Lepton collider probes for Majorana neutrino effective interactions.

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Abstract

We exploit the remarkable angular resolution in future lepton colliders to study the sensitivity of forward-backward asymmetries to discover the possible single production of heavy right-handed Majorana neutrinos via $e^+e^- \to N\nu$, followed by a purely leptonic decay $N \to \mu^-\mu^+\nu$ or a semi-leptonic decay $N \to \mu^-$jj, for masses $m_N > 50$ GeV. In this regime, we consider the N production and decays to be dominated by scalar and vectorial four-fermion $d = 6$ single N_R operators in an effective field theory framework. We find that a forward-backward asymmetry between the final muons in the pure leptonic decay mode provides a sensitivity up to 12σ for $m_N = 100$ GeV, for effective couplings $\alpha = 0.2$ and new physics scale $\Lambda = 1$ TeV. In the case of the semi-leptonic decay, we can compare the final muon and higher p_T jet flight directions, again finding up to 12σ sensitivity to the effective signals.

Effective interactions formalism

The SM lagrangian is extended with only *one* right-handed neutrino N_R with a Majorana mass term, which gives a massive state N as an observable degree of freedom. The new physics effects are parametrized by a set of effective operators $\mathcal{O}_{\mathcal{J}}$ constructed with the SM and the N_R fields and satisfying the $SU(2)_L \otimes U(1)_Y$ gauge symmetry [1]. The effect of these operators is suppressed by inverse powers of the new physics scale Λ. The total lagrangian is organized as follows:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d=6}^{\infty} \frac{1}{\Lambda^{d-4}} \sum_{\mathcal{J}} \alpha_{\mathcal{J}} \mathcal{O}_{\mathcal{J}}^{d} \quad (1)$$

where d is the mass dimension of the operator $\mathcal{O}_{\mathcal{J}}^{d}$, $\alpha_{\mathcal{J}}$ are the effective couplings and the sum in $\mathcal{J}$ goes over all independent interactions at a given dimension d.

We take into account existing constraints on the operators contributing to neutrinoless double beta decay ($0\nu\beta\beta$-decay) and we set the bound $\alpha_{0\nu\beta\beta} = 3.2 \times 10^{-2} \left(\frac{m_N}{100 GeV}\right)^{1/2}$ for $\Lambda = 1$ TeV. We simplify the parameter space setting all the other effective couplings $\alpha_{\mathcal{J}}$ in eq. (1) and Tab.1 to the same numerical value α.

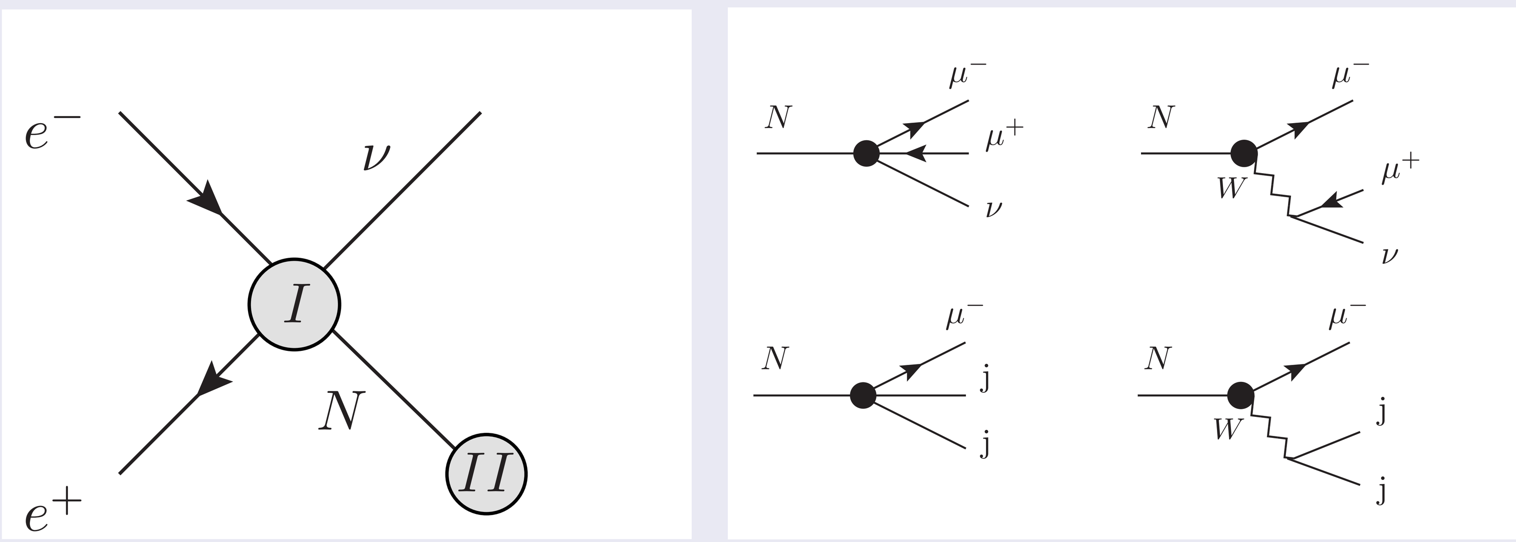
[1] F. del Aguila, S. Bar Shalom, A. Soni y J. Wudka. Phys. Lett. B 670, 399 (2009), 0806.0876

Operator	Notation	Type	Coupling	Operator	Notation	Type	Coupling
$(\phi^\dagger\phi)(\bar{L}_i N\tilde{\phi})$	$\mathcal{O}^{(i)}_{LN\phi}$	S	$\alpha^{(i)}_{\phi}$				
$i(\phi^T\epsilon D_\mu\phi)(\bar{N}\gamma^\mu l_i)$	$\mathcal{O}^{(i)}_{Nl\phi}$	V	$\alpha^{(i)}_{W}$	$i(\phi^\dagger \overleftrightarrow{D_\mu}\phi)(\bar{N}\gamma^\mu N)$	$\mathcal{O}_{NN\phi}$	V	α_Z
$(\bar{N}\gamma_\mu l_i)(\bar{d}_j\gamma^\mu u_j)$	$\mathcal{O}^{(i,j)}_{duNl}$	V	$\alpha^{(i,j)}_{V_0}$	$(\bar{N}\gamma_\mu N)(\bar{f}_i\gamma^\mu f_i)$	$\mathcal{O}^{(i)}_{fNN}$	V	$\alpha^{(i)}_{V_f}$
$(\bar{Q}_i u_i)(\bar{N}L_j)$	$\mathcal{O}^{(i,j)}_{QuNL}$	S	$\alpha^{(i,j)}_{S_1}$	$(\bar{L}_i N)\epsilon(\bar{L}_j l_j)$	$\mathcal{O}^{(i,j)}_{LNLl}$	S	$\alpha^{(i,j)}_{S_0}$
$(\bar{L}_i N)\epsilon(\bar{Q}_j d_j)$	$\mathcal{O}^{(i,j)}_{LNQd}$	S	$\alpha^{(i,j)}_{S_2}$	$(\bar{Q}_i N)\epsilon(\bar{L}_j, d_j)$	$\mathcal{O}^{(i,j)}_{QNLd}$	S	$\alpha^{(i,j)}_{S_3}$
$(\bar{L}_i\sigma^{\mu\nu}\tau^I N)\tilde{\phi}W^I_{\mu\nu}$	$\mathcal{O}^{(i)}_{NW}$	T	$\alpha^{(i)}_{NW}$	$(\bar{L}_i\sigma^{\mu\nu}N)\tilde{\phi}B_{\mu\nu}$	$\mathcal{O}^{(i)}_{NB}$	T	$\alpha^{(i)}_{NB}$

Table: Basis of dimension $d = 6$ baryon number conserving operators with a right-handed neutrino N [1]. Here l_i, u_i, d_i and L_i, Q_i denote, for the family labelled i, the right handed $SU(2)$ singlet and the left-handed $SU(2)$ doublets, respectively (collectively f_i). The field ϕ is the scalar doublet, $B_{\mu\nu}$ and $W^I_{\mu\nu}$ represent the $U(1)_Y$ and $SU(2)_L$ field strengths respectively. Also $\sigma^{\mu\nu}$ is the Dirac tensor, γ^μ are the Dirac matrices, and $\epsilon = i\sigma^2$ is the anti symmetric symbol in two dimensions. Types V, S and T stand for scalar, vectorial and tensorial (one-loop level generated) structures.

Collider signals

The signal scattering process considered can be represented in the following Feynmann diagrams:
$e^+e^- \to N\nu \to \nu\mu^-\mu^+\nu$ and $e^+e^- \to N\nu \to \nu$ j j μ^-



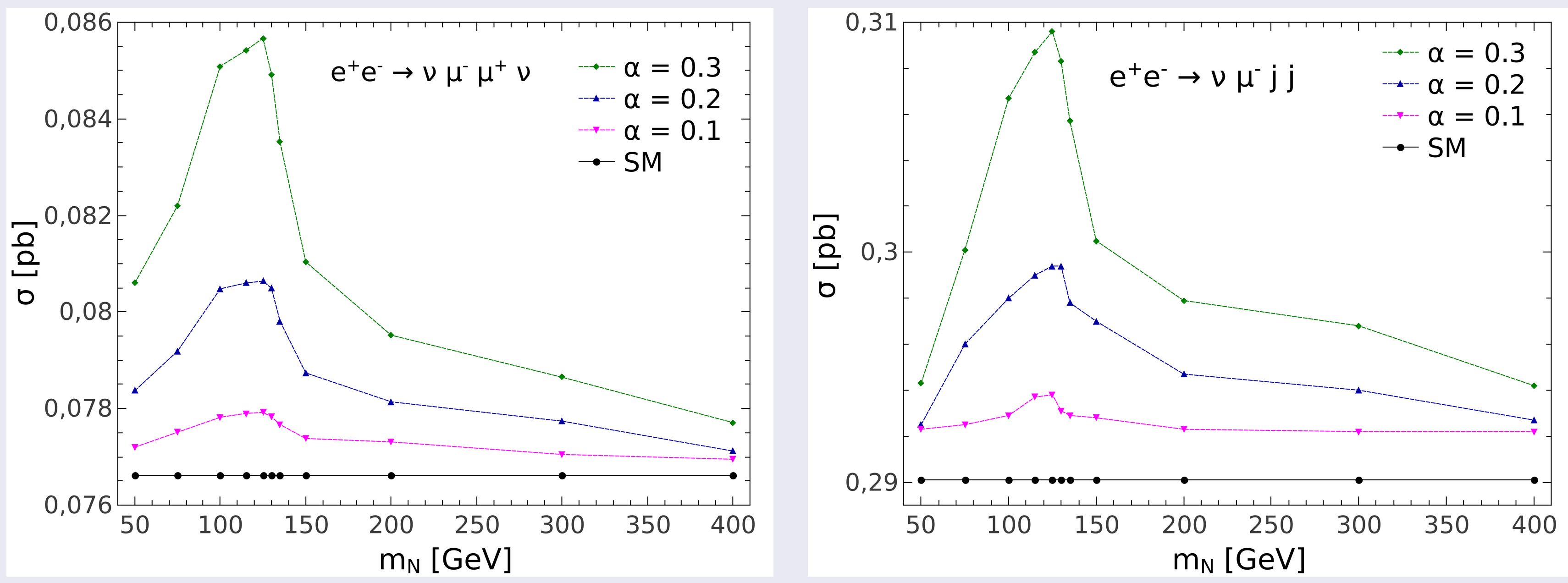
(a) (b)

Figure: Single N production and decay in the di-muon channel and di-jet channels.

The vertices with a dot or a shaded circle correspond to non-standard interactions, given by the effective operators.

We consider an e^+e^- collider with center of mass energy $\sqrt{s} = 500$ GeV and integrated luminosity $\mathcal{L} = 500\ fb^{-1}$.

We build our model in FeynRules 2.3and use MadGraph5_aMC@NLO 2.5.5 to generate LHE events at parton level, which are read by the embedded version of PYTHIA 8 and then are interphased to DELPHES 3.5.0.



(a) (b)

Figure: Parton-level cross sections for the pure leptonic (a) and semi-leptonic (b) processes, with acceptance cuts (see text).

Acceptance cuts: $p_T^{\rm j} > 20$ GeV, $p_T^{\ell} > 10$ GeV, $|\eta_{\rm j}| < 5$, $|\eta_\ell| < 2.5$, $\Delta R_{\rm jj,\ell\ell,lj} > 0.4$.

Results: Leptonic and Semi-Leptonic channels

- We define a forward-backward asymmetry as: $A^{FB}_{X_1X_2} = \frac{N_+ - N_-}{N_+ + N_-}$, where $N_\pm$ is the number of events with a positive (negative) value of $\cos(\theta)$, the angle between the final particles X_1 and X_2 flight directions in the Lab (or CM) frame in the e^+e^- collision. The label shows the value Z of the number of standard deviations $Z\sigma$ of statistical significance we obtain for each dataset with a $\Delta\chi^2$ test.

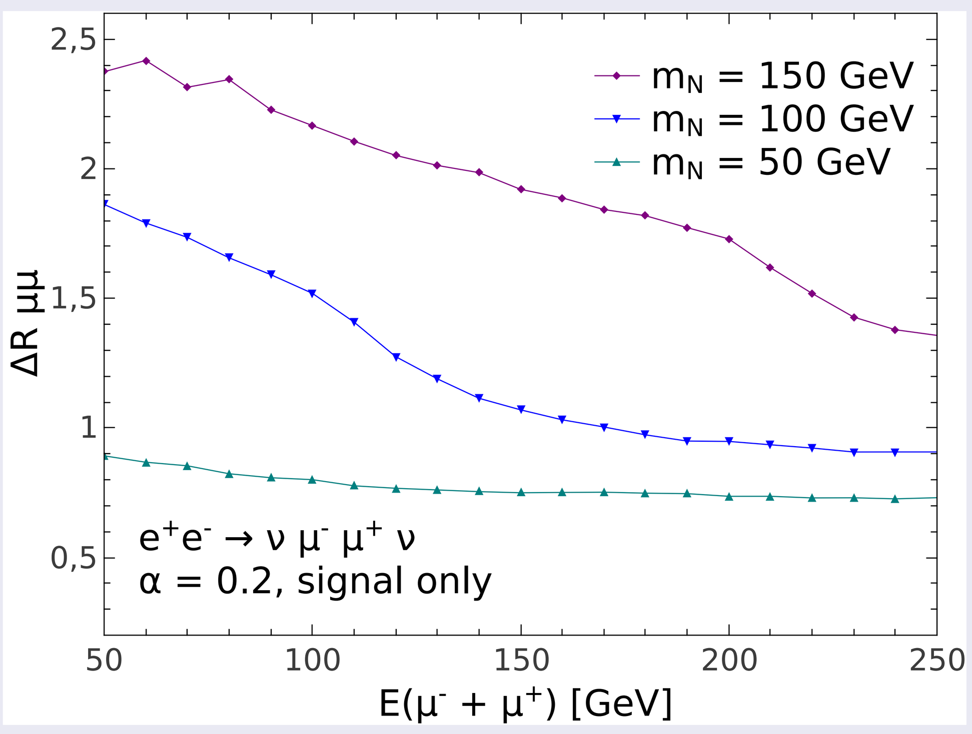


Figure: Average $\Delta R_{\mu\mu}$ distribution with $E_{\mu\mu}$, signal-only (S) no cuts.

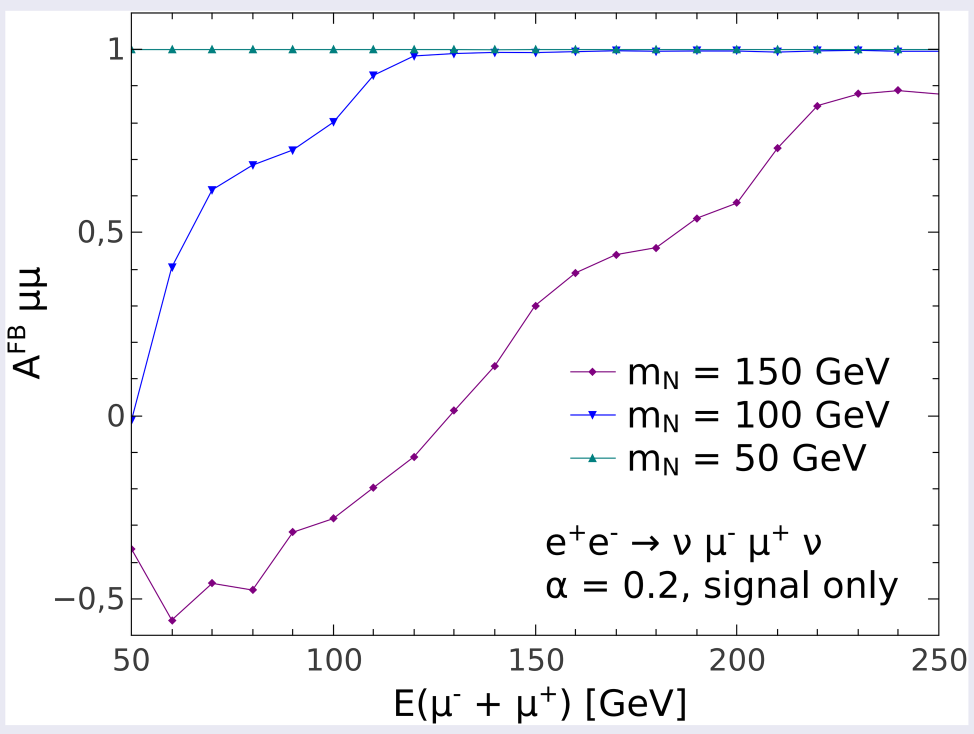


Figure: $A^{FB}_{\mu\mu}$ distribution with $E_{\mu\mu}$ signal only, without cuts.

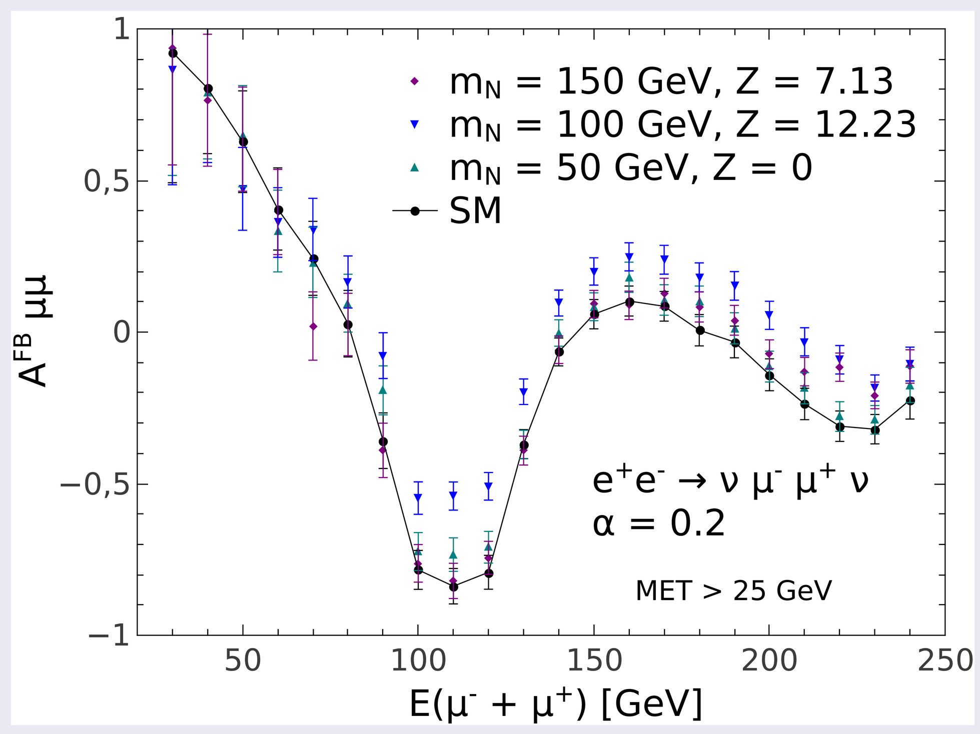


Figure: $A^{FB}_{\mu\mu}$ distribution with $E_{\mu\mu}$, for $\alpha = 0.2$, $\Lambda = 1\,TeV$.

- For low N mass the muons are boosted and emerge in the same direction ($A^{FB}_{\mu\mu} = 1$) and tend to separate ($A^{FB}_{\mu\mu} < 1$) even coming out mostly in opposite directions ($A^{FB}_{\mu\mu} < 0$) when m_N increases for low values of the summed energies of the outgoing muons. When their energy increases, the muon pairs tend to be very boosted, giving a positive asymmetry value.

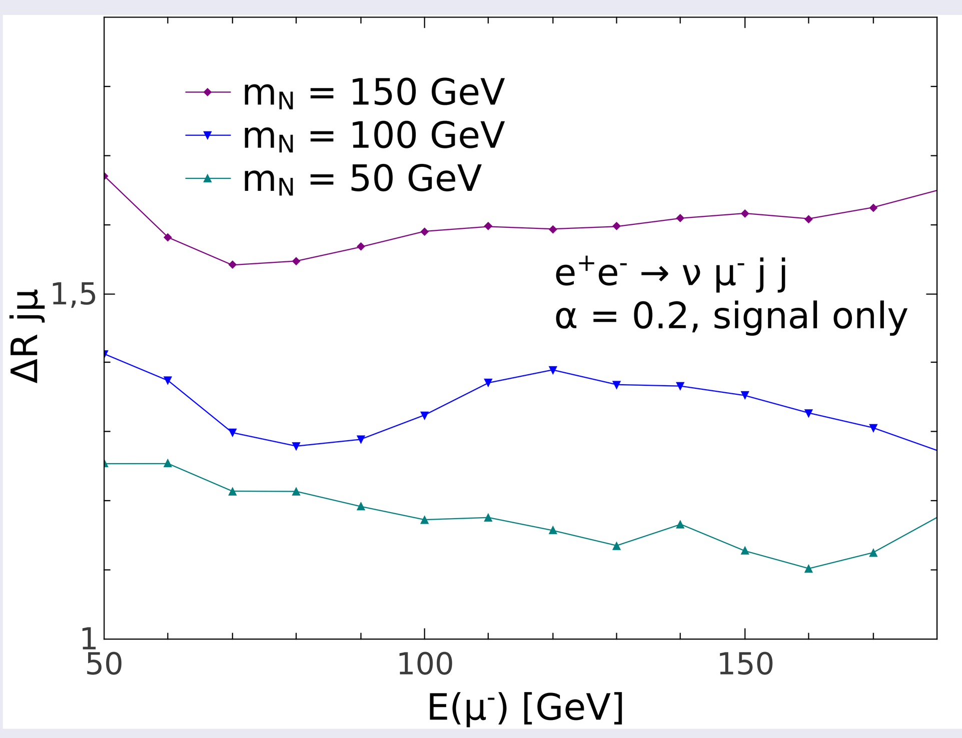


Figure: Average $\Delta R_{j\mu}$ distribution with E_μ, signal-only (S) no cuts.

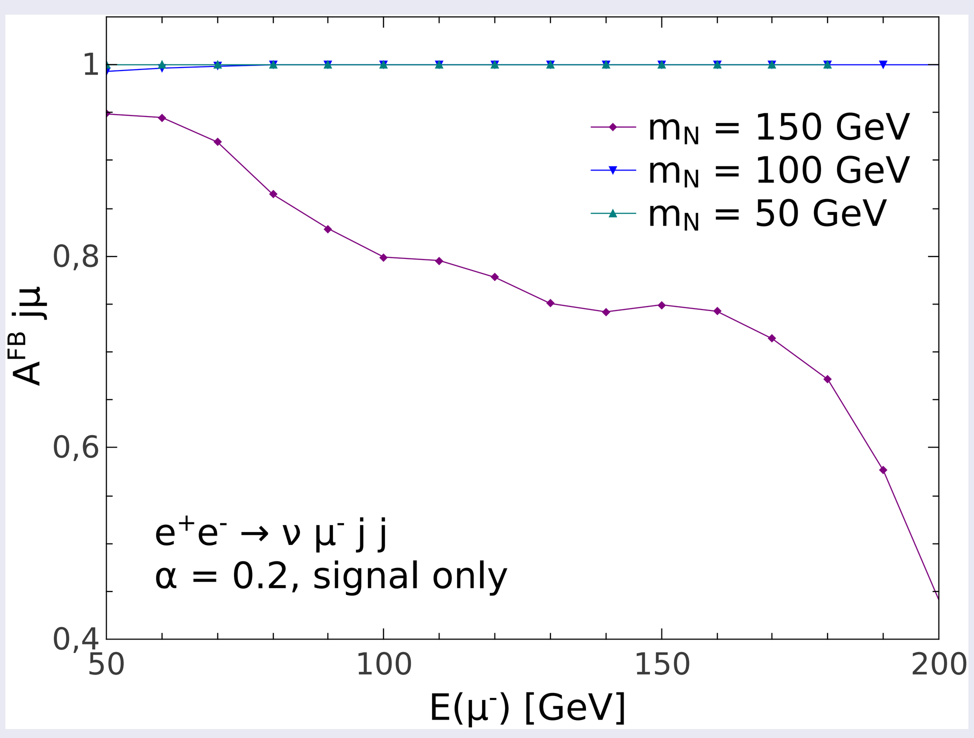


Figure: $A^{FB}_{j\mu}$ distribution with E_μ signal only, without cuts.

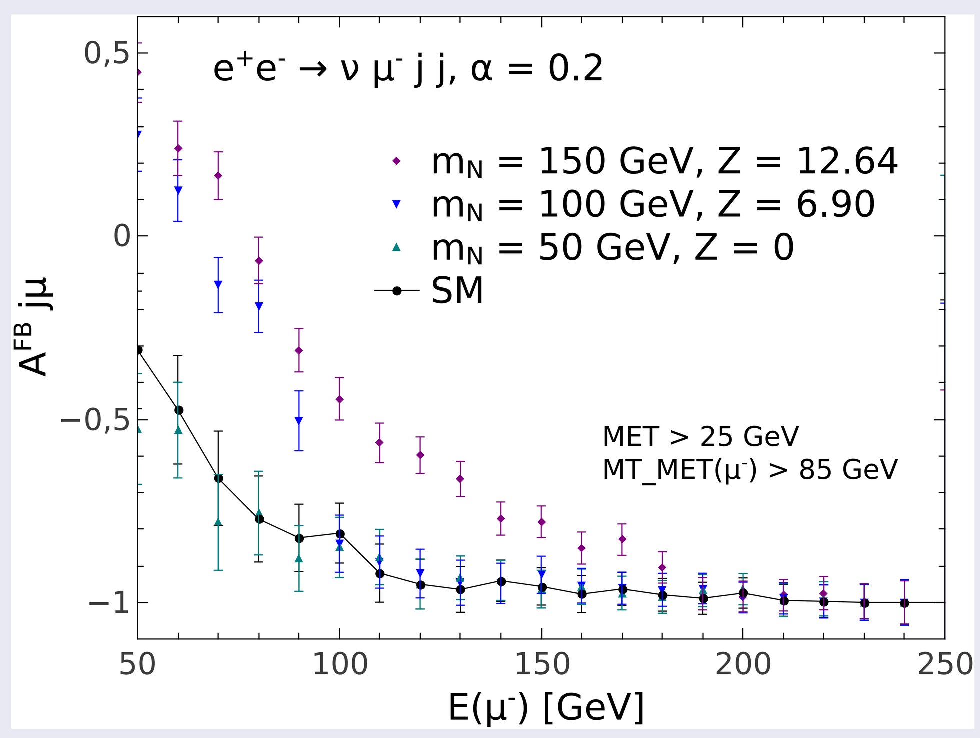


Figure: $A^{FB}_{j\mu}$ distribution with E_μ, for $\alpha = 0.2$, $\Lambda = 1\,TeV$.

- The events with a lighter N produce a maximal value $A^{FB}_{j\mu} = 1$: The muon and jet emerge in the same direction. For the higher m_N values the N is less boosted and the muon and jet emerge in an increasingly open angle for higher muon energies.
- We apply a selection cut for both processes, keeping MET > 25 GeV, accounting for neutrinos in the final state.
- For the semi-leptonic channel, we use a cut on the transverse mass of the $\mu - \not{E}_T$ system, selecting events with MT-MET(μ)> 85 GeV to reduce the SM background.

Conclusions

We conclude that the use of forward-backward asymmetries in future lepton colliders can probe heavy neutrino new physics in final states with light neutrinos which challenge simpler analyses, with a sensitivity up to 12σ that will eventually allow to put bounds on four-fermion effective operators for a higher m_N mass regime, complementary to proposed displaced vertices searches.