Exploring Right Handed Neutrinos at ILC

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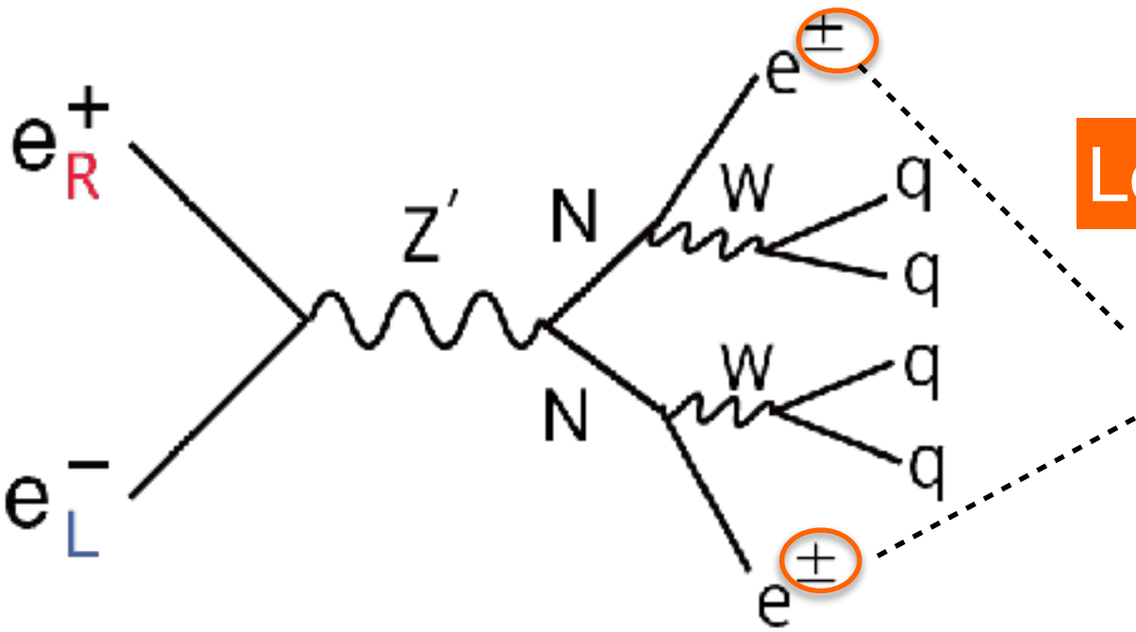
Motivation and Introduction

The right handed neutrino(RHN) can address the following big questions

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

Right handed neutrino is assumed to be a Majorana particle.($\nu = \bar{\nu}$)

RHN **pair** production *OK!*



Lepton # violation is possible!

↓

Same sign leptons possible

↓

No SM BG!

Model

Gauged B-L extension of Standard Model(SM)

The unique anomaly free global symmetry in the SM

$$G_{B-L} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

Gauge boson : Z'

- Anomaly free requirement → RHNs
- Seesaw mechanism ← automatically include

If B-L symmetry breaks spontaneously → Z' becomes **massive**

minimal B-L model

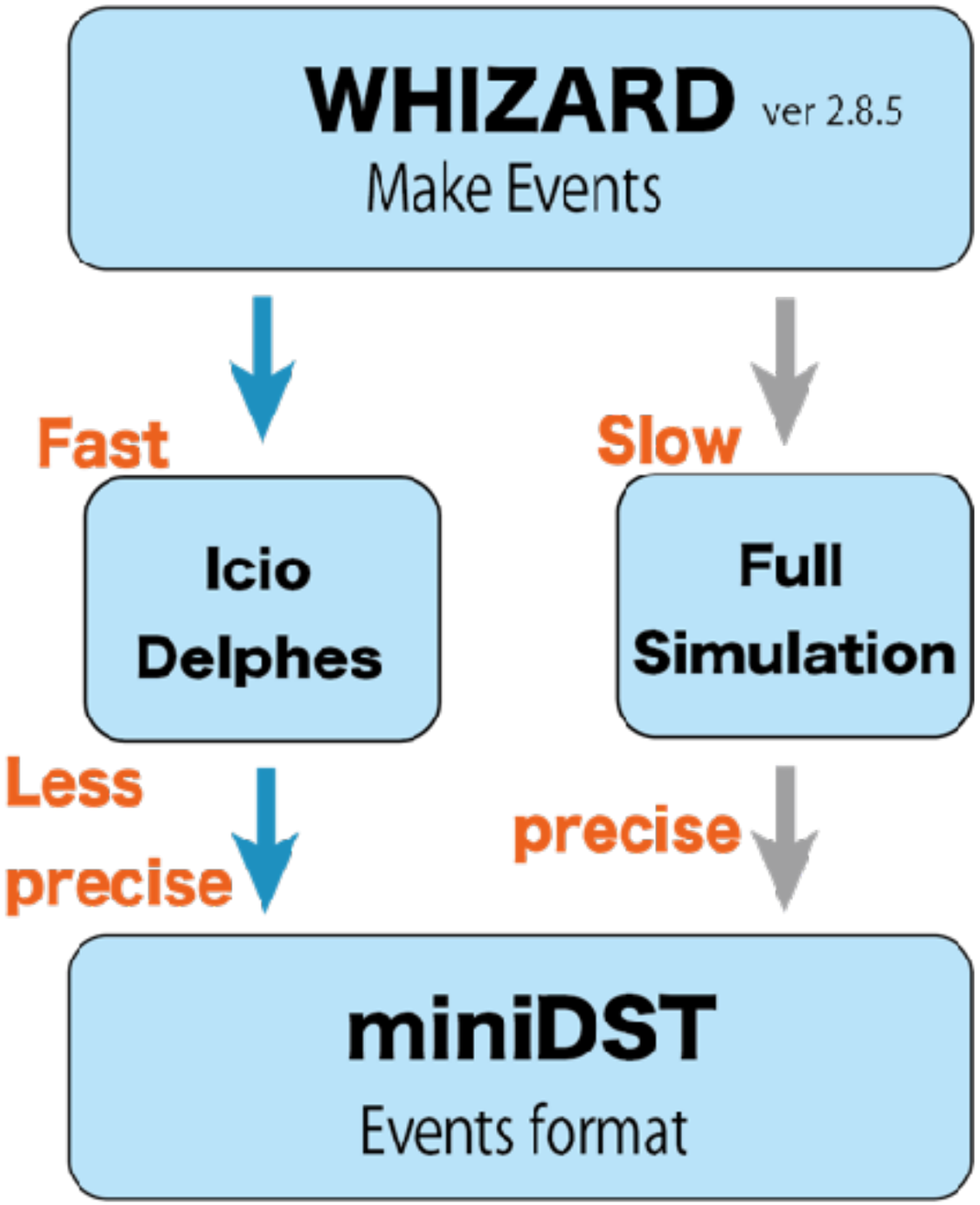
	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
N_R^i	1	1	0	-1
Φ	1	1	0	2

i=1,2,3

arXiV[1812.11931]

Arindam Das, Nobuchika Okada, Satomi Okada, Digesh Raut

Analysis tool

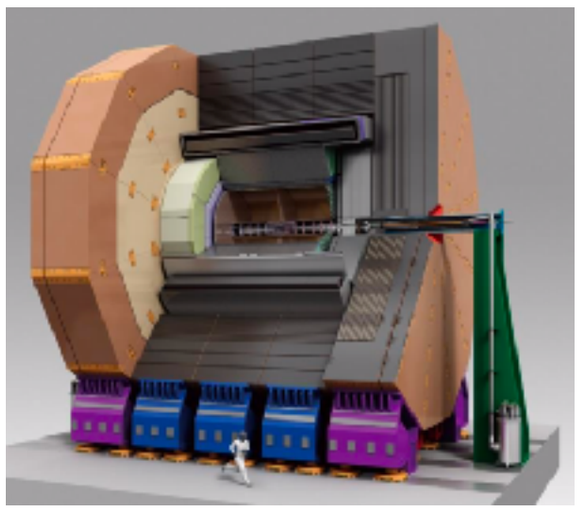


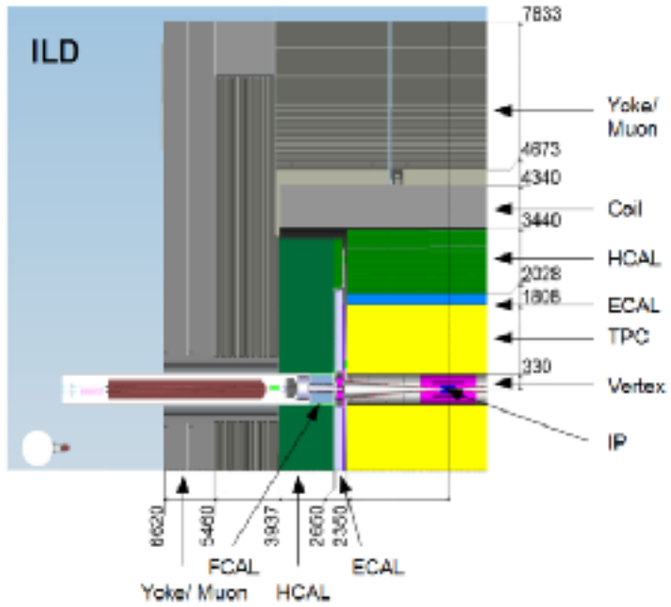
Fast simulation

Using Delphes with the
"**generic ILC detector card**"
recently prepared for the US Snowmass study

Full simulation

Calculating all values in detectors
(Full geant4 simulation of ILD)





We prepared fast and full simulation signal samples.

Benchmark points

Not excluded by LHC

M_N [GeV]	$M_{Z'}$ [TeV]	g1'	$\lvert V_{eN}\rvert^2$	σ_{LR} (ee→NN) [fb]	Event # [4000fb^{-1}]
100	7	1	0.001	7.08E-01	**1261**
200	7	1	0.005	1.63E-01	**131**

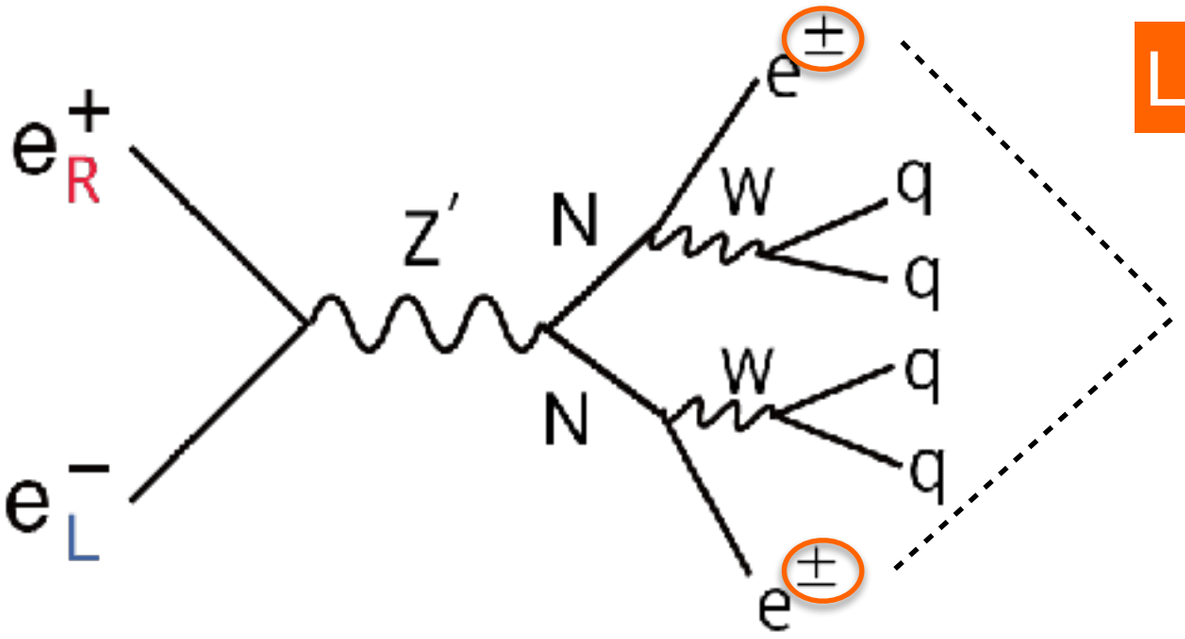
- minimal $U(1)_{B\text{-}L}$ model

  ✦$\sigma_{LR} = \sigma_{RL}$

- ILC 500 with initial state radiation(ISR) and beamstrahlung(BS)
  - 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 : RHN mass
$M_{Z'}$: Z' mass
g1' : $U(1)_{B\text{-}L}$ coupling constant
V_{eN} : mixing angle

Backgrounds



Lepton # violation is possible!

↓

Same sign leptons possible

↓

No SM BG!

However… We need to consider

Choosing the wrong particle as an electron

Add to full simulation background samples.

eexyyx, xxxxee, yyyyee

x…up type fermion
y…down type fermion

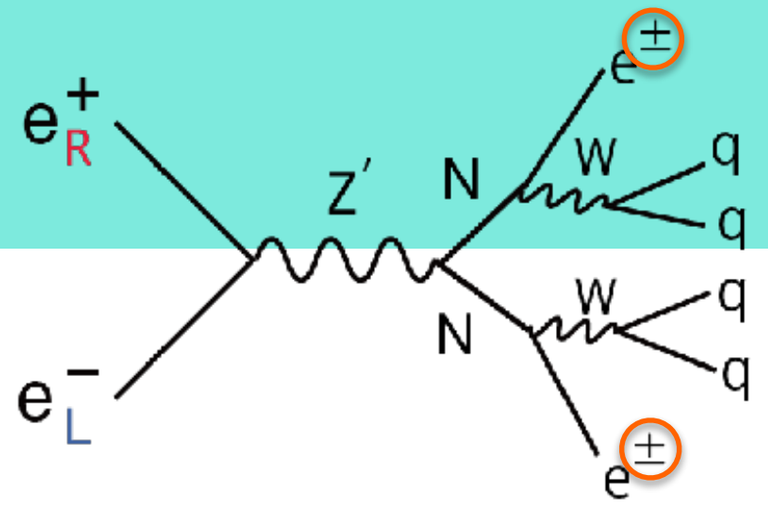
Cross section — Background

x…up type fermion
y…down type fermion

(100%,100%)	eexyyx [fb]	xxxxee [fb]	yyyyee [fb]
eLpR	16.4	0.0871	0.145
eRpL	3.64	0.0462	0.0531
eLpL	6.63	0.0338	0.022
eRpR	6.61	0.033	0.0197

“eexyyx" process is dominant

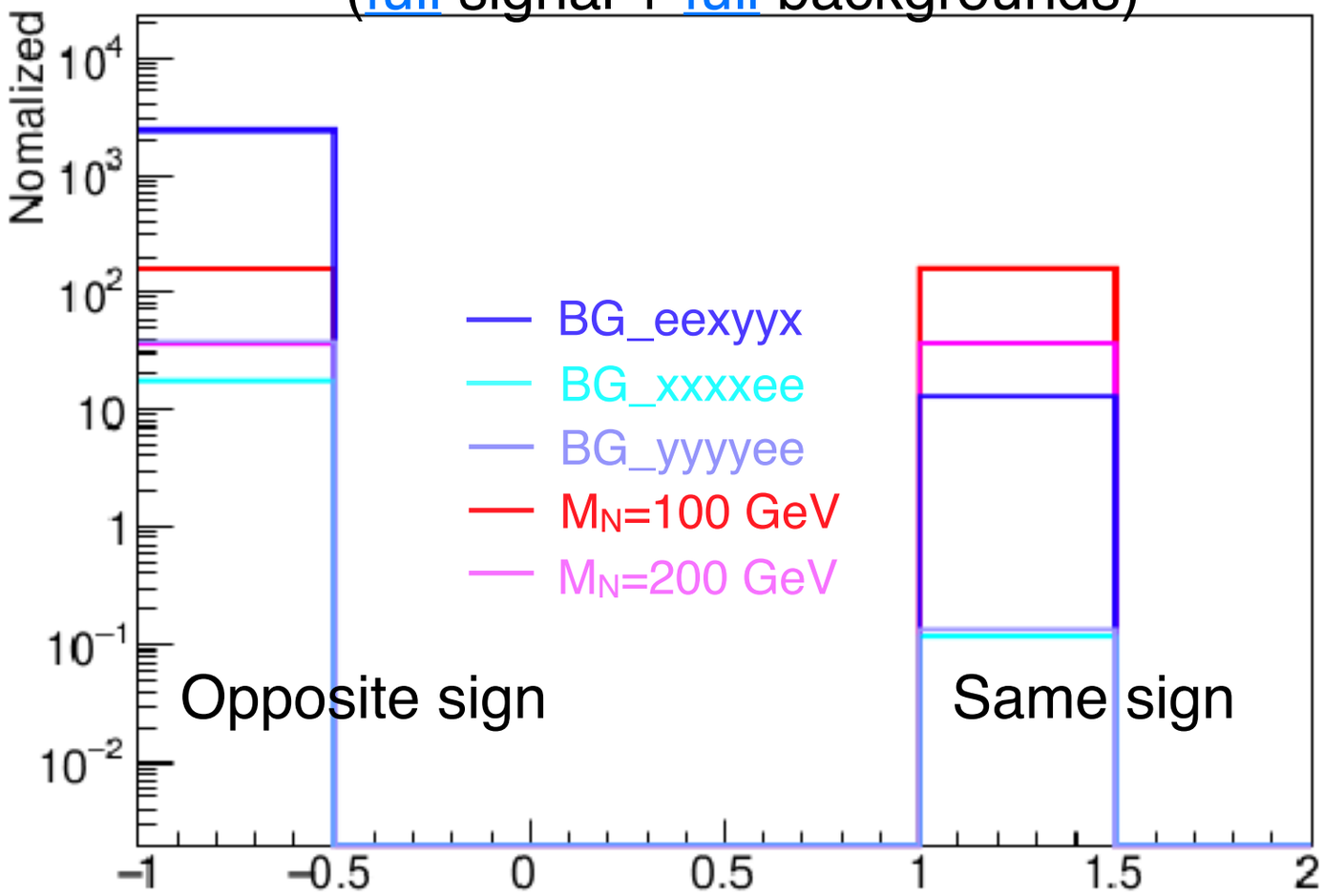
Electron Charge



- ILC 500 with ISR / BS
- Pol(e^-, e^+) = (-0.8, +0.3)
- Isolated e # = 2 && Isolated γ # =0

Isolated electrons charge

(full signal + full backgrounds)



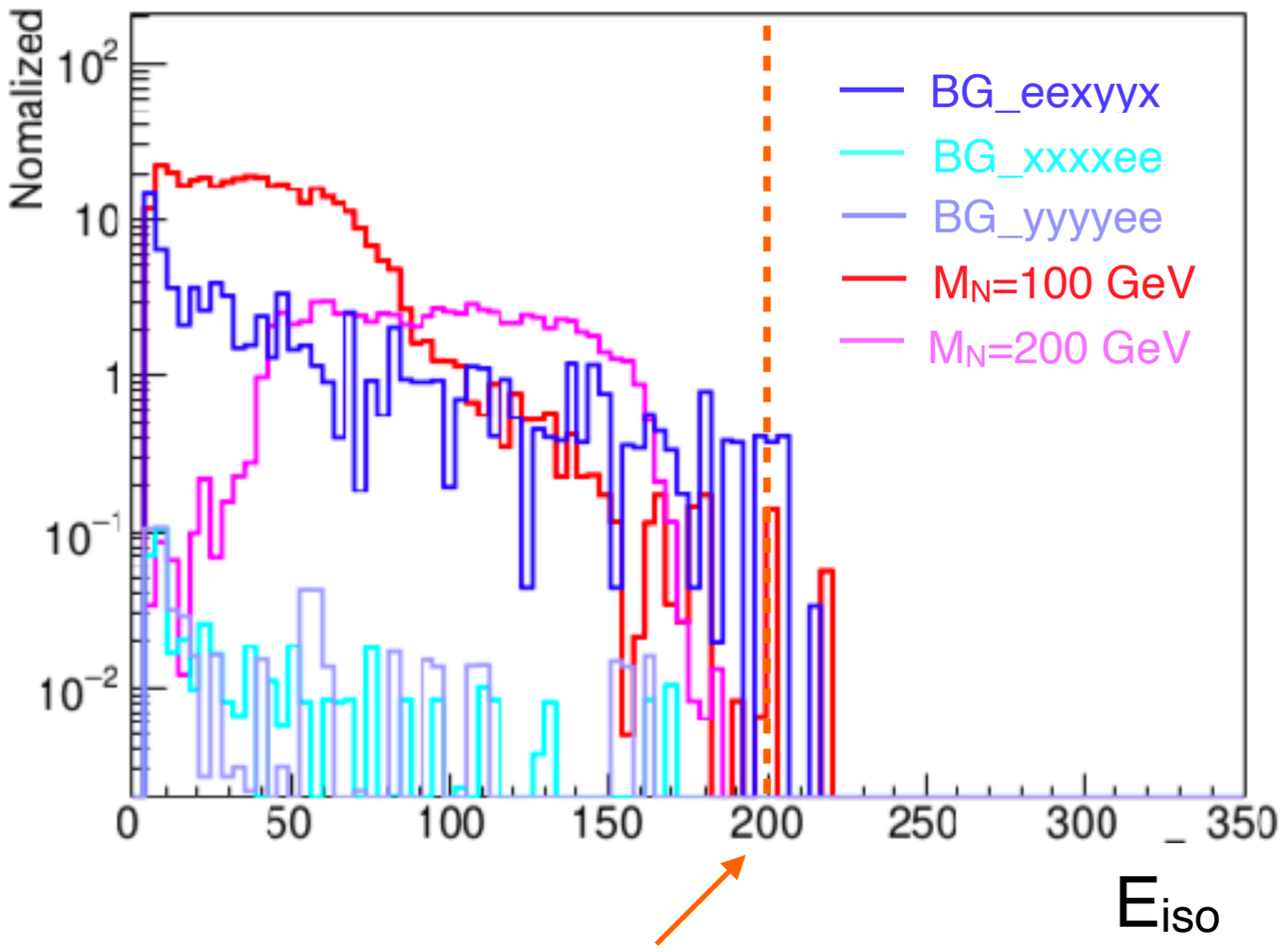
We use only same sign samples **Charge == 1**

Distribution of Isolated electron energy

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

- Isolated e # = 2 && Isolated γ # =0
- Isolated e is same sign($e_1 \times e_2 = 1$)

Isolated electron energy
(full signal + full backgrounds)



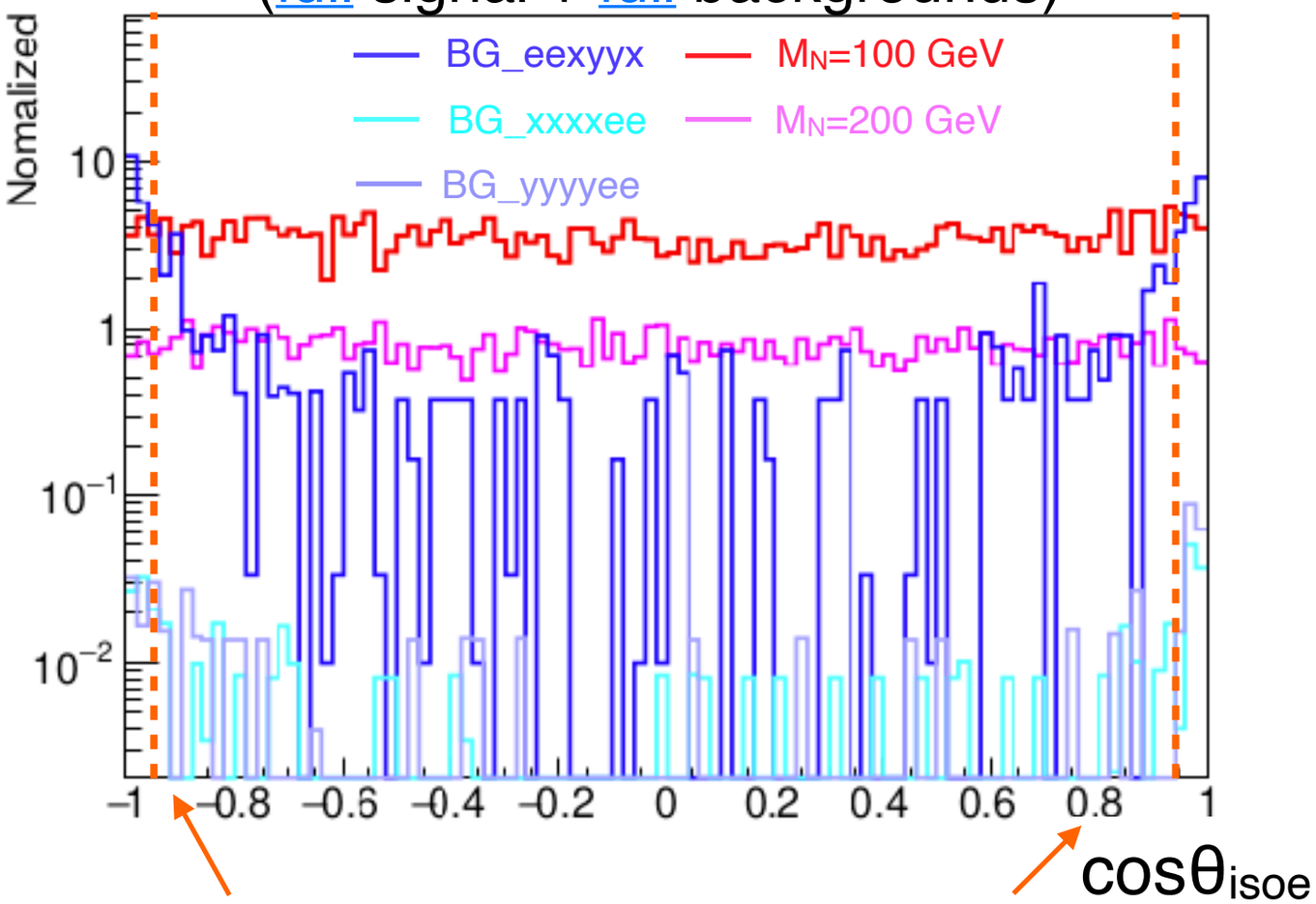
E_{iso} < 200 [GeV]

Distribution of $\cos\theta_{isoe}$

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

- Isolated e # = 2 && Isolated γ # =0
- Isolated e is same sign($e_1 \times e_2 = 1$)
- $E_{iso} < 200$ [GeV]

$\cos\theta_{isoe}$
(full signal + full backgrounds)

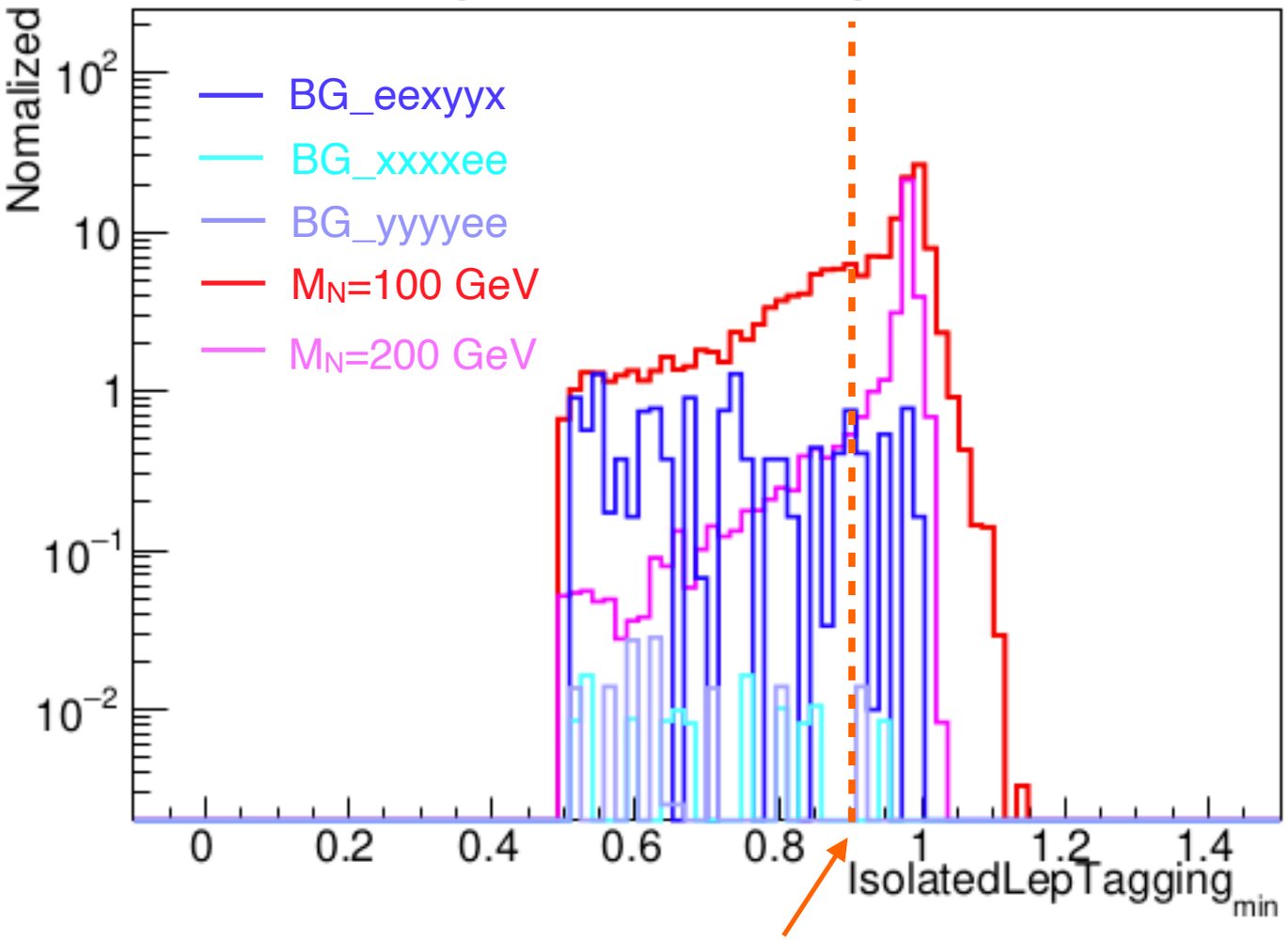


$-0.95 < \cos\theta_{isoe} < 0.95$

Distribution of IsolatedLepTagging

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

Minimum of isolated lepton tagging
(full signal + full backgrounds)



- Isolated e # = 2 && Isolated γ # =0
- Isolated e is same sign($e_1 \times e_2 = 1$)
- $E_{iso} < 200$ [GeV]
- $-0.95 < \cos\theta_{isoe} < 0.95$

Isolated lepton tagging
… "output" parameter of neural network to identify isolated lepton

→ Output for e is **near 1**

IsolatedLepTagging$_{min}$ > 0.9

Cut flow (eLpR)

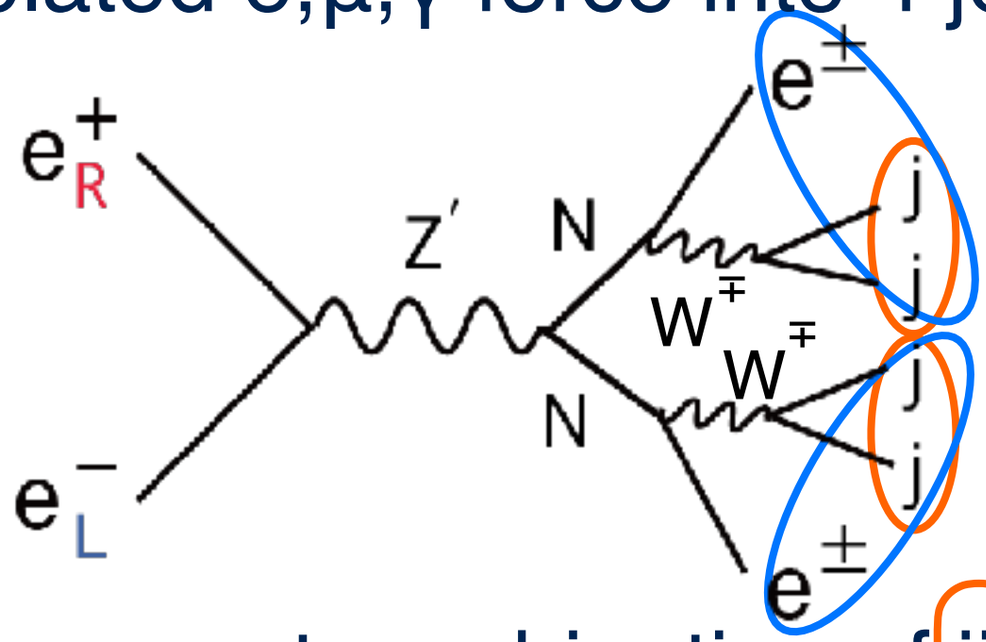
	Signal Entries		Background Entries			Total background
	M_N =100	M_N=200	eexyyx	xxxxee	yyyyee	
No cut	1109	286	23472	118	207	23797
e_{iso} # = 2	837	252	14697	75	146	14918
$e_{iso\gamma}$ # = 0	701	158	9348	50	97	9495
Same sign ($e_{iso1} \times e_{iso2} = 1$)	355	79	80	0.47	0.55	81.02
$E_{iso} < 200$ [GeV]	355	79	78	0.47	0.55	79.02
$-0.95 < \cos\theta_{isoe} < 0.95$	315	72	26	0.23	0.27	26.50
$\text{IsolatedLepTagging}_{min} > 0.9$	186	62	3.76	0.001	0.005	3.77

Cut flow (eRpL)

	Signal Entries		Back ground Entries			Total background
	M_N =100	M_N=200	eexyyx	xxxxee	yyyyee	
No cut	1116	287	7691	68	91	7850
e_{iso} # = 2	841	252	3769	40	60	3869
$e_{iso}\gamma$ # = 0	697	162	2406	26	41	2473
Same sign ($e_{iso1}\times e_{iso2}$ = 1)	345	82	29	0.34	0.34	29.68
E_{iso} < 200 [GeV]	345	82	28	0.33	0.34	28.67
-0.95< $\cos\theta_{isoe}$ < 0.95	318	74	6.57	0.12	0.17	6.86
$IsolatedLepTagging_{min}$ > 0.9	189	64	0.96	0.02	0.01	0.99

Reconstruction methods

After removing isolated e,μ,γ force into 4 jets (Durham)



Search for the correct combination of jj and jje

Jet pair 1 $\rightarrow M_{jj1}$, Jet pair 2 $\rightarrow M_{jj2}$

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

Best jet pair 1 + iso e $\rightarrow M_{jje1}$

Best jet pair 2 + iso e $\rightarrow M_{jje2}$

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

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

Choose combination with minimum F

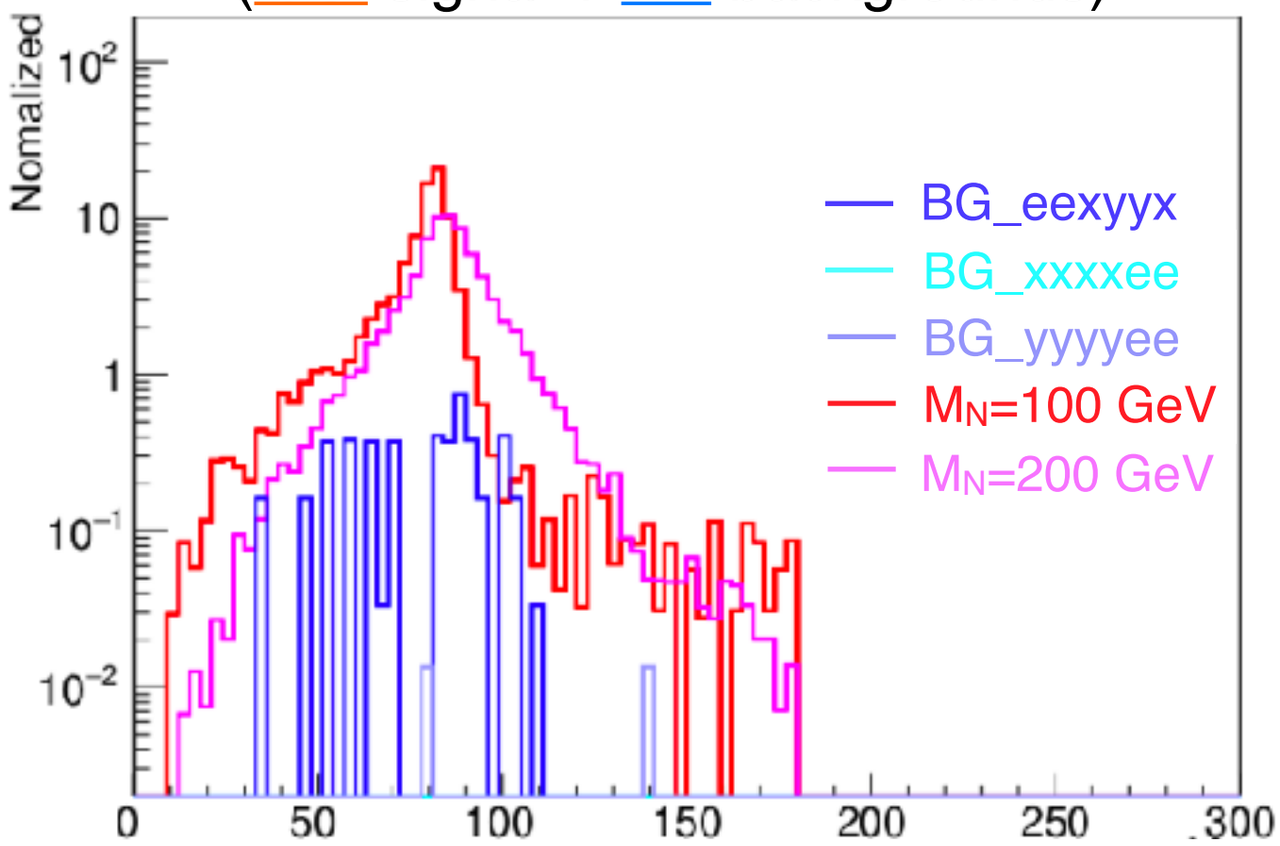
Results — Reconstructed W

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

- Isolated e # = 2 && Isolated γ # =0
- Isolated e is same sign($e_1 \times e_2 = 1$)
- $E_{iso} < 200$ [GeV]
- $-0.95 < \cos\theta_{isoe} < 0.95$
- $\text{IsolatedLepTagging}_{min} > 0.9$

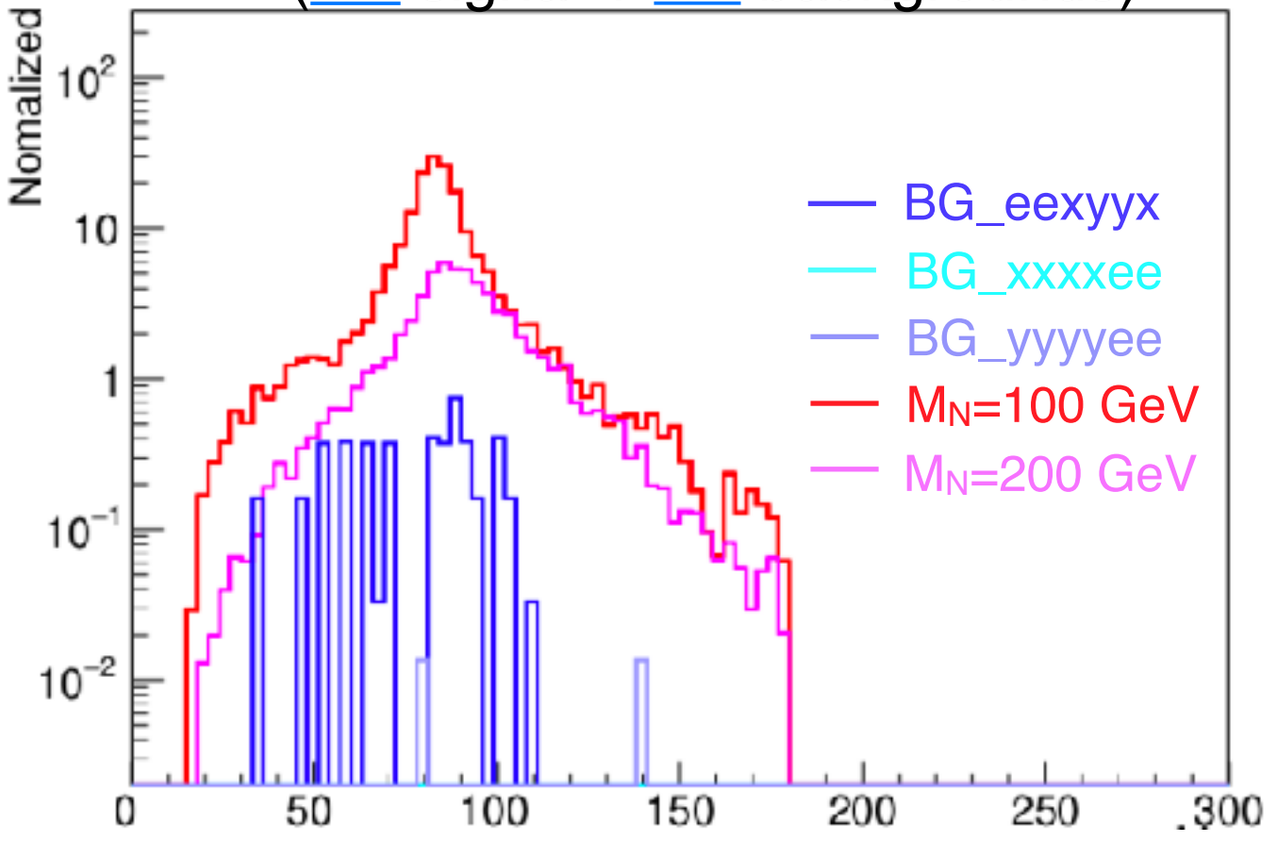
W mass

(fast signal + full backgrounds)



W mass

(full signal + full backgrounds)

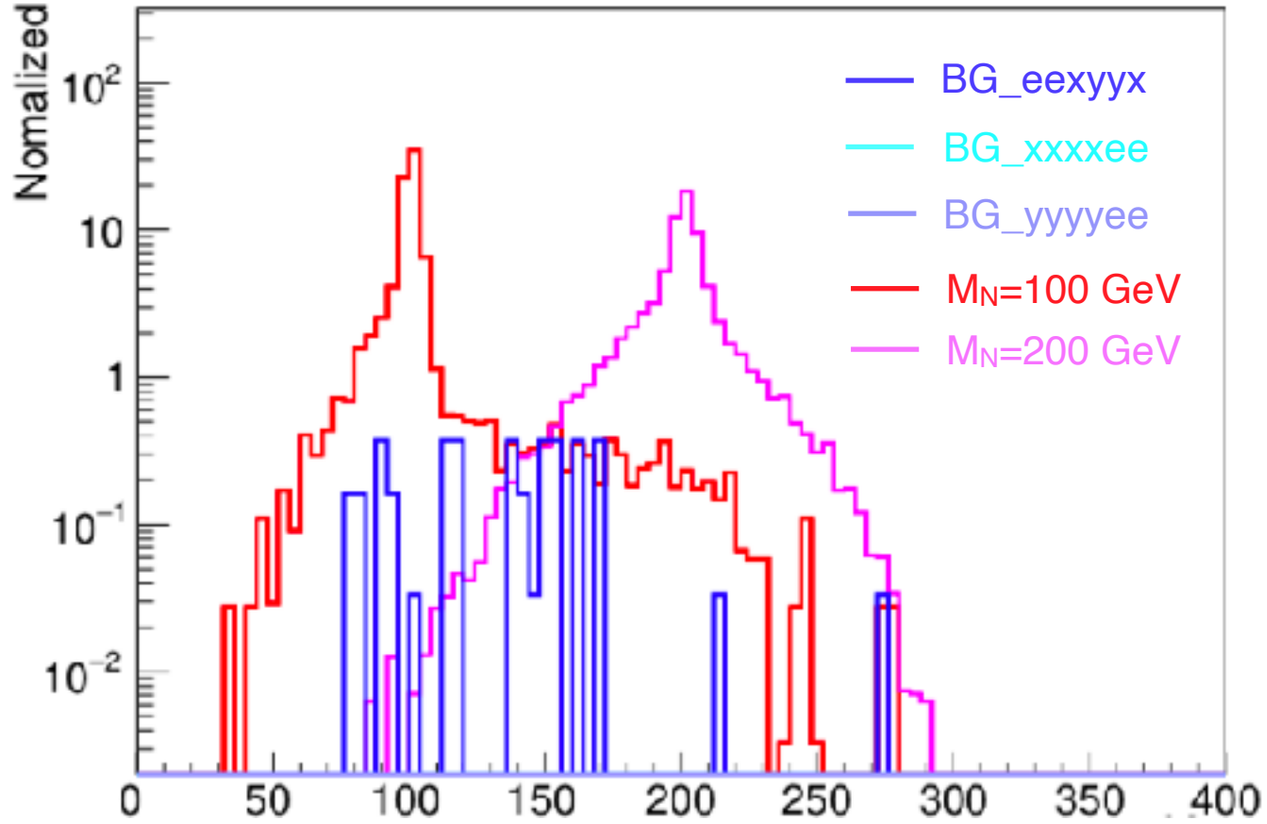


Results — Reconstructed RHN

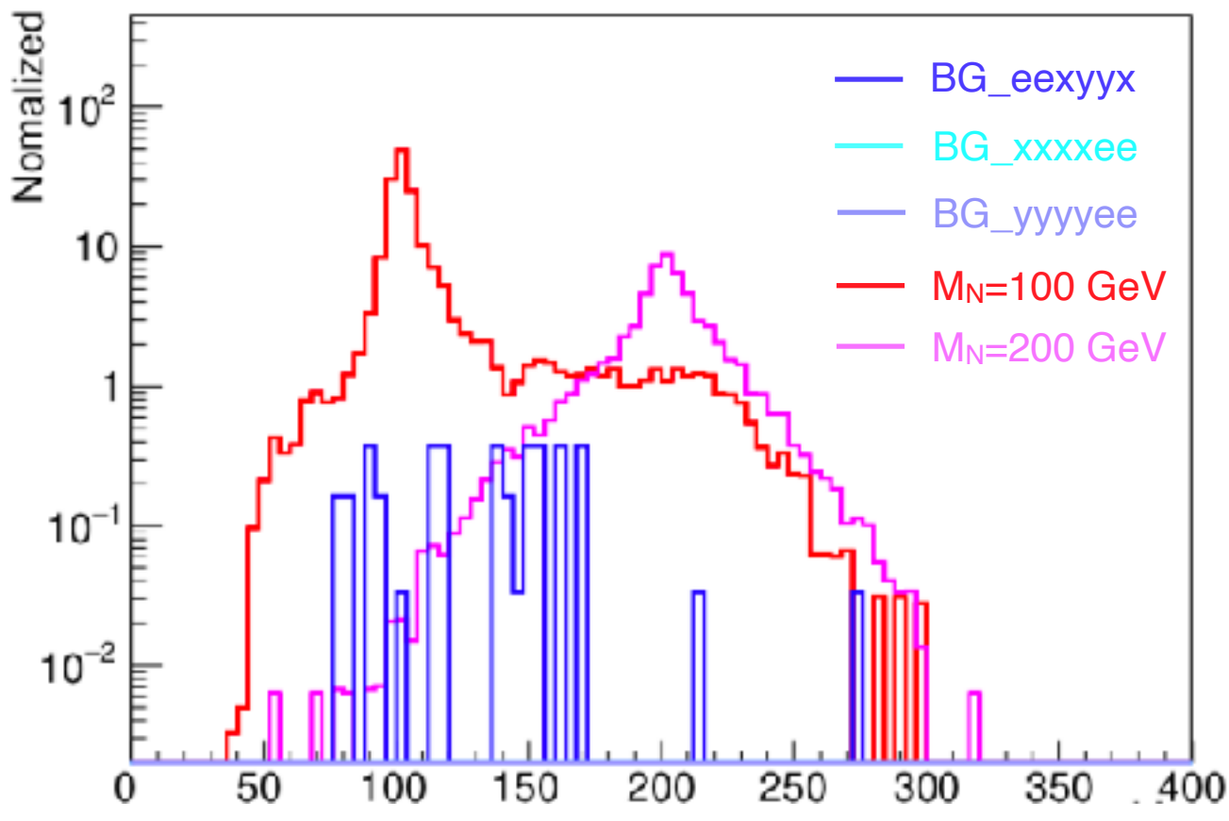
- ILC 500 with ISR / BS
- Pol(e^-, e^+) = (-0.8, +0.3)

- Isolated e # = 2 && Isolated γ # =0
- Isolated e is same sign($e_1 \times e_2 = 1$)
- $E_{iso} < 200$ [GeV]
- $-0.95 < \cos\theta_{isoe} < 0.95$
- $\text{IsolatedLepTagging}_{min} > 0.9$

RHN mass
(fast signal + full backgrounds)



RHN mass
(full signal + full backgrounds)



Summary

- We analyze “RHN **pair** production” by full simulation and fast simulation

- There are **small** difference between fast simulation and full simulation

- Background events are a few for 1600 [fb^{-1}] of ILC500

→ “RHN pair production” is **almost background free**

Next step

- There are **small** difference between fast simulation and full simulation

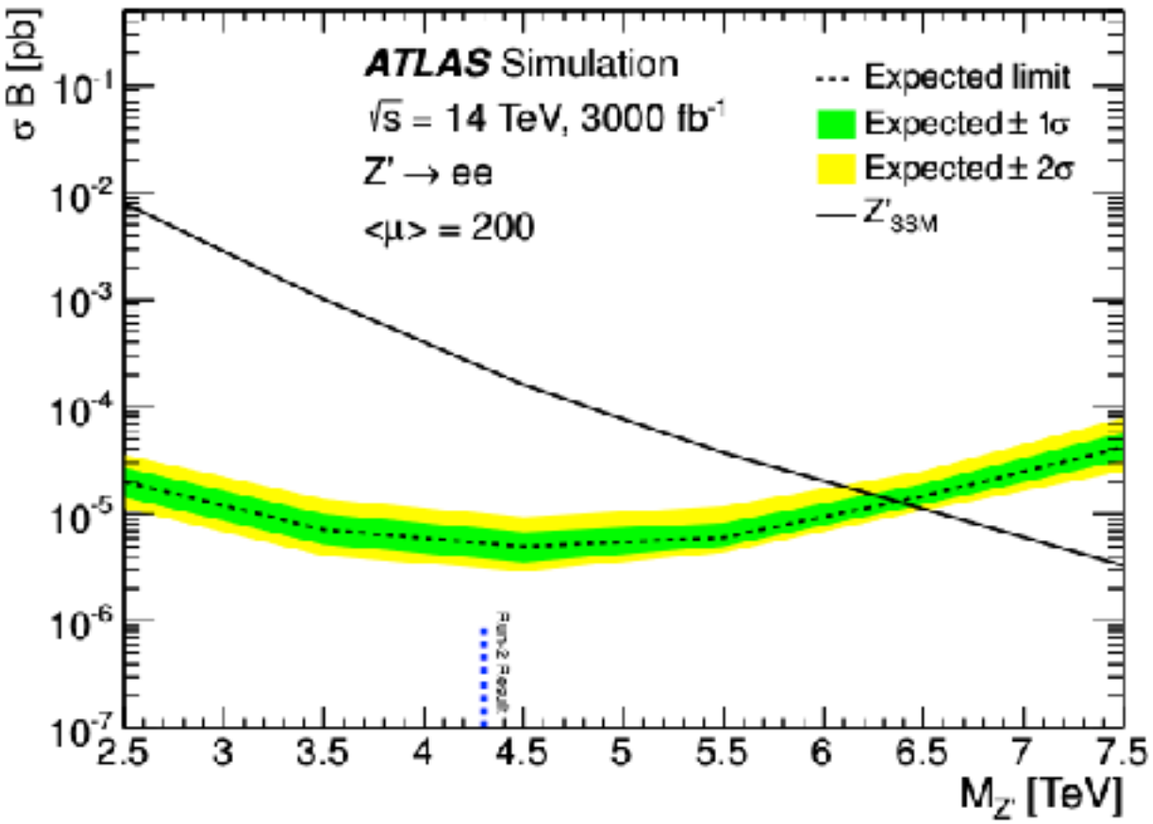
  ⟶ What is the cause? -> overlay events …? etc..?

I want to deepen my understanding.

Backup

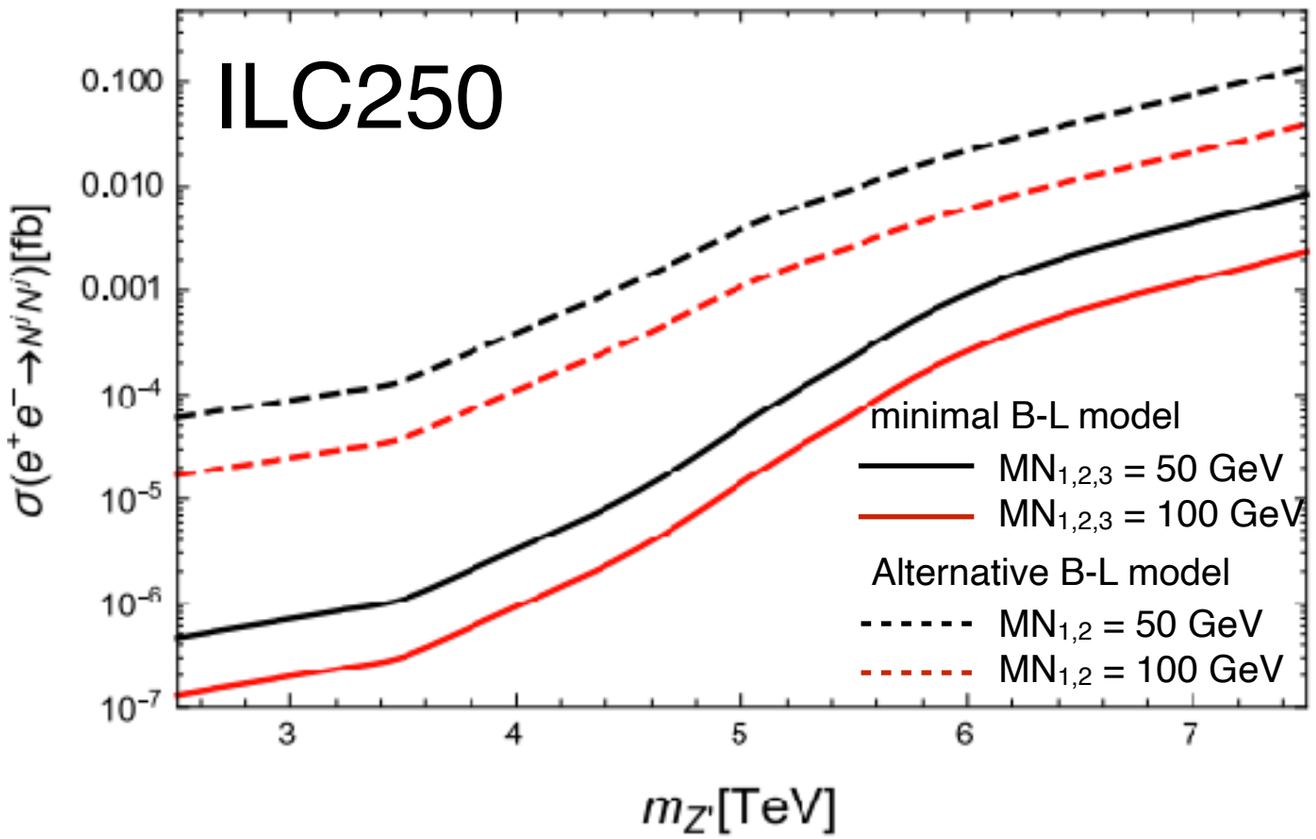
Current limits - Z' mass

SM like Z' coupling



ATLAS-TDR-LHCC2017-2018

HL-LHC prospects limit for $U(1)_{B-L}$ model

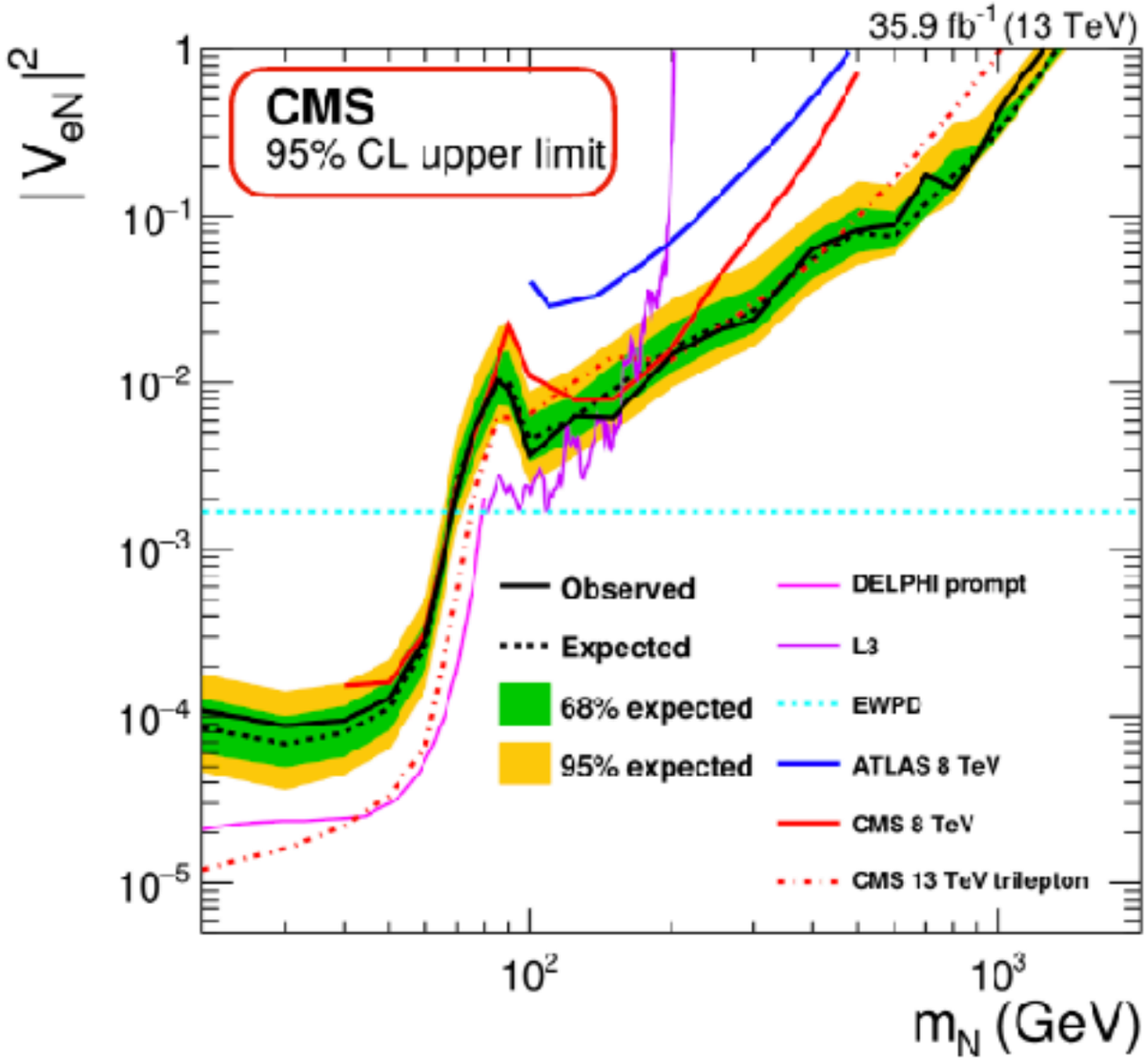


arXiV[1812.11931]

The heavier Z' mass less constrained by LHC

Current limits $|V_{eN}|^2$

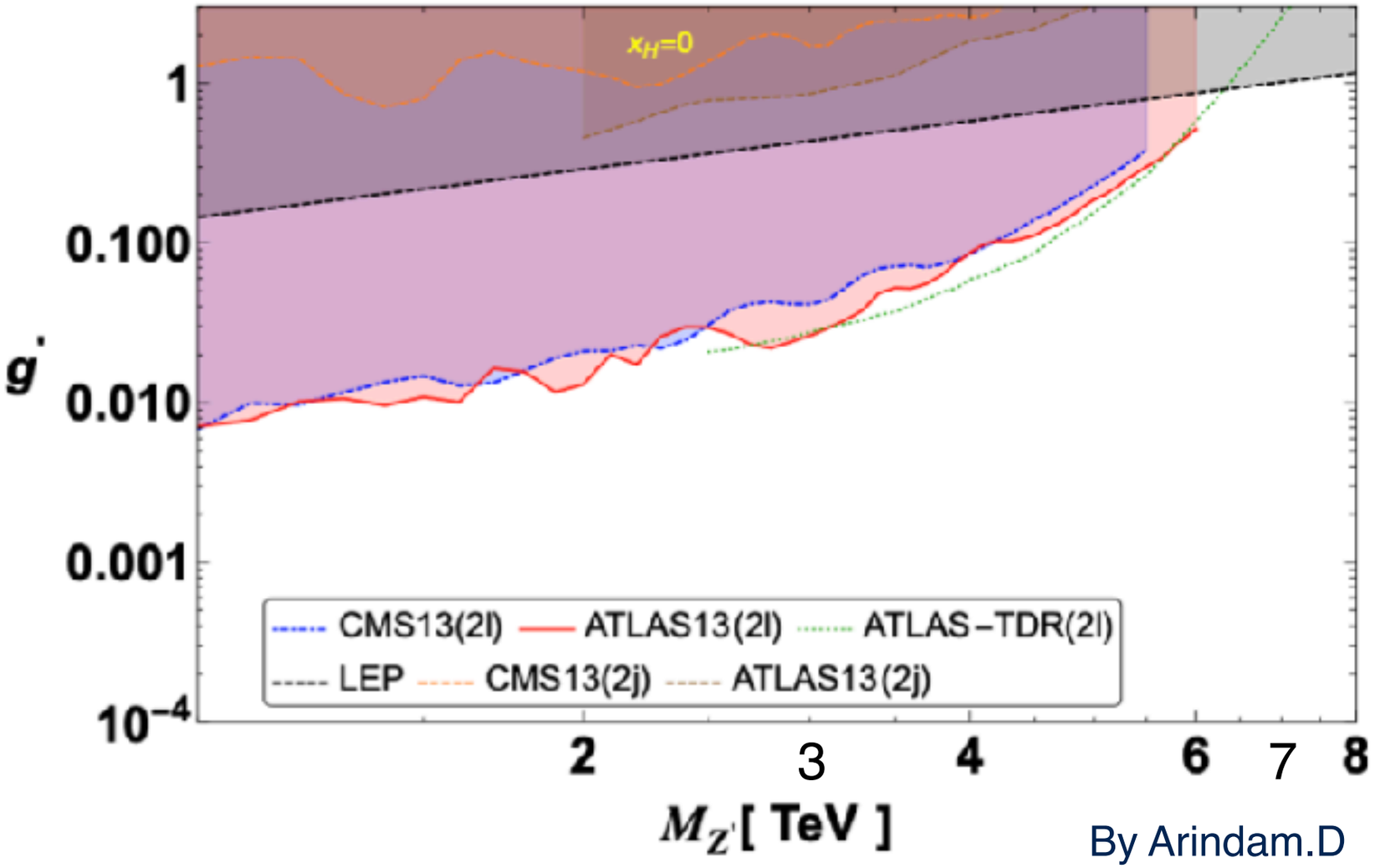
$|V_{eN}|^2$: the “light-heavy” neutrino mixing matrix



CMS PAS EXO-19-019

Current Limits and prospects - Z' mass,g1'

G1' :$U(1)_{B\text{-}L}$ gauge coupling constant

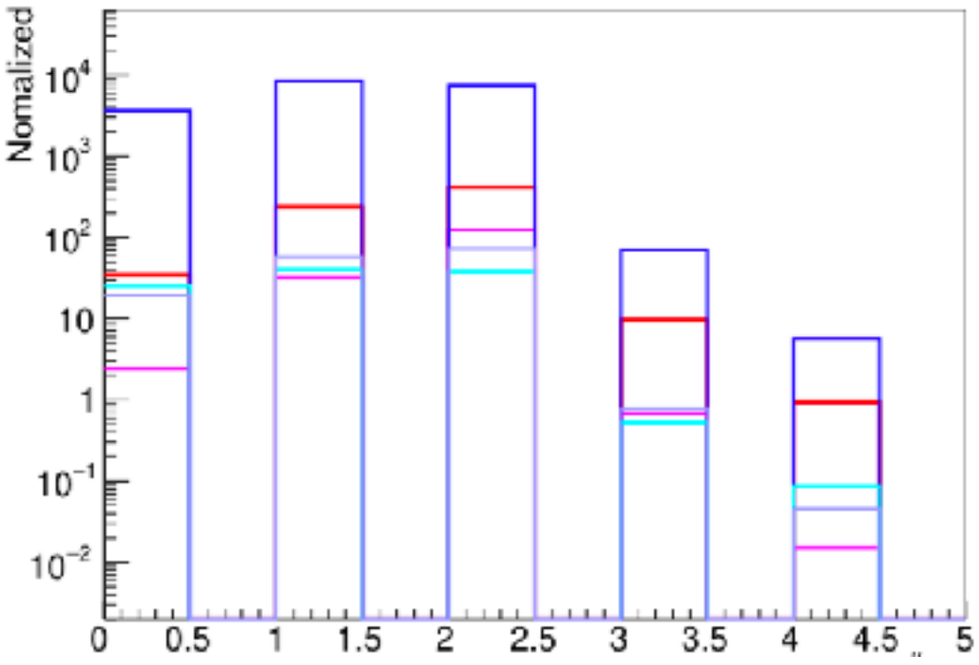


By Arindam.D

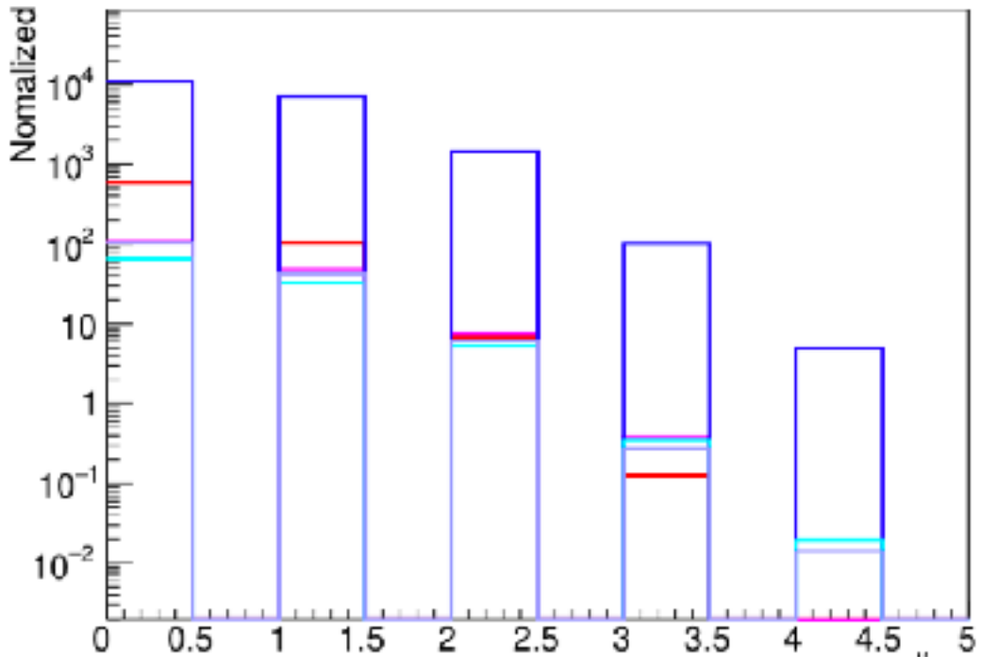
M_N [GeV]	$M_{Z'}$ [TeV]	g1'
100	7	1
200	7	1

Isolated e,γ,μ (full signal + full background)

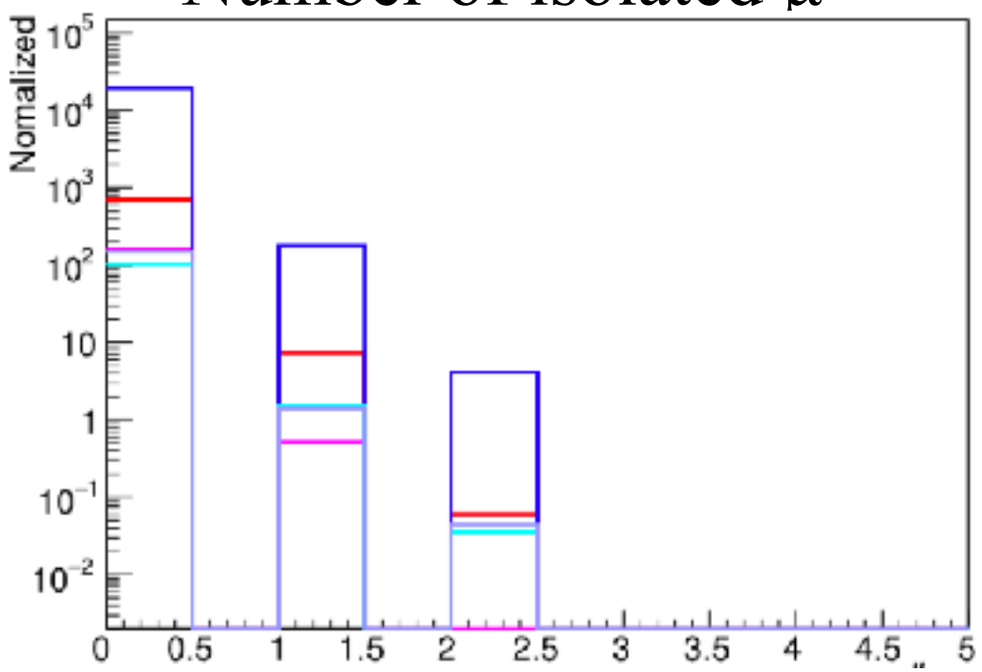
Number of isolated e



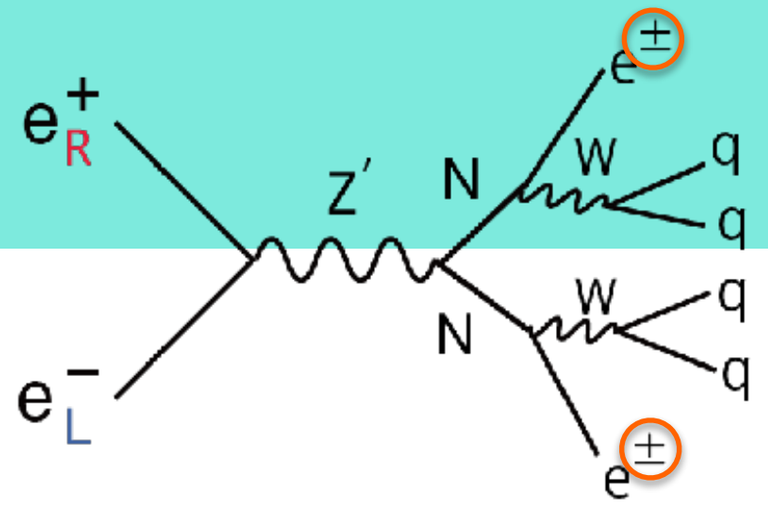
Number of isolated γ



Number of isolated μ



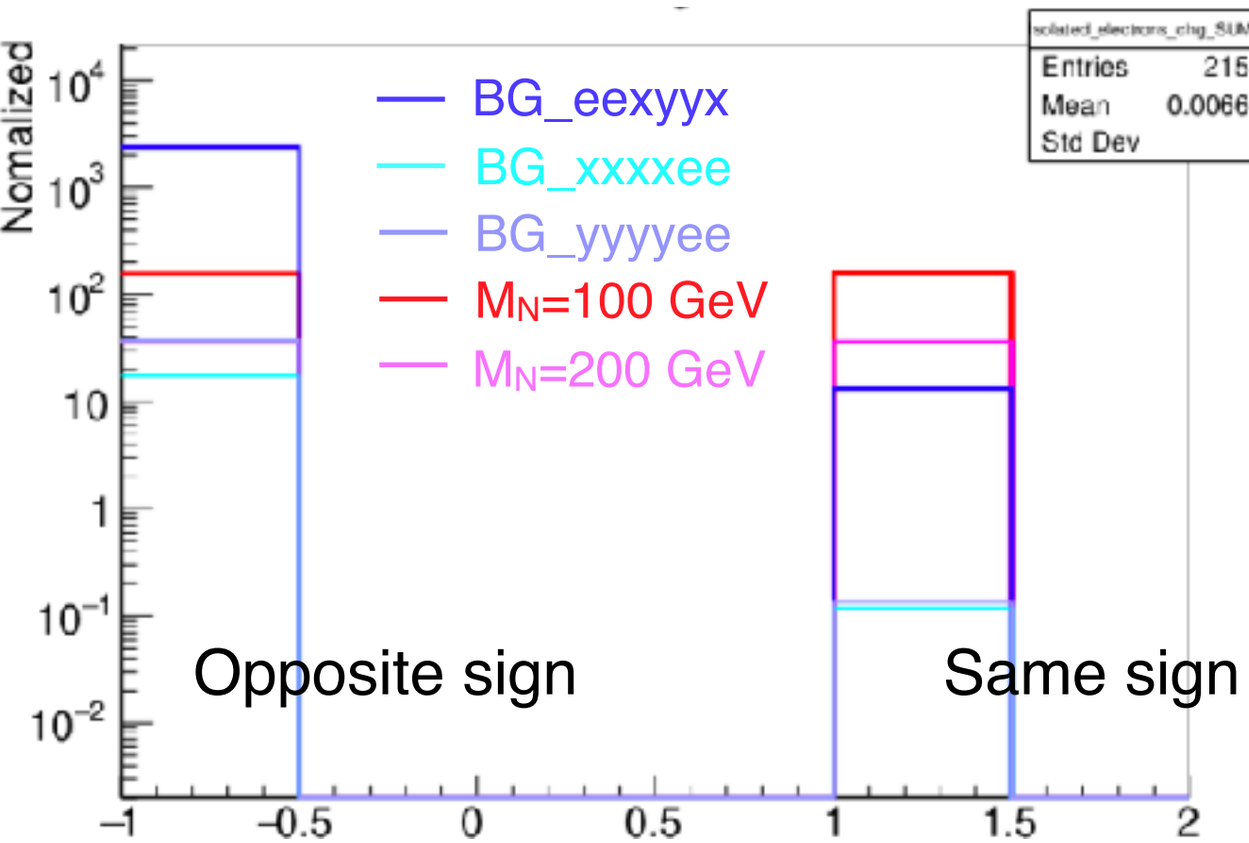
Electron Charge



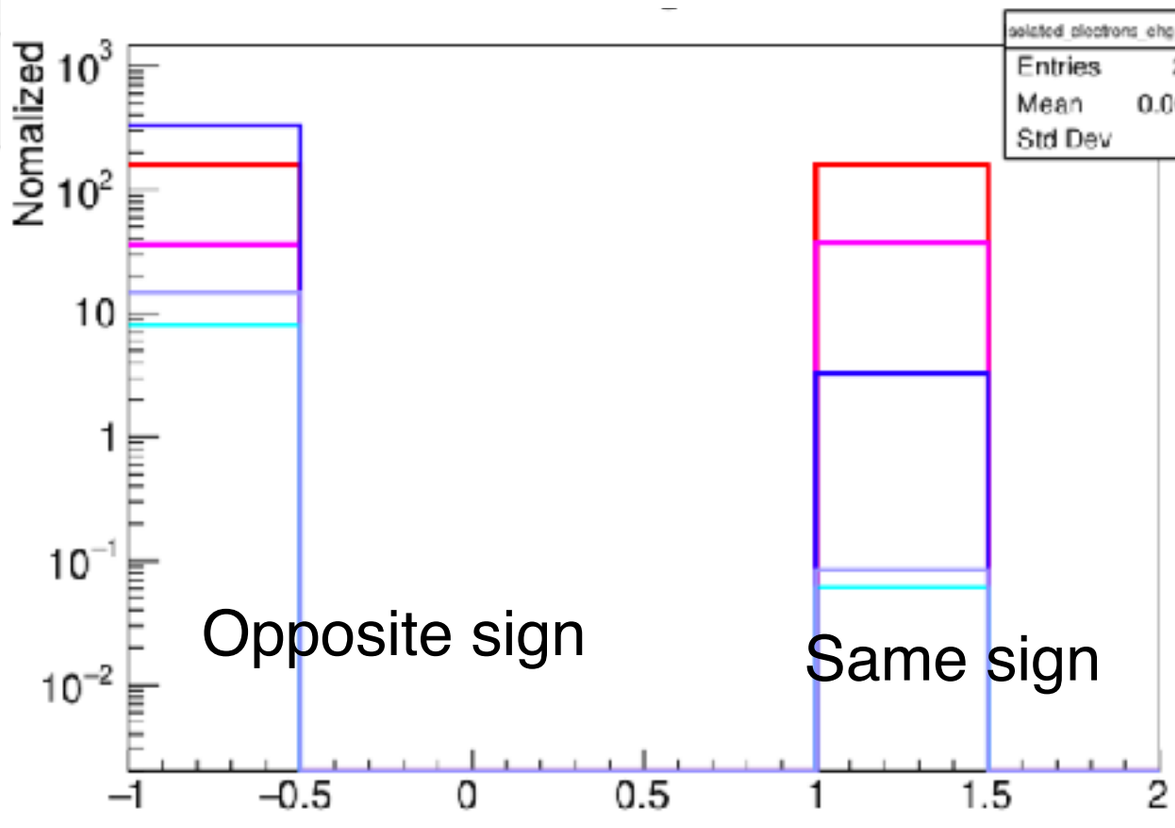
ILC 500 with ISR / BS

isolated electrons =2 && # isolated photons = 0

Isolated electrons charge(eLpR)



Isolated electrons charge(eRpL)



We use only same sign samples **Charge == 1**

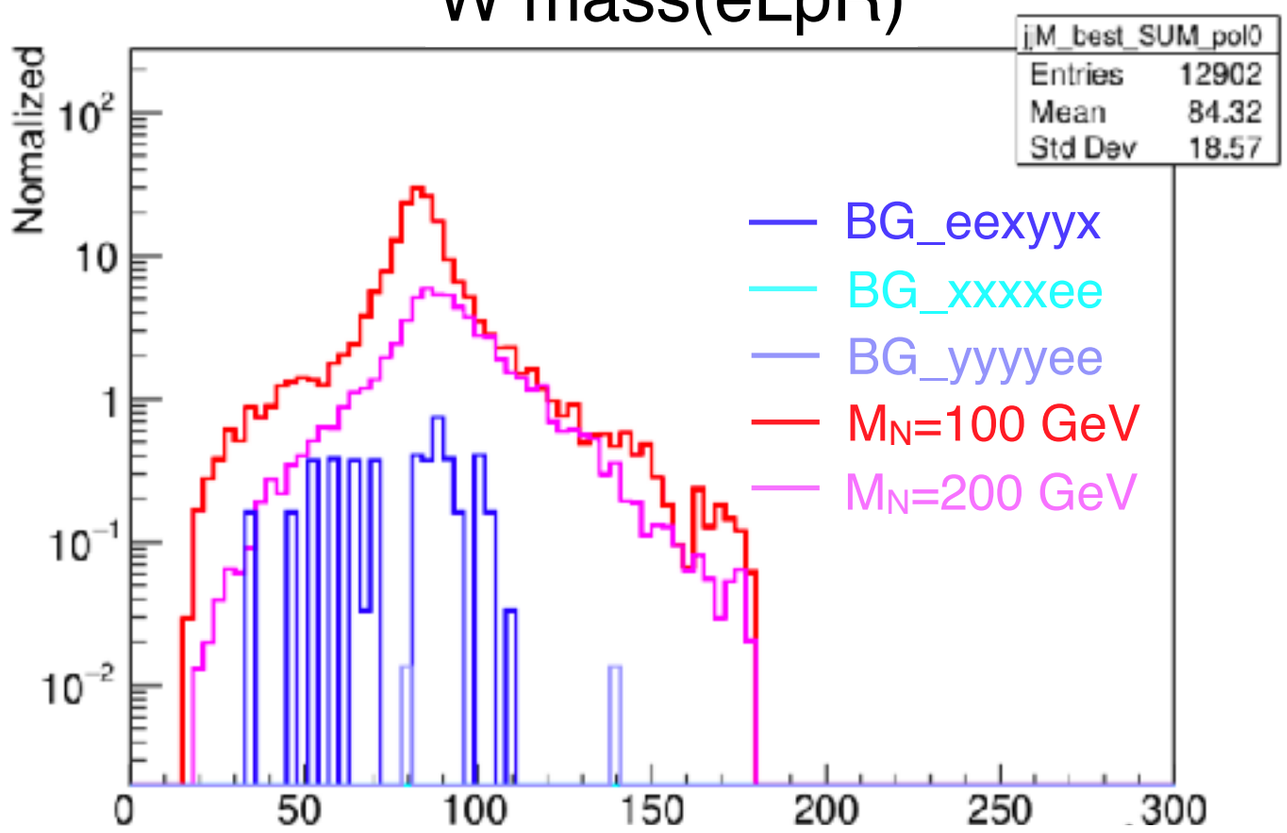
Results — Reconstructed W

- ILC 500 with ISR / BS

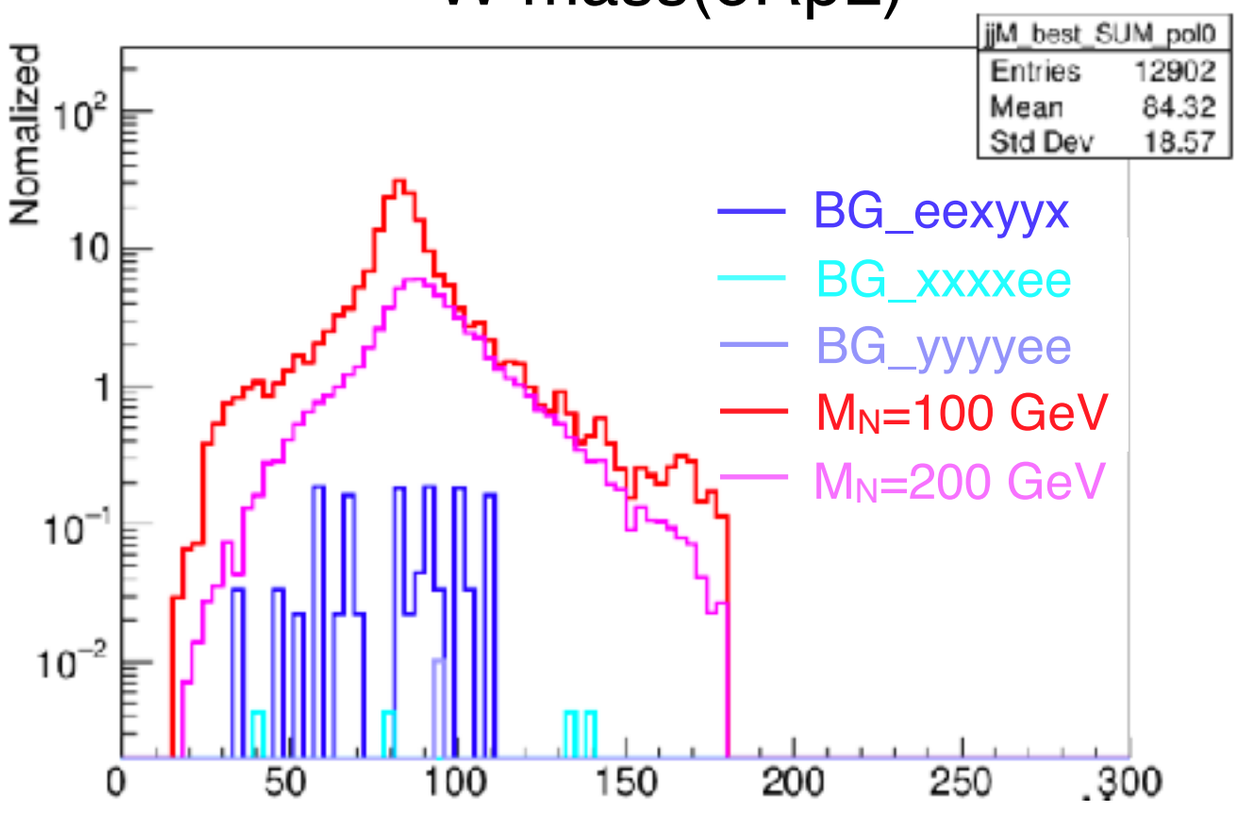
(full signal + full backgrounds)

- Isolated e # = 2
- Isolated e is same sign($e_1 \times e_2 = 1$)
- $E_{iso} < 200$ [GeV]
- $-0.95 < \cos\theta_{isoe} < 0.95$
- $\mathrm{IsolatedLepTagging}_{min} > 0.9$

W mass(eLpR)



W mass(eRpL)



Results — Reconstructed RHN

- ILC 500 with ISR / BS

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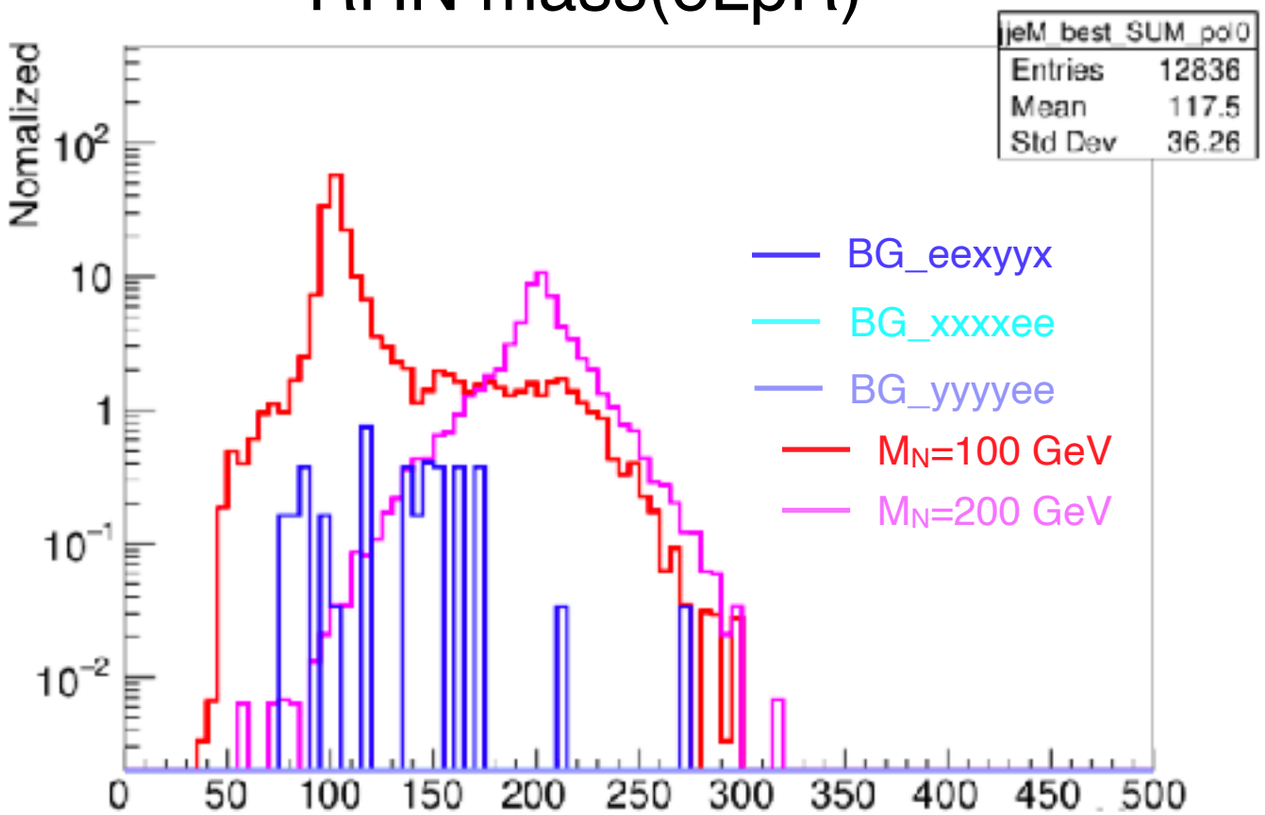
RHN mass(eLpR)



RHN mass(eRpL)