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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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Quirks in Quark Flavour Physics - Zadar 18th June 2024

Overview:

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1. $B \to D^* \ell N$ 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. $B \to D^*\ell N$ 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

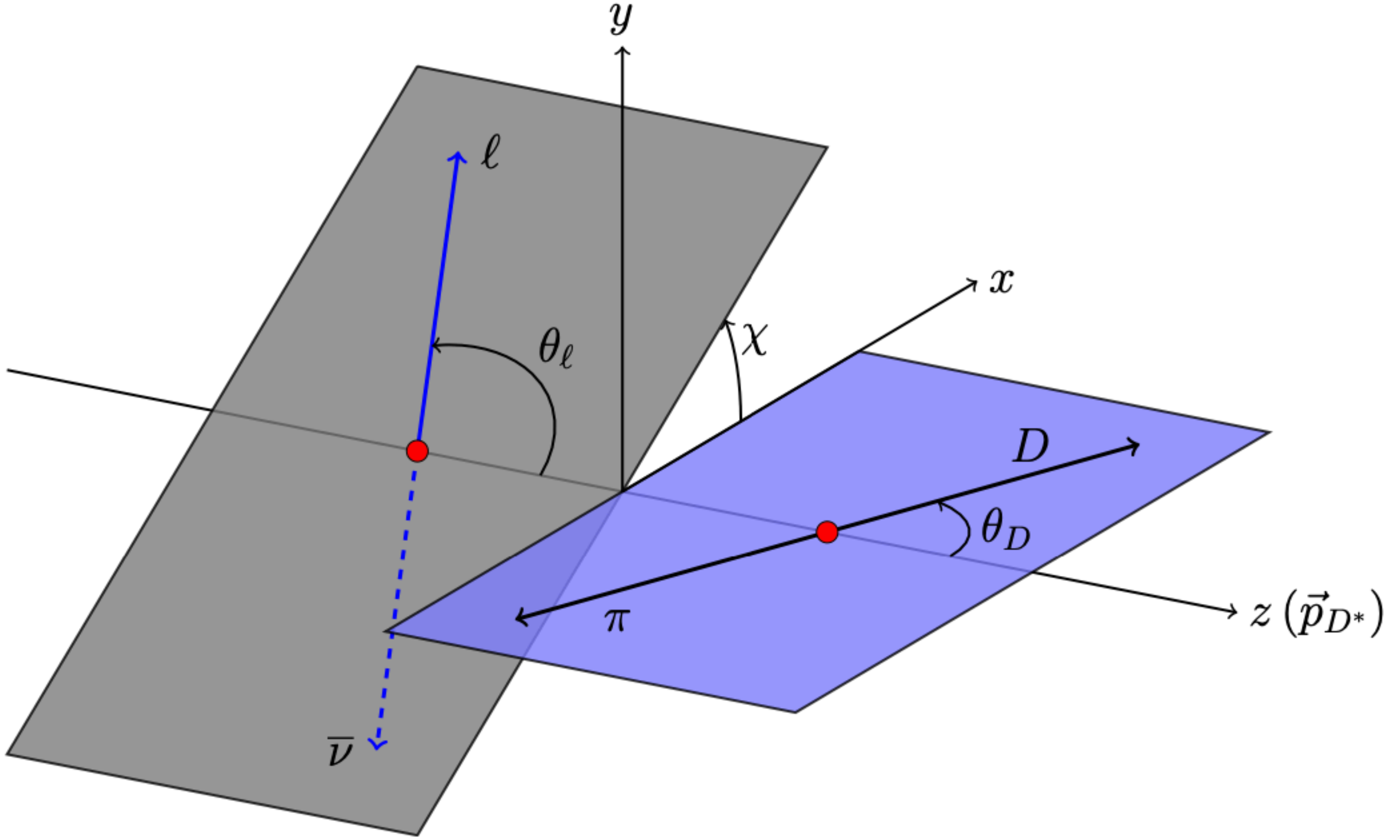
$$\mathscr{L}_I = \frac{gV_{N\alpha}}{\sqrt{2}} W_\mu^+ \overline{N}^c \gamma^\mu P_L \ell_\alpha^- + \frac{gV_{N\alpha}}{\cos\theta_w} Z_\mu \overline{N}^c \gamma^\mu P_L \nu_\alpha + \mathrm{h.c.}$$

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

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

- 4-body decay $B \to D^*[\to D\pi]\ell\nu$ 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 $B \to D^* \ell \nu$

$$\frac{32\pi}{9}\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_D d\chi} = (J_{1s} + J_{2s}\cos 2\theta_\ell + J_{6s}\cos\theta_\ell)\sin^2\theta_D +$$
$$(J_{1c} + J_{2c}\cos 2\theta_\ell + J_{6c}\cos\theta_\ell)\cos^2\theta_D +$$
$$(J_3\cos 2\chi + J_9\sin 2\chi)\sin^2\theta_D\sin^2\theta_\ell +$$
$$(J_4\cos\chi + J_8\sin\chi)\sin 2\theta_D\sin 2\theta_\ell +$$
$$(J_5\cos\chi + J_7\sin\chi)\sin 2\theta_D\sin 2\theta_\ell +$$

→ J_i coefficients measurable in experiment!

N new physics contribution to B Decays

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

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(\bar{c}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma^\mu \nu_{\ell,L}) + g^N_{V_R} (\bar{c}_R \gamma_\mu b_R)(\bar{\ell}_R \gamma^\mu N_R) + g^N_{S_L} (\bar{c}_R b_L)(\bar{\ell}_L N_R)$$

$$+ g^N_{S_R} (\bar{c}_L b_R)(\bar{\ell}_L N_R) + g^N_T (\bar{c}_L \sigma_{\mu\nu} b_R)(\bar{\ell}_L \sigma^{\mu\nu} N_R) + \text{h.c.} \Big]$$

Robinson, Shakya and Zupan, 1807.04753

N new physics contribution to B Decays

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

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

- Angular Coefficients are incoherent sum of SM and NP

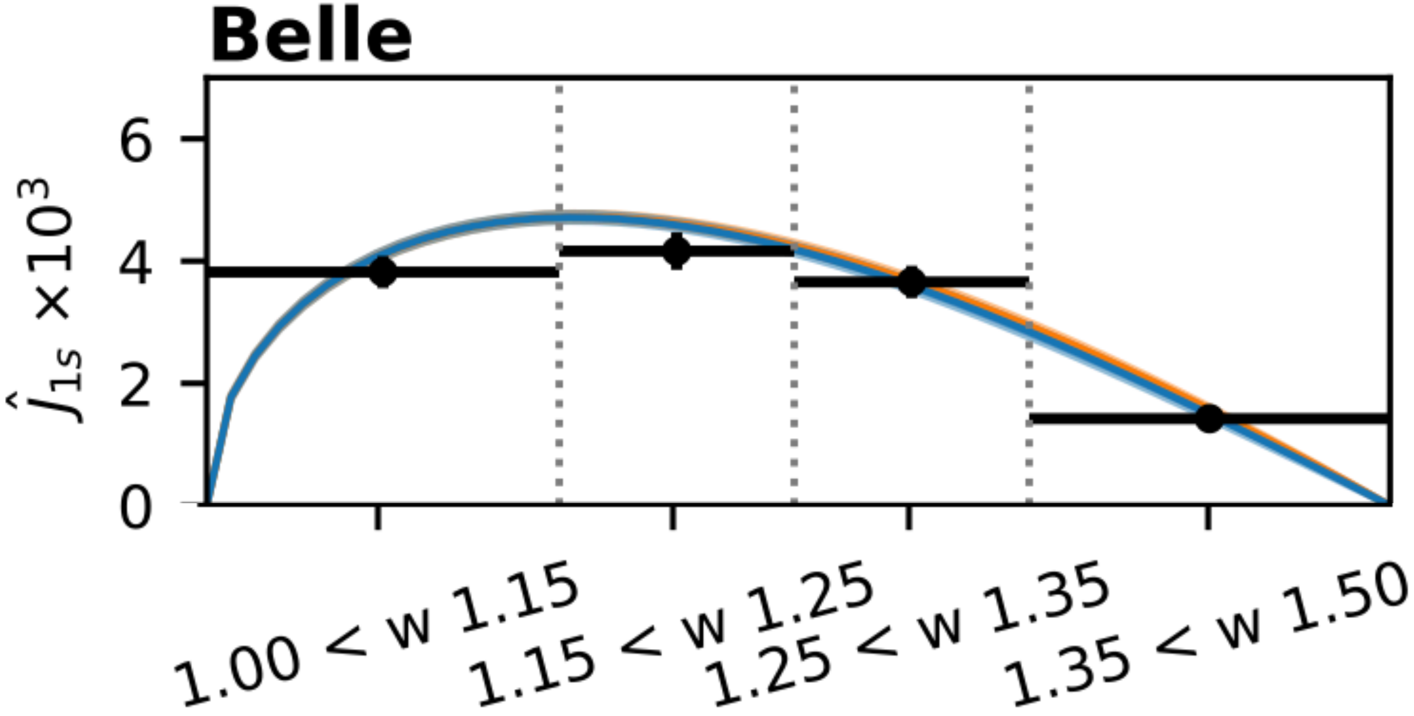
$$J_i = J_i^{SM} + J_i^{NP}(g_j^N, m_N)$$

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 $g_{V_R}^N, g_{S_L}^N, \ldots$ at a time.
- Belle II preliminary data, average of leptons $\Rightarrow$ LFU WC analysis
- Result insensitive to choice of form factors (FNAL/MILC, JLQCD,…)

Fit to data



Hadronic recoil parameter:

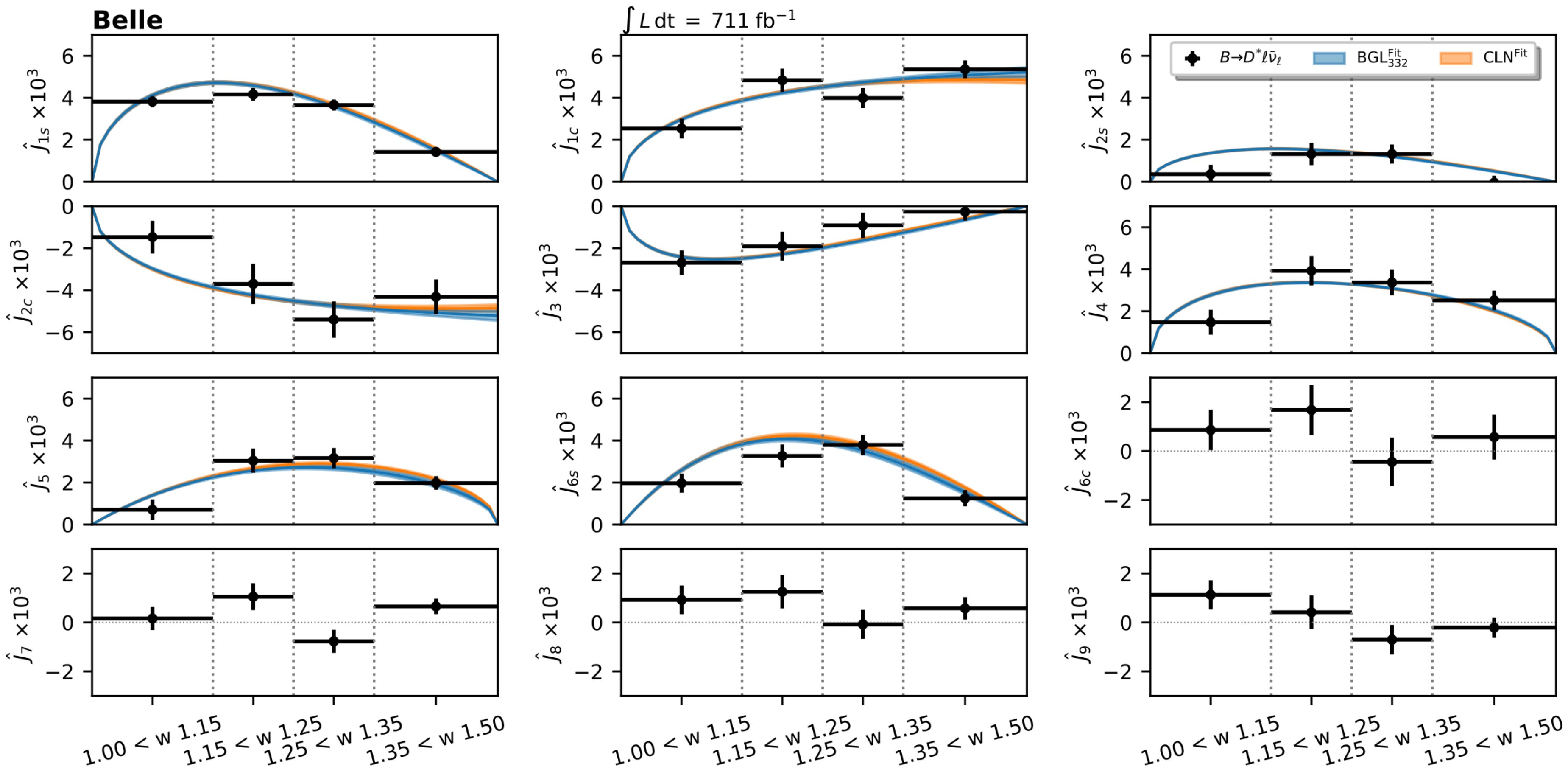
$$w = \frac{m_B^2 + m_{D*}^2 - q^2}{2 m_B m_{D*}}$$

Normalized angular coefficient:

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

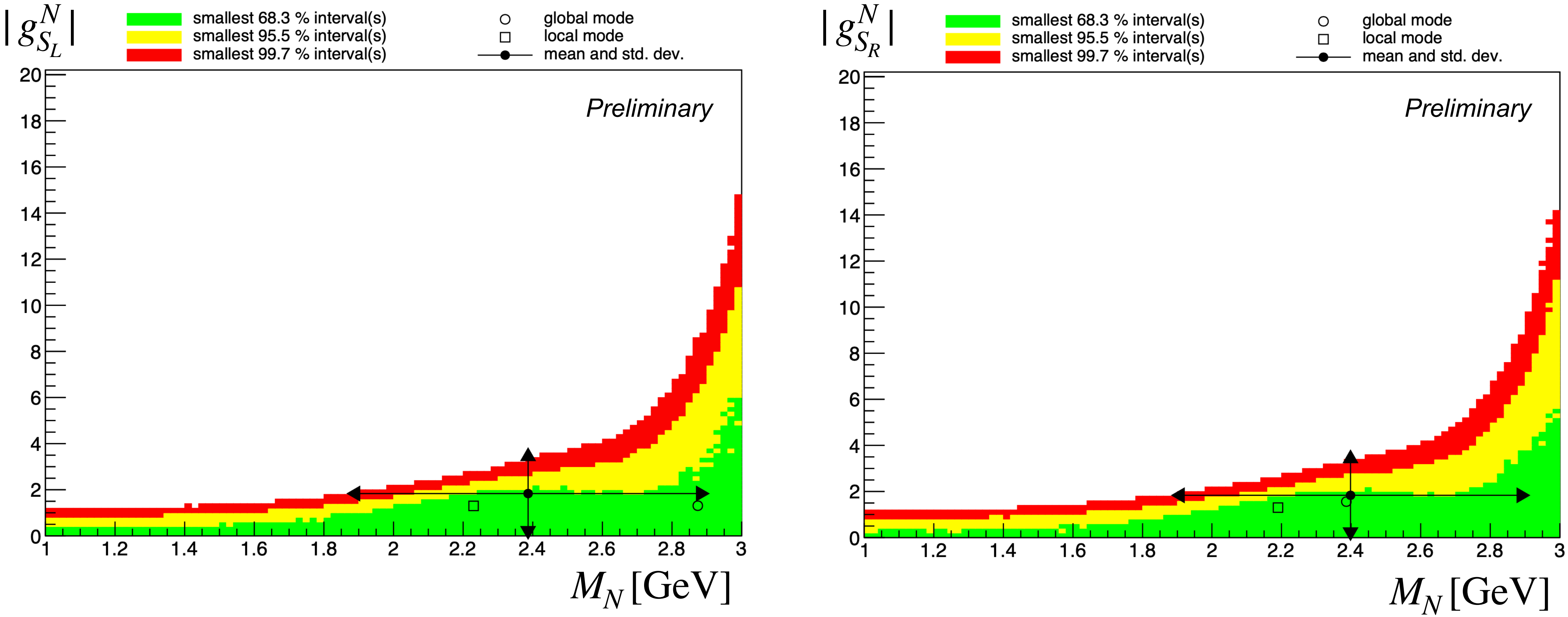
Prim et al., 2310.20286

Fit to data

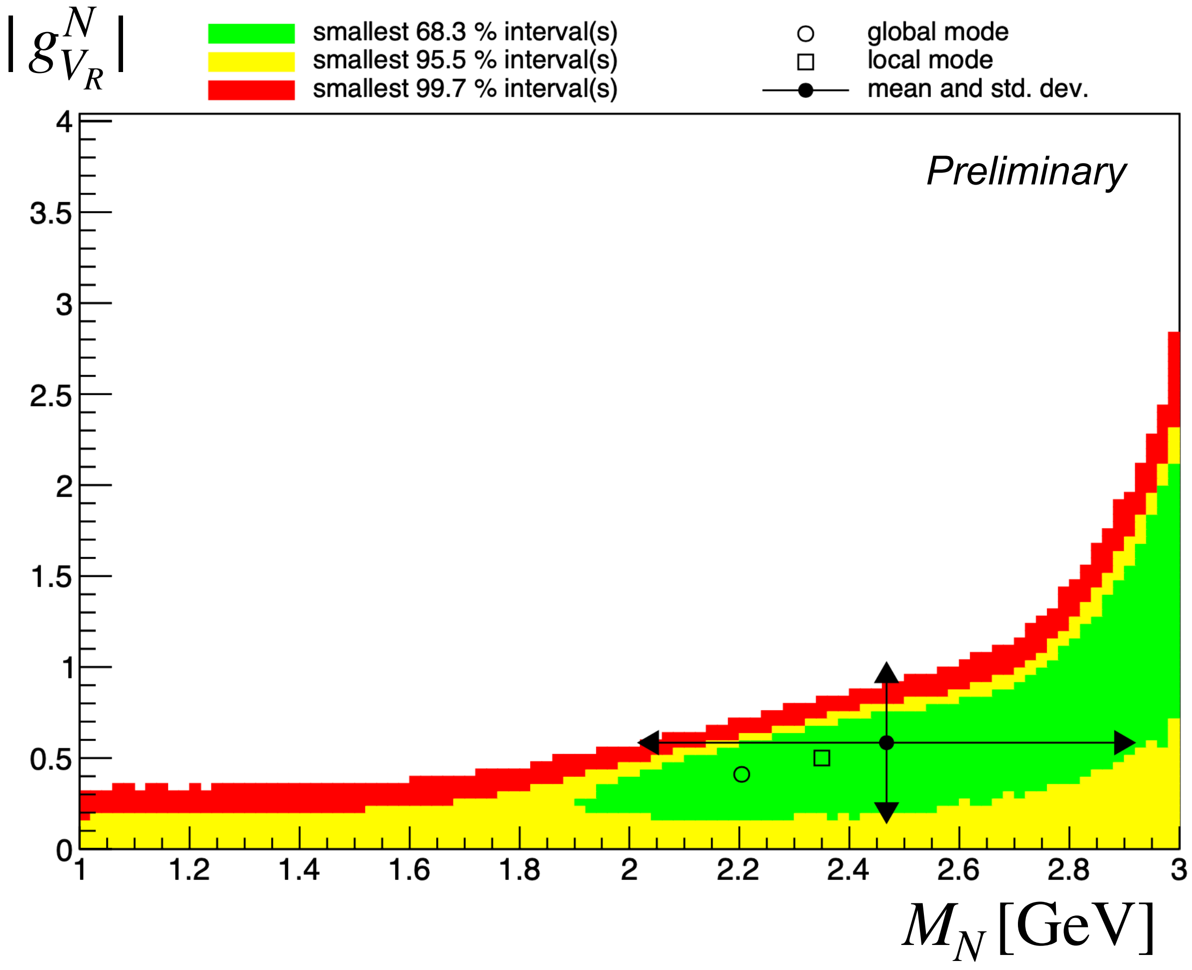


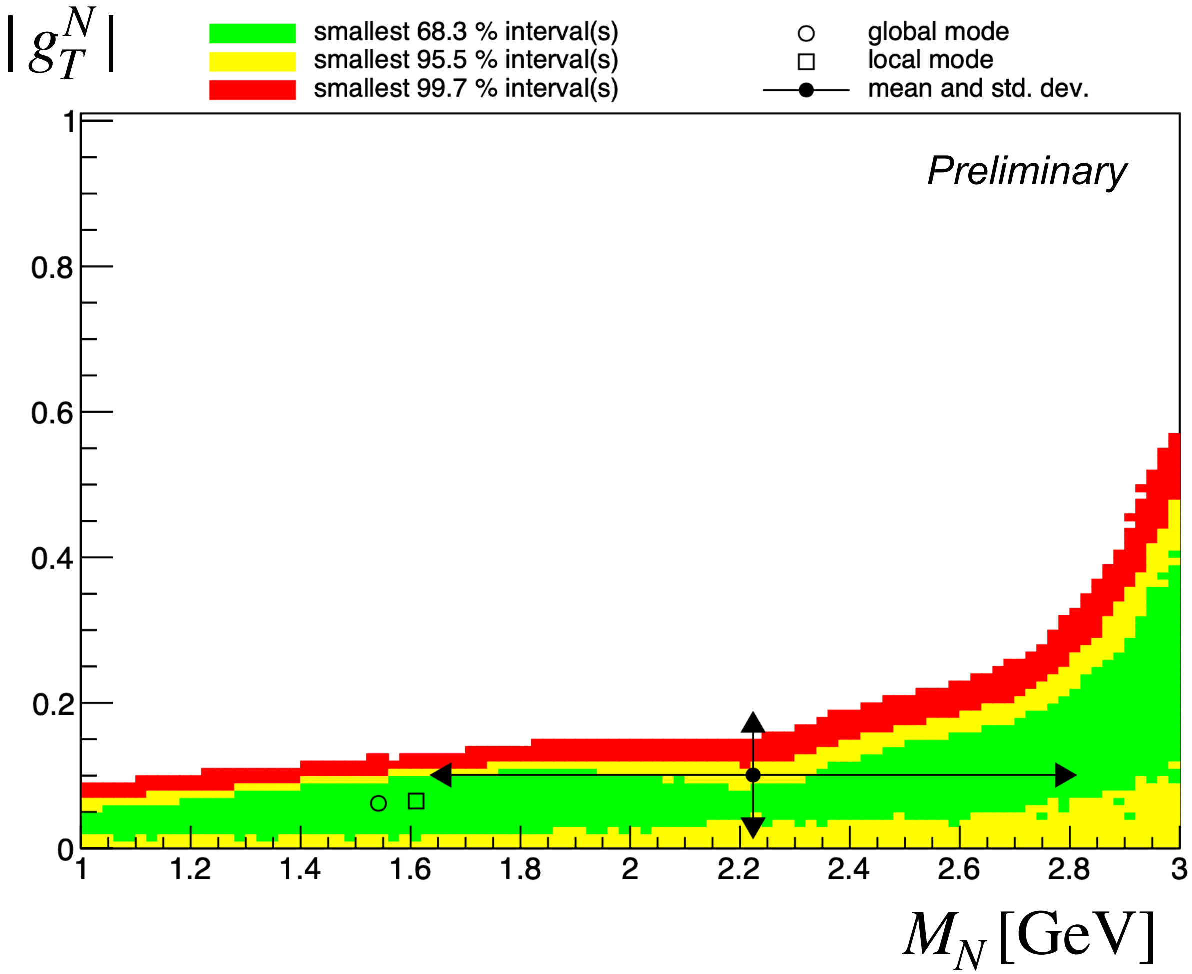
Prim et al., 2310.20286

Allowed parameter region



Allowed parameter region

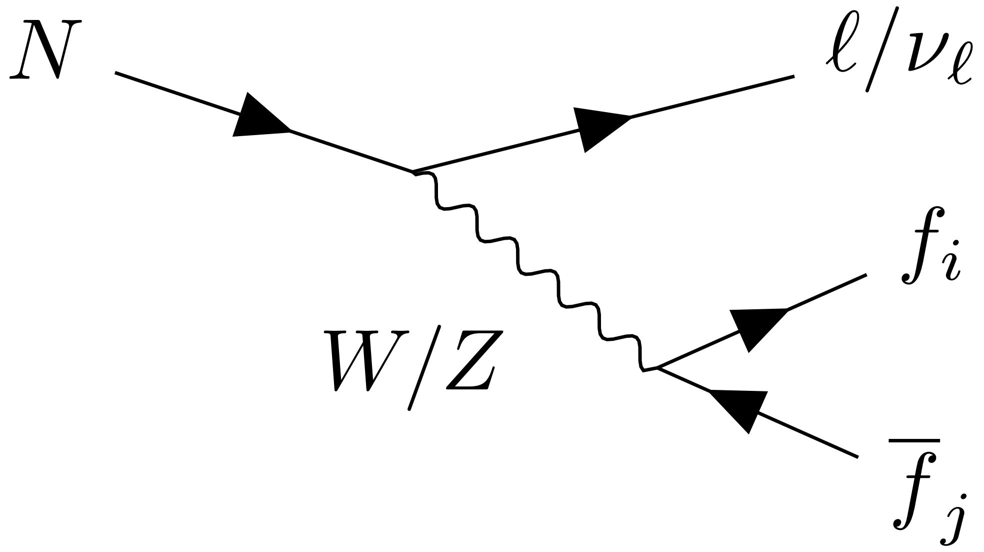




3. QCD corrections to semi-hadronic N decay rates

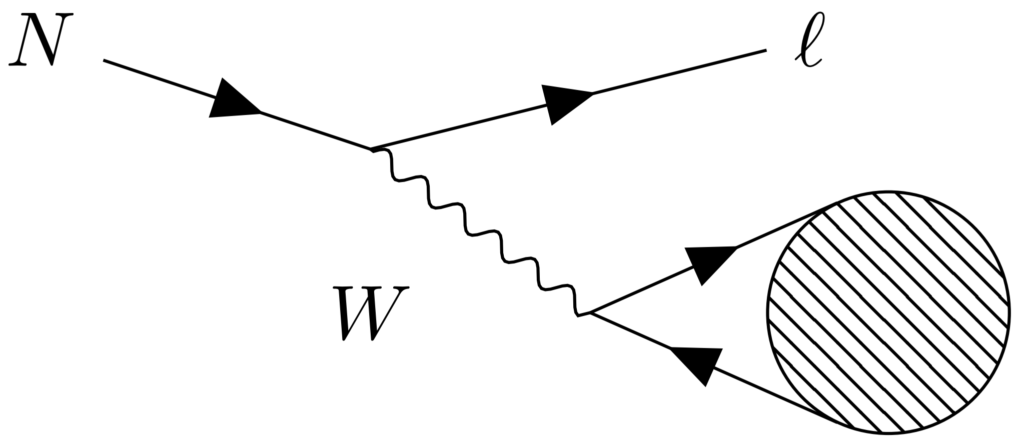
TK, Nierste 2024:

- $W^{\pm}, Z$ -mediated decays of sterile neutrino via mixing with active ν
- For $m_N \sim 2\,\mathrm{GeV}$ hadronic decay rates could be sizeable
- QCD corrections to $W^* \to \bar{f}_i f_j$ and $Z^* \to \bar{f}_j f_j$ are known



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

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



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

$x_\ell = m_\ell / M_N$

0806.3156

QCD correlators

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

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

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

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

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

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

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

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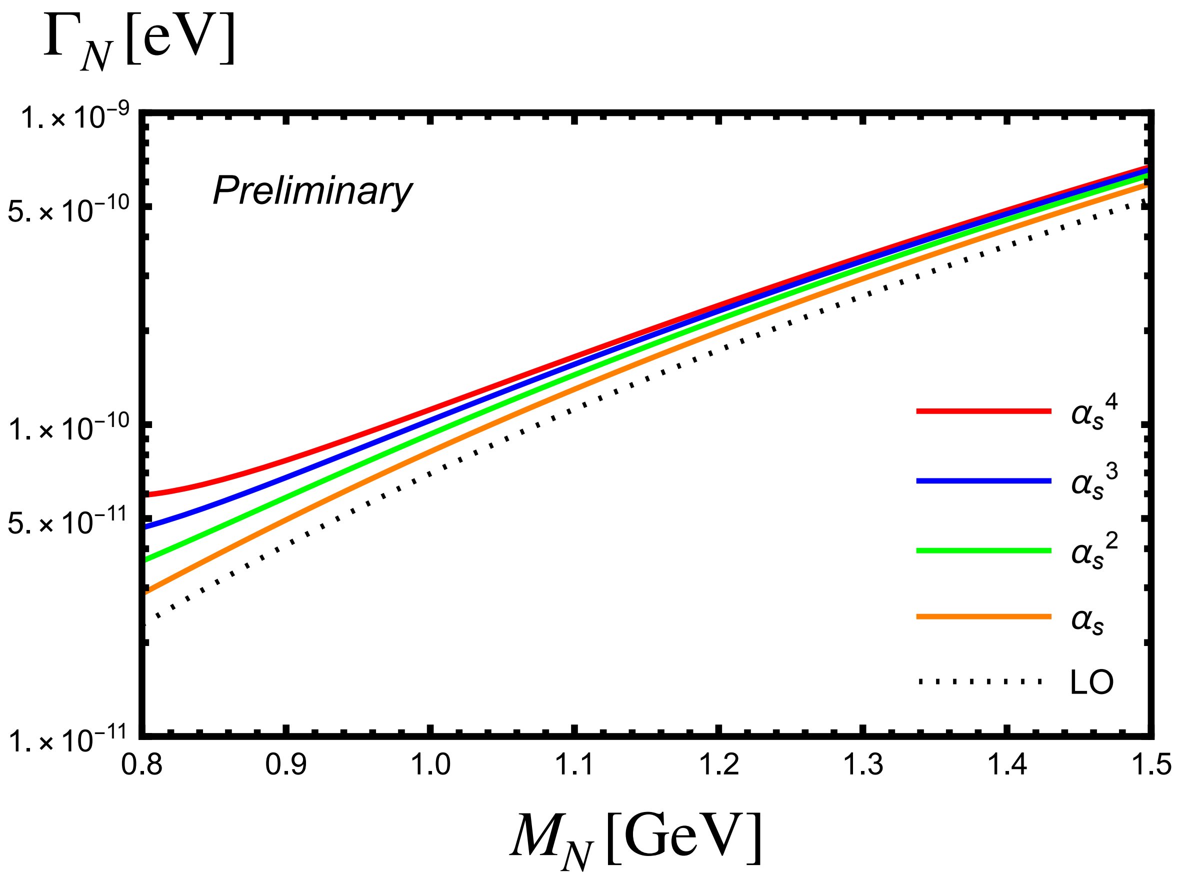
- In the limit of vanishing lepton mass we reproduce τ-decay:

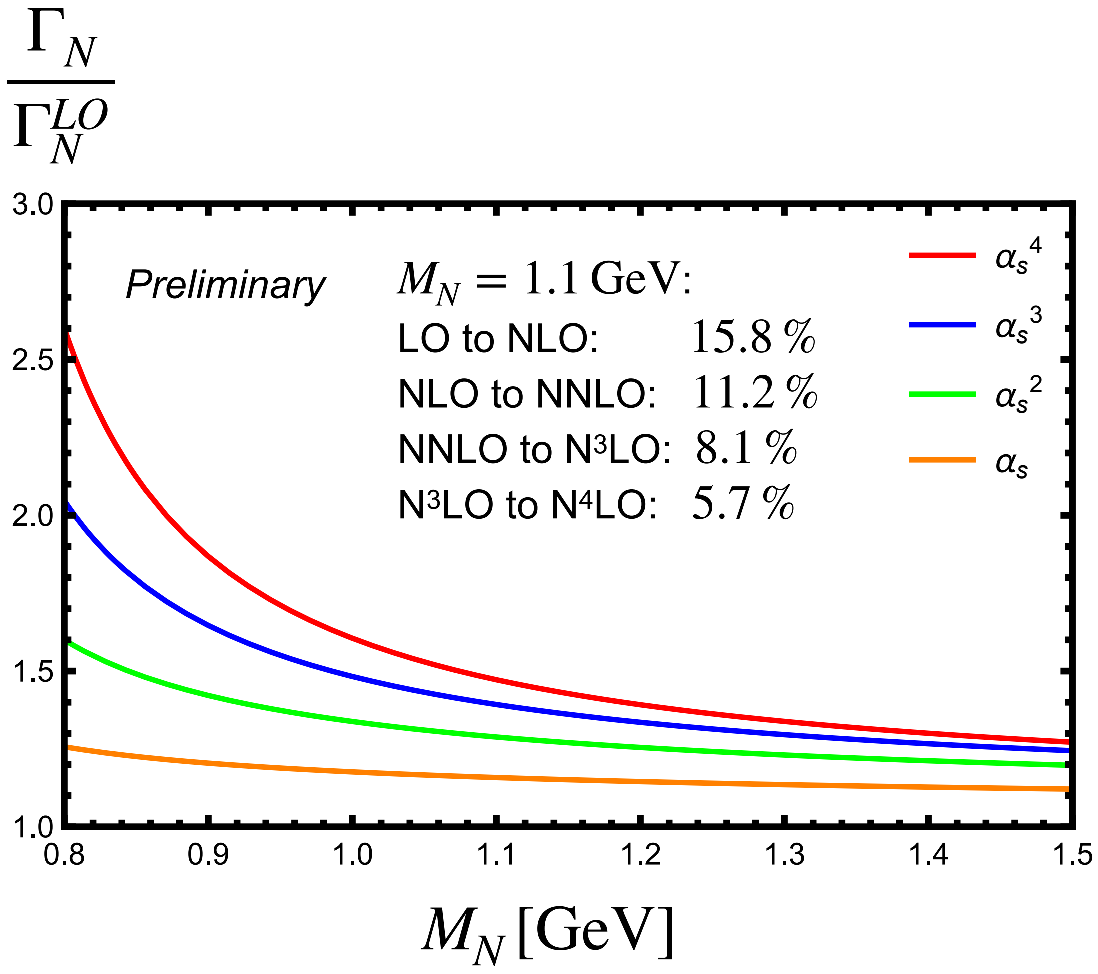
$$R_N(x_\ell = 0) = \frac{\Gamma_N}{|V_{N\ell}|^2 |V_{q\bar{q}}|^2 \Gamma(N \to e^- e^+ \nu_e)} = N_c \left[1 + a_S + 5.202 a_S^2 + 26.366 a_S^3 + 127.079 a_S^4\right]$$

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

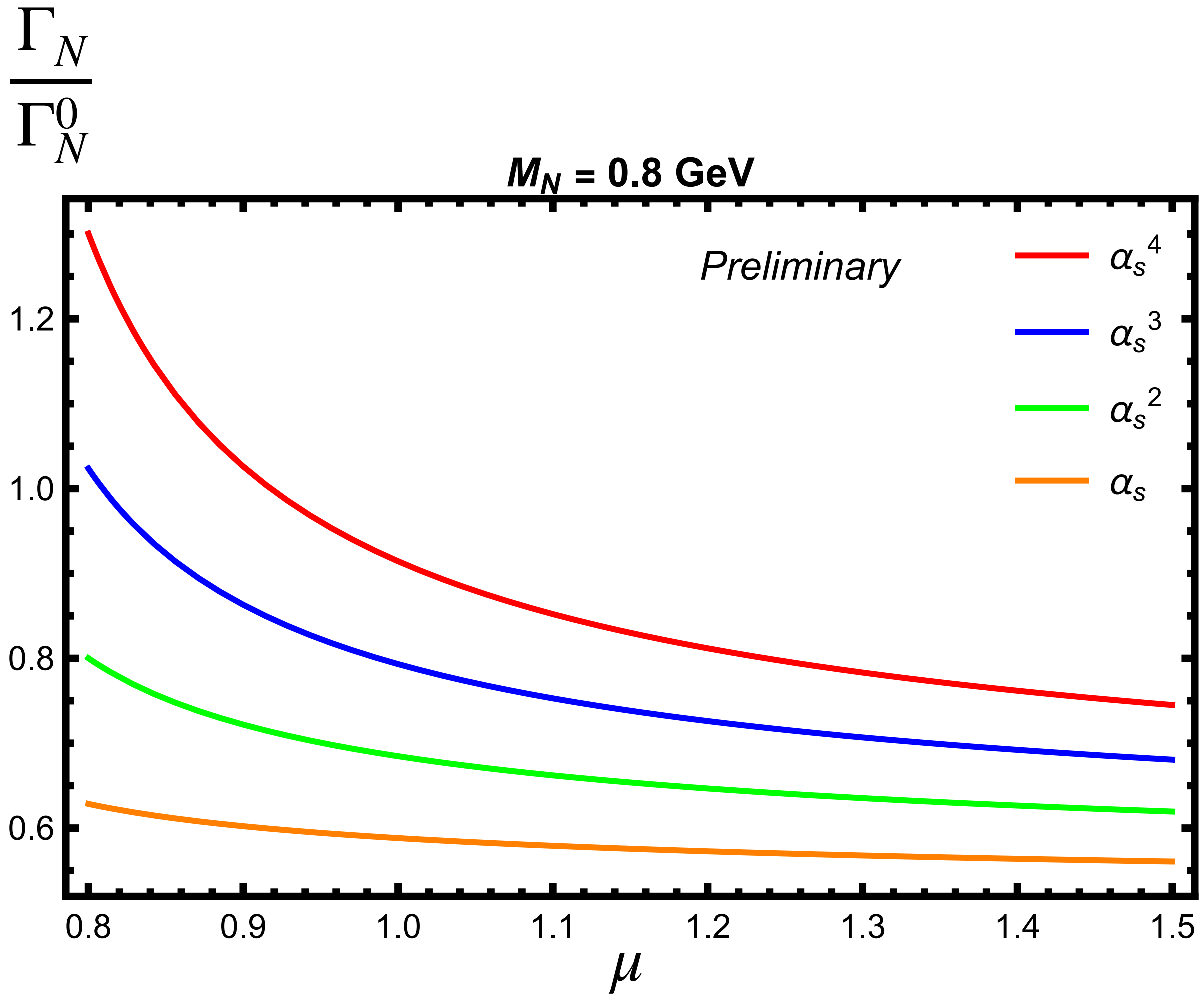
$x_\ell = m_\ell / M_N, a_S = \alpha_S / \pi$

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

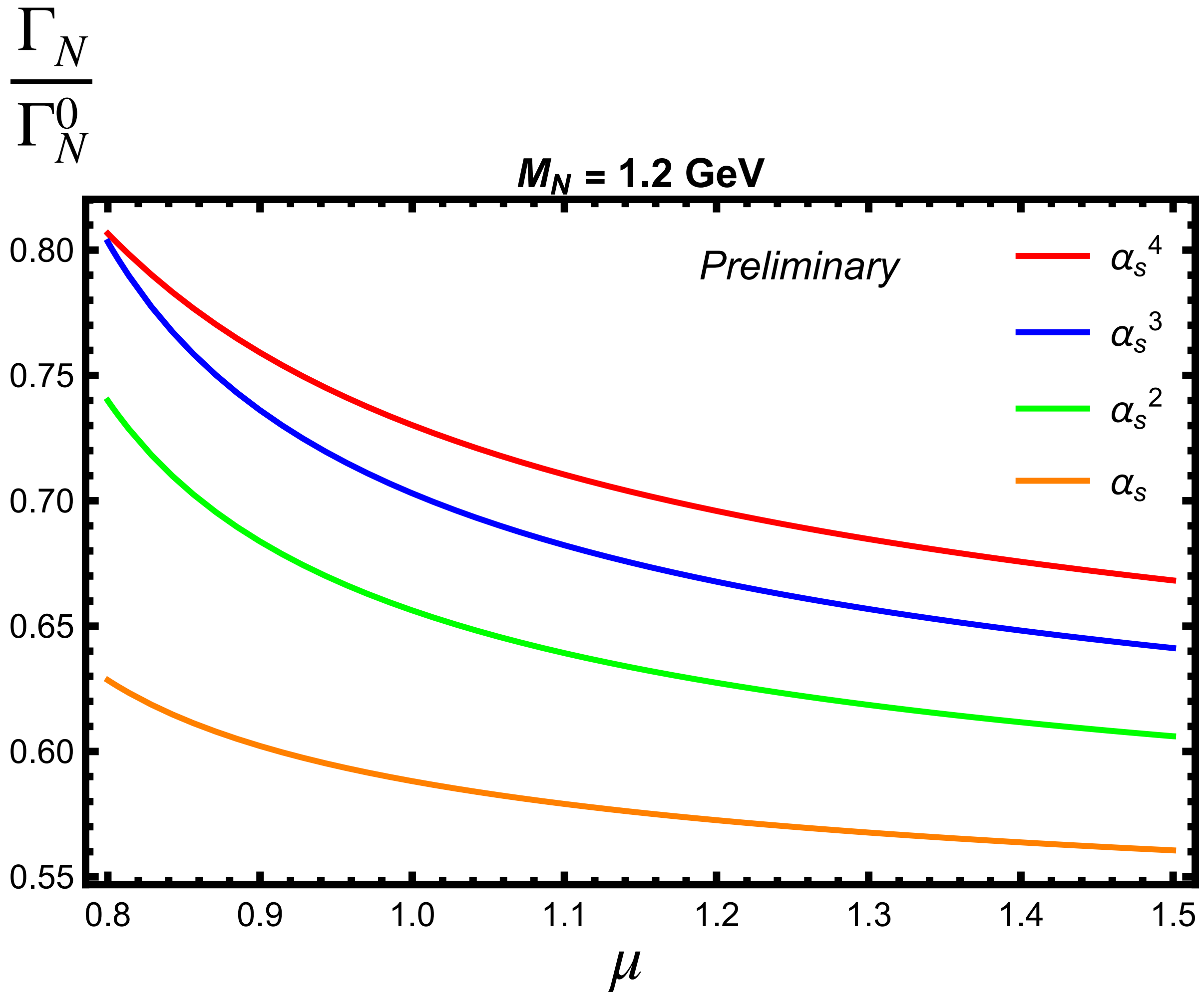




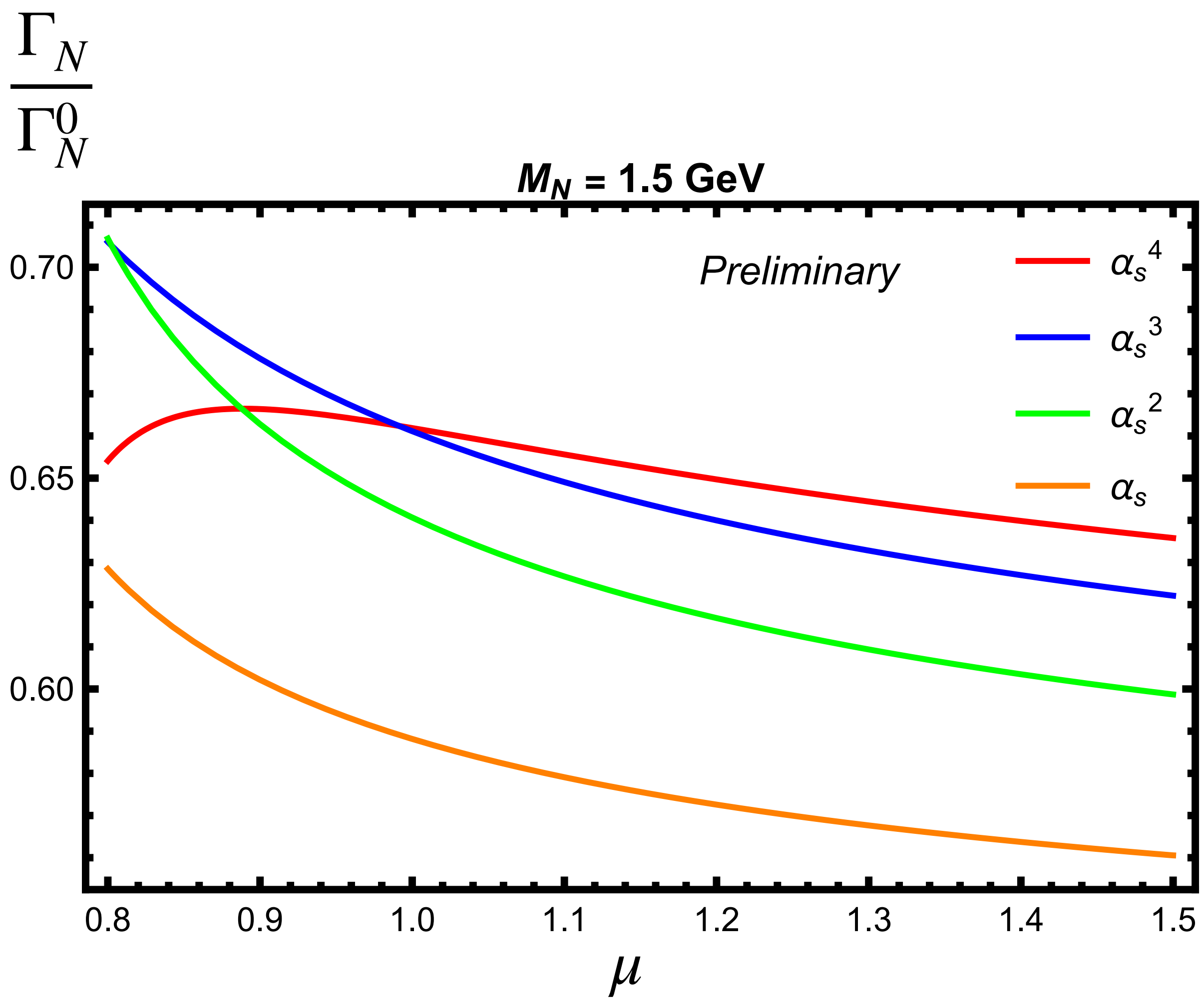
Running of $\Gamma(N \to \ell\,\text{had.})$ for $m_\ell = 0$



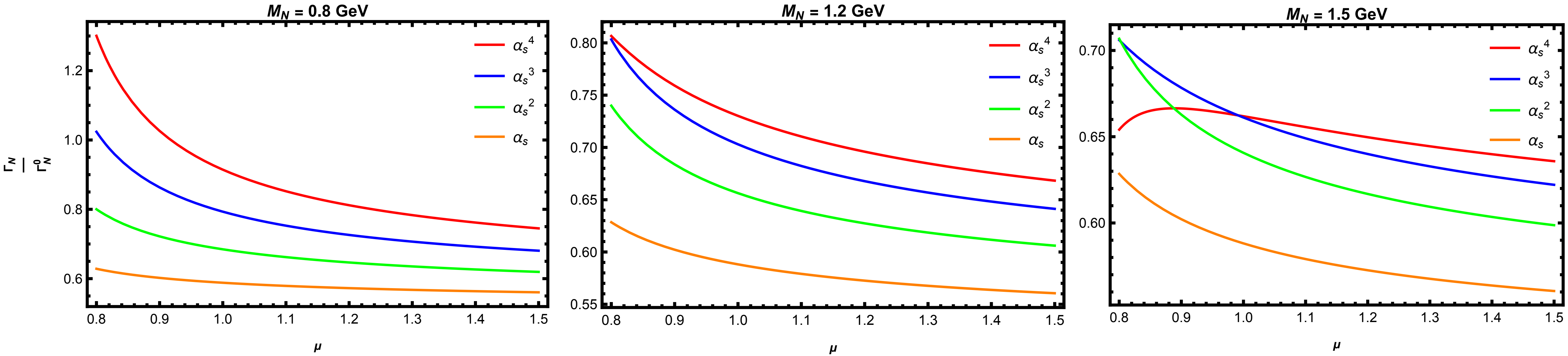
Running of $\Gamma(N \to \ell\,\text{had.})$ for $m_\ell = 0$



Running of $\Gamma(N \to \ell\,\mathrm{had.})$ for $m_\ell = 0$



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



Preliminary

4. Conclusion

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- 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 $N \to \ell \bar{q} q$, $\ell = e, \mu$ perturbation theory works for $M_N \geq 1.1$ GeV