Fat jet signature of a heavy neutrino at a lepton collider

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12th July, 2019

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- Neutrino oscillations:
  solar $\theta_{12} \simeq 34^\circ$, $\Delta m^2_{12} \simeq 7.5 \times 10^{-5}\mathrm{eV}^2$
  atmospheric $\theta_{23} \simeq 42^\circ$, $\Delta m^2_{23} \simeq 2.5 \times 10^{-3}\mathrm{eV}^2$
  reactor $\theta_{13} \simeq 8.5^\circ$
- Mass Scale:
  cosmology: $\sum m_{\nu_i} < 0.23\mathrm{eV}$
  β decay: $m_{\nu_e} < 2.05\mathrm{eV}$
- Standard model: no ν mass term, lepton flavor is conserved.
  Solutions: Seesaw models, Radiative models, R-parity violating Supersymmetry etc.

P.F.de salas et. al(2017)

Dirac Neutrino and Majorana Neutrino:

Gauge singlet right handed neutrino ν_R

$$\mathcal{L} = -Y_\ell \bar{L}\phi\ell_R - Y_\nu \bar{L}\tilde{\phi}\nu_R + h.c. \tag{1}$$

Once ϕ gets vev we have,

$$\mathcal{L} = -m_\ell \bar{\ell}_L \ell_R - m_D \bar{\nu}_L \nu_R + h.c. \tag{2}$$

To have eV range mass for active neutrino $Y_\nu \sim 10^{-11}$

$$\mathcal{L} = -Y_\ell \bar{L}\phi\ell_R - Y_\nu \bar{L}\tilde{\phi}\nu_R - \frac{1}{2} M_R \bar{\nu_R} \nu_R^c + h.c. \tag{3}$$

After symmetry breaking

$$\phi = \begin{bmatrix} 0 \\ v \end{bmatrix}$$

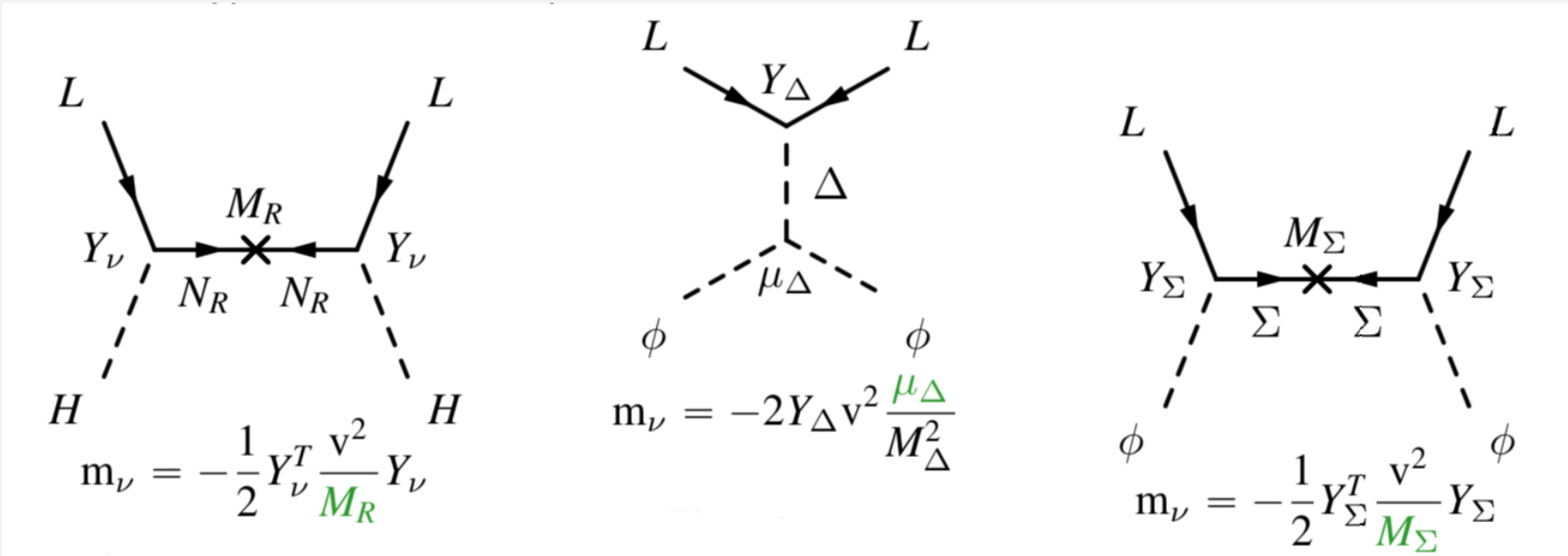
,

$$\mathcal{L} = -m_\ell \bar{\ell}_L \ell_R - m_D \bar{\nu}_L \nu_R - \frac{1}{2} M_R \bar{\nu_R} \nu_R^c + h.c. \tag{4}$$

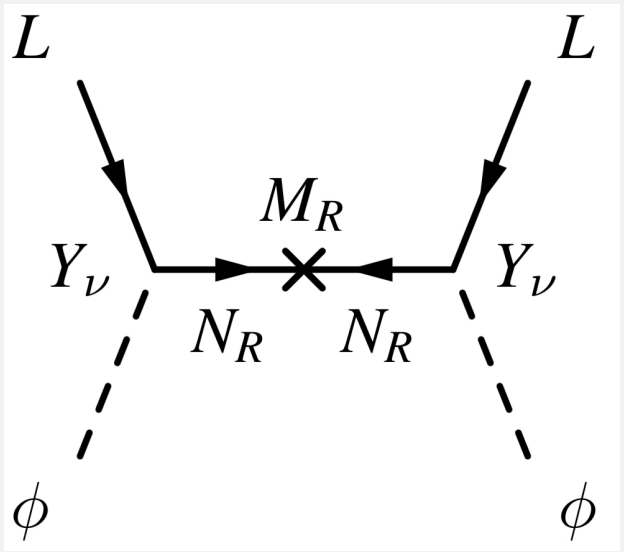
Neutrino Mass:

Origin of smallness of Neutrino masses can be understood using seesaw mechanism:

- Type-I seesaw: Right handed neutrino.
- Type-II seesaw: $SU(2)$ triplet scalar.
- Type-III seesaw: $SU(2)$ triplet fermion.



Type-I seesaw:



Minkowski
Gell-Mann, Ramond, Slansky
Yanagida
Mohapatra, Senjanovic

Active neutrino mass:

$m_\nu = -\frac{m_D^T m_D}{M_R}$

m_ν in the eV range:

$Y_\nu \sim 1$ *and* $M_R \sim 10^{14}\,GeV$

$Y_\nu \sim 10^{-6}$ *and* $M_R \sim 10^{2}\,GeV$

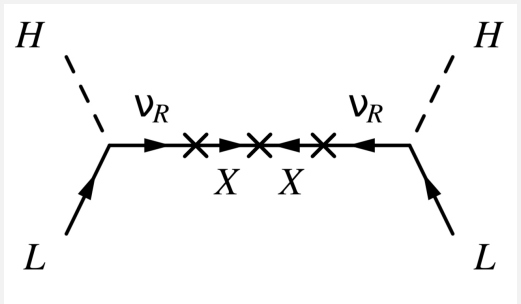
The active sterile mixing:

$|V_{\ell N}| \sim \frac{m_D}{M_R} \sim 10^{-6}\sqrt{\frac{100\mathrm{GeV}}{M_R}}$

Low scale seesaw: Large active sterile mixing(Inverse seesaw)

- Adding a fermionic gauge singlets $\nu_R(L=+1)$ and $X(L=-1)$

$$\mathcal{L}_{inverse} = -Y_\nu \bar{L}\tilde{\phi}\nu_R - M_R\bar{\nu_R^c}X - \frac{1}{2}\mu_X \bar{X^c}X + h.c. \tag{5}$$



$$m_\nu \sim \frac{m_D^2}{M_R^2}\mu_X \tag{6}$$

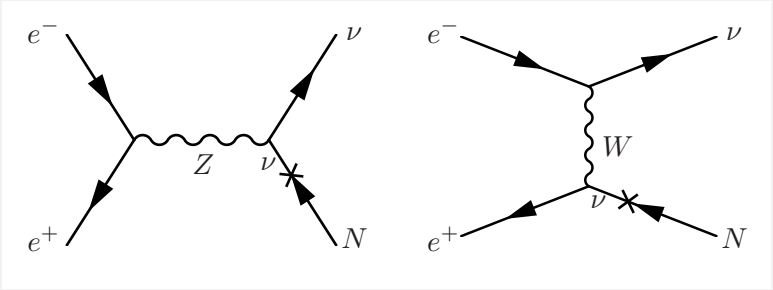
$$m_{N_1,N_2} \sim \mp M_R + \frac{\mu_X}{2} \tag{7}$$

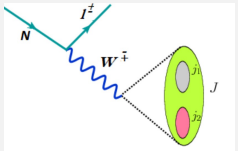
Here $Y_\nu \sim 1$ and $M_R \sim 1\text{TeV}$ allowed.

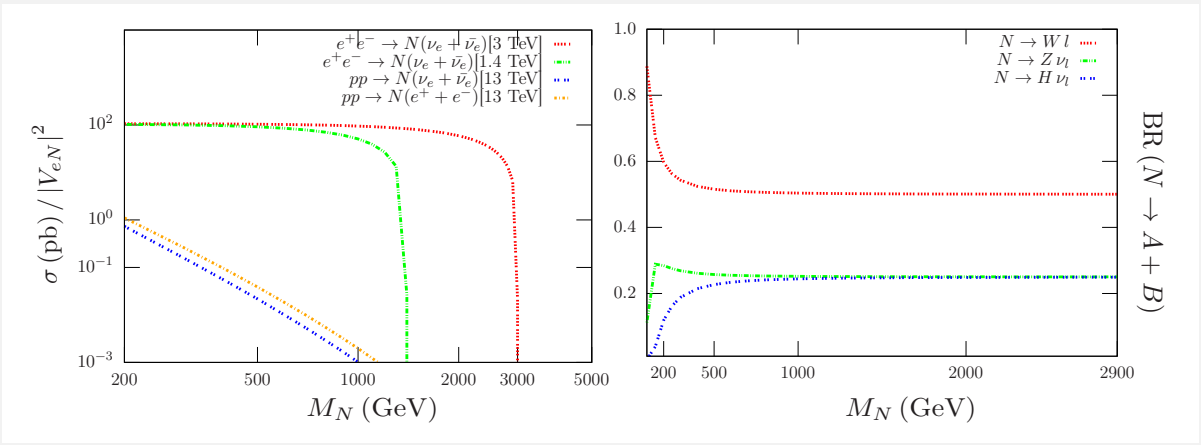
Inverse seesaw: collider signature

Interactions of right-handed neutrino:

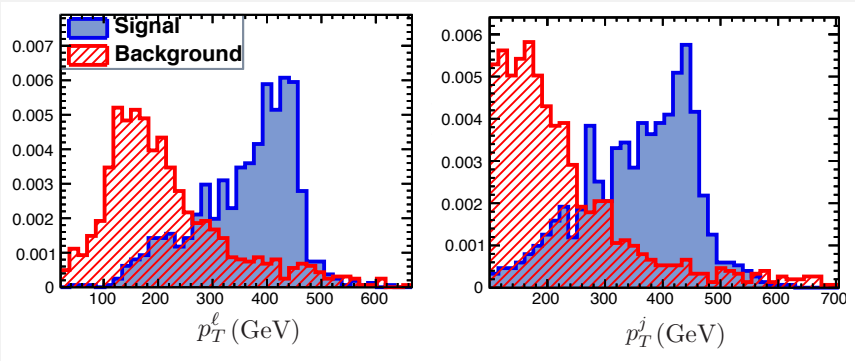
$$
\begin{aligned}
\nu_{L_\alpha} &= U\,\nu_{L_i} + V N^c_{R_j} \\
-\mathcal{L}_{CC} &= \frac{g}{\sqrt{2}} W^-_\mu\, \bar{\ell}_i \gamma^\mu P_L V_{ij} N_j + \text{h.c.} \\
-\mathcal{L}_{NC} &= \frac{g}{2\cos\theta_w} Z_\mu \left\{ (U^\dagger V)_{ij}\, \bar{\nu}_i \gamma^\mu P_L N_j + \text{h.c.} \right\} \\
-\mathcal{L}_H &= \frac{g M_j}{4 M_W} H \left\{ (U^\dagger V)_{ij}\, \bar{\nu}_i P_R N_j + \text{h.c.} \right\};
\end{aligned}
$$

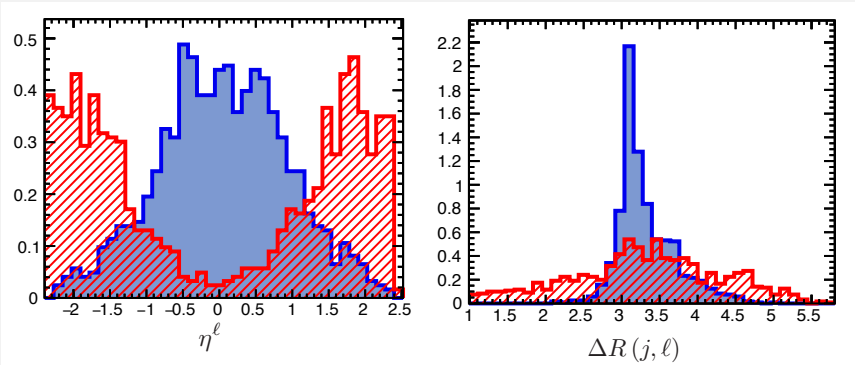




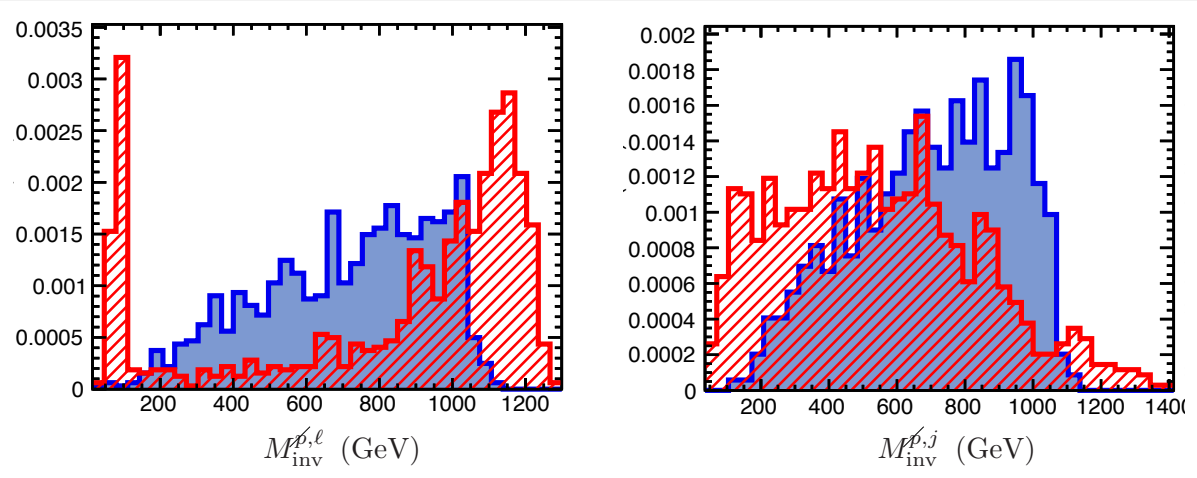


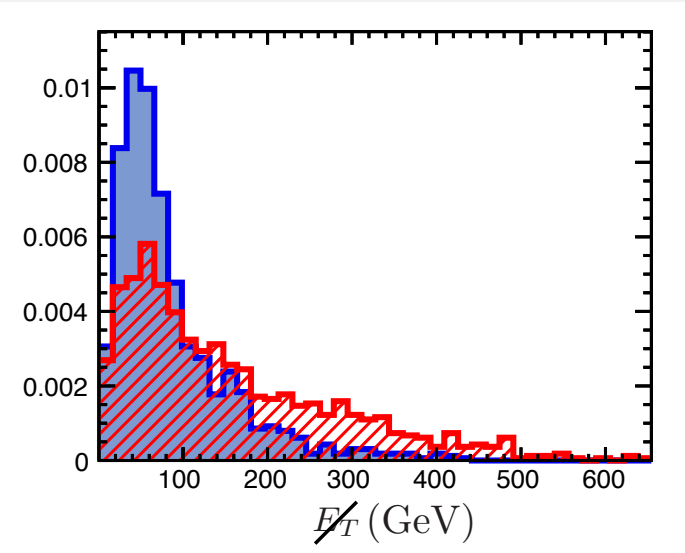
Background: $e^+e^- \to e^\pm \nu_e / \bar{\nu}_e jj$





S.Chakraborty, M.Mitra, **SS** Phys.Rev.D100,015012


0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
200
400
600
800
1000
1200
$M_{\rm inv}^{\not{p},\ell}$ (GeV)
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
200
400
600
800
1000
1200
$M_{\rm inv}^{\not{p},j}$ (GeV)


0.01
0.008
0.006
0.004
0.002
0
100
200
300
400
500
600
$\not{E}_T$ (GeV)

CBA-I for $M_N = 600 - 900$ GeV

- Transverse momentum for $e^{\pm}$: $p_T > 200$ GeV.
- Transverse momentum of the fat-jet: $p_T > 200$ GeV.
- Transverse missing energy: $\not{E}_T < 150.0$ GeV.
- Pseudo-rapidity of $e^{\pm}$: $-1.0 < \eta^{\ell} < 1.0$.
- Jet-lepton separation: $2.8 < \Delta R(j, \ell) < 3.8$..
- Invariant mass of $\not{p}$ and lepton: $150\,\mathrm{GeV} < M_{\mathrm{inv}}^{\not{p},\ell} < 950$ GeV.
- Invariant mass of $\not{p}$ and jet: $M_{\mathrm{inv}}^{\not{p},j} > 600.0$ GeV.

CBA-II for $M_N = 1000 - 1200$ GeV

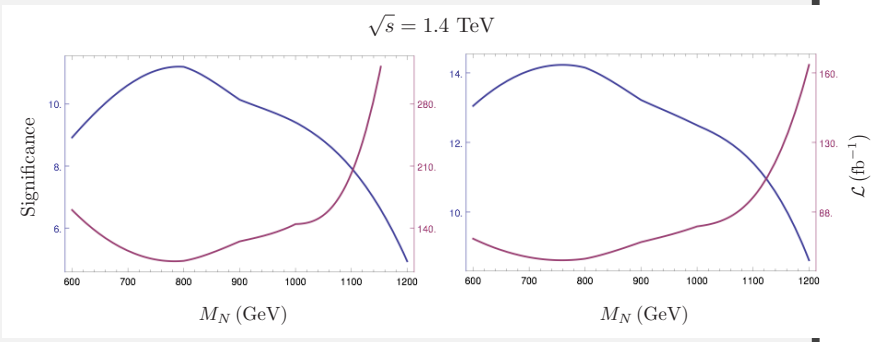
- Transverse momentum for $e^{\pm}$: $p_T > 350$ GeV.
- Transverse momentum of the fat-jet: $p_T > 350$ GeV.
- Transverse missing energy: $\not{E}_T < 150.0$.
- Pseudo-rapidity of $e^{\pm}$: $-1.0 < \eta^{\ell} < 1.0$.
- Jet-lepton separation: $2.8 < \Delta R(j, \ell) < 3.8$.
- Invariant mass of $\not{p}$ and lepton: $150\,\mathrm{GeV} < M_{\mathrm{inv}}^{\not{p},\ell} < 950$ GeV.
- Invariant mass of $\not{p}$ and jet: $M_{\mathrm{inv}}^{\not{p},j} > 400.0$ GeV.

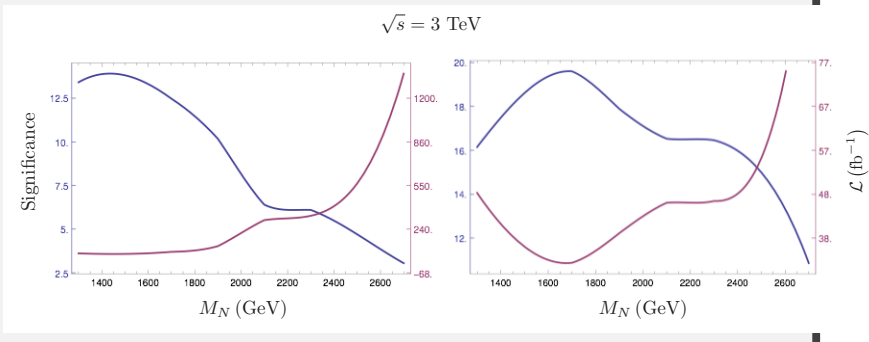
Mass and cross-section			Significance	
Mass (GeV)	$\sigma_{partonic}$ (fb)	σ_D (fb)	CBA-I	BDT
600	2.39	0.63	8.92	13.05
700	2.24	0.77	10.61	14.06
800	2.03	0.82	11.20	14.15
900	1.78	0.73	10.14	13.22
Background	751.42	1.86	-	-

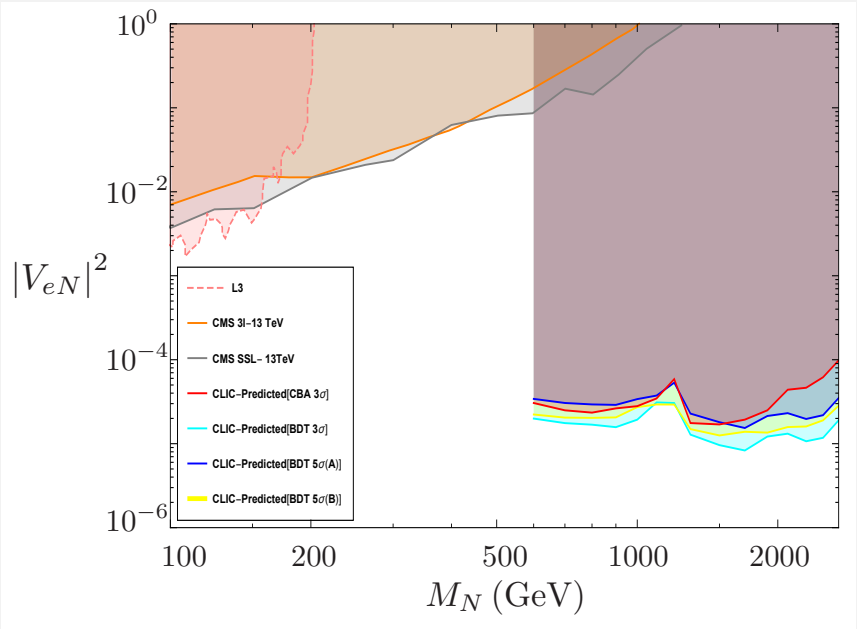
Table: Significance for $\mathrm{M_N} = 600 - 900\,\mathrm{GeV}$

Mass and cross-section			Significance	
Mass (GeV)	$\sigma_{partonic}$ (fb)	σ_D (fb)	CBA-II	BDT
1000	1.49	0.62	9.41	12.49
1100	1.16	0.51	7.94	11.41
1200	0.80	0.30	4.93	8.61
Background	751.42	1.55	-	-

Table: Significance for $\mathrm{M_N} = 1000 - 1200\,\mathrm{GeV}$


$\sqrt{s} = 1.4$ TeV
Significance
$\mathcal{L}$ (fb^{-1})
M_N (GeV)
M_N (GeV)


$\sqrt{s} = 3$ TeV
Significance
$\mathcal{L}$ (fb^{-1})
M_N (GeV)
M_N (GeV)


$|V_{eN}|^2$
M_N (GeV)
L3
CMS 3l-13 TeV
CMS SSL- 13TeV
CLIC-Predicted[CBA 3σ]
CLIC-Predicted[BDT 3σ]
CLIC-Predicted[BDT 5σ(A)]
CLIC-Predicted[BDT 5σ(B)]

conclusion

- Origin of Neutrino mass is one of the most important problem we need to understand. Seesaw Mechanism is one of the most promising model which explains neutrino mass.
- As LHC have very less sensitivity for heavy mass of right handed neutrino its important to have leptonic collider.
- In our study we saw leptonic collider can give stronger bound compare to existing search. Also we saw boosted analysis is important in the case of heavy mass searches.

backup slides

backup slides

CBA-III for $M_N = 1300 - 1900$ GeV

- p_T for electron $p_T > 450$ GeV.
- Pseudo-rapidity of $e^{\pm}$: $-1.0 < \eta^{\ell} < 1.0$.
- Jet-$\not{p}$ rapidity separation $\Delta\eta(j, \not{p})$: $\Delta\eta(j, \not{p}) > 3.0$.
- Jet-lepton rapidity separation $\Delta\eta(j, \ell)$: $\Delta\eta(j, \ell) < 2.0$.
- Invariant mass of $\not{p}$ and lepton: $200\,\mathrm{GeV} < M_{\mathrm{inv}}^{\not{p},\ell} < 2500$ GeV.
- Invariant mass of $\not{p}$ and jet: $M_{\mathrm{inv}}^{\not{p},j} > 1300.0$ GeV.

CBA-IV for $M_N = 2100 - 2700$ GeV

- p_T for electron: $p_T > 600$ GeV.
- Missing transverse energy: $\not{E}_T < 200.0$ GeV.
- Jet-$\not{p}$ rapidity separation $\Delta\eta(j, \not{p})$: $\Delta\eta(j, \not{p}) > 0.5$.
- Jet-$\not{p}$ azimuthal angle separation $\Delta\phi(j, \not{p})$: $\Delta\phi(j, \not{p}) < 2.0$.
- Invariant mass of $\not{p}$ and lepton: $200\,\mathrm{GeV} < M_{\mathrm{inv}}^{\not{p},\ell} < 2000$ GeV.
- Invariant mass of $\not{p}$ and jet: $200.0\,\mathrm{GeV} < M_{\mathrm{inv}}^{\not{p},j} < 2000.0$ GeV.
- Jet mass M_J: $80.0 < M_J < 90.0$.