



Heavy Sterile Neutrinos from B Decays and new QCD Corrections to their semi-hadronic Decay Rates

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Based on work with:

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Overview:

1. $B \rightarrow D^* \ell N$ with heavy sterile neutrino N
2. Parameter analysis with decay distributions from **Belle II**
3. QCD corrections to semi-hadronic N decay rates
4. Conclusion

1. $B \rightarrow D^* \ell N$ with heavy sterile neutrino N

sterile Neutrinos = heavy neutral leptons (HNL) arise in many NP models e.g. for Dark Matter, ν Oscillations and baryon asymmetry (see e.g. Bodarenko et al., 1805.08567)

Mixing with active neutrino ν_α encoded in $V_{N\alpha}$ in

$$\mathcal{L}_I = \frac{g V_{N\alpha}}{\sqrt{2}} W_\mu^+ \bar{N}^c \gamma^\mu P_L \ell_\alpha^- + \frac{g V_{N\alpha}}{\cos \theta_w} Z_\mu \bar{N}^c \gamma^\mu P_L \nu_\alpha + \text{h.c.}$$

with weak coupling g and weak mixing angle θ_w and $P_L = (1 - \gamma_5)/2$.

$$B \rightarrow D^* \ell \nu$$

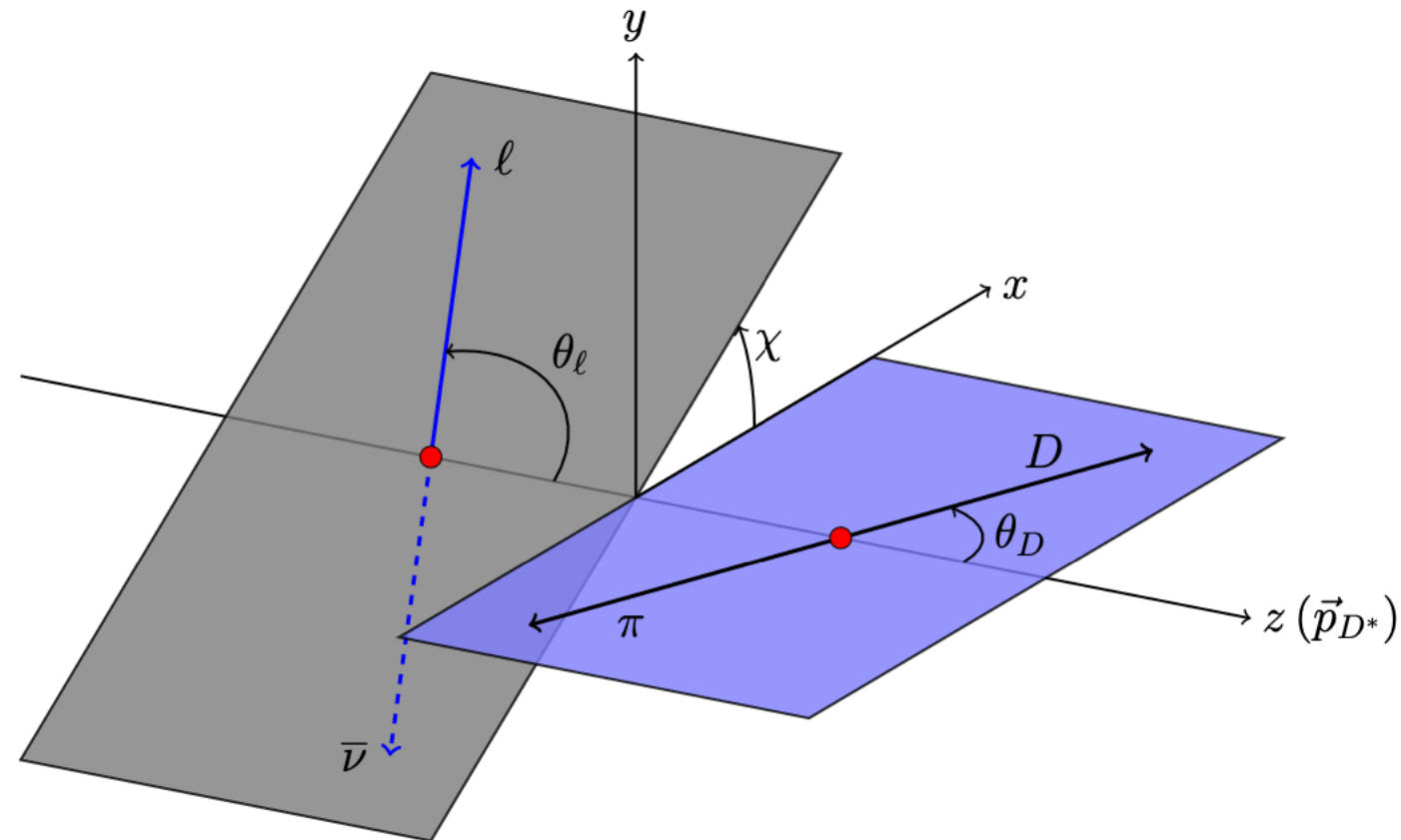
■ 4-body decay $B \rightarrow D^* [\rightarrow D\pi] \ell \nu$ with $\ell = e, \mu$.

■ We use recent **Belle II** data on **angular distributions**.

■ Standard Model (SM): only contribution from the dimension-6 Fermi

operator $\mathcal{O}^{(6)} = \bar{c}_L \gamma_\mu b_L \bar{\ell}_L \gamma^\mu \nu_{\ell,L}$

Angles of the decay distribution



graphic taken from Bečirević et al., 1907.02257

Differential decay rate of $B \rightarrow D^* \ell \nu$

$$\frac{32\pi}{9} \frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_D d\chi} = (J_{1s} + J_{2s} \cos 2\theta_\ell + J_{6s} \cos \theta_\ell) \sin^2 \theta_D +$$

$$(J_{1c} + J_{2c} \cos 2\theta_\ell + J_{6c} \cos \theta_\ell) \cos^2 \theta_D +$$

$$(J_3 \cos 2\chi + J_9 \sin 2\chi) \sin^2 \theta_D \sin^2 \theta_\ell +$$

$$(J_4 \cos \chi + J_8 \sin \chi) \sin 2\theta_D \sin 2\theta_\ell +$$

$$(J_5 \cos \chi + J_7 \sin \chi) \sin 2\theta_D \sin 2\theta_\ell +$$

 J_i coefficients measurable in experiment!

N new physics contribution to B Decays

- New physics (NP) contributions alter J_i from their SM expressions
- Heavy sterile neutrinos: permit arbitrary NP through dimension-6 operators:

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(\bar{c}_L \gamma_\mu b_L) (\bar{\ell}_L \gamma^\mu \nu_{\ell,L}) + g_{V_R}^N (\bar{c}_R \gamma_\mu b_R) (\bar{\ell}_R \gamma^\mu N_R) + g_{S_L}^N (\bar{c}_R b_L) (\bar{\ell}_L N_R) \right. \\ \left. + g_{S_R}^N (\bar{c}_L b_R) (\bar{\ell}_L N_R) + g_T^N (\bar{c}_L \sigma_{\mu\nu} b_R) (\bar{\ell}_L \sigma^{\mu\nu} N_R) + \text{h.c.} \right]$$

Robinson, Shakya and Zupan, 1807.04753

N new physics contribution to B Decays

- Other operators are higher dimensional e.g. left-handed vector current

$$\mathcal{O}_{V_L} = (\bar{Q}_L \tilde{H} \gamma_\mu H^\dagger Q_L) (\bar{\ell}_R \gamma_\mu N_R)$$

- Angular Coefficients are incoherent sum of SM and NP

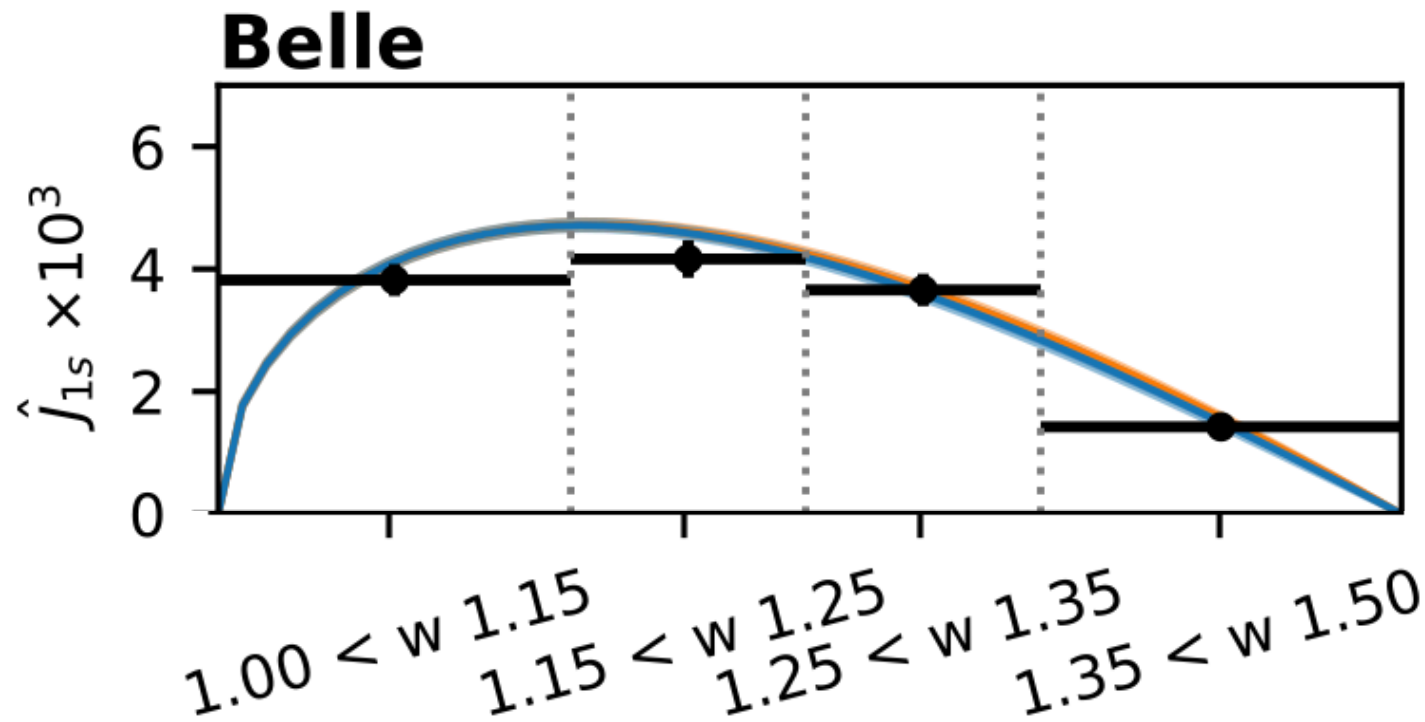
$$J_i = J_i^{SM} + J_i^{NP}(g_j^N, m_N)$$

2. Parameter analysis with decay distributions from **Belle II**

Bernlochner, Fedele, TK, Nierste, Prim 2024:

- We have fitted angular coefficients J_i to recent **Belle II** data
- Bayesian analysis, fitted parameters: (g_j^N, m_N, FF) , one Wilson coefficient $g_{V_R}^N, g_{S_L}^N, \dots$ at a time.
- Belle II data \Rightarrow LFUV WC analysis
- Result insensitive to choice of form factors (FNAL/MILC, JLQCD,...)

Fit to data



Hadronic recoil parameter:

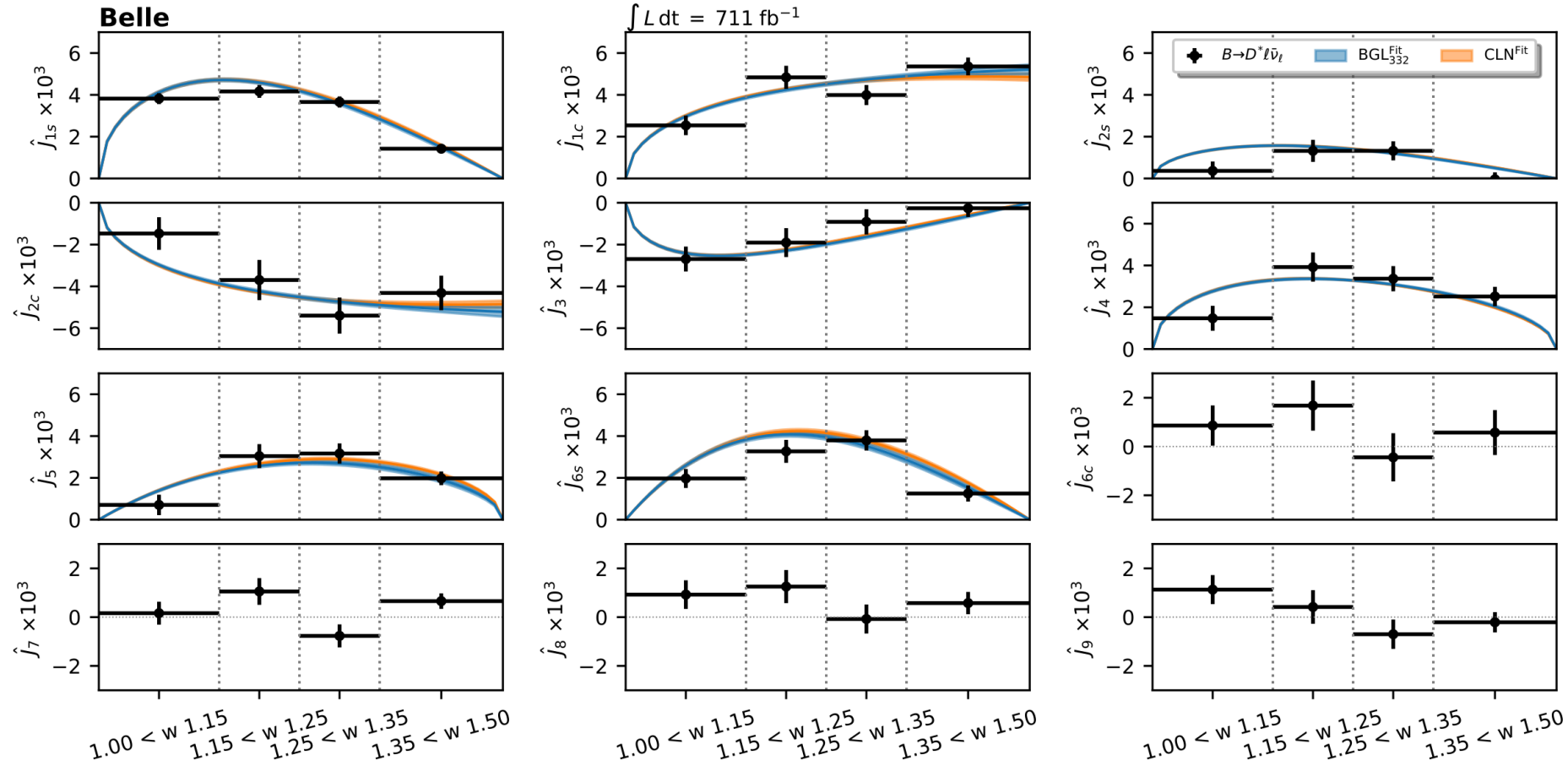
$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$$

Normalized angular coefficient:

$$\hat{j}_i^{(n)} = \frac{\int_{\Delta w^{(n)}} dw J_i(w)}{\int_{w_{\min}}^{w_{\max}} dw \frac{d\Gamma}{dw}}$$

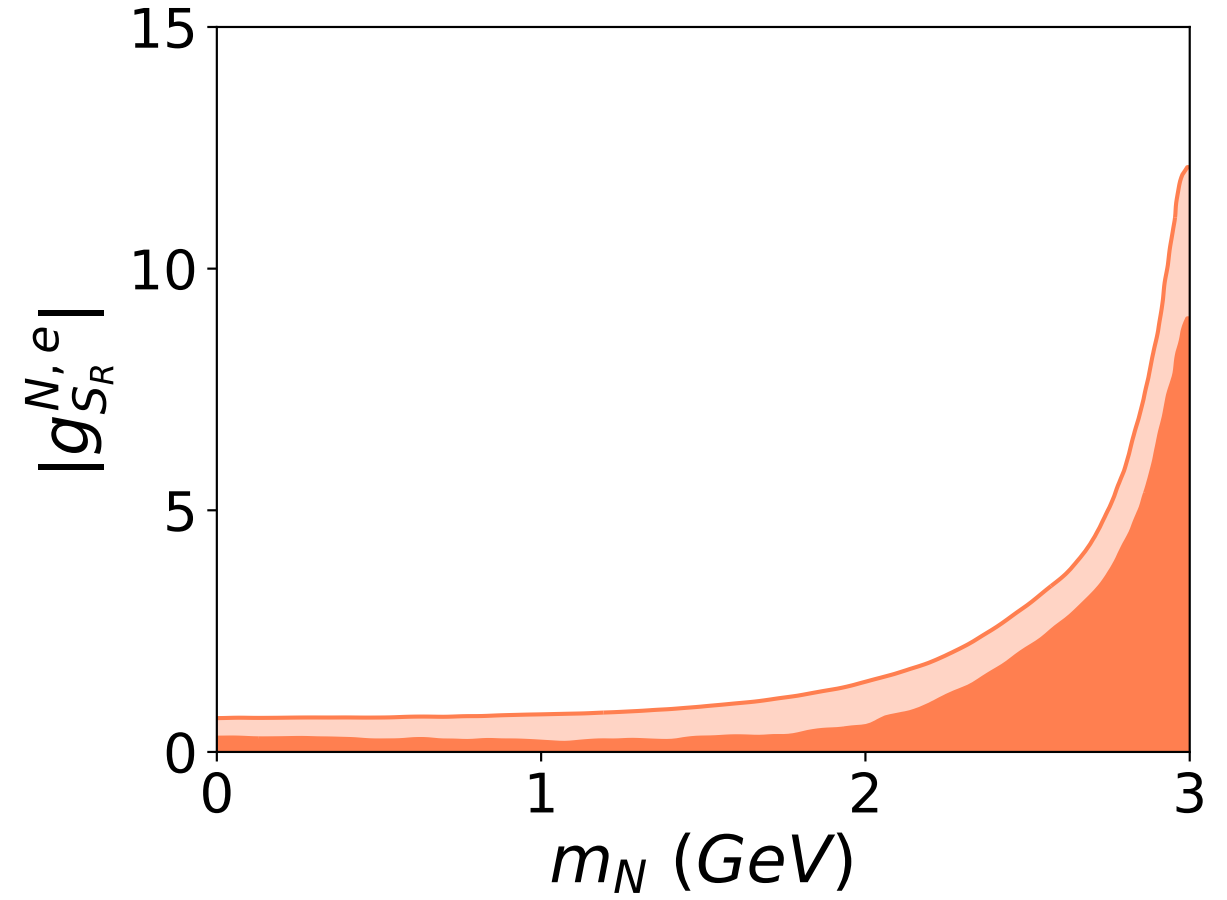
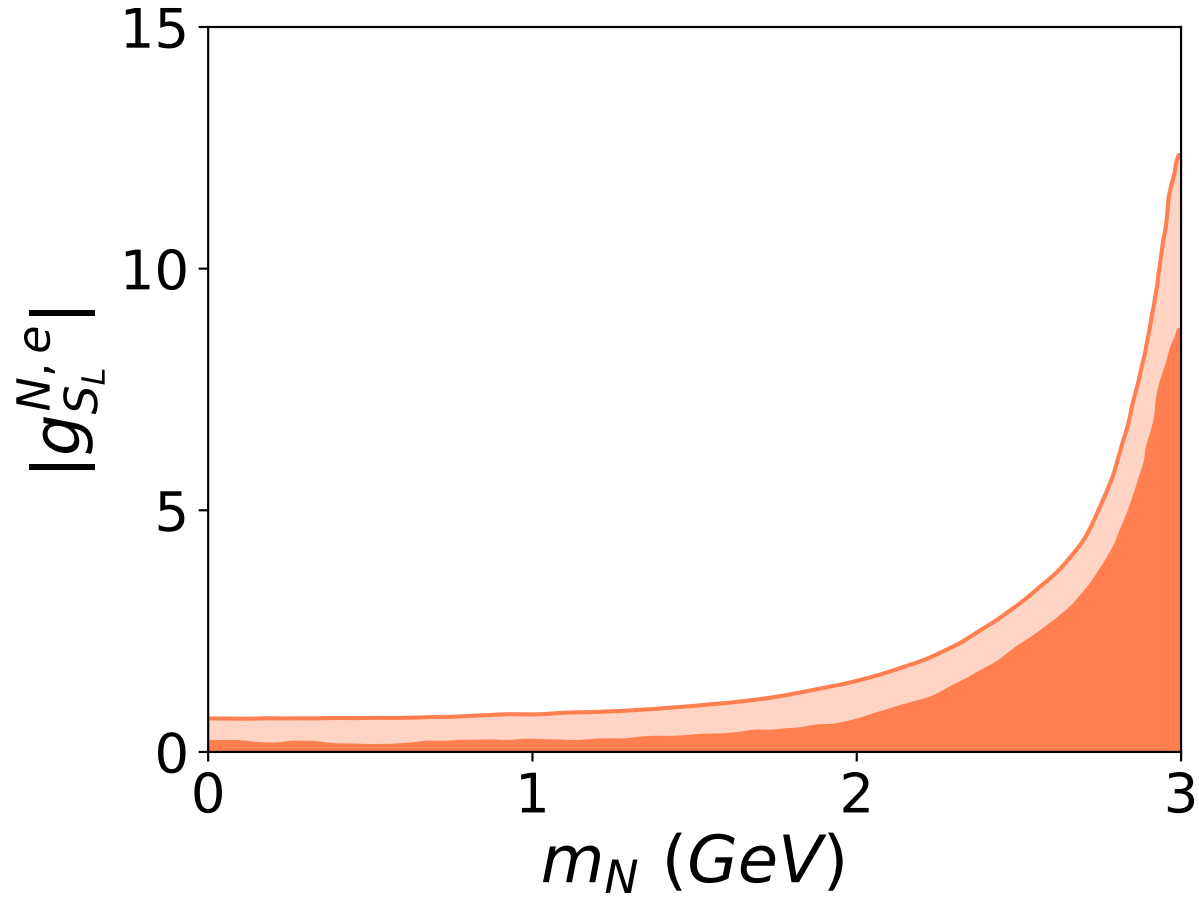
Prim et al., 2310.20286

Fit to data

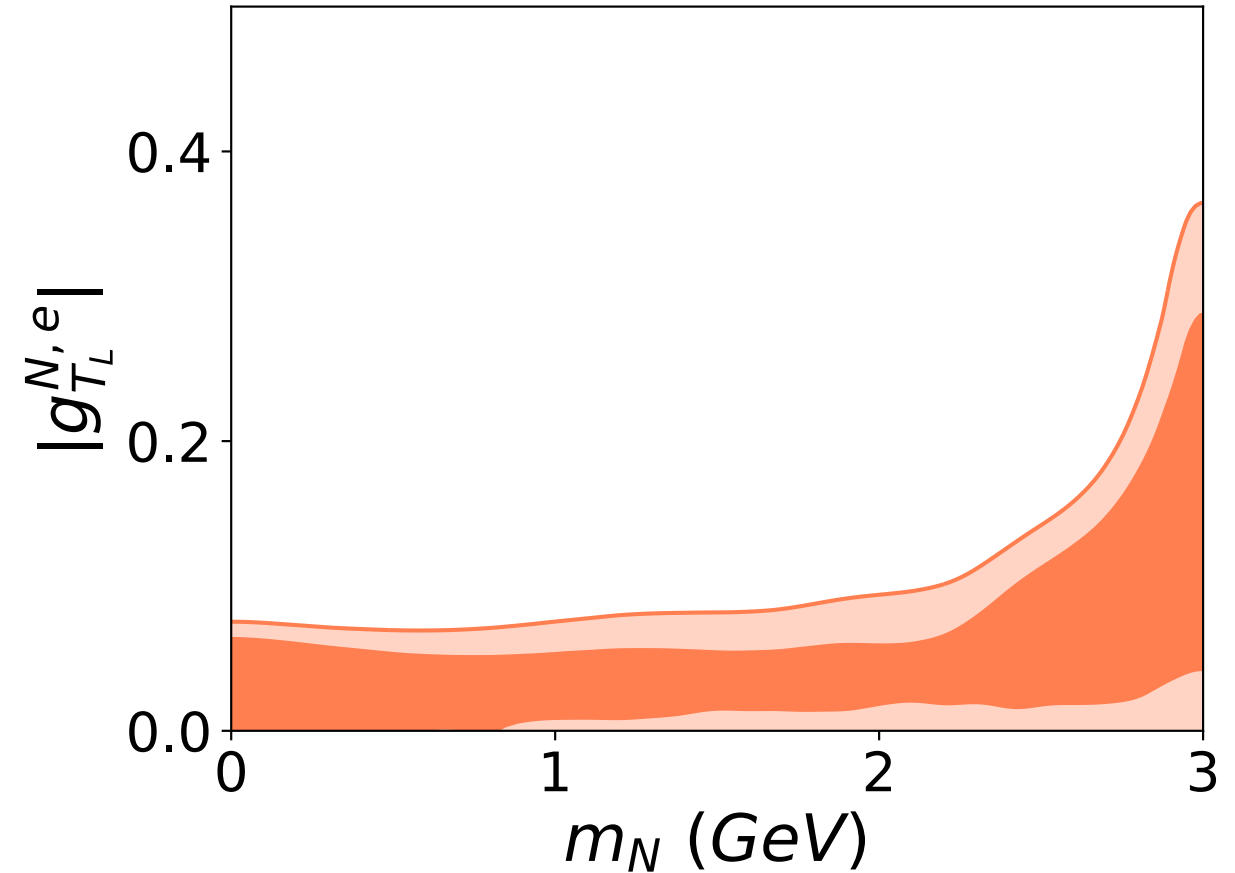
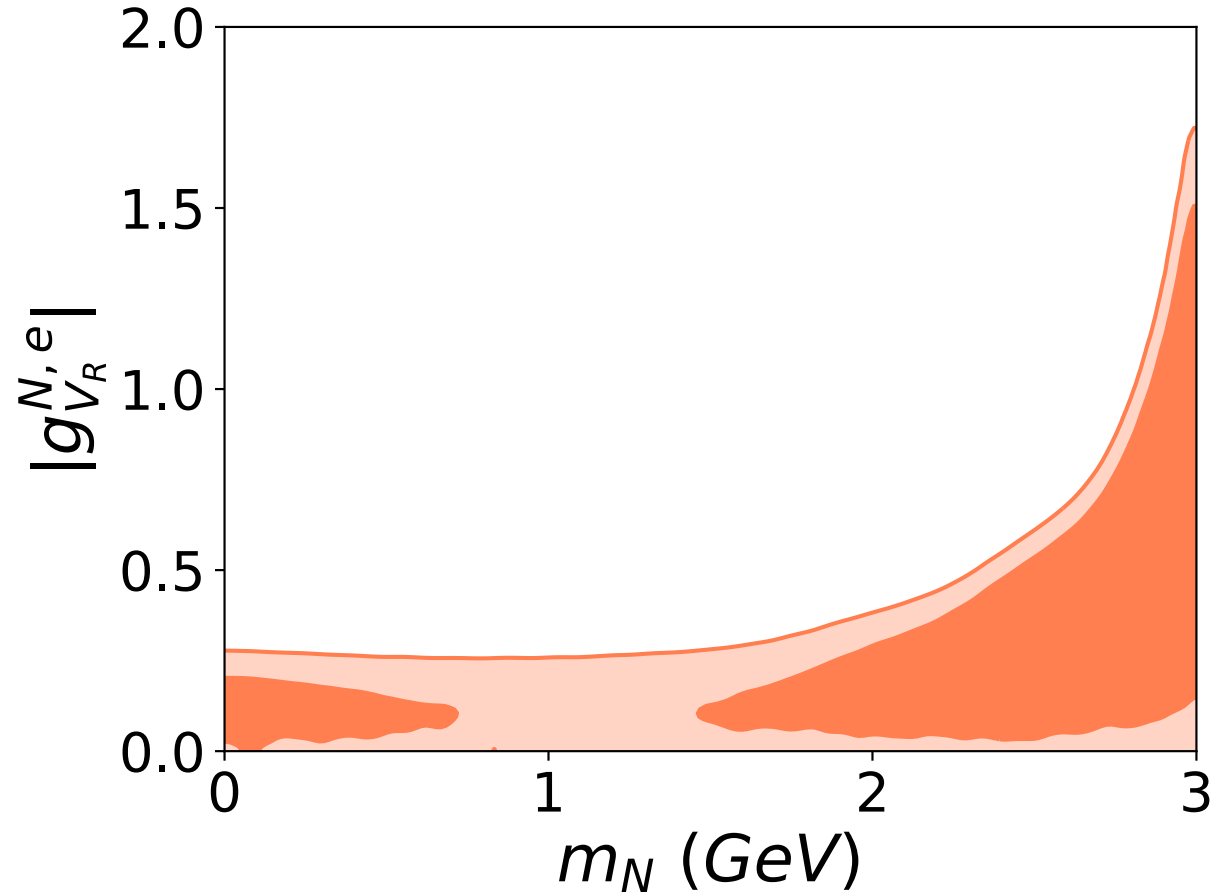


Prim et al., 2310.20286

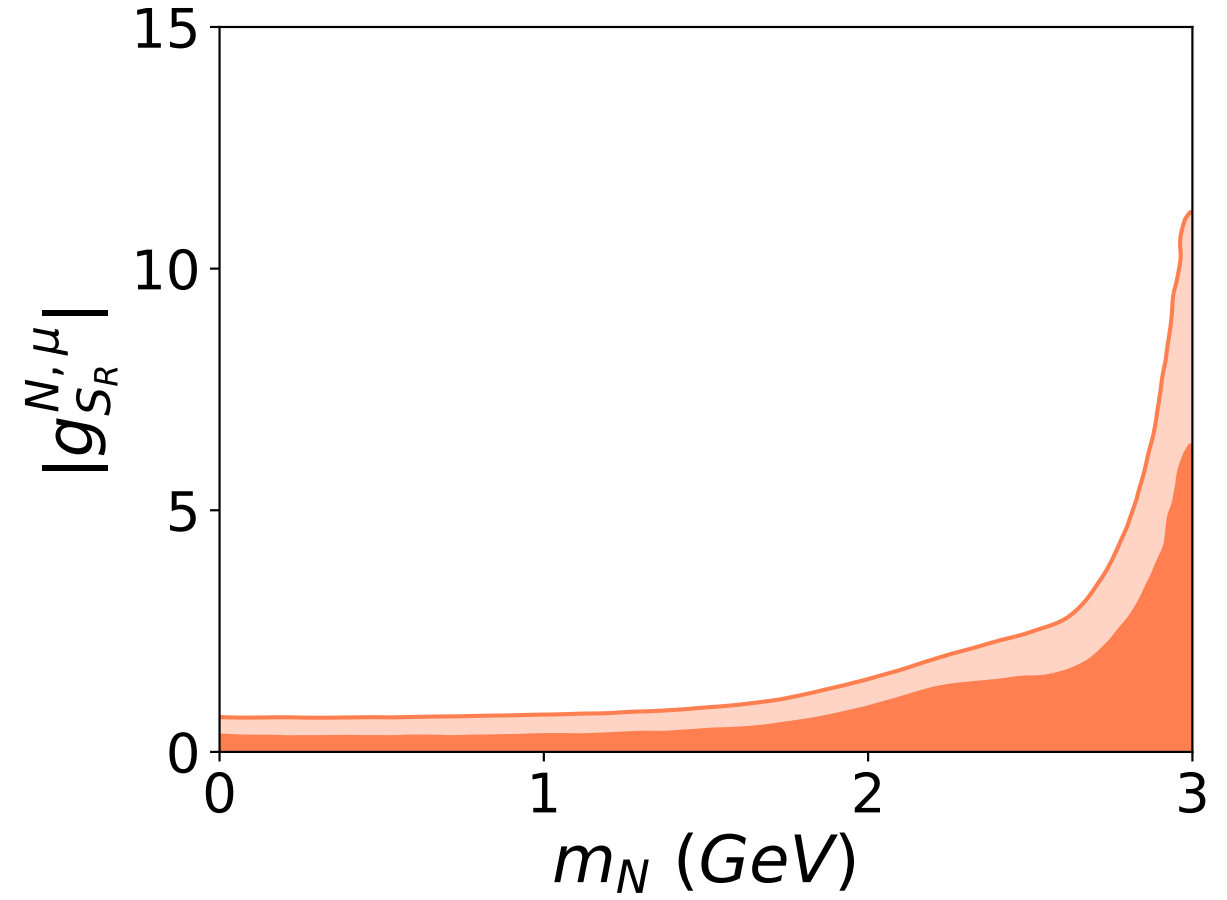
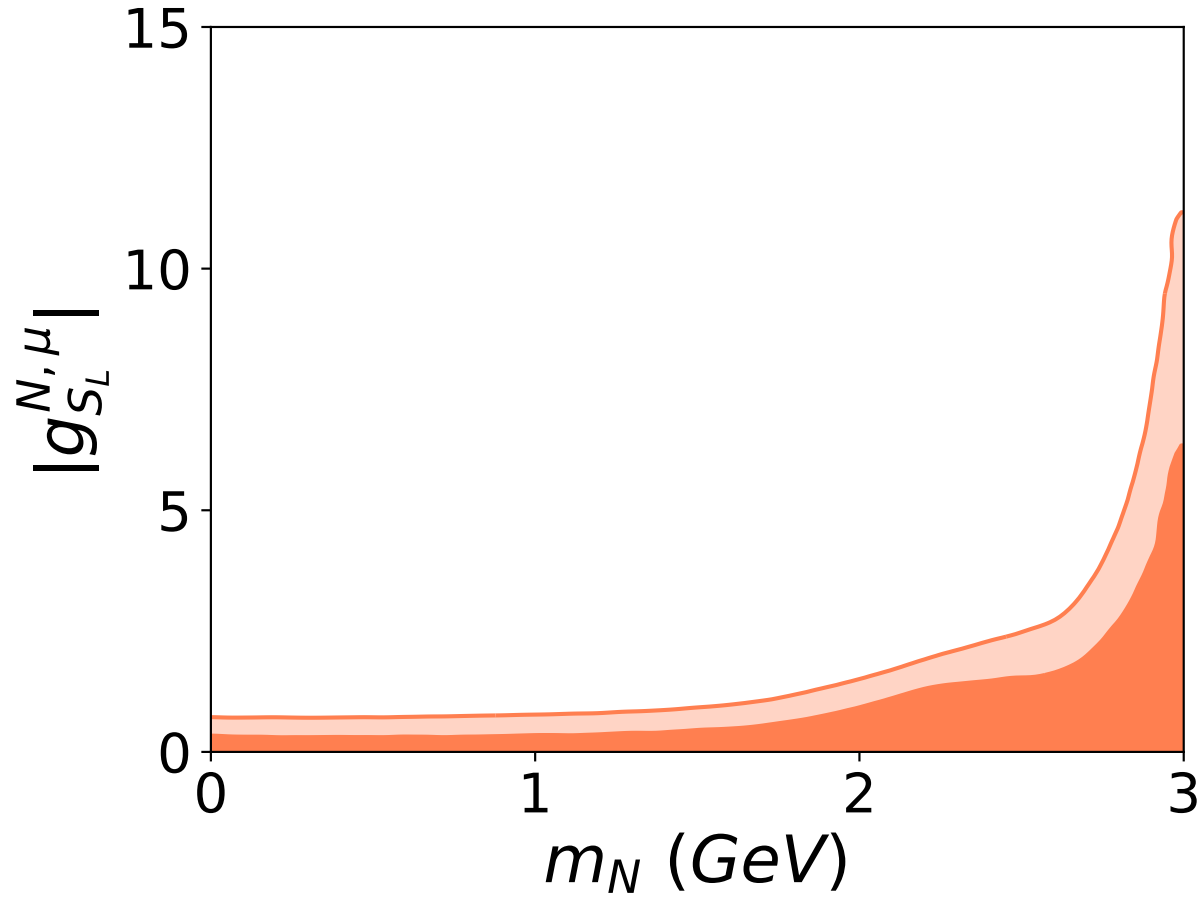
Allowed Parameter Region



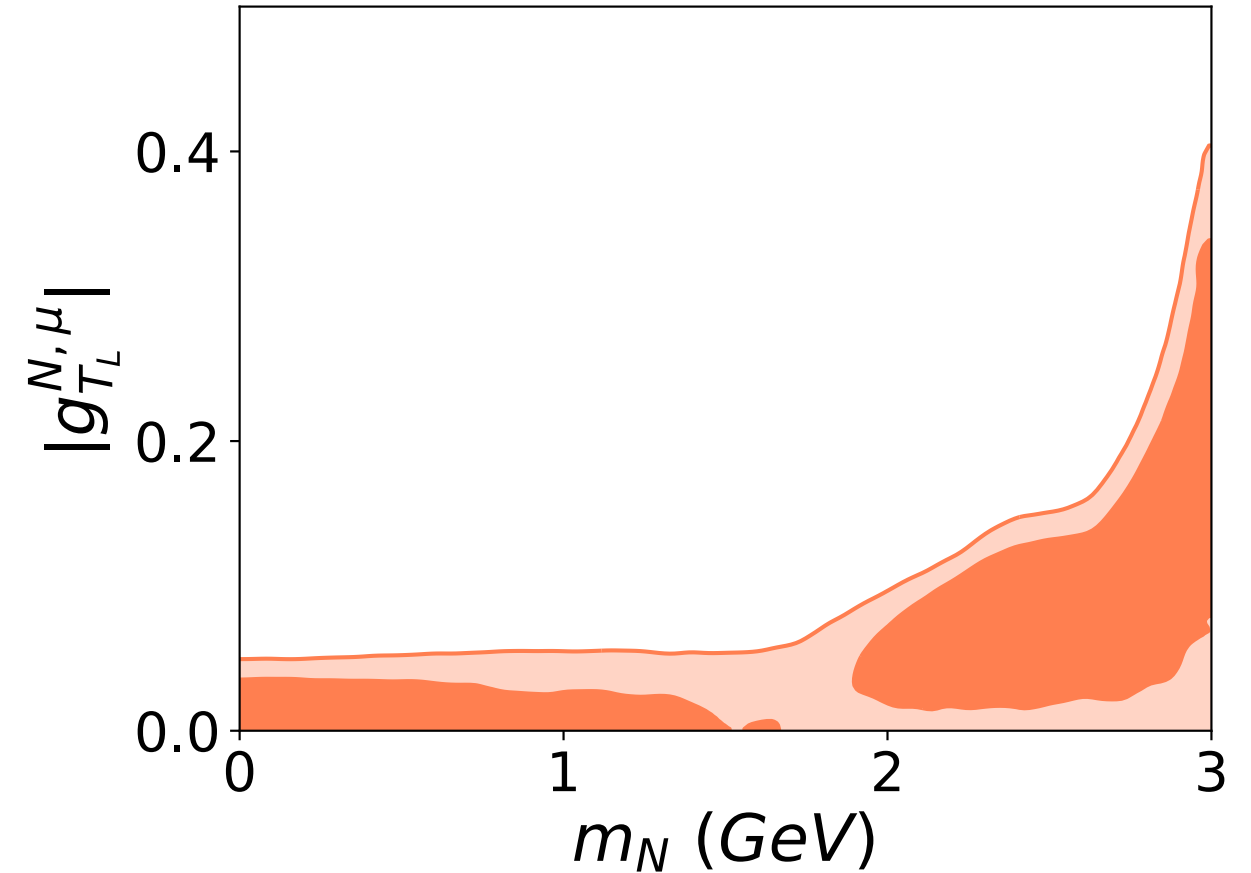
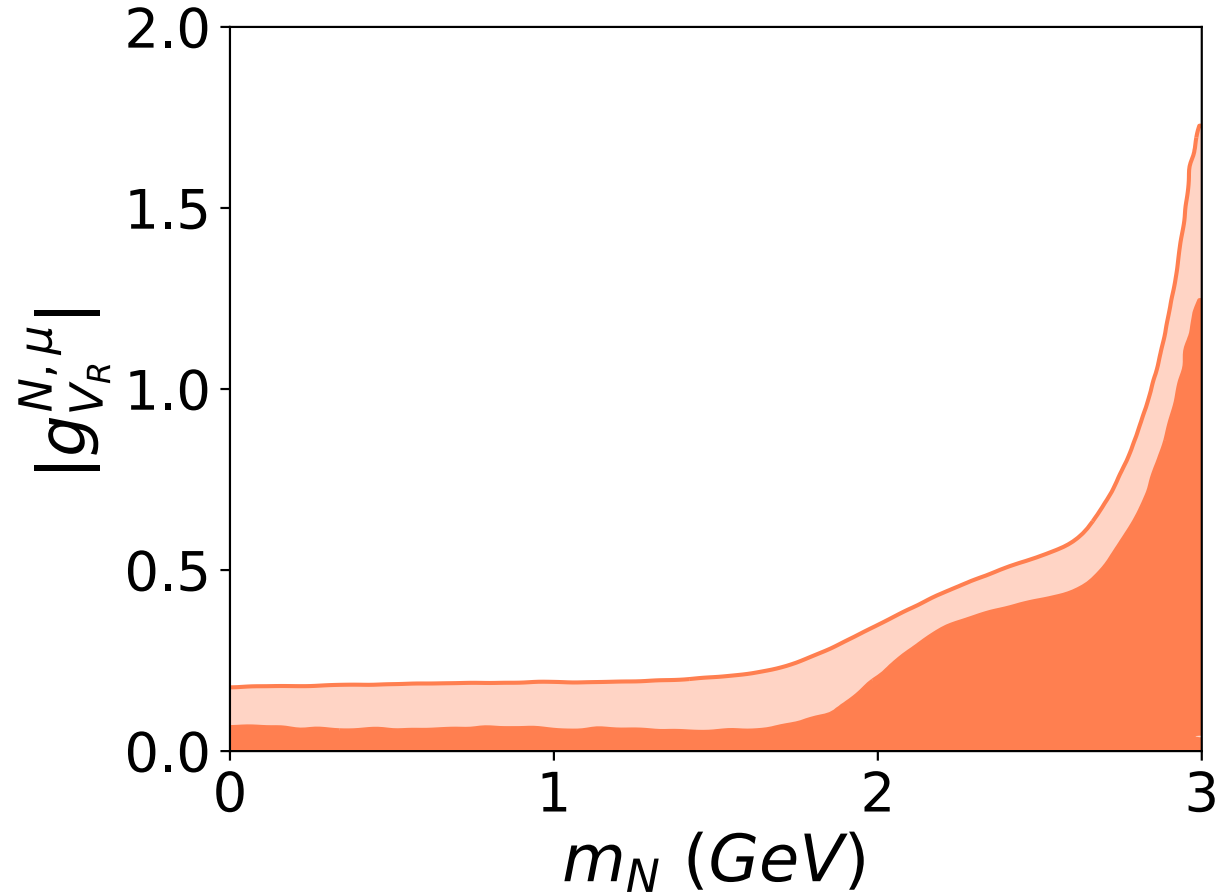
Allowed Parameter Region



Allowed Parameter Region



Allowed Parameter Region



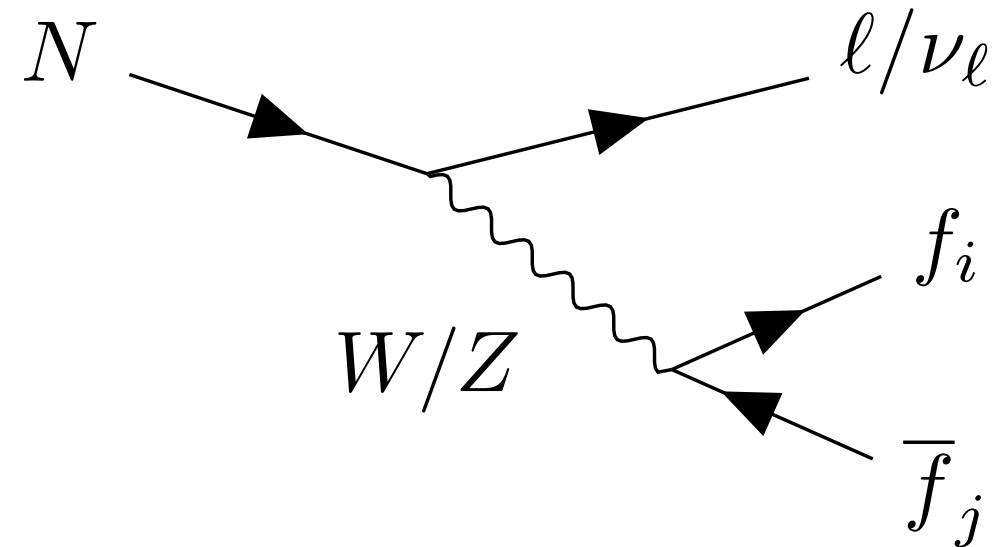
3. QCD corrections to semi-hadronic N decay rates

TK, Nierste 2024:

- W^\pm, Z -mediated decays of sterile neutrino via mixing with active ν

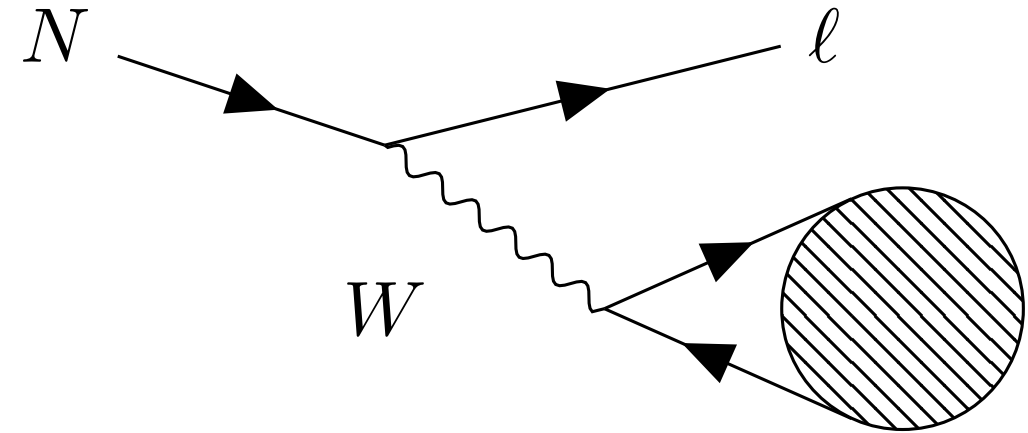
- For $m_N \sim 2 \text{ GeV}$ hadronic decay rates could be sizeable

- QCD corrections to $W^* \rightarrow \bar{f}_i f_j$ and $Z^* \rightarrow \bar{f}_j f_j$ are known



Inclusive decay rate $\Gamma(N \rightarrow \ell \text{ had.})$

- Decays to exclusive multi-hadron final states difficult to estimate
- Inclusive decay rate:



$$\Gamma_N = N_c \frac{G_F^2 M_N^5 |V_{N\ell}|^2 |V_{q\bar{q}}|^2}{192\pi^3} \cdot 12\pi \int_0^{(1-x_\ell)^2} dx (1+x_\ell^2-x)(1+2x+x_\ell^2) \sqrt{\lambda(1,x,x_\ell^2)} \text{Im} \Pi^{(1+0)}(M_N^2 x)$$

$$x_\ell = m_\ell / M_N$$

Beneke and Jamin 0806.3156

QCD correlators

Correlator:
$$\Pi_{\mu\nu, ij}^{V/A} = i \int dx e^{ipx} \langle \Omega | T \{ J_{\mu, ij}^{V/A}(x) J_{\nu, ij}^{V/A}(0)^\dagger \} | \Omega \rangle$$

Lorentz Decomposition:
$$\Pi_{\mu\nu, ij}^{V/A}(p) = (p_\mu p_\nu - g_{\mu\nu} p^2) \Pi_{ij}^{V/A, (1)}(p^2) + p_\mu p_\nu \Pi_{ij}^{V/A, (0)}(p^2)$$

Used correlator:
$$\Pi^{(1+0)} = \Pi_{ij}^{V, (1)} + \Pi_{ij}^{A, (1)} + \Pi_{ij}^{V, (0)} + \Pi_{ij}^{A, (0)}$$

QCD correlators

- QCD correlator known up to $\mathcal{O}(\alpha_S^4)$ for massless quarks [1]
- Massive quark corrections known up to $\mathcal{O}(\alpha_S^3)$ (see eg. [2,3])
- For massless quarks no scalar contribution, neglect

$$\Pi^{(0)} \sim \frac{m_q^2}{q^2} \Pi_2^{(0)}$$

[1] Baikov, Chetyrkin and Kühn, 0801.1821

[2] Chetyrkin, Haarlander and Kühn, hep-ph/0005139

[3] Baikov, Chetyrkin and Kühn, Nucl.Phys.B Proc.Suppl. 144 (2005) 81-87

QCD calculation of W contribution to total semi-hadronic decay rate

- Up to $\mathcal{O}(\alpha_S^3)$ we have calculated analytical results in massless case for charged current decays, utilising the known results for the correlators.
- At $\mathcal{O}(\alpha_S^4)$ we have calculated semi-analytical results.
- Example: Predict

$$\frac{\Gamma(N \rightarrow \tau^- \pi^+)}{\Gamma(N \rightarrow \tau^- X_{\text{had}}^+)} = 0.057, \quad M_N = 3 \text{ GeV}$$

- Z contribution to follow soon, needed to predict branching ratios.

$\Gamma(N \rightarrow \ell \text{ had.})$ for $m_\ell = 0$ vs. $m_\ell = M_\tau$

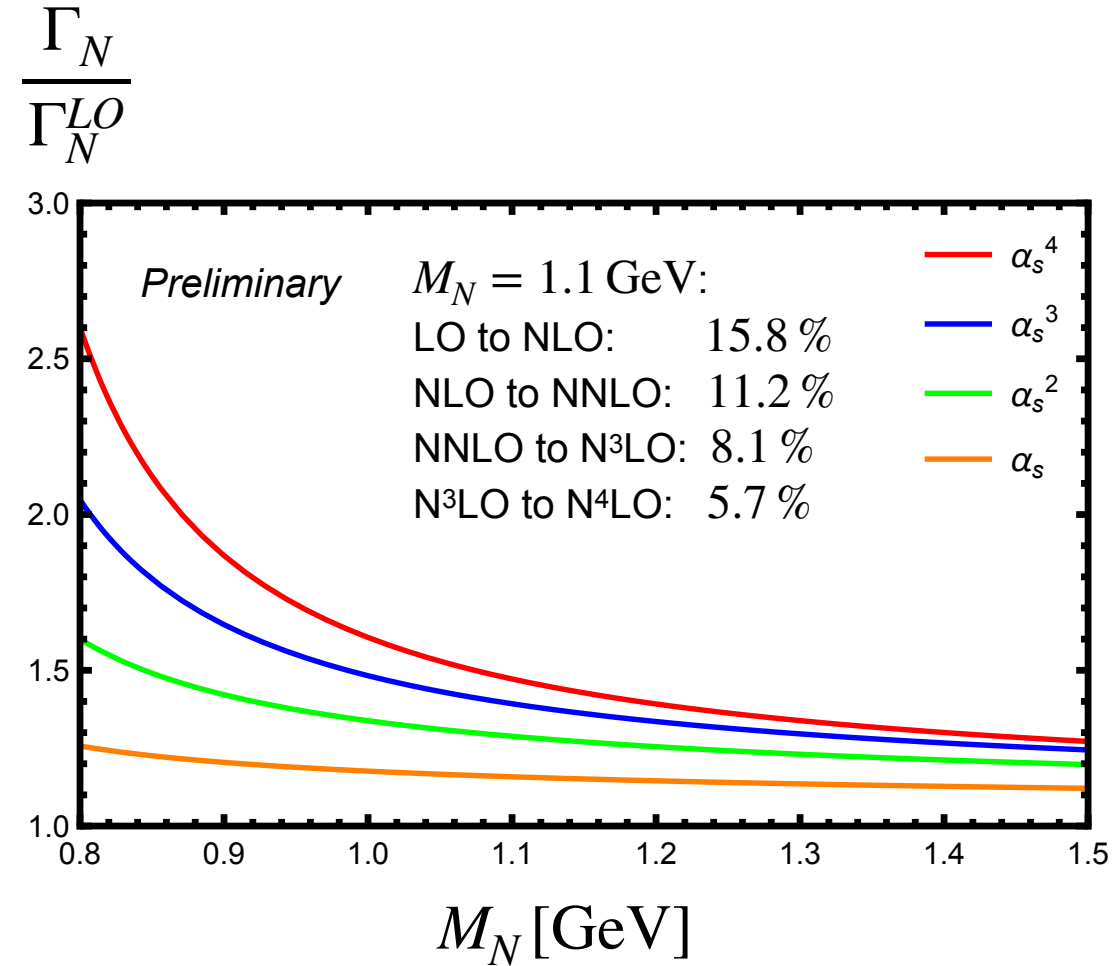
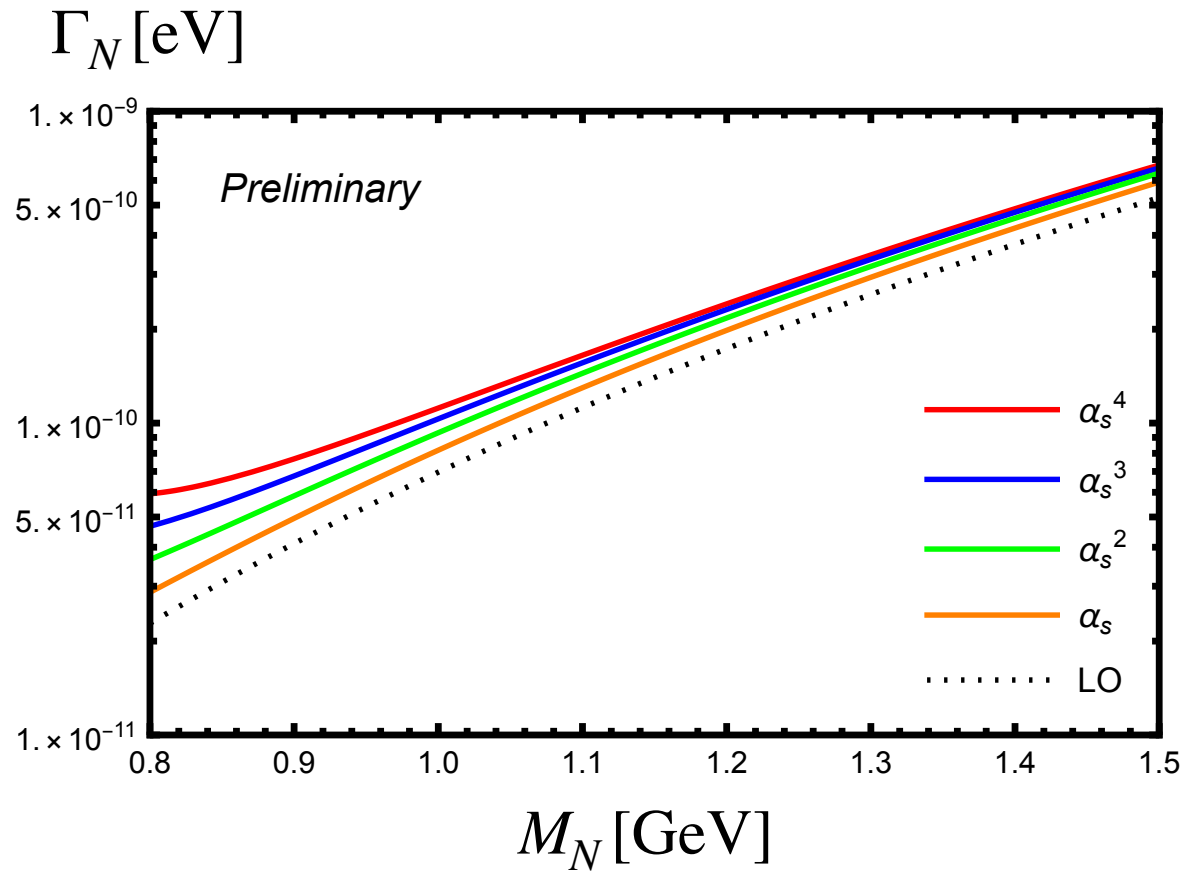
■ In the limit of vanishing lepton mass we reproduce τ -decay:

$$R_N(x_\ell = 0) = \frac{\Gamma_N}{|V_{N\ell}|^2 |V_{q\bar{q}}|^2 \Gamma(N \rightarrow e^- e^+ \nu_e)} = N_c \left[1 + a_S + 5.202a_S^2 + 26.366a_S^3 + 127.079a_S^4 \right]$$

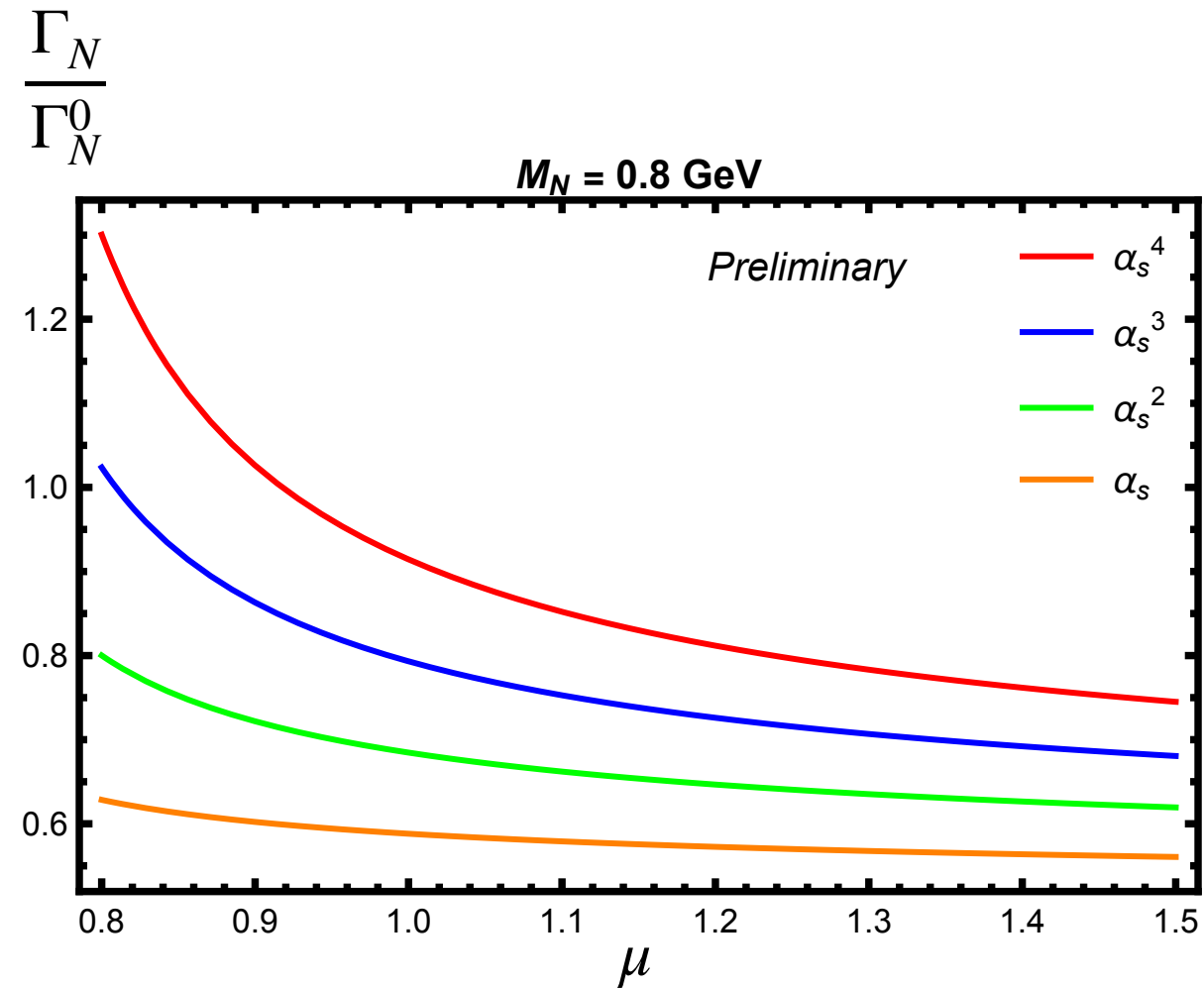
$$R_N(x_\ell = 0.6) = \frac{\Gamma_N}{|V_{N\ell}|^2 |V_{q\bar{q}}|^2 \Gamma(N \rightarrow e^- e^+ \nu_e)} = N_c \left[0.260(1 + a_S) + 2.234a_S^2 + 20.587a_S^3 + 192.819a_S^4 \right]$$

$$x_\ell = m_\ell / M_N, a_S = \alpha_S / \pi$$

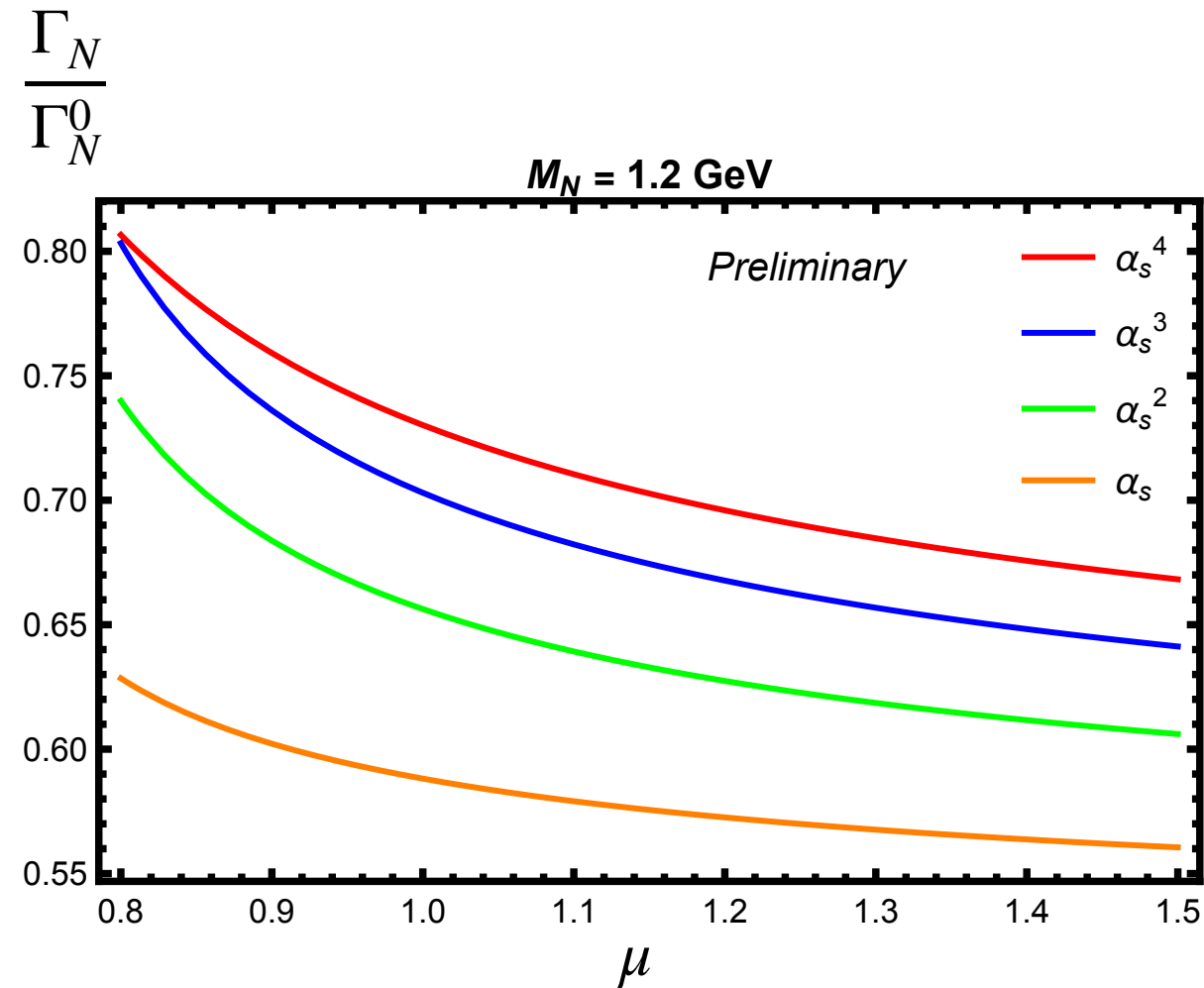
$\Gamma(N \rightarrow \ell \text{had.})$ for $m_\ell = 0$ and $V_{N\ell} = 10^{-3}$



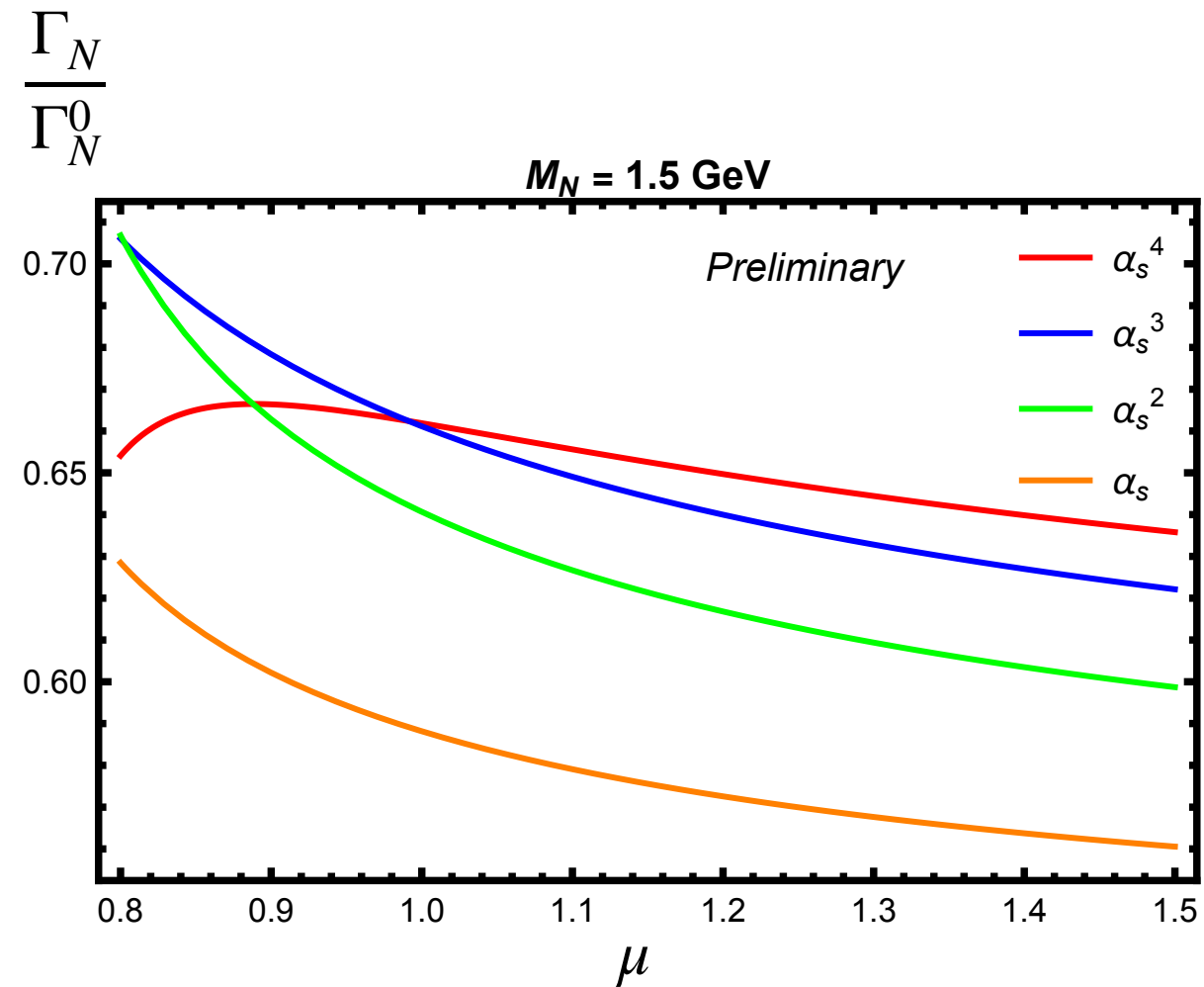
Running of $\Gamma(N \rightarrow \ell \text{had.})$ for $m_\ell = 0$



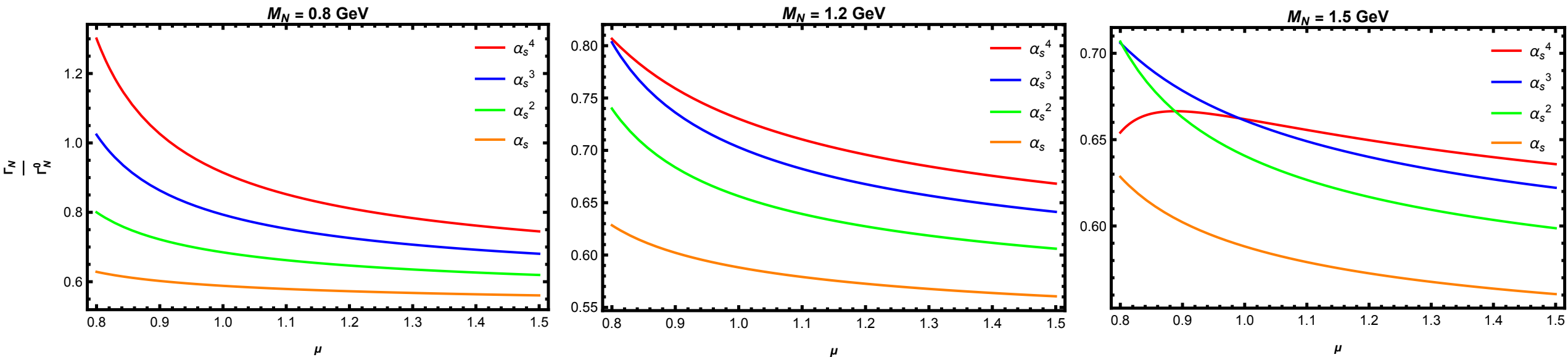
Running of $\Gamma(N \rightarrow \ell \text{had.})$ for $m_\ell = 0$



Running of $\Gamma(N \rightarrow \ell \text{had.})$ for $m_\ell = 0$



Running of $\Gamma(N \rightarrow \ell \text{had.})$ for $m_\ell = 0$



Preliminary

4. Conclusion

- Heavy sterile neutrinos: permit arbitrary NP through dimension-6 operators
- Currently no evidence for sterile neutrino contribution in **Belle II** data
- Sterile neutrino W contribution to decay to massless quarks calculated to $\mathcal{O}(\alpha_s^4)$.
- Higher order corrections yield sizeable effect and are instrumental to decide for which values of M_N perturbation theory works.
Result: In $N \rightarrow \ell \bar{q} q$, $\ell = e, \mu$ perturbation theory works for $M_N \geq 1.1 \text{ GeV}$