Searching for Right Handed Neutrinos using same sign leptons 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?
- Do quarks and leptons unify?
- Why is neutrino mass so small?

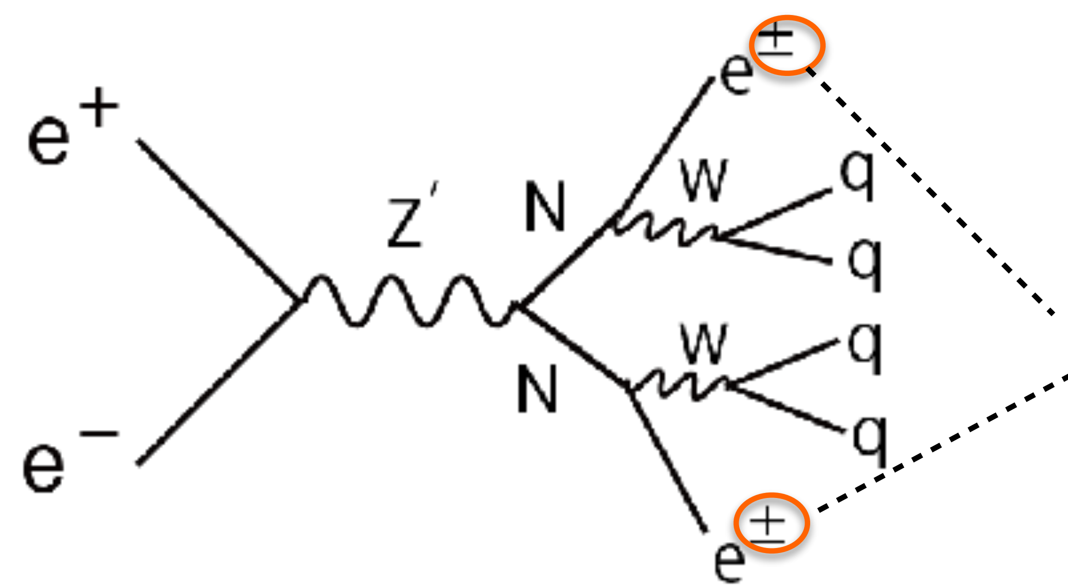
RHN is assumed to be

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

gauge boson : Z'

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

→ RHN **pair** production



Lepton # violation is possible!

↓

Same sign leptons possible

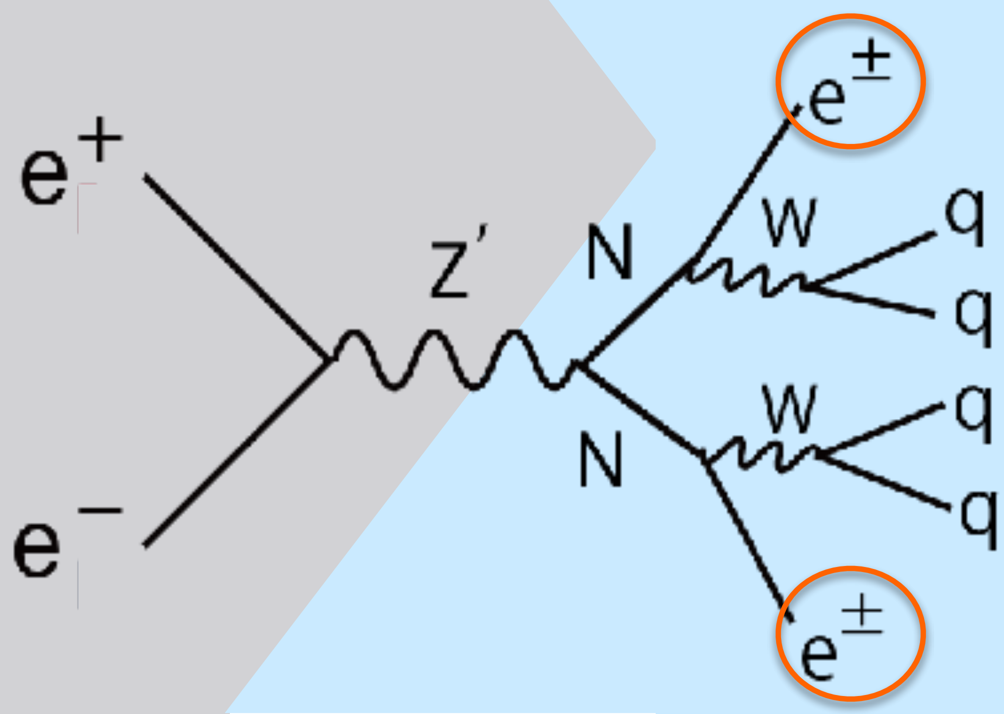
↓

Very small SM BG!

Study flow

Same sign electron

ILC **500**



ILC **250**

Same sign muon

ILC **500**
+
ILC **250**

Almost done
(Most of today's talk)

Now
(Briefly report)

Future plan

ILC 500

Benchmark points @ ILC 500

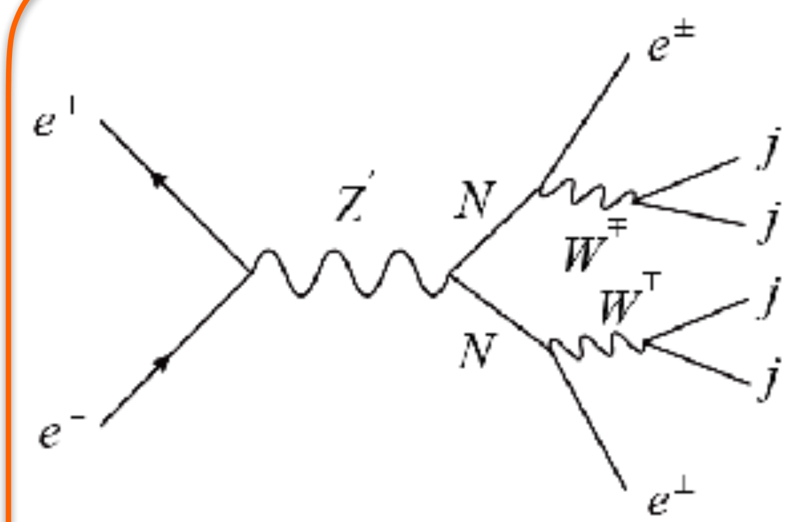
- Pol(e⁻, e⁺) = (−0.8, +0.3), (+0.8, −0.3): $\mathcal{L} = 1600\,[\mathrm{fb}^{-1}]$
- Pol(e⁻, e⁺) = (−0.8, −0.3), (+0.8, +0.3): $\mathcal{L} = 400\,[\mathrm{fb}^{-1}]$

M_N [GeV] RHN mass	$M_{Z'}$ [TeV] Z' mass	g_1' $U(1)_{B-L}$ coupling	$\lvert V_{eN}\rvert^2$ mixing angle	$BR(N \to eW)$	σ_{LR} [fb] 100% polarisation	σ_{RL} [fb] 100% polarisation
100	7	1	0.003	0.44	0.55	0.71
150	7	1	0.003	0.43	0.36	0.45
200	7	1	0.003	0.30	0.14	0.16
225	7	1	0.003	0.29	0.046	0.0052

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

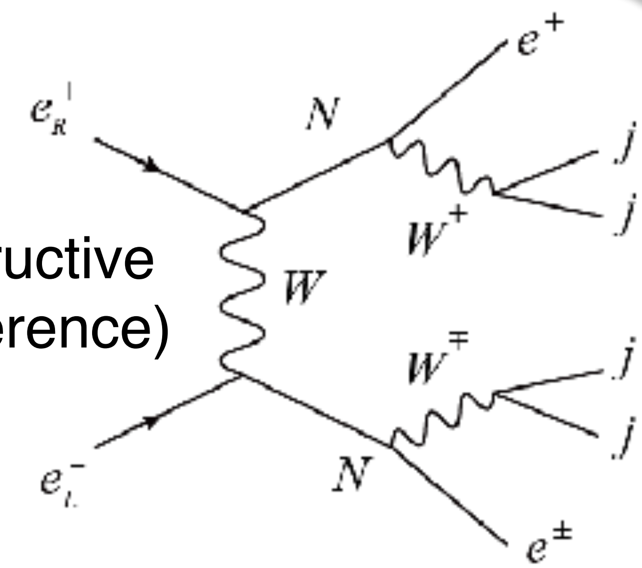
Analysis tool and signal + backgrounds

ILC500 Signal process:



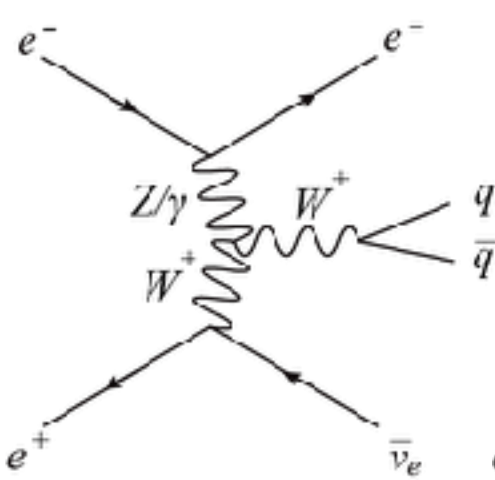
s-channel via Z'

\+ (Destructive interference)

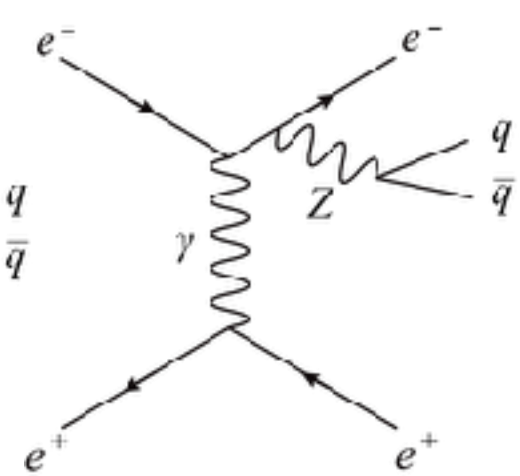


t-channel via W
(only e_L)

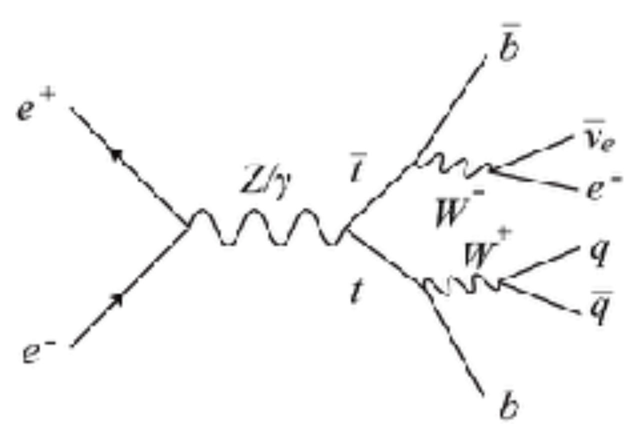
6f and 4f major background processes:



4 fermions singleW
semileptonic



4 fermions singleZee
semileptonic



6 fermions ttbar
1electron

WHIZARD ver 2.8.5
Make Events

ILD Full Simulation & Reconstruction (Geant4)

miniDST
Events format

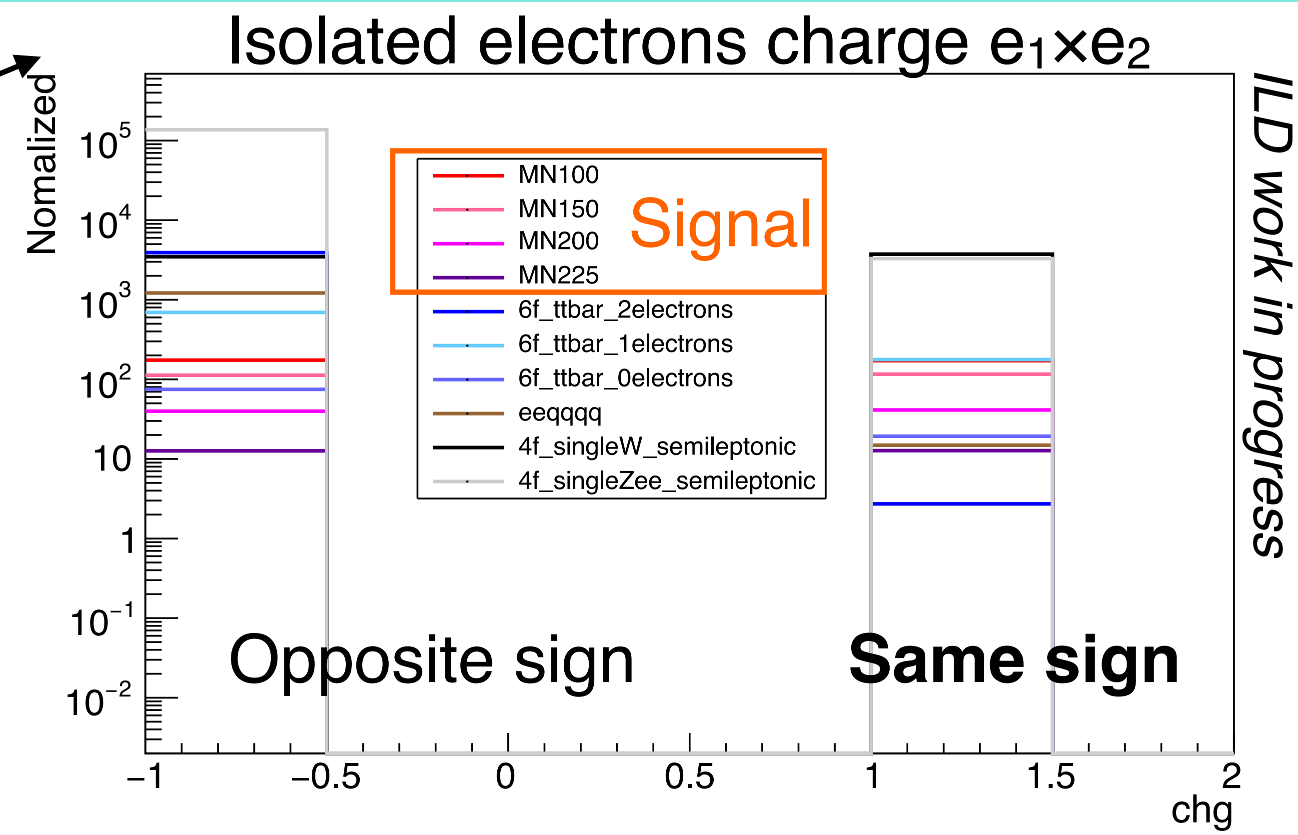
Cut conditions to select signal events

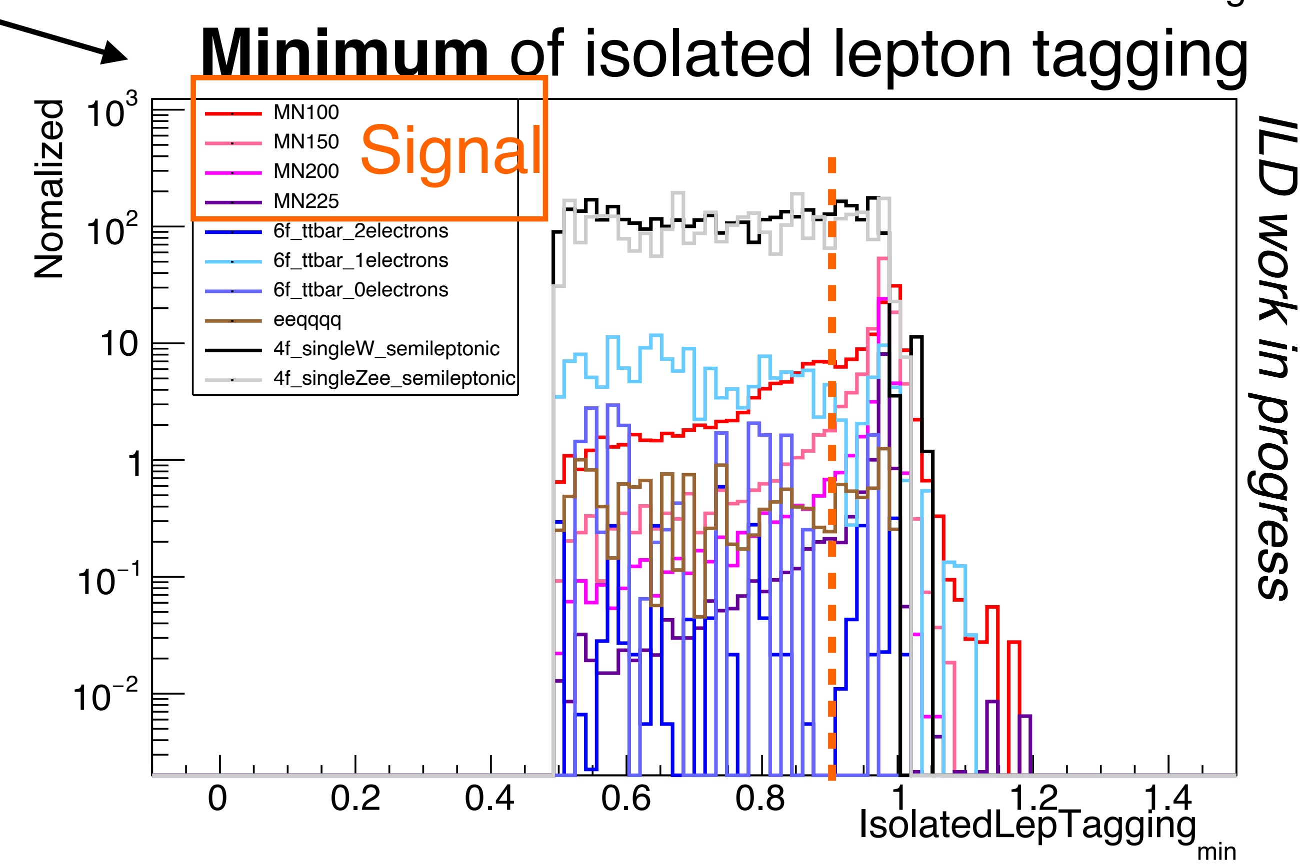
- ILC 500 with ISR / BS
- **Pol(e^-, e^+) = (+0.8, −0.3)**

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

Signal efficiency ∼ **20%**

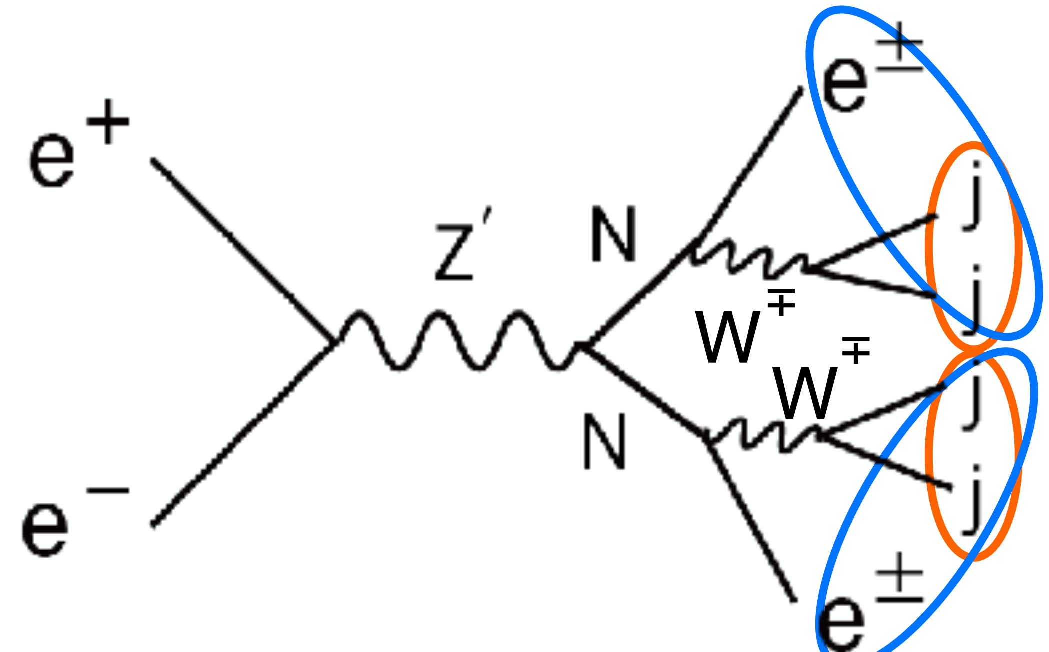
Remaining backgrounds ∼ **150** (eLpR), **20** (eRpL)





Reconstruction methods

After removing isolated electrons force into 4 jets (Durham)



Search for the correct combination of jj and jje

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

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

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

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

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

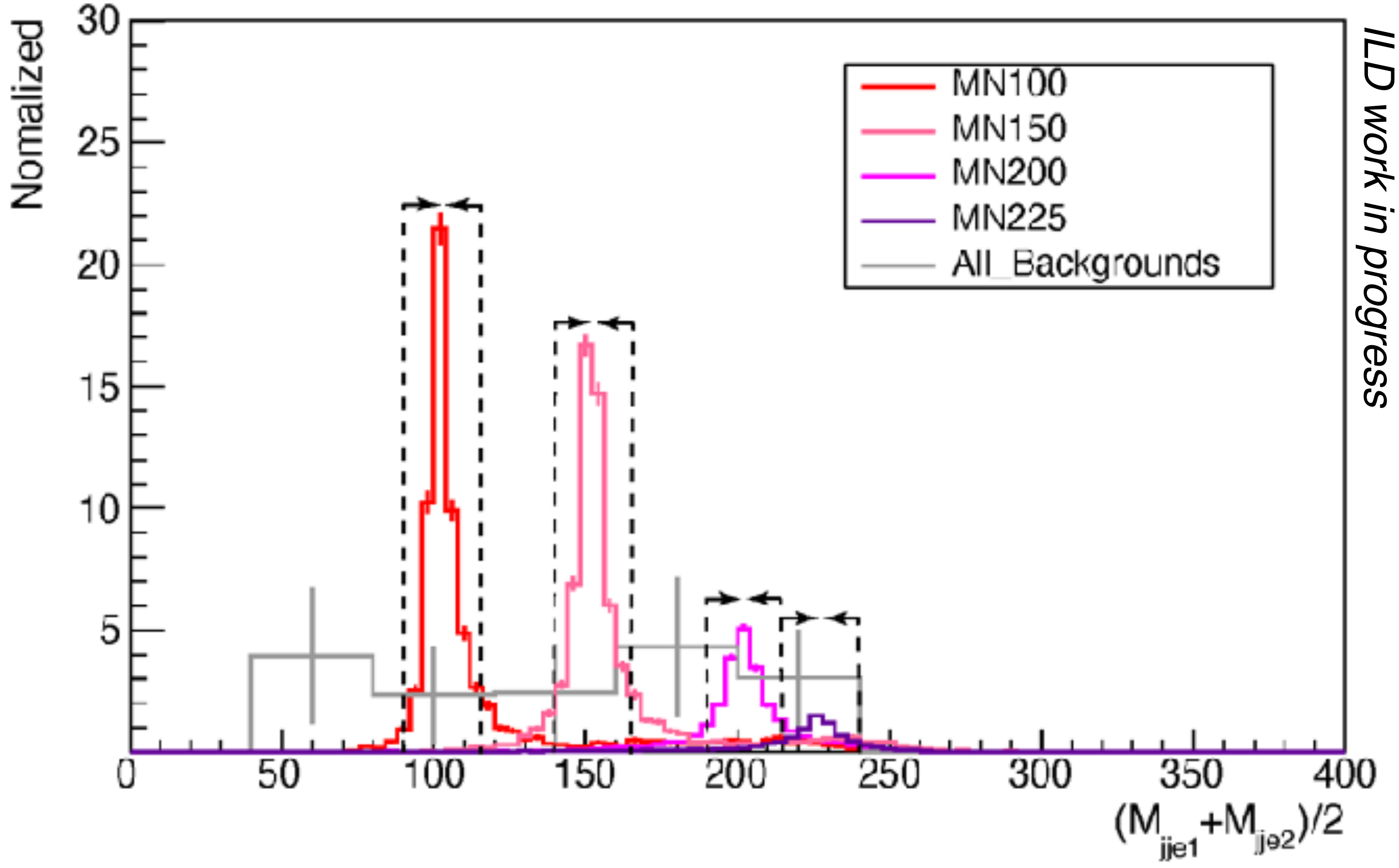
$$F_2 = (M_{jje1} - M_{jje2})^2$$

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

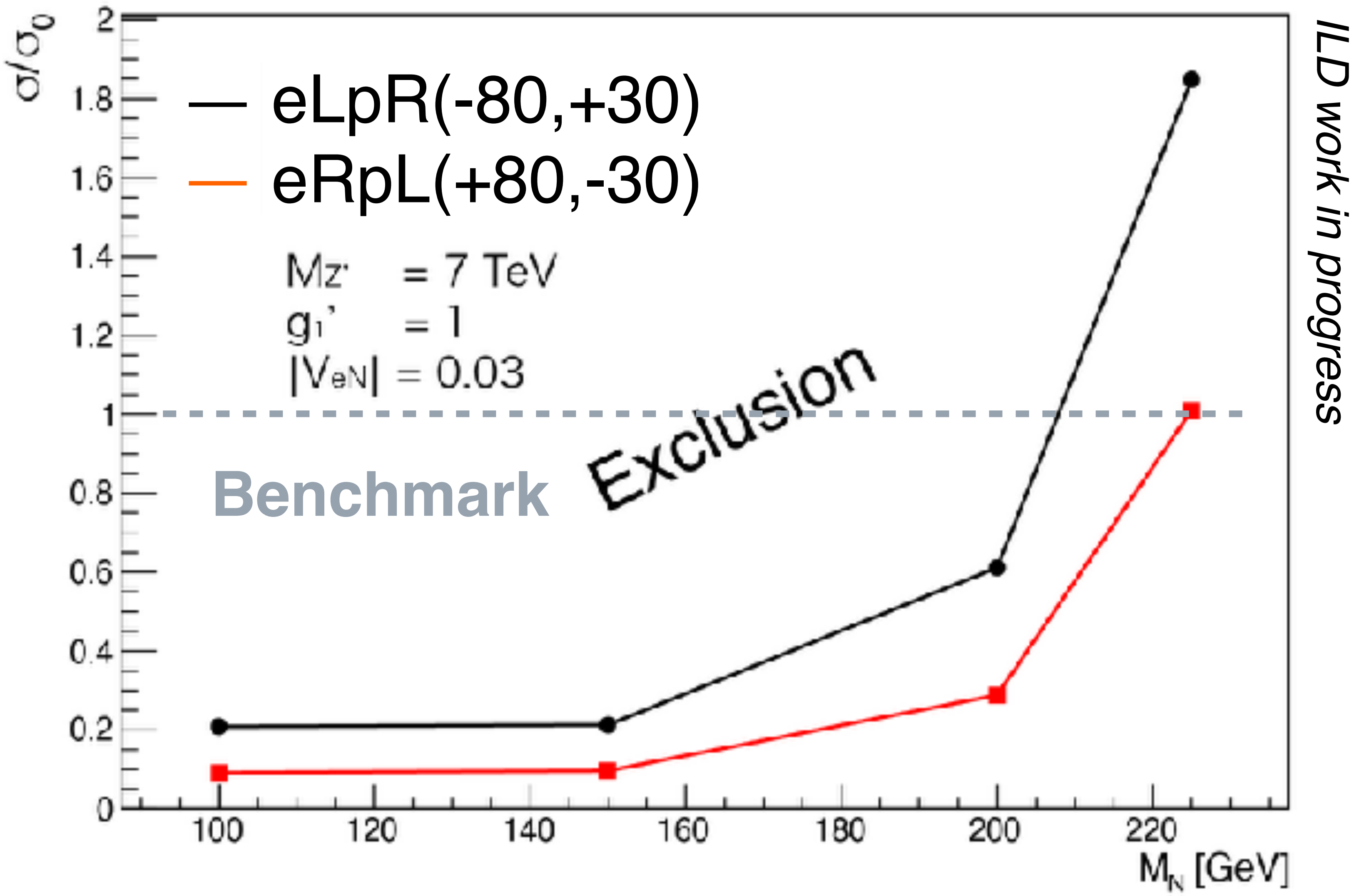
Results

	M_N [GeV]	N_S # of Signal After cut	N_B # of BG After cut	$\frac{N_S}{\sqrt{N_B+N_S}}$ Significance	$\frac{\sigma_{95}}{\sigma_0}$
LR 80,30	100	53	20.12	6.25	0.21
	150	52		6.18	0.21
	200	18		2.95	0.61
	225	5		1.18	1.8
RL 80,30	100	66	3.24	7.98	0.0092
	150	63		7.77	0.097
	200	21		4.29	0.29
	225	6		1.99	1

Exclusion plot on cross-section

Calculate 95% UL on cross-section

σ_0 : benchmark cross-section



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

Summary of ILC 500 case

- We analyze “RHN **pair** production” by full simulation at ILC500.

- 4 fermion semileptonic processes are dominant backgrounds.
  Background is mostly removed, 20(eLpR) and 3(eRpL) events remain.

- 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!

ILC 250

Benchmark points @ ILC 250

$\mathrm{Pol}\,(e^+, e^-) = (-0.8, +0.3), (+0.8, -0.3) : \mathcal{L} = 900\,[\mathrm{fb}^{-1}]$
$\mathrm{Pol}\,(e^+, e^-) = (-0.8, -0.3), (+0.8, +0.3) : \mathcal{L} = 100\,[\mathrm{fb}^{-1}]$

M_N [GeV] RHN mass	$M_{Z'}$ [TeV] Z' mass	g1' $U(1)_{B-L}$ coupling	$\lvert V_{eN}\rvert^2$ mixing angle	$BR(N \to eW)$	σ_{LR} [fb] 100% polarisation	σ_{RL} [fb] 100% polarisation
85	7	1	0.003	0.50	0.048	0.089
95	7	1	0.003	0.48	0.033	0.060
100	7	1	0.003	0.44	0.026	0.046
110	7	1	0.003	0.40	0.012	0.021
120	7	1	0.003	0.37	0.0021	0.0035

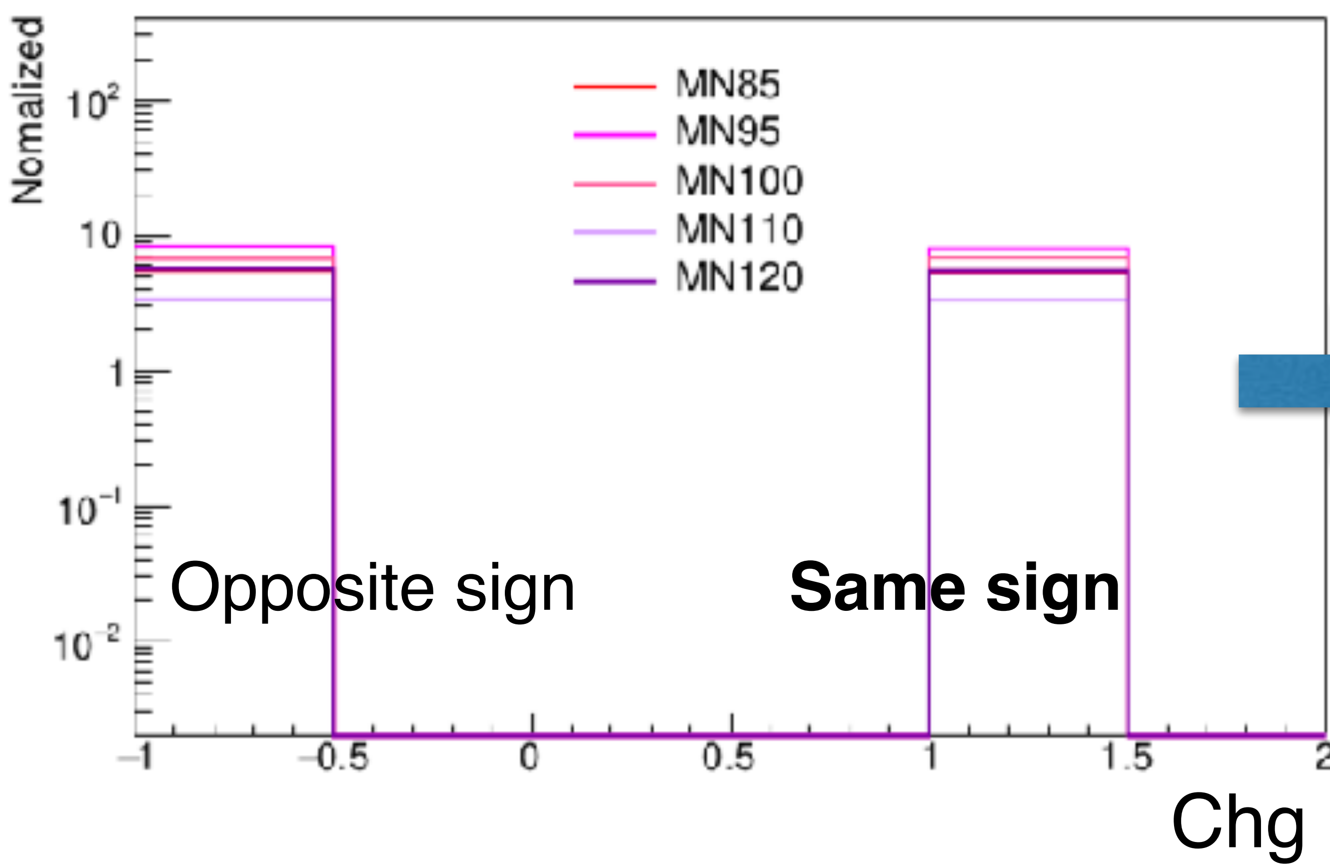
- minimal $U(1)_{B-L}$ model
- ILC 250 with initial state radiation (ISR) and beamstrahlung (BS)

Preliminary results

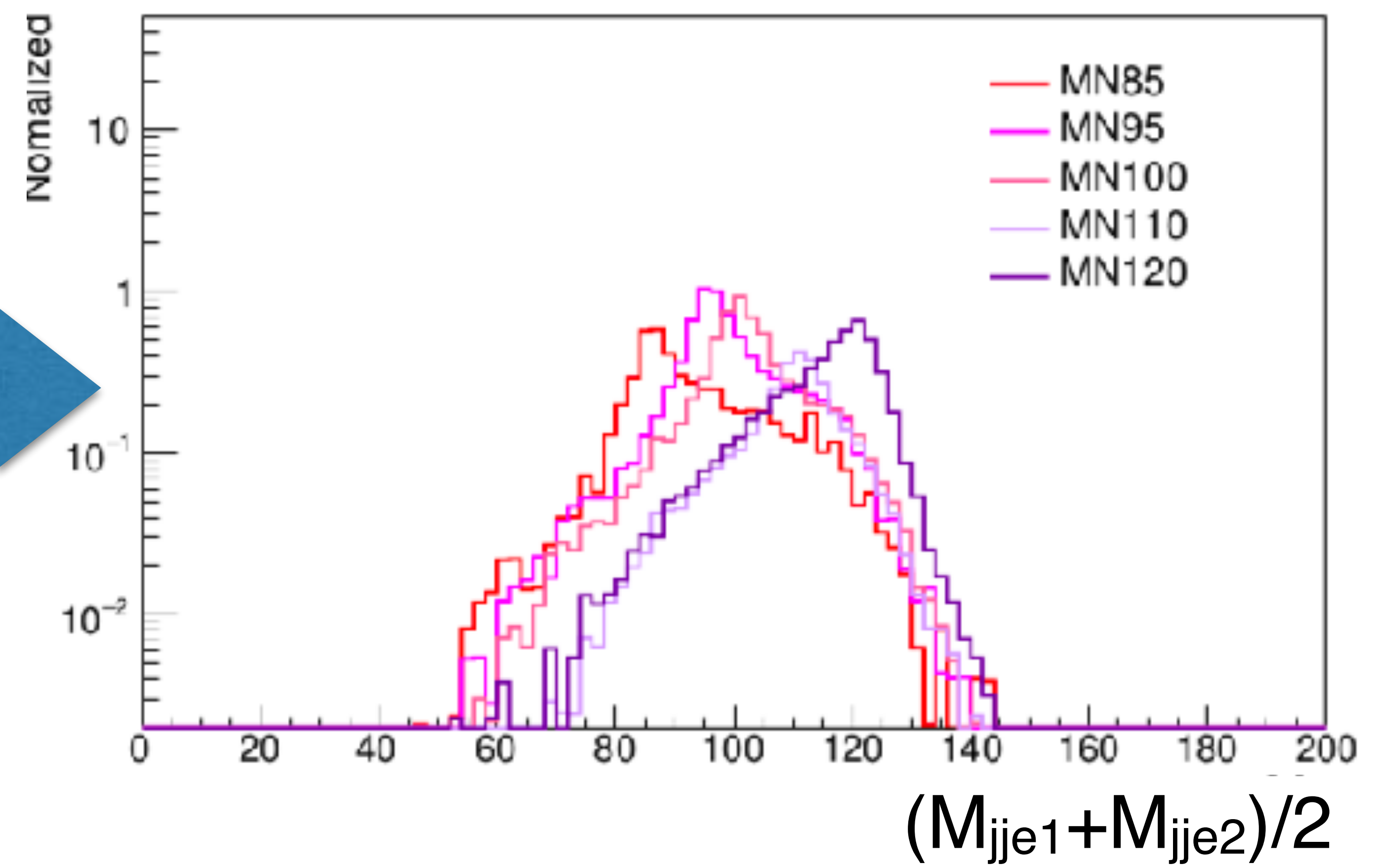
- ILC 250 with ISR / BS
- **Pol(e^-, e^+) = (+0.8, -0.3)**

Isolation cut == Isolated e # = 2 && Isolated γ, μ # = 0

Isolated electrons charge $e_1 \times e_2$
(Isolation cut)



Reconstruction RHN
(Isolation + same sign cut)



Signal efficiency about 10 - 20 %
(Remaing signal events < 10)

Next step

- I add background events for these signal events.
  Ex) 4 and 6 fermions events in the final state

  -> Shinichi.K is preparing minidst files of backgrounds for me.

- I need to consider “cut condition”.

- Finding the exclusion limit on cross-section

Back up

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): $\mathcal{L} = 400\,[\mathrm{fb}^{-1}]$

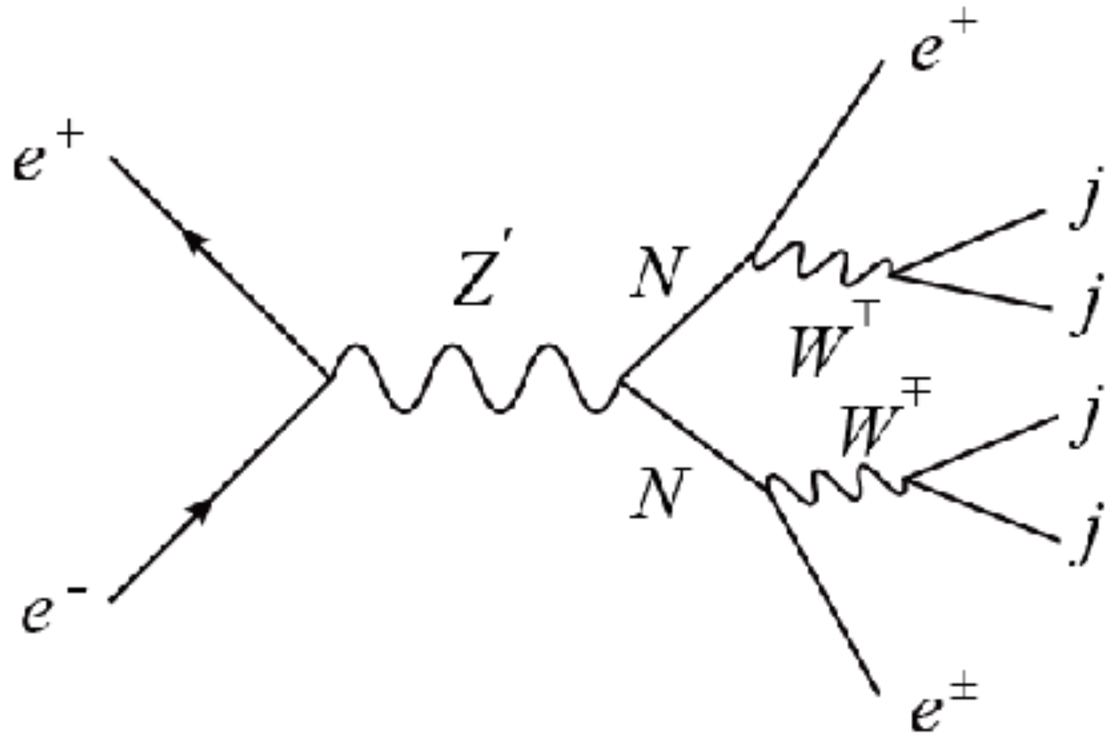
M_N [GeV] RHN mass	$M_{Z'}$ [TeV] Z' mass	g_1' $U(1)_{B-L}$ coupling	$\lvert V_{eN}\rvert^2$ mixing angle	BR $(N\to eW)$	$\sigma(e_L^- e_R^+ \to NN)$ 100% polarization [fb]	Event # at ILC500 [4000fb^{-1}]
100	7	1	0.003	0.44	0.71	**1261**
150	7	1	0.003	0.33	0.45	**229**
200	7	1	0.003	0.30	0.16	**131**
225	7	1	0.003	0.29	0.052	**18**

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

Signal events

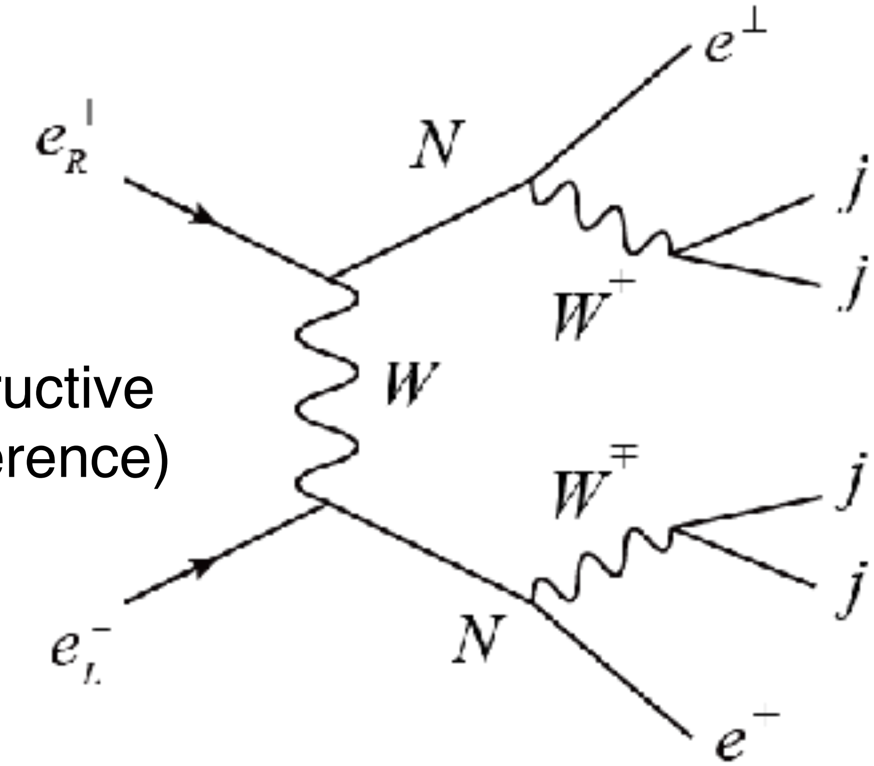
ILC250

Signal process:



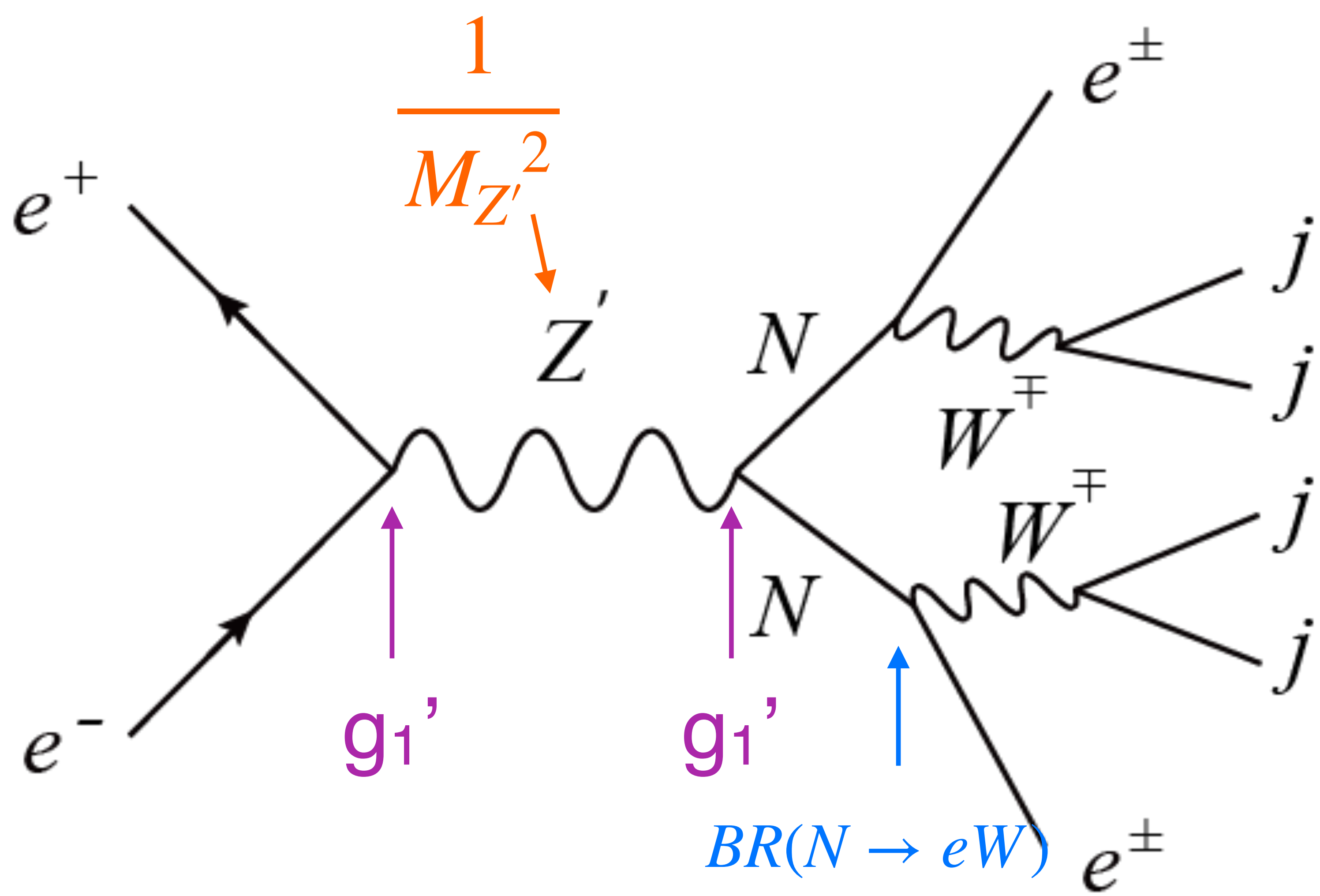
s-channel via Z'

+ (Destructive interference)



t-channel via W
(only e_L)

Model parameters



$$\sigma = \sigma(ee \to NN) \times (BR(N \to e^\pm W^\mp))^2$$

$$\propto {g_1'}^4 \frac{1}{{M_{Z'}}^4} (BR(N \to e^\pm W^\mp))^2 \equiv \alpha$$

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

Gauged B-L extension of Standard Model (SM)

The unique anomaly free global symmetry in the SM

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

Gauge boson : Z'

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

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

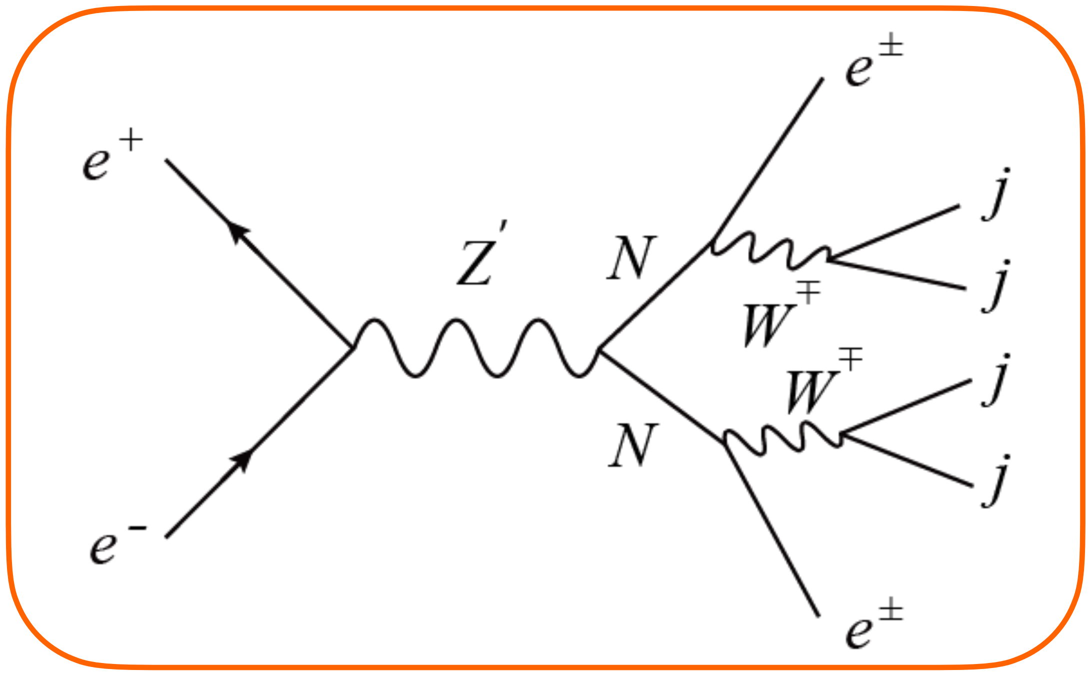
minimal $U(1)_{B-L}$ model : charge

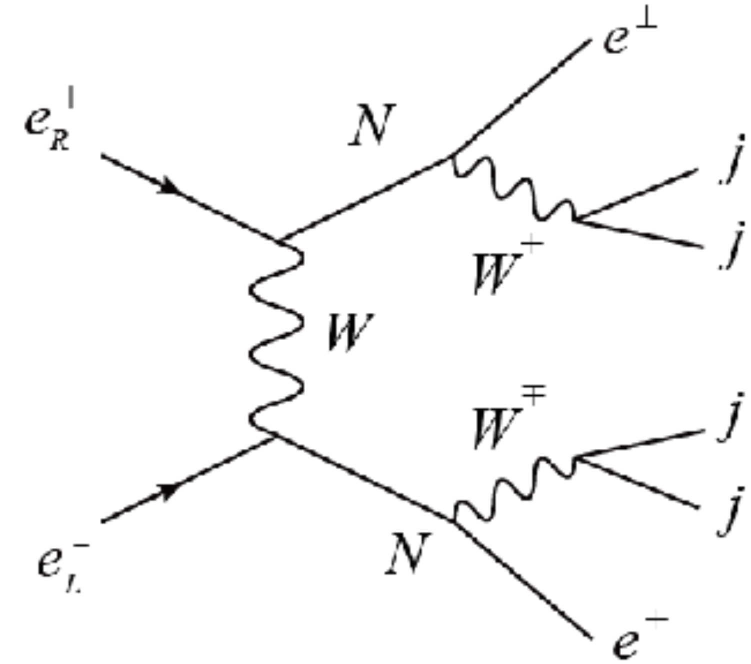
		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
RHN	N_R^i	1	1	0	-1
New Higgs field	Φ	1	1	0	2

i=1,2,3

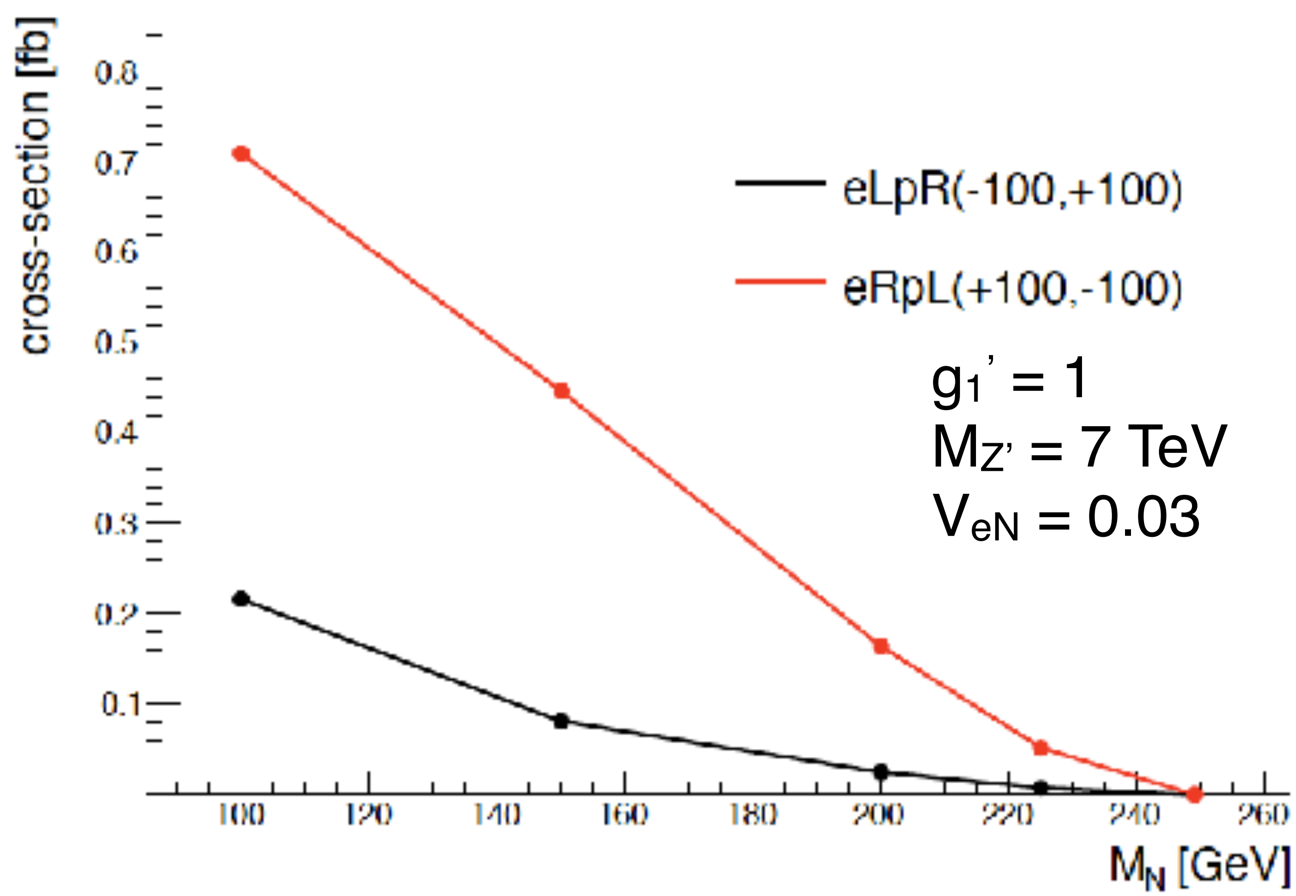
arXiV[1812.11931]
Arindam Das, Nobuchika Okada, Satomi Okada, Digesh Raut

Signal





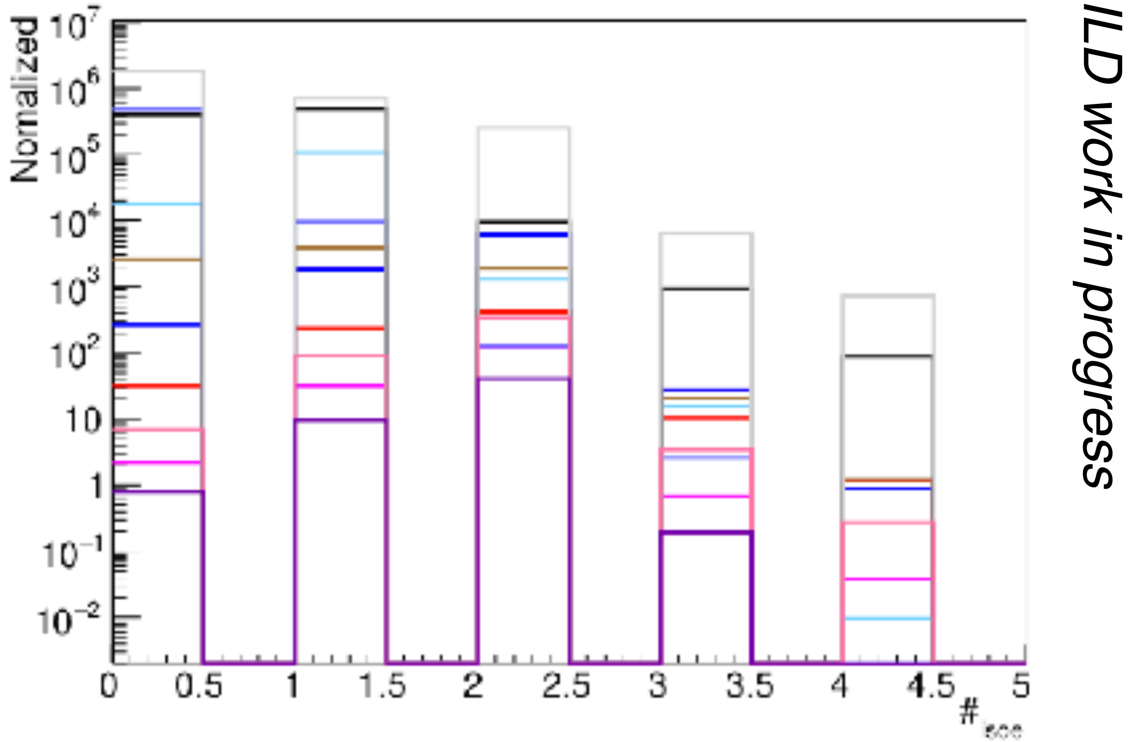
Destructive interference



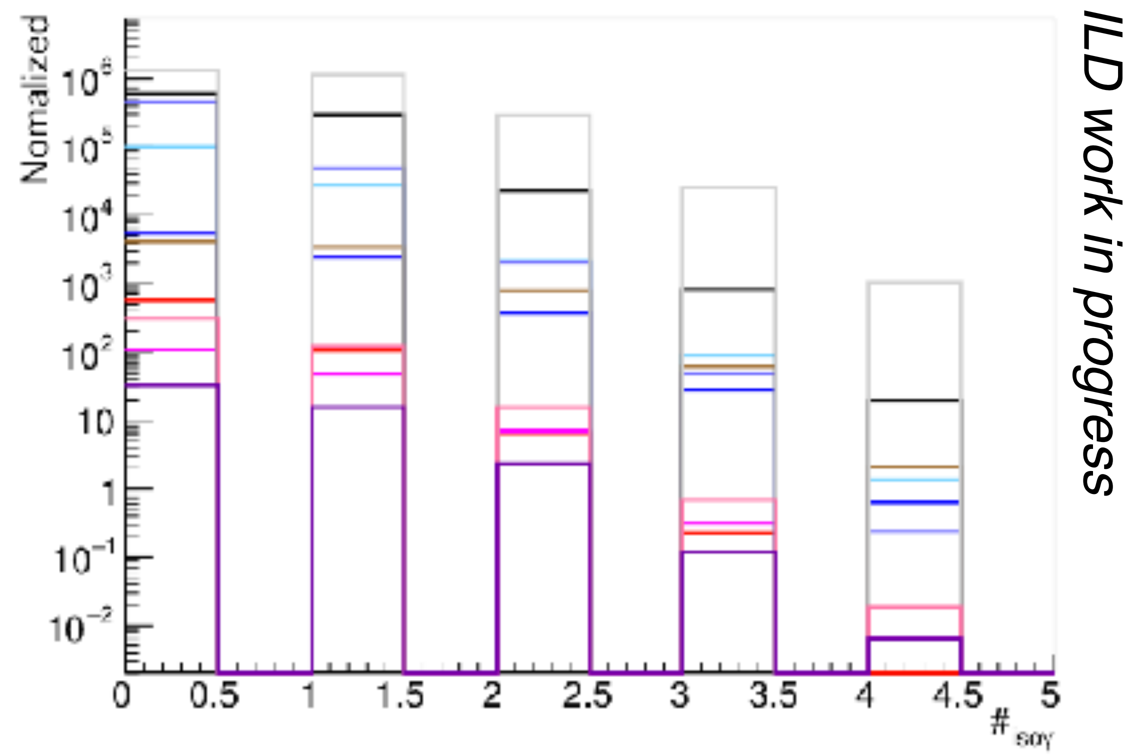
Isolated e,γ,μ

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

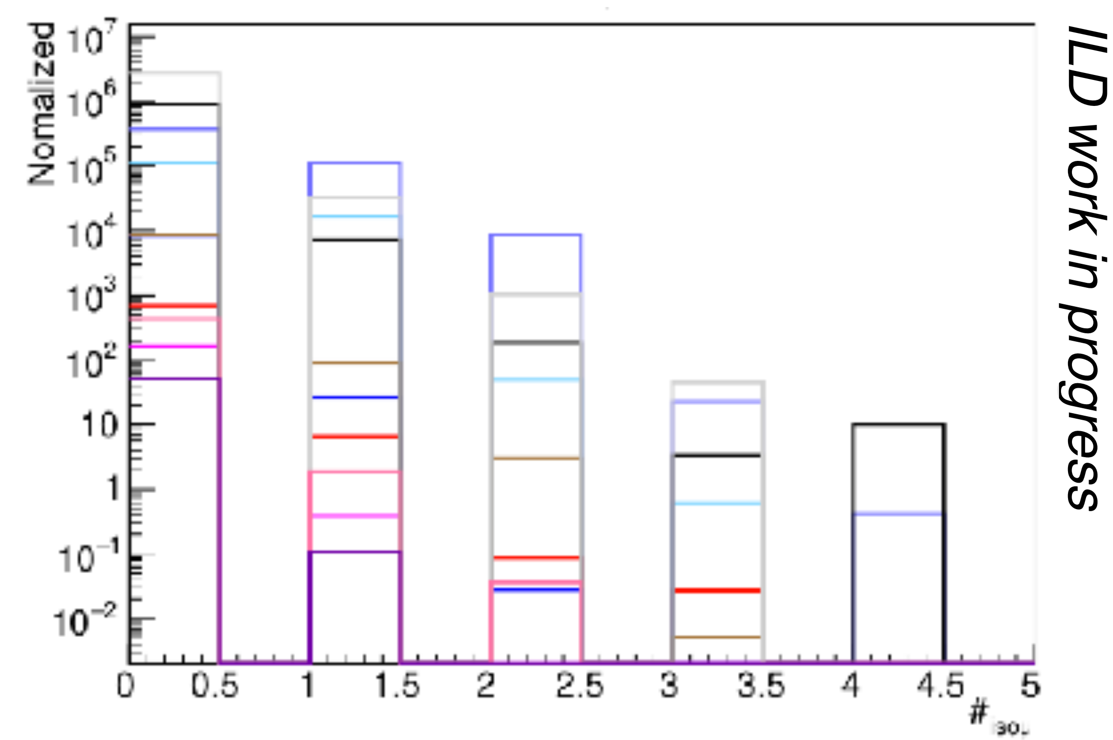
Number of isolated e



Number of isolated γ



Number of isolated μ



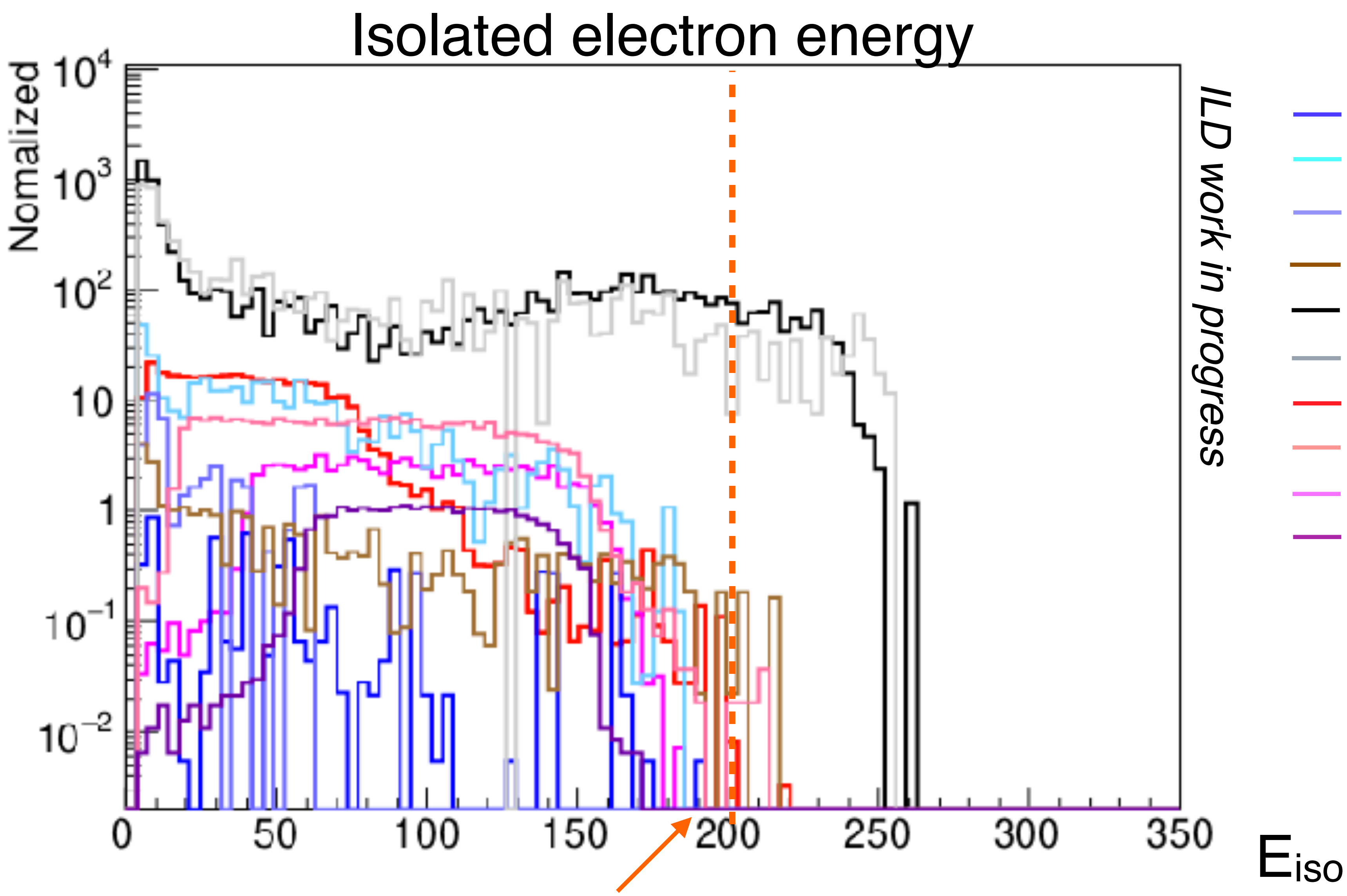
- M_N=100 GeV
- M_N=150GeV
- M_N=200 GeV
- M_N=225 GeV
- BG_6f_ttbar_2e
- BG_6f_ttbar_1e
- BG_6f_ttbar_0e
- BG_4f_sw_sl
- BG_4f_sze_sl
- BG_eeqqqq

- Isolated e # = 2 && Isolated γ, **<u>μ = 0</u>**

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 ($e_1 \times e_2 = 1$)

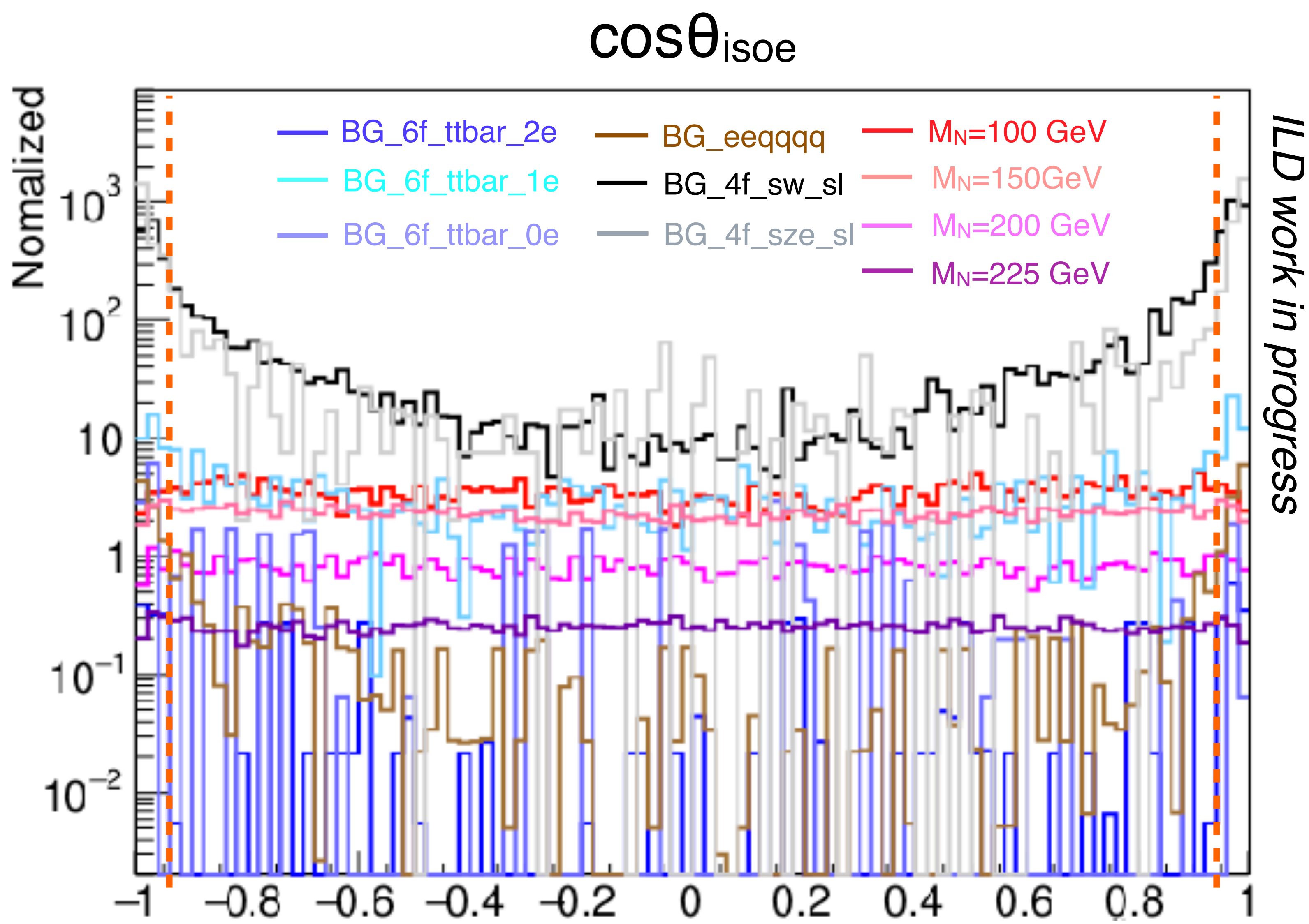


E_{iso} < 200 [GeV]

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 ($e_1 \times e_2 = 1$)



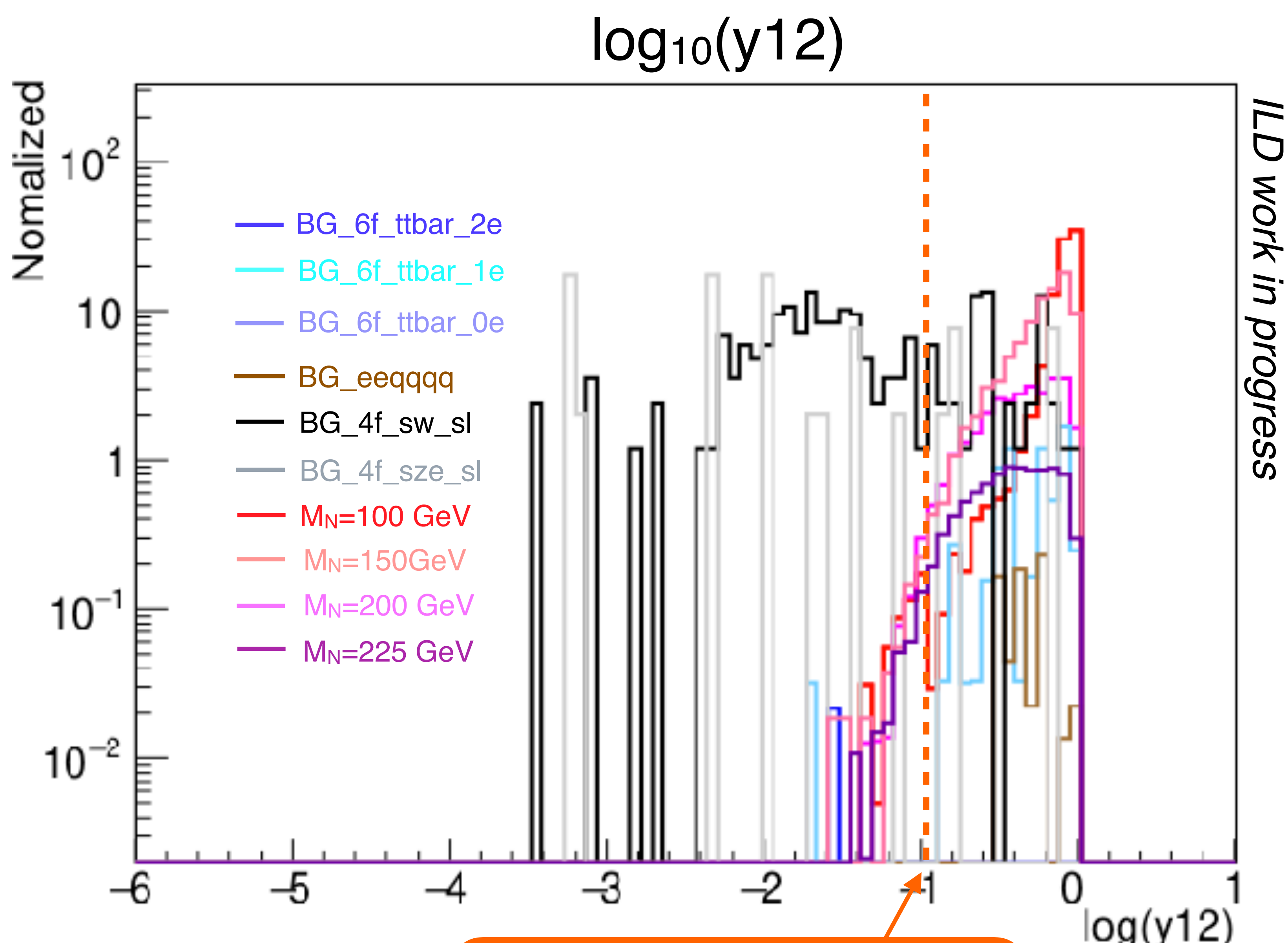
$-0.95 < \cos\theta_{isoe} < 0.95$

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 ($e_1 \times e_2 = 1$)

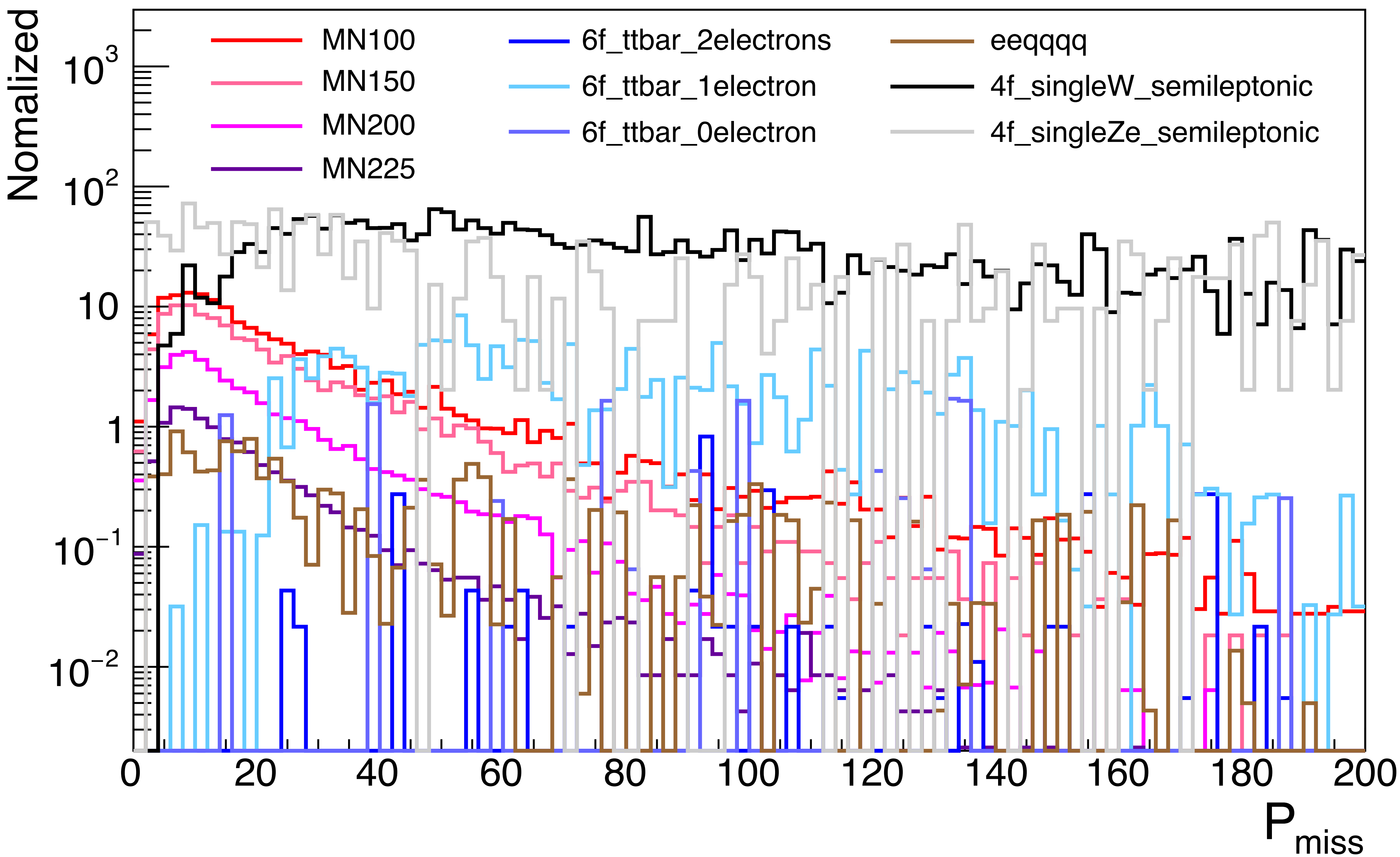


$\log_{10}(y12) > -1$

Distribution of P_{miss}

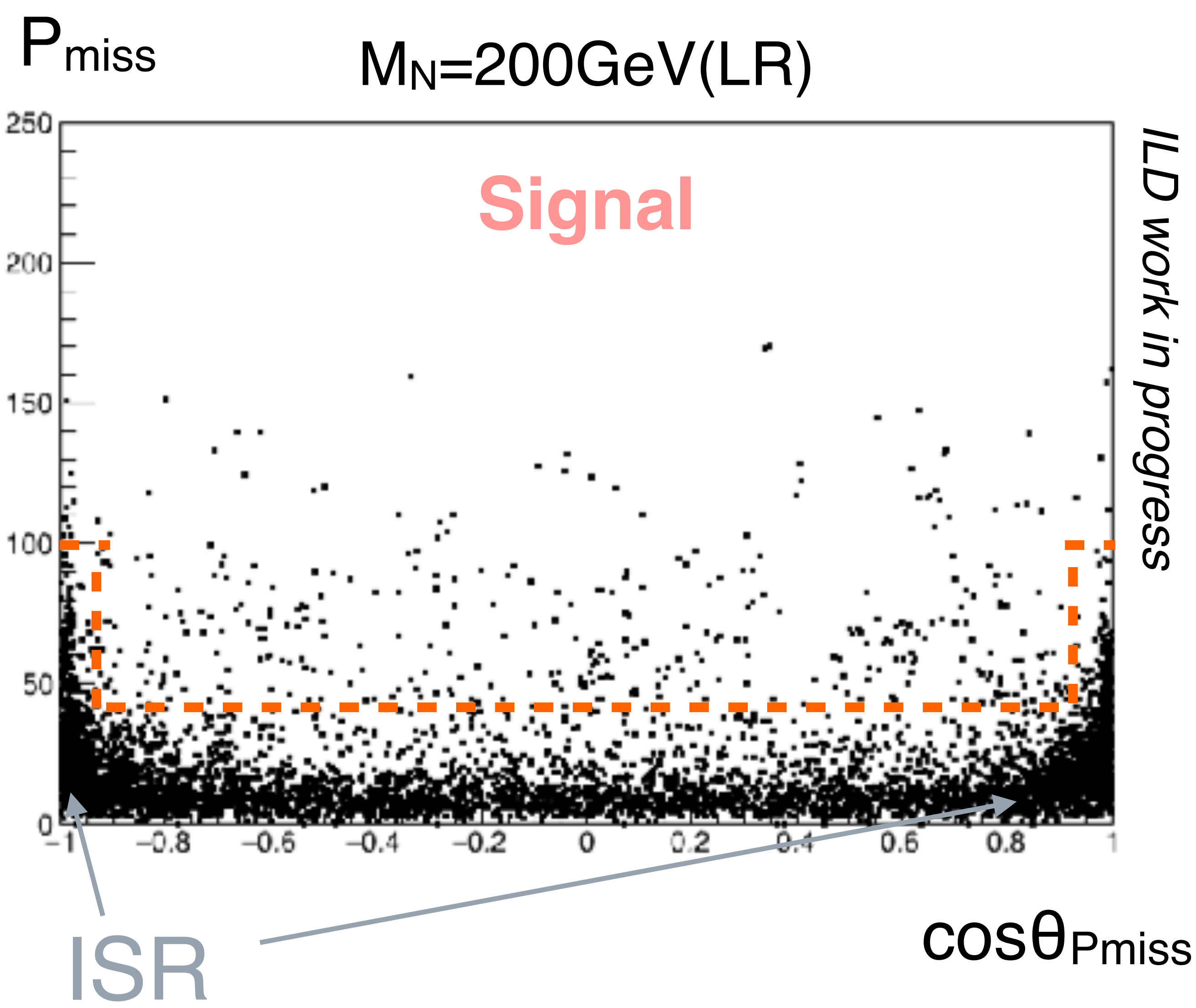
- ILC 500 with ISR / BS
- **Pol(e⁻, e⁺) = (–0.8, +0.3)**

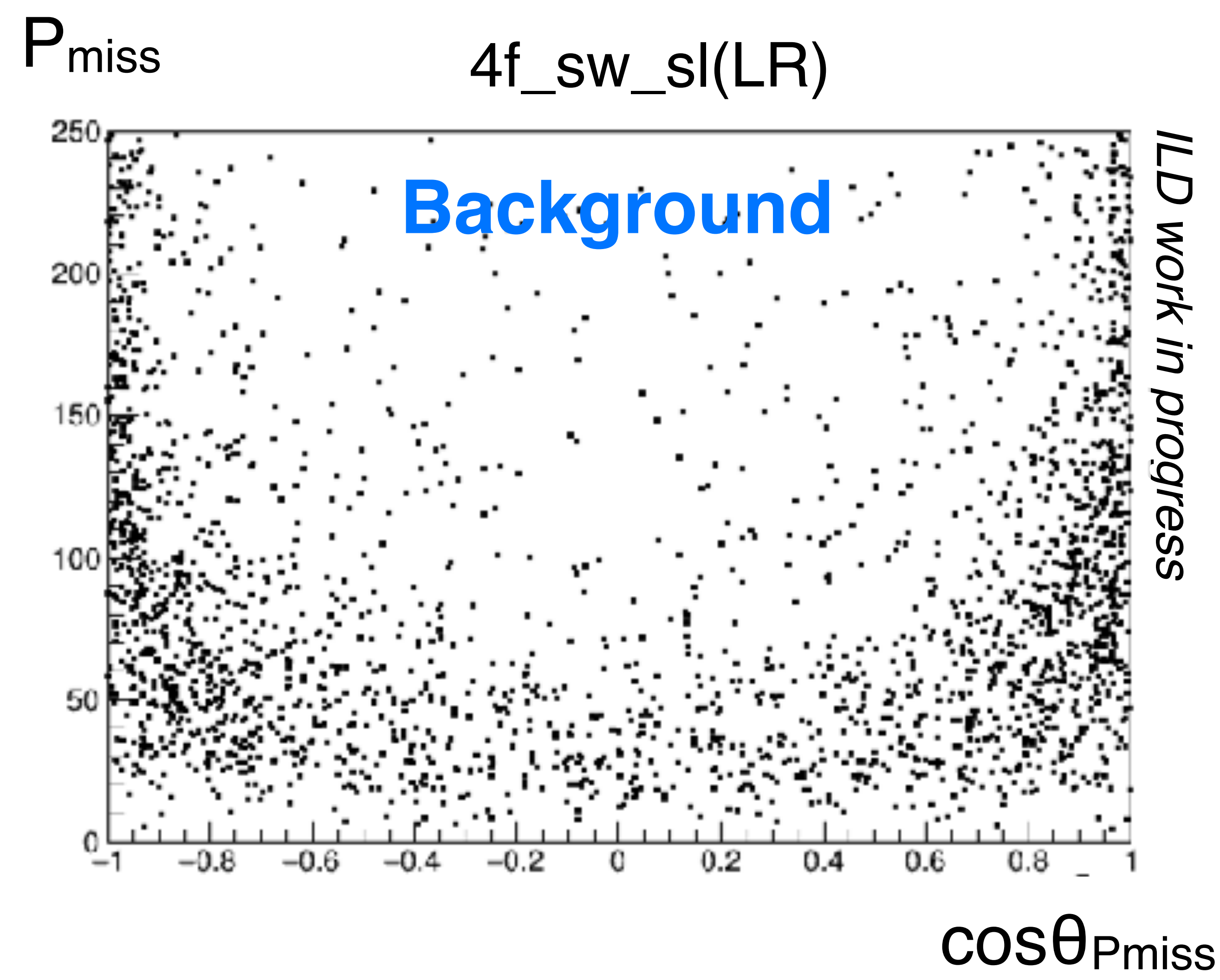
- Isolated e # = 2 && Isolated γ # = 0 && Isolated μ # = 0
- Isolated e is same sign ($e_1 \times e_2 = 1$)



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

- ILC 500 with ISR / BS





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

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

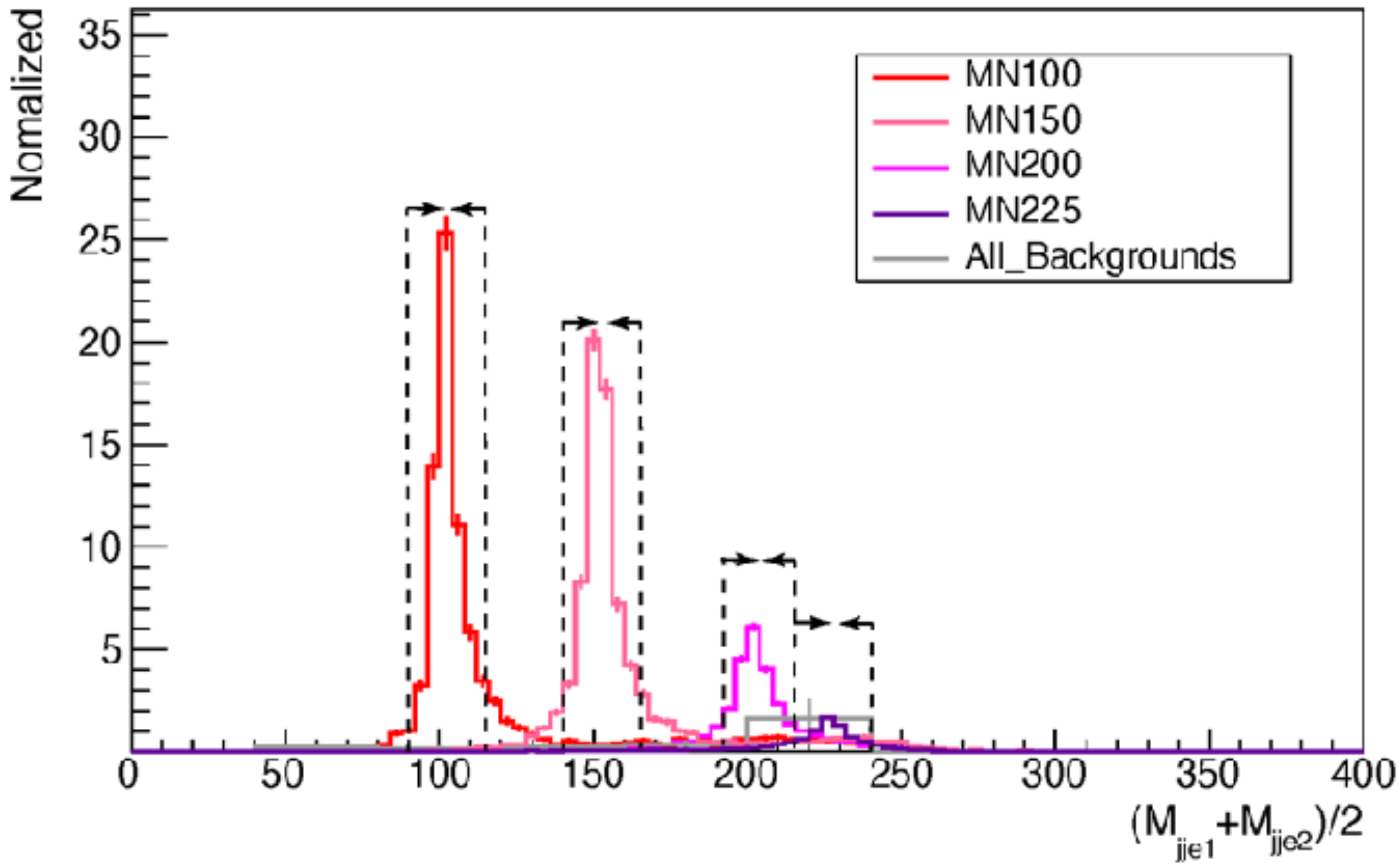
	Expected signal				Expected background					
	M_N=100	M_N=150	M_N=200	M_N=225	eeqqqq	4f_singleW _semileptonic	4f_singleZee_ semileptonic	6f_ttbar 2electrons	6f_ttbar 1electron	6f_ttbar 0electron
No cut	558	394	143	45	3925	258648	612455	7100	56233	4894
e_{iso} #=2 && γ_{iso} #=0 &&	420	343	126	40	1935	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
$\mathrm{IsolatedLepTagging}_{min} > 0.9$	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

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

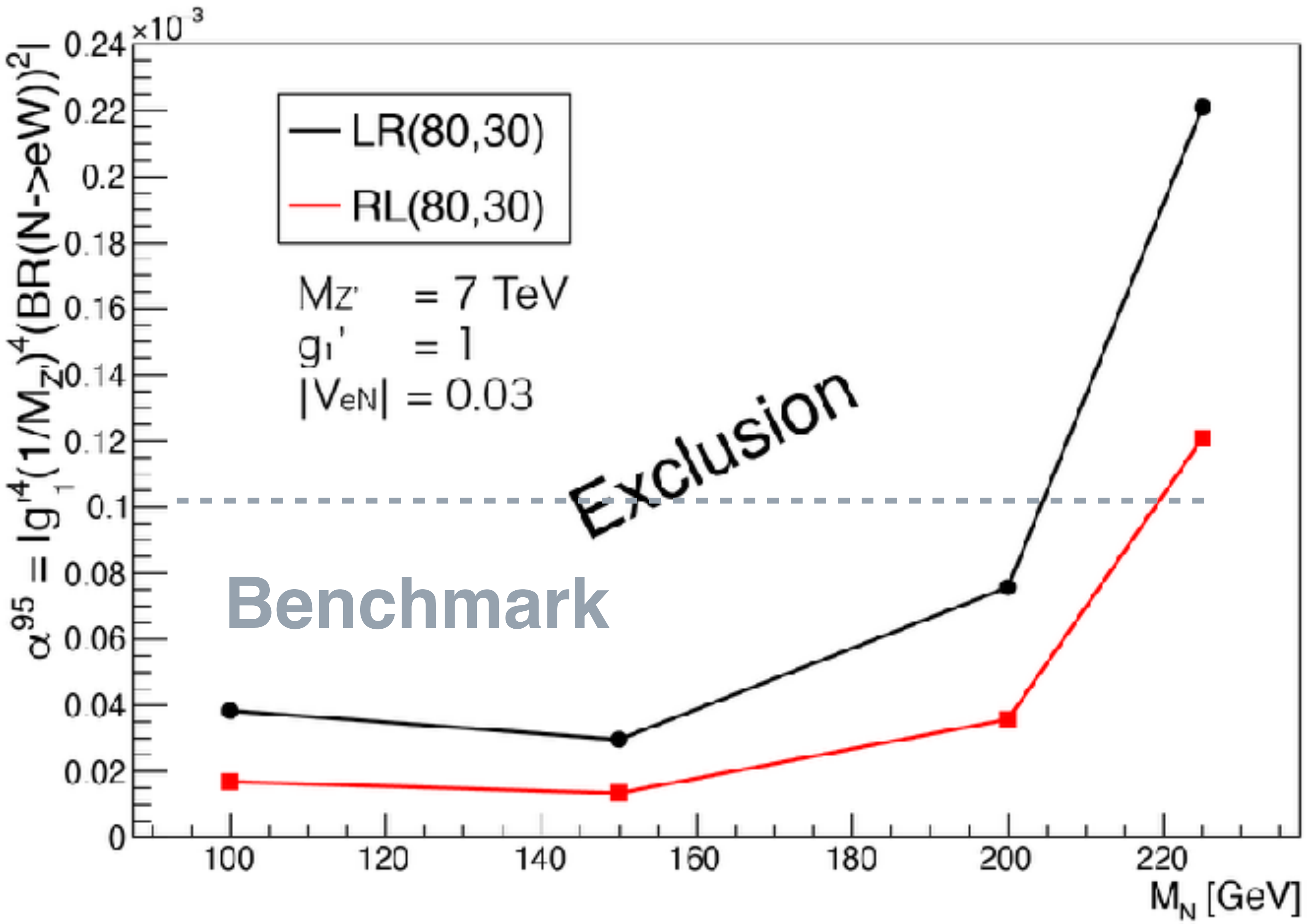
20 (eLpR) and 3 (eRpL) background events remain in mass window

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

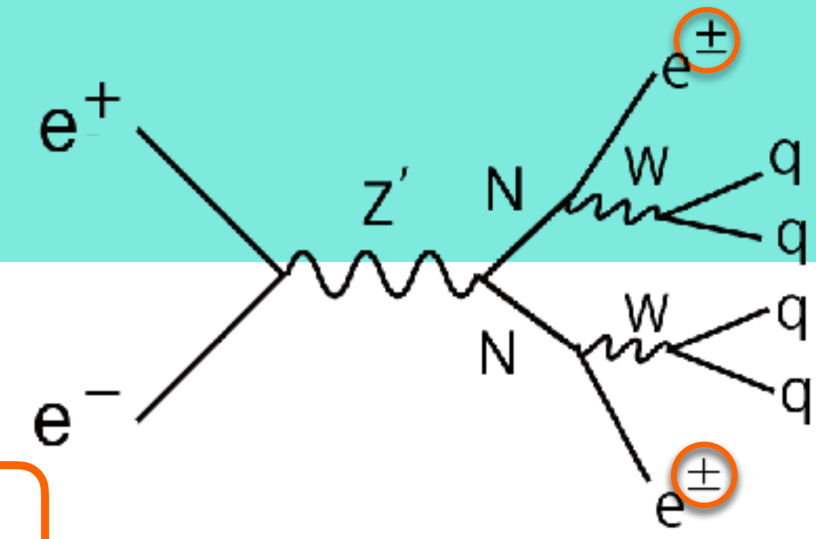
Cut flow (eLpR)

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

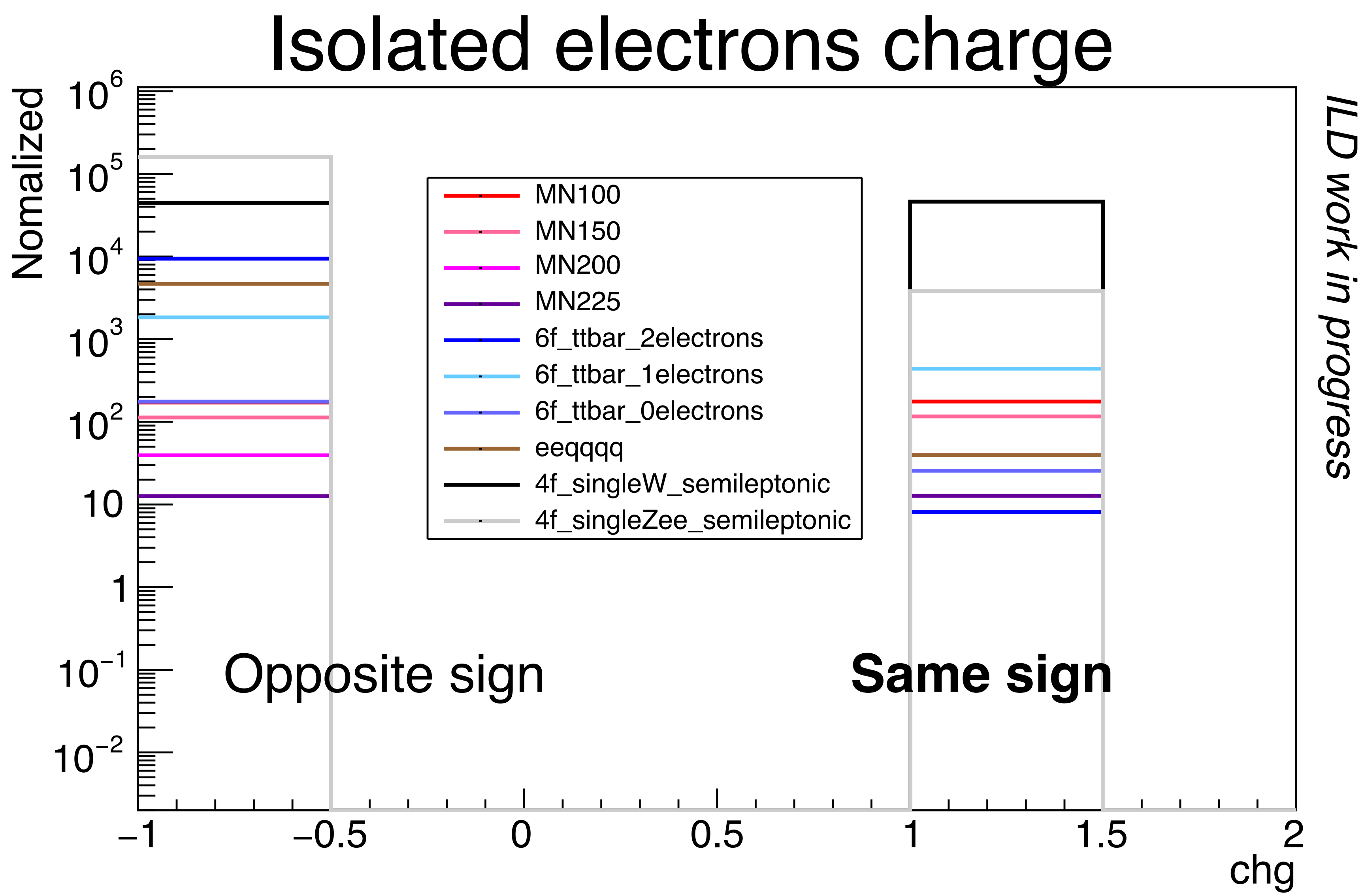
ILD work in progress

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

Electron Charge



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



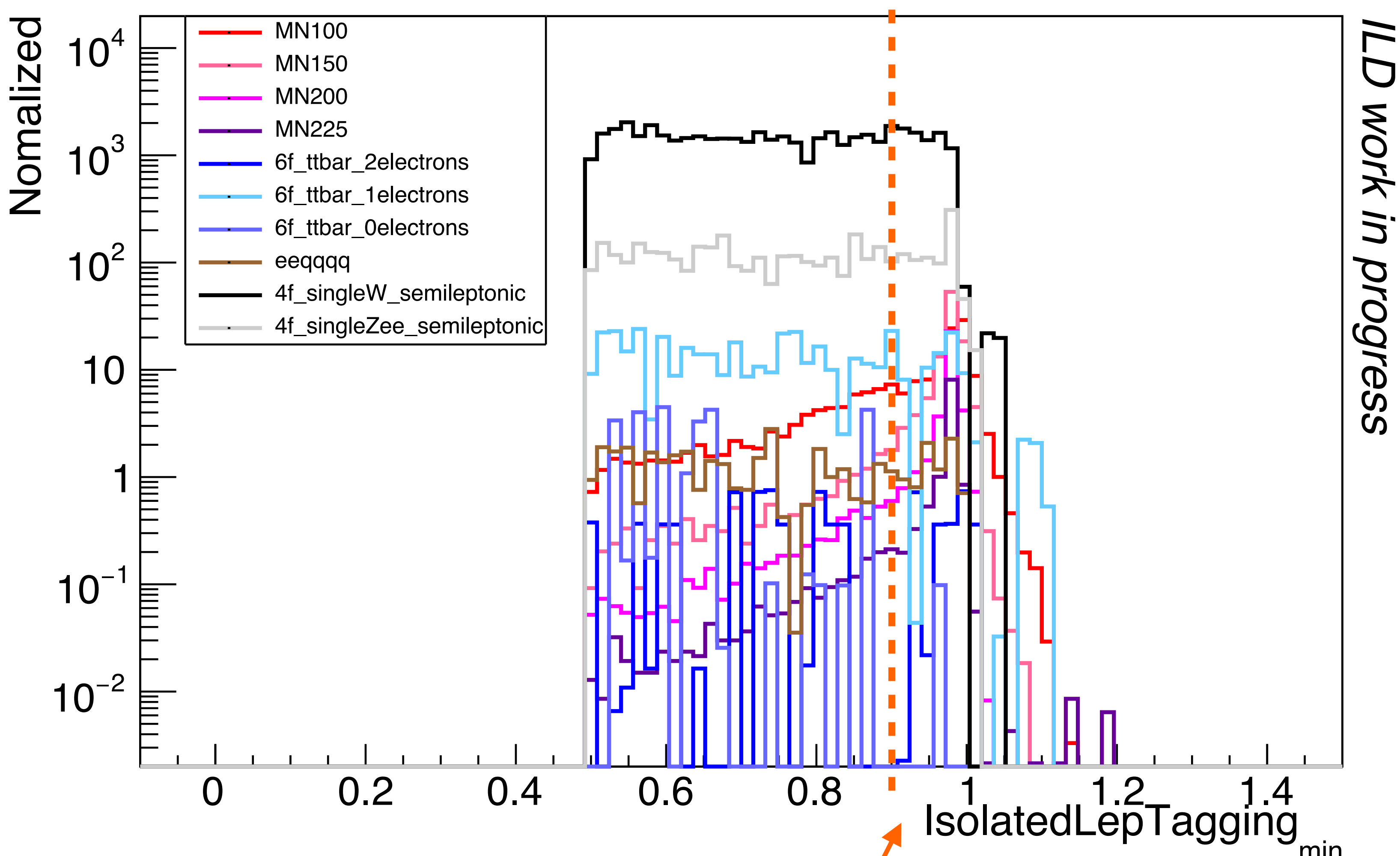
We use only same sign samples $\boxed{e_1 \times e_2 = 1}$

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**

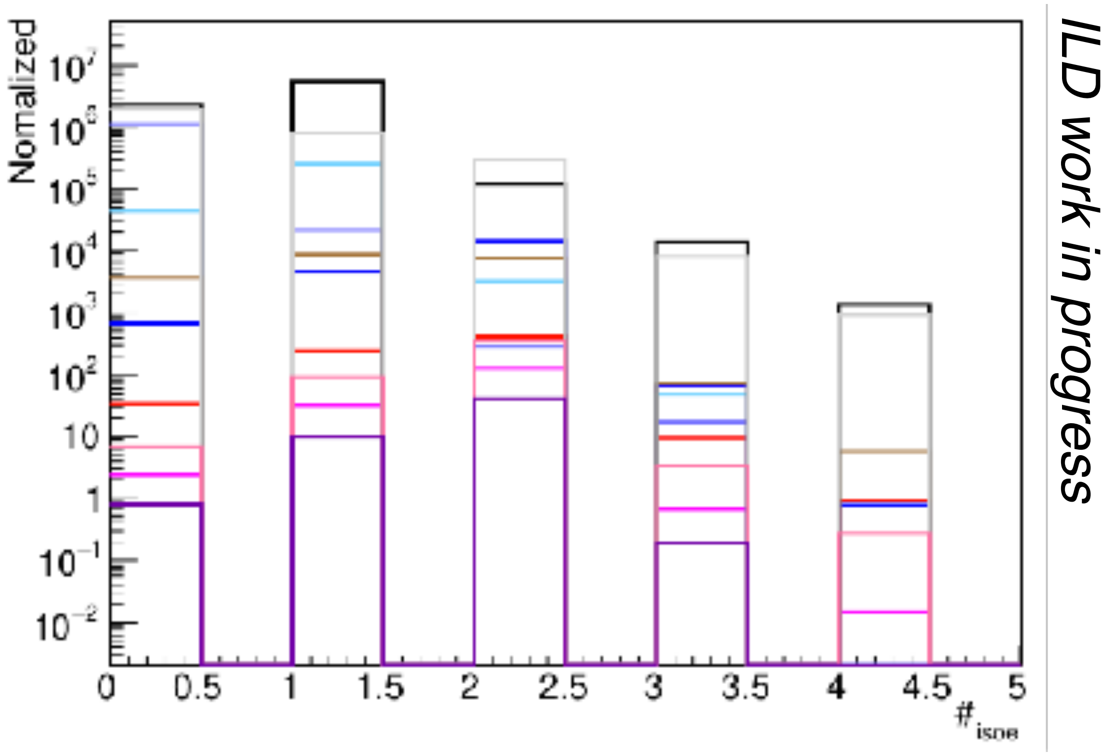
Usually second background electron is fake

IsolatedLepTagging$_{min}$ > 0.9

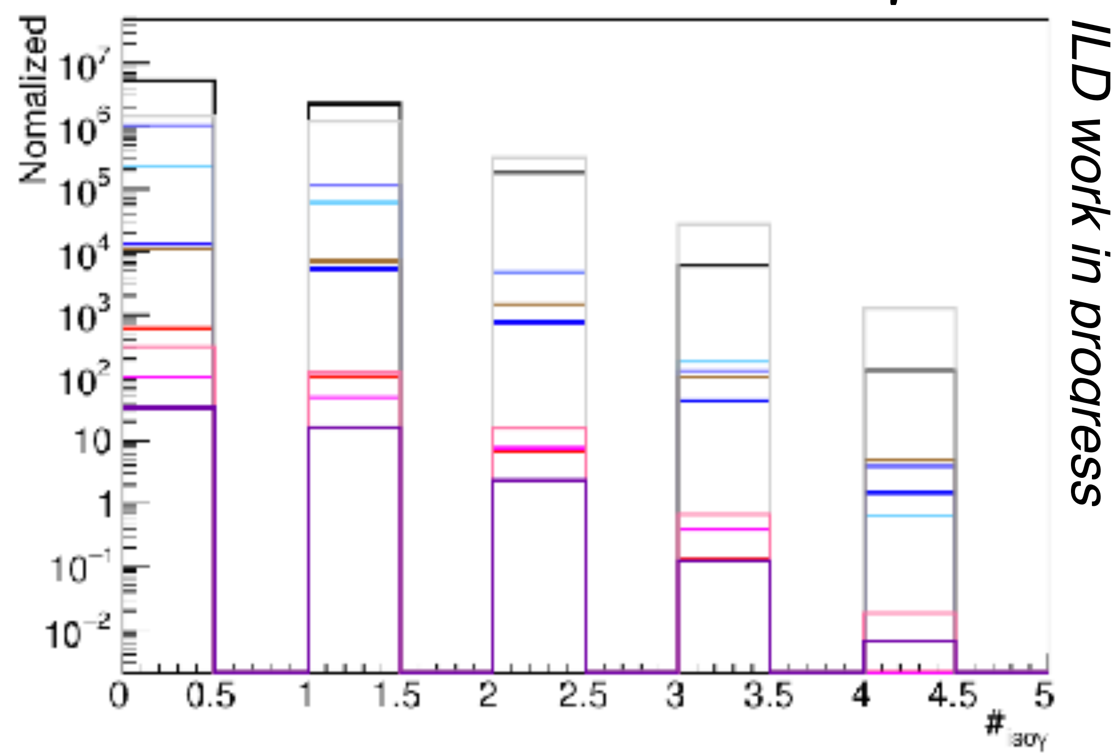
Isolated e,γ,μ

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

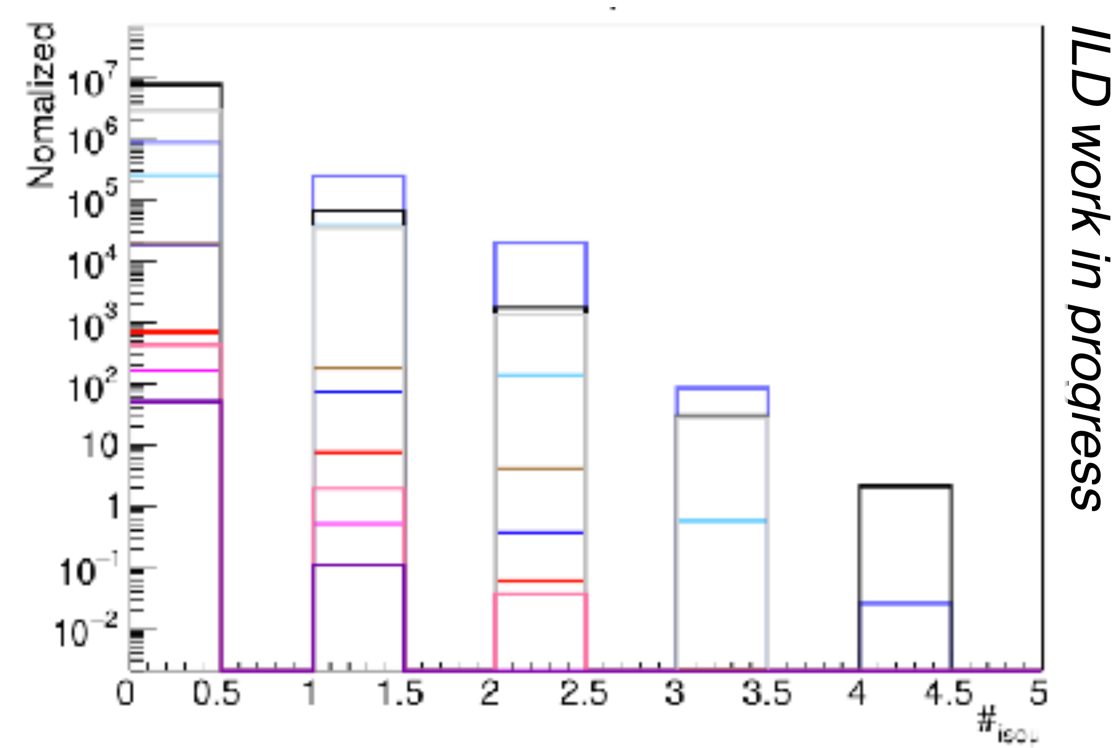
Number of isolated e



Number of isolated γ



Number of isolated μ



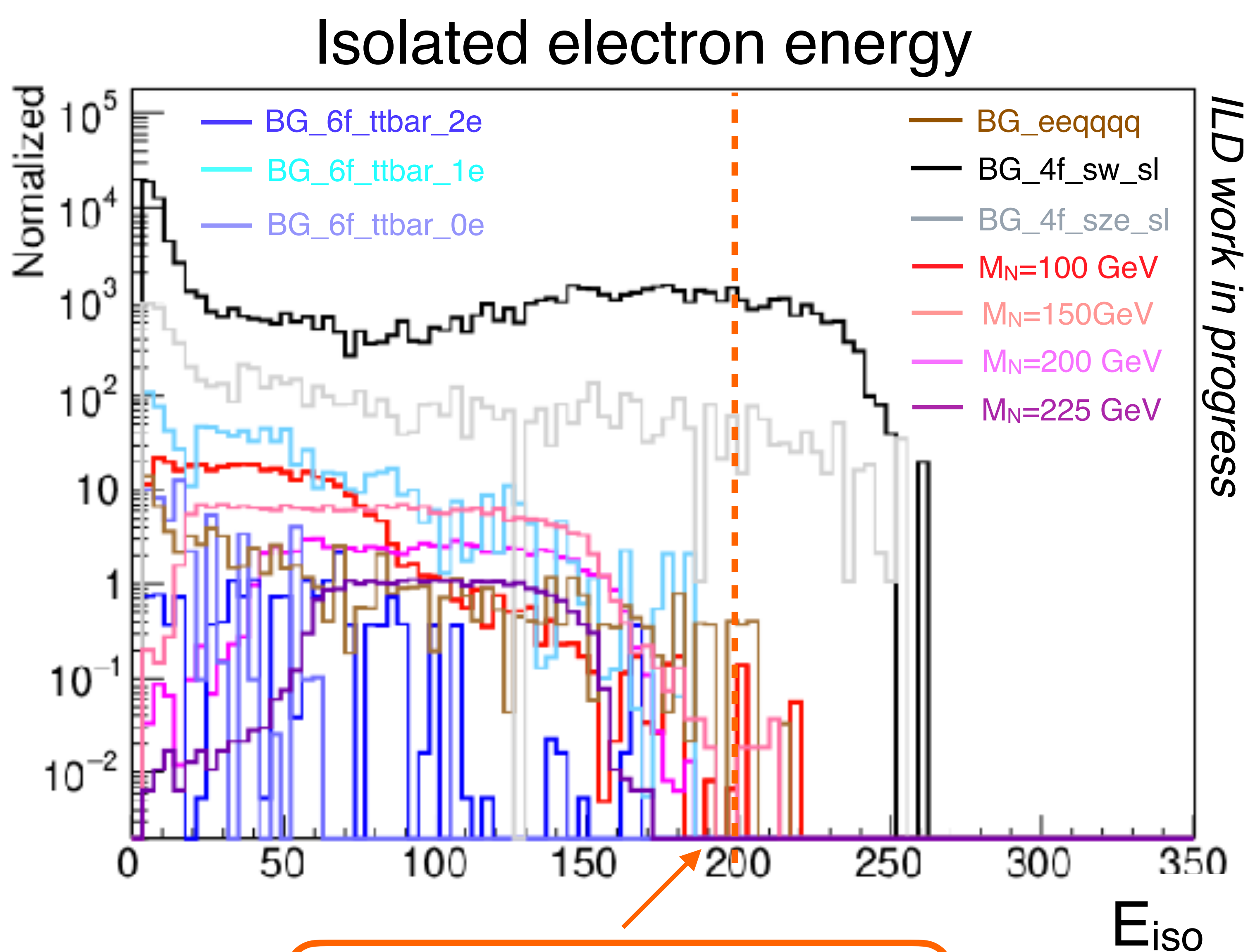
- M_N=100 GeV
- M_N=150GeV
- M_N=200 GeV
- M_N=225 GeV
- BG_6f_ttbar_2e
- BG_6f_ttbar_1e
- BG_6f_ttbar_0e
- BG_4f_sw_sl
- BG_4f_sze_sl
- BG_eeqqqq

- Isolated e # = 2 && Isolated γ, **<u>μ = 0</u>**

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 ($e_1 \times e_2 = 1$)

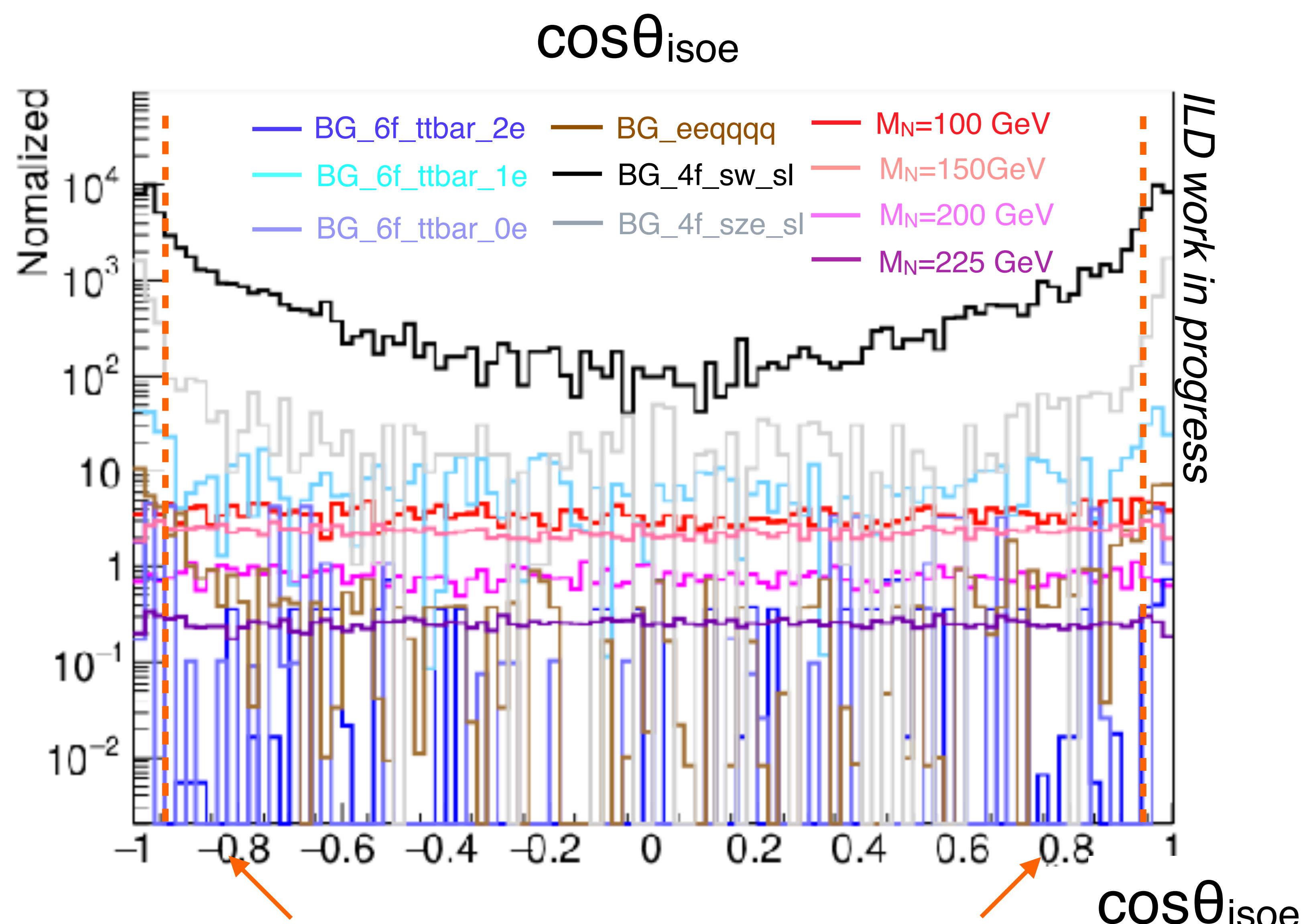


E_{iso} < 200 [GeV]

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 ($e_1 \times e_2 = 1$)



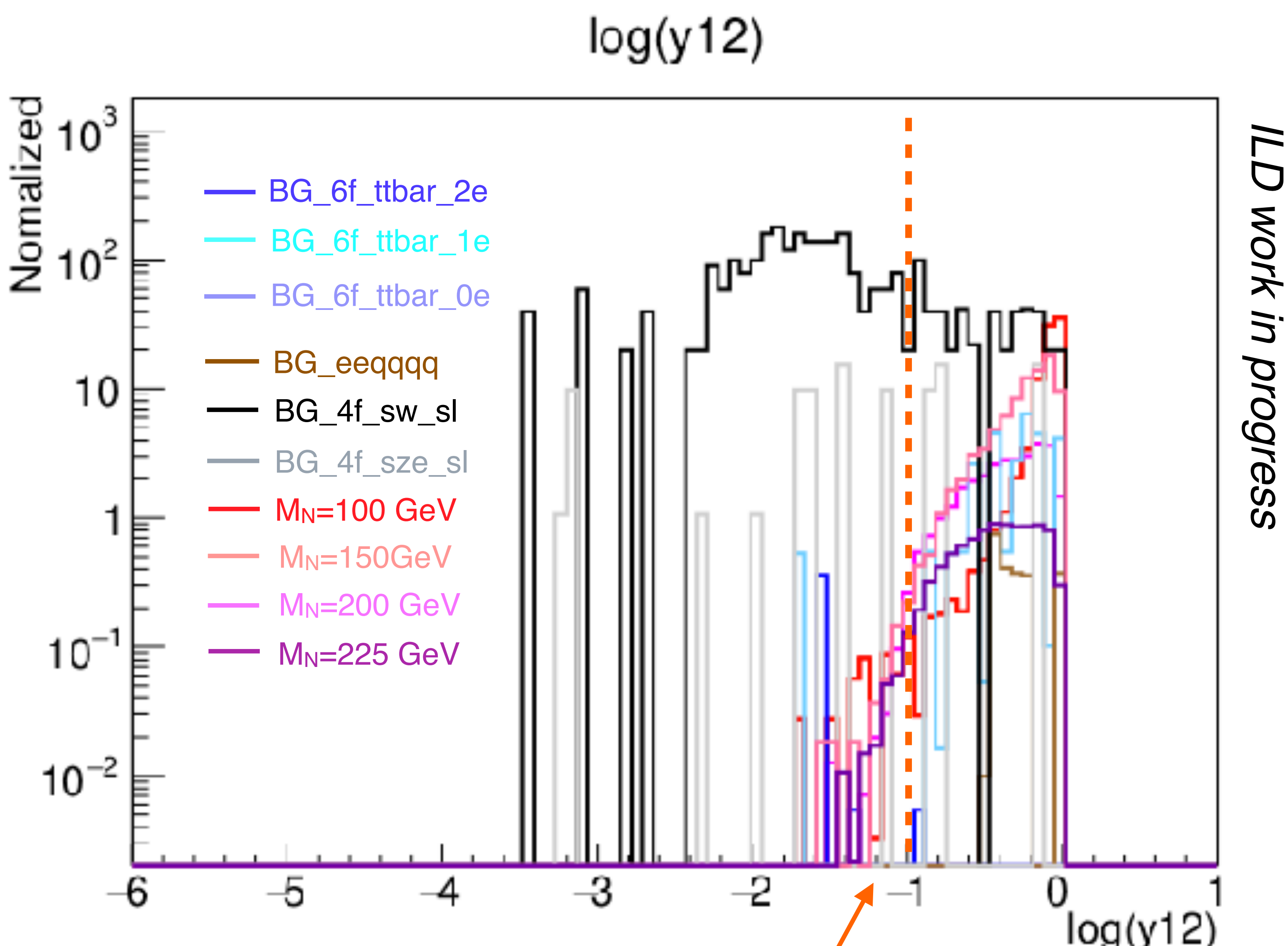
$-0.95 < \cos\theta_{isoe} < 0.95$

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 ($e_1 \times e_2 = 1$)

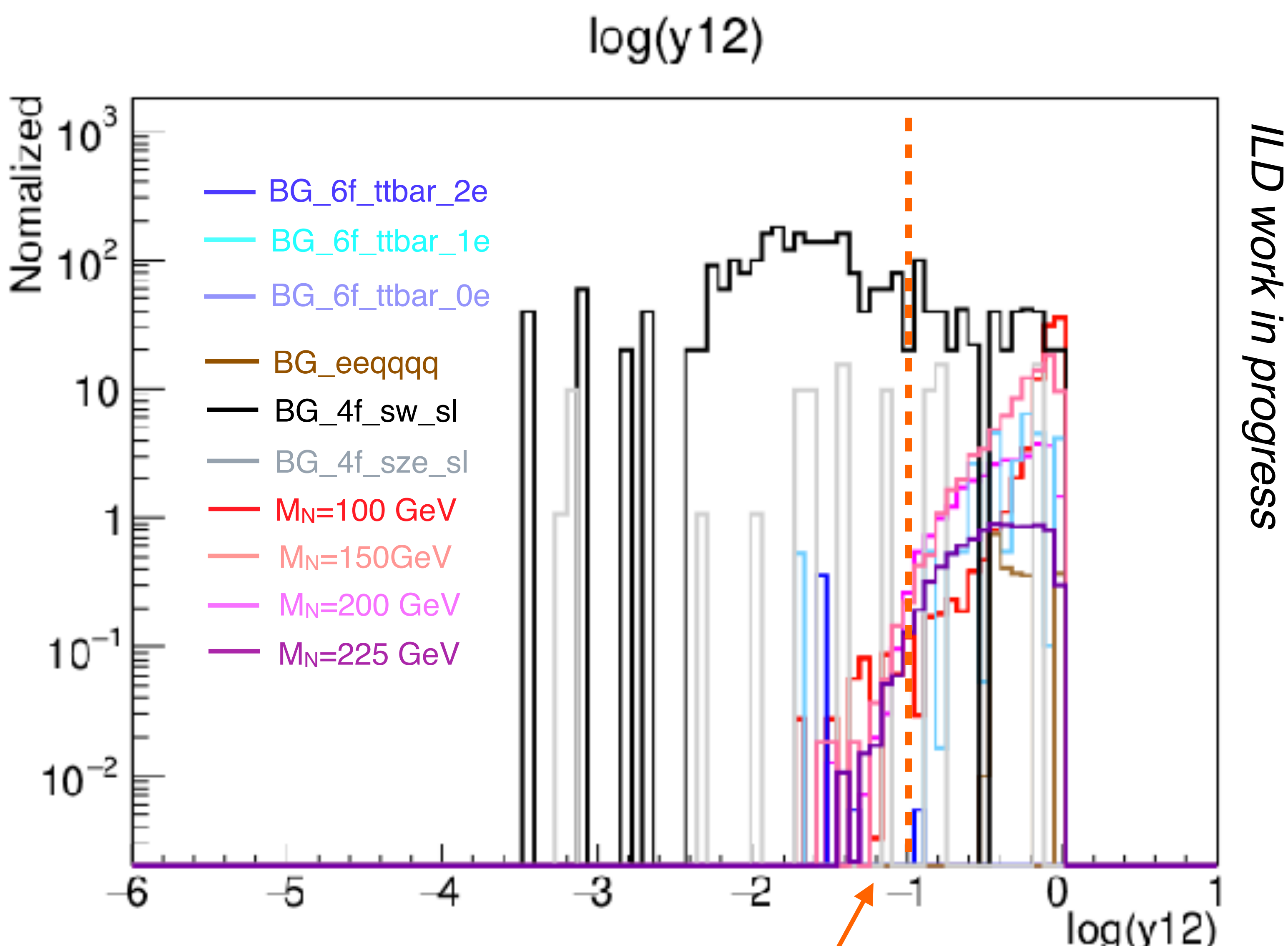


$\log_{10}(y12) > -1$

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 ($e_1 \times e_2 = 1$)

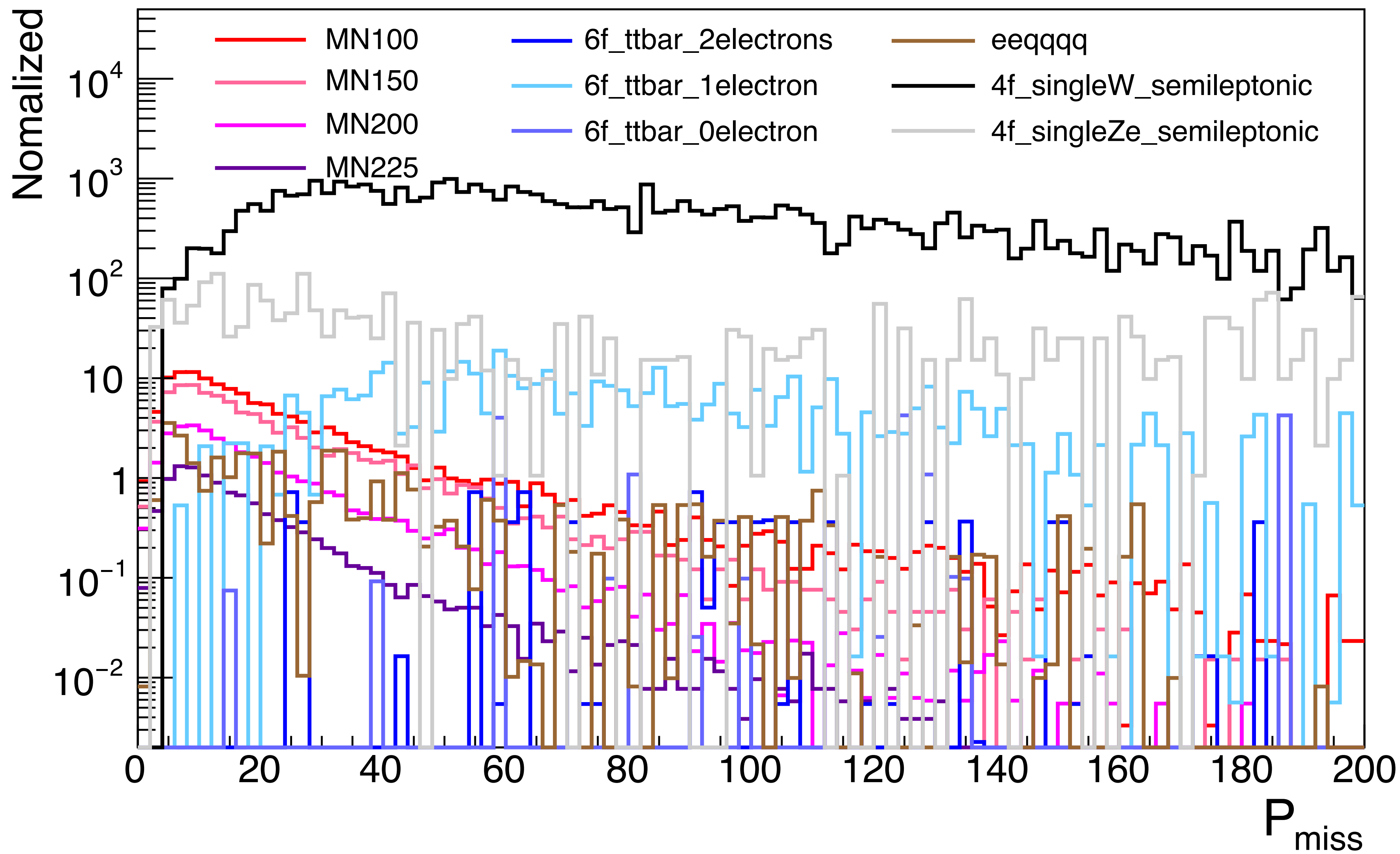


$\log_{10}(y12) > -1$

Distribution of P_{miss}

- 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

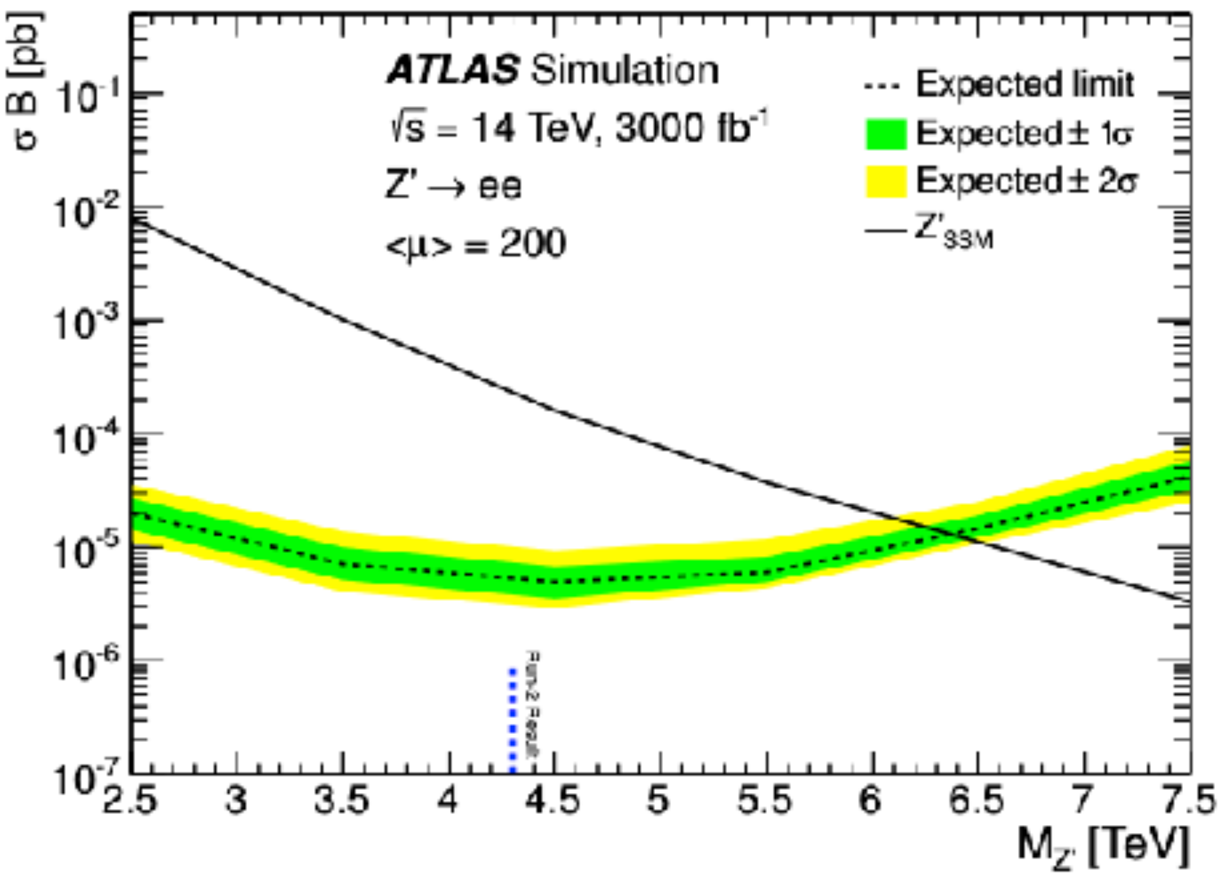
- ILC 500 with ISR / BS

(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

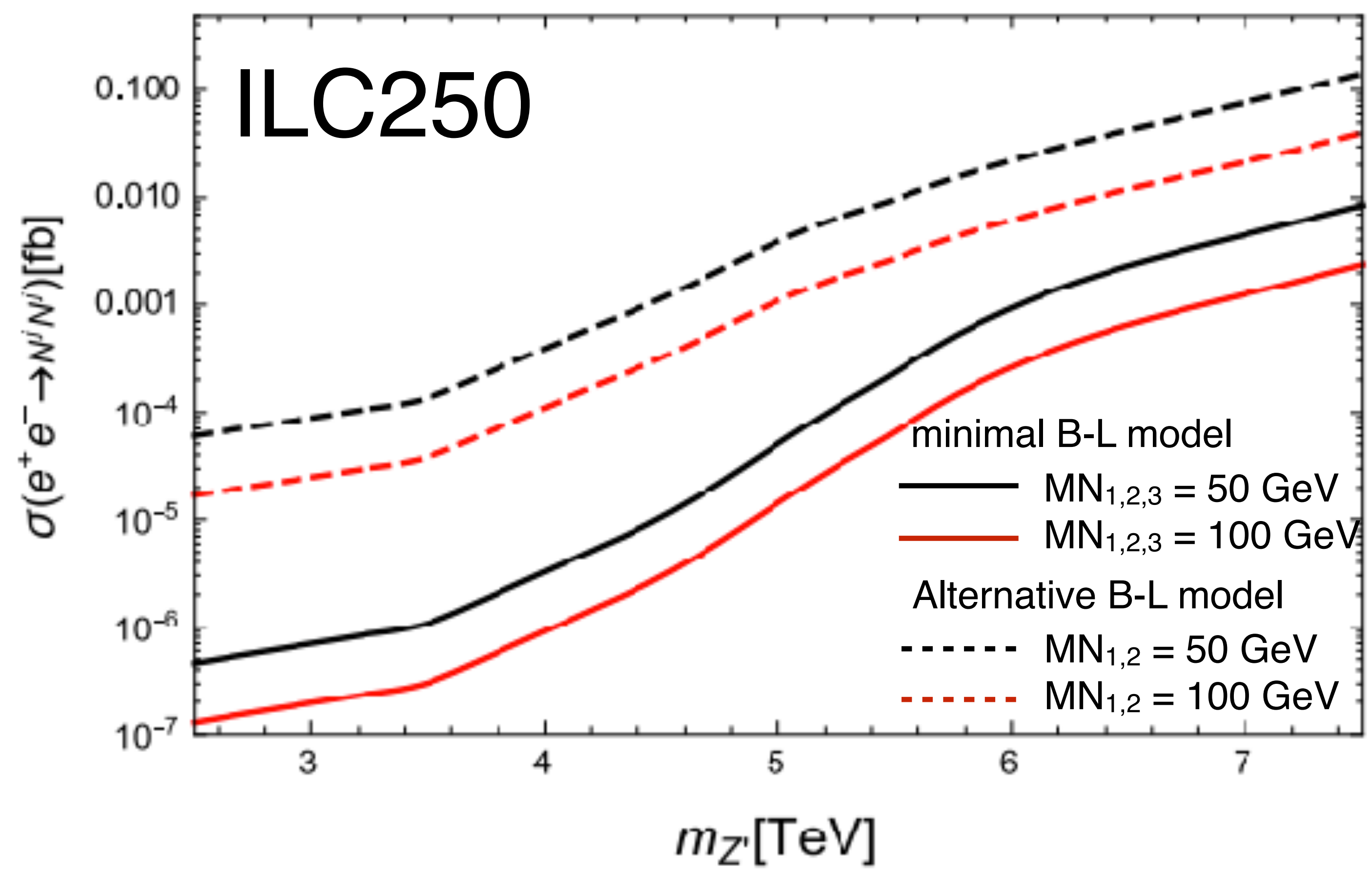
Current limits - Z' mass

SM like Z' coupling



ATLAS-TDR-LHCC2017-2018

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

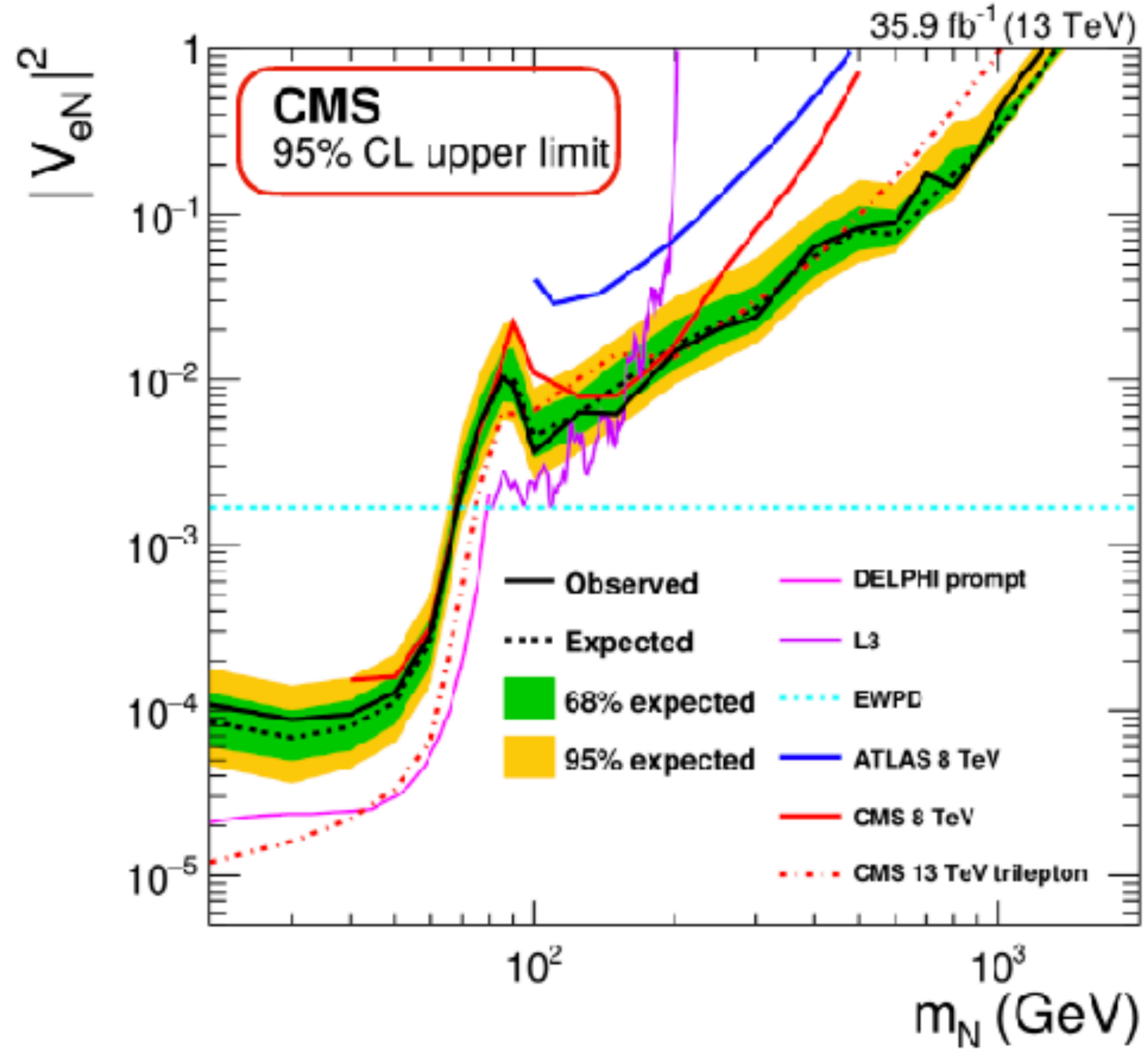


arXiV[1812.11931]

The heavier Z' mass less constrained by LHC

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

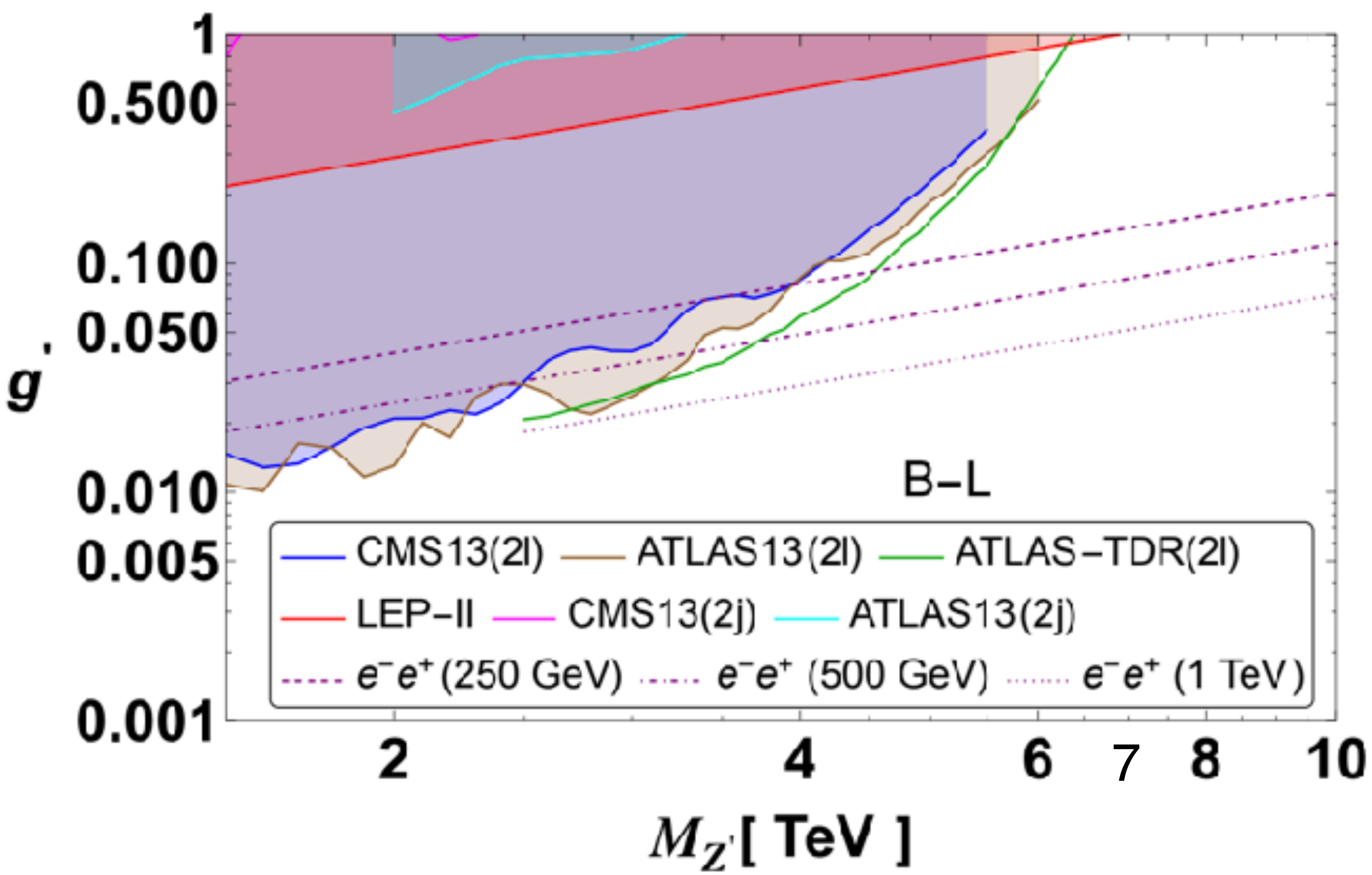
$|V_{eN}|^2$: the “light-heavy” neutrino mixing matrix



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

Current Limits and prospects - Z' mass,g1'

g_1' :U(1)$_{B\text{-}L}$ gauge coupling constant



arXiv:2203.06929