New-ν constraints from hadron decays

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Based on work with
Florian Bernlochner, Marco Fedele, Ulrich Nierste and Markus T. Prim
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New-ν Physics: From Colliders to Cosmology - Durham University 10.04.2025

Content

1. Overview

- A Sterile Neutrino = Heavy Neutral Lepton (HNL) arises in many NP models on e.g. Dark Matter, ν Oscillations and baryon asymmetry (see e.g. Bodarenko et al. 1805.08567)
- Most commonly sterile neutrino interactions are parametrised by a mixing parameter i.e. $V_{N\alpha}$

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

  with weak coupling g and weak mixing angle θ_w and $P_L = (1-\gamma_5)/2$
- $B \to D^* \ell N$ deviates from mixing parameter description!

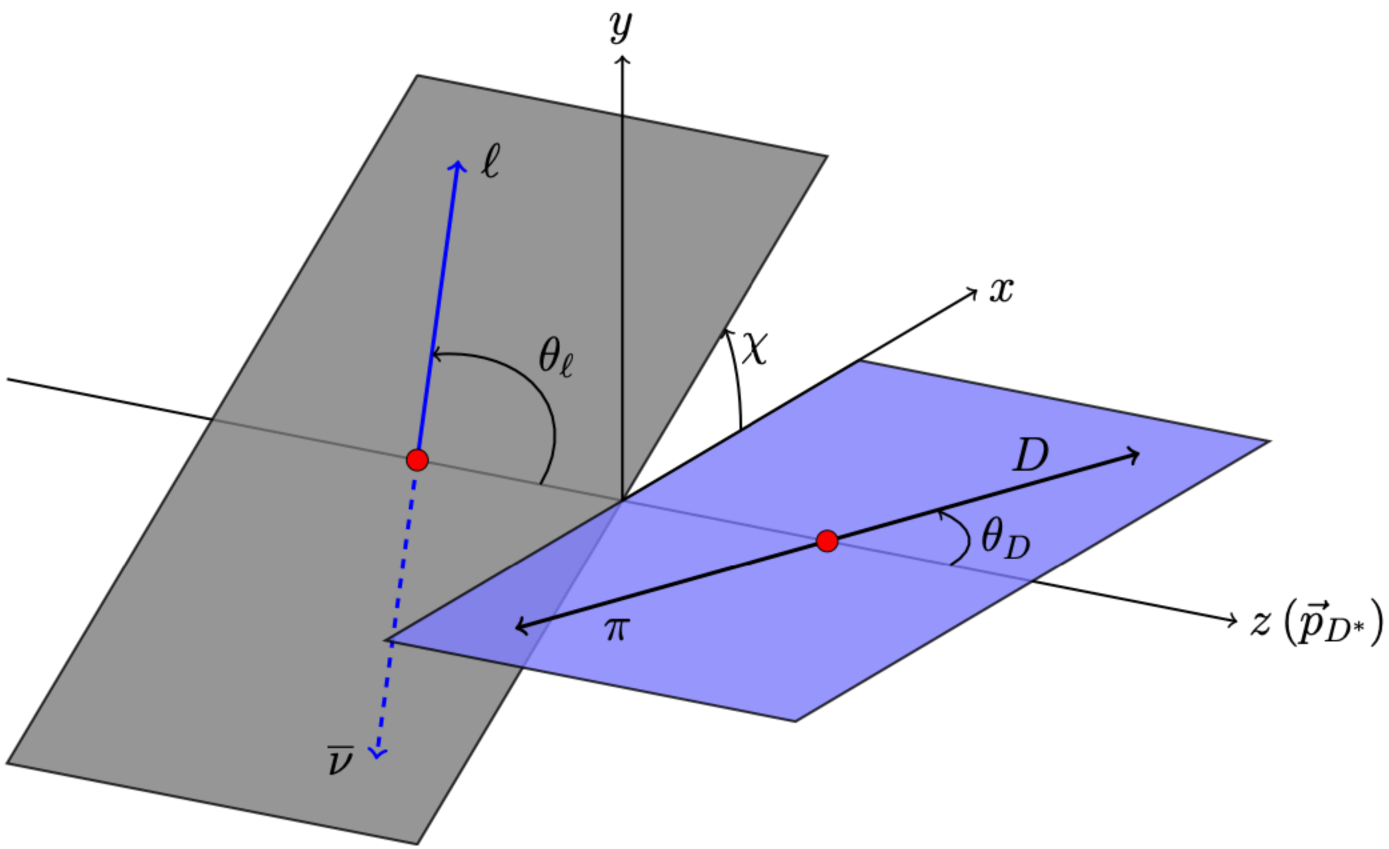
2. Sterile Neutrinos from $B \to D^*\ell N$

- Idea: Data sample on Standard Model (SM) process $B \to D^*\ell\nu$ could contain a new-physics (NP) contribution $B \to D^*\ell N$
- SM and NP decay are 4-body decays: $B \to D^*[\to D\pi]\ell\nu$ with $\ell = e, \mu$
- The SM decay was investigated by Belle II

  $\to$ access to angular distributions!
- SM described by 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 decay

- SM and NP sum incoherently $J_i = J_i^{SM} + J_i^{NP}(\{g_j\})$
- Sterile neutrinos described by four energy dimension-6 operators

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

Robinson, Shakya and Zupan, 1807.04753

N new physics contribution to B decay

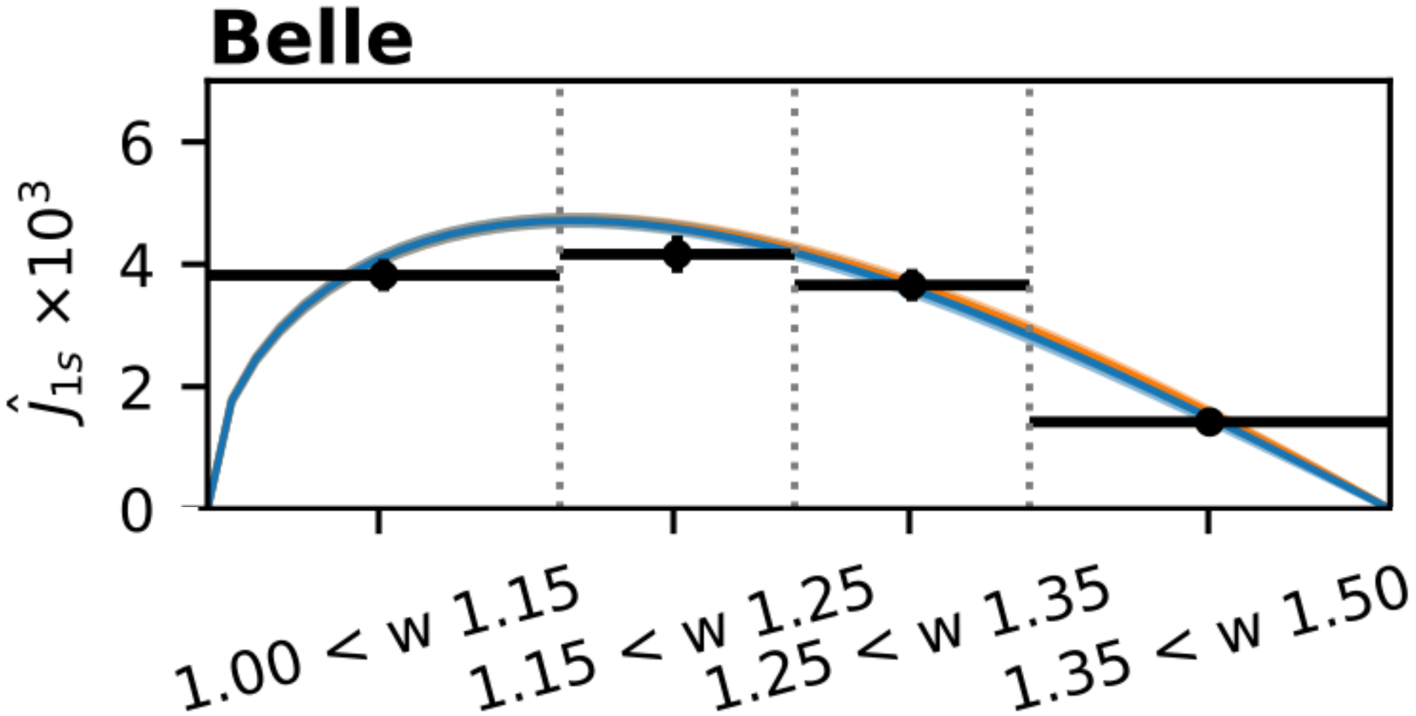
- Higher energy dimension operators are neglected
- E.g. operator with left-handed quarks is dimension-8

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

- This description is a deviation from the mixing angle description. In terms of quark operators a mixing angle would be energy dimension-7

Belle II Measurements

- Belle II measured these J_i coefficients:



Hadronic recoil parameter:

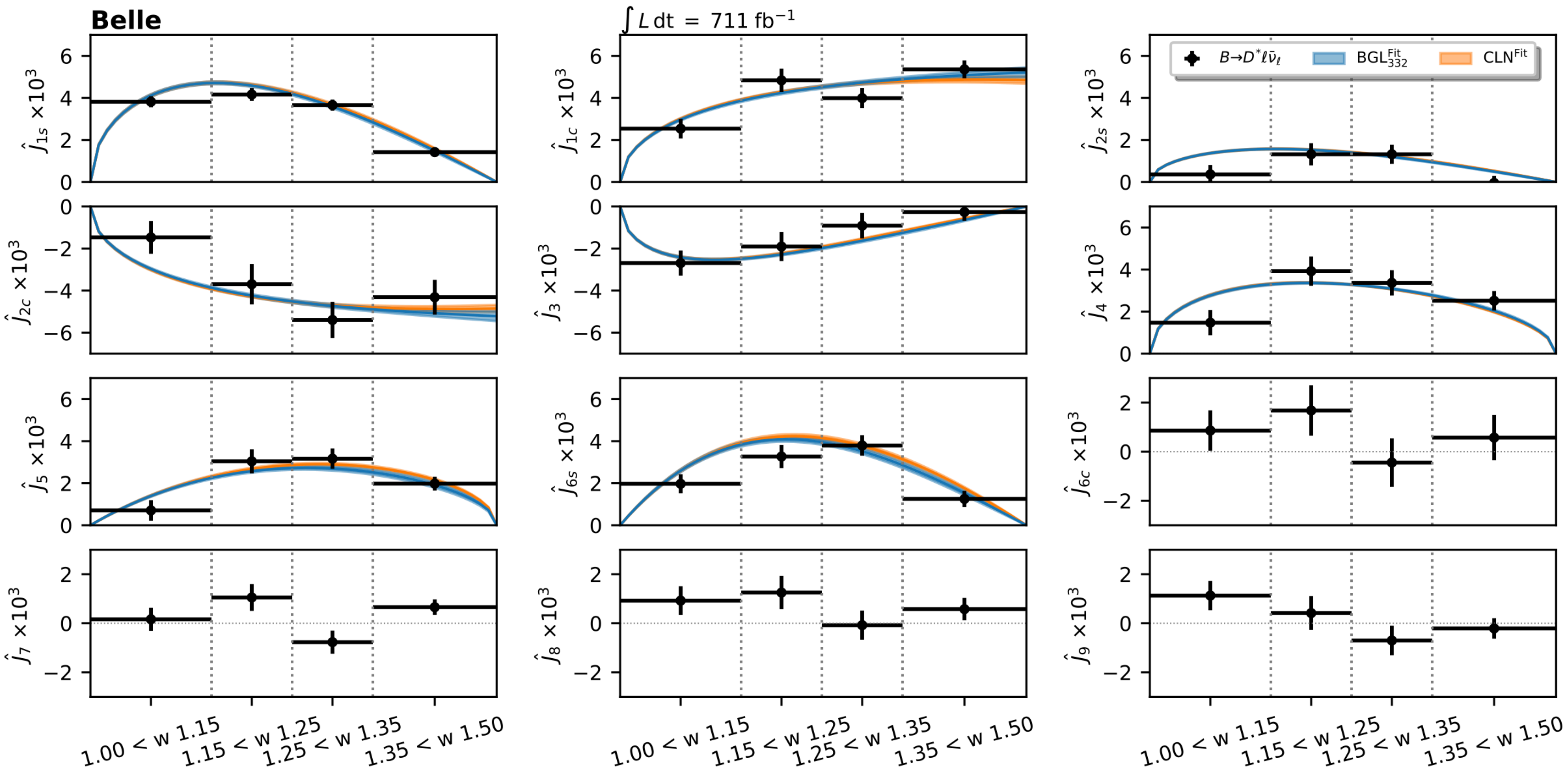
$$w = \frac{m_B^2 + m_{D*}^2 - q^2}{2 m_B m_{D*}}$$

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

Belle II Measurements



Prim et al., 2310.20286

Parameter Analysis with decay distributions from Belle II

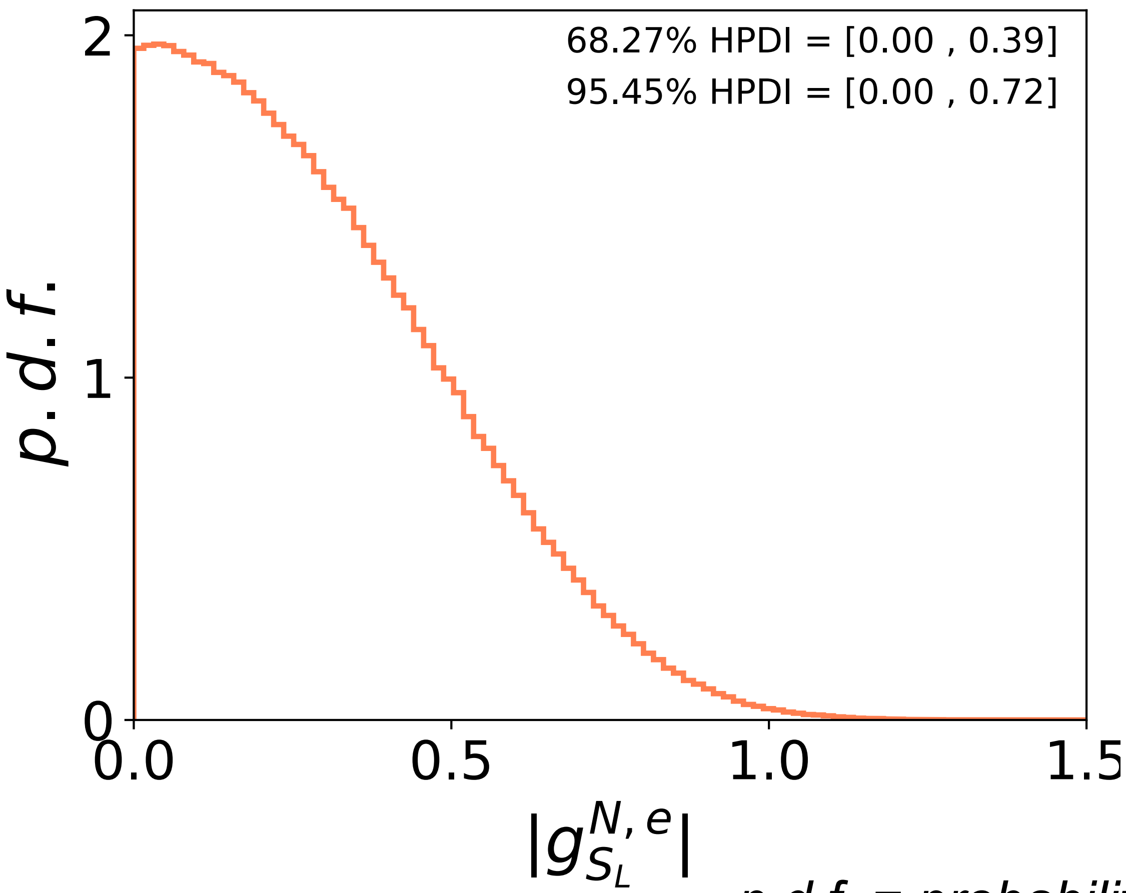
Bernlochner, Fedele, TK, Nierste, Prim [2410.11945]:

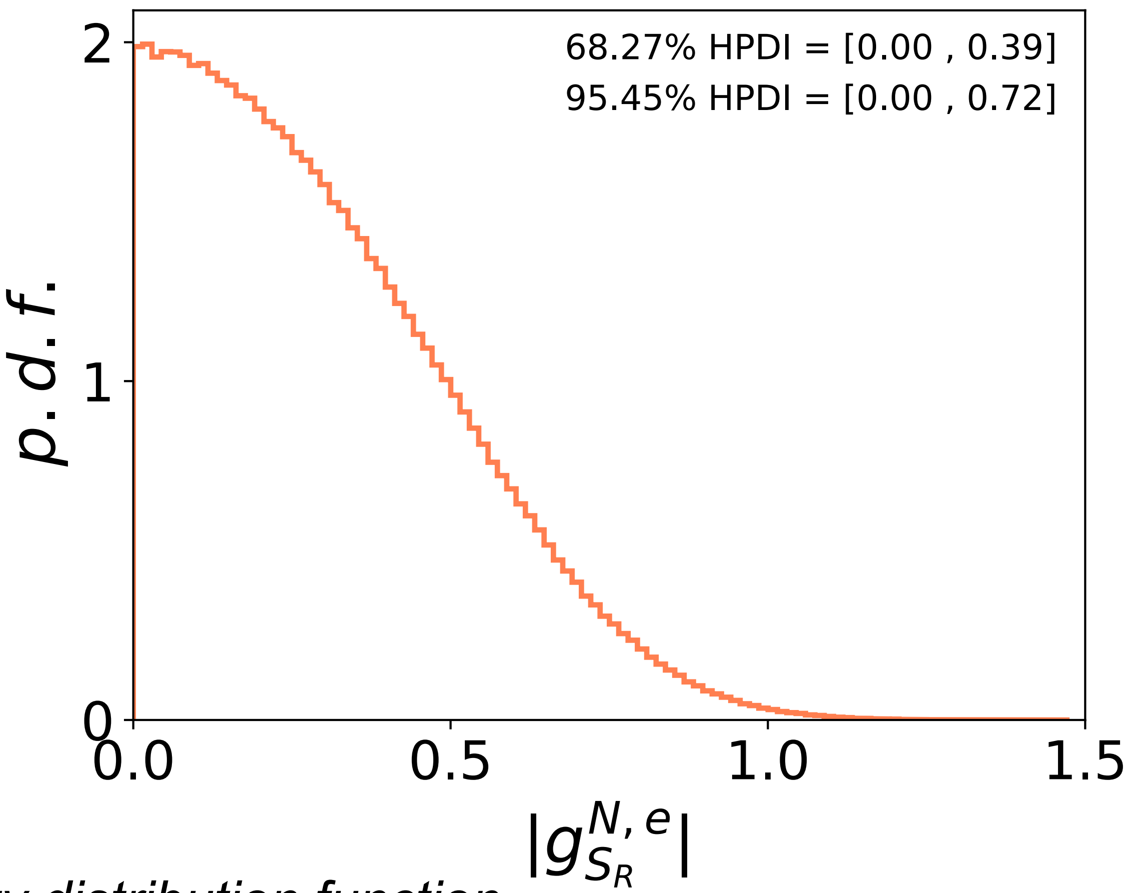
- We have fitted the J_i to the recent Belle II data
- Bayesian analysis, fitted parameters: (g_j^N, m_N, FF). Two scenarios: One non-zero WC and varying all WC at the same time.
- Analysis performed for both $\ell = e$ and $\ell = \mu$
- Fit insensitive to choice of form factors (FNAL/MILC, JLQCD, …)

Results

- Angular coefficients only sensitive for $m_N \leq 62.5\,\mathrm{MeV}$

$$\ell = e$$

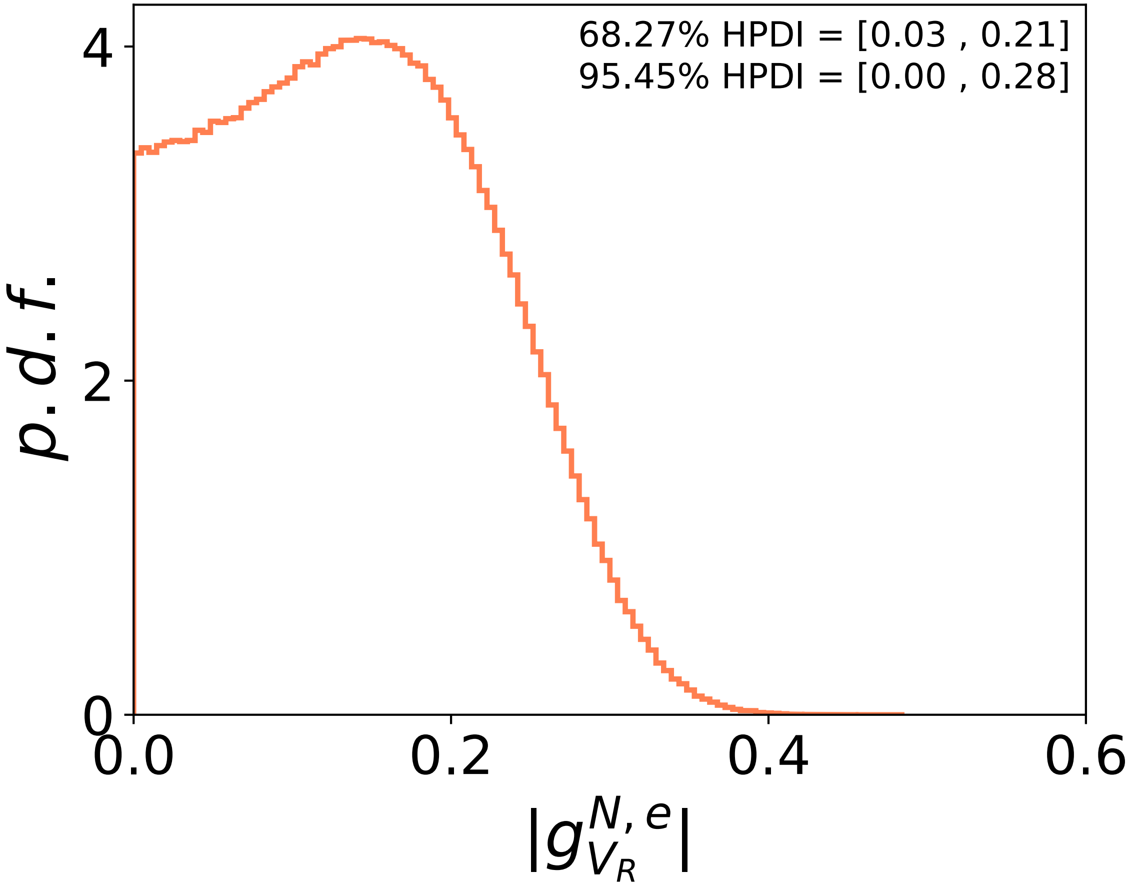


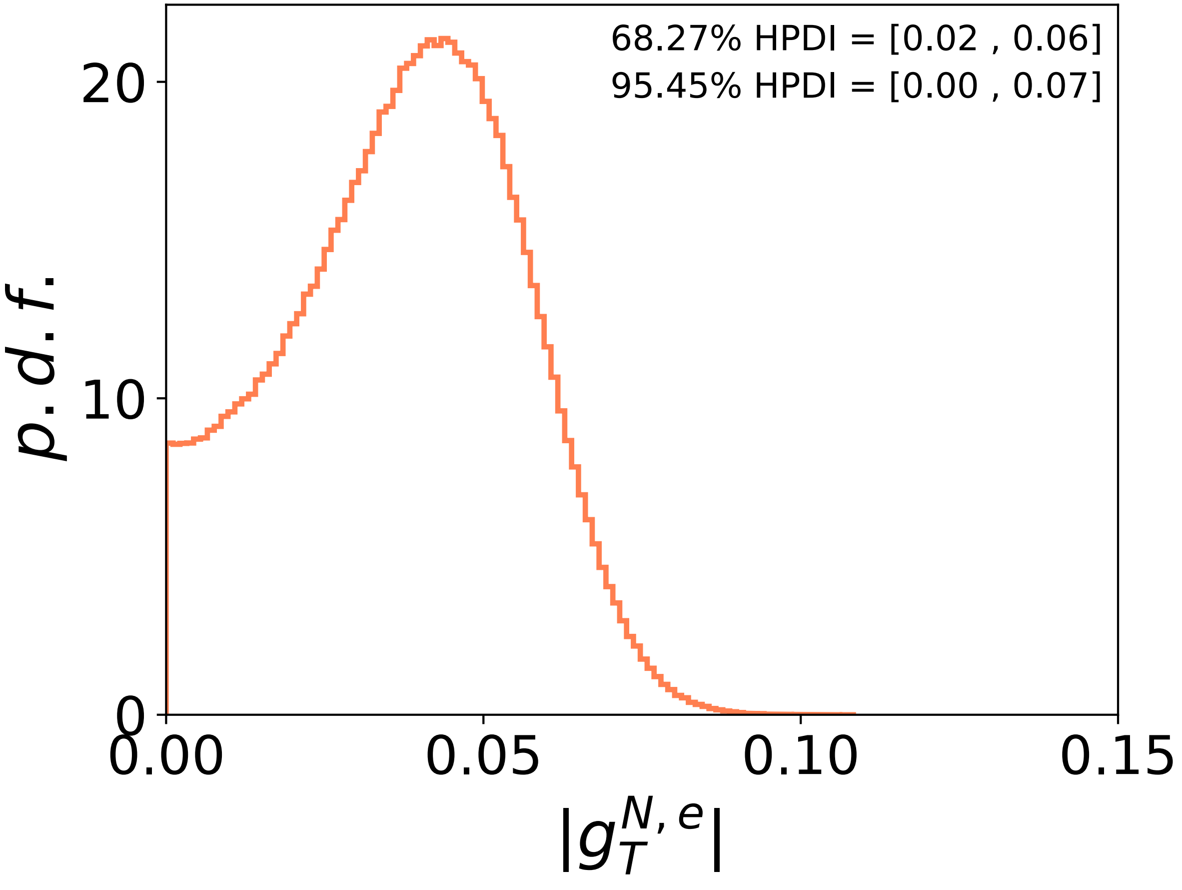


p.d.f. = probability distribution function

Results

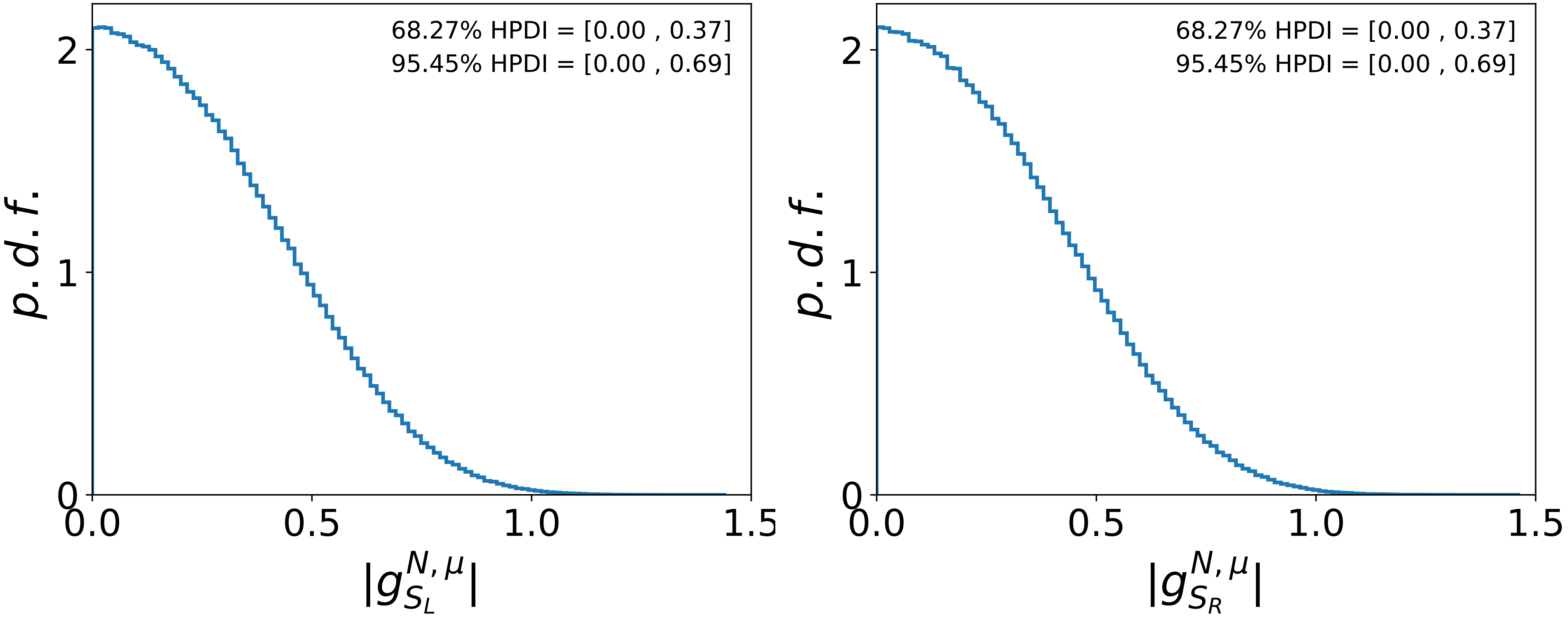
$$\ell = e$$





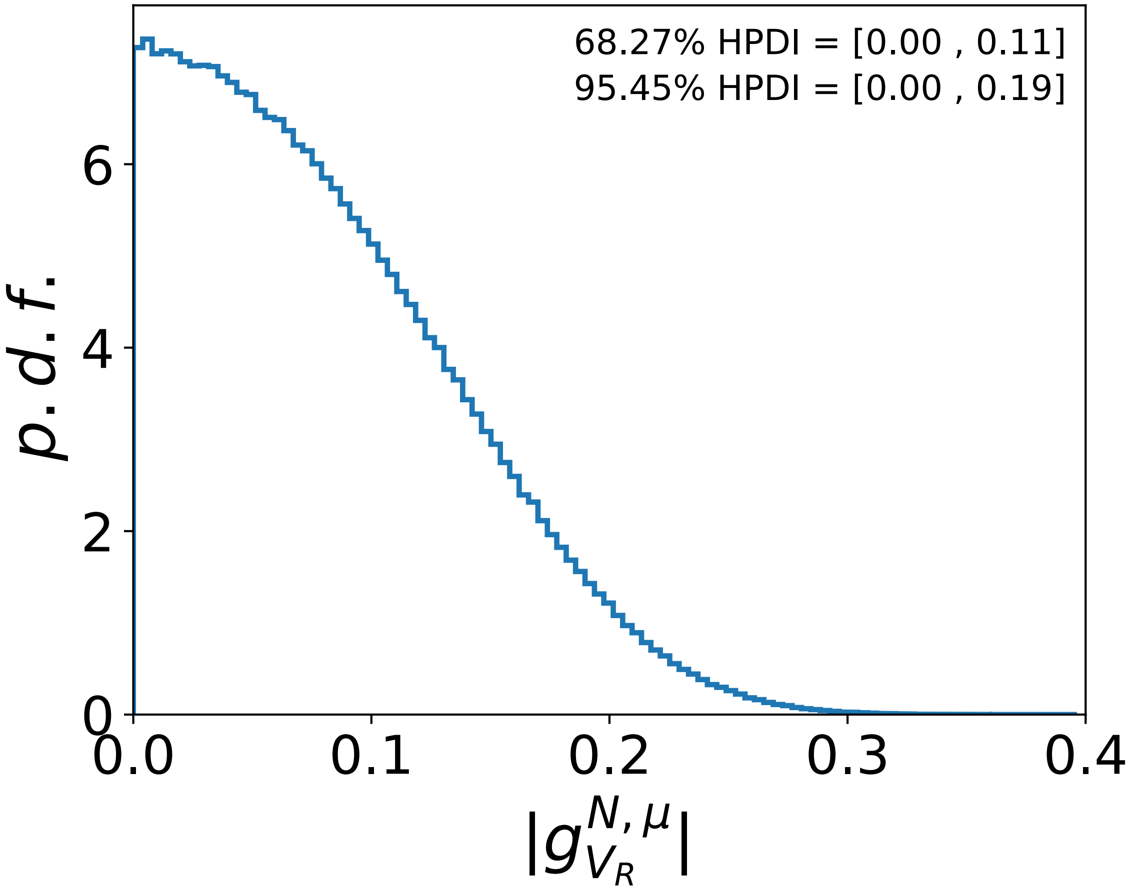
Results

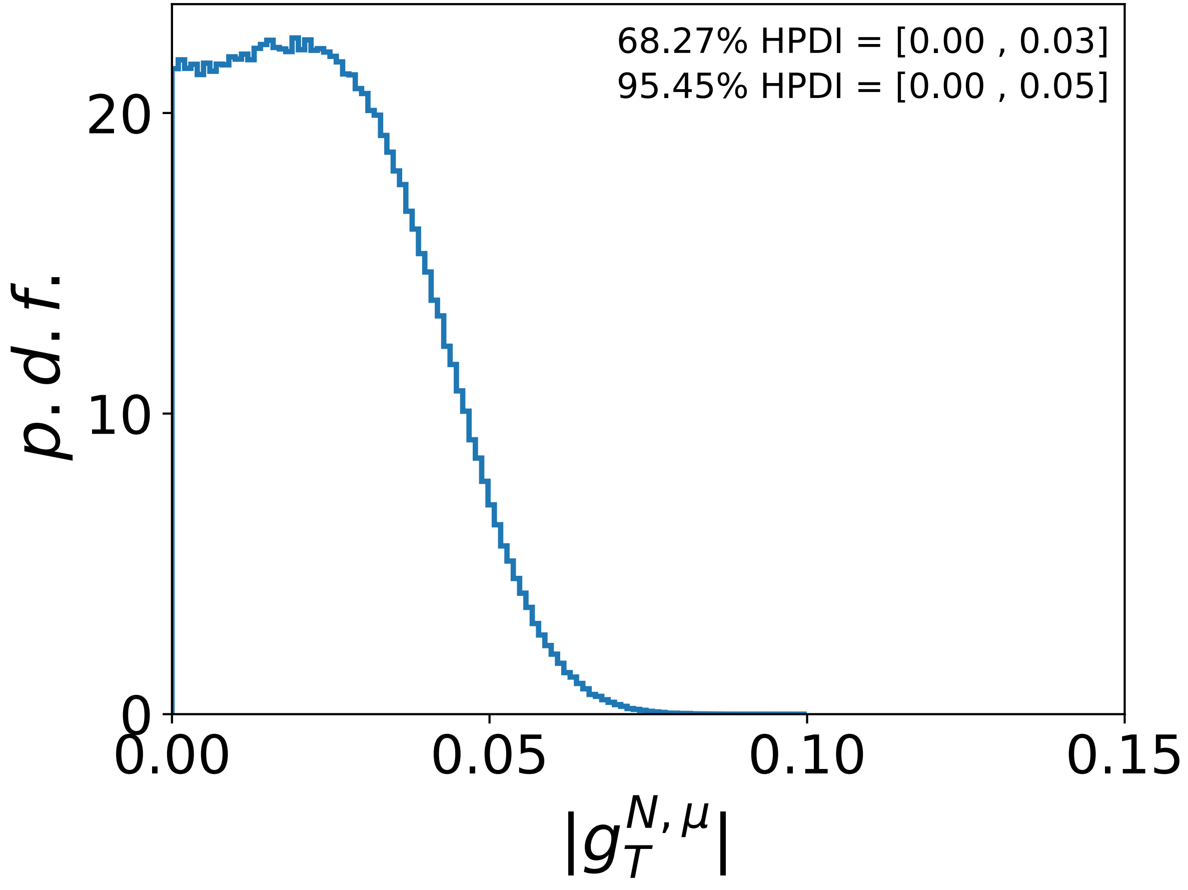
$\ell = \mu$



Results

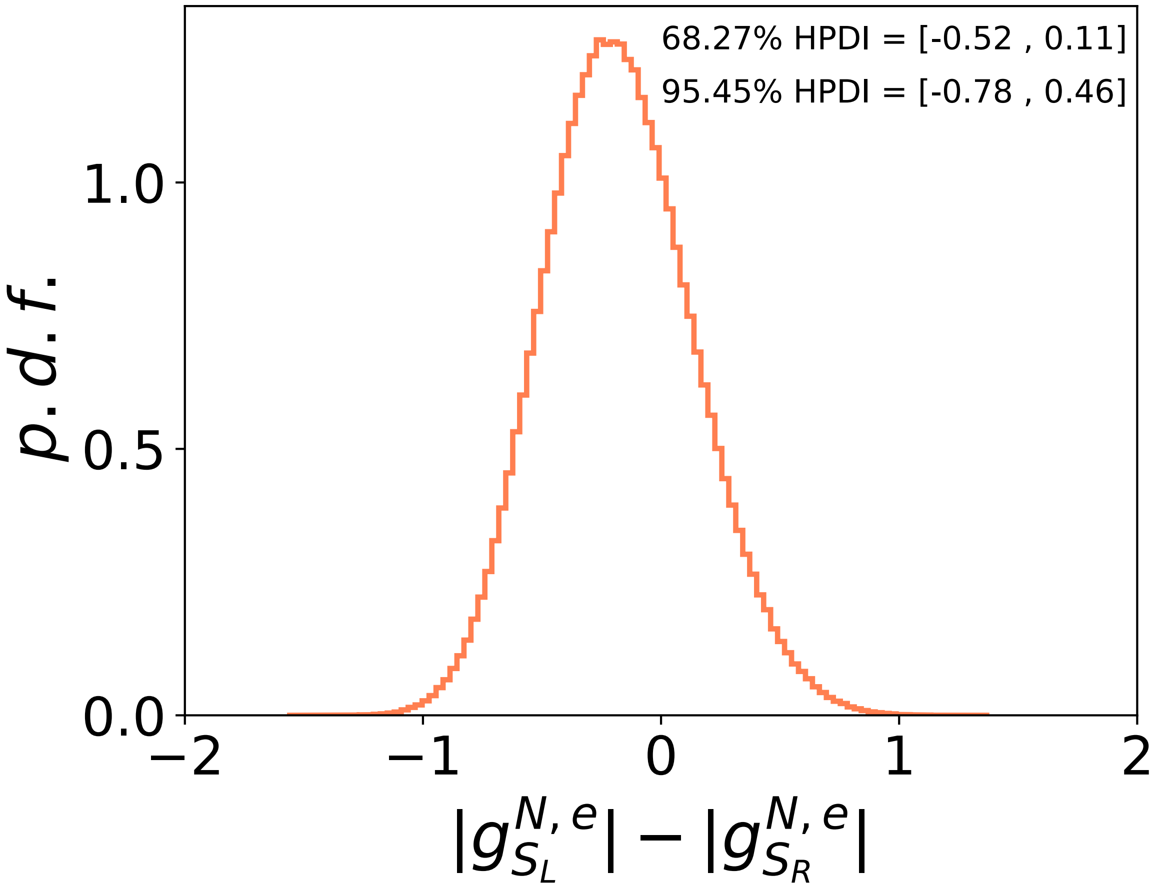
$\ell = \mu$



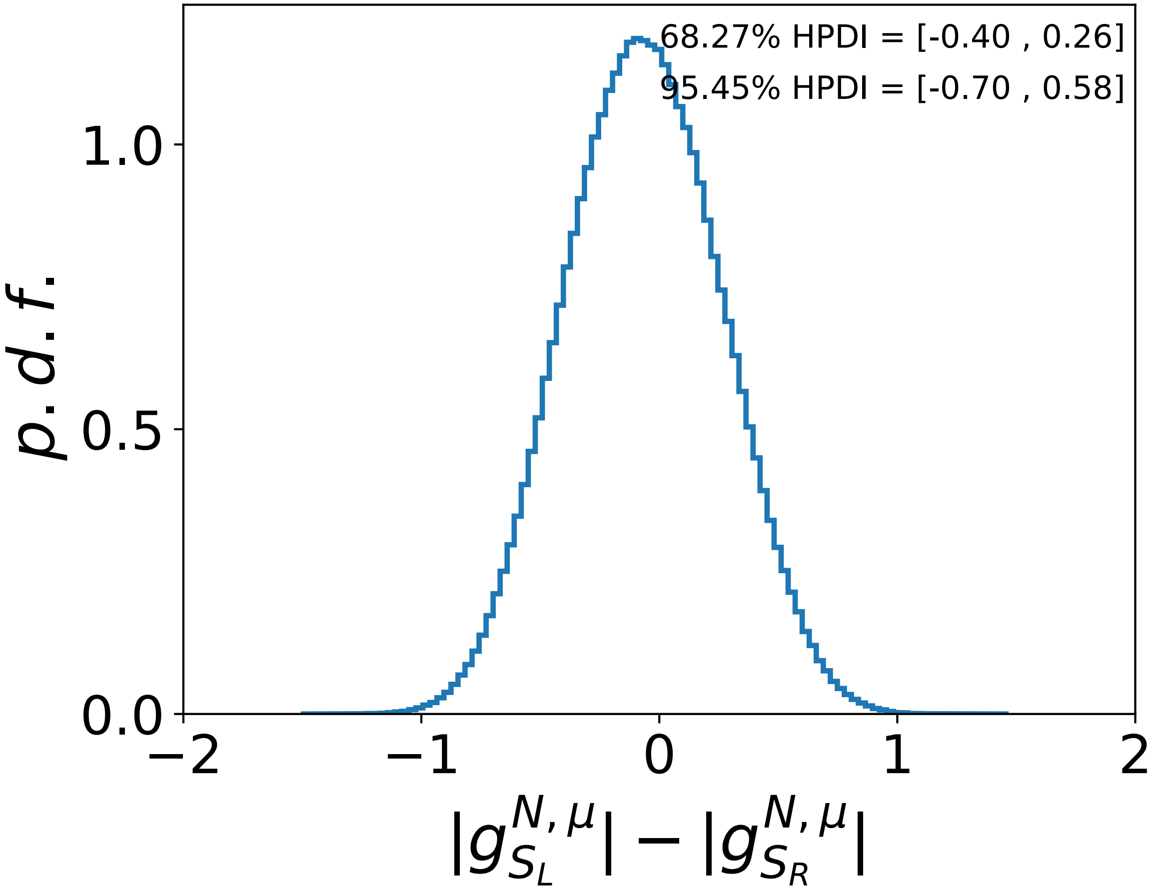


Results

$\ell = e$

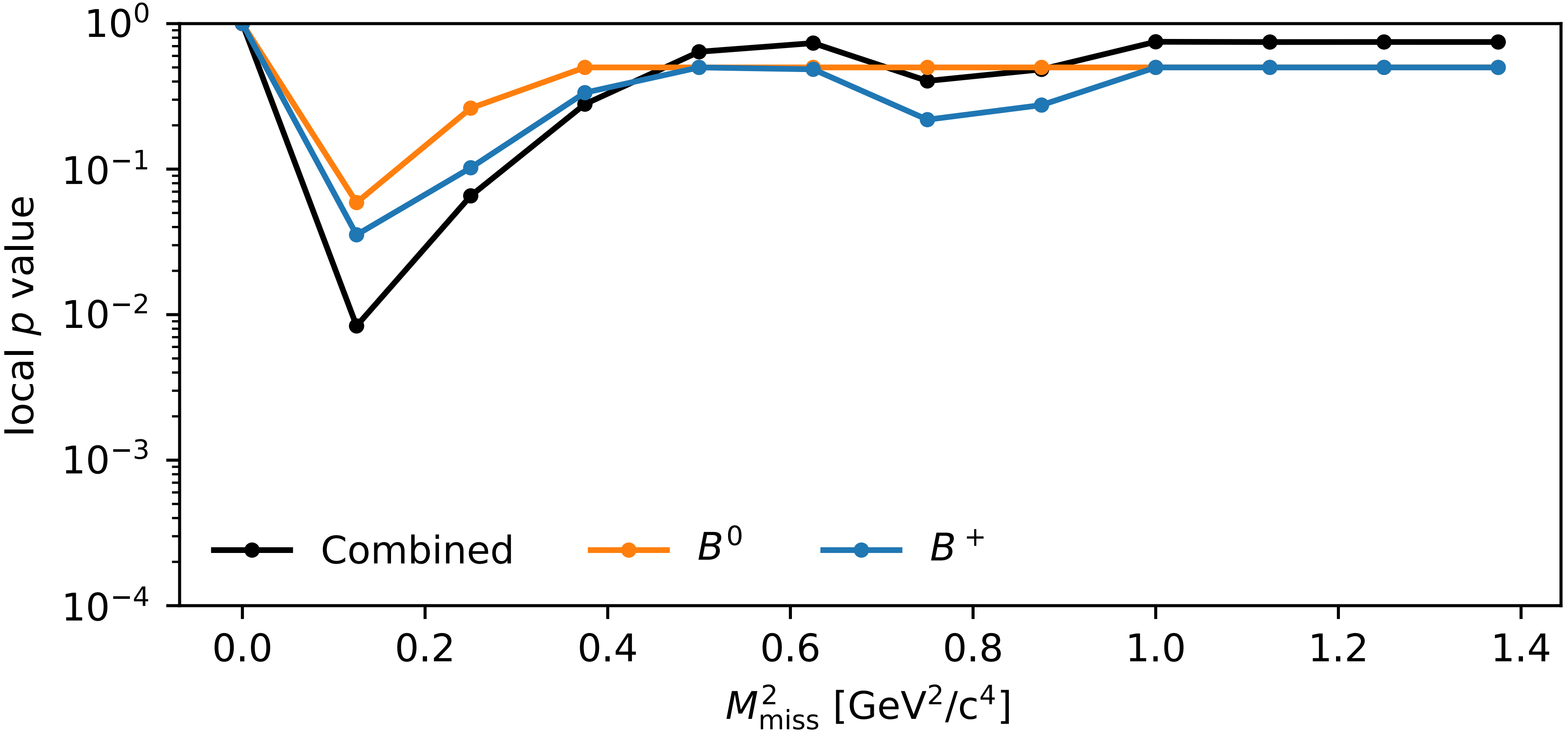


$\ell = \mu$

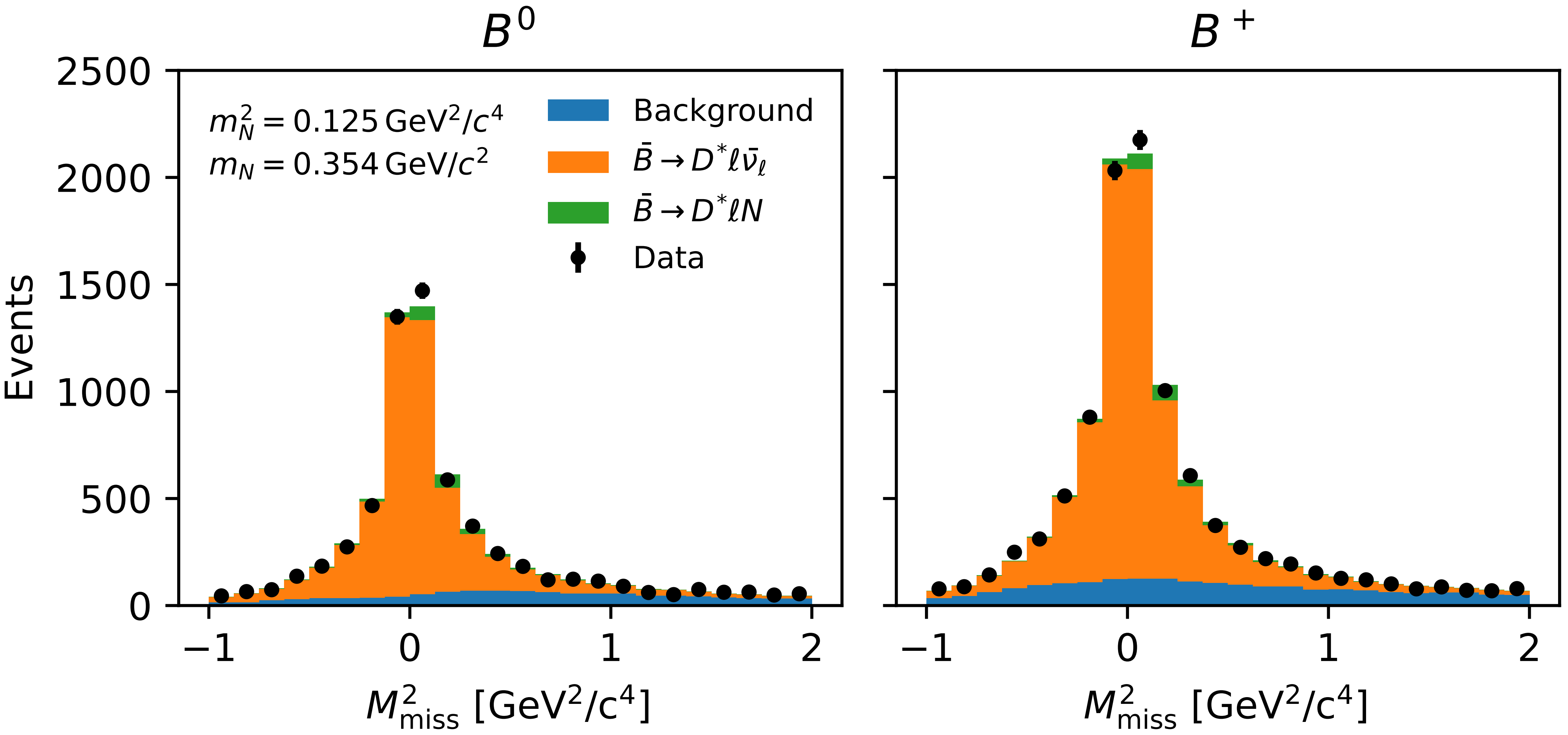


Results

- Hint at sterile neutrino with a mass of $m_N = 354\,\mathrm{MeV}$



Results

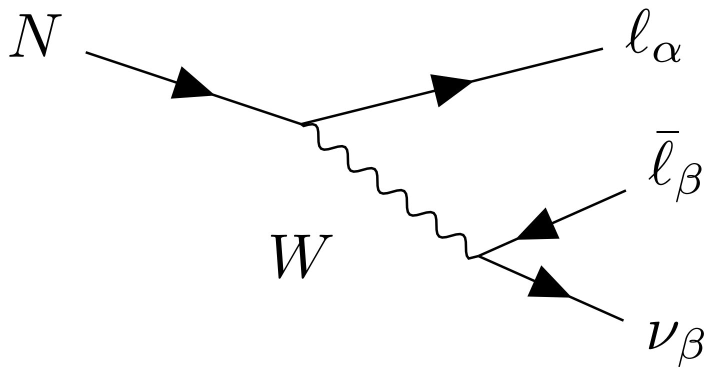


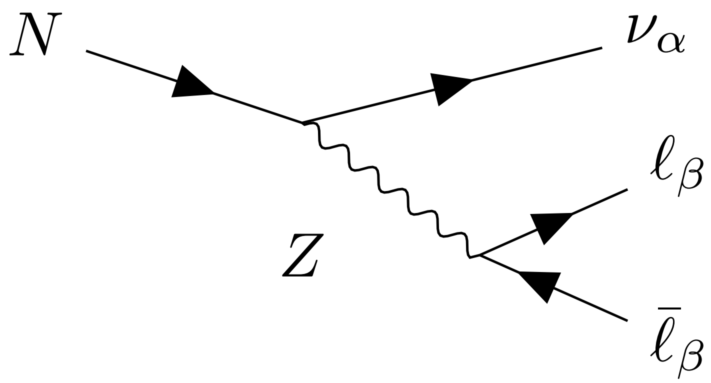
B^0
B^+
$m_N^2 = 0.125\,\mathrm{GeV}^2/c^4$
$m_N = 0.354\,\mathrm{GeV}/c^2$
Background
$\bar{B} \to D^* \ell \bar{\nu}_\ell$
$\bar{B} \to D^* \ell N$
Data
Events
2500
2000
1500
1000
500
0
−1
0
1
2
M^2_{miss} [GeV^2/c^4]

3. Hadronic Sterile Neutrino Decays

TK, Nierste 2025:

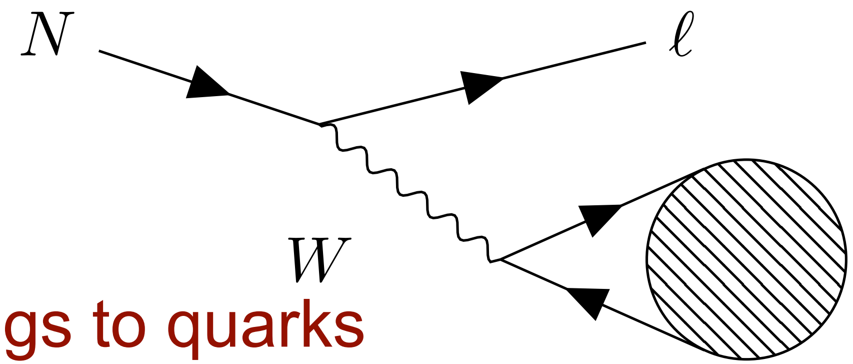
- Return to mixing angle description
- Sterile neutrinos with $m_N > 1\,\mathrm{GeV}$ can decay into leptons and into hadrons $\pi^0, \pi^\pm, K^\pm, D^\pm \ldots$ via the weak gauge bosons $W^\pm, Z$
- At tree-level this is known





Multi-Hadron Final States

- While tree-level results for $N \to \ell q\bar{q}$ and $N \to \nu q\bar{q}$ are well known, decay rates into multi-hadron final states (i.e. $N \to \ell \pi\pi\pi$) and QCD corrections are completely unknown.
- In principle these contributions could be sizeable
- QCD behaviour is fully governed by W^*, Z^* couplings to quarks
- W^*, Z^* correlation functions have already been calculated [1] up to $\mathcal{O}(\alpha_S^4)$!



[1] see e.g. Baikov, Chetyrkin and Kühn, 0801.1821

Fully Inclusive Decay Rate $N \to \ell\,\text{had}$.

- Fully inclusive decay width calculable using the gauge boson correlator
- Neutral current decay similar albeit more subtle due to triangles!

$$\Gamma(N \to \ell\,\text{had.}) = \frac{G_F^2 m_N^5 |V_{N\ell}|^2}{192\pi^3} S_{EW} 12\pi \times \int_0^{(1-x_\ell)^2} dx \sqrt{\lambda(1, x, x_\ell^2)} \left((1 - x + x_\ell^2)(1 + 2x + x_\ell^2) - 4x_\ell^2 \right) \Im(\Pi^{(1+0)}(m_N^2 x))$$

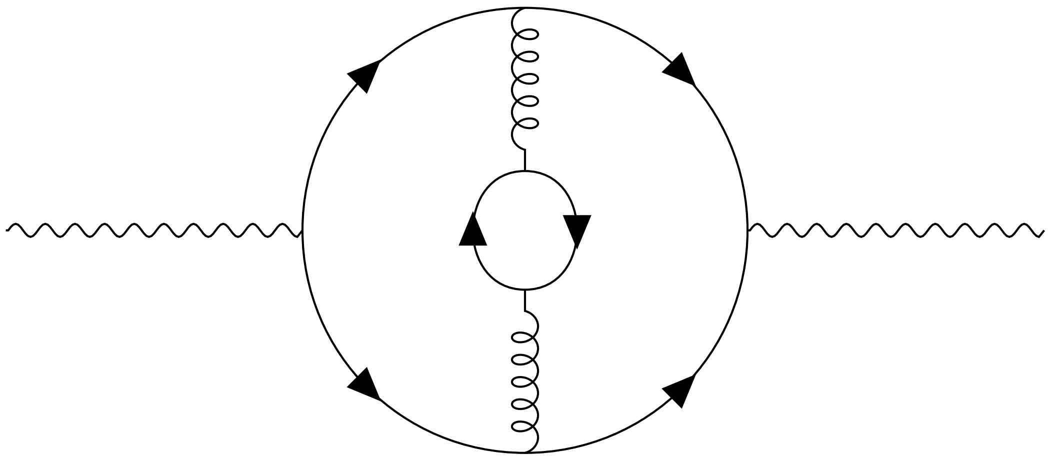
here: $x_\ell = \dfrac{m_\ell}{m_N}$

QCD Correlator

- Here $\Pi^{(1+0)}(s) = \Pi^{(1)}(s) + \Pi^{(0)}(s)$ is the sum of the transversal and longitudinal part of the correlator $(s = q^2)$:

$$\Pi^{V/A}_{\mu\nu,ij} = (-g_{\mu\nu}q^2 + q_\mu q_\nu)\Pi^{(1)}_{ij,V/A}(s) + q_\mu q_\nu \Pi^{(0)}_{ij,V/A}(s)$$

- Corresponds to QCD corrections to W like

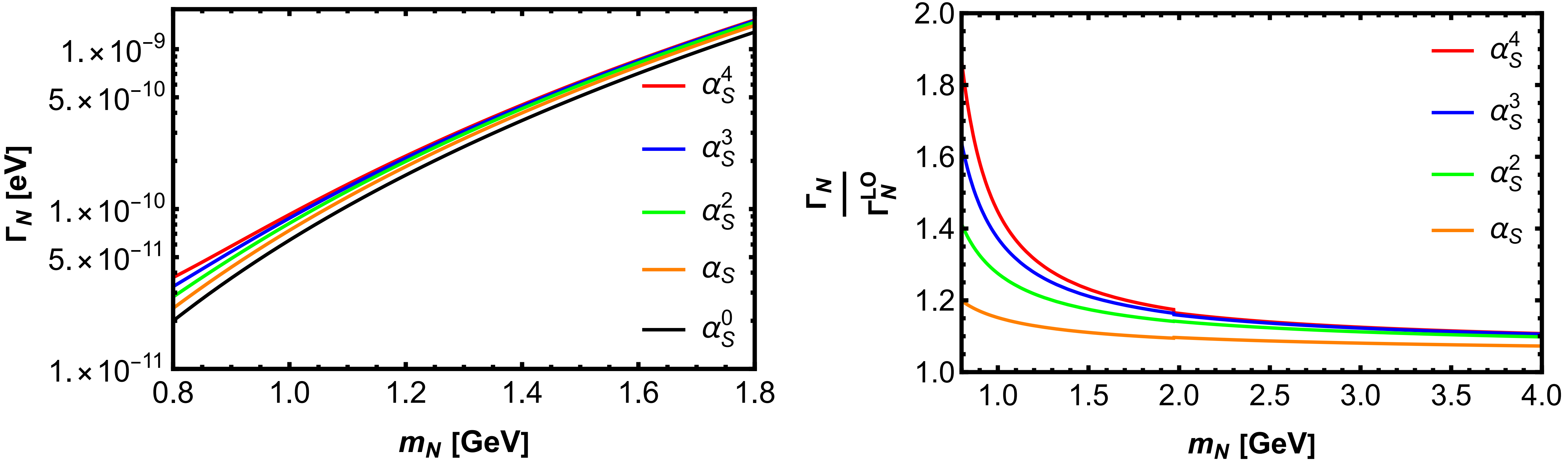


Results

- We calculated the fully inclusive decay width up to $\mathcal{O}(\alpha_S^4)$ in chiral limit $m_q = 0$ for the charged current
- Up to $\mathcal{O}(\alpha_S^3)$ fully analytical
- At $\mathcal{O}(\alpha_S^4)$ semi-analytical
- We can estimate the stability of the perturbative expansion
- Neutral current decay to follow soon.

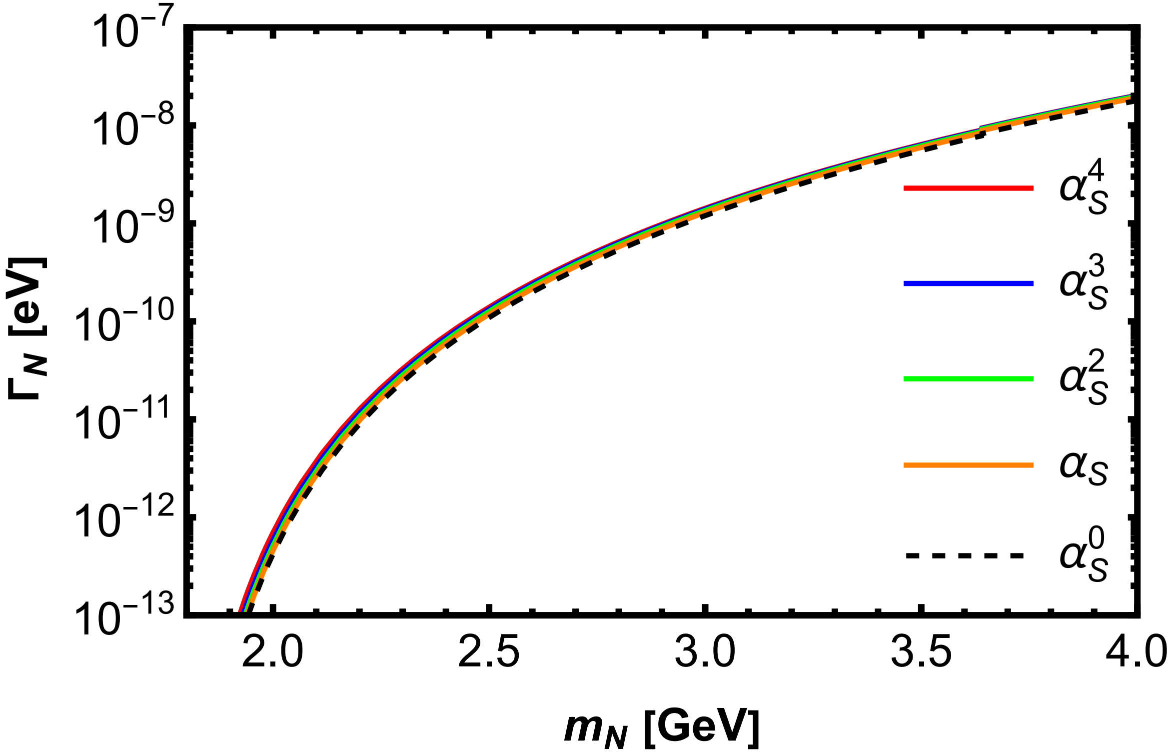
Results

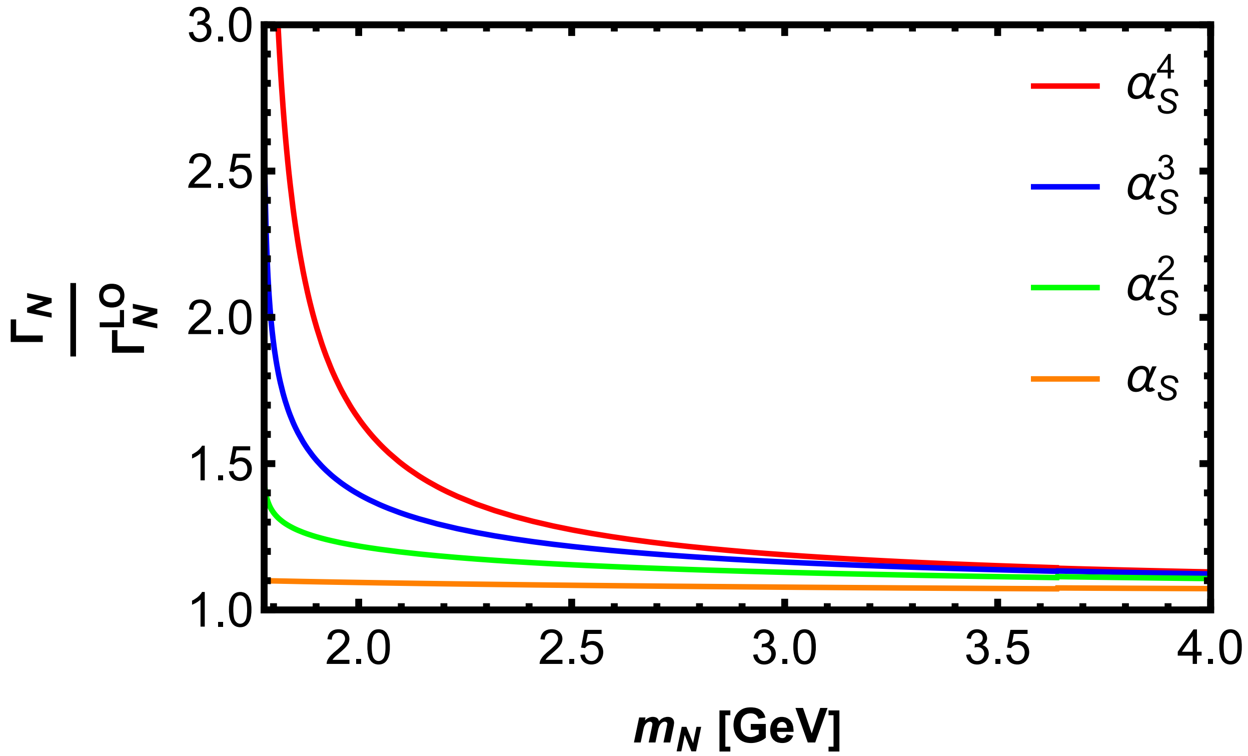
$\ell = \mu$



Results

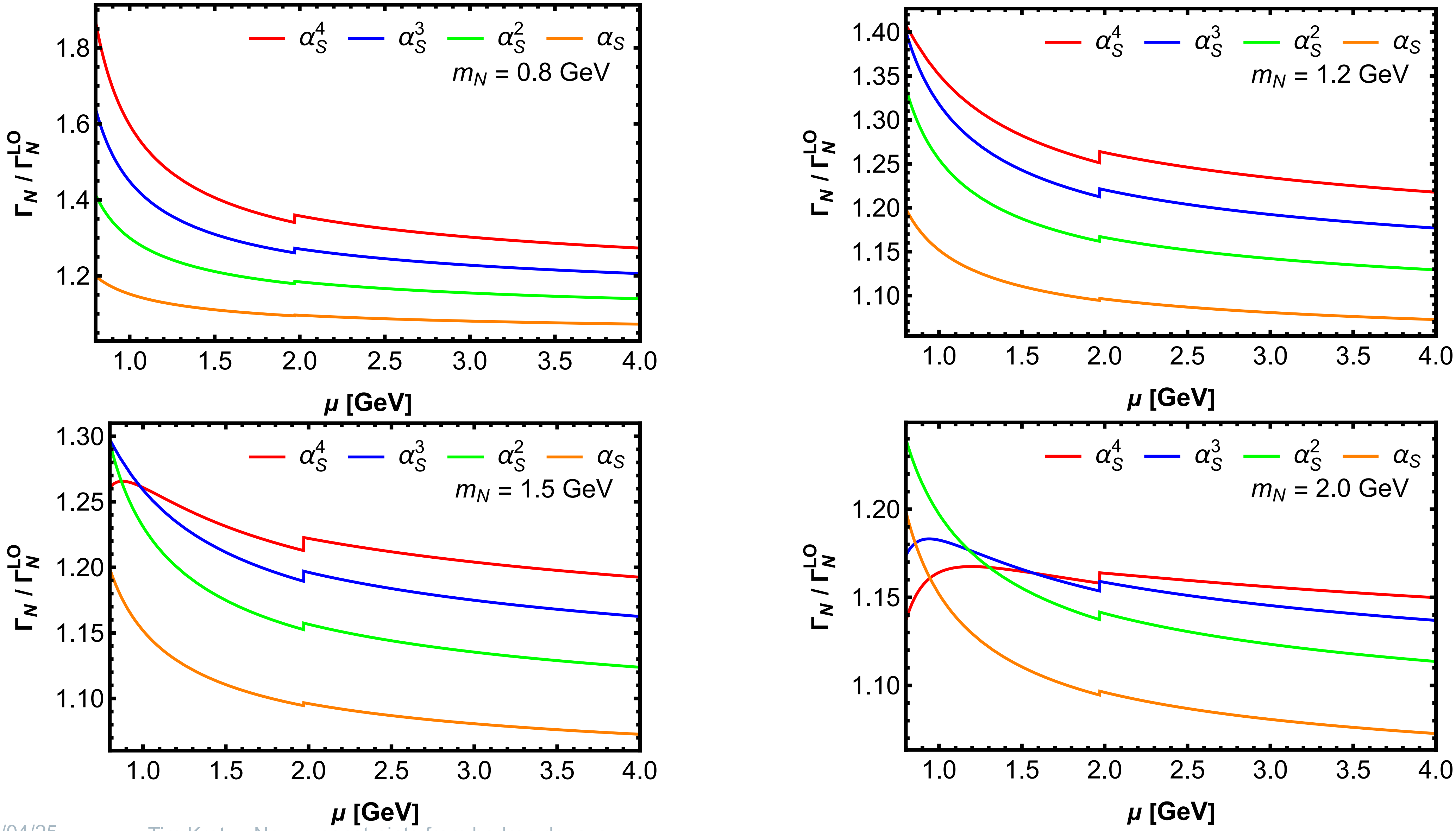
$\ell = \tau$





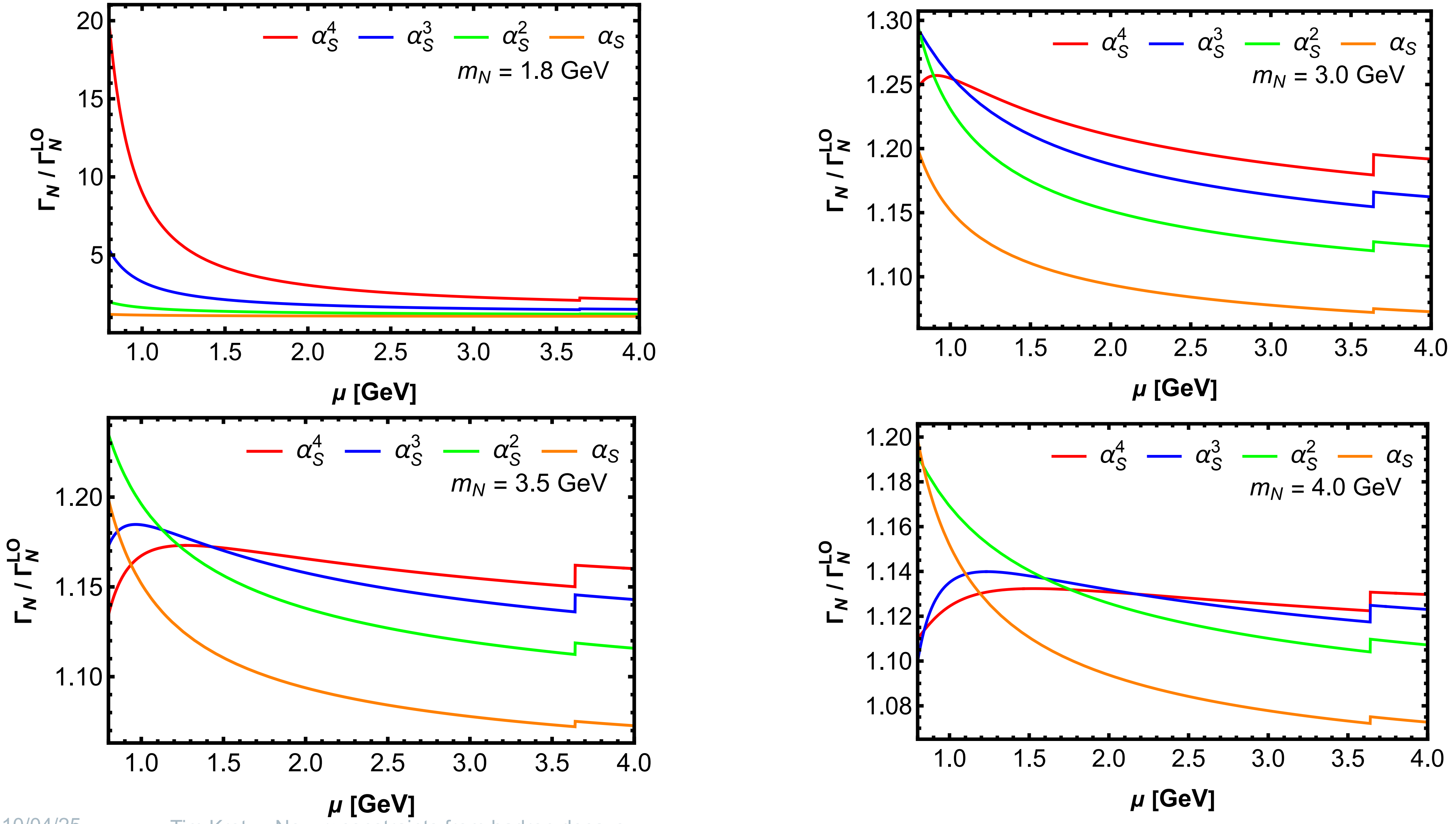
Results

$\ell = \mu$



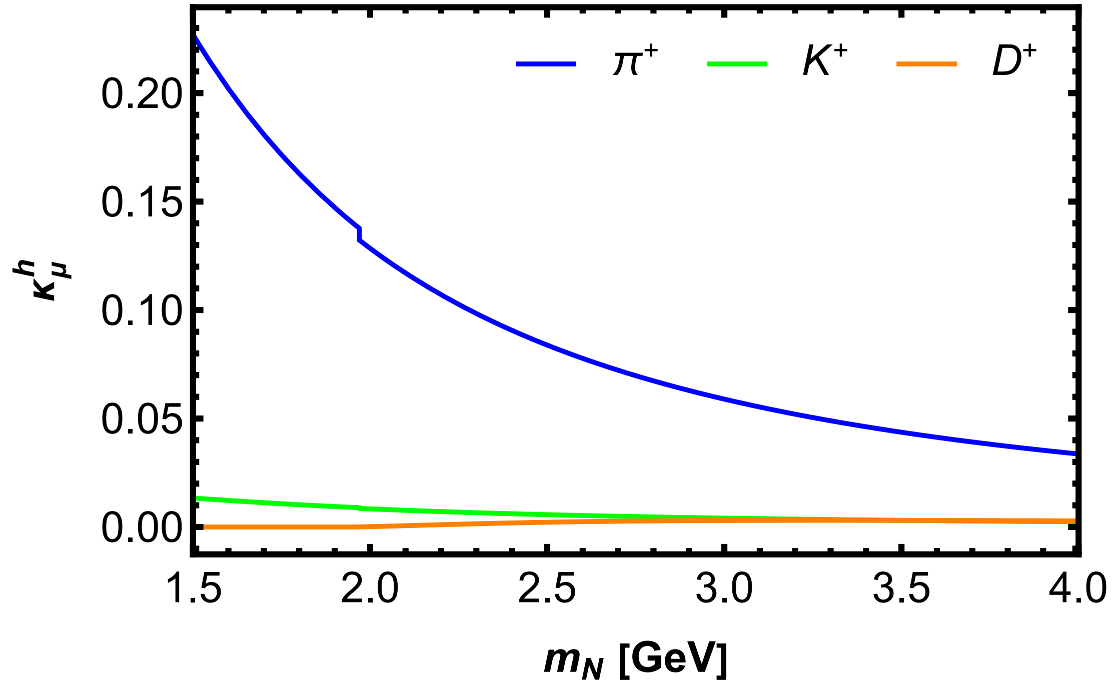
Results

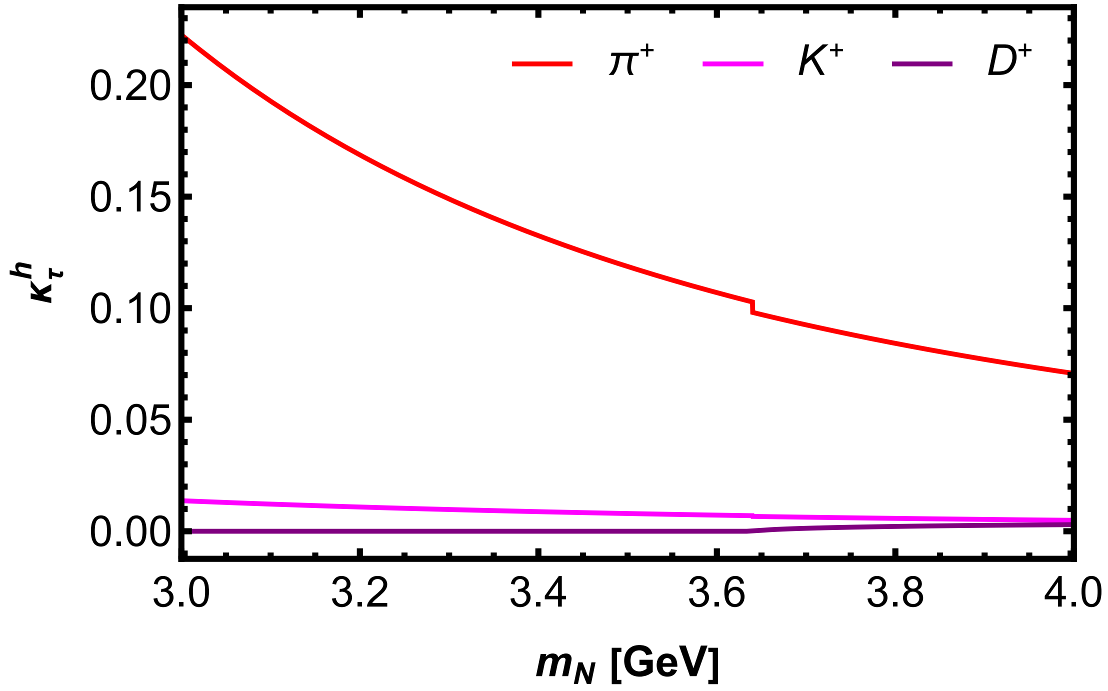
$\ell = \tau$



Results

$$\kappa_\ell^h = \frac{Br(N \to \ell h)}{Br(N \to \ell X)} = \frac{\Gamma(N \to \ell h)}{\Gamma(N \to \ell X)}$$



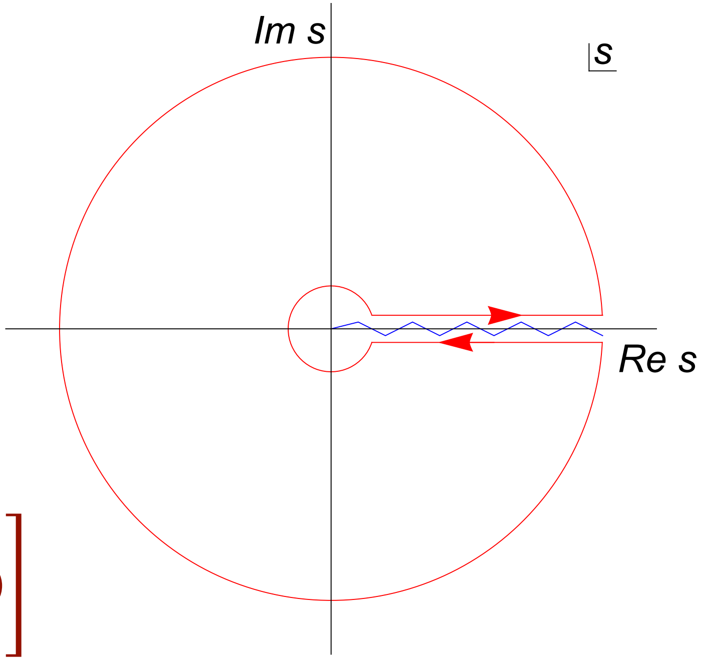


Conclusion

- Bump Hunt in Belle II hints at $m_N = 354\,\text{MeV}$
- Angular Coefficients show no preference for new physics
- Heavy Sterile Neutrinos can decay semi-hadronically
- We calculated the charged current inclusive decay rate up to $\mathcal{O}(\alpha_S^4)$
- For $\ell = e, \mu$ perturbativity ok for $m_N > 1.5\,\text{GeV}$
- For $\ell = \tau$ perturbativity ok for $m_N > 3\,\text{GeV}$
- Neutral Current comparable in magnitude

KIT

Backup: Contour Integration



- Integration over Keyhole contour
- Low energy regime does not contribute!

$$\Gamma(N \to \ell x) \propto 12\pi \int_0^{m_N^2} ds \left(1 - \frac{s}{m_N^2}\right)^2 \left[\left(1 + 2\frac{s}{m_N^2}\right)\Im\Pi^{(1+0)(s)} - 2\frac{s}{m_N^2}\Im\Pi^{(0)}(s)\right]$$

$$= 6\pi i \oint_{s=m_N^2} ds \left(1 - \frac{s}{m_N^2}\right)^2 \left[\left(1 + 2\frac{s}{m_N^2}\right)\Pi^{(1+0)(s)} - 2\frac{s}{m_N^2}\Pi^{(0)}(s)\right]$$

see e.g. Braaten, Narison and Pich; Nucl.Phys.B 373 (1992) 581-612