Exploring Right Handed Neutrinos at ILC500

Work in progress

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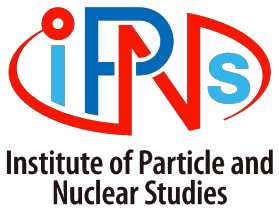


Motivation and introduction

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

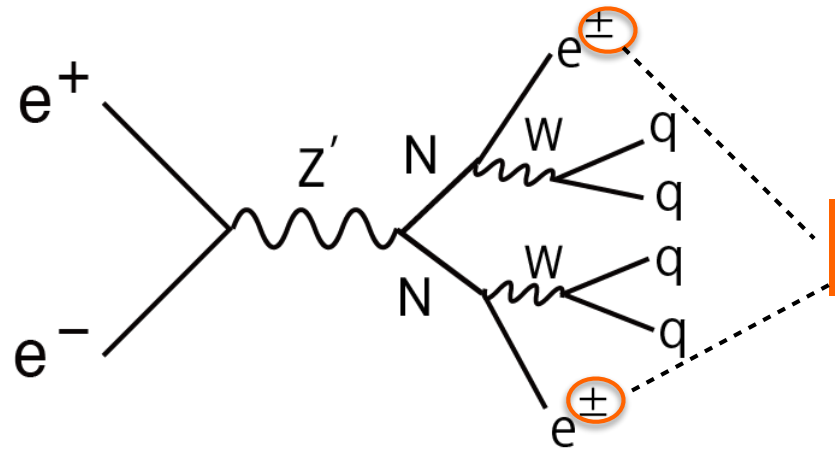
- a Majorana particle ($N = \bar{N}$)
- minimal $U(1)_{B\text{-}L}$ model

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

gauge boson : Z'

→ RHN **pair** production

arXiV[1812.11931]



Lepton # violation is possible!

↓

Same sign leptons possible

↓

Very small SM BG!

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

Benchmark points

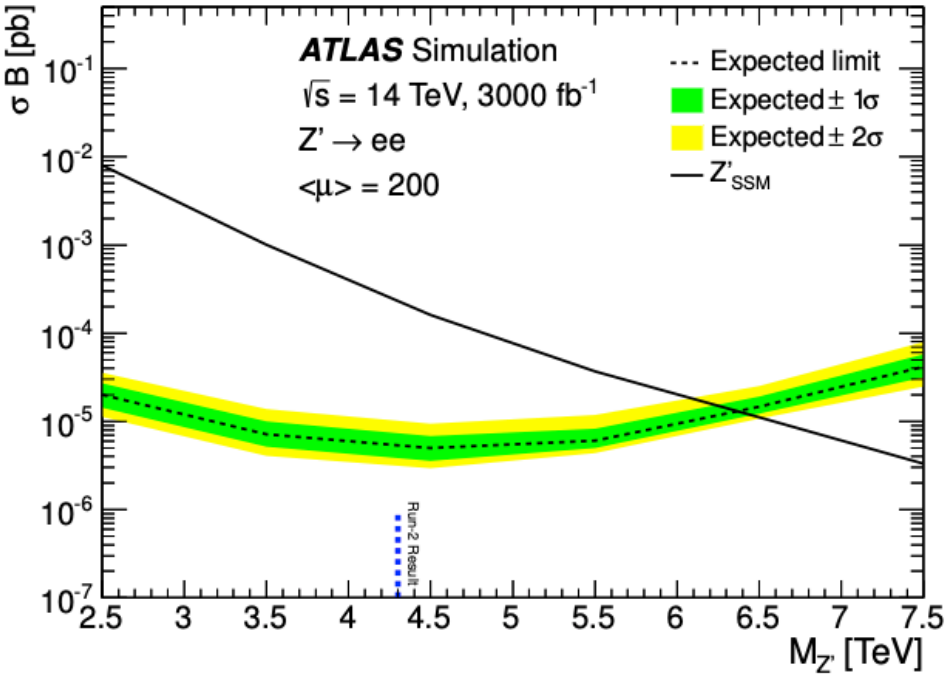
- Pol(e^-, e^+) = (–0.8, +0.3), (+0.8, –0.3): $\mathcal{L} = 1600\,[\mathrm{fb}^{-1}]$
- Pol(e^-, e^+) = (–0.8, –0.3), (+0.8, +0.3): $\mathcal{L} = 400\,[\mathrm{fb}^{-1}]$

M_N [GeV] RHN mass	$M_{Z'}$ [TeV] Z' mass	g_1' $U(1)_{B-L}$ coupling	$\lvert V_{eN}\rvert^2$ mixing angle	BR $(N \to eW)$	$\sigma(e_L^- e_R^+ \to NN)$ 100% polarization [fb]	Event # at ILC500 [4000fb^{-1}]
100	7	1	0,0009	0,44	0,71	1261
150	7	1	0,0009	0,33	0,45	229
200	7	1	0,0009	0,30	0,16	131
225	7	1	0,0009	0,29	0,052	18

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

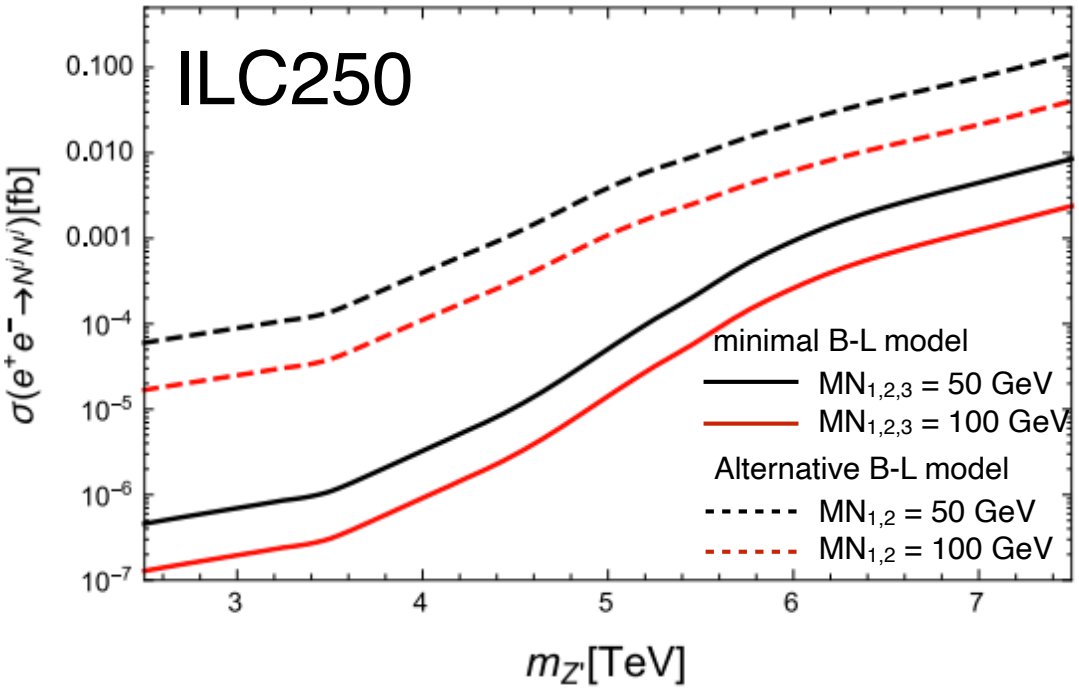
Current limits - Z' mass

SM like Z' coupling



ATLAS-TDR-LHCC2017-2018

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



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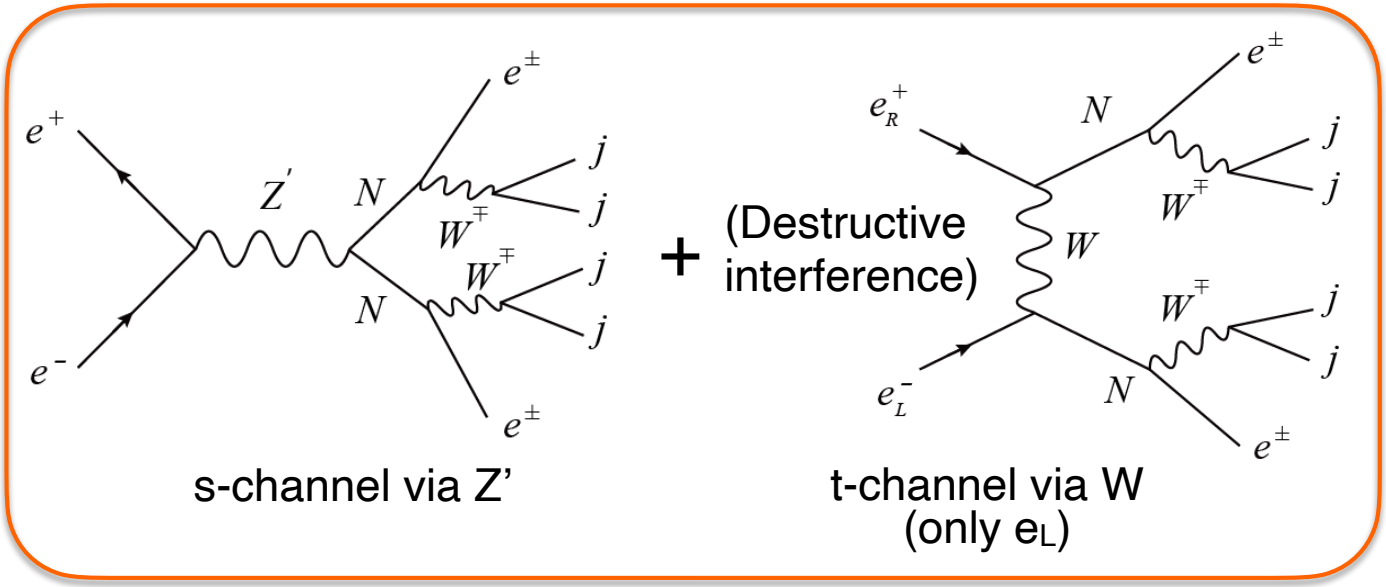
The heavier Z' mass less constrained by LHC

Analysis tool and backgrounds

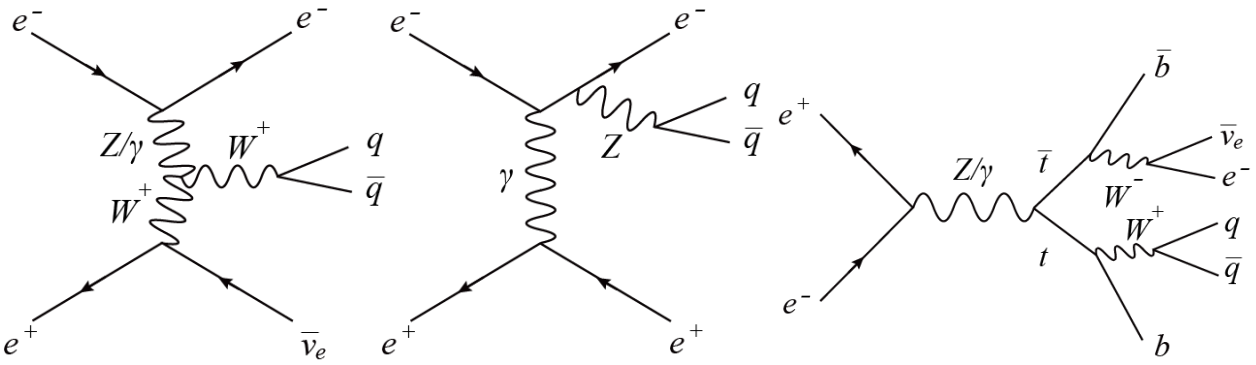
ILC**500** Signal process:



s-channel via Z'

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

↓

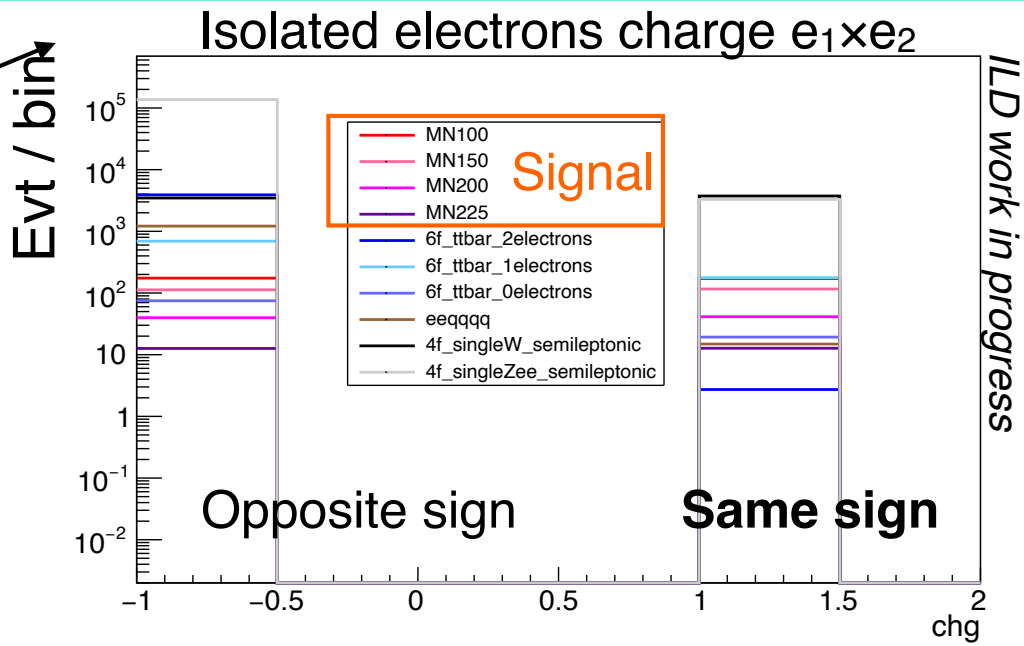
ILD Full Simulation
& (Geant4)
Reconstruction

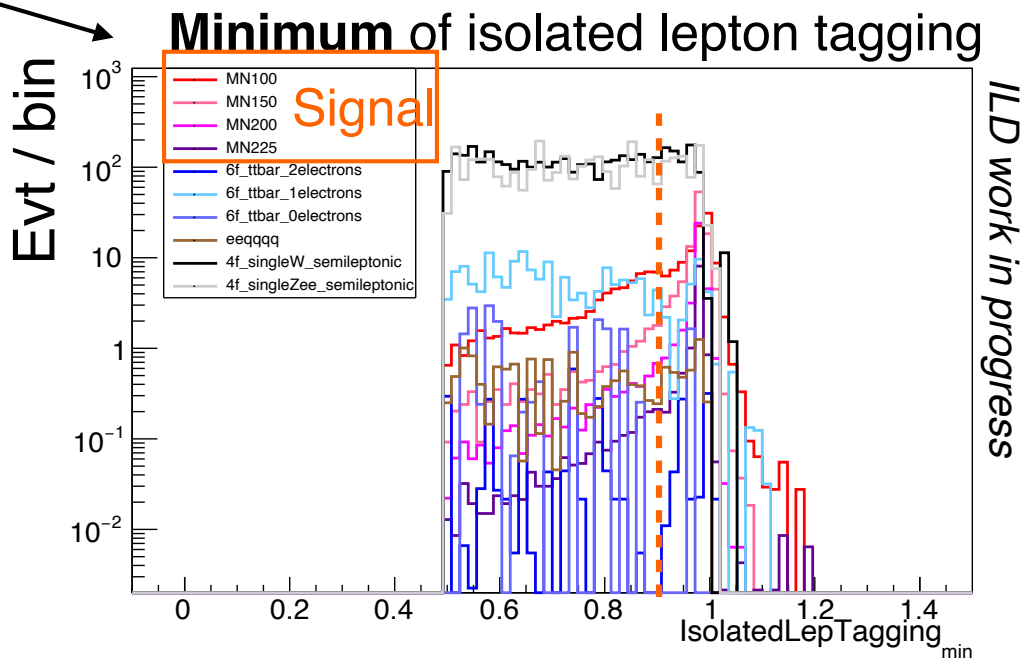
↓

miniDST
Events format

Cut conditions to select signal events

- Isolated e # = 2 && Isolated γ, μ # = 0
- Same sign isolated electrons
- Isolated electron energies $E_{iso} < 200$ [GeV]
- Isolated electron 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] II $|\cos\theta_{Pmiss}| > 0.95$)



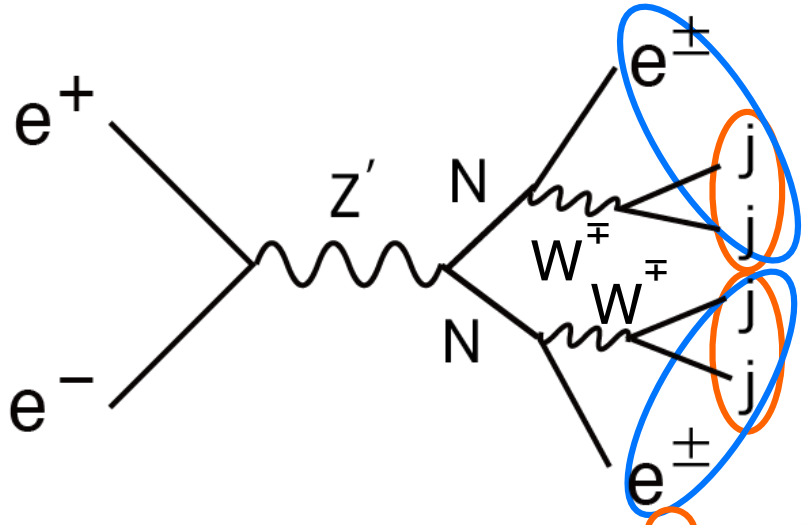


Signal efficiency ~ **20%**

Remaining backgrounds events
~ **150** (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 "$M_{jje1} = M_{jje2}$"

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

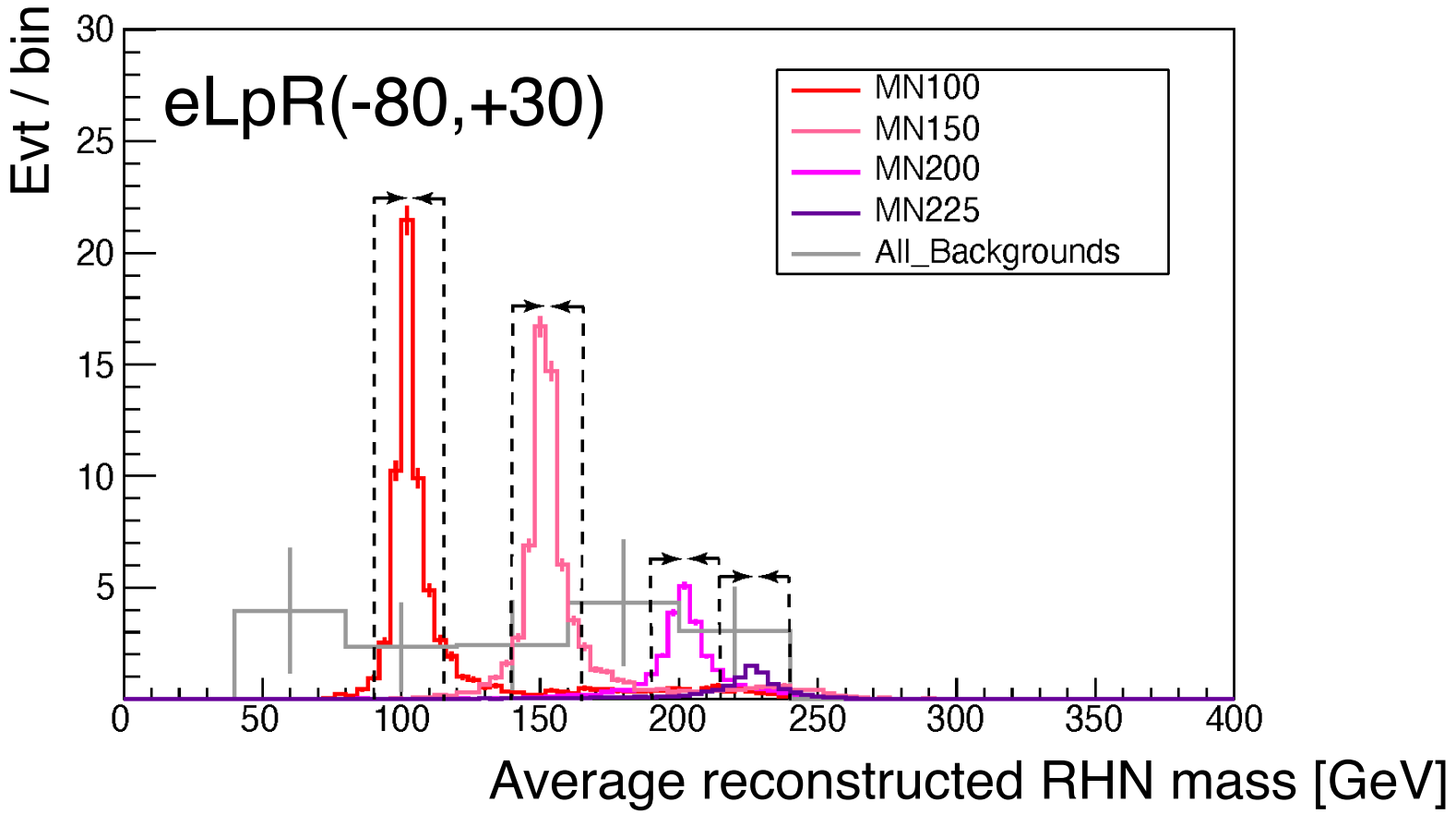
Choose combination with minimum F_1,F_2

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]



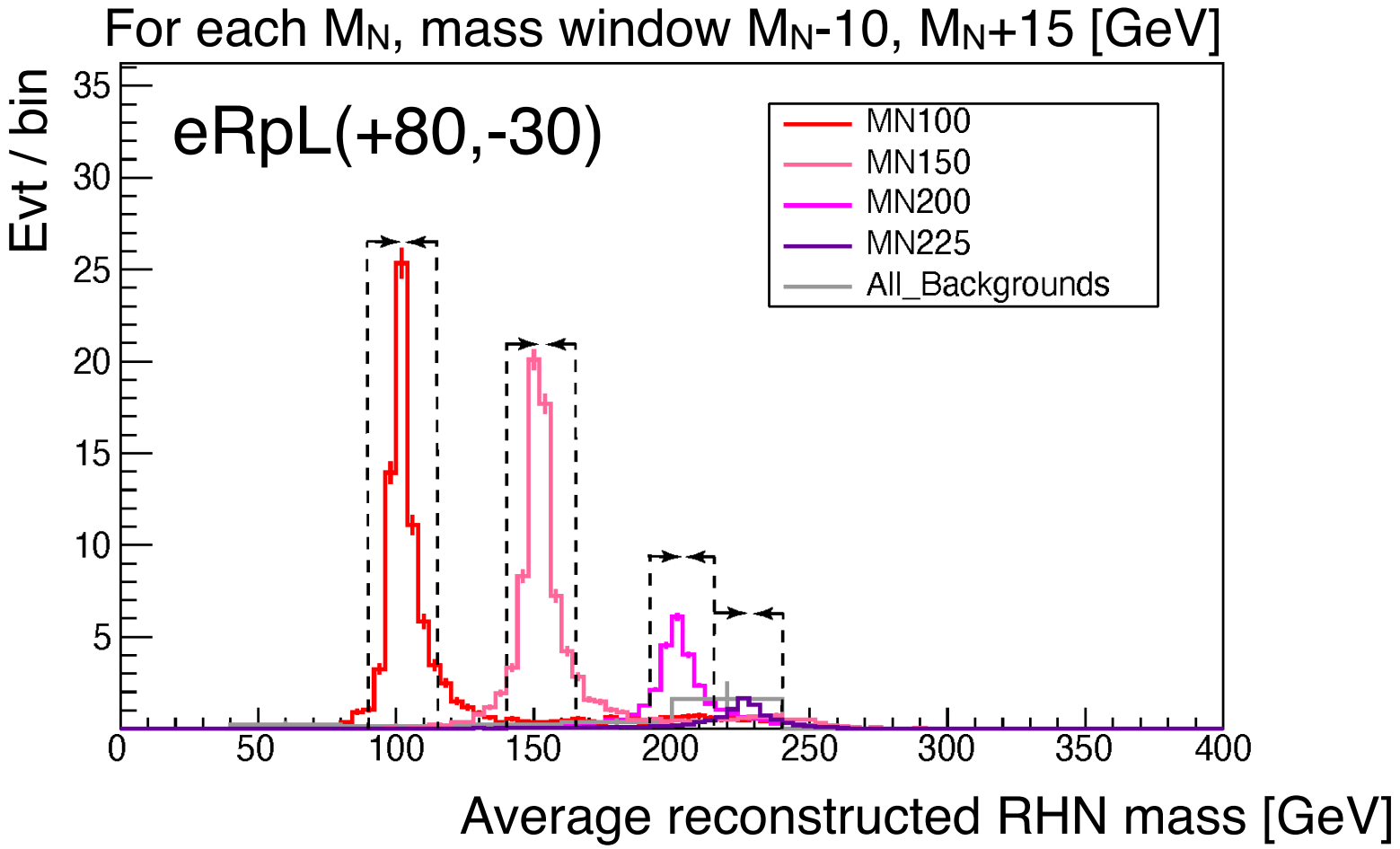
Assume background distribution is flat

20 (eLpR) background events remain in mass window

Signal mass cut

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

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



Assume background distribution is flat

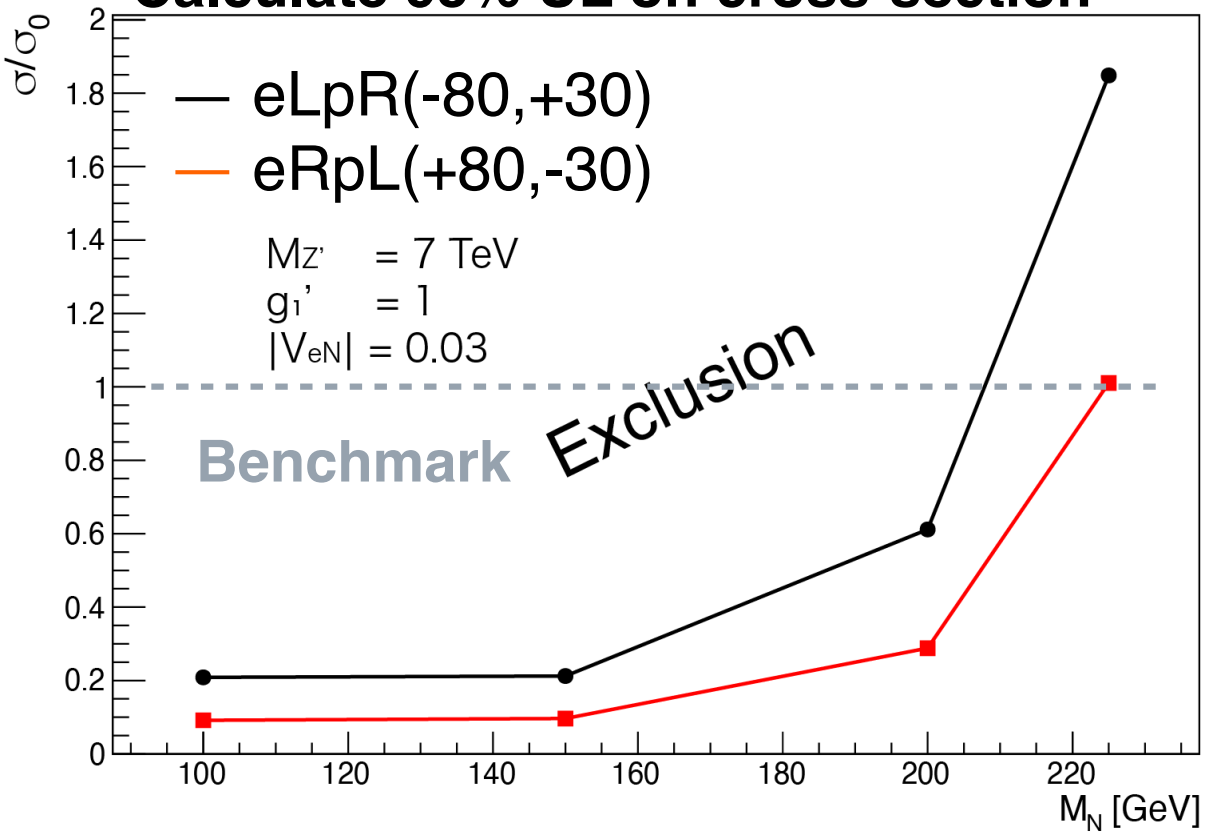
20 (eLpR) and 3 (eRpL) background events remain in mass window

Less backgrounds thanks to beam polarization
Reduce W contribution

Exclusion plot on cross-section

σ_0 : benchmark cross-section

Calculate 95% UL on cross-section



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

Conclusion:

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

Current Activity & Future Plan

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

- ILC 250 with ISR / BS
- $\mathrm{Pol}\,(e^+, e^-) = (+0.8, -0.3) : \mathcal{L} = 900\,[\mathrm{fb}^{-1}]$

ILD work in progress

	Signal Entries				
	M_N=85	M_N=95	M_N=100	M_N=110	M_N=120
No cut	48	48	39	19	3
e_{iso} #=2 && γ_{iso} #=0 && μ_{iso} #=0	10	16	13	6	1

- Same sign muons
  → Expect smaller backgrounds

Part1 : RHN

Model : minimal $U(1)_{B-L}$

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 included

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

minimal $U(1)_{B-L}$ model : charge

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

i=1,2,3

arXiV[1812.11931]

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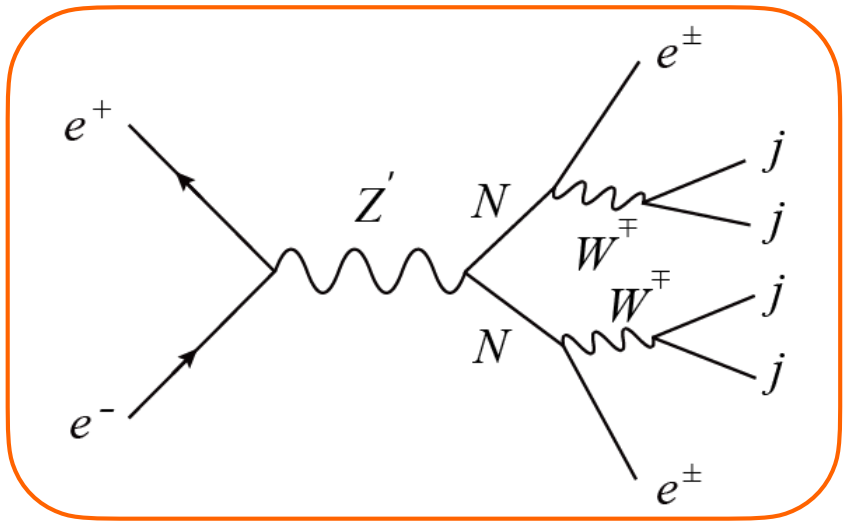
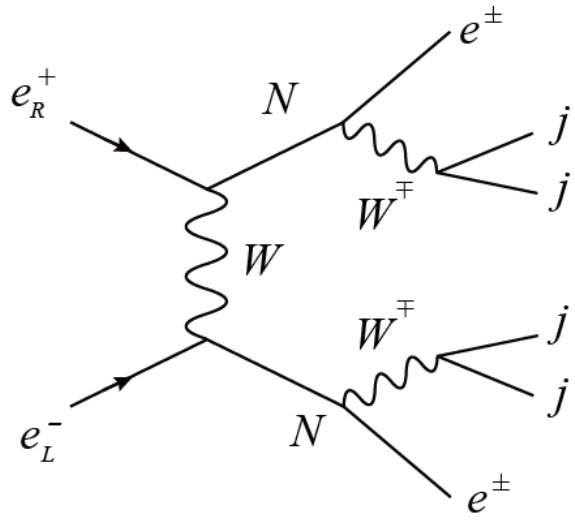
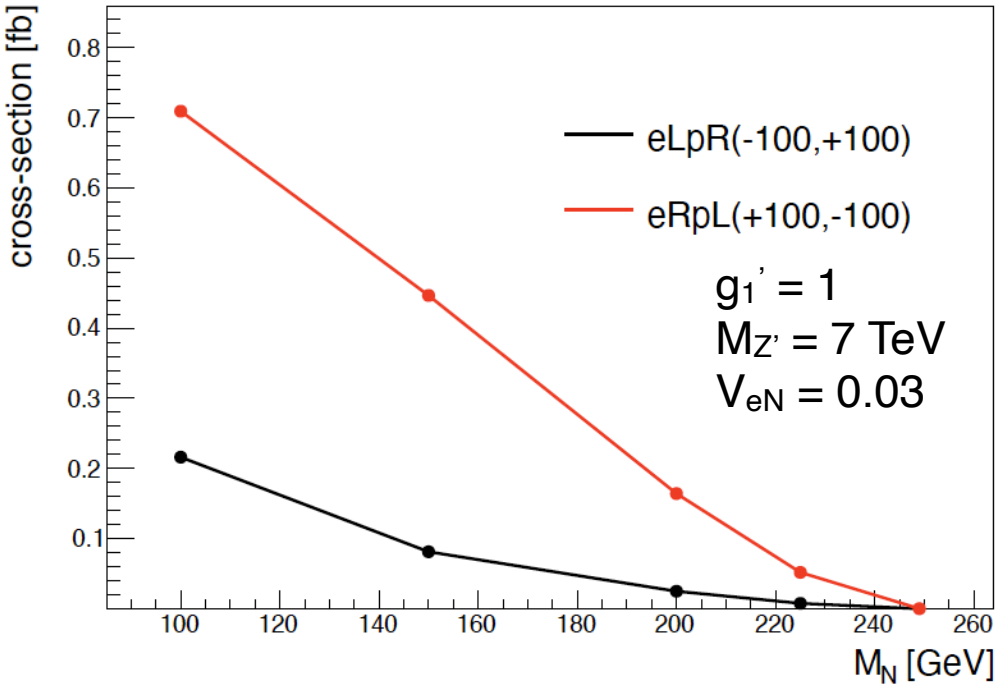
Signal





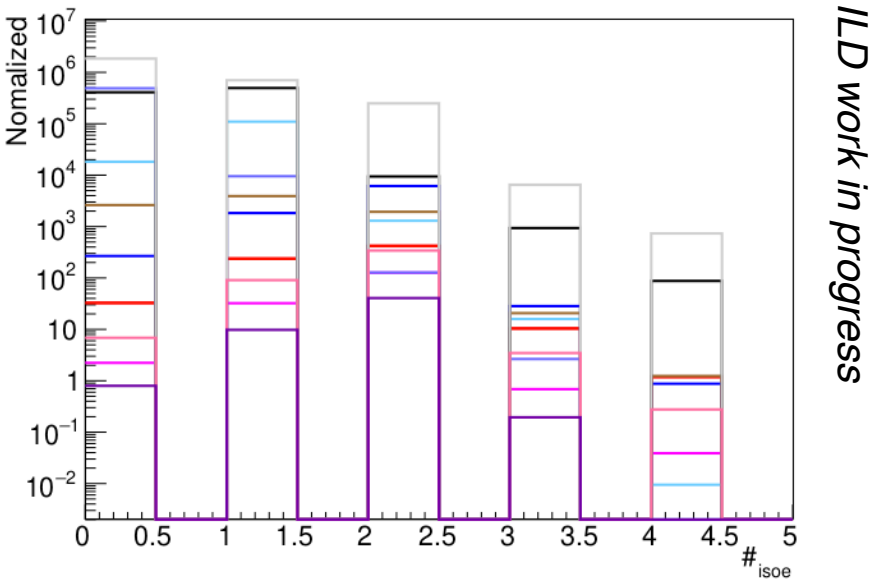
Destructive interference



Isolated e,γ,μ

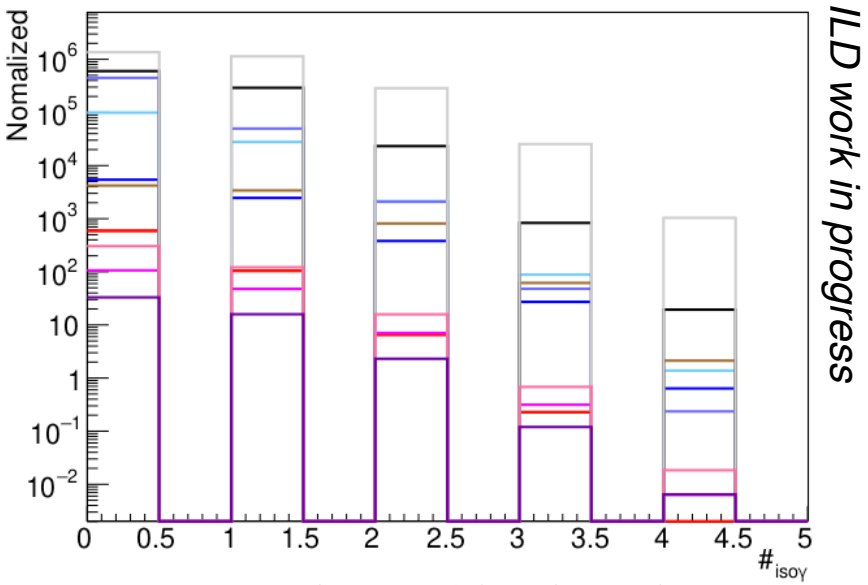
- ILC 500 with ISR / BS
- **Pol(e^-, e^+) = (+0.8, –0.3)**

Number of isolated e

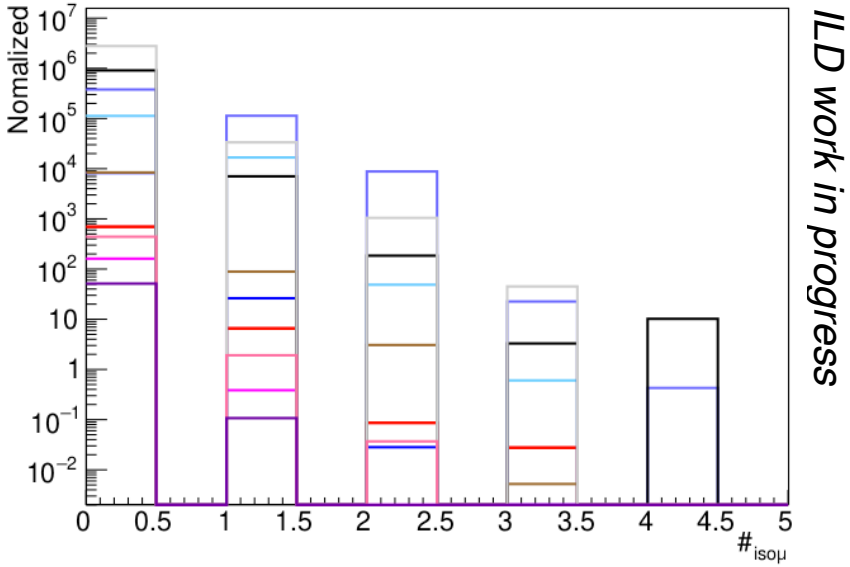


- M_N=100 GeV
- M_N=150GeV
- M_N=200 GeV
- M_N=225 GeV
- BG_6f_ttbar_2e
- BG_6f_ttbar_1e
- BG_6f_ttbar_0e
- BG_4f_sw_sl
- BG_4f_sze_sl
- BG_eeqqqq

Number of isolated γ



Number of isolated μ

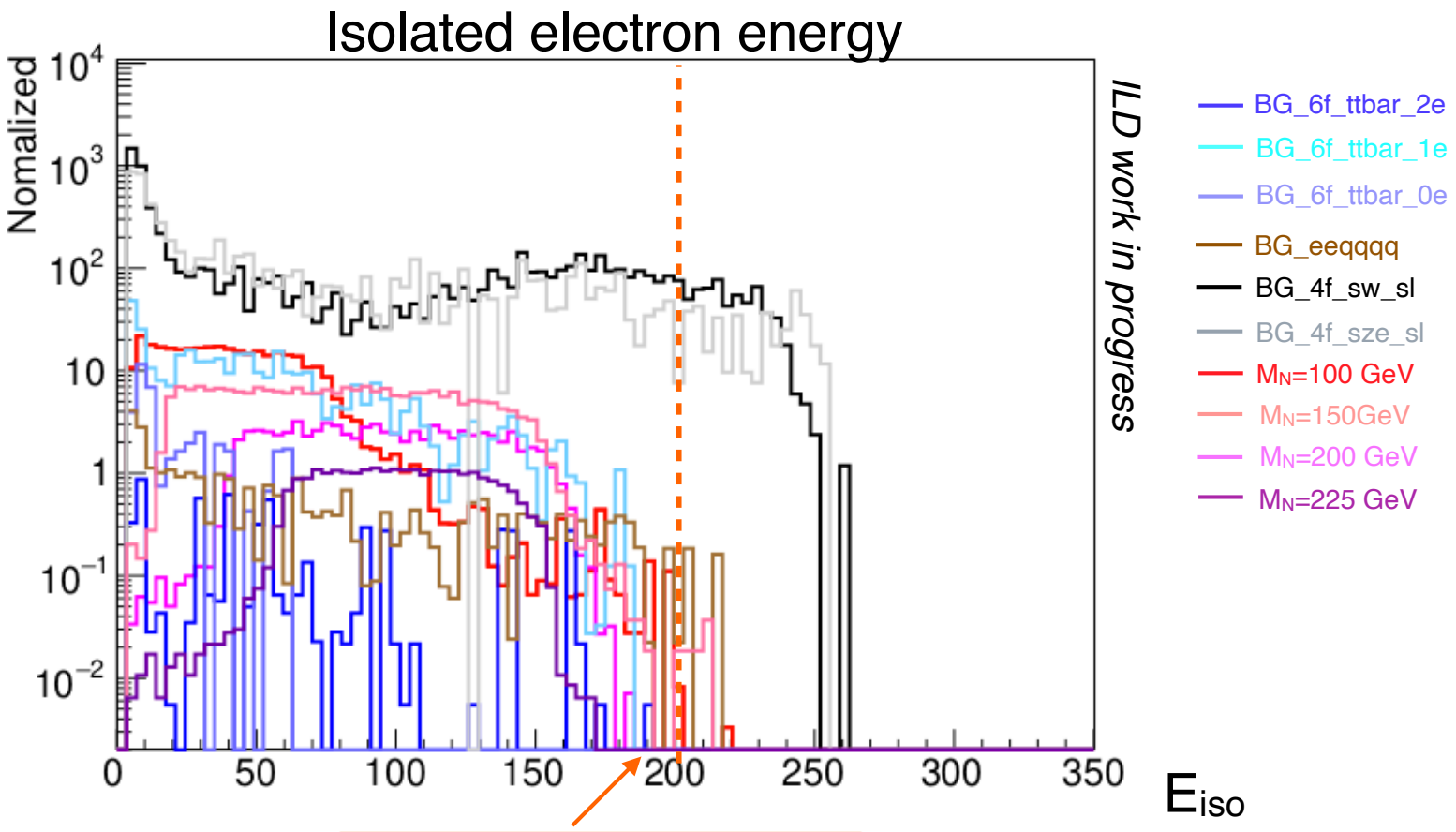


- Isolated e # = 2 && Isolated γ, **μ = 0**

Distribution of Isolated electron energy

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

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

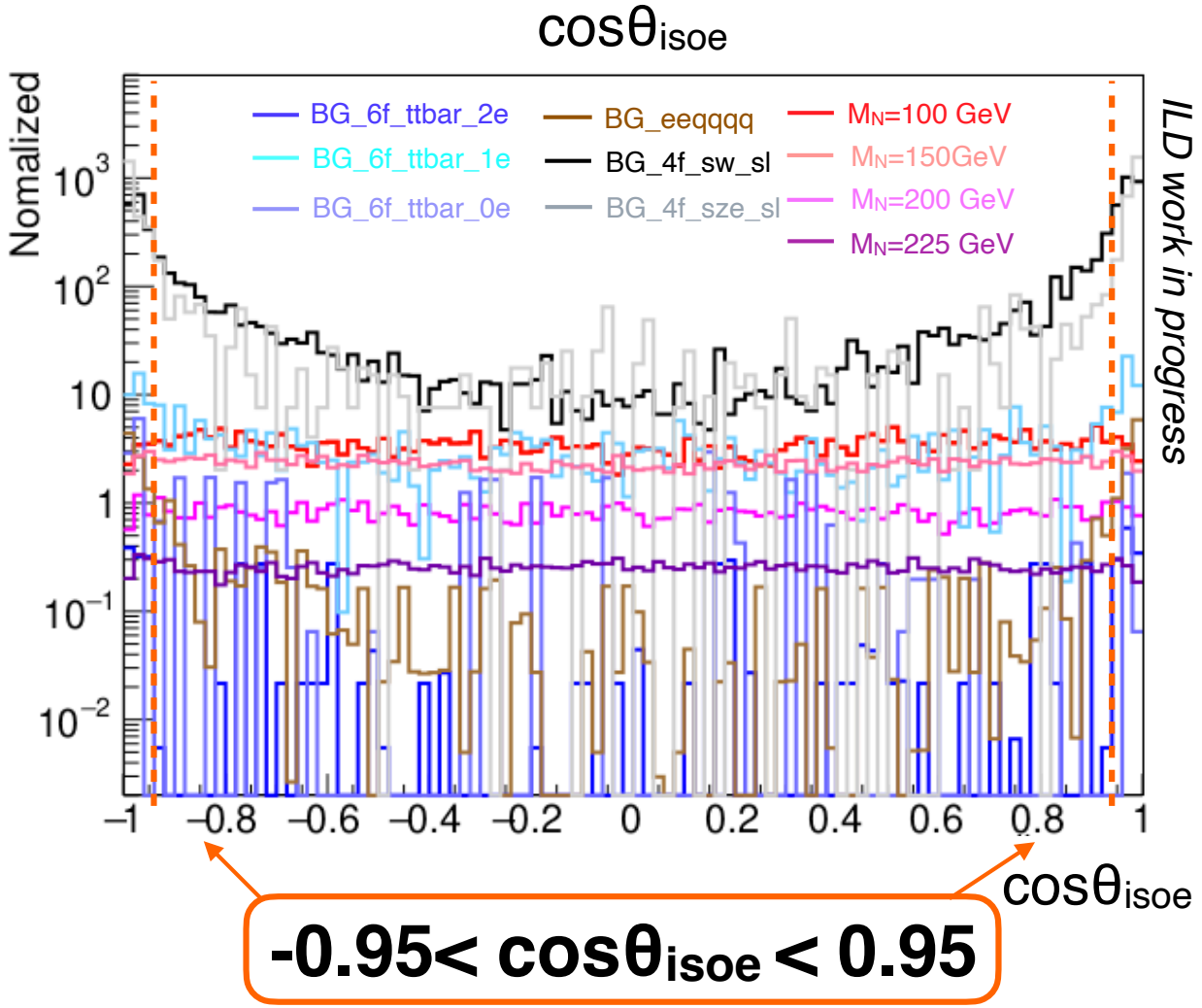


E_{iso} < 200 [GeV]

Distribution of $\cos\theta_{isoe}$

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

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

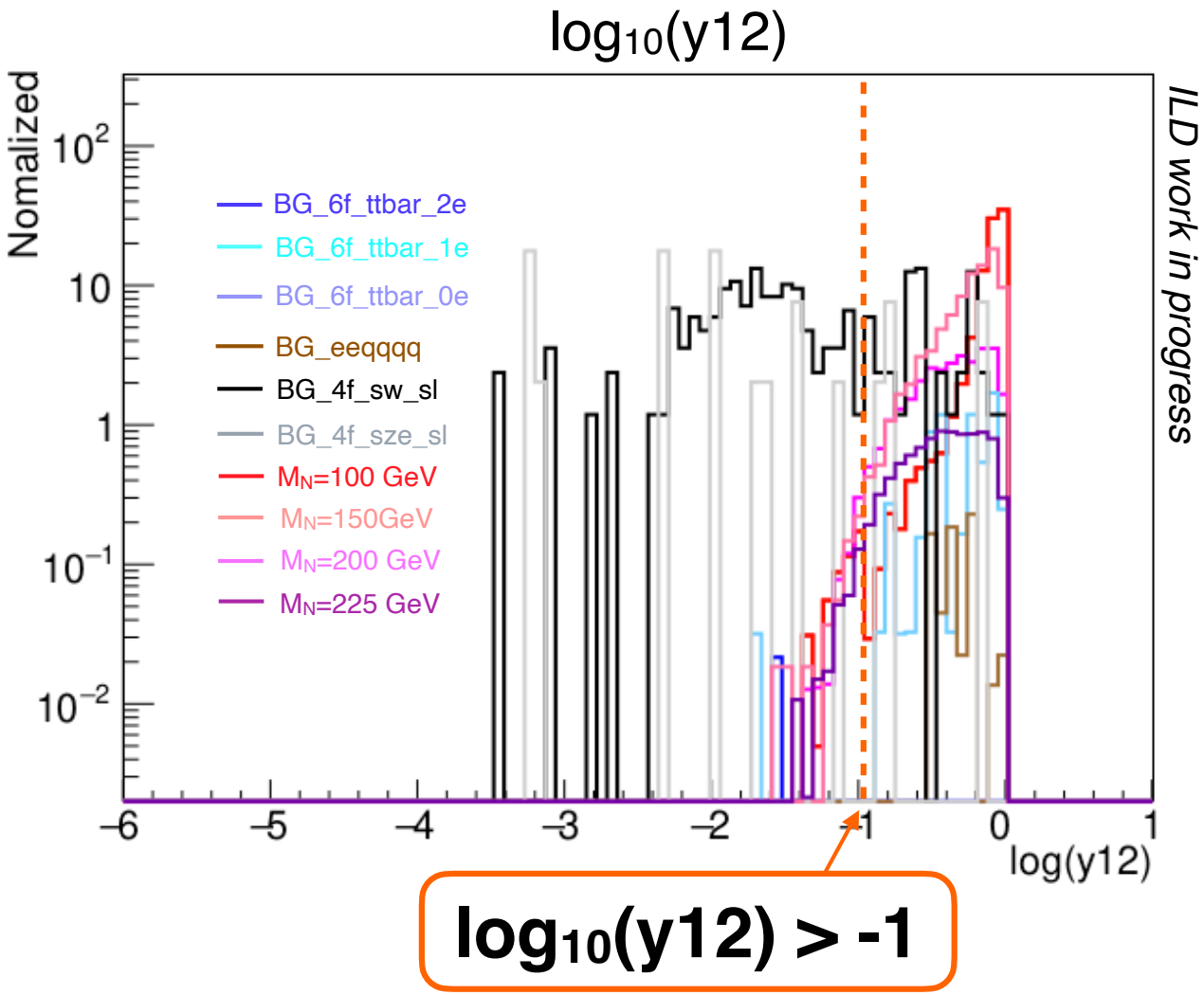


4 fermions semi leptonic processes in t-channel→ distributed in $|\cos\theta_{isoe}| \sim 1$

Distribution of y12 (Durham)

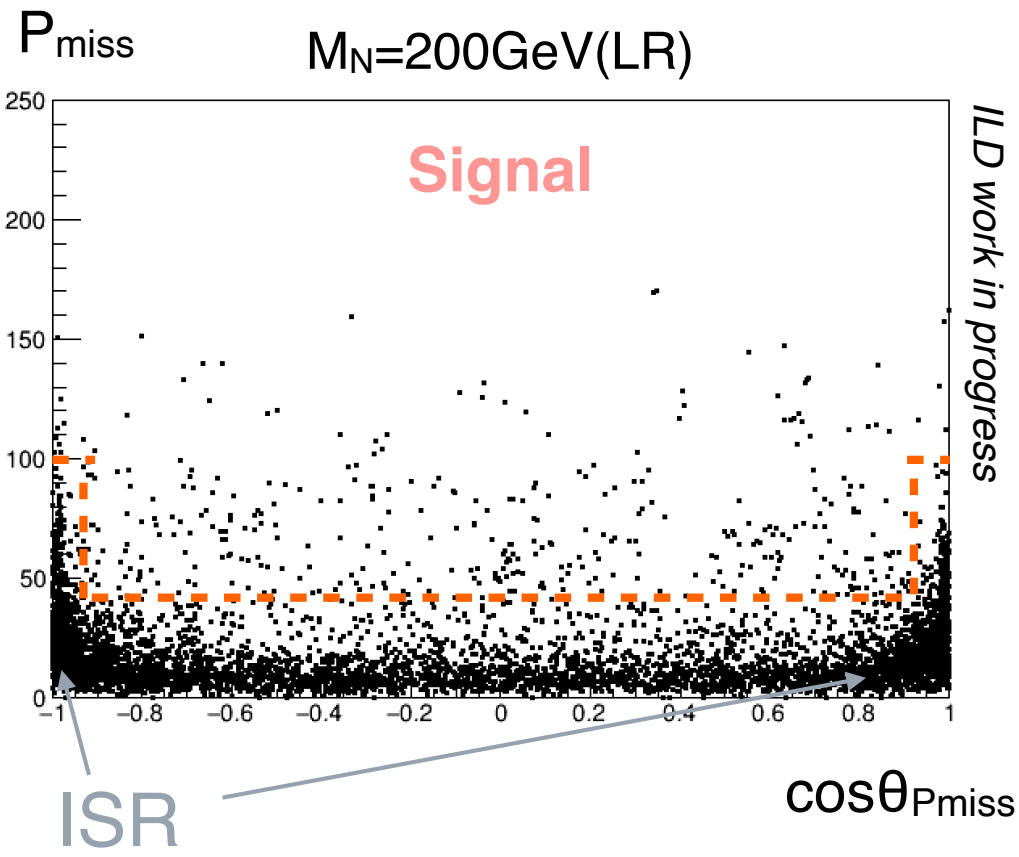
- ILC 500 with ISR / BS
- **Pol(e^-, e^+) = (+0.8, –0.3)**

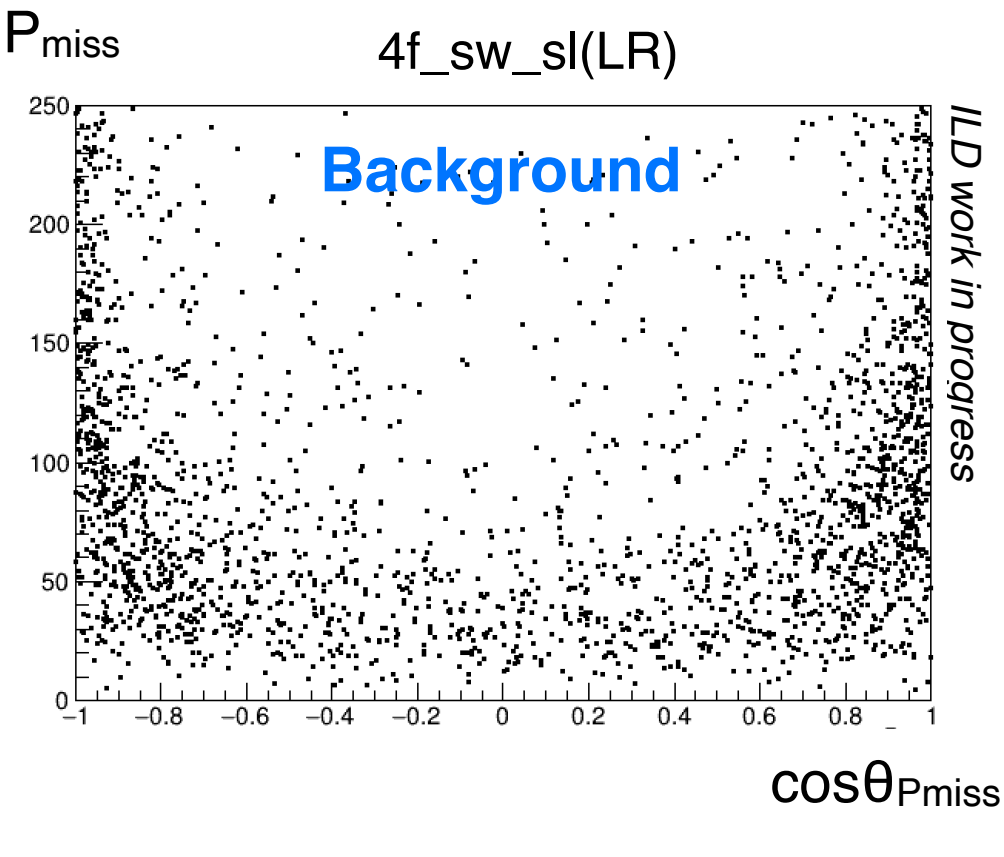
- Isolated e # = 2 && Isolated γ # = 0 && Isolated μ # = 0
- Isolated e is same sign ($e_1 \times e_2 = 1$)



$Cos\theta_{Pmiss}$ vs Magnitude of missing momentum P_{miss}

- ILC 500 with ISR / BS





$P_{miss} < 100$ &&($P_{miss} < 40$ || $|\cos\theta_{Pmiss}| > 0.95$)

Cut flow (eRpL)

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

ILD work in progress

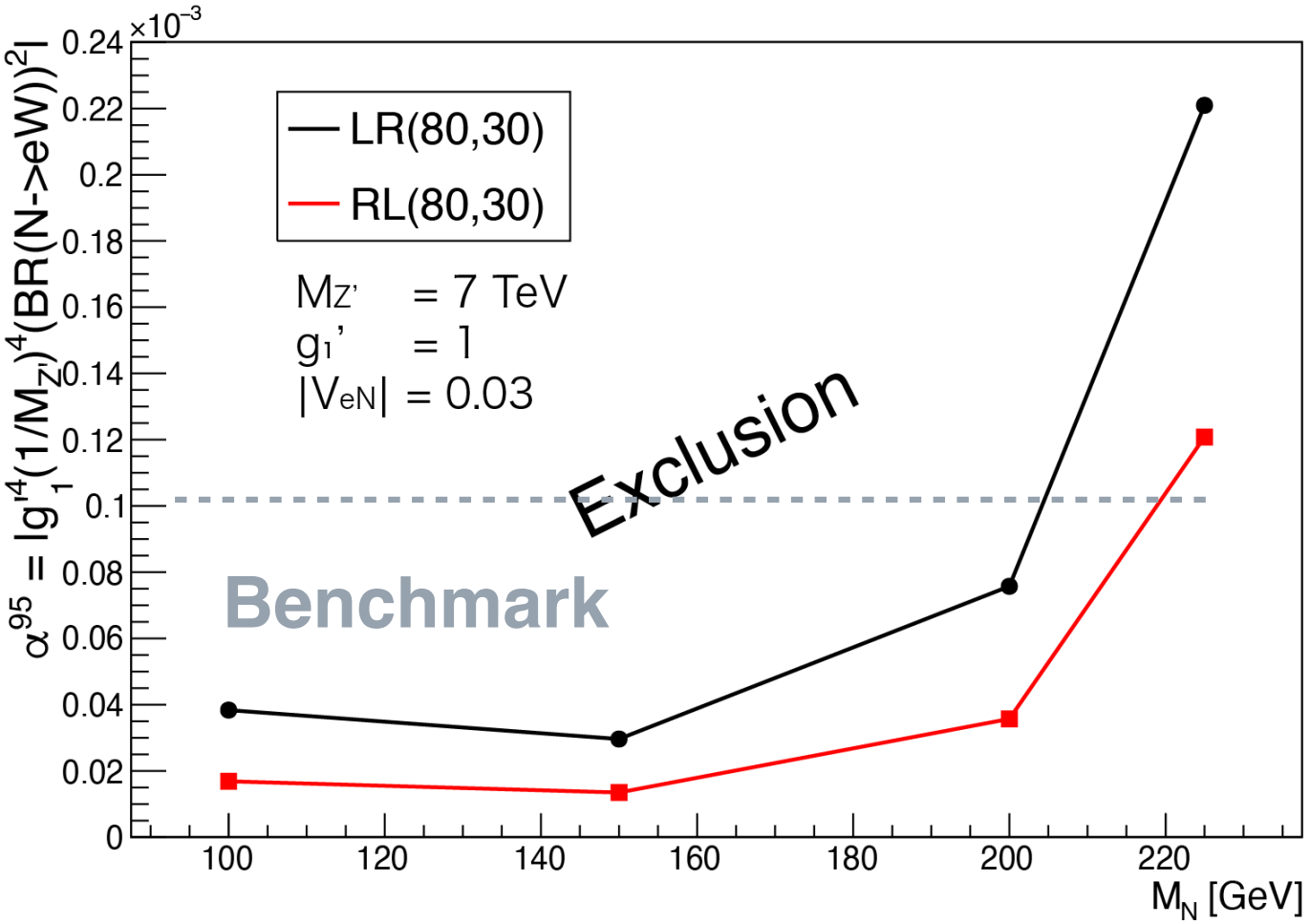
	Expected signal				Expected background					
	M_N=100	M_N=150	M_N=200	M_N=225	eeqqqq	4f_singleW _semileptonic	4f_singleZee_ semileptonic	6f_ttbar 2electrons	6f_ttbar 1electron	6f_ttbar 0electron
No cut	558	394	143	45	3925	258648	612455	7100	56233	4894
e_{iso} #=2 && γ_{iso} #=0 &&	420	343	126	40	1935	9426	249000	6142	1295	127
Same sign ($e_{iso1} \times e_{iso2} = 1$)	346	115	81	12	1231	7210	140176	3911	870	94
$E_{iso} < 200$ [GeV]	171	114	41	12	14	3741	3294	2	177	19
$-0.95 < \cos\theta_{isoe} < 0.95$	158	103	37	11	3	1324	475	1	113	12
IsolatedLepTagging$_{min} > 0.9$	96	91	32	10	0	198	101	0	15	1
$\log_{10}(y12) > -1$	88	90	30	9	0	199	86	0	6	0
$P_{miss} < 100$ && ($P_{miss} < 40$ || $\lvert\cos\theta_{Pmiss}\rvert > 0.95$)	86	84	29	9	0	4	15	0	2	0

Results

	M_N [GeV]	# of Signal After cut	# of BG After cut	Signal Significance	σ_0 [fb] Initial benchmark	σ^{95} [fb] 95% exclusion limit	$\frac{\sigma^{95}}{\sigma_0}$	α^{95} [TeV^{-4}]
LR 80,30	100	53,64	20,12	6,25	0,55	0,12	0,21	3,83E-05
	150	52,73		6,18	0,36	0,076	0,21	2,96E-05
	200	18,30		2,95	0,14	0,086	0,61	7,57E-05
	225	5,51		1,18	0,046	0,085	1,8	2,21E-04
RL 80,30	100	66,75	3,24	7,98	0,71	0,065	0,092	1,69E-05
	150	63,41		7,77	0,45	0,043	0,097	1,35E-05
	200	21,23		4,29	0,16	0,047	0,29	3,57E-05
	225	6,077		1,99	0,052	0,052	1	1,21E-04

Exclusion plot on $U(1)_{B-L}$ parameters

Translate to the $U(1)_{B-L}$ model parameters



The benchmark points isn't excluded only at $M_N = 225$ GeV

eLpR case

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 Entries				Background Entries					
	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
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
$P_{miss} < 100$ && ($P_{miss} < 40$ || $\lvert\cos\theta_{Pmiss}\rvert > 0.95$)	84	84	28	9	1	79	30	0	9	0

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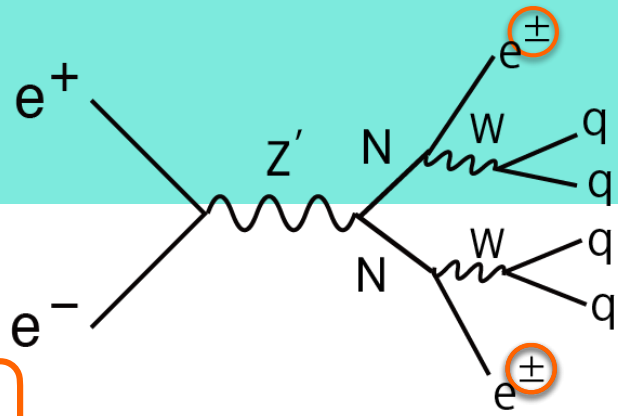
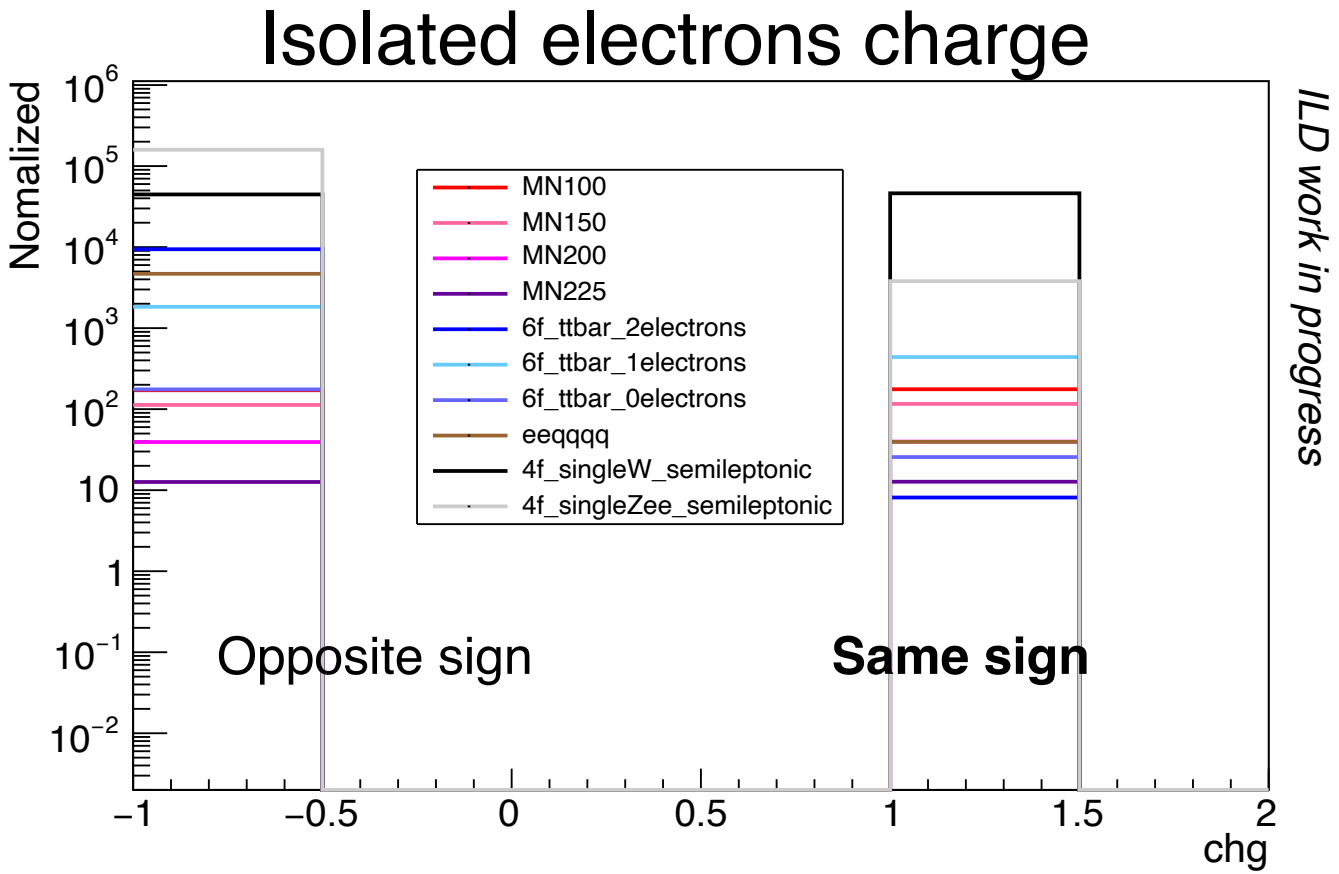
Electron Charge



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



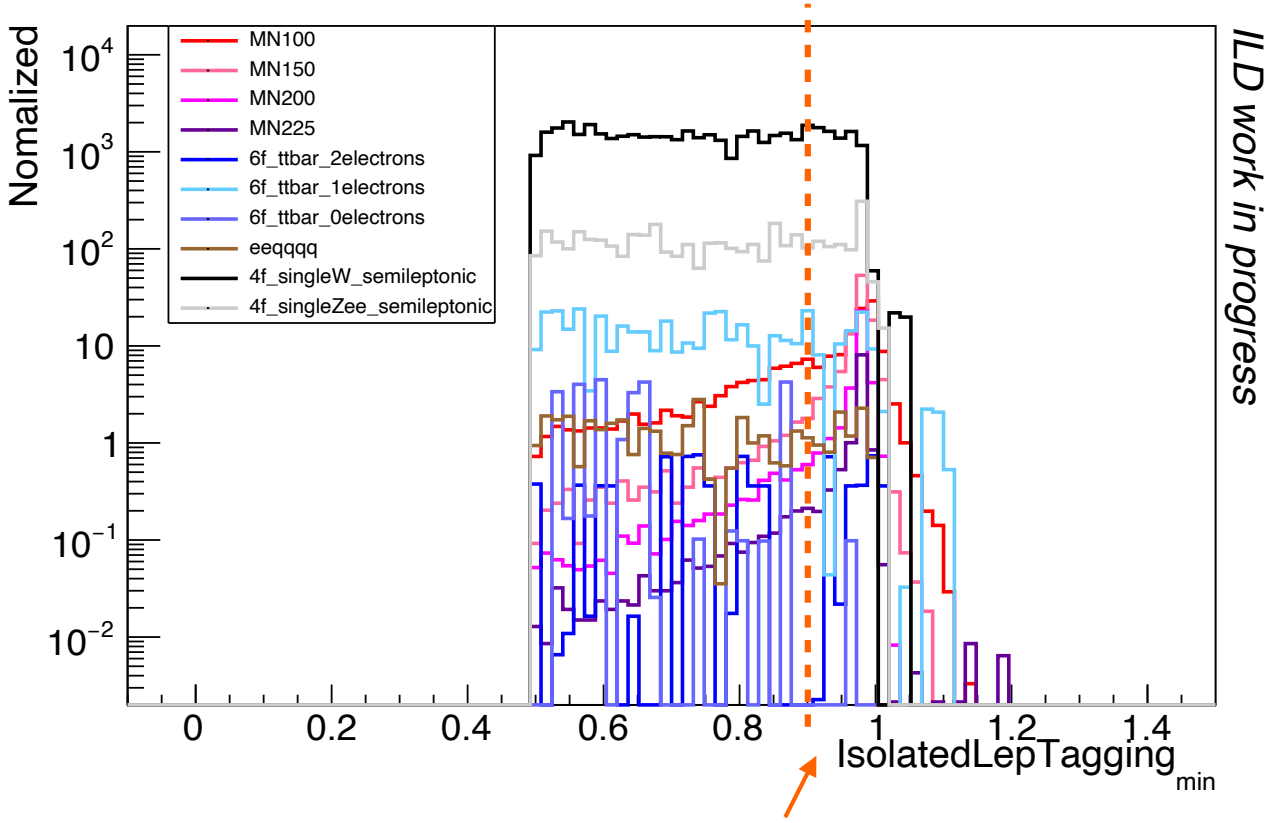
We use only same sign samples $e_1 \times e_2 = 1$

Distribution of IsolatedLepTagging

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

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

Minimum of isolated lepton tagging



Isolated lepton tagging
… "output" parameter of MVA to identify isolated lepton

→ Output for e is **near 1**

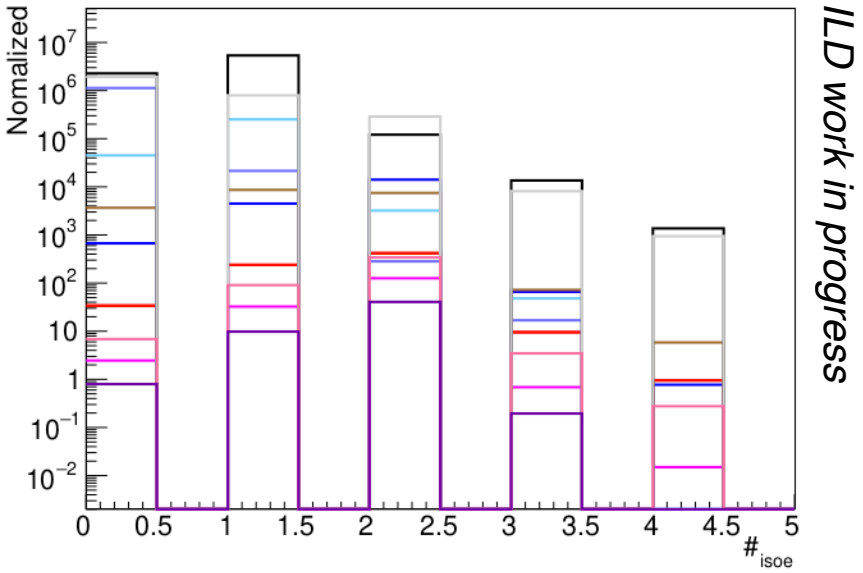
Usually second background electron is fake

$\text{IsolatedLepTagging}_{\text{min}} > 0.9$

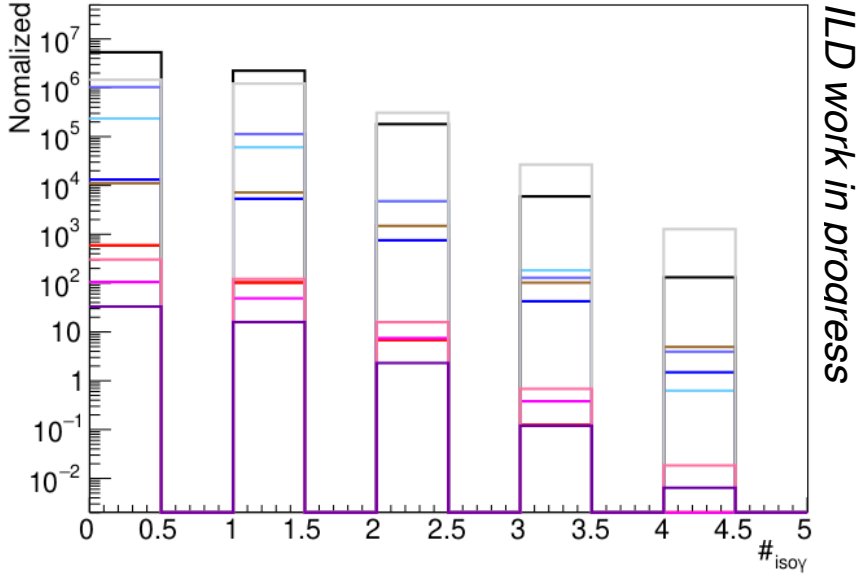
Isolated e,γ,μ

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

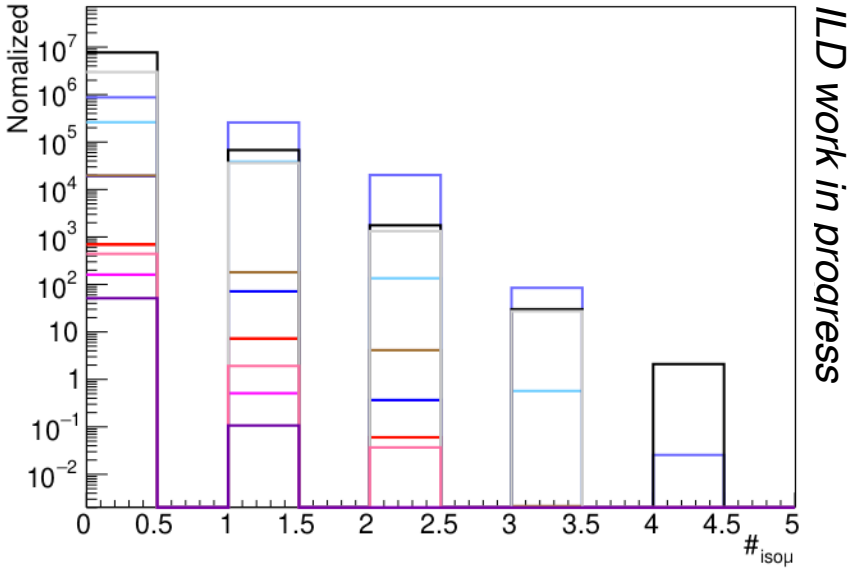
Number of isolated e



Number of isolated γ



Number of isolated μ



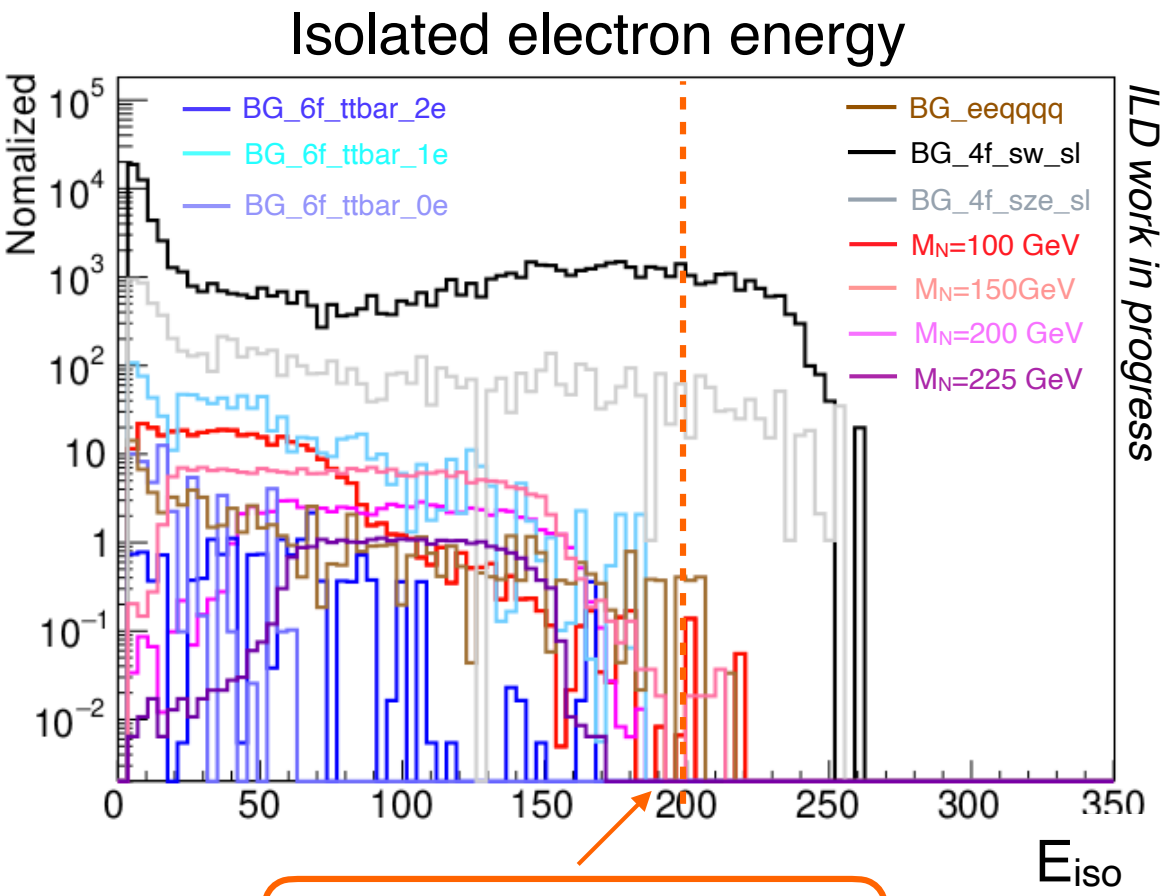
- M_N=100 GeV
- M_N=150GeV
- M_N=200 GeV
- M_N=225 GeV
- BG_6f_ttbar_2e
- BG_6f_ttbar_1e
- BG_6f_ttbar_0e
- BG_4f_sw_sl
- BG_4f_sze_sl
- BG_eeqqqq

- Isolated e # = 2 && Isolated γ, **μ = 0**

Distribution of Isolated electron energy

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

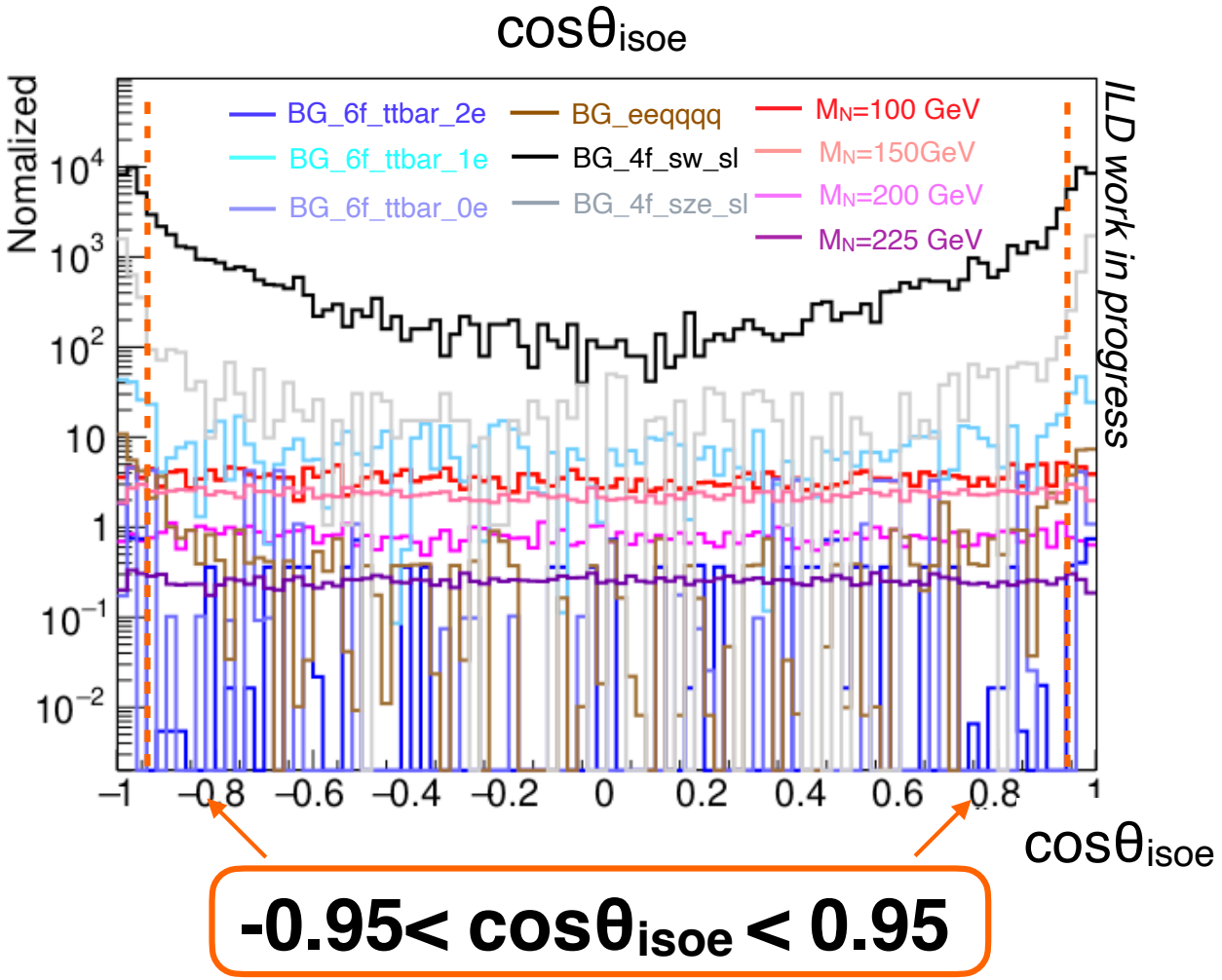
- Isolated e # = 2 && Isolated γ # = 0 && Isolated μ # = 0
- Isolated e is same sign ($e_1 \times e_2 = 1$)



Distribution of $\cos\theta_{isoe}$

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

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



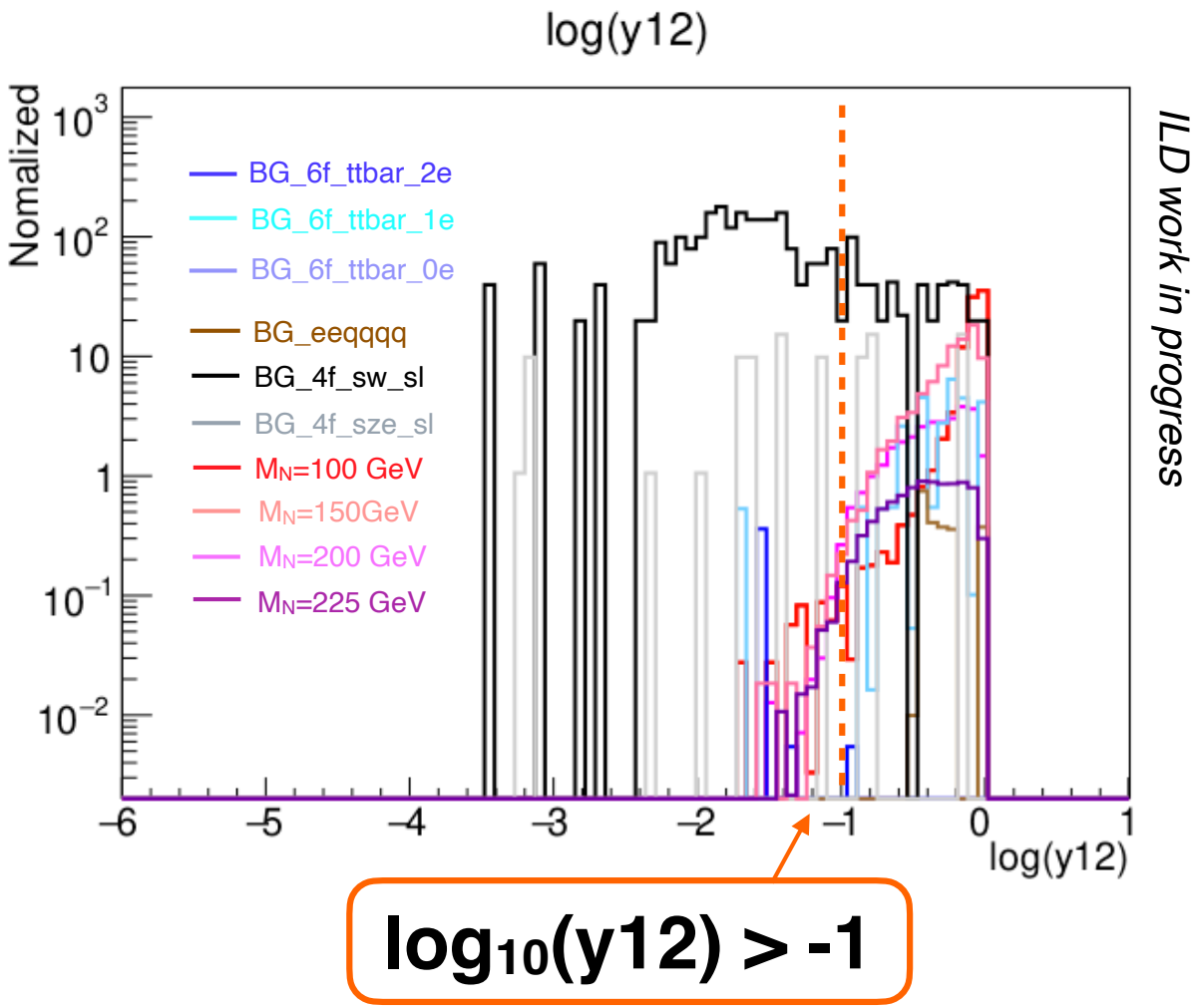
-0.95< $\cos\theta_{isoe}$ < 0.95

4 fermions semi leptonic processes in t-channel→ distributed in $|\cos\theta_{isoe}| \sim 1$

Distribution of y12 (Durham)

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

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



4f and 6f background information

Cross section — BG

- ILC 500 with ISR / BS

(100%,100%)	eeqqqq			4f_singleW_semileptonic	4f_singleZee_semileptonic
	eexyyx	xxxxee	yyyyee	4f_sw_sl	4f_sze_sl
eLpR	1,64E+01	8,71E-02	1,45E-01	7,81E+03	1,96E+03
eRpL	3,64	4,62E-02	5,31E-02	2,28E+01	1,73E+03
eLpL	6,63	3,38E-02	2,20E-02	7,53E+02	1,78E+03
eRpR	6,61	3,30E-02	1,97E-02	7,50E+02	1,78E+03

Cross section — BG

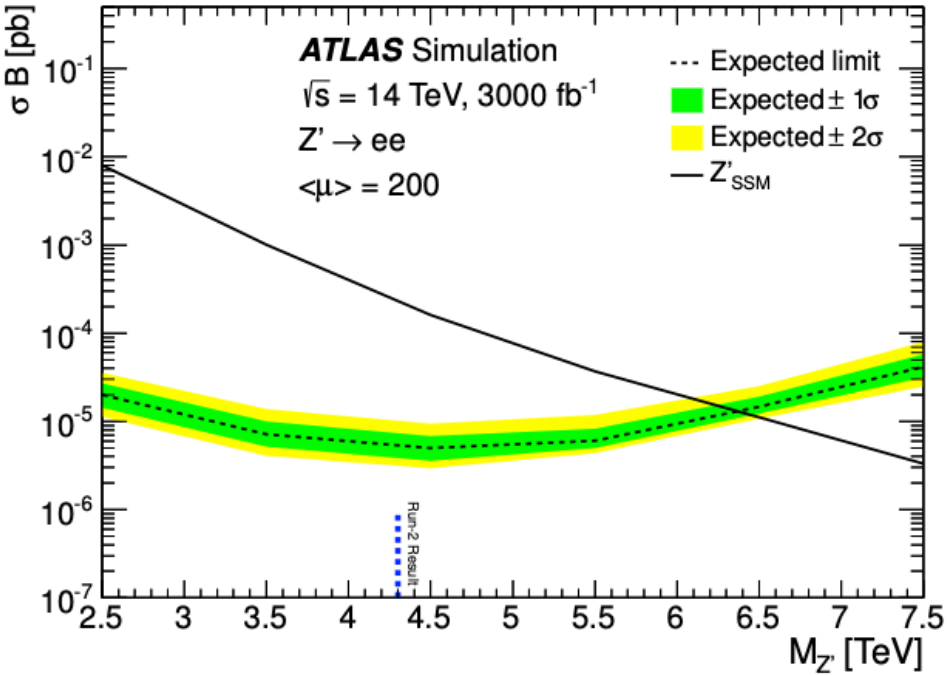
- ILC 500 with ISR / BS

(100%, 100%)	6f_ttbar											
	yyveev	yyvelv	yyvlev	yyveyx	yyxyev	yyvllv	yyvlyx	yyxylv	yyuyyu	yyuyyc	yycyyu	yycyyc
eLpR	2,01E+01	3,96E+01	3,96E+01	1,17E+02	1,17E+02	7,87E+01	2,32E+02	2,31E+02	1,67E+02	1,64E+02	1,65E+02	1,63E+02
eRpL	7,56E+00	1,50E+01	1,50E+01	4,45E+01	4,45E+01	3,01E+01	8,91E+01	8,89E+01	6,45E+01	6,44E+01	6,41E+01	6,07E+01
eLpL	1,08E-01	1,89E-01		5,46E-01								
eRpR	1,09E-01		1,88E-01		5,42E-01							

Information associated with $U(1)_{B\text{-}L}$ model

Current limits - Z' mass

SM like Z' coupling



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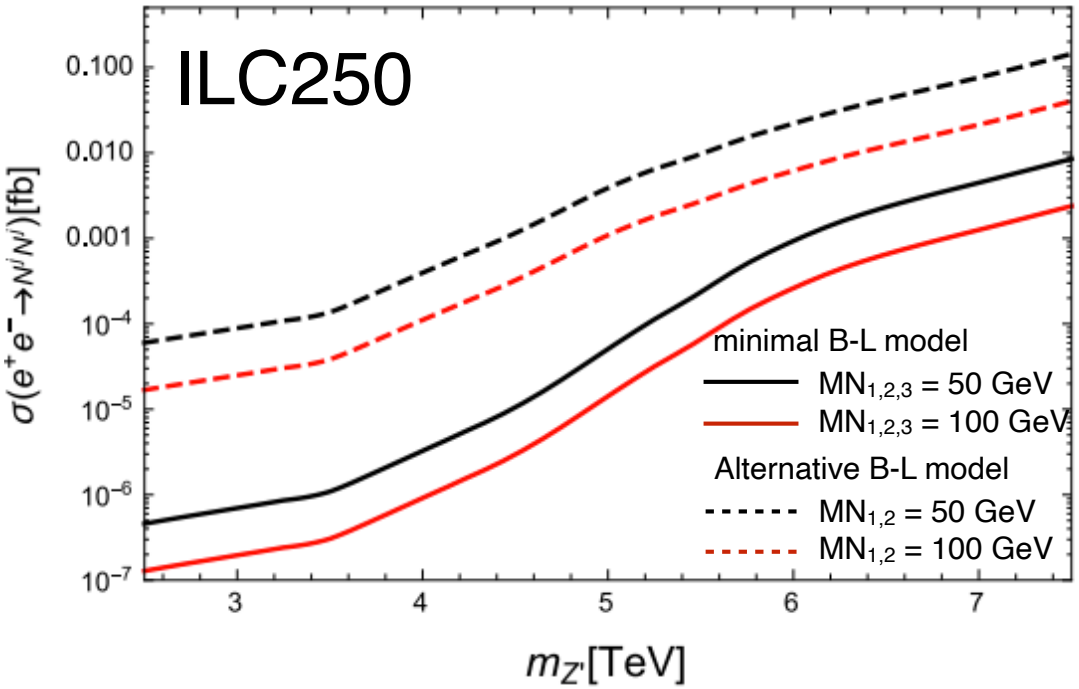
HL-LHC prospects limit for $U(1)_{B-L}$ model

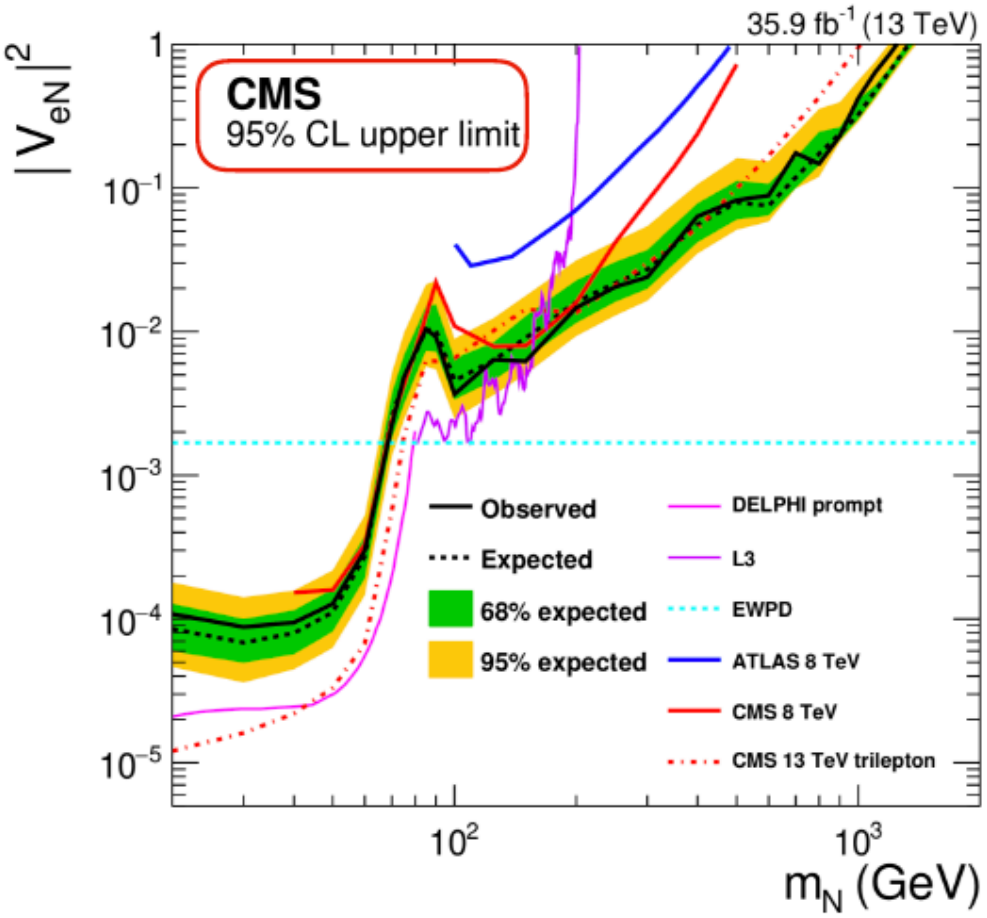


arXiV[1812.11931]

The heavier Z' mass less constrained by LHC

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

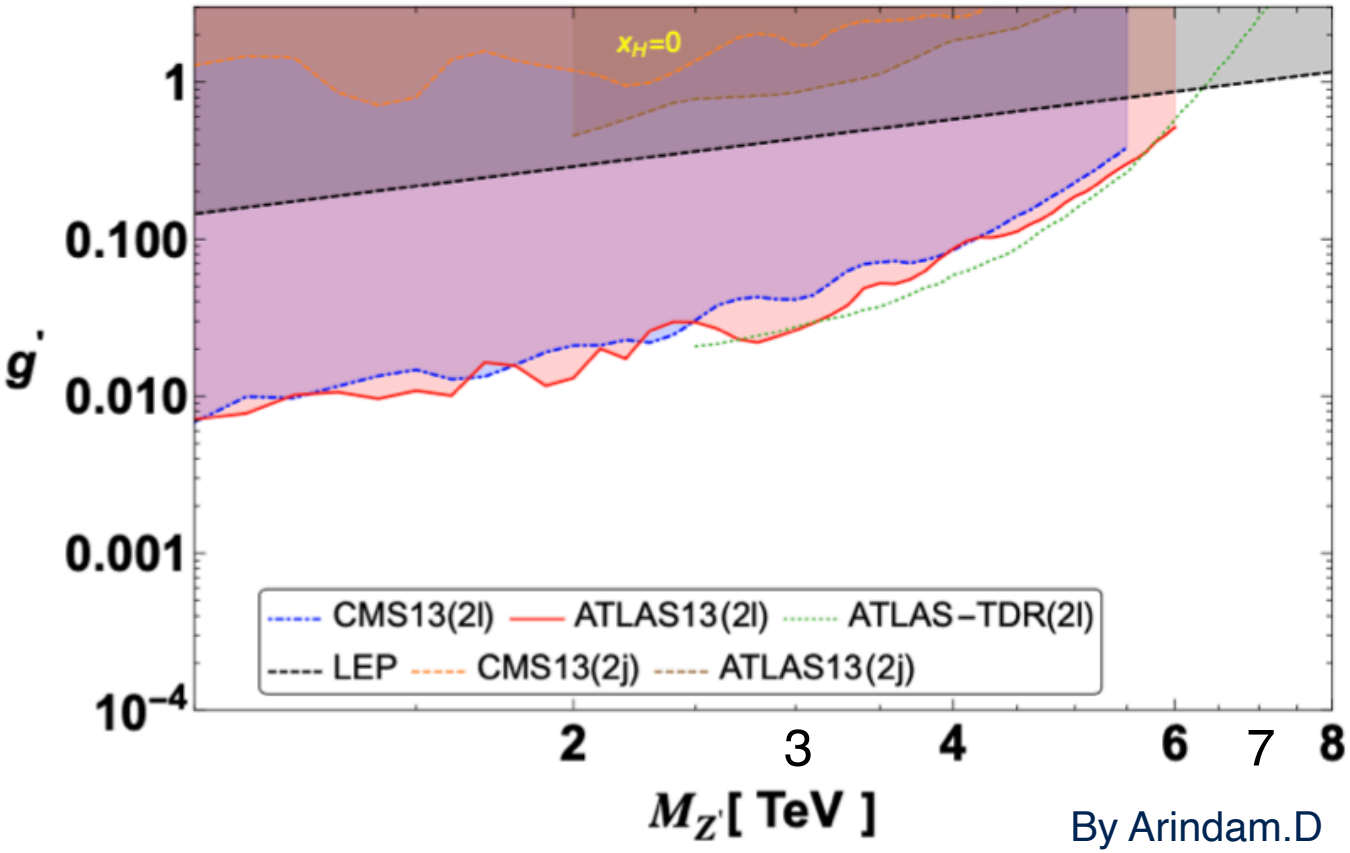
$|V_{eN}|^2$: the “light-heavy” neutrino mixing matrix



https://arxiv.org/pdf/1802.02965.pdf

Current Limits and prospects - Z' mass,g1'

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



By Arindam.D

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