

Exploring Right-Handed Neutrinos in Semileptonic B Decays

Kumar Pandey

University of Mississippi

PHENO 2026

(WIP)



THE UNIVERSITY of
MISSISSIPPI

Why Standard Model of Particle Physics ?

- Standard Model (SM) → describes **electromagnetic, weak, and strong** and explains fundamental particles **quarks, leptons, and gauge bosons**.
- SM → **doesn't include gravity** (Einstein 1915).
- Neutrino oscillation experiments → neutrinos have **nonzero masses**, contradicting the SM (Super-Kamiokande 1998; SNO Collaboration 2001)

	three generations of matter (fermions)			interactions / forces (bosons)	
	I	II	III		
mass	≈ 2.2 MeV	≈ 1.3 GeV	≈ 173 GeV	0	≈ 125 GeV
charge	+2/3	+2/3	+2/3	0	0
spin	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs
QUARKS					
	≈ 4.7 MeV	≈ 96 MeV	≈ 4.2 GeV	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	γ photon	
LEPTONS					
	≈ 0.511 MeV	≈ 106 MeV	≈ 1.777 GeV	≈ 80.4 GeV	
	-1	-1	-1	±1	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	W W boson	
	< 1.0 eV	< 0.17 eV	< 18.2 MeV	≈ 91.2 GeV	
	0	0	0	0	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson	
					GAUGE BOSONS VECTOR BOSONS
					SCALAR BOSONS

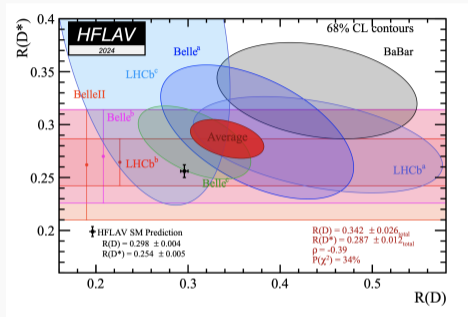
Standard Model of Elementary Particles

Motivation from Experimental Anomalies

- Recent Measurements of $R(D)$ and $R(D^*)$ show a combined deviation of approximately 3.8σ from Standard Model (SM) predictions (HFLAV 2024).

$$R(D) = \frac{\mathcal{B}(B \rightarrow D\tau^- \nu_\tau)}{\mathcal{B}(B \rightarrow D\ell^- \nu_\ell)} \quad (\ell = e, \mu)$$

$$R(D^*) = \frac{\mathcal{B}(B \rightarrow D^*\tau^- \nu_\tau)}{\mathcal{B}(B \rightarrow D^*\ell^- \nu_\ell)} \quad (\ell = e, \mu)$$



Flavor anomalies

Observable	SM Prediction	Measurement (WA)
$R_{D^*}^{\tau/\ell}$	0.254 ± 0.005	0.287 ± 0.012
$R_D^{\tau/\ell}$	0.298 ± 0.004	0.342 ± 0.026
$R_{D^*}^{\mu/e}$	~ 1.0	$0.990 \pm 0.021 \pm 0.023$

Why Study B Decays?

- The decay $B \rightarrow D^* \ell \nu$ has been precisely measured across multiple experiments, enabling strong experimental control ([Belle II Collaboration](#), [LHCb Collaboration](#))
- **Right-handed neutrinos** can help explain the $R(D)$ and $R(D^*)$ anomalies, and studies show that angular observables are especially sensitive to RH-neutrino effects ([Mandal et al., 2020](#)).
- The **forward-backward asymmetry** ΔA_{FB} in $\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}$ shows deviation from the SM, motivating detailed NP studies and improved Monte Carlo tools ([Bhattacharya et al., 2022](#)).

Effective Hamiltonian and Amplitude

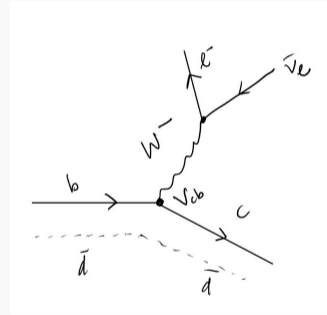
- Interaction \rightarrow **right-handed current** that couples right-handed leptons to right-handed quarks.
- The **effective Hamiltonian** is:

$$\mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} C_{V_{RR}} (\bar{c}\gamma^\alpha P_R b) (\bar{\ell}\gamma_\alpha P_R N) \quad (1)$$

where $P_R = \frac{1+\gamma^5}{2}$ and N , right-handed neutrino

- Using this Hamiltonian, the **invariant amplitude** is constructed as:

$$\mathcal{M}(B \rightarrow D^* \ell N) = \frac{4G_F V_{cb}}{\sqrt{2}} C_{V_{RR}} \langle D^* | \bar{c}\gamma^\alpha P_R b | \bar{B} \rangle (\bar{\ell}\gamma_\alpha P_R N) \quad (2)$$



Feynman diagram

- **BGL** parameterization for Hadronic Form Factors

New Physics Implementation In EvtGen

- **EVTGEN** → **heavy-flavor decay** generator in B-factory experiments.
- Our work uses a new EvtGen model → **BTODSTARLNUNP**, supports both SM and NP decay.
- **NP Couplings** → (C_{VLL} , C_{VRR}) directly inside the user decay file.

```
## first argument is cartesian(0) or polar(1)
## representation of NP coefficients which are three
## consecutive numbers {id, Re(C), Im(C)} or {coeff id, |C|, Arg(C)}
## id==0 C_VLL -- left-handed vector coefficient change from SM
## id==1 C_VRR -- right-handed right handed vector coefficient

Decay B0
## B0 -> D*+ e+ nu_e is generated with the Standard Model only
1 D*+ e+ nu_e BTODSTARLNUNP;
Enddecay

Decay anti-B0
## anti-B0 -> D*+ mu- anti-nu_mu generated with the addition of NP
1 D*+ mu- anti-nu_mu BTODSTARLNUNP 0 0 -1 0 1 1 0;
Enddecay
End
```

Example: EvtGen NP decay file

Simulation Setup

- Studied the decay channel $\rightarrow B^+ \rightarrow \bar{D}^{*0} e^+ \nu_e$
- Generated **10 million events** \rightarrow right-handed neutrino masses
 $m_N = 0.1, 0.5, 1.5$ GeV.
- Simulations were performed \rightarrow NP decay model BTODSTARLNUNP with

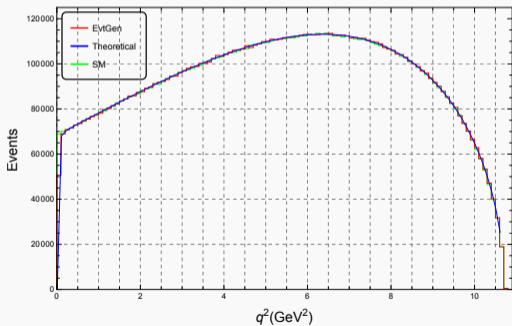
$$C_{V_{RR}} = 1$$

- For each mass point \rightarrow full set of distributions was reconstructed for:

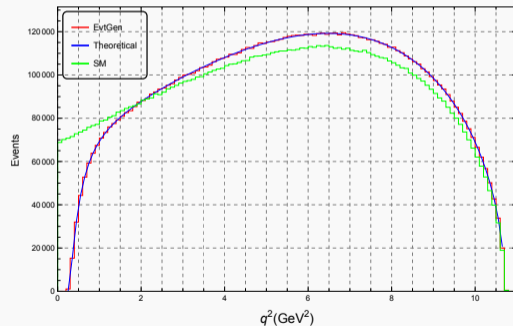
$$q^2, \quad \text{Cos}\theta_{D^*}, \quad \text{Cos}\theta_\ell, \quad \chi$$

- The resulting distributions were compared with Standard Model predictions

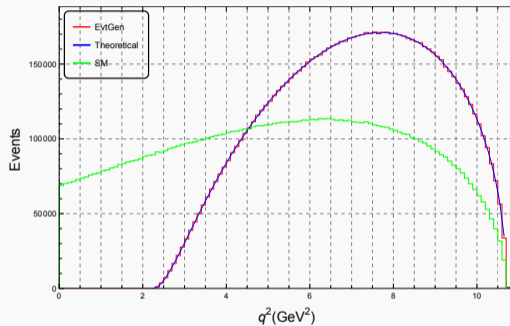
- Event rates are suppressed at low q^2 , peak at intermediate values, and fall off toward higher q^2 .
- For the mass (0.5 GeV) show smaller but noticeable differences.



(a) $m_N = 0.1$ GeV



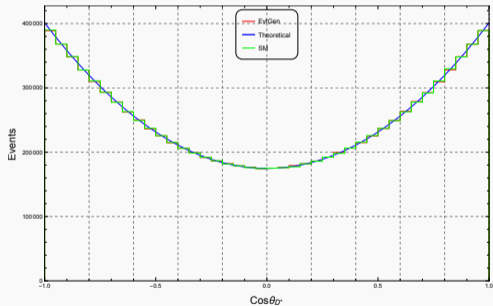
(b) $m_N = 0.5$ GeV



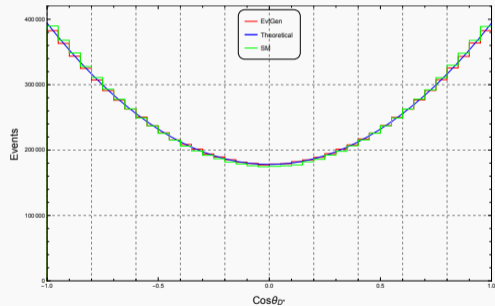
(c) $m_N = 1.5 \text{ GeV}$

- The deviation is strongest for the heavier case ($m_N = 1.5 \text{ GeV}$), where the NP curve is broader and peaks higher.

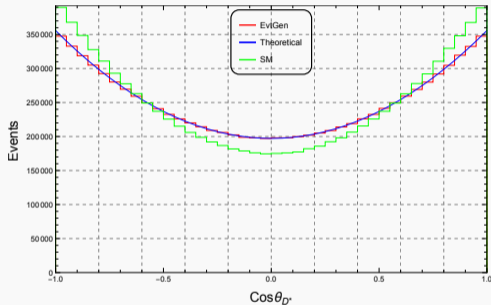
- The angular distribution shows a clear trend where the event rate peaks near the extremes of $\text{Cos}\theta_{D^*} = \pm 1$ producing a characteristic “U-shaped” angular distribution.



(a) $m_N = 0.1$ GeV



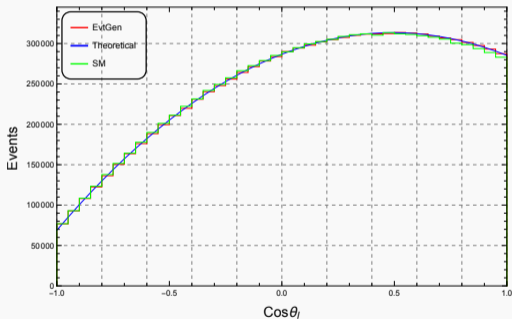
(b) $m_N = 0.5$ GeV



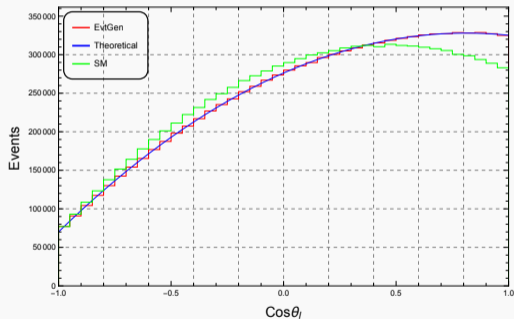
(c) $m_N = 1.5$ GeV

- NP distribution shows a clear deviation from the SM shape for higher mass.

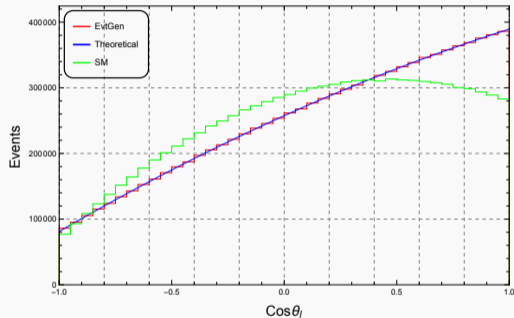
- For $m_N = 0.1$ and 0.5 GeV, the events increases from $\text{Cos}\theta_\ell = -1$ to $+1$.
- Deviation from SM is mild for these lighter masses.



(a) $m_N = 0.1$ GeV



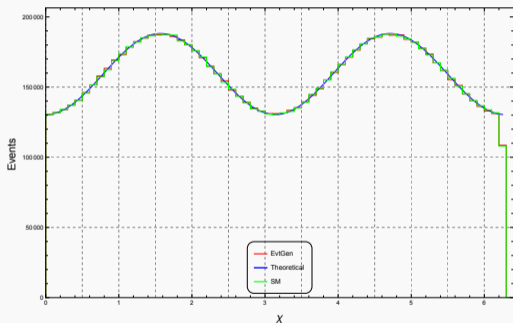
(b) $m_N = 0.5$ GeV



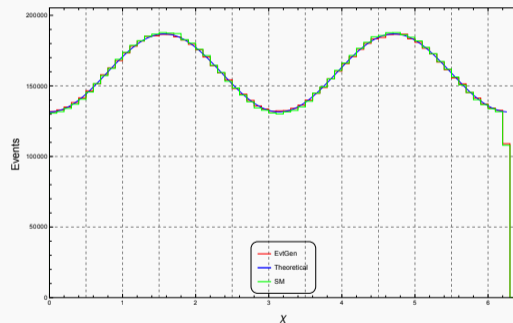
(c) $m_N = 1.5$ GeV

- NP distribution at $m_N = 1.5$ GeV shows noticeable deviation from SM.

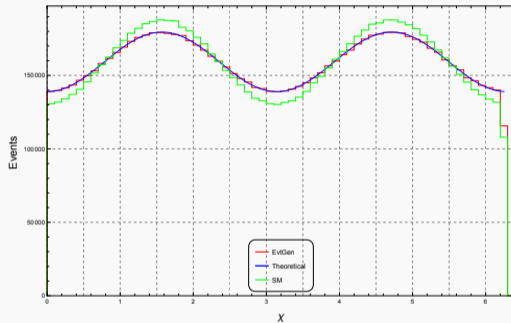
- For the smaller masses ($m_N = 0.1$ & 0.5 GeV), the χ distribution shows a smooth sinusoidal pattern.



(a) $m_N = 0.1$ GeV



(b) $m_N = 0.5$ GeV



(c) $m_N = 1.5$ GeV

- For the heavier mass ($m_N = 1.5$ GeV), the χ distribution keeps the same sinusoidal shape but with a larger difference from the SM.
- NP rises higher than the SM in parts of the oscillation.

- Compared to the SM, NP distributions show clear shape differences in q^2 , $\text{Cos}\theta_{D^*}$, $\text{Cos}\theta_\ell$, and χ .
- The deviation from the SM increases with the RH–neutrino mass, with the largest effects at $m_N = 1.5$ GeV.
- Overall, RH neutrinos produce detectable changes in semileptonic B decays, making these channels valuable probes of new physics.

- Extend the study to the full Low-Energy Effective Theory (LEFT) operator basis (left/right currents, scalar, vector, tensor).

$$\mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \left(\mathcal{O}_{LL}^V + \sum_{X=S,V,T; \alpha=L,R; \beta=R} c_{\alpha\beta}^X \mathcal{O}_{\alpha\beta}^X \right)$$

- Calculate the angular observables (A_{FB} , S_3 , S_5 , etc.).

Acknowledgements

I would like to thank my collaborators for their guidance and valuable discussions:

Alakabha Datta (Advisor)
Bhubhanjyoti Bhattacharya
Alexei Shibidanov
Nilakshi Das
Lucien Cremaldi
Tejhas Kapoor
Thomas E. Browder

This work is supported by the **NSF Grant No. PHY-2309937**

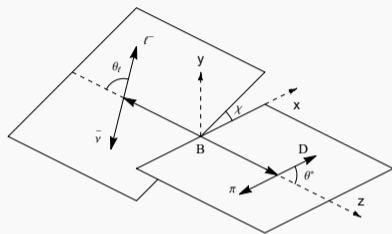
Thank You for Listening

Questions are welcome.

Backup Slides

Decay Kinematics of $B \rightarrow D^* \mu \bar{N}$

- Coordinate axes are chosen such that the \bar{B} meson is at rest and the D^* momentum points along the z -axis.
- $D^* \rightarrow D\pi$ decay plane \rightarrow defines the angle θ_{D^*} (angle between D direction and B direction in the D^* rest frame).
- $W^* \rightarrow \ell\nu$ decay plane \rightarrow gives the angle θ_ℓ (angle between the lepton and W^* direction in the leptonic rest frame).
- Relative orientation of the two planes \rightarrow produces the azimuthal angle χ .
- $q^2 = (p_\ell + p_\nu)^2$ is the invariant mass squared of the lepton–neutrino system.



Schematic diagram defining the various kinematic angles in the decay $\bar{B} \rightarrow D^*(\rightarrow D\pi)\ell^-\bar{\nu}$.

The hadronic part of the amplitudes can be expressed by dressing the quark bilinears with the initial and final state mesons as:

$$\langle D^*(k, \epsilon) | (\bar{c} \gamma_\alpha b) | \bar{B}(p) \rangle = -i \epsilon_{\alpha\beta\gamma\delta} \epsilon^{*\beta} p^\gamma k^\delta \frac{2V(q^2)}{m_B + m_{D^*}}, \quad (3)$$

$$\begin{aligned} \langle D^*(k, \epsilon) | (\bar{c} \gamma_\alpha \gamma^5 b) | \bar{B}(p) \rangle &= \epsilon_\alpha^* (m_B + m_{D^*}) A_1(q^2) - (p + k)_\alpha (\epsilon^* \cdot q) \frac{A_2(q^2)}{m_B + m_{D^*}} \\ &\quad - q_\alpha (\epsilon^* \cdot q) \frac{2m_{D^*}}{q^2} (A_3(q^2) - A_0(q^2)). \end{aligned} \quad (4)$$

Here, $A_0(q^2)$, $A_1(q^2)$, $A_2(q^2)$, $A_3(q^2)$, and $V(q^2)$ are hadronic form factors governing the $B \rightarrow D^*$ transition, these are BGL (Boyd–Grinstein–Lebed) parameterized (Boyd, Grinstein & Lebed, 1997).

Full Angular Distribution for $B \rightarrow D^*(\rightarrow D\pi)\ell\bar{N}$

- For nonzero m_N , the four-fold differential decay rate is (Datta, Liu & Marfatia, 2022):

$$\frac{d^4\Gamma_{D^*}}{dq^2 d\cos\theta_\ell d\cos\theta_{D^*} d\chi} = \frac{3}{8\pi} \sum_i l_i(q^2, C, m_N) f_i(\cos\theta_\ell, \cos\theta_{D^*}, \chi). \quad (5)$$

- Expanding this expression yields:

$$\begin{aligned} \frac{d^4\Gamma_{D^*}}{dq^2 d\cos\theta_\ell d\cos\theta_{D^*} d\chi} = \frac{3}{8\pi} \Big[& (l_{1s} + l_{2s} \cos 2\theta_\ell + l_{6s} \cos \theta_\ell) \sin^2 \theta_{D^*} \\ & + (l_{1c} + l_{2c} \cos 2\theta_\ell + l_{6c} \cos \theta_\ell) \cos^2 \theta_{D^*} \\ & + (l_3 \cos 2\chi + l_9 \sin 2\chi) \sin^2 \theta_{D^*} \sin^2 \theta_\ell \\ & + (l_4 \cos \chi + l_8 \sin \chi) \sin 2\theta_{D^*} \sin 2\theta_\ell \\ & + (l_5 \cos \chi + l_7 \sin \chi) \sin 2\theta_{D^*} \sin \theta_\ell \Big]. \end{aligned} \quad (6)$$

- Similarly angular observables in terms of five \mathcal{I} functions is given as

$$A_{FB}^{D^*}(q^2) = - \frac{l_{6s}(q^2) + \frac{1}{2}l_{6c}(q^2)}{\frac{d\Gamma_{D^*}}{dq^2}} \quad (7)$$

$$S_i(q^2) = \frac{l_i(q^2)}{\frac{d\Gamma_{D^*}}{dq^2}}, \quad i = \{3, 4, 5, 7, 8, 9\} \quad (8)$$