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Asymmetries from effective interactions of heavy Majorana neutrinos in future lepton colliders.

Dr. Lucía Duarte

Neutrinos en Colombia: NuCo 2021

With T. Urruzola (UdelaR, Uruguay), G. Zapata and O. A. Sampayo (UNMdP, Argentina)
Based on Eur.Phys.J.C 80 (2020) arXiv: 2006.11216 and [to appear!!]

Outline

1 Motivation: SM Neutrino EFT (SMNEFT)

2 Asymmetries in future lepton colliders

1) $e^+e^- \rightarrow B \rightarrow \mu\nu\gamma$ Belle II

2) $e^+e^- \rightarrow 2\mu\bar{\nu}\gamma\gamma$ Heavy Majorana neutrino mediated

3) $e^+e^- \rightarrow \nu\mu\bar{\nu}\nu$

Masses in the standard model (SM)

- Gauge symmetry breaking

$$[SU(2)_L \times U(1)_Y]_{EW} \Rightarrow U(1)_Q$$
$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \\ \phi^- \end{pmatrix} \Rightarrow \langle \phi \rangle = \begin{pmatrix} 0 \\ v \\ 0 \end{pmatrix}$$

- Dirac mass in Yukawa
Lagrangian:

$$-\mathcal{L}_Y \supset \Gamma_\ell^{ij} \overline{\ell_L^i} \phi \ell_R^j \Rightarrow \frac{\Gamma_\ell^{ij} v}{\sqrt{2}} \overline{\ell_L^i} \ell_R^j$$

- Massless neutrinos $\nu_{\ell L} \dots$
- Lepton number is conserved...
- But it needs to be extended to include neutrino masses!

Three Generations of Matter (Fermions) spin 1/2												
	I			II			III					
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0	g	0	0	0	0	0	0	
charge →	2/3	2/3	2/3	-1/3	-1/3	-1/3	-1/3	-1/3	-1/3	-1/3	-1/3	
name →	u up	c charm	t top	d down	s strange	b bottom	v _e electron neutrino	v _μ muon neutrino	v _τ tau neutrino	Z ⁰ weak force	H Higgs boson	
Quarks	Left Right	Left Right	Left Right	Left Right	Left Right	Left Right	Left Right	Left Right	Left Right	Left Right	Left Right	
Leptons	0 eV electron neutrino	0 eV muon neutrino	0 eV tau neutrino	0.511 MeV electron	105.7 MeV muon	1.777 GeV tau	e electron	μ muon	τ tau	W ⁺ weak force	W ⁻ weak force	
Bosons (Forces) spin 1	0	0	0	0	0	0	0	0	0	>114 GeV	spin 0	

$\ell^i = e, \mu, \tau$

$L_L = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_L$

$\ell_R = \overline{\ell_R^-}$

Seesaw Mechanism (Type I)

- Incorporate sterile $N_{i,R}$

$$\mathcal{L}_\nu = -\Gamma_{\ell j} \overline{L}_{\ell,L} \epsilon \tilde{\phi}^* N_{j,R} - \frac{1}{2} (N_{i,R})^T C M_{ij} N_{j,R} + h.c.$$

$$\mathcal{L}_\nu = -\bar{\nu}_{\ell,L} M_{\ell j}^D N_{j,R} - \frac{1}{2} \overline{N_{i,R}^c} M_{ij}^N N_{j,R}$$

$\frac{2}{3}$ Left u up	$\frac{2}{3}$ Left c charm	$\frac{2}{3}$ Left t top
2.4 MeV $\frac{2}{3}$ Left d down	1.27 GeV $\frac{2}{3}$ Left s strange	171.2 GeV $\frac{2}{3}$ Left b bottom
4.8 MeV $-\frac{1}{3}$ Left e electron	104 MeV $-\frac{1}{3}$ Left μ muon	4.2 GeV $-\frac{1}{3}$ Left τ tau
$<0.0001 \text{ eV}$ 0 Left ν_e electron neutrino	$\sim 0.01 \text{ eV}$ 0 Left ν_μ muon neutrino	$\sim 0.04 \text{ eV}$ 0 Left ν_τ tau neutrino
0.511 MeV -1 Left e electron	105.7 MeV -1 Left μ muon	1.777 GeV -1 Left τ tau

- 6 massive states: Majorana fermions
- 3 Light ν_m

$$m_\nu \sim (M^D)^2 (M^N)^{-1}$$

- 3 Heavy N



$$M_N \sim M^N$$

- Mixing of the active-massive states:

$$\nu_{\ell,L} = U_{\ell m} \nu_m + U_{\ell N} N$$

So Tiny!

$$U_{\ell N} \lesssim 1 \times 10^{-6} \sqrt{\frac{100 \text{ GeV}}{M_N}}$$

SMNEFT: our dim6 simplified benchmark scenario

- EFT with N_R^i and SM fields

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_\nu + \mathcal{L}^5 + \mathcal{L}^6 + \dots$$

- Discard the mixing term in the renormalizable lagrangian:

$$\mathcal{L}_\nu \supset \Gamma_{\ell j} \overline{L_{\ell, R}} \epsilon \tilde{\phi}^* N_{j, R} \rightarrow 0 \sim U_{\ell N} \rightarrow 0$$

- Consider only one massive heavy N ($N \equiv N_R$) with a Majorana mass: it is a Majorana particle!
- Only dim 5 interaction with ONE N is $\mathcal{O}_{N\phi}^{(5)} = \bar{N}_{i,R} N_{j,R}^c \phi^\dagger \phi$: reabsorb contribution to M_N in N physical mass m_N and discard hNN term
- Gain intuition!

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d=6}^{\infty} \left(\frac{1}{\Lambda^{d-4}} \sum_{\mathcal{J}} \alpha_{\mathcal{J}} \mathcal{O}_{\mathcal{J}}^d + h.c. \right)$$

Effective operators with Majorana N

New interactions: dim = 6

Standard Bosons (*SVB*)

$$\mathcal{O}_{LN\phi} = (\phi^\dagger \phi) (\bar{L}_i N \tilde{\phi}) \quad \alpha_{\phi}^{(i)} \quad (\alpha_{LNH}^{(i)}) \quad SCALAR$$

$$\mathcal{O}_{NN\phi} = i(\phi^\dagger D_\mu \phi) (\bar{N} \gamma^\mu N) \quad \alpha_Z \quad (\alpha_{HN})$$

$$\mathcal{O}_{NL\phi} = i(\phi^T \epsilon D_\mu \phi) (\bar{N} \gamma^\mu l_i) \quad \alpha_W^{(i)} \quad (\alpha_{HNe}^{(i)}) \quad VECTORIAL$$

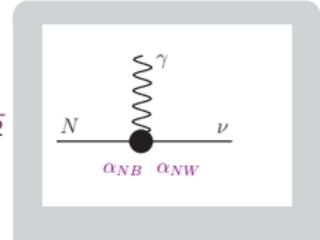
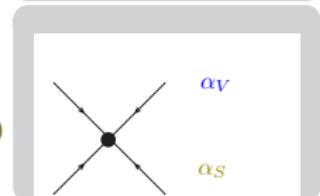
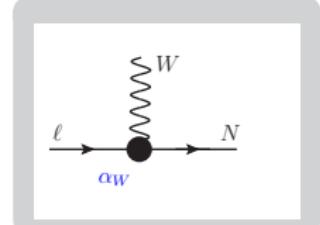
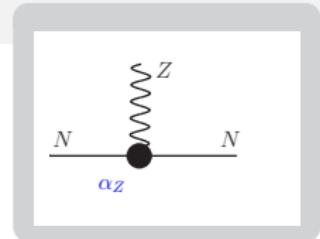
4-fermions ($4 - f$)

$$\mathcal{O}_{duNL} = (\bar{d}_j \gamma^\mu u_j) (\bar{N} \gamma_\mu l_i) \quad \alpha_{V_0}^{(i,j)}$$

$$\mathcal{O}_{fNN} = (\bar{f}_i \gamma^\mu f_i) (\bar{N} \gamma_\mu N) \quad \alpha_{V_1 \dots V_5}^{(i)}$$

$$\mathcal{O}_{QuNL} = (\bar{Q}_i u_i) (\bar{N} L_j) \quad \alpha_{S_1}^{(i,j)}, \quad \mathcal{O}_{QNLd} = (\bar{Q}_i N) \epsilon (\bar{L}_j d_j) \quad \alpha_{S_3}^{(i,j)}$$

$$\mathcal{O}_{LNQd} = (\bar{L}_i N) \epsilon (\bar{Q}_j d_j) \quad \alpha_{S_2}^{(i,j)}, \quad \mathcal{O}_{LNLI} = (\bar{L}_i N) \epsilon (\bar{L}_j l_j) \quad \alpha_{S_0}^{(i,j)}$$



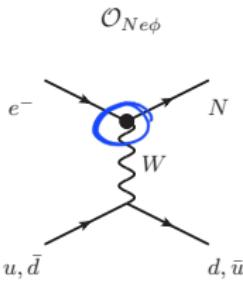
1-loop generated ($1 - loop$)

$$\mathcal{O}_{NB} = (\bar{L}_i \sigma^{\mu\nu} N) \tilde{\phi} B_{\mu\nu} \quad \alpha_{NB}^{(i)}$$

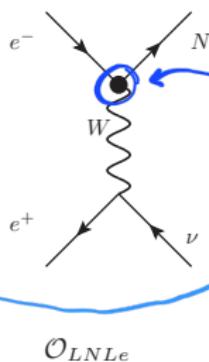
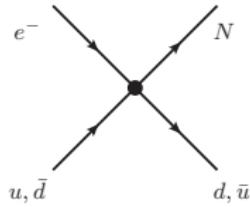
$$\mathcal{O}_{NW} = (\bar{L}_i \sigma^{\mu\nu} \tau^I N) \tilde{\phi} W_{\mu\nu}^I \quad \alpha_{NW}^{(i)} \dots \quad TENSORIAL$$

$$\alpha^{1-loop} = \frac{\alpha^{tree}}{16\pi^2}$$

Effective operators with one Majorana N (dim=6) [1]



$\mathcal{O}_{duNe}, \mathcal{O}_{QuNL}, \mathcal{O}_{LNQd}, \mathcal{O}_{QNLd}$



Tree-level generated :

$$\mathcal{O}_{Nl\phi}^i = i(\phi^T \epsilon D_\mu \phi)(\bar{N} \gamma^\mu l_i)$$

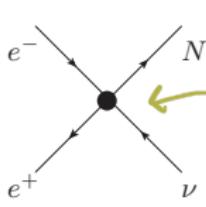
$$\mathcal{O}_{duNi}^{i,j} = (\bar{d}_j \gamma^\mu u_j)(\bar{N} \gamma_\mu l_i)$$

$$\mathcal{O}_{LNQd}^{i,j} = (\bar{L}_i N) \epsilon (\bar{Q}_j d_j)$$

$$\mathcal{O}_{QuNL}^{i,j} = (\bar{Q}_i u_i)(\bar{N} l_j)$$

$$\mathcal{O}_{QNLd}^{i,j} = (\bar{Q}_i N) \epsilon (\bar{L}_j d_j)$$

$$\mathcal{O}_{LNLI}^{i,j} = (\bar{L}_i N) \epsilon (\bar{L}_j l_j)$$



- 4 – f operators with Majorana fields need renormalizable completion to be implemented in FeynRules model

[1] F. del Aguila PLB (2009) 0806.0876, Liao PRD(2017) 1612.04527, Bhattacharya PRD(2016) 1505.05264

Bounds on the couplings $\alpha_{\mathcal{J}}^{(i)}$

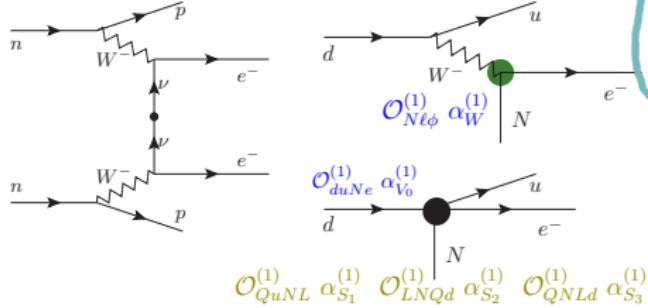
$$\mathcal{L}_{NI\phi}^{d=6} \supset \frac{-\nu m_W}{\sqrt{2}} \frac{\alpha_W^{(i)}}{\Lambda^2} \bar{l}_i \gamma^\mu P_R N W_\mu^-$$

$$\mathcal{L}_{\nu}^{d=4} \supset \frac{-g}{\sqrt{2}} U_{l_i N} \bar{l}_i \gamma^\mu P_L N W_\mu^-$$

$$g = \frac{2m_W}{\nu}$$

- Neutrinoless double beta decay:

KamLAND-Zen $\tau_{0\nu\beta\beta} \geq 1.1 \times 10^{26} \text{ yr}$

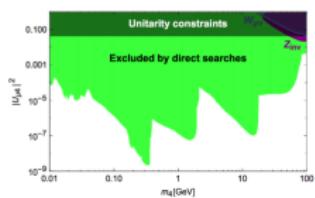
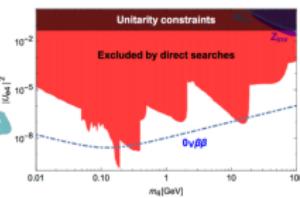


- We exploit the existing bounds for the $U_{l_i N}$ mixings taking

$$U_{l_i N} \simeq \frac{\alpha^{(i)} \nu^2}{2\Lambda^2}, \Lambda = 1 \text{ TeV}$$

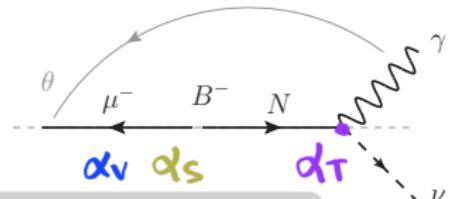
ONLY FIRST FAMILY

- $\alpha_{0\nu\beta\beta}^{\text{bound}} \lesssim 3.2 \times 10^{-2} \left(\frac{m_N}{100 \text{ GeV}}\right)^{1/2}$
- $\alpha_{\text{collider}}^{(2),(3)} \leq 2.3$ (DELPHI)



Abada (JHEP 2018) 1712.03984

Forward-backward asymmetry in $B \rightarrow \mu\nu\gamma$ (Belle II) [2]

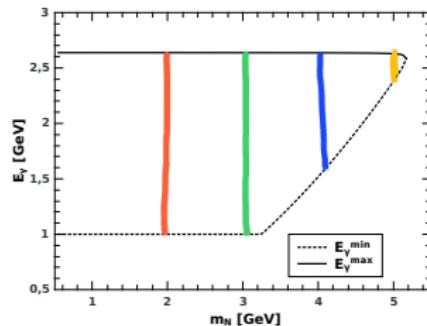
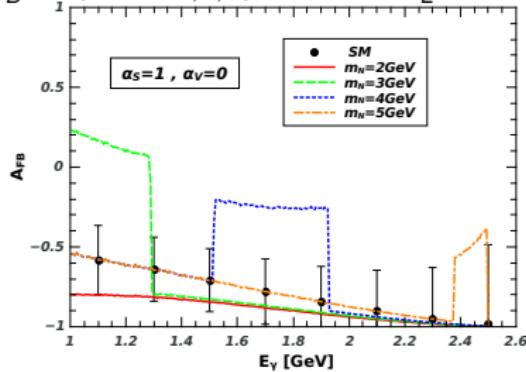


$$A_{FB}^{\mu\gamma} = \frac{N(\cos \theta > 0) - N(\cos \theta < 0)}{N(\cos \theta > 0) + N(\cos \theta < 0)}$$

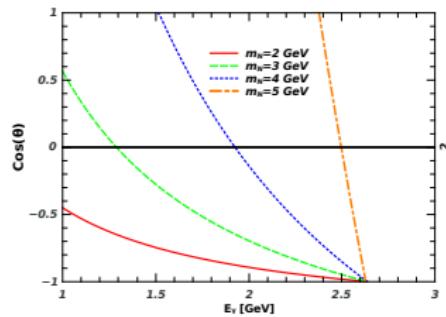
- $A_{FB}^{\mu\gamma} < 0$ in SM

$$\overline{\mu^-} \overline{B^-} \sim \sim$$

- $A_{FB}^{\mu\gamma} \text{ eff } (m_N, \alpha_V, \alpha_S, \alpha_T)$: $\alpha_T = \frac{|\alpha_V| + |\alpha_S|}{2}$

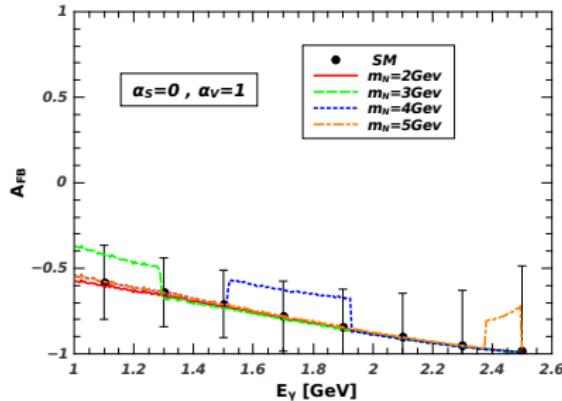
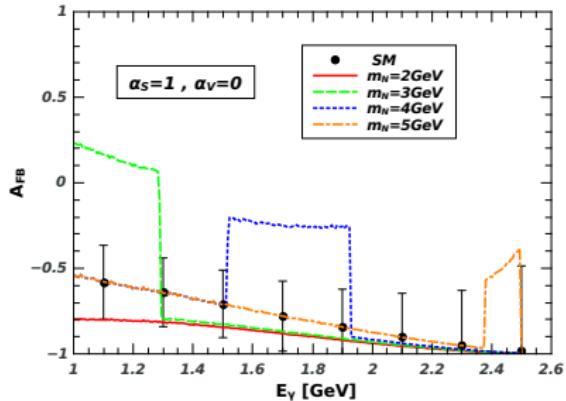


$$\cos(\theta) = \frac{1}{\beta_N} \left(\frac{m_N}{2\gamma_N E_\gamma} - 1 \right)$$

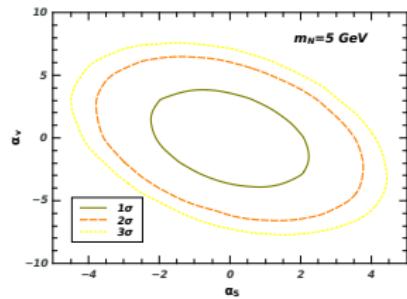
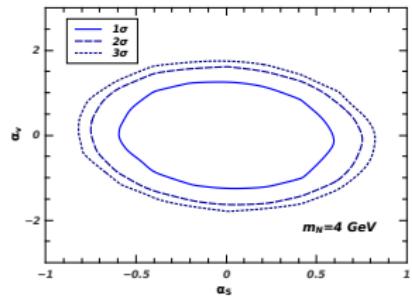
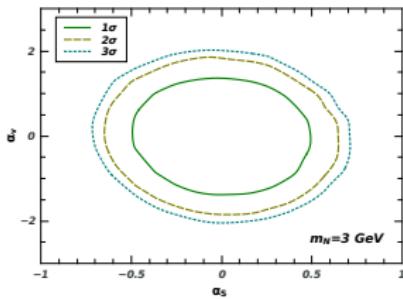


[2] LD Eur.Phys.J.C 80 (2020) 2006.11216

Forward-backward asymmetry in $B \rightarrow \mu\nu\gamma$ (Belle II) [2]



$$\Delta\chi^2 = \sum_{E_i} \frac{(A_{FB}^{SM}(E_i) - A_{FB}^{Tot}(E_i, m_N, \alpha_V, \alpha_S))^2}{\delta_i^2}, \quad \alpha_T = \frac{|\alpha_V| + |\alpha_S|}{2}$$

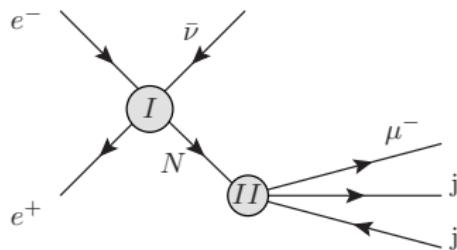


[2] LD Eur.Phys.J.C 80 (2020) 2006.11216

Asymmetries in future e^+e^- colliders: work in progress!

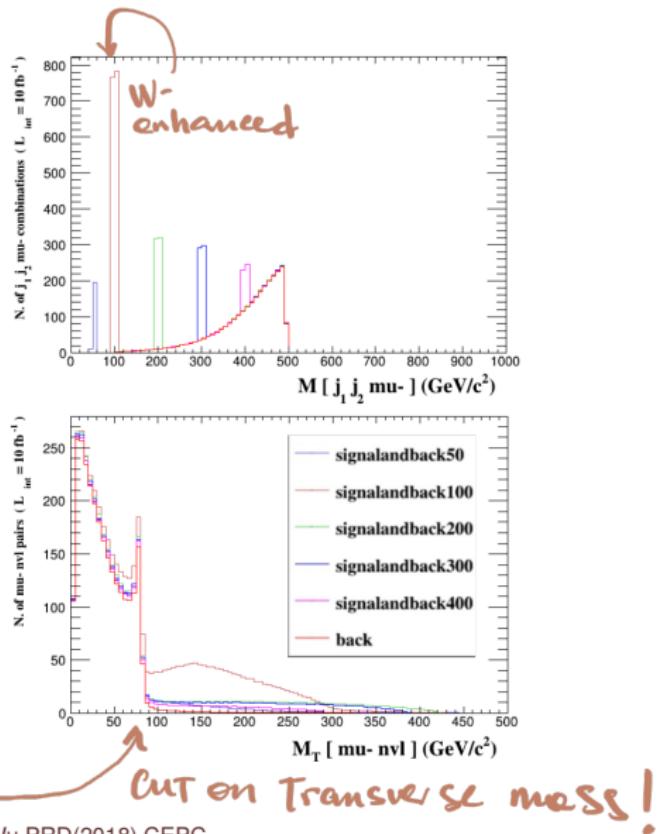
$$e^+e^- \rightarrow \nu\mu jj$$

- Tests $\mathcal{O}_{LNLI}^{i,j}$, $\mathcal{O}_{NL\phi}^{i,j}$ in (I) and
 $\mathcal{O}_{LNQd}^{i,j}$, $\mathcal{O}_{QuNL}^{i,j}$, $\mathcal{O}_{QNLd}^{i,j}$, $\mathcal{O}_{NL\phi}^{i,j}$ in (II)



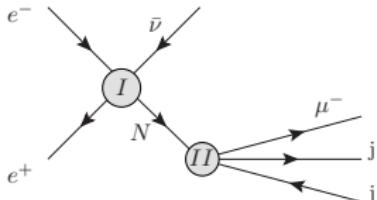
- $\sqrt{s} = 500 \text{ GeV}$, $\mathcal{L} = 500 \text{ fb}^{-1}$
- $m_N = 50, 100, 200, 300, 400 \text{ GeV}$
- $\alpha_V = \alpha_S = \alpha_T$ scan
- SM bkg $\sigma \sim 0.27 \text{ pb}$
- mostly gives $\nu\mu$ pair from W

See also: S.Banerjee PRD(2015) ILC, Wei Liao and Xiao-Hong Wu PRD(2018) CEPC



Asymmetries in future e^+e^- colliders: work in progress!

$$e^+e^- \rightarrow \nu\mu jj$$

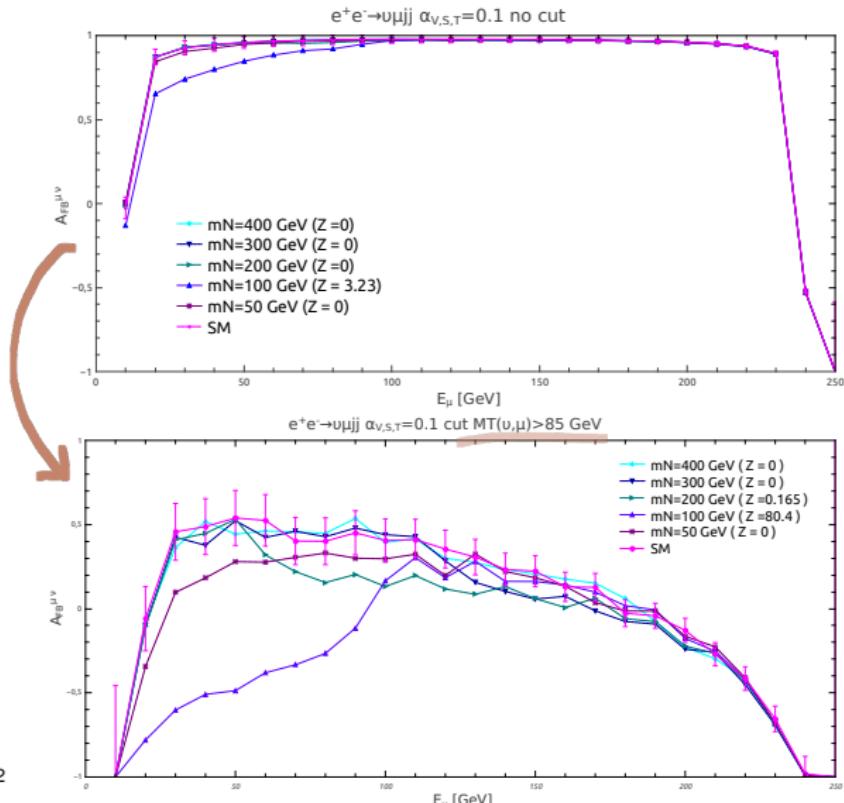


- Parton level MC
MadGraph5
- $\sqrt{s} = 500 \text{ GeV}, \mathcal{L} = 500 \text{ fb}^{-1}$

$$A_{FB}^{\nu\mu} = \frac{N(\cos \theta > 0) - N(\cos \theta < 0)}{N(\cos \theta > 0) + N(\cos \theta < 0)}$$

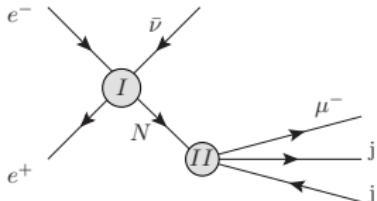
Deviation from SM-only in $z\sigma$

$$\Delta\chi^2 = \sum_{E_i} \frac{(A_{FB}^{SM}(E_i) - A_{FB}^{Tot}(E_i, m_N, \alpha_V, \alpha_S))^2}{\delta_i^2}$$



Asymmetries in future e^+e^- colliders: work in progress!

$$e^+e^- \rightarrow \nu\mu jj$$



- Parton level MC

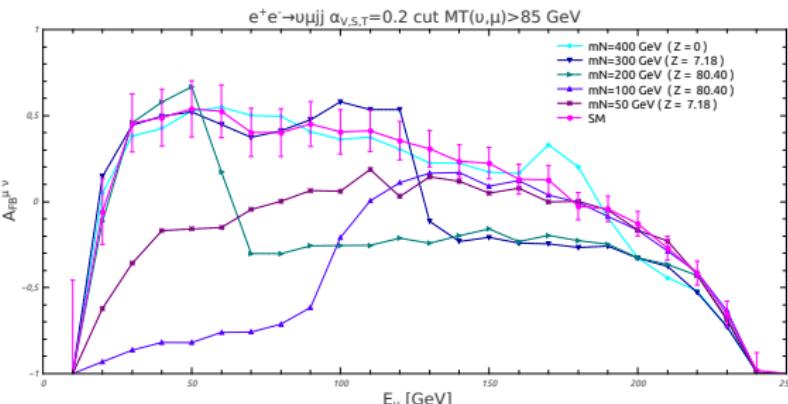
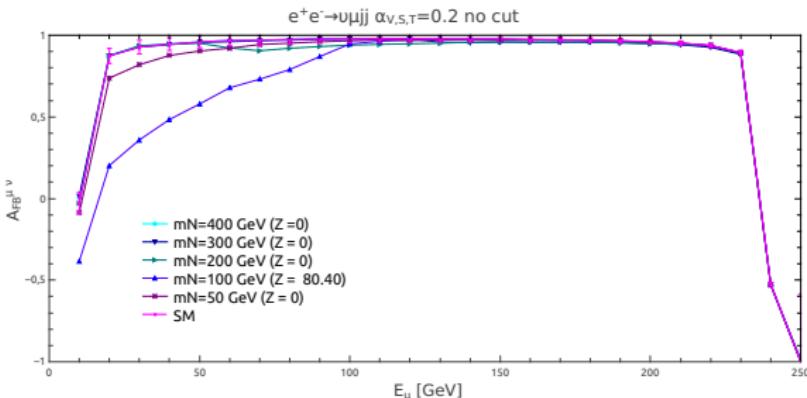
MadGraph5

- $\sqrt{s} = 500 \text{ GeV}, \mathcal{L} = 500 \text{ fb}^{-1}$

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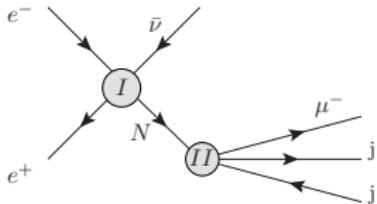
Deviation from SM-only in $z\sigma$

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Asymmetries in future e^+e^- colliders: work in progress!

$$e^+e^- \rightarrow \nu\mu jj$$



- Parton level MC

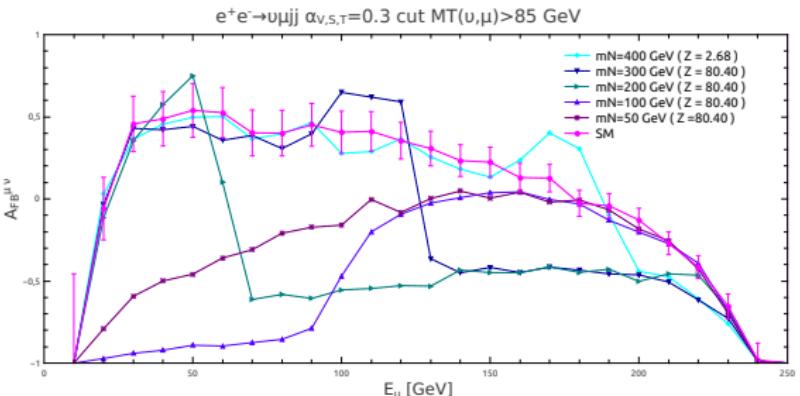
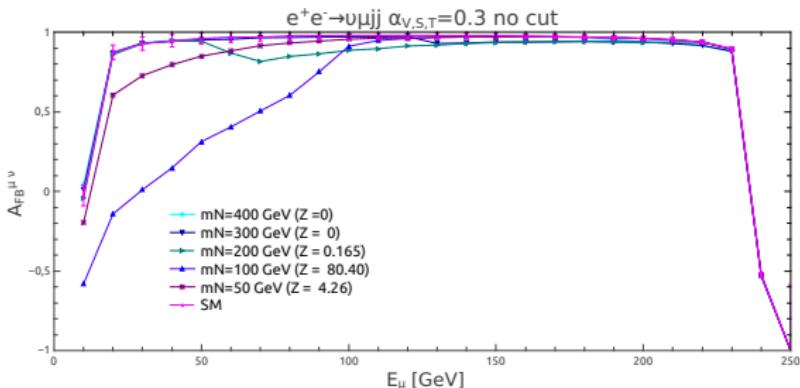
MadGraph5

- $\sqrt{s} = 500 \text{ GeV}, \mathcal{L} = 500 \text{ fb}^{-1}$

$$A_{FB}^{\nu\mu} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

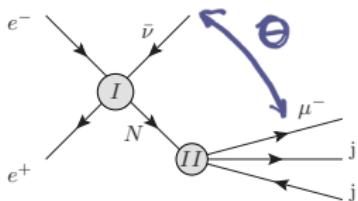
Deviation from SM-only in $z\sigma$

$$\Delta\chi^2 = \sum_{E_i} \frac{(A_{FB}^{SM}(E_i) - A_{FB}^{Tot}(E_i, m_N, \alpha_V, S))^2}{\delta_i^2}$$



Asymmetries in future e^+e^- colliders: work in progress!

$$e^+e^- \rightarrow \nu\mu jj$$

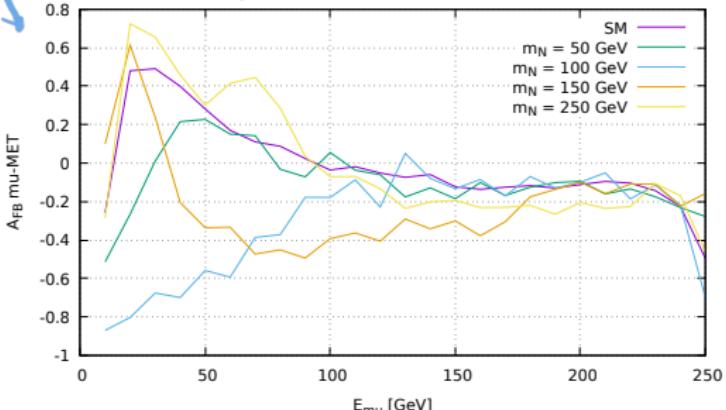
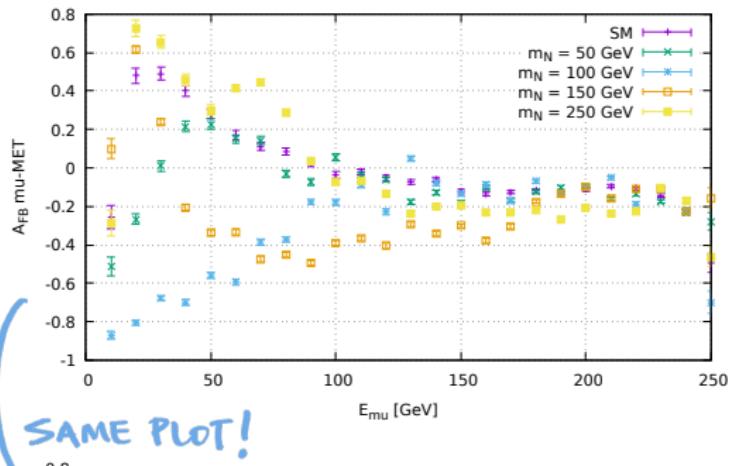


- Pythia8 and Delphes (CEPC default)

● $\sqrt{s} = 500 \text{ GeV}, \mathcal{L} = 500 \text{ fb}^{-1}$

● $\alpha_V = \alpha_S = \alpha_T = 1$

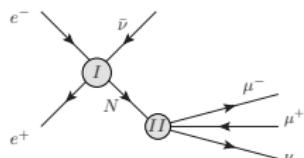
$$A_{FB}^{\mu-MET} = \frac{N(\cos \theta > 0) - N(\cos \theta < 0)}{N(\cos \theta > 0) + N(\cos \theta < 0)}$$



Asymmetries in future e^+e^- colliders: work in progress!

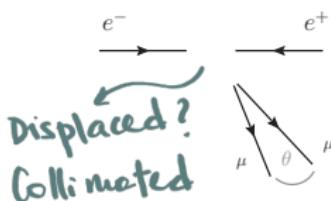
What about leptons-only?

$$e^+e^- \rightarrow \nu\mu\mu\nu$$



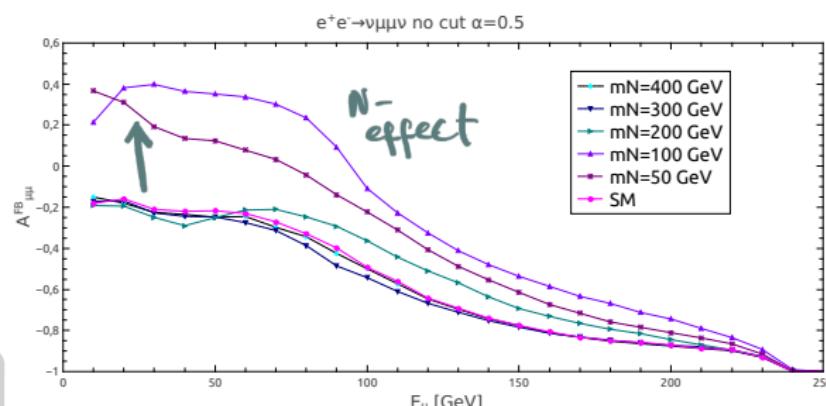
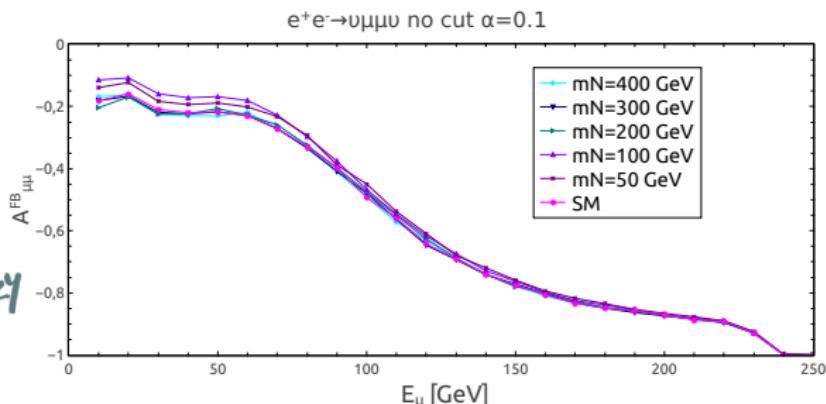
MUONS ASYMMETRY

- Tests $\mathcal{O}_{LNLI}^{i,j}$, $\mathcal{O}_{NL\phi}^{i,j}$ in (I) and (II)



- Part-lev MC MadGraph5
 $\sqrt{s} = 500 \text{ GeV}$, $\mathcal{L} = 500 \text{ fb}^{-1}$

$$A_{FB}^{\mu\mu} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

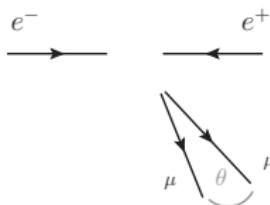


Asymmetries in future e^+e^- colliders: work in progress!

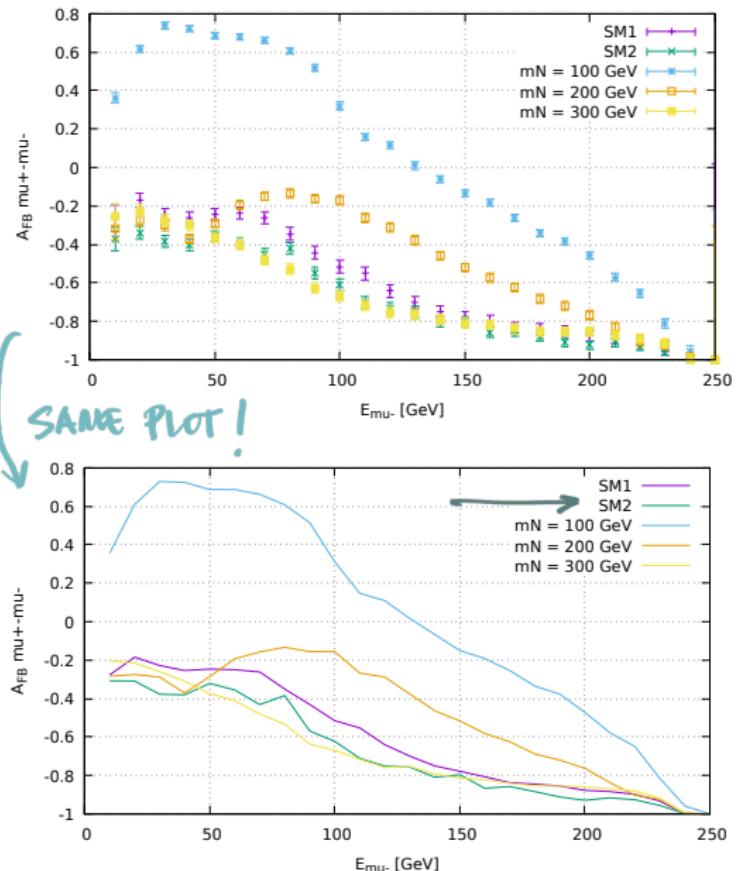
What about leptons-only?

$$e^+e^- \rightarrow \nu\mu\mu\nu$$

- Pythia8 and Delphes (CEPC default)
- $\sqrt{s} = 500 \text{ GeV}$, $\mathcal{L} = 500 \text{ fb}^{-1}$
- $\alpha_V = \alpha_S = \alpha_T = 1$
- Can we see something?



$$A_{FB}^{\mu\mu} = \frac{N(\cos \theta > 0) - N(\cos \theta < 0)}{N(\cos \theta > 0) + N(\cos \theta < 0)}$$



Final thoughts

- SMNEFT: model independent info on new physics (beyond mixing!) contributions to N phenomenology
- Forward-Backward asymmetries can help discover (or rule out) effective interactions
- They are complementary to displaced observables
- Lots of parameter space to be explored yet!

¡Thanks for your attention!



SMNEFT: (Backup)

- EFT with N_R^i and SM fields

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_\nu + \mathcal{L}^5 + \mathcal{L}^6 + \dots$$

- Non-renormalizable operators ($\text{dim} > 5$) [1]:

$$\mathcal{O}_W^{(5)} = \sum_{\ell\ell'} \frac{(\alpha_W)_{\ell\ell'}}{\Lambda} \bar{L}_{\ell,L} \tilde{\phi}^* \tilde{\phi}^\dagger L_{\ell',L} + h.c. \quad (\mathcal{O}_{LH})$$

$$\mathcal{O}_{N\phi}^{(5)} = \sum_{ij} \frac{(\alpha_{N\phi})_{ij}}{\Lambda} \bar{N}_{i,R} N_{j,R}^c \phi^\dagger \phi + h.c. \quad (\mathcal{O}_{NNH})$$

$$\mathcal{O}_{NB}^{(5)} = \sum_{i \neq j} \frac{(\alpha_{NB})_{ij}}{\Lambda} \bar{N}_{i,R} \sigma_{\mu\nu} N_{j,R}^c B^{\mu\nu} + h.c. \quad (\mathcal{O}_{NNB})$$

[1] See: Graesser PRD(2007) 0704.0438, Aparici (PRD 2009) 0904.3244 and Caputo (JHEP 2017) 1704.08721

Dim= 6 operators: (Backup) renormalizable implementation

$$\begin{aligned} \mathcal{L}^{tree} &\supset \frac{1}{\Lambda^2} \sum_{i,j} \left\{ -\alpha_W^{(i)} \frac{v m_W}{\sqrt{2}} \bar{l}_i \gamma^\nu P_R N W_\mu^- \right. \\ &+ \alpha_{V_0}^{(i,j)} (\bar{u}_j \gamma^\nu P_R d_j \bar{l}_i \gamma_\nu P_R N) \text{ O}_d vNL \\ &+ \alpha_{S_0}^{(i,j)} (\bar{\nu}_i P_R N \bar{l}_j P_R l_j - \bar{\nu}_j P_R l_j \bar{l}_i P_R N) \\ &+ \alpha_{S_1}^{(i,j)} (\bar{u}_j P_L d_j \bar{l}_i P_R N + \bar{u}_j P_L u_j \bar{\nu}_i P_R N) \\ &+ \alpha_{S_2}^{(i,j)} (\bar{d}_j P_R d_j \bar{\nu}_i P_R N - \bar{u}_j P_R d_j \bar{l}_i P_R N) \\ &+ \alpha_{S_3}^{(i,j)} (\bar{u}_i P_R N \bar{l}_j P_R d_j - \bar{d}_i P_R N \bar{\nu}_j P_R d_j) \\ &+ \text{h.c.} \left. \right\} \end{aligned}$$

Scalar-leptoquark K

See also: G. Cottin 2105.13851

VECTOR MEDIATOR



SCALAR MEDIATORS

