alpha\beta} = -\frac{g_Z^0 \lambda_{\alpha\gamma}\lambda^*_{\beta\gamma}}{32\pi^2}\left[\ln\frac{M^2}{m_\phi^2} + c_Z + f_1(q^2, m_\phi, M) + \mathcal{O}\left(\frac{1}{M^2}\right)\right]$$

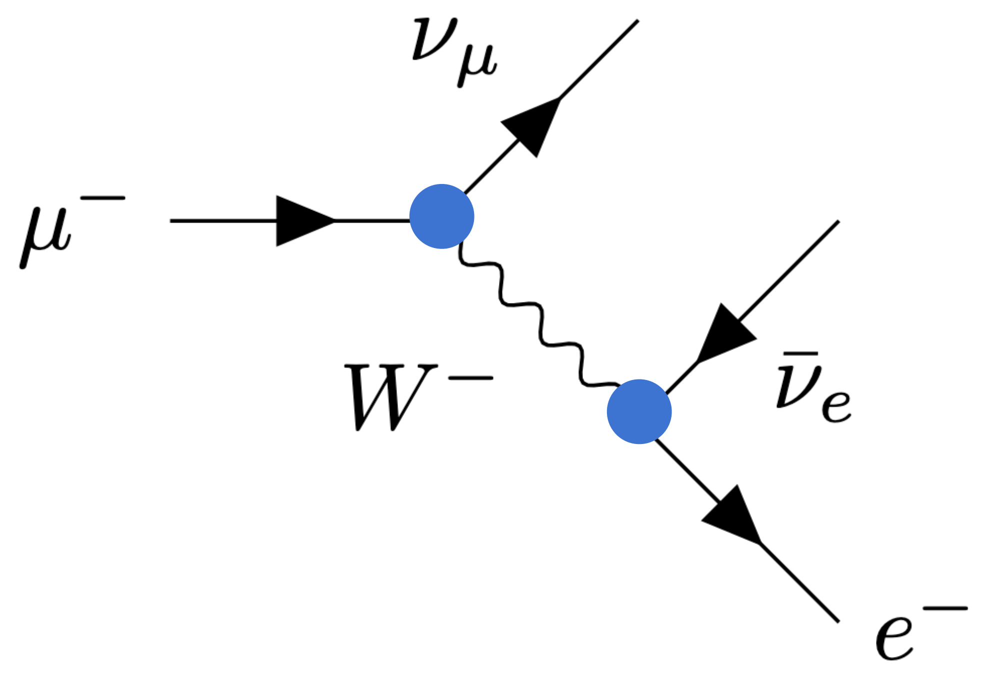
$$(\delta g_W)_{\alpha\beta} = -\frac{g_W^0 \lambda_{\alpha\gamma}\lambda^*_{\beta\gamma}}{64\pi^2}\left[\ln\frac{M^2}{m_\phi^2} + c_W + \mathcal{O}\left(\frac{1}{M^2}\right)\right]$$

Light mediators→ Log enhancement irrespective of the UV completion details

Impact on Electroweak Precision

The Fermi Constant

$$G_F \equiv \sqrt{2} g^2 / (8 m_W^2)$$



$$\frac{1}{\tau_\mu} \simeq \left(1 + \Delta r^{\mathrm{SI}\nu}\right)^2 \left(\frac{1}{\tau_\mu}\right)_{\mathrm{SM}}$$

Neutrinophilic scalar coupling to $e/\mu \rightarrow$ Radiative corrections modify the extraction of G_F from μ lifetime measurements

$$\Delta r^{\mathrm{SI}\nu} \equiv \frac{(\delta g_W)_{ee} + (\delta g_W)_{\mu\mu}}{g_W^0} = -\frac{|\lambda_{ee}|^2 + |\lambda_{\mu\mu}|^2}{64\pi^2} \left(\ln \frac{M^2}{m_\phi^2} + c_W \right)$$

$$\boxed{G_F = \frac{G_\mu}{1 + \Delta r^{\mathrm{SI}\nu}} \simeq (1 - \Delta r^{\mathrm{SI}\nu}) G_\mu}$$

$G_\mu \equiv 1.16637 \times 10^{-5}\,\mathrm{GeV}^{-2}$

Light mediators $\rightarrow$ SIν leads to increase in the extracted value of G_F

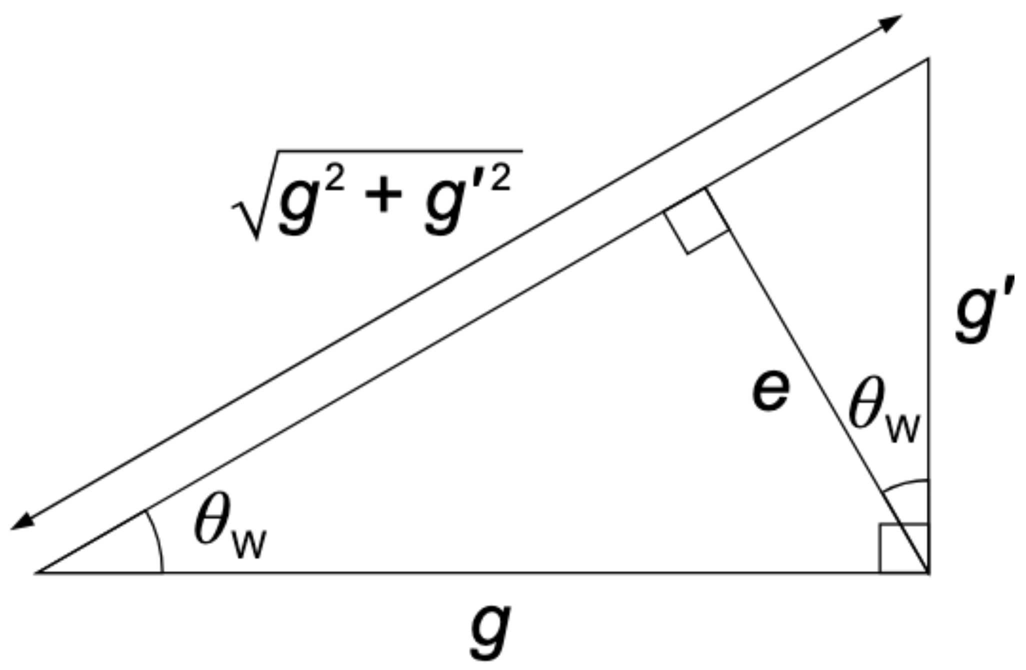
G_F measurements alone cannot constrain NP $\rightarrow$ Use to construct other EW observables

Marciano (1999)

Impact on Electroweak Precision

Weak Mixing Angle

$$\sin^2\theta_W = 1 - \left(\frac{m_W^2}{m_Z^2}\right)$$



$$\sin^2\theta_W^{\rm SM}\cos^2\theta_W^{\rm SM} = \frac{\pi\alpha}{\sqrt{2}G_\mu m_Z^2(1-\Delta r^{\rm SM})}$$

Radiative corrections in SM

Sirlin (1980)

Modification of the Fermi constant affects the weak mixing angle → Replace G_μ by G_F

$$\sin^2\theta_W\cos^2\theta_W = \frac{\sin^2\theta_W^{\rm SM}\cos^2\theta_W^{\rm SM}}{1-\Delta r^{\rm SI\nu}}$$

$$\sin\theta_W \simeq \sin\theta_W^{\rm SM}\left[1 + \frac{1+\sec(2\theta_W^{\rm SM})}{4}\Delta r^{\rm SI\nu}\right]$$

$\sin^2\theta_W^{\rm SM} = 0.23122$

SIν effects encoded in Δr parameter → Naive estimates from $\Delta r \leq 0.0012\ (2\sigma)$

Erler, Ramsey-Musolf (2005)

~ 10 mins

Impact on Electroweak Precision

Input Parameters & W-boson Observables

Freely varying within their experimentally determined ranges

	Parameter	Input value
QCD	$\alpha_s(m_Z^2)$	0.1177 ± 0.0009
QED	$\Delta\alpha_{\text{had}}^{(5)}(m_Z^2)^{(\Delta)}$	0.02758 ± 0.00010
	m_Z [GeV]	91.188 ± 0.0020
	m_t [GeV]	172.56 ± 0.61
	M_H [GeV]	125.1 ± 0.1

$+G_F$

Masses of light quarks and leptons kept fixed

Simplified model (SIν) $\rightarrow$ $+\{\lambda, m_\phi, M\}$

m_W is modified from the corrections to the weak mixing angle

$$m_W \equiv m_Z \cos\theta_W$$

Corrections to the total W decay width Γ_W

$$\Gamma_{W^-} = \Gamma_{W^-}^{\text{SM}}\left(\Delta r^{\text{SI}\nu}\right) + \delta\Gamma_{W^-\to\ell\bar{\nu}} + \Gamma_{W^-\to\ell\nu\phi^*}$$

No log enhancement of the form $\ln\left(M^2/m_\phi^2\right)$ for $m_W \gg m_\phi$

$$\delta\Gamma_{W\to\ell\nu} + \Gamma_{W\to\ell\nu\phi} \simeq -\frac{G_\mu m_W^3 |\lambda_{\alpha\alpha}|^2}{192\sqrt{2}\pi^3}\left(\ln\frac{M^2}{m_W^2} + \frac{17+2c_W}{6}\right)$$

CDF, D0 (2012); ATLAS (2024)

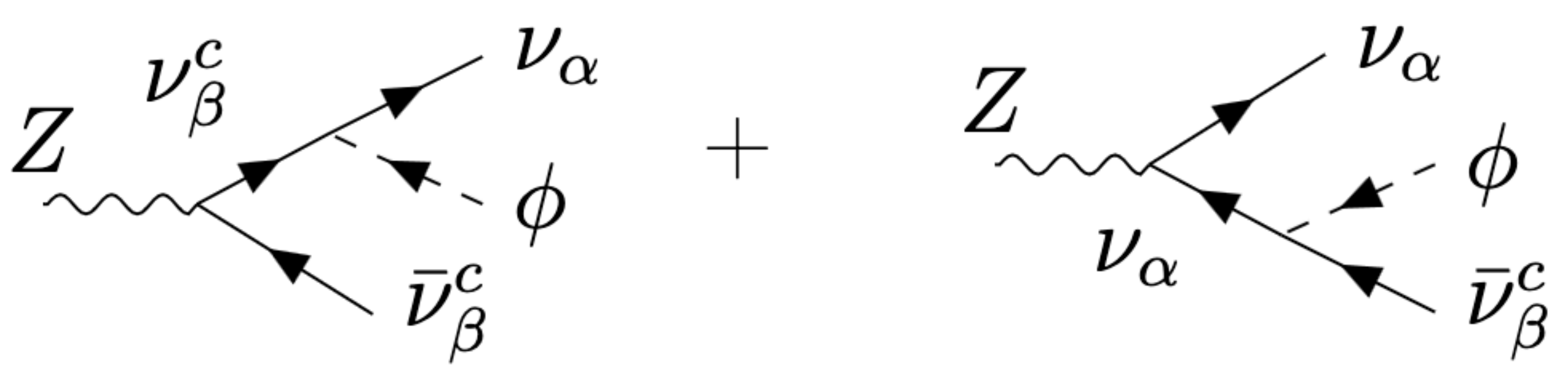
Impact on Electroweak Precision

Z-pole Observables

$e^+e^- \to f\bar{f}$

LEP, SLD (2006)

$$g_{V,f} = \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f \kappa_Z^f \sin^2\theta_W\right),\ g_{A,f} = \sqrt{\rho_Z^f}\, I_3^f$$



$$\Delta\Gamma_{\rm inv}^{\rm SI\nu} = \delta\Gamma_{Z\to\nu\bar{\nu}} + \left(\Gamma_{Z\to\nu\nu\phi^*} + \Gamma_{Z\to\bar{\nu}\bar{\nu}\phi}\right)$$

$$\simeq -\frac{G_\mu m_Z^3 |\lambda_{\alpha\alpha}|^2}{96\sqrt{2}\pi^3}\left(\ln\frac{M^2}{m_Z^2} + \frac{17+3c_Z}{6}\right)$$

No log enhancement of the form $\ln\left(M^2/m_\phi^2\right)$ for $m_Z \gg m_\phi$

$$A_f = \frac{2g_{V,f}g_{A,f}}{g_{V,f}^2 + g_{A,f}^2}$$

Asymmetry parameter

$$A_{\rm FB}^f = \frac{\sigma_F^f - \sigma_B^f}{\sigma_F^f + \sigma_B^f} = \frac{3}{4}A_e A_f$$

Forward-backward asymmetry

$$\Gamma_Z = \Gamma_Z^{\rm SM}(\Delta r) + \Delta\Gamma_{\rm inv}^{\rm SI\nu}$$

Total decay width

$$\sin^2\theta_{\rm eff}^\ell = \kappa_Z^\ell \sin^2\theta_W$$

Effective weak mixing angle

$$R_\ell = \frac{\Gamma_{\rm had}}{\Gamma_\ell},\ R_q = \frac{\Gamma_q}{\Gamma_{\rm had}}$$

Partial width ratios

$$\sigma_{\rm had} = \frac{12\pi}{m_Z^2}\frac{\Gamma_e\Gamma_{\rm had}}{\Gamma_Z^2}$$

Total hadronic CS

Precision Constraints

Global Fits

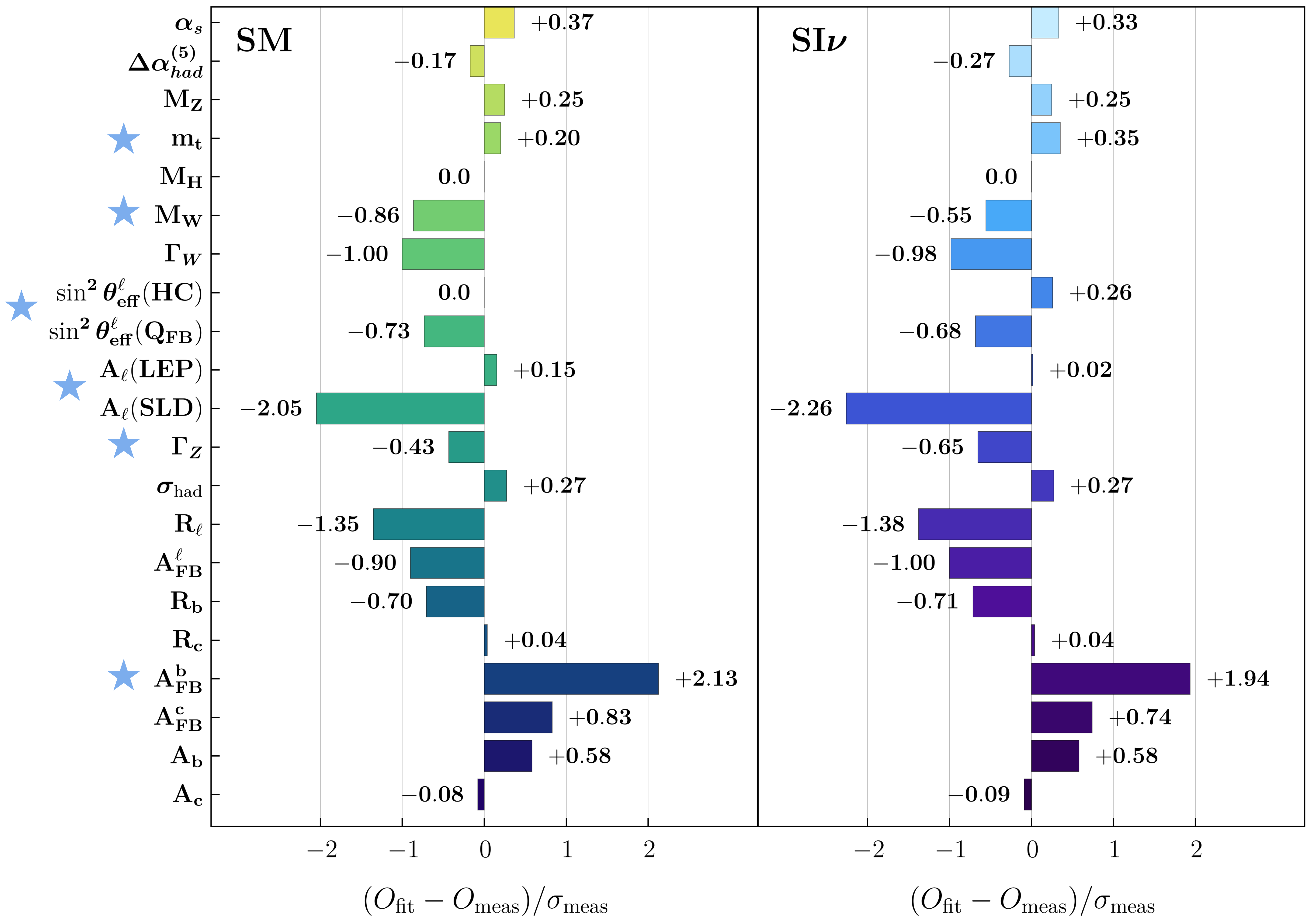
Global fits of SM predictions to EW precision data → Powerful probes of BSM physics

SIν effects are added to the Gfitter package, based on ROOT Minuit algorithm

Frequentist method → Global minimum of squares

$$\chi^2(y_i) \equiv -2 \ln \mathcal{L}(y_i)$$

$M = 1$ TeV, $\lambda \in [0.001 - 1.0]$, $m_\phi \in [0.001 - 200$ GeV$]$

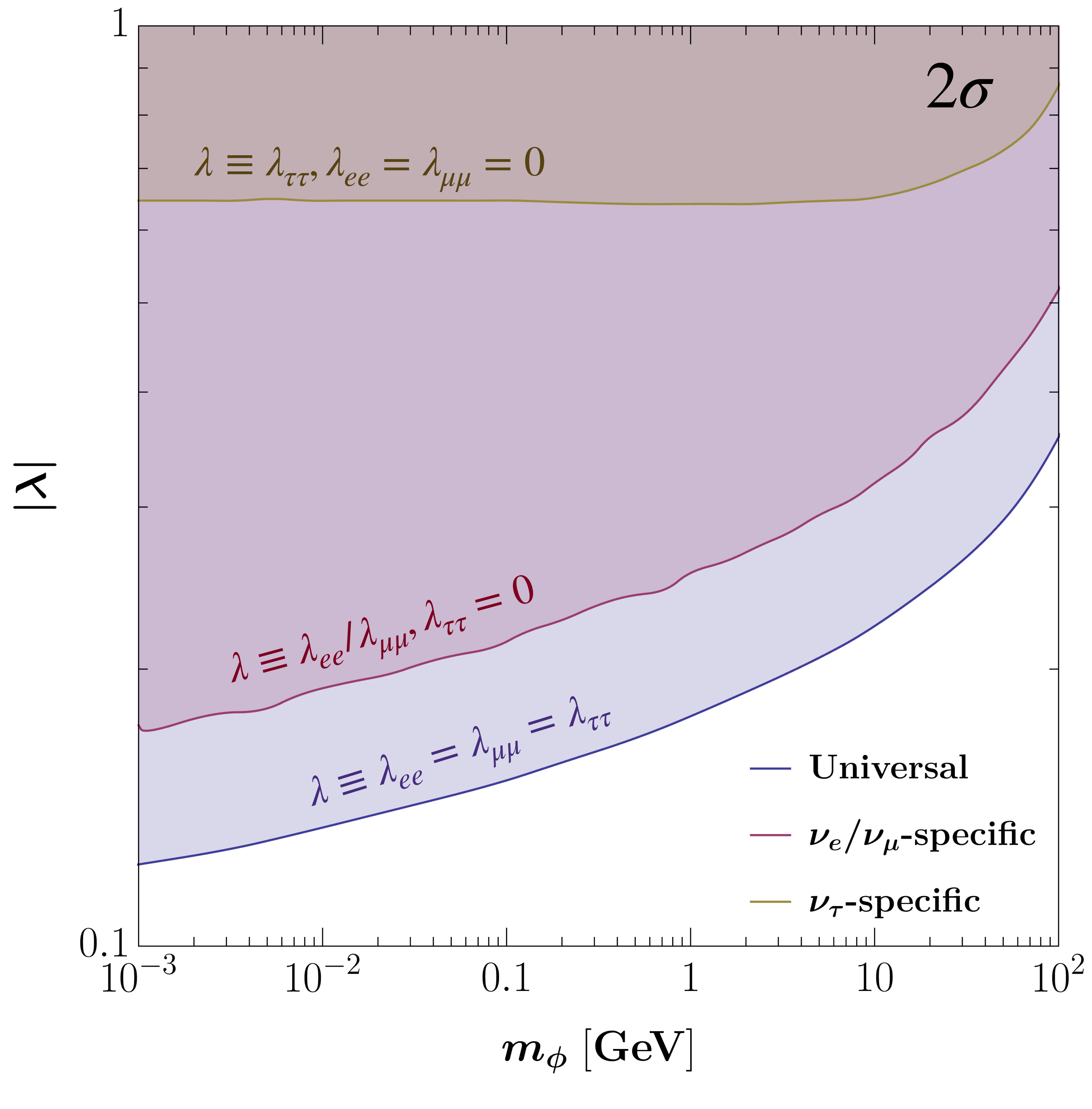


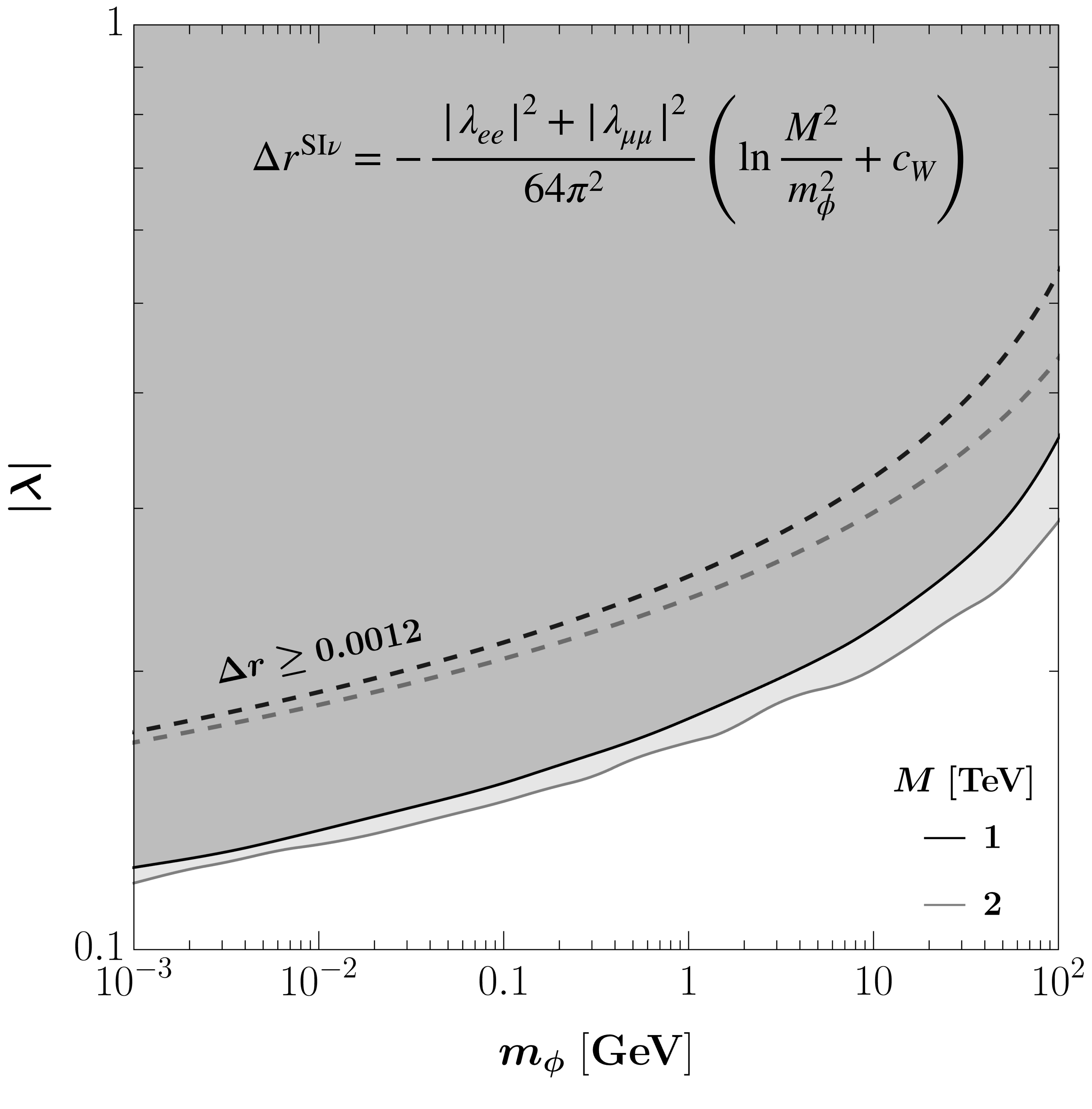
$G_F = 1.166379 \times 10^{-5}$
$\chi^2_{\min} = 13.99$

$G_F = 1.166649 \times 10^{-5}$
$\chi^2_{\min} = 13.60$

Precision Constraints

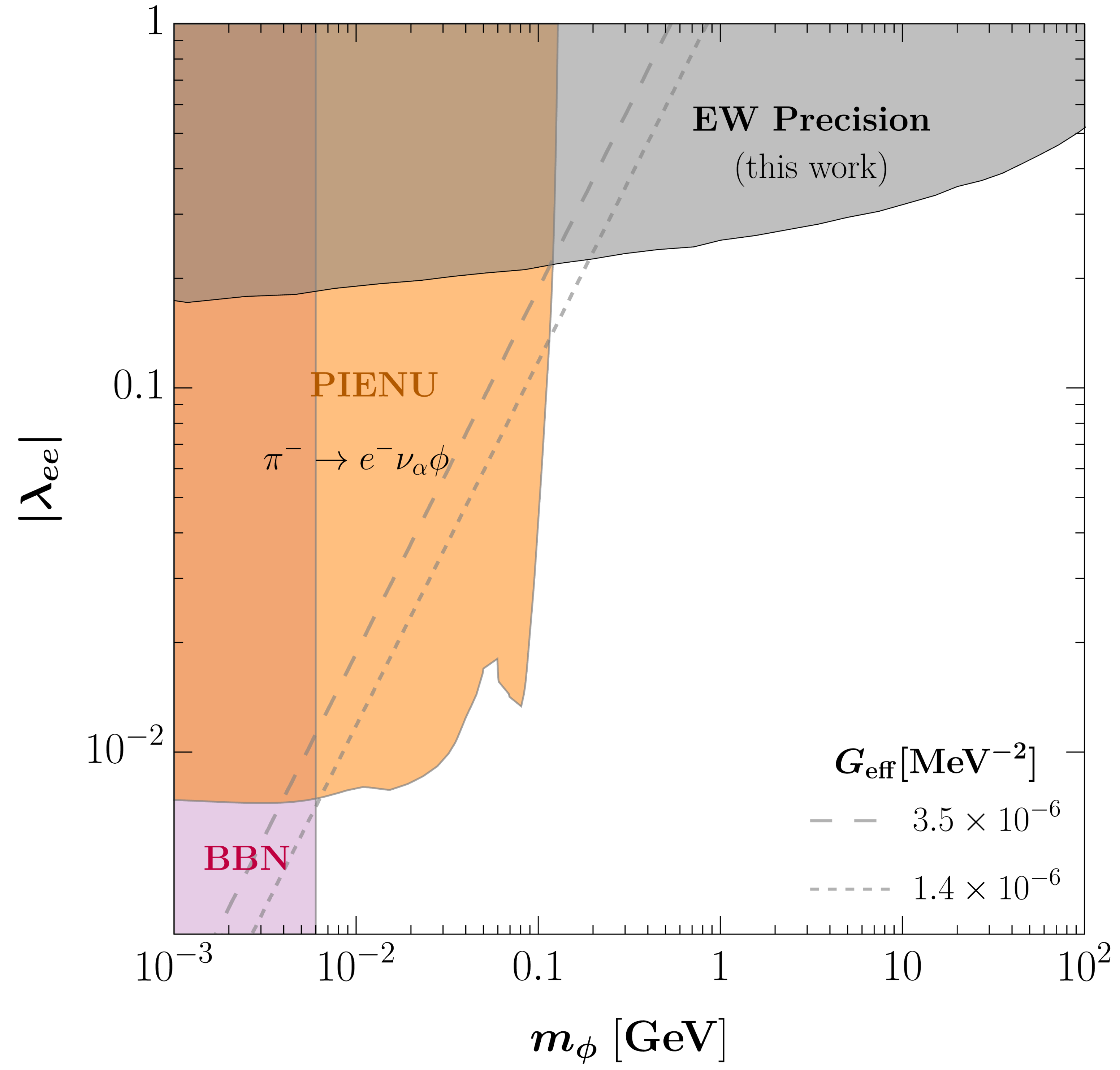
Simplified Model

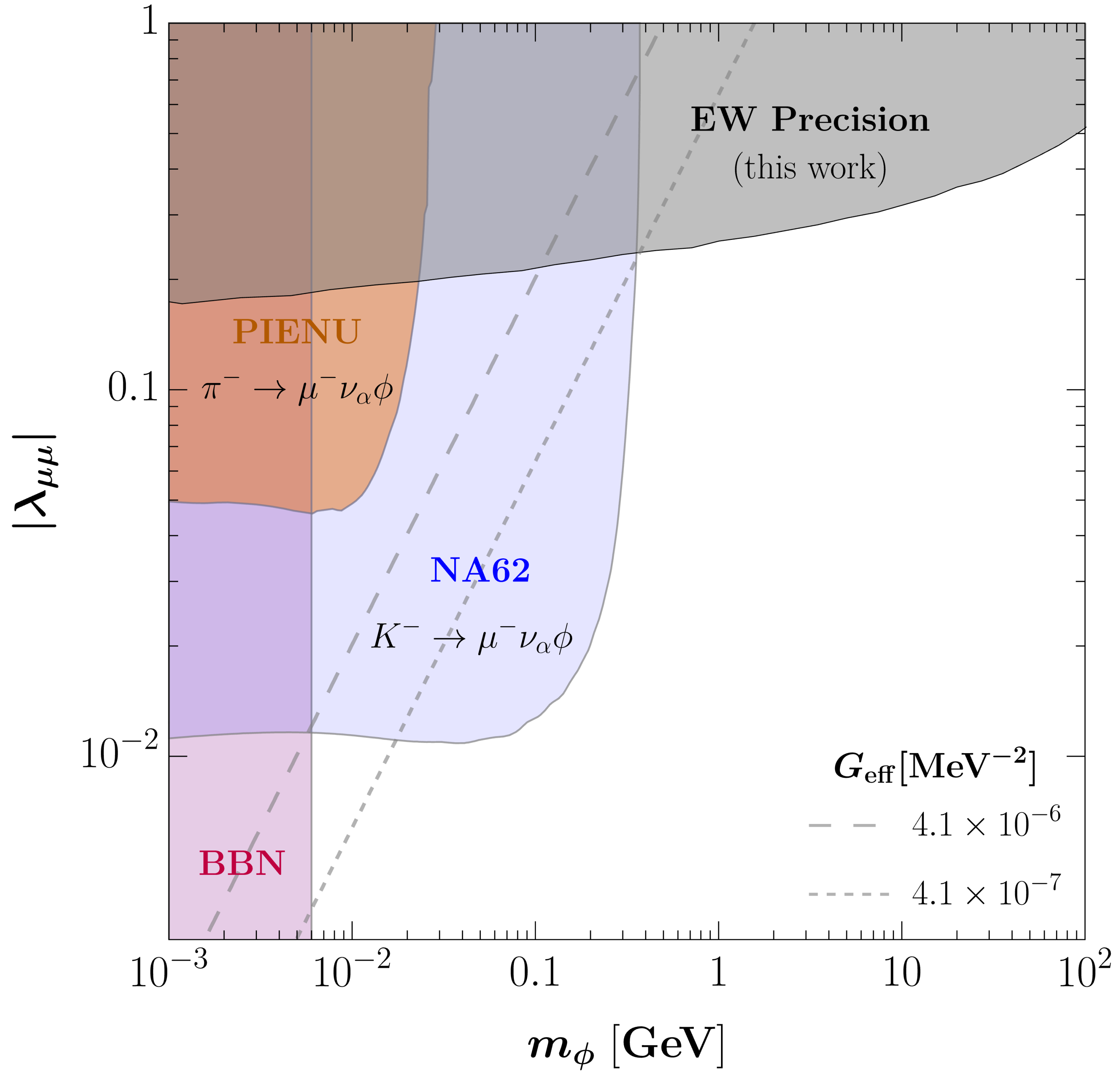


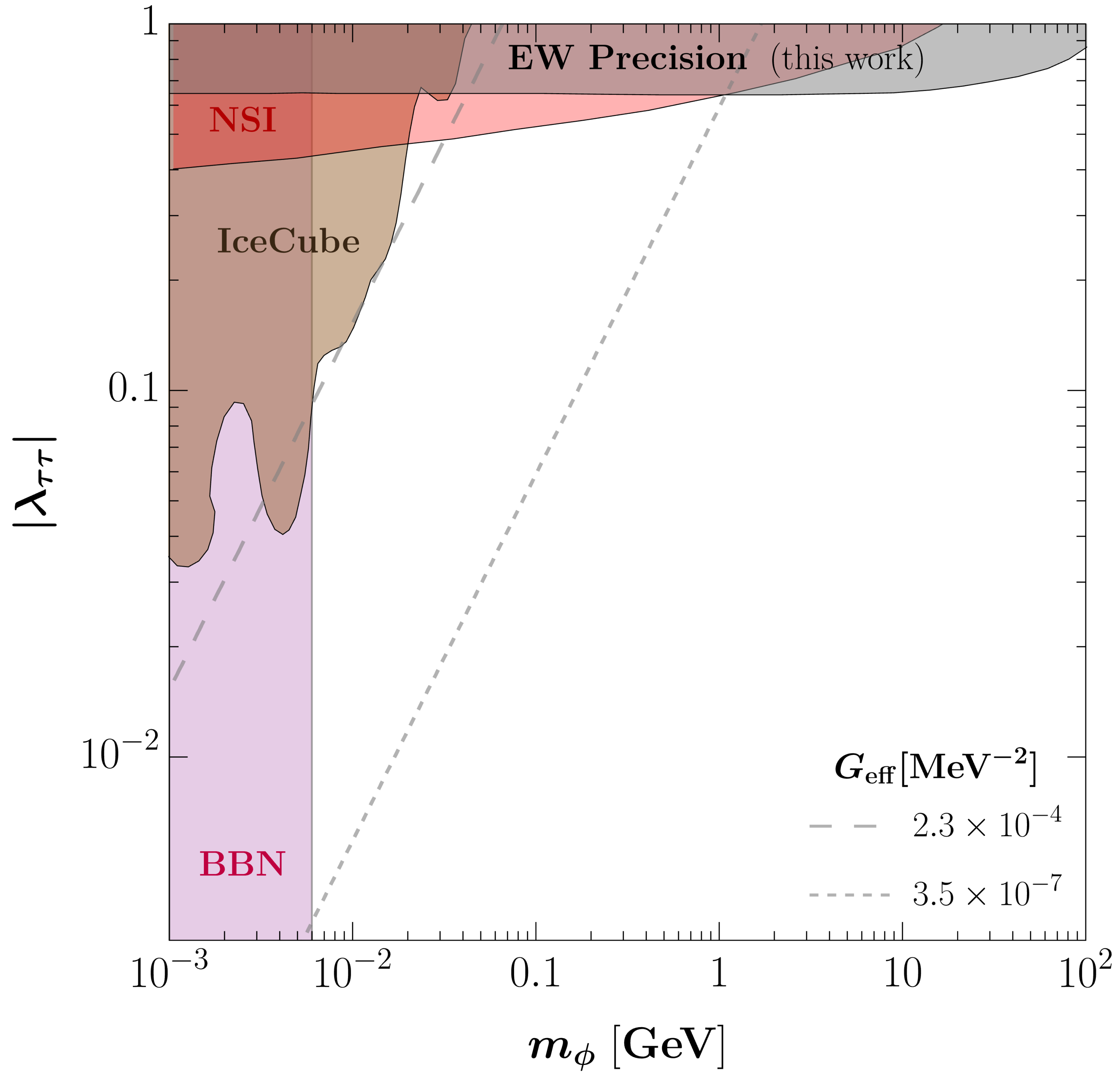


Parameter Space

Neutrinophilic Scalar







Constraints from $\Delta N_{\rm eff}$ at BBN → $m_\phi > 6$ MeV

Exotic three body decays of charged mesons $\to \mathfrak{m}^+ \to \ell_\alpha^+ \nu_\alpha X$

Tauphilic case → Constraints from IceCube measurements, global fit to ν oscillation data

Nollett, Steigman (2014)

Esteban, Pandey, Brdar, Beacom (2021)

~ 5 mins

UV Completion

with a Scalar Triplet

A concrete UV-complete model required for SIν $\rightarrow$ Extend SM with $SU(2)_L$ CS triplet + CS singlet

$$\mathscr{L} = \mathrm{Tr}[(D^\mu T)^\dagger (D_\mu T)] - M^2 \mathrm{Tr}[T^\dagger T] + \partial^\mu \phi^\dagger \partial_\mu \phi - \mu_\phi^2 |\phi|^2 - \sum_{\alpha,\beta=e,\mu,\tau} \frac{y_{\alpha\beta}}{2} \bar{L}_\alpha T i\sigma_2 L_\beta^c - \boxed{y' H^T i\sigma_2 T H \phi^*} + \mathrm{h.c.}$$

After EWSSB ϕ mixes with T^0 that couples only to neutrinos $\rightarrow$ SIν mediated by ϕ

$$\sin\theta \simeq \frac{|y'| v^2}{2M^2} \simeq 0.03 |y'| \left(\frac{1\,\mathrm{TeV}}{M}\right)^2 \qquad \boxed{\lambda_{\alpha\beta} \simeq y_{\alpha\beta} \sin\theta}$$

New tree-level decay channel due to the mixing: $Z \rightarrow \phi\phi^*$ $(m_Z > 2m_\phi)$

Radiative corrections to the gauge couplings from both the triplet and the singlet

$$\delta g_V = \boxed{(\delta g_V)_\phi + \left[(\delta g_V)_T - (\delta g_V)_{T,\theta=0}\right]} + (\delta g_V)_{T,\theta=0}$$

$\lambda^2 \ln(M^2/m_\phi^2)$

$y^2 q^2/M^2$

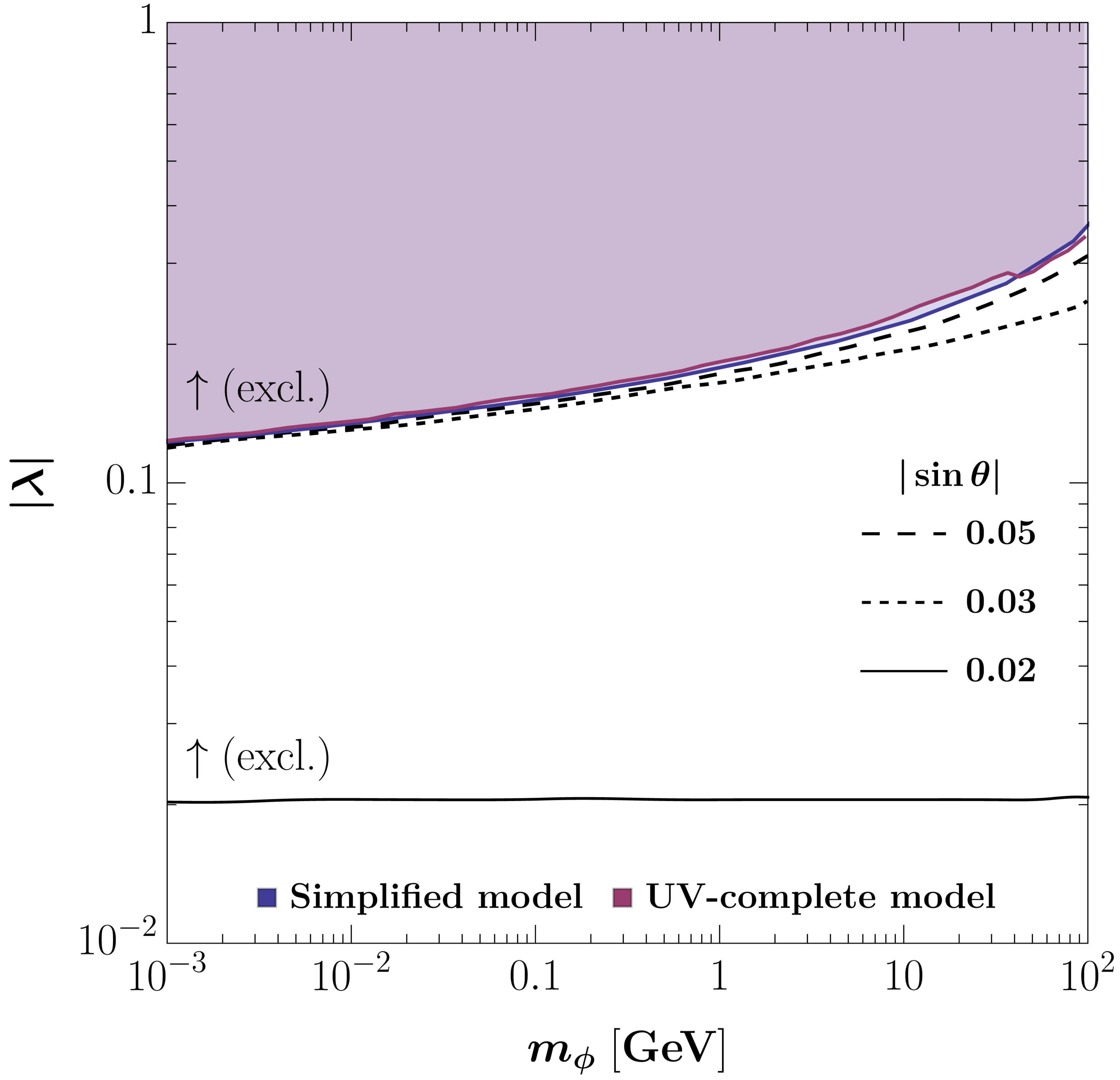
$$\boxed{c_Z = -11/2, c_W = -2}$$

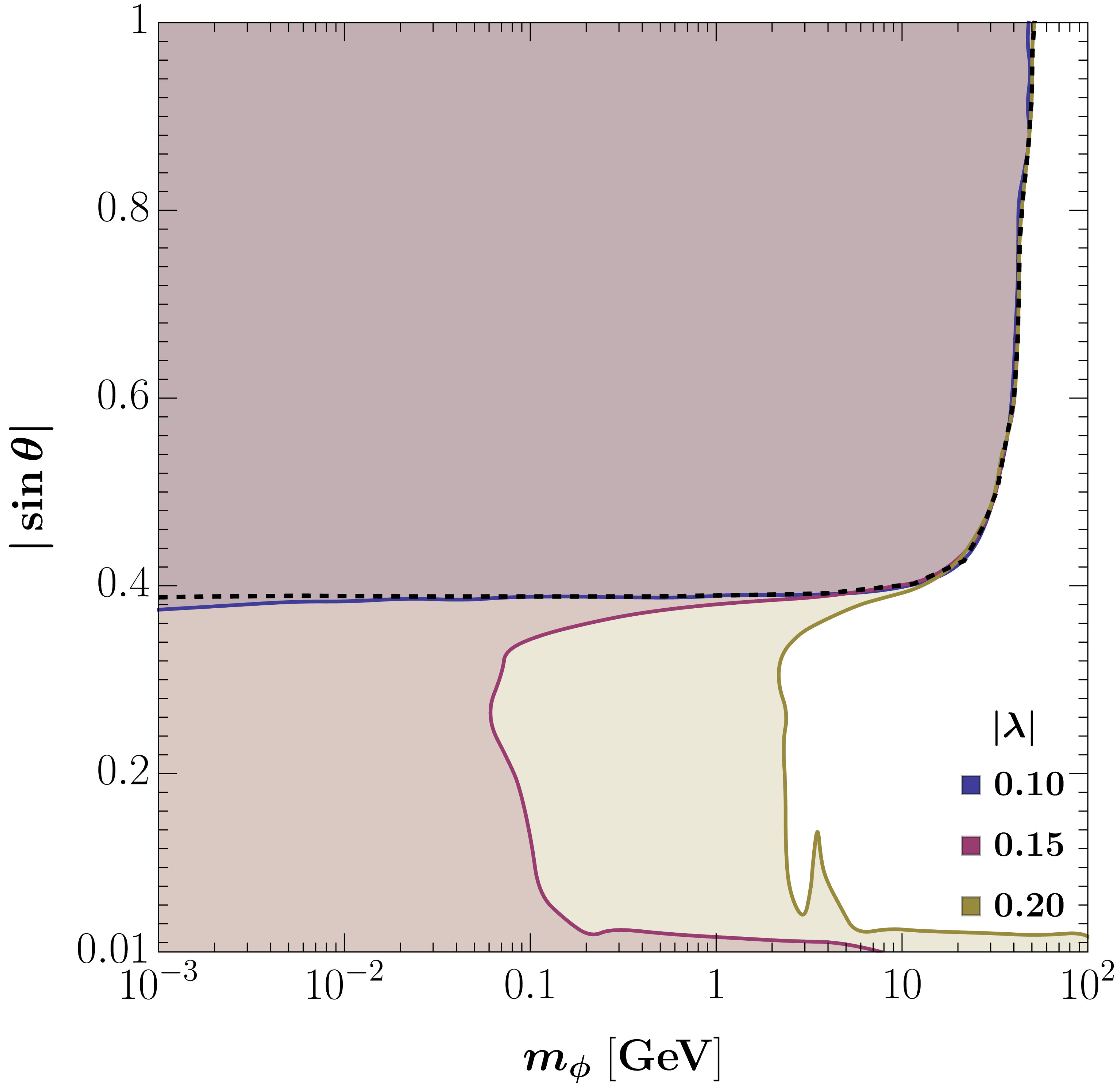
UV Completion

Parameter Space

UV complete model → $+\{\lambda, m_\phi, M, \sin\theta, \Delta M\}$

ϕ contribution dominates over T for $\sin\theta \geq 0.03$





Neutrinophilic Scalars

Conclusions

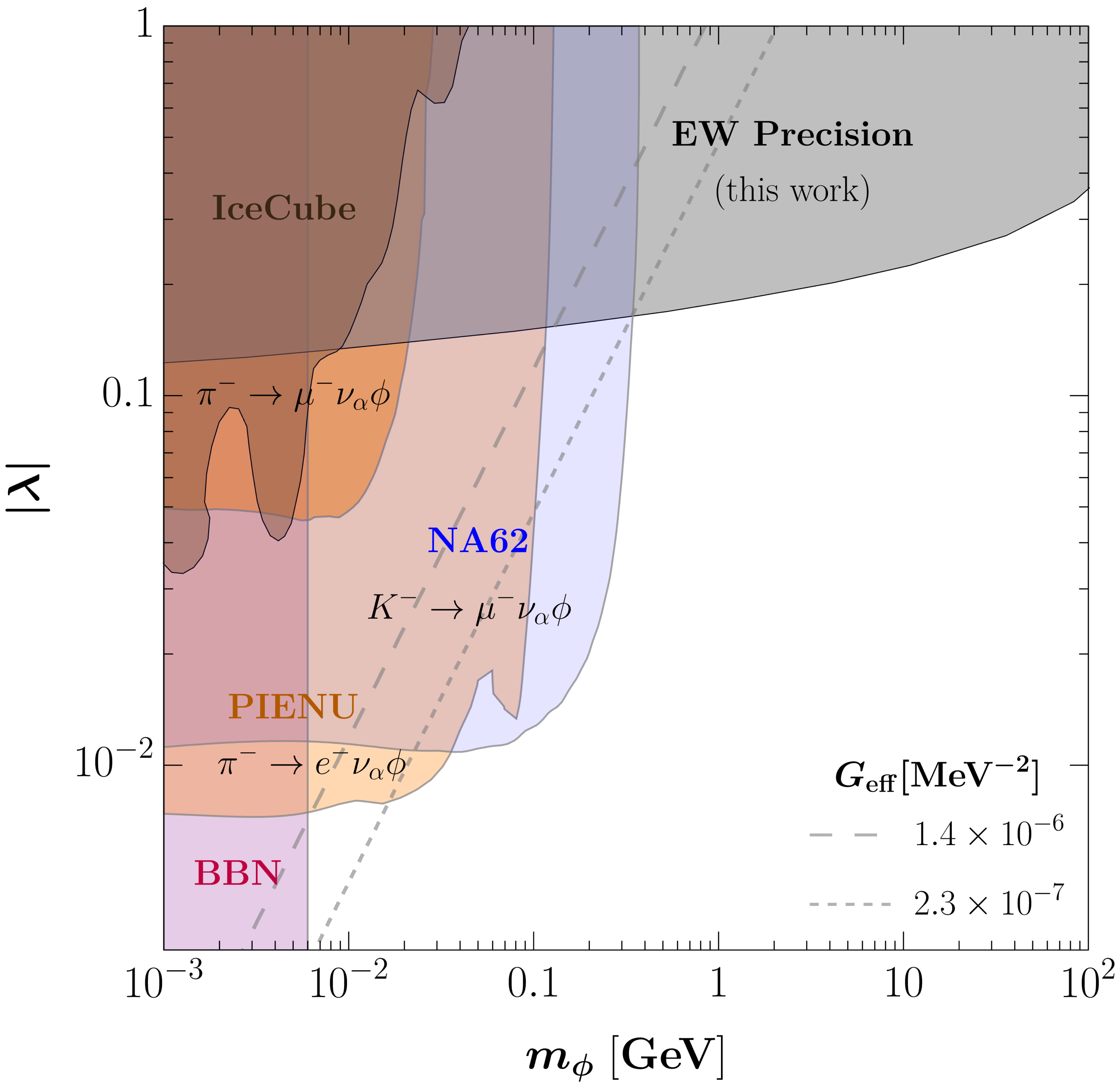
Neutrino self-interactions with strength stronger than Fermi theory are well motivated NP candidates

Light neutrinophilic scalars are common targets of laboratory and cosmological probes

One loop radiative corrections important for EW precision, log enhancement for light mediators

SIν effects contribute to the Δr parameter $\rightarrow$ $G_F, \sin^2\theta_W$ modified, other EW observables affected

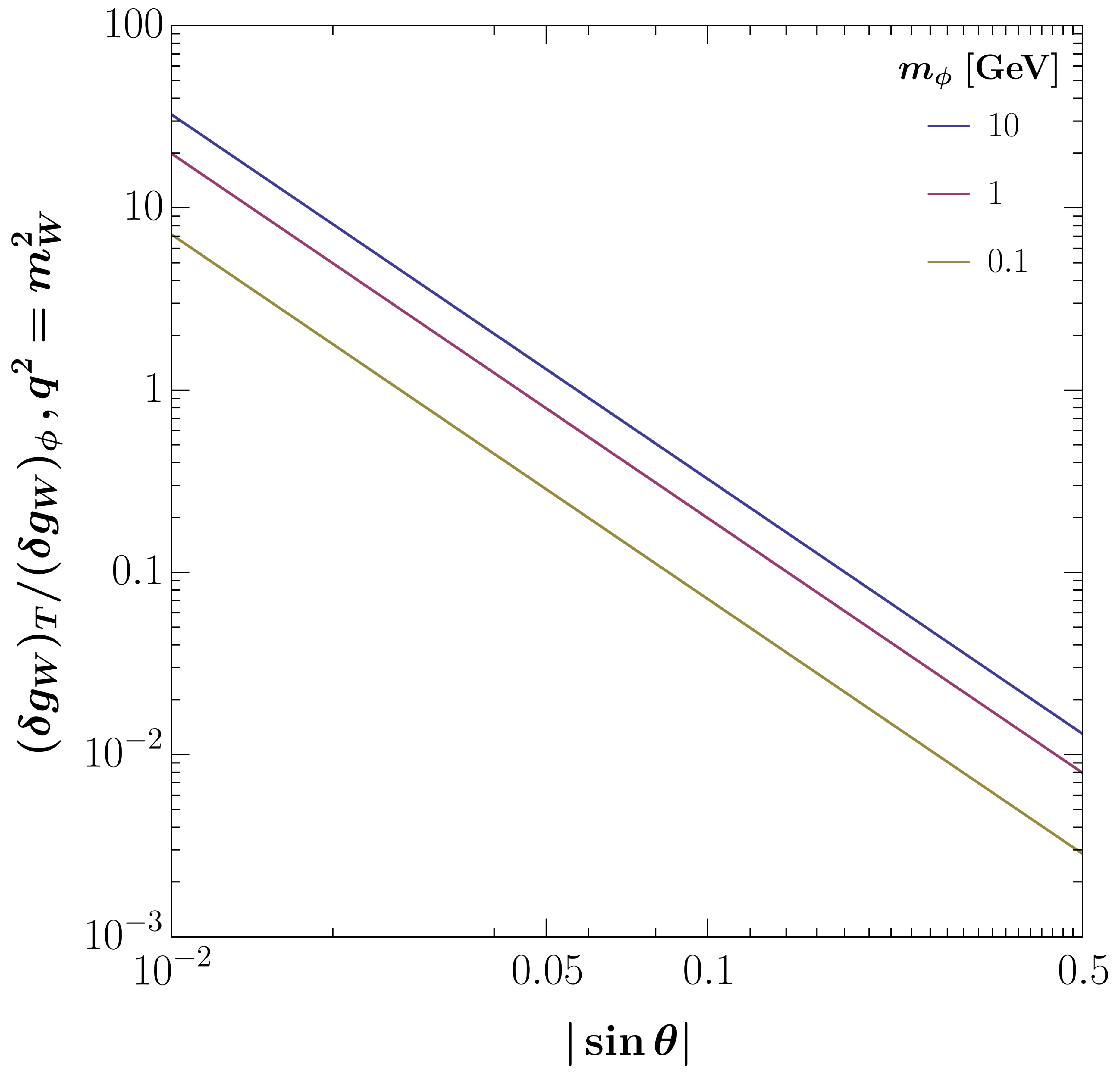
EW constraints determined for the simplified + UV model via fits to experimental data → Leading constraints for $m_\phi \gtrsim \mathcal{O}(100\ \text{MeV})$

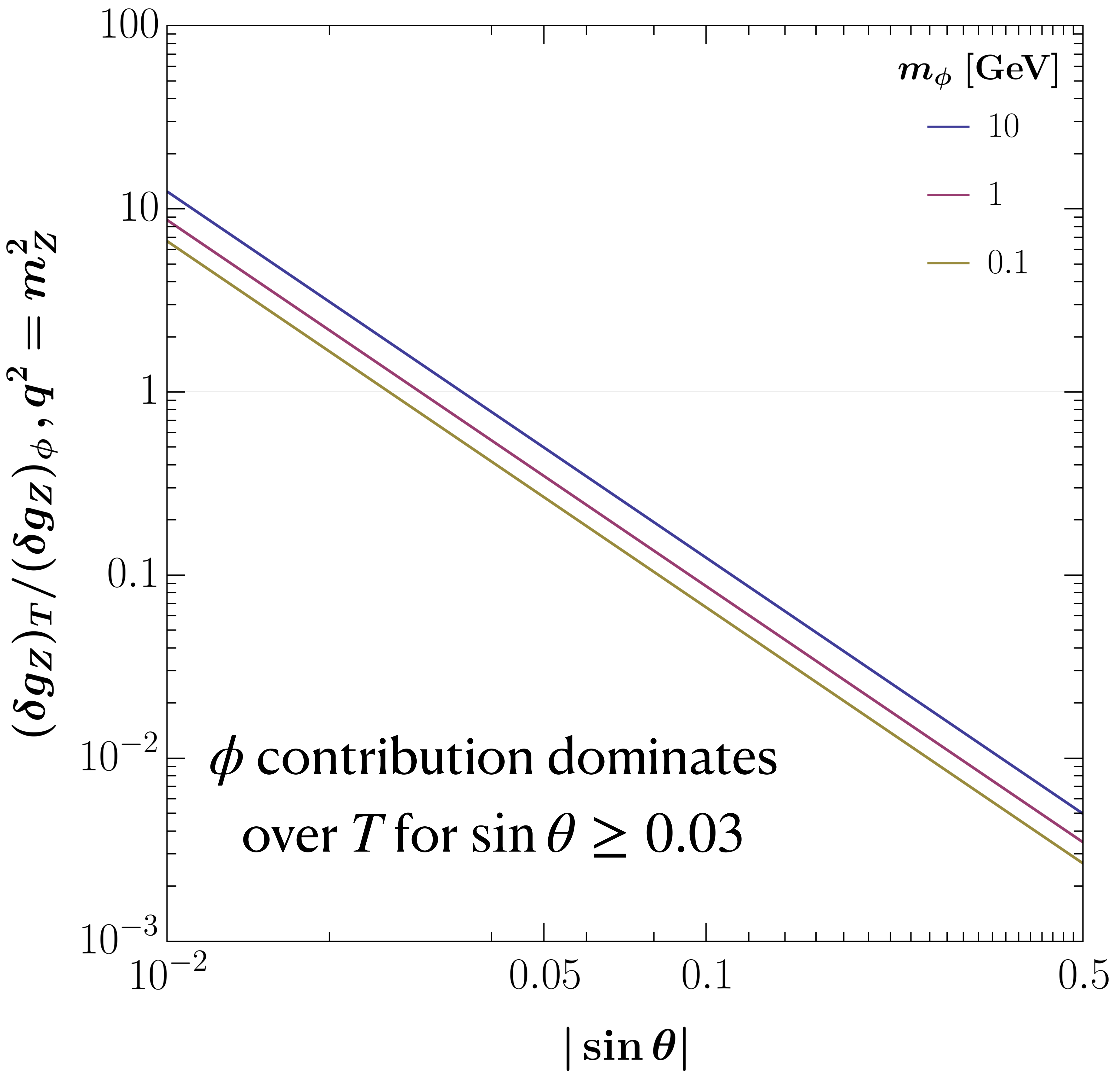


Backup

UV Completion

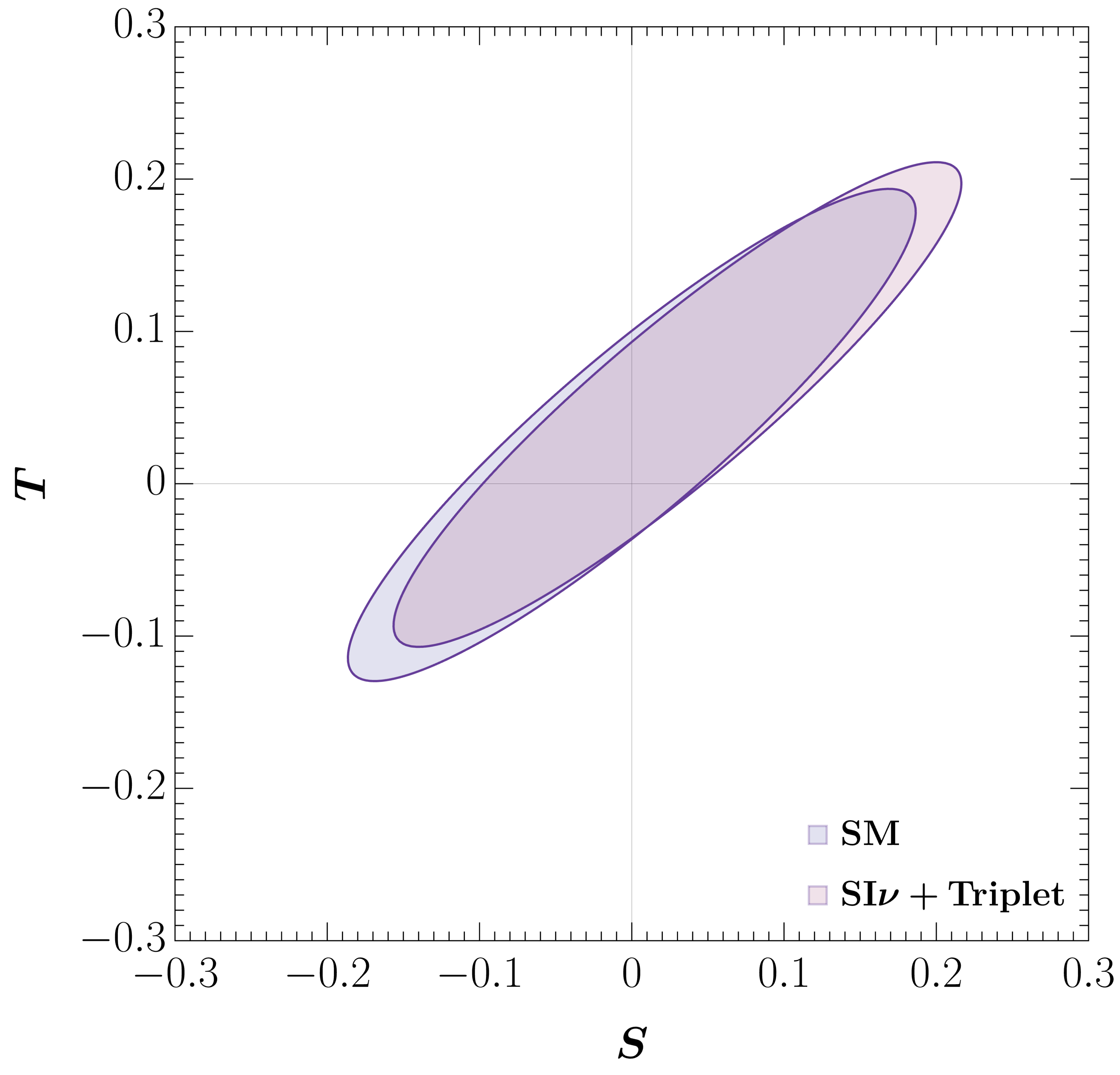
Radiative Corrections to Gauge Couplings

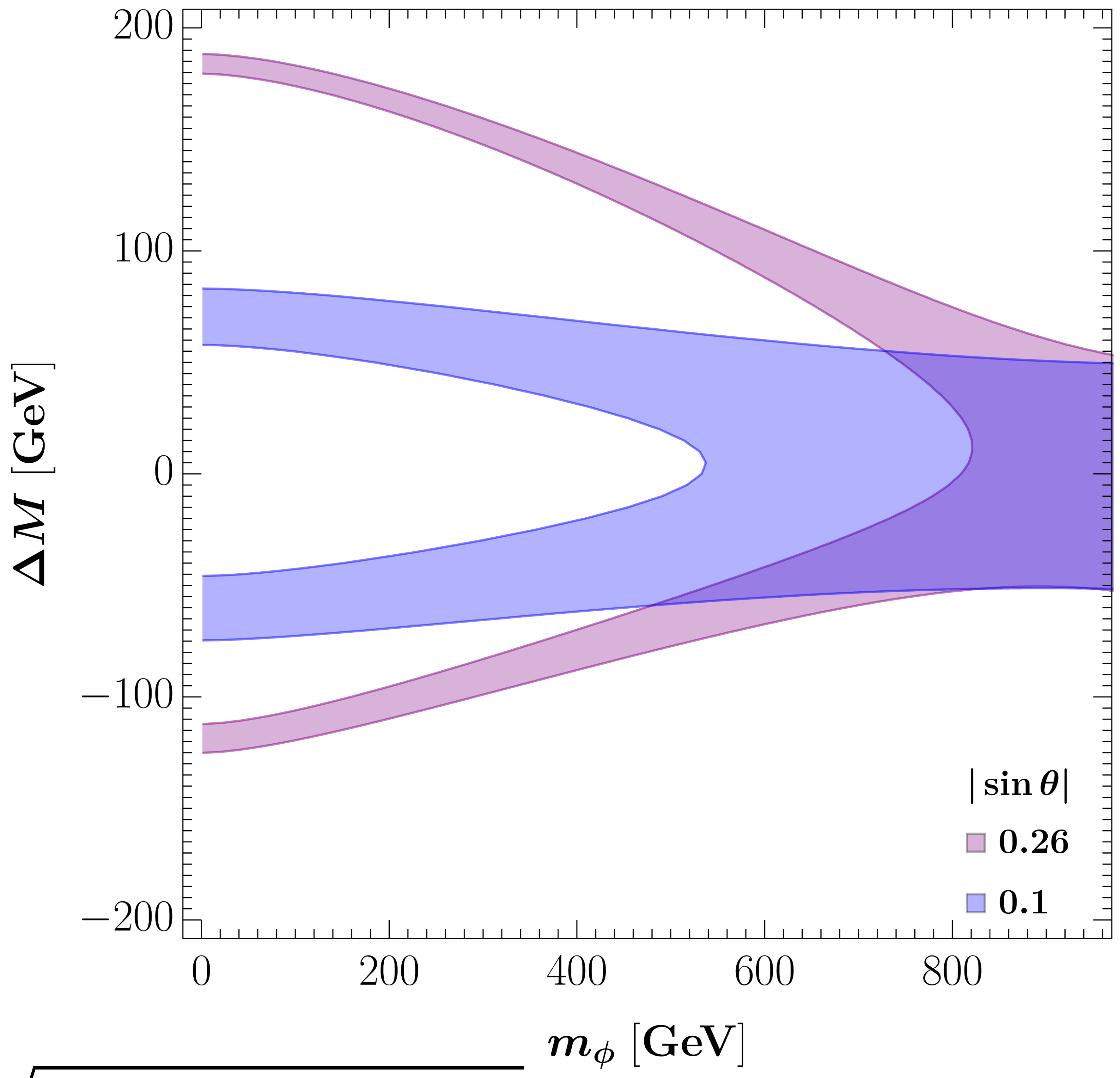




UV Completion

Oblique Parameters





$$m_{T^-} = M, \quad m_{T^0} = M + \Delta M, \quad m_{T^{--}} = \sqrt{M^2 - 2M\Delta M - (\Delta M)^2}$$