it’s 3am in Japan...

Right Handed neutrino pair production at ILC

Work in progress

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Motivation and introduction

The Right Handed Neutrino (RHN) can address the following big questions

- Why does matter dominate anti-matter in our universe?
- Do quarks and leptons unify?
- Why is neutrino mass so small?

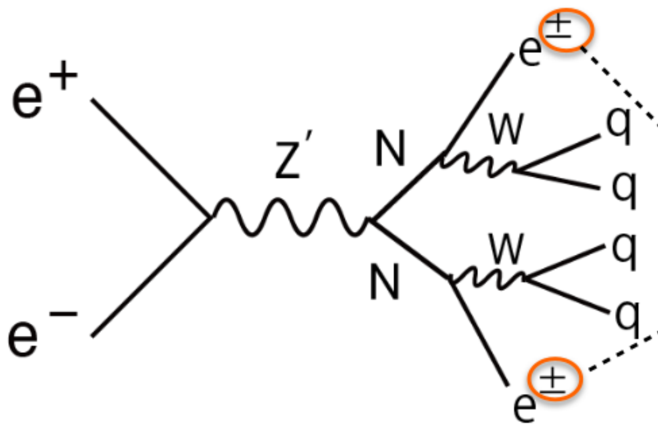
RHN is assumed to be

arXiV[1812.11931]

- ☐ a Majorana particle ($N = \bar{N}$)
- ☐ minimal $U(1)_{B-L}$ model

$G_{B-L} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ → gauge boson : Z'

→ RHN **pair** production



Lepton # violation is possible!

↓

Same sign leptons possible

↓

Very small SM BG!

Benchmark points with $M_N = 100, 150, 200, 225$ GeV

Benchmark points

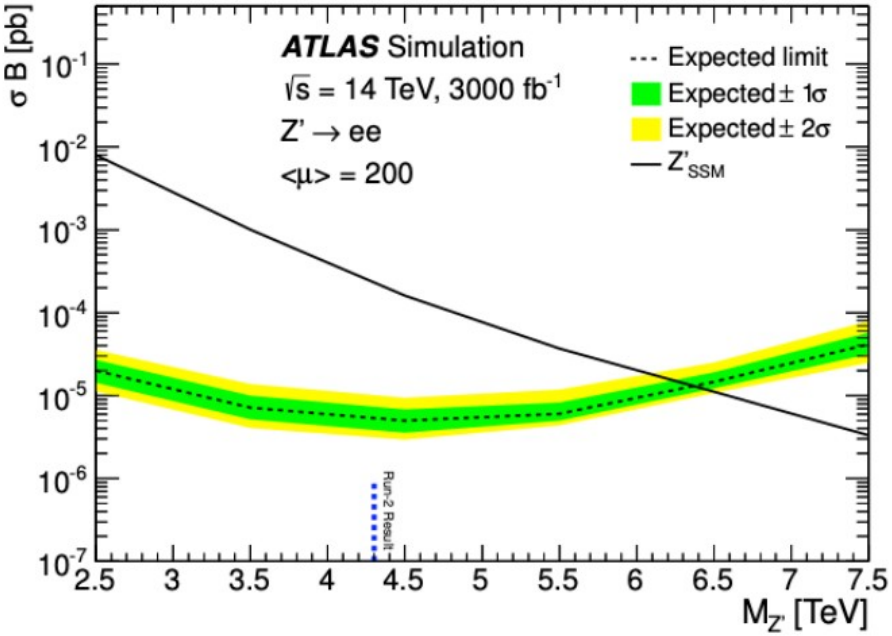
- Pol(e⁻, e⁺) = (−0.8, +0.3), (+0.8, −0.3): $\mathcal{L} = 1600\,[\mathrm{fb}^{-1}]$
- Pol(e⁻, e⁺) = (−0.8, −0.3), (+0.8, +0.3): $\mathcal{L} = 400\,[\mathrm{fb}^{-1}]$

M_N [GeV] RHN mass	$M_{Z'}$ [TeV] Z' mass	g_1' $U(1)_{B-L}$ coupling	$\|V_{eN}\|^2$ mixing angle	$\sigma_0(e^-_L e^+_R \to NN)$ 100% polarization [fb]	BR $(N \to e^+ W^-)$	Event # at ILC500 [$4000 fb^{-1}$]
100	7	1	0.0009	0.55	0.44	1446
150	7	1	0.0009	0.36	0.33	925
200	7	1	0.0009	0.14	0.30	349
225	7	1	0.0009	0.046	0.29	112

- minimal $U(1)_{B-L}$ model
- ILC 500 with initial state radiation (ISR) and beamstrahlung (BS)

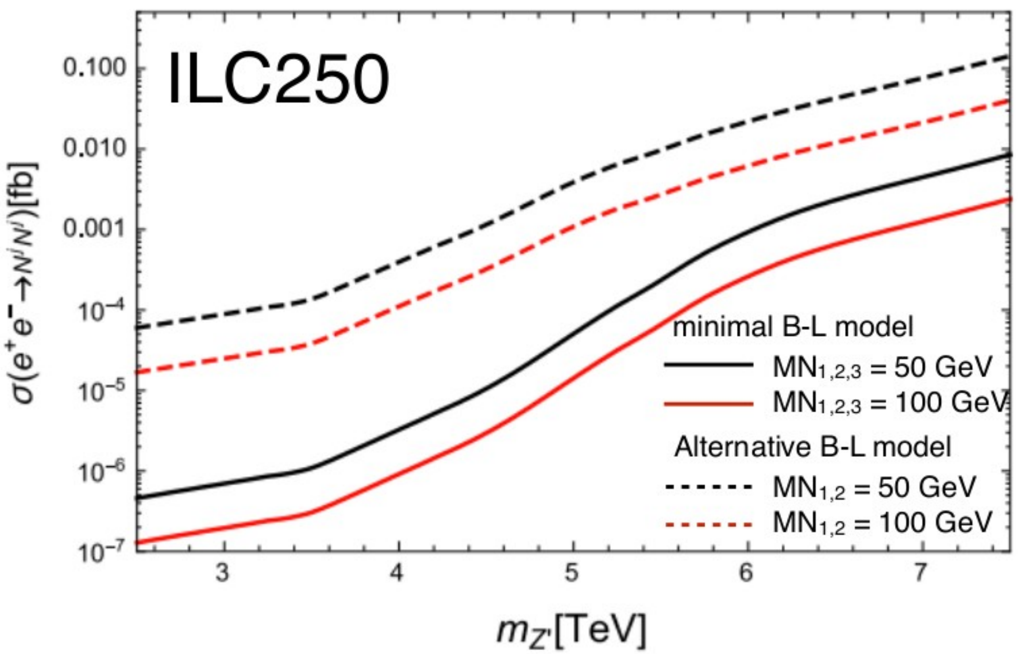
Current limits - Z' mass

SM like Z' coupling



ATLAS-TDR-LHCC2017-2018

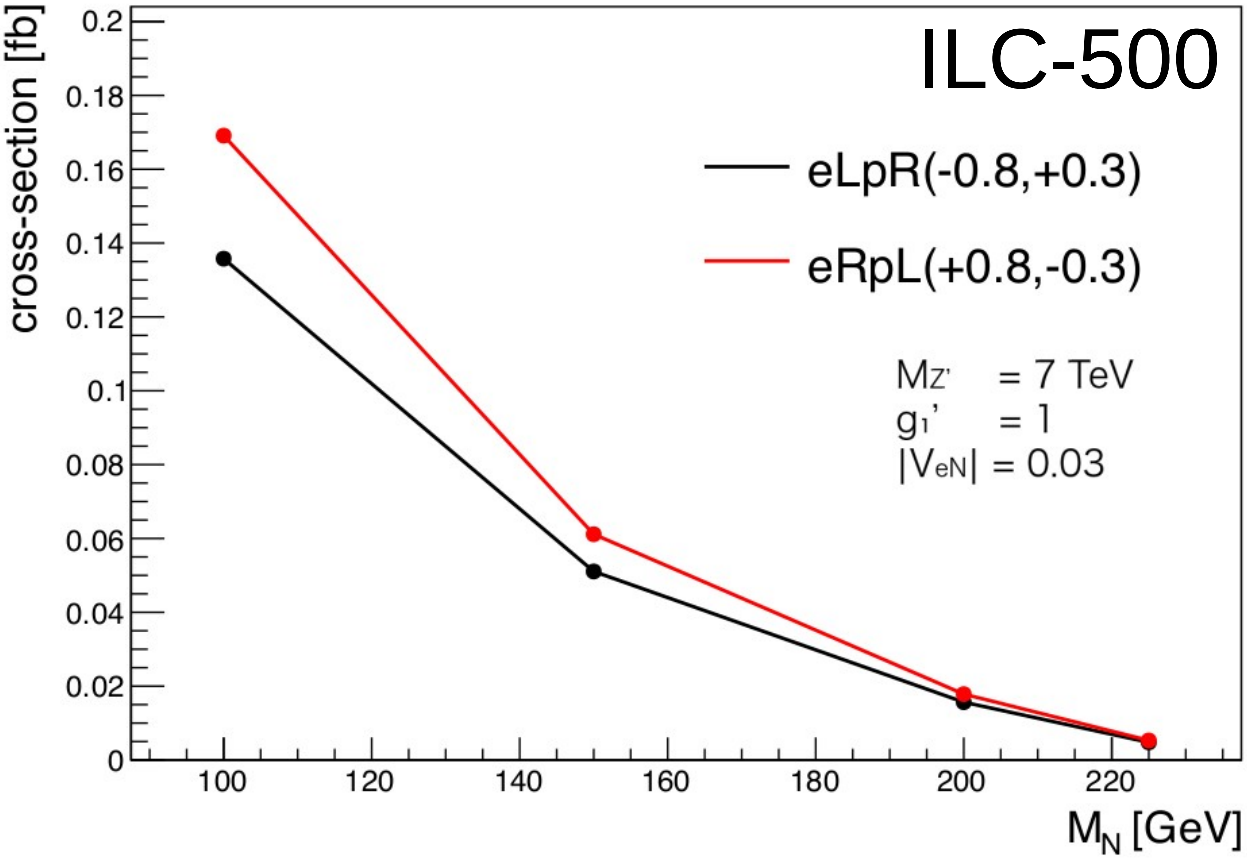
RHN pair production crosssection at ILC250 for expected HL-LHC limits on $M_{Z'}/g'$



arXiV[1812.11931]

The heavier Z' mass less constrained by LHC

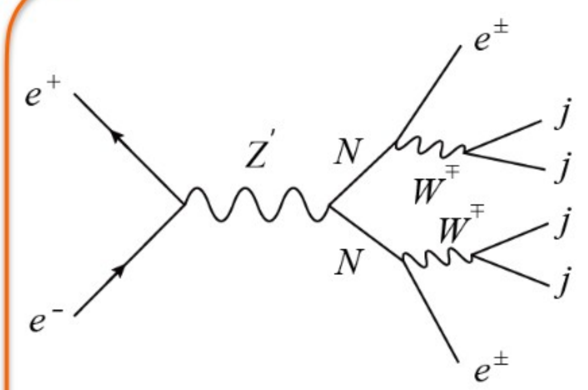
Same sign cross-section vs M_N



$$\text{cross}-\text{section} = \sigma(\text{ee} \to \text{NN} \to \text{e}^{\pm}\text{e}^{\pm}\text{W}^{\mp}\text{W}^{\mp})$$
$$= \sigma_0(ee \to NN) \times 2(BR(N \to e^- W^+)^2)$$

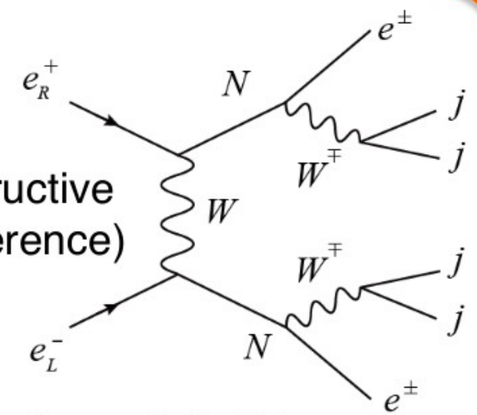
Analysis tool and backgrounds

ILC500 Signal process:



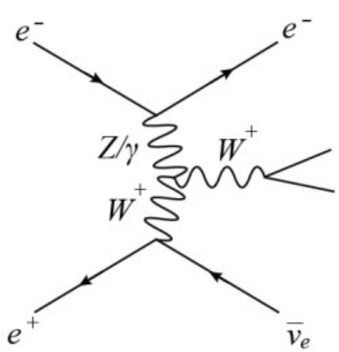
s-channel via Z'

+ (Destructive interference)

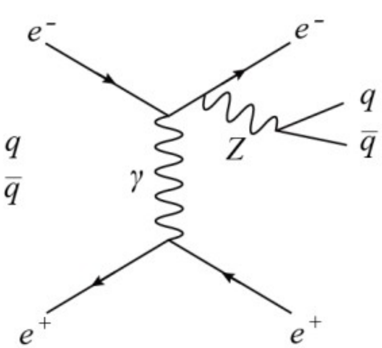


t-channel via W (only e_L)

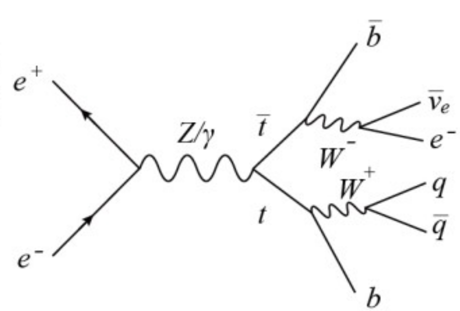
6f and 4f major background processes:



$e^+e^- \to e\nu qq$



$e^+e^- \to eeqq$



$e^+e^- \to tt$

UFO model files

↓

WHIZARD ver 2.8.5
Make Events

↓

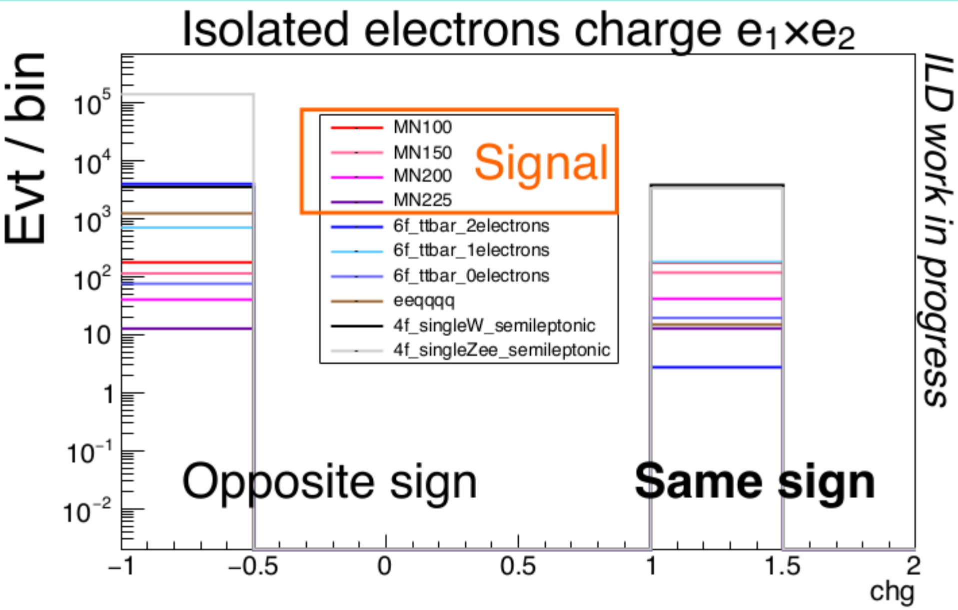
ILD Full Simulation & Reconstruction (Geant4)

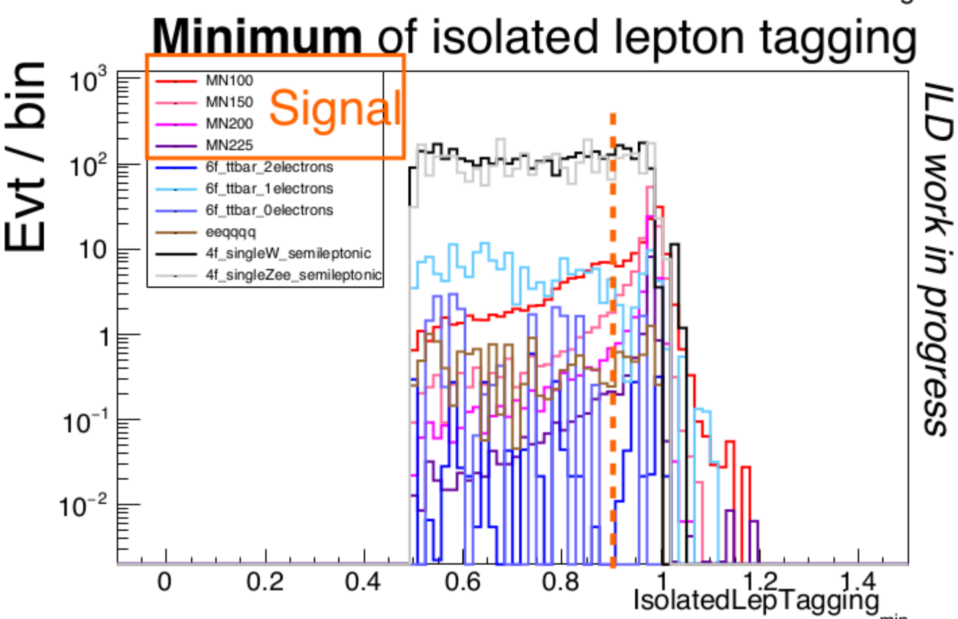
↓

miniDST
Events format

Cut conditions to select signal events

- 2 isolated electron && 0 isolated γ, μ
- **Same sign isolated electrons**
- Isolated electron energies
  $E_{iso} < 200$ [GeV]
- Isolated electron polar angles
  $|\cos\theta_{isoe}| < 0.95$
- **IsolatedLepTagging(min) > 0.9**
- Jet clustering with Durham
  $\log_{10}(y12) > -1$
- $P_{miss} < 100$ [GeV] &&
  ($P_{miss} < 40$ [GeV] || $|\cos\theta_{Pmiss}| > 0.95$)





Cut flow (eLpR)

- ILC 500 with ISR / BS
- **Pol(e⁻, e⁺) = (–0.8, +0.3)** $\mathcal{L} = 1600\,[\mathrm{fb}^{-1}]$

ILD work in progress

	Signal Events (ee→NN)				Background Events					
	M_N=100	M_N=150	M_N=200	M_N=225	eeqqqq	4f_singleW_semileptonic	4f_singleZee_semileptonic	6f_ttbar 2electrons	6f_ttbar 1electron	6f_ttbar 0electron
No cut	554	394	143	45	11898	2825010	699475	16425	129283	11028
e_{iso} #=2 && γ_{iso} #=0 &&	347	343	79	40	4721	90818	162774	9422	2271	201
Same sign ($e_{iso1} \times e_{iso2} = 1$)	176	115	39	12	39	46138	3800	8	439	25
$E_{iso} < 200$ [GeV]	175	114	39	12	39	41319	3557	8	439	25
$-0.95 < \cos\theta_{isoe} < 0.95$	156	103	36	11	13	17506	623	4	266	15
$\mathrm{IsolatedLepTagging}_{min} > 0.9$	94	91	31	10	2	2632	128	1	50	0
$\log_{10}(y12) > -1$	94	90	31	9	2	2632	128	1	50	0
$P_{miss} < 100$ && ($P_{miss} < 40$ || $\|\cos\theta_{Pmiss}\| > 0.95$)	84	84	28	9	1	79	30	0	9	0

Cut flow (eLpR)

- ILC 500 with ISR / BS
- **Pol(e⁻, e⁺) = (–0.8, +0.3)** $\mathcal{L} = 1600\,[\mathrm{fb}^{-1}]$

ILD work in progress

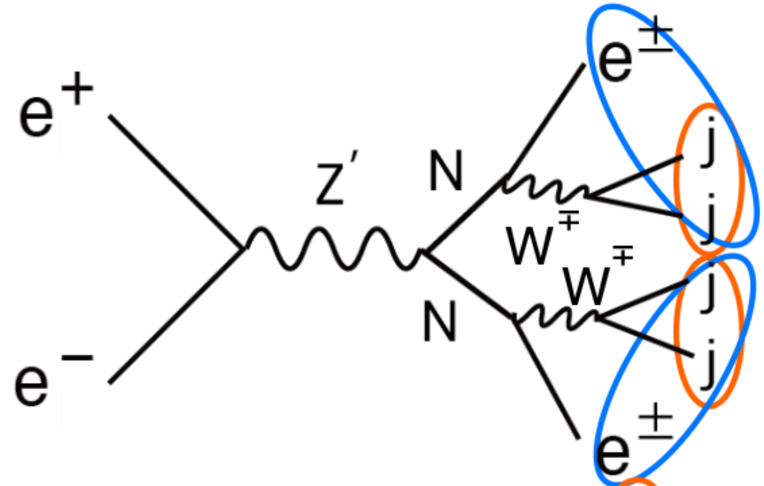
	Signal Events (ee→NN)				Background Events					
	M_N=100	M_N=150	M_N=200	M_N=225	eeqqqq	4f_singleW_semileptonic	4f_singleZee_semileptonic	6f_ttbar 2electrons	6f_ttbar 1electron	6f_ttbar 0electron
No cut	554	394	143	45	11898	2825010	699475	16425	129283	11028
e_{iso} #=2 && γ_{iso} #=0 &&	347	343	79	40	4721	90818	162774	9422	2271	201
Same sign ($e_{iso1} \times e_{iso2} = 1$)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	25
$E_{iso} < 200$ [GeV]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	25
$-0.95 < \cos\theta_{isoe} < 0.95$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	266	15
IsolatedLepTagging$_{min}$ > 0.9	94	91	31	10	2	2632	128	1	50	0
$\log_{10}(y12) > -1$	94	90	31	9	2	2632	128	1	50	0
$P_{miss} < 100$ && ($P_{miss} < 40$ || $\|\cos\theta_{Pmiss}\| > 0.95$)	84	84	28	9	1	79	30	0	9	0

Signal efficiency ~ **20%**

Remaining backgrounds events ~ **120** eLpR), **20** (eRpL)

Reconstruction methods

After removing isolated electrons force into 4 jets (Durham)



Search for the correct combination of jj and jje

Jet pair 1 → M_{jj1}, Jet pair 2 → M_{jj2}

$$F_1 = (M_{jj1} - M_w)^2 + (M_{jj2} - M_w)^2$$

Best jet pair 1 + iso e → M_{jje1}

Best jet pair 2 + iso e → M_{jje2}

We expect for "$M_{jje1} = M_{jje2}$"

$$F_2 = (M_{jje1} - M_{jje2})^2$$

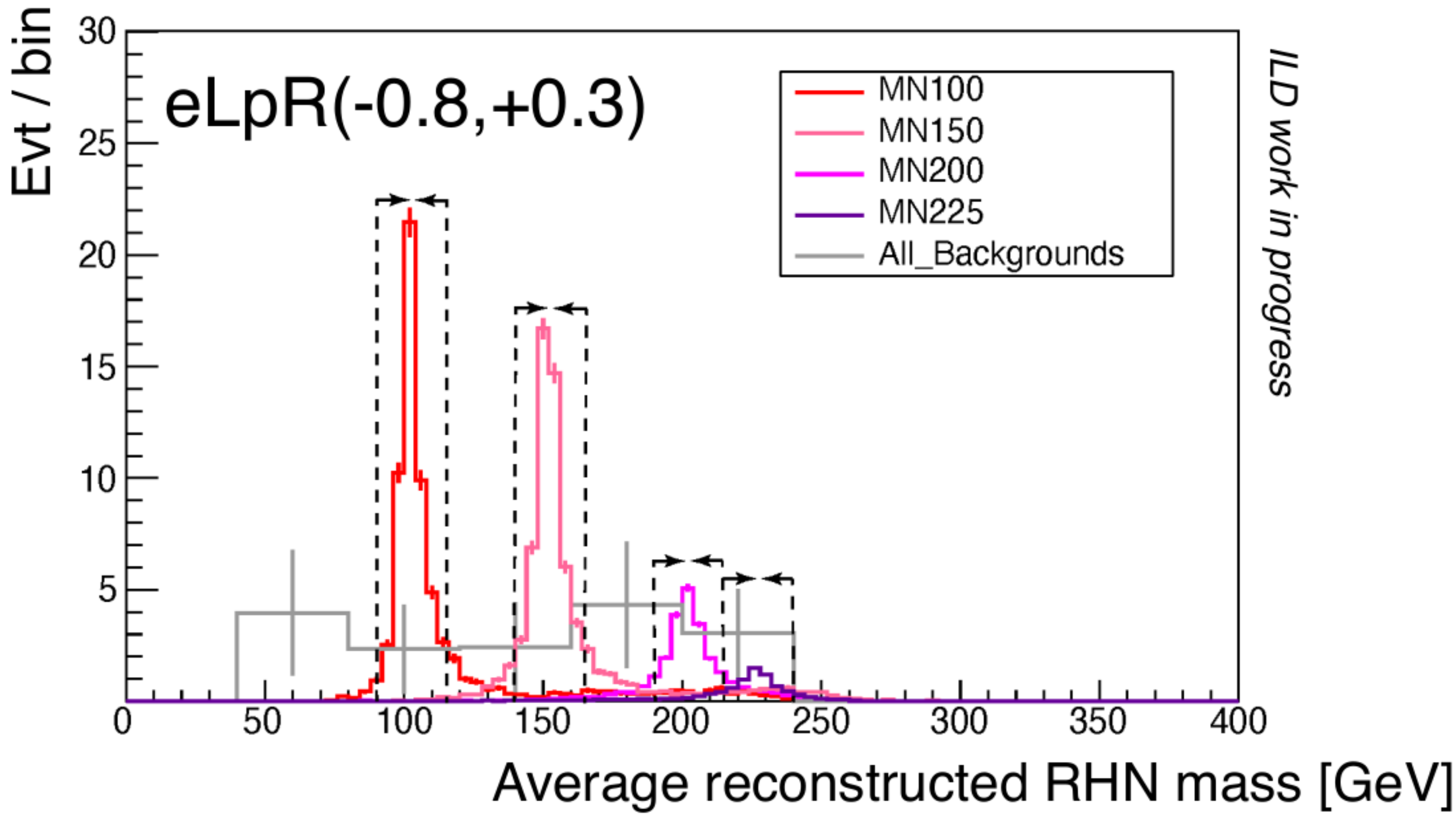
Choose combination with minimum F_1,F_2

Signal mass cut

- ILC 500 with ISR / BS
- Pol(e^-, e^+) = (-0.8, +0.3)

$\mathcal{L} = 1600\,[\mathrm{fb}^{-1}]$

For each M_N, mass window M_N-10, M_N+15 [GeV]



Assume background distribution is flat

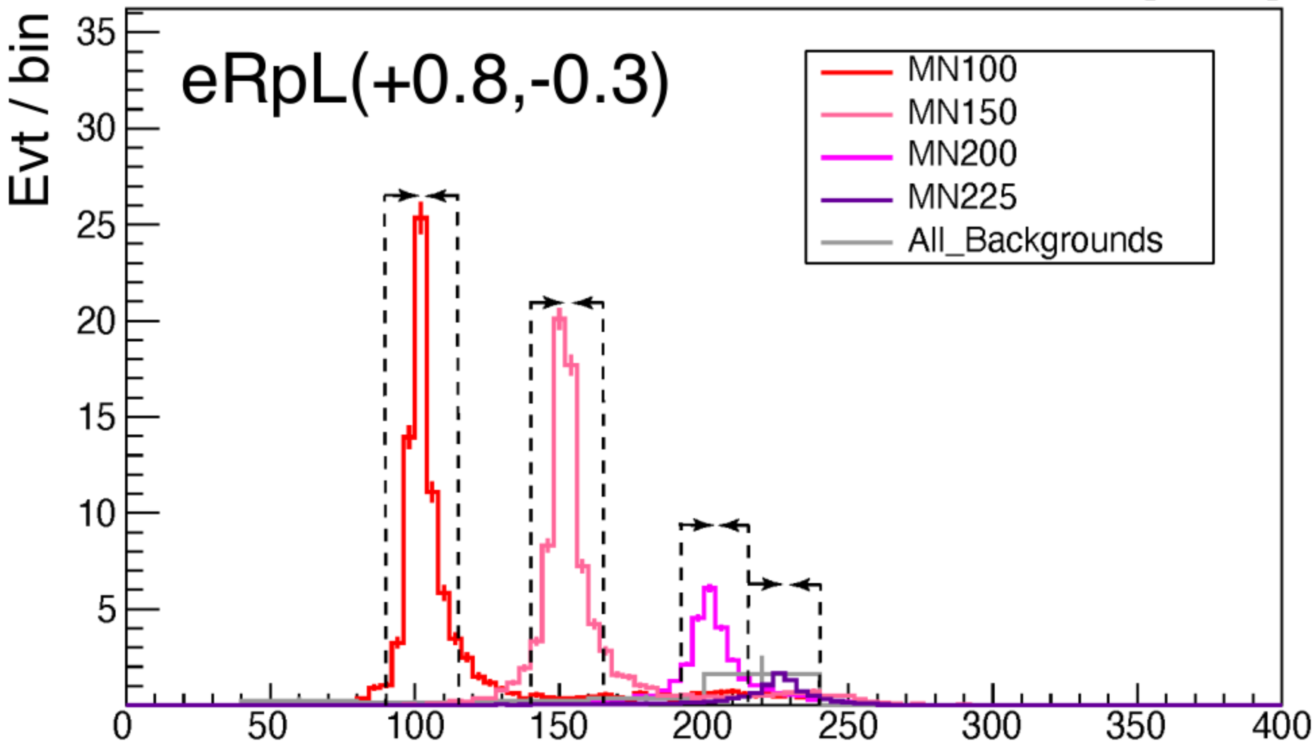
20 (eLpR) background events remain in mass window

Signal mass cut

- ILC 500 with ISR / BS
- Pol(e⁻, e⁺) = (+0.8, −0.3)

$\mathcal{L} = 1600\,[\mathrm{fb}^{-1}]$

For each M_N, mass window M_N-10, M_N+15 [GeV]



Assume background distribution is flat

20 (eLpR) and 3 (eRpL) background events remain in mass window

Less backgrounds thanks to beam polarization
Reduce W contribution

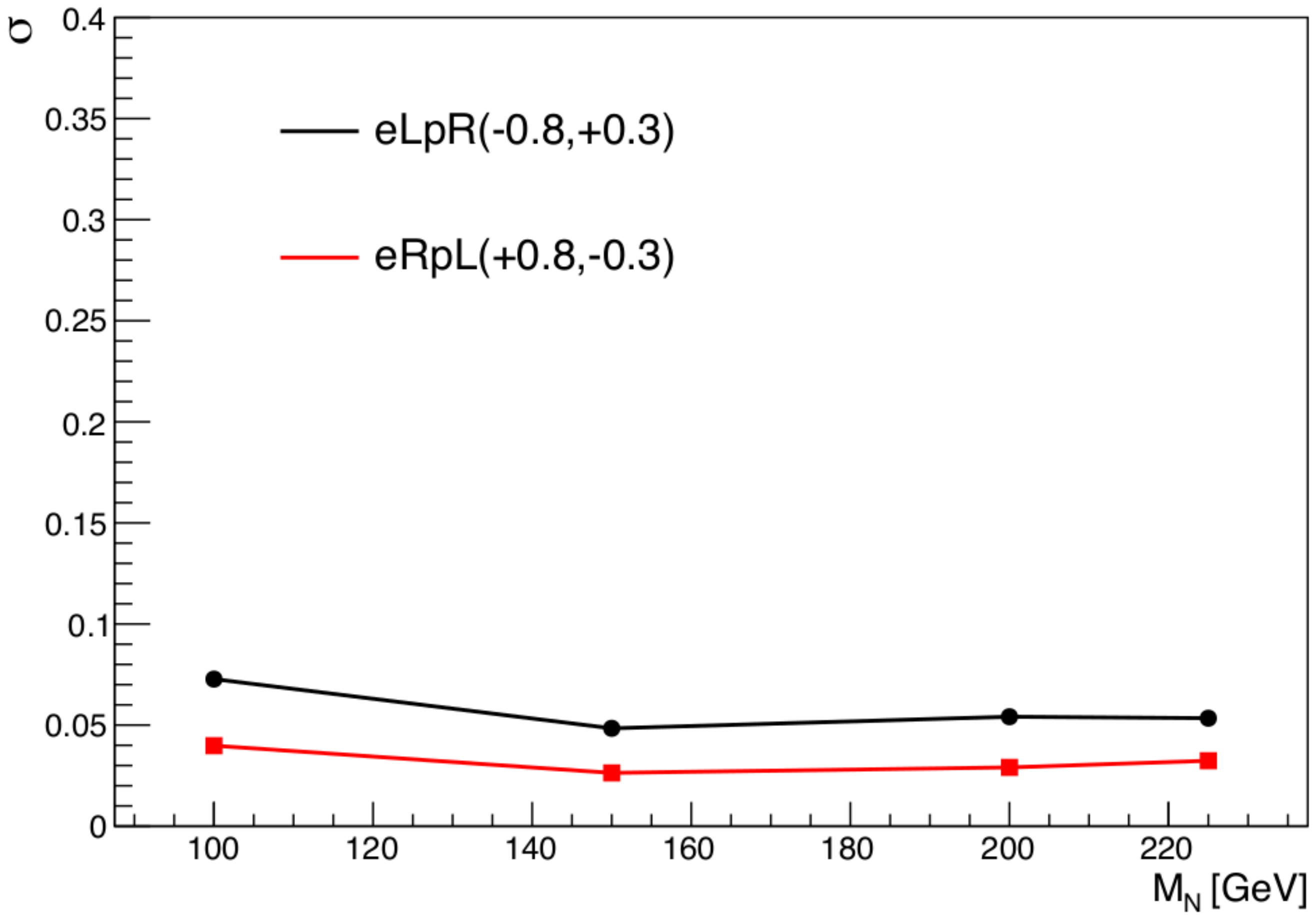
Results

	M_N [GeV]	# of Signal After mass cut	# of BG After cut	σ_0 [fb] Initial benchmark (ee→NN)	σ_{95} [fb] 95% exclusion limit (ee→NN)	$\frac{\sigma_{95}}{\sigma_0}$
LR **80,30**	100	53.64	20.12	0.35	0.073	0.21
	150	52.73		0.22	0.048	0.21
	200	18.30		0.088	0.054	0.61
	225	5.51		0.029	0.053	1.8
RL **80,30**	100	66.75	3.24	0.43	0.040	0.092
	150	63.41		0.27	0.026	0.097
	200	21.23		0.10	0.029	0.29
	225	6.08		0.032	0.032	1

Exclusion plot on cross-section $\sigma(ee \to NN)$

$$\sigma = \sigma_0 \times \left\{ \frac{2}{N_S} \left(1 + \sqrt{1 + N_B}\right) \right\}$$

Calculate 95% UL on $\sigma(ee \to NN)$

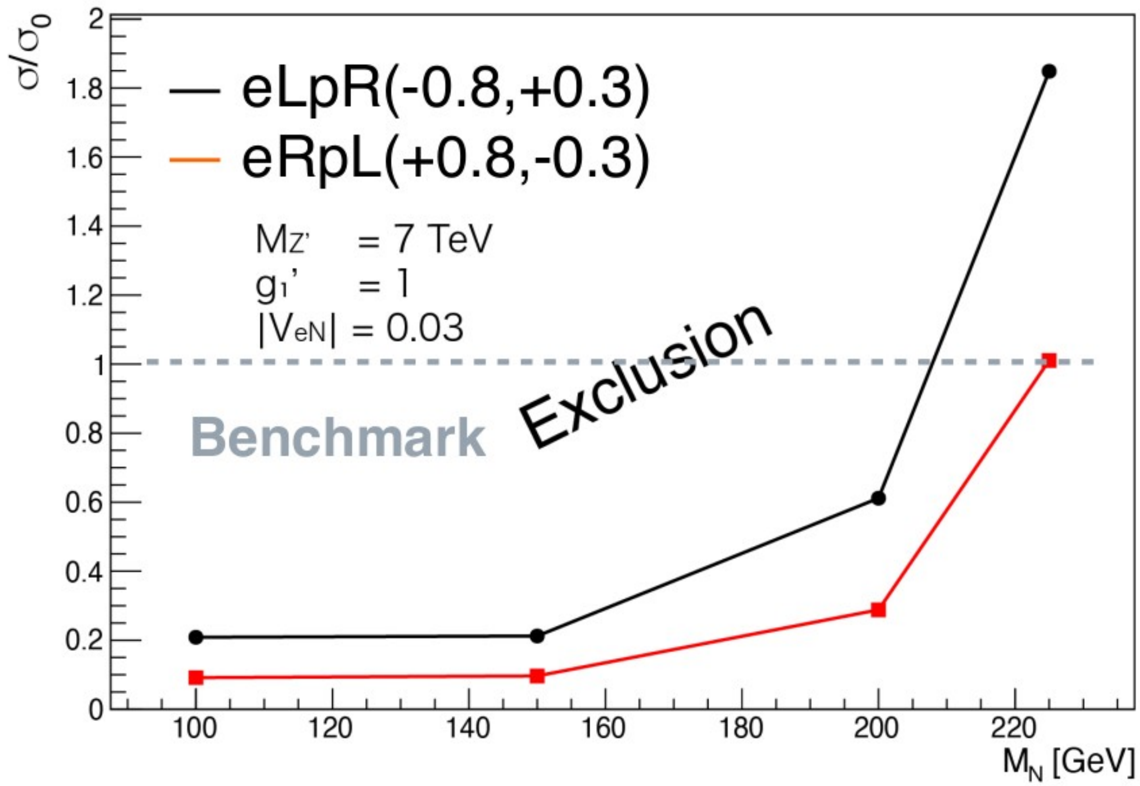


Exclusion plot on σ/σ_0

Normalised to benchmark cross-section

Calculate 95% UL on σ/σ_0

σ_0 : benchmark cross-section



Exclude benchmark points and cross-sections up to 10x smaller

Summary

Conclusion:

Can use same sign lepton signature to set powerful limits on RHN at ILC!

or, if we are lucky, good prospects to discover them

Current activity & future plan:

- ILC250 case (on going)
  → Try to improve signal efficiency

- Same sign muons
  → Expect smaller backgrounds

+ check all other SM processes for possible background contributions