Exploring Right Handed Neutrinos at ILC

Work in progress

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Motivation and Introduction

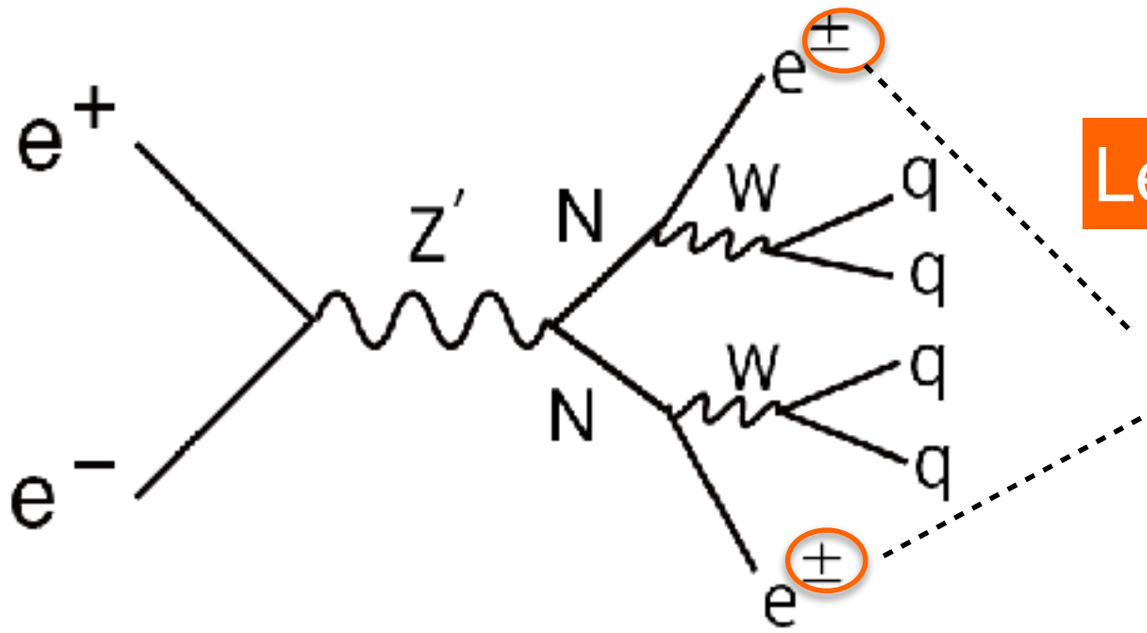
The right handed neutrino (RHN) can address the following big questions

Ex)

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

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

RHN **pair** production



Lepton # violation is possible!

↓

Same sign leptons possible

↓

Very small 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 included

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

minimal 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

Benchmark points

Not excluded by LHC arXiV[1812.11931]

M_N [GeV] RHN mass	$M_{Z'}$ [TeV] Z' mass	g1' $U(1)_{B-L}$ coupling constant	$\|V_{eN}\|^2$ mixing angle	$\sigma(e_L^- e_R^+ \to NN)$ [fb]	Event # at ILC500 [4000fb^{-1}]
100	7	1	0.001	0.71	**1261**
200	7	1	0.005	0.16	**131**

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

  ✦$\sigma_{LR} = \sigma_{RL}$

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

- ILC 500 with initial state radiation (ISR) and beamstrahlung (BS)

Analysis tool

WHIZARD ver 2.8.5
Make Events

↓

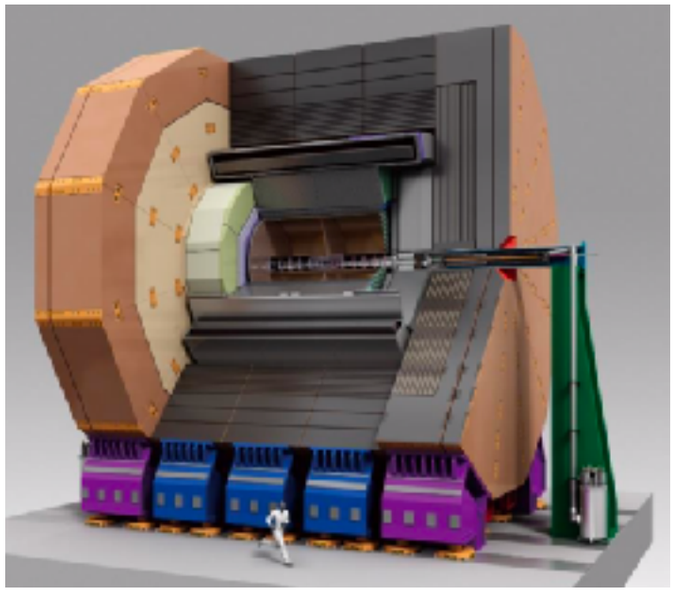
ILD Full Simulation

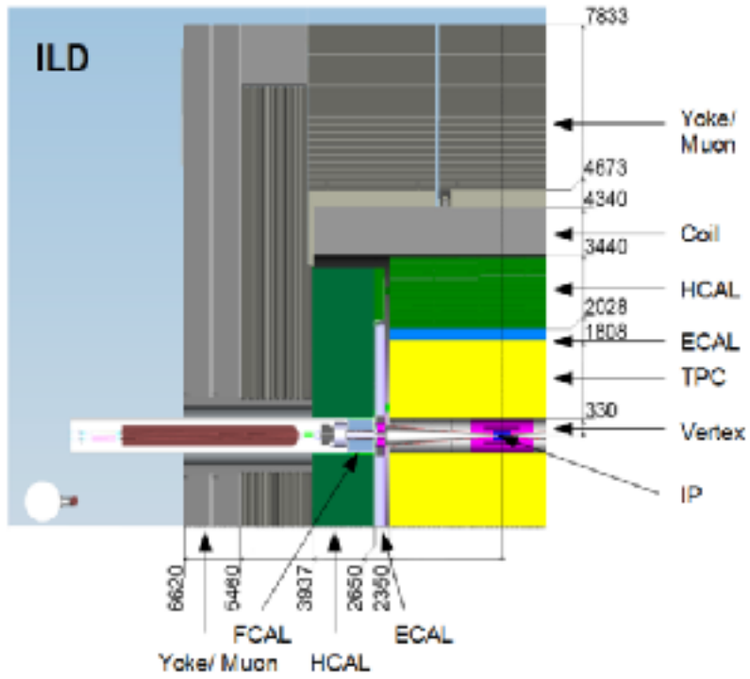
↓

miniDST
Events format

Full simulation

Full geant4 simulation of ILD
Realistic reconstruction





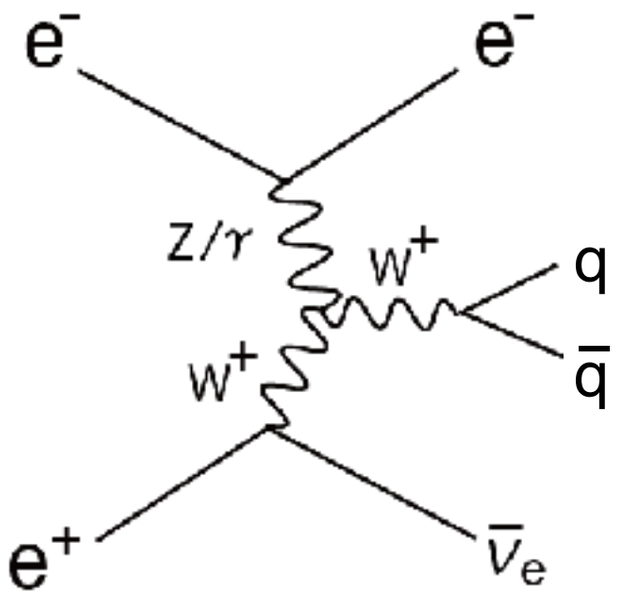
We prepared full simulation signal samples.

Signal vs Backgrounds

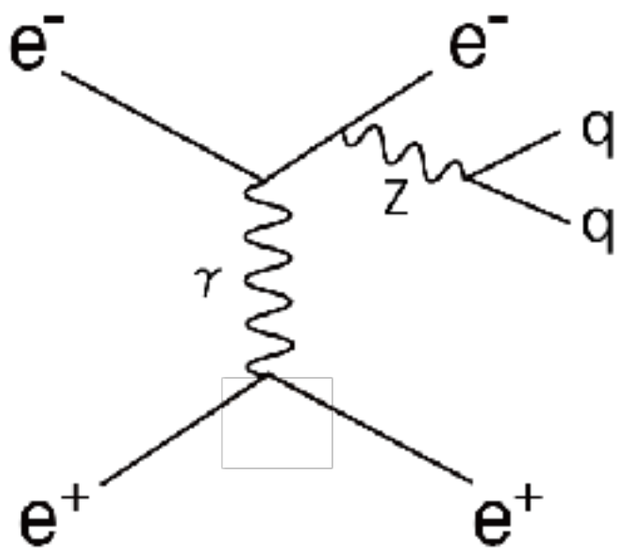
We consider 6f and 4f background samples.

- eeqqqq
- 6f_ttbar
- 4f_singleW_semileptonic
- 4f_singleZee_semileptonic

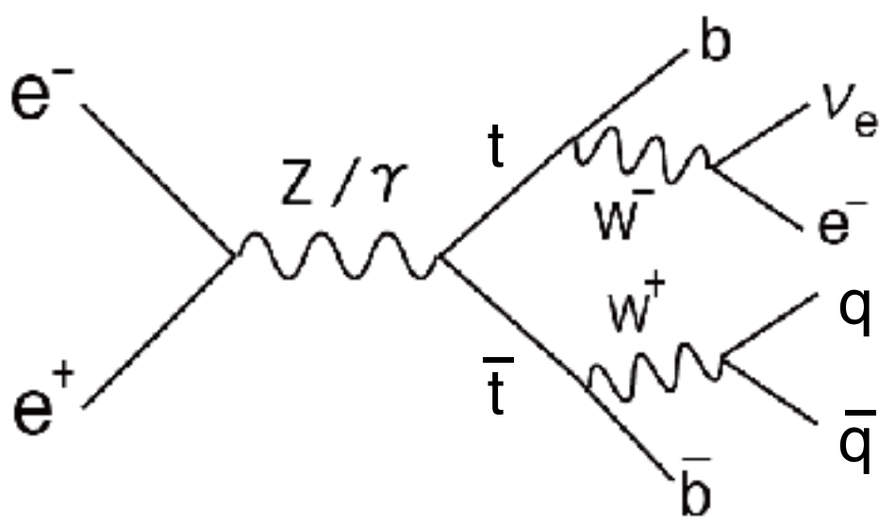
4 fermions singleW semileptonic



4 fermions singleZee semileptonic



6 fermions ttbar 1electron

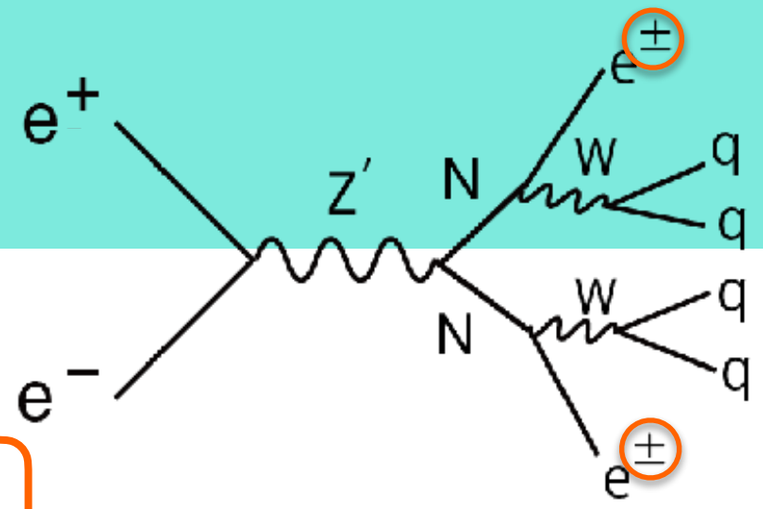


Cut Conditions to select signal events

- Isolated e # = 2 && Isolated γ, μ # = 0
- Isolated e is same sign ($e_1 \times e_2 = 1$)
- Isolated electron energy $E_{iso} < 200$ [GeV]
- Isolated electron angle $|\cos\theta_{isoe}| < 0.95$
- $\text{IsolatedLepTagging}_{min} > 0.9$
- Jet clustering with Durham $\log_{10}(y12) > -1$
- $P_{miss} < 100$ && ($P_{miss} < 40$ || $|\cos\theta_{Pmiss}| > 0.95$)

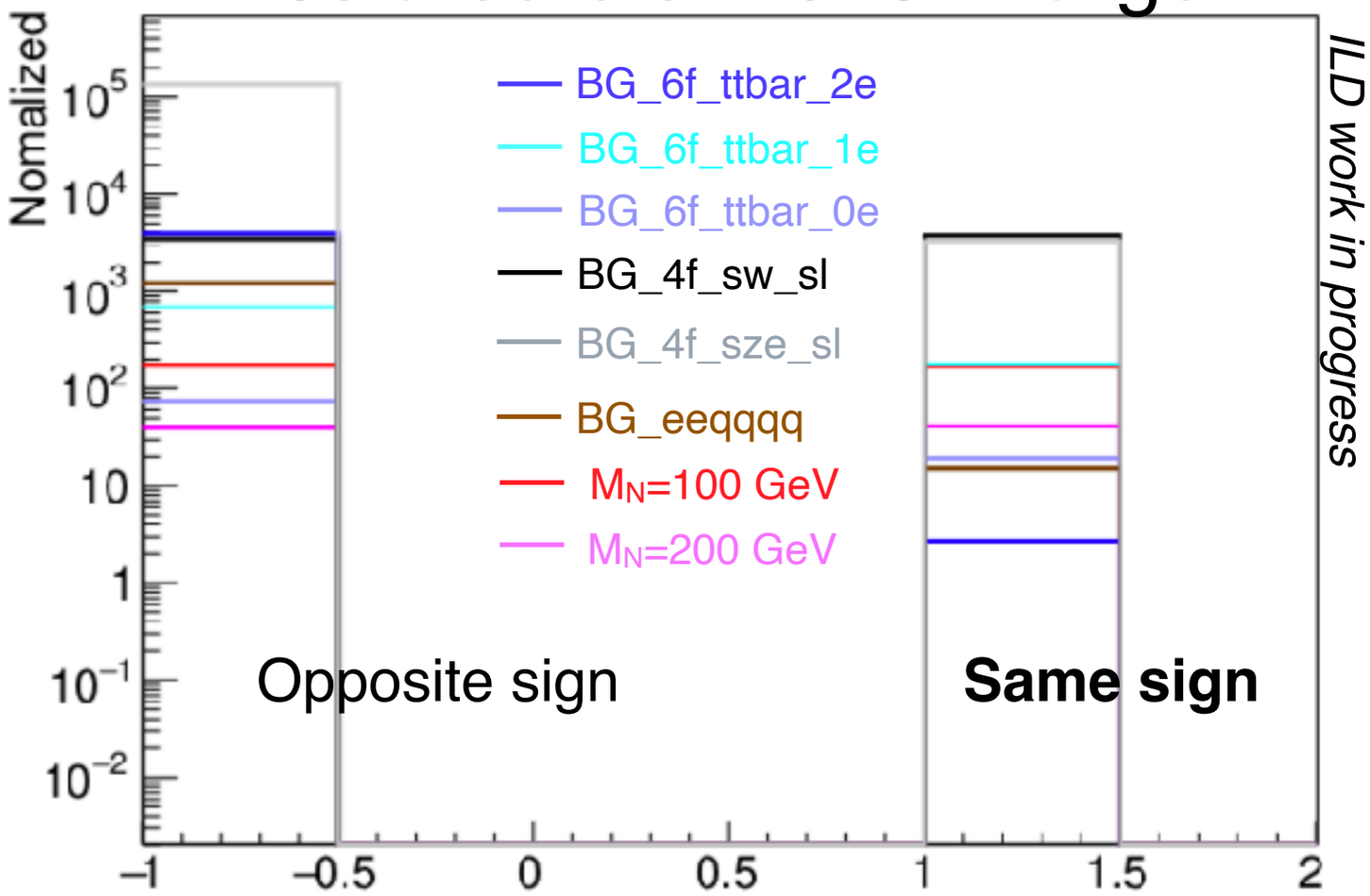
I focus on three cut conditions.

Electron Charge



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

Isolated electrons charge



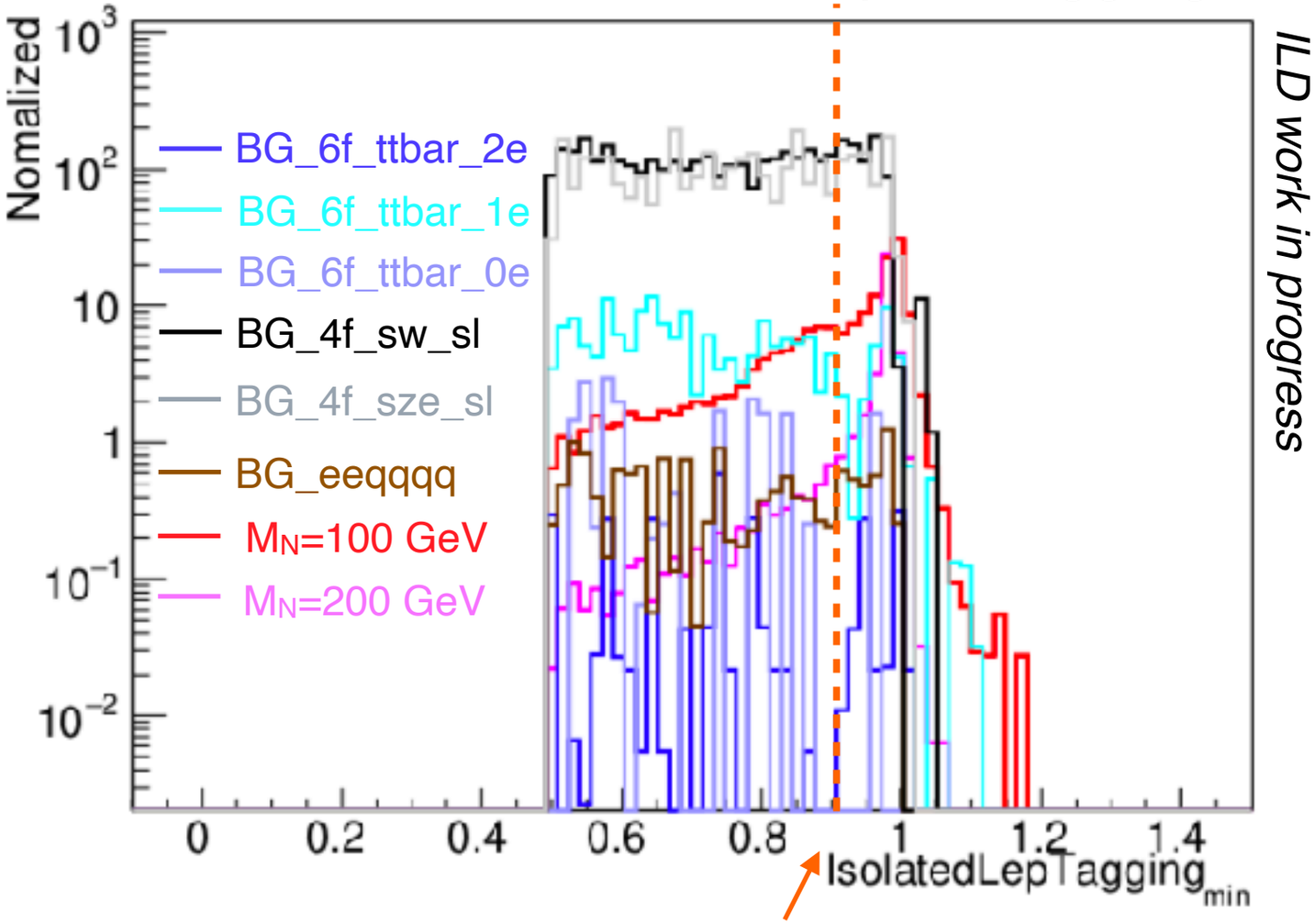
We use only same sign samples $e_1 \times e_2 = 1$

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

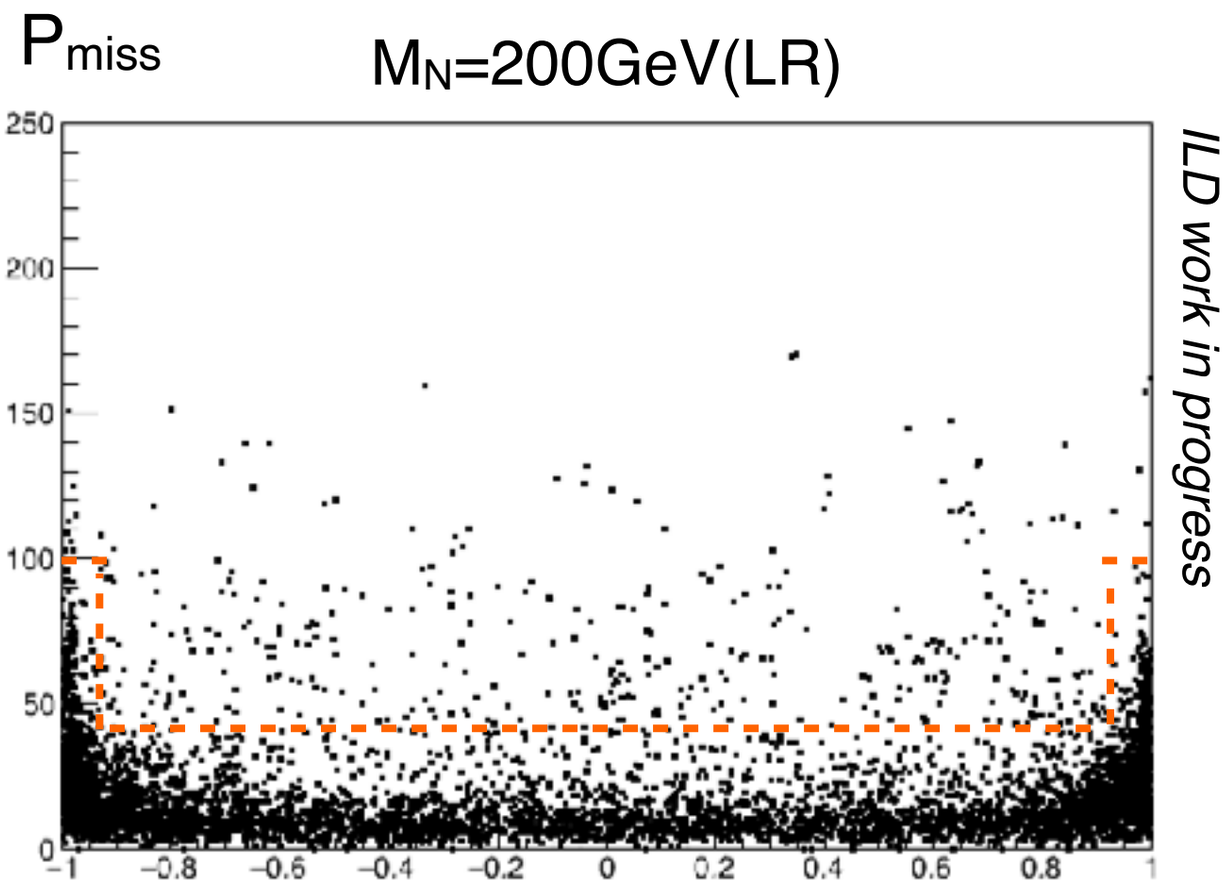
→ Output for e is near 1

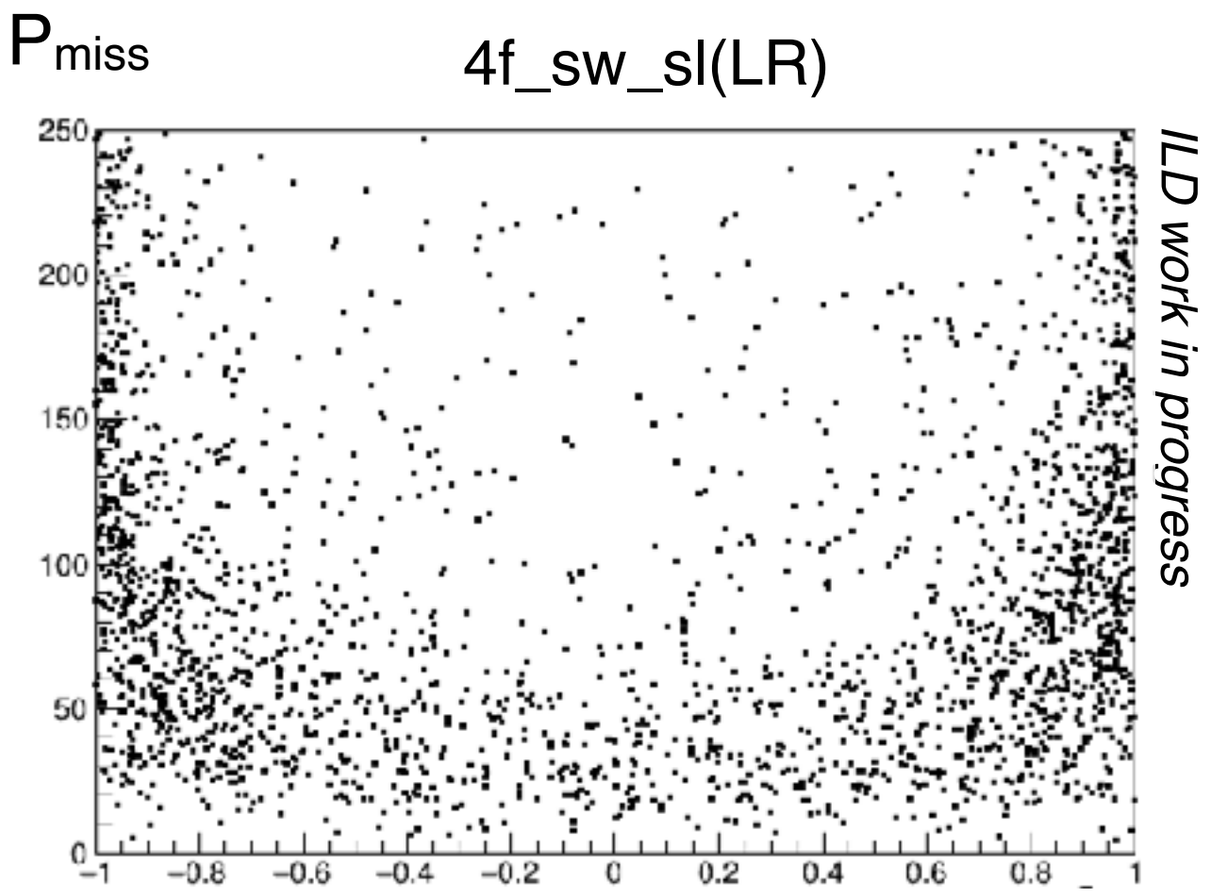
Usually second background electron is fake

IsolatedLepTagging$_{min}$ > 0.9

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

- 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

	Signal Entries		Background Entries					
	M_N=100	M_N=200	eeqqqq	4f_singleW _semileptonic	4f_singleZee _semileptonic	6f_ttbar 2electrons	6f_ttbar 1electron	6f_ttbar 0electron
No cut	558	143	3925	258648	612455	7100	56233	4894
e_{iso} #=2 && γ_{iso} #=0 && μ_{iso} #=0	420	126	1935	9426	249000	6142	1295	127
Same sign ($e_{iso1} \times e_{iso2} = 1$)	346	81	1231	7210	140176	3911	870	94
$E_{iso} < 200$ [GeV]	171	41	14	3741	3294	2	177	19
$-0.95 < \cos\theta_{isoe} < 0.95$	158	37	3	1324	475	1	113	12
IsolatedLepTaggi $ng_{min} > 0.9$	96	32	0	198	101	0	15	1
$\log_{10}(y12) > -1$	88	30	0	199	86	0	6	0
$P_{miss} < 100$ && ($P_{miss} < 40$ || $\lvert\cos\theta_{Pmiss}\rvert > 0.95$)	86	29	0	4	15	0	2	0

Cut flow (eLpR)

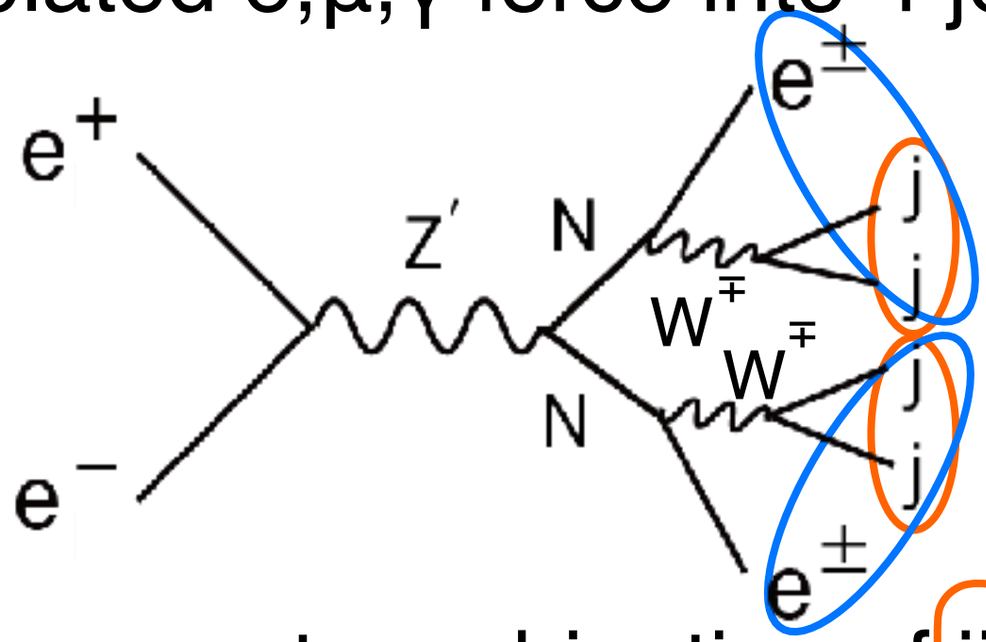
- ILC 500 with ISR / BS
- **Pol(e^-, e^+) = (–0.8, +0.3)** $\mathcal{L} = 1600\,[\mathrm{fb}^{-1}]$

ILD work in progress

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

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 → 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 "$M_{jje1} = M_{jje2}$"

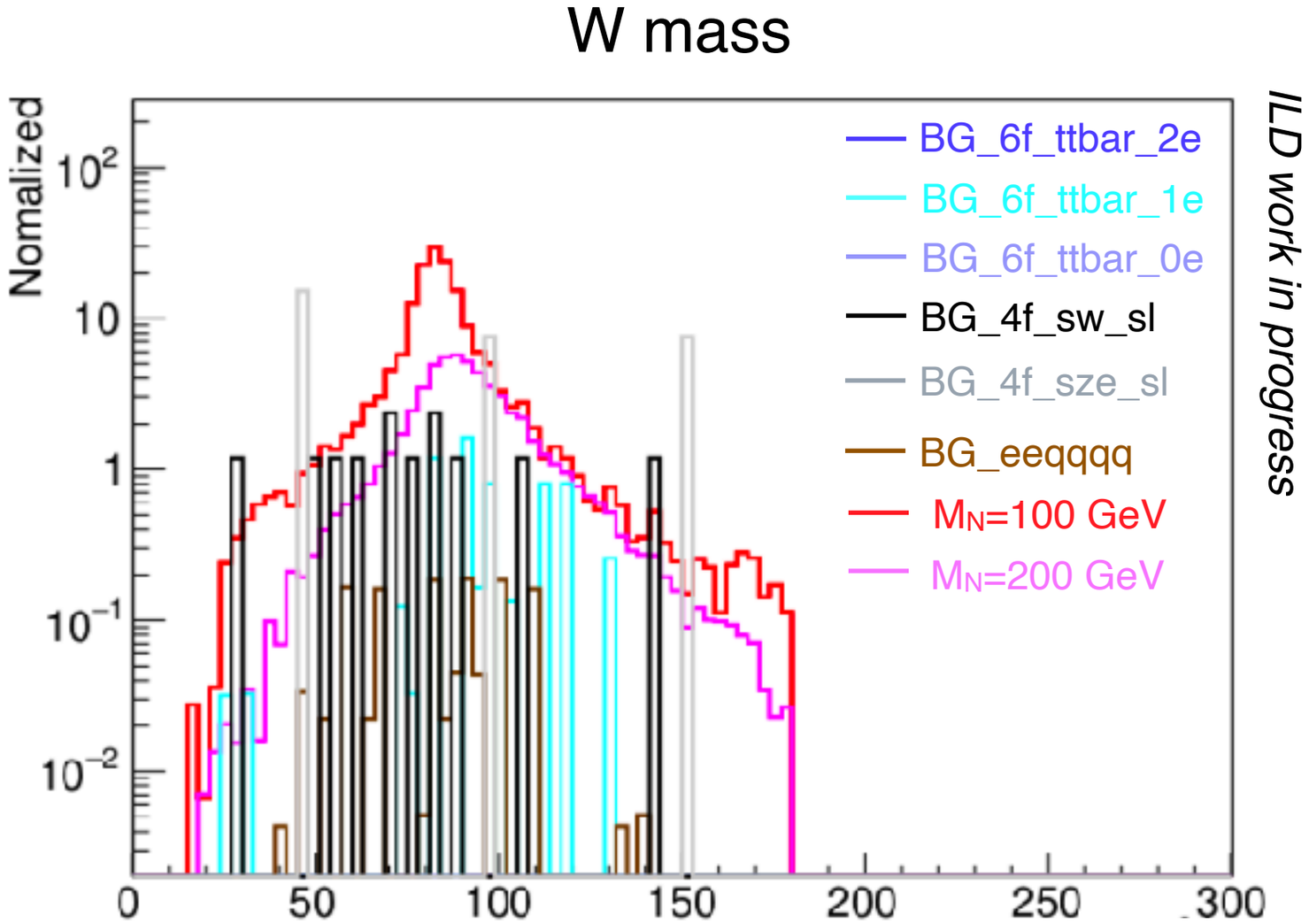
$$F_2 = (M_{jje1} - M_{jje2})^2$$

Choose combination with minimum F_1,F_2

Reconstructed W mass

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

- Isolated e # = 2 && Isolated γ, μ # = 0
- Isolated e is same sign ($e_1 \times e_2 = 1$)
- $E_{iso} < 200$ [GeV]
- $-0.95 < \cos\theta_{isoe} < 0.95$
- $\mathrm{IsolatedLepTagging}_{min} > 0.9$
- $P_{miss} < 100$ && ($P_{miss} < 40$ || $|\cos\theta_{Pmiss}| > 0.95$)
- $\log_{10}(y12) > -1$



Reconstructed RHN mass

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

- Isolated e # = 2 && Isolated γ, μ # = 0
- Isolated e is same sign ($e_1 \times e_2 = 1$)
- $E_{iso} < 200$ [GeV]
- $-0.95 < \cos\theta_{isoe} < 0.95$
- $\mathrm{IsolatedLepTagging}_{min} > 0.9$
- $P_{miss} < 100$ && ($P_{miss} < 40$ || $|\cos\theta_{Pmiss}| > 0.95$)
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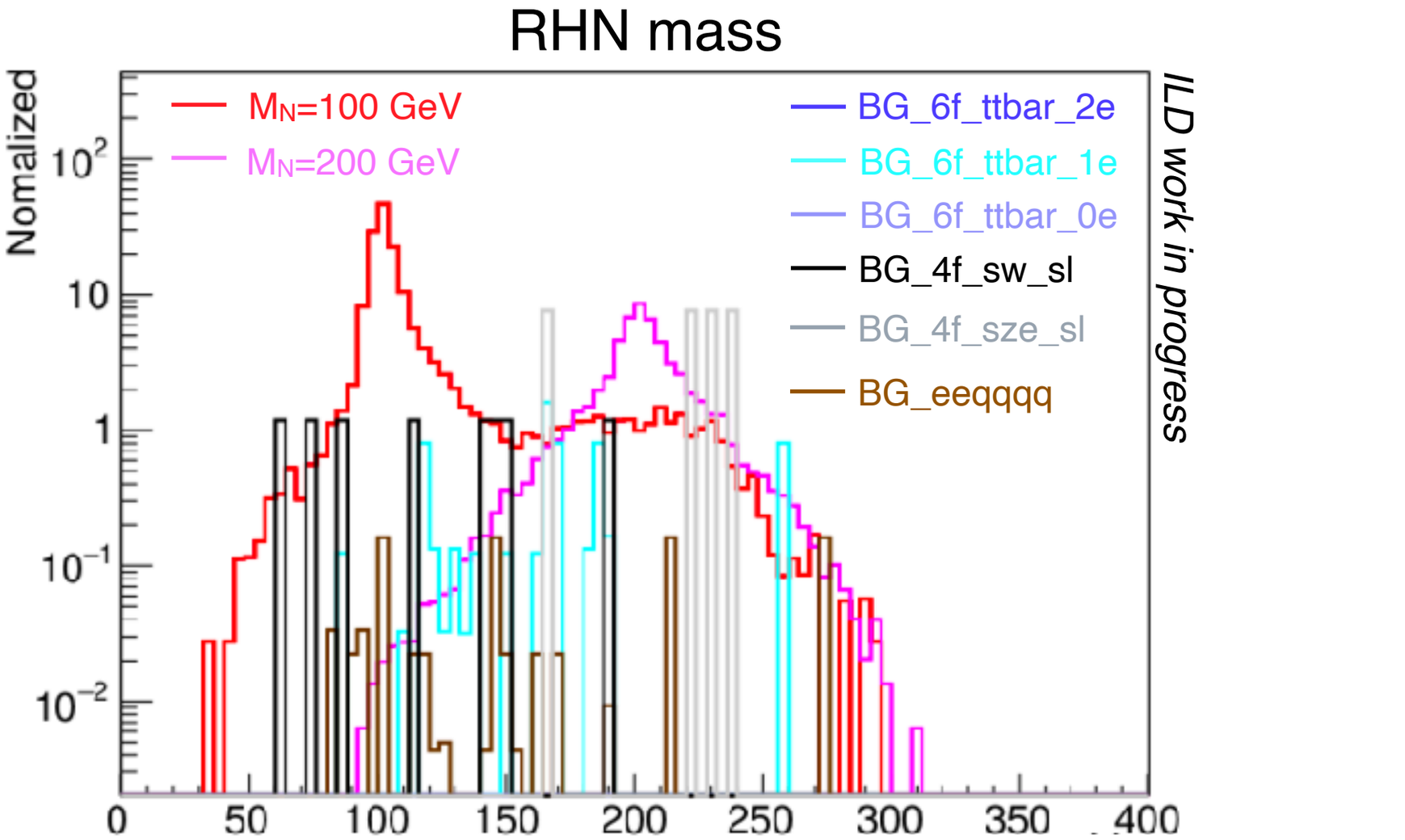


Summary

- Right handed neutrino (RHN) has some merits for new physics.
- If RHN is Majorana particle, we can focus on "RHN **pair** production".
  This pair production is unique process and is almost background free.
  The main signature is **a pair of same sign electrons**.
- We analyze "RHN **pair** production" by full simulation.
- 4 fermion semileptonic processes are dominant backgrounds.
  ← Additional electron from misidentification or heavy quark decay.
  Background is mostly removed, 120(eLpR) and 21(eRpL) events remain.

Next step

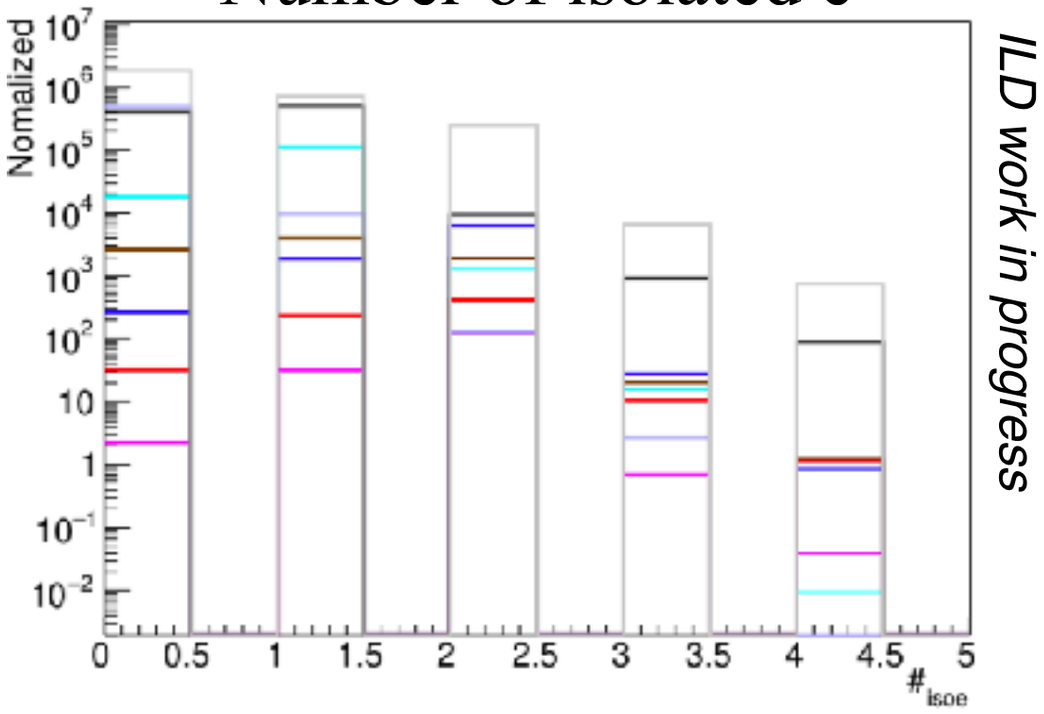
- Improve and optimize cut conditions. (MVA?)
- Scan RHN mass and coupling → exclusion plot

Backup

Isolated e,γ,μ

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

Number of isolated e



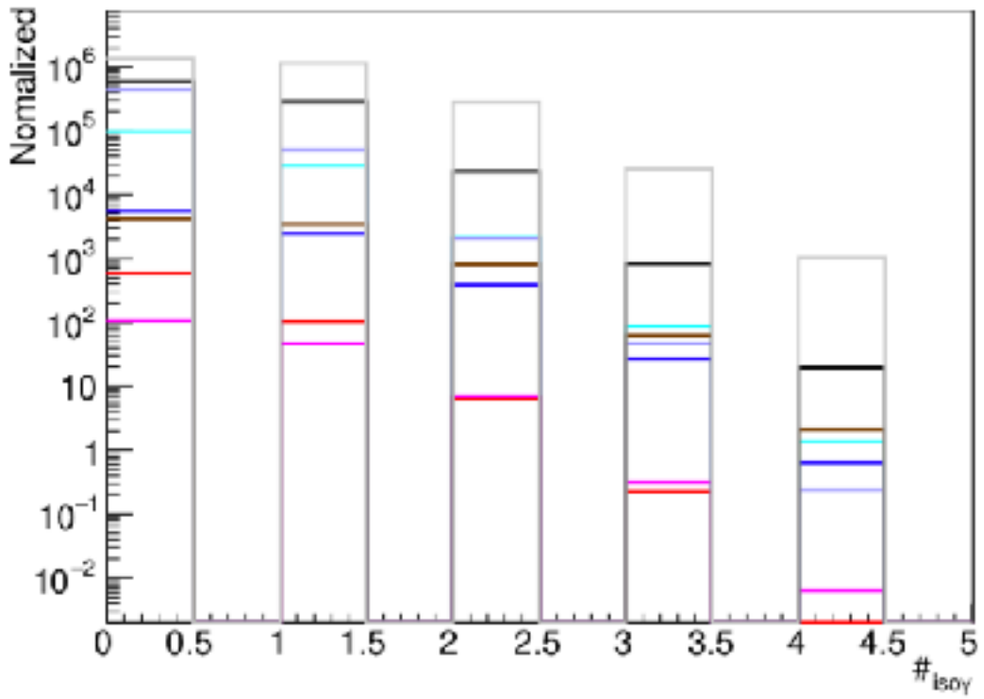
ILD work in progress

— M_N=100 GeV
— M_N=200 GeV

— BG_6f_ttbar_2e
— BG_6f_ttbar_1e
— BG_6f_ttbar_0e
— BG_4f_sw_sl
— BG_4f_sze_sl
— BG_eeqqqq

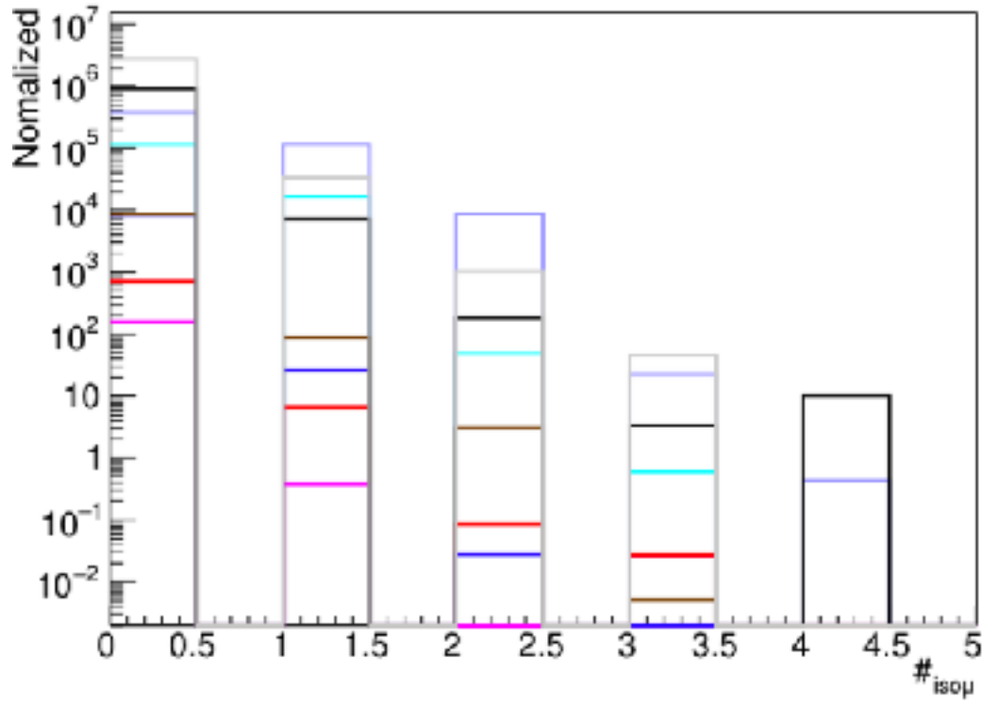
- Isolated e # = 2 && Isolated γ, **μ = 0**

Number of isolated γ



ILD work in progress

Number of isolated μ

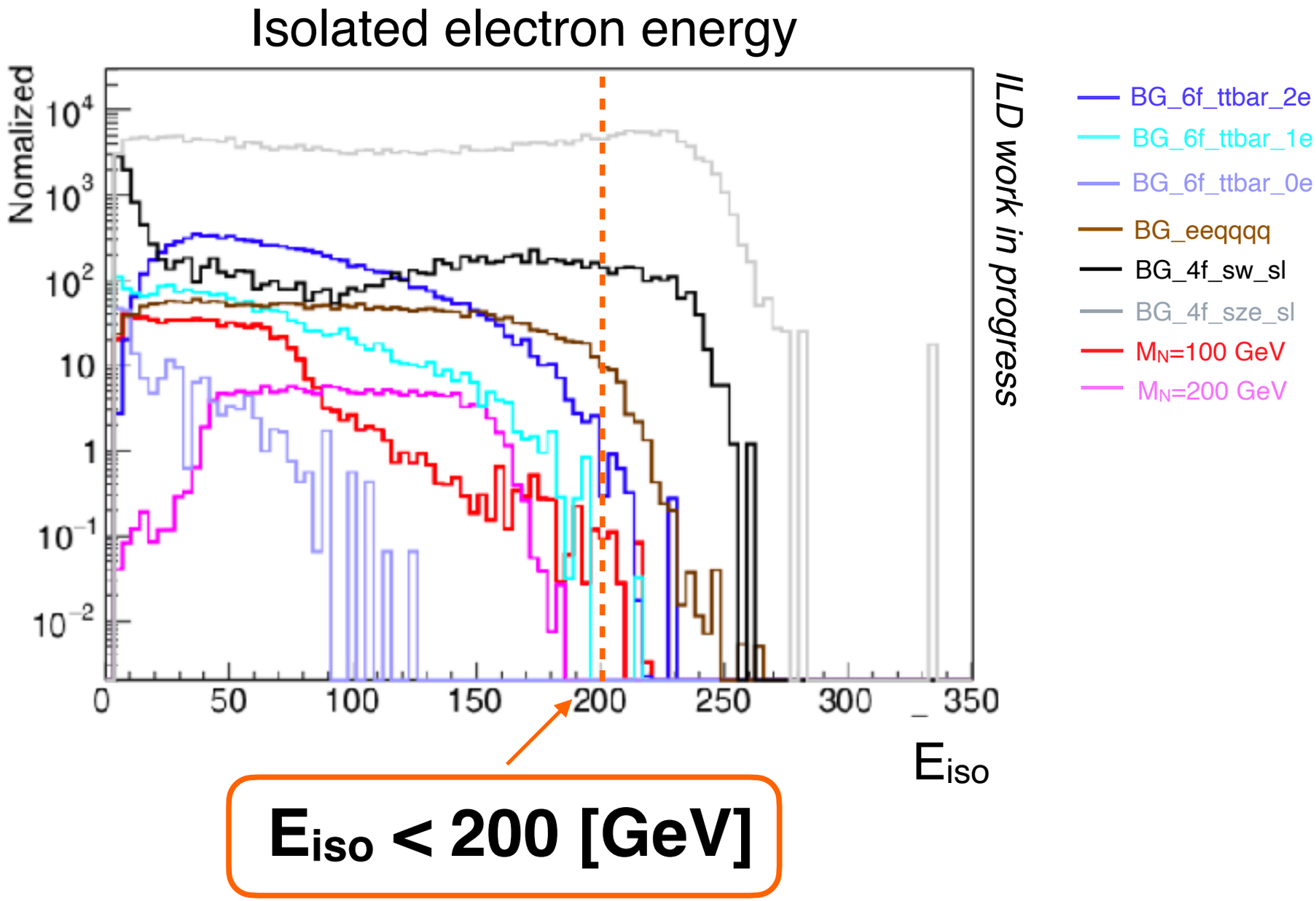


ILD work in progress

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 ($e_1 \times e_2 = 1$)

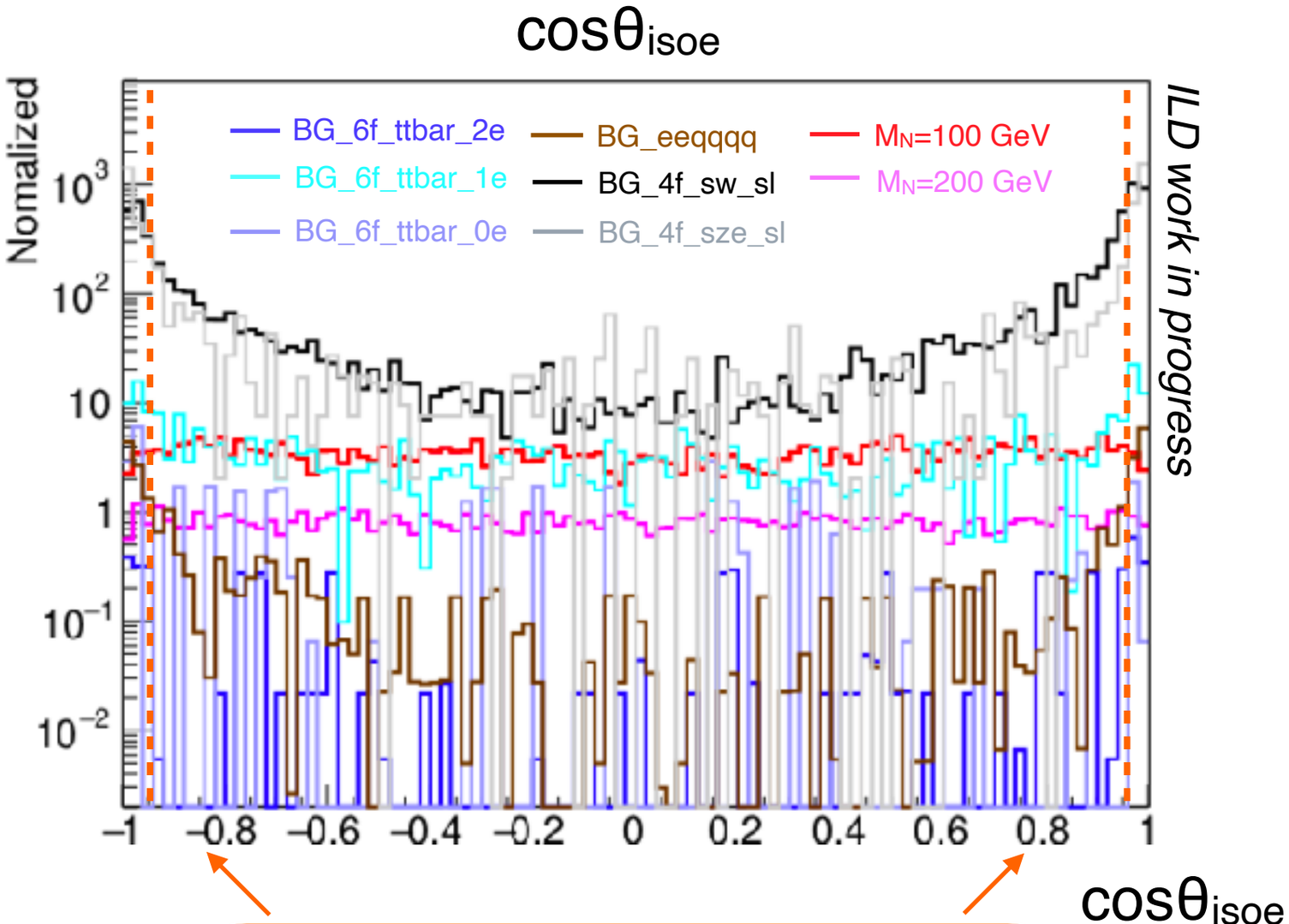


E_{iso} < 200 [GeV]

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 ($e_1 \times e_2 = 1$)



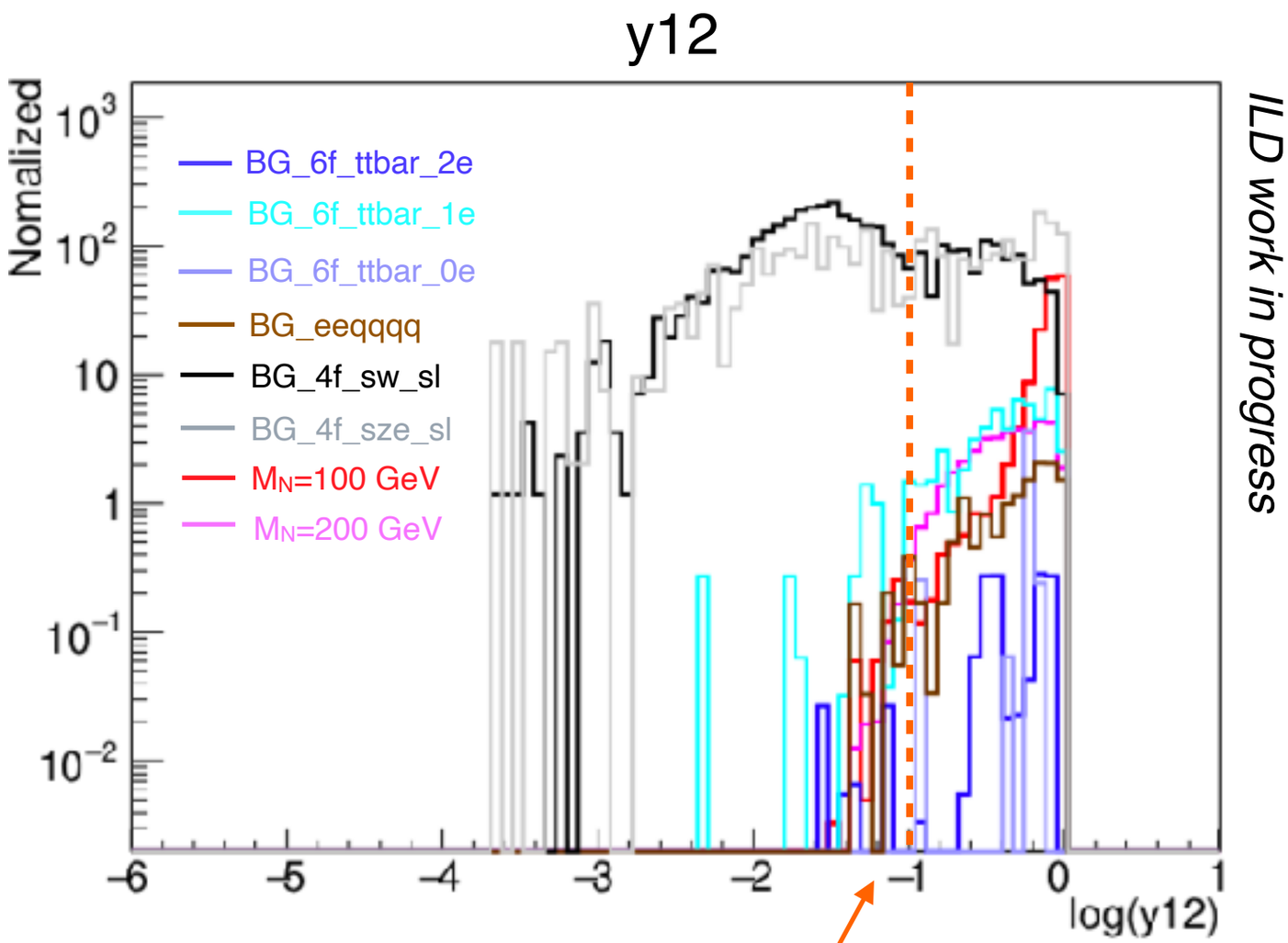
-0.95< $\cos\theta_{isoe}$ < 0.95

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)**

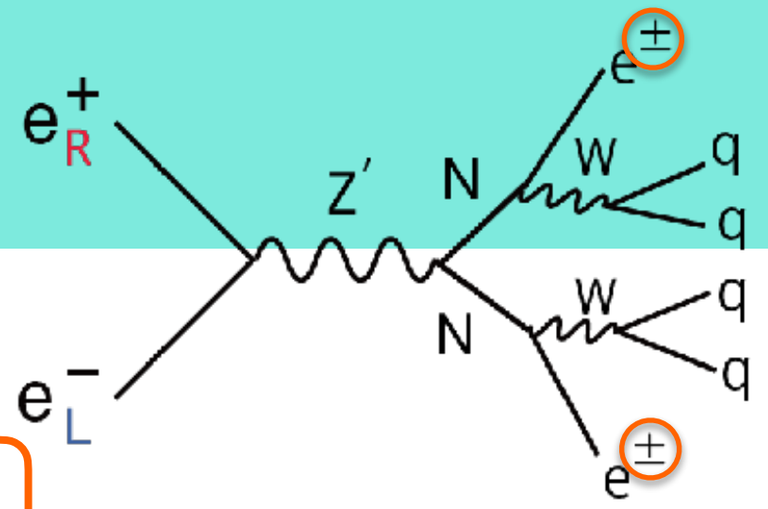
- Isolated e # = 2 && Isolated γ # = 0 && Isolated μ # = 0
- Isolated e is same sign ($e_1 \times e_2 = 1$)



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

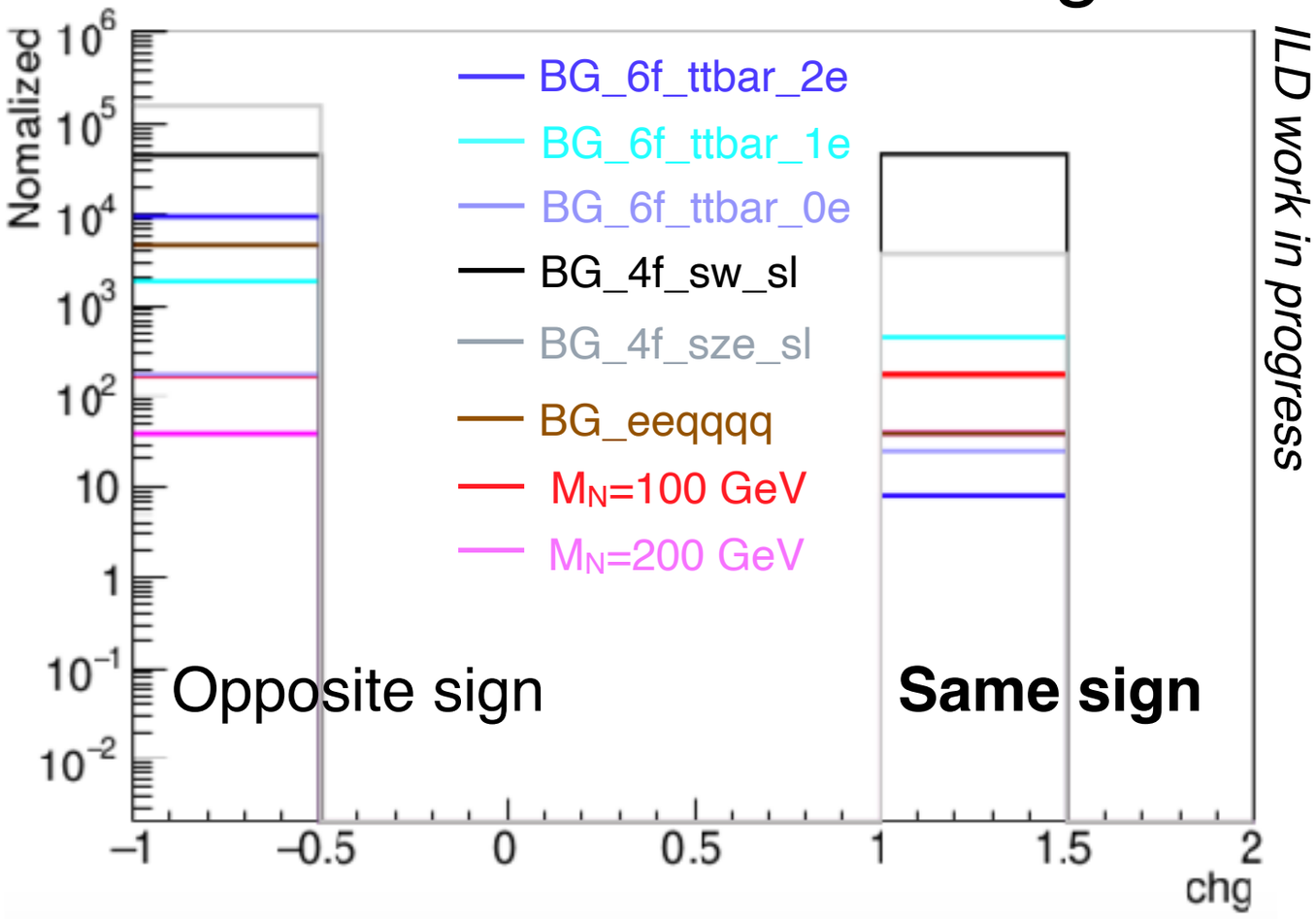
eLpR case

Electron Charge



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

Isolated electrons charge



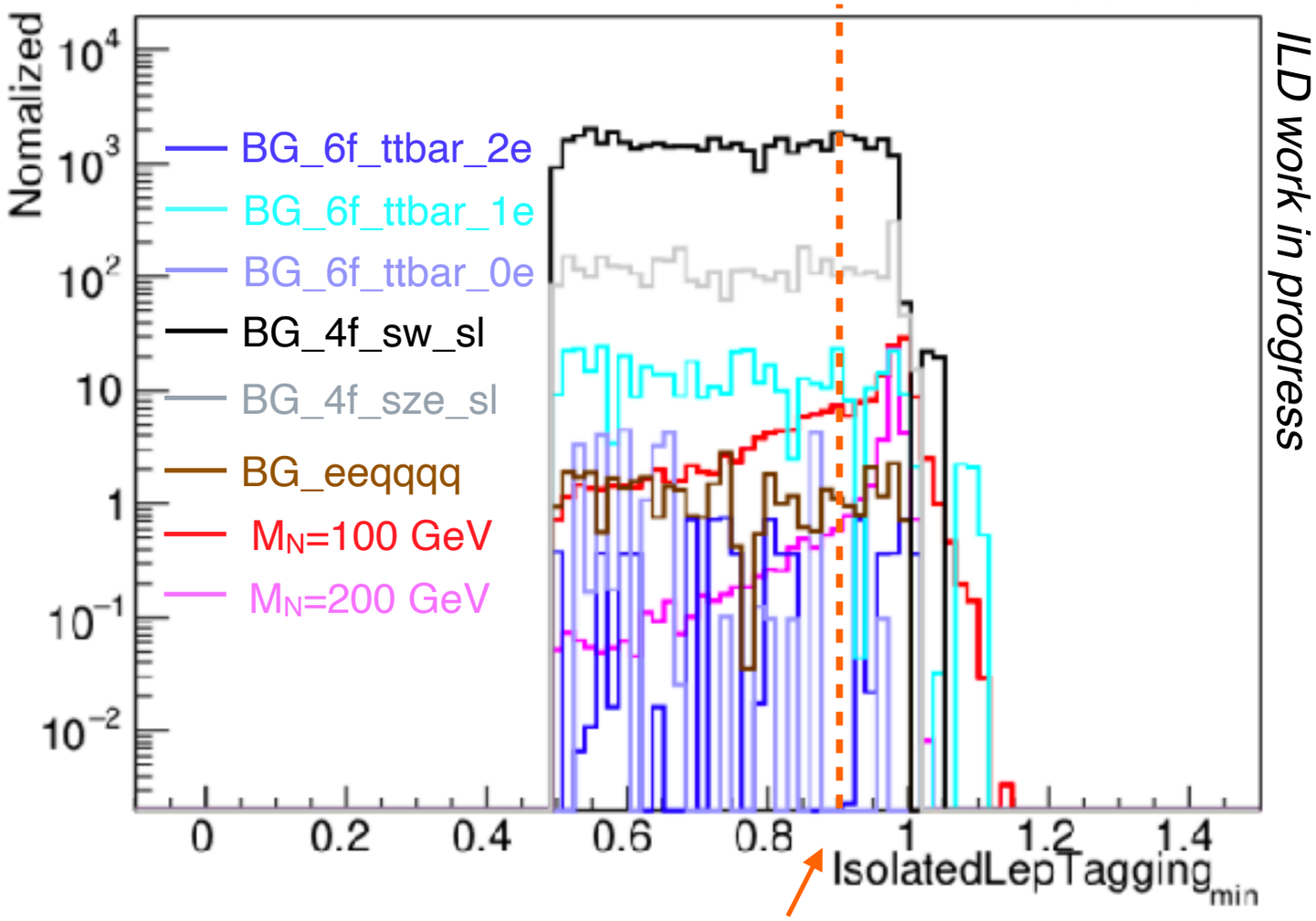
We use only same sign samples $e_1 \times e_2 = 1$

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



<u>Isolated lepton tagging</u>
… "output" parameter of MVA to identify isolated lepton

→ Output for e is <u>**near 1**</u>

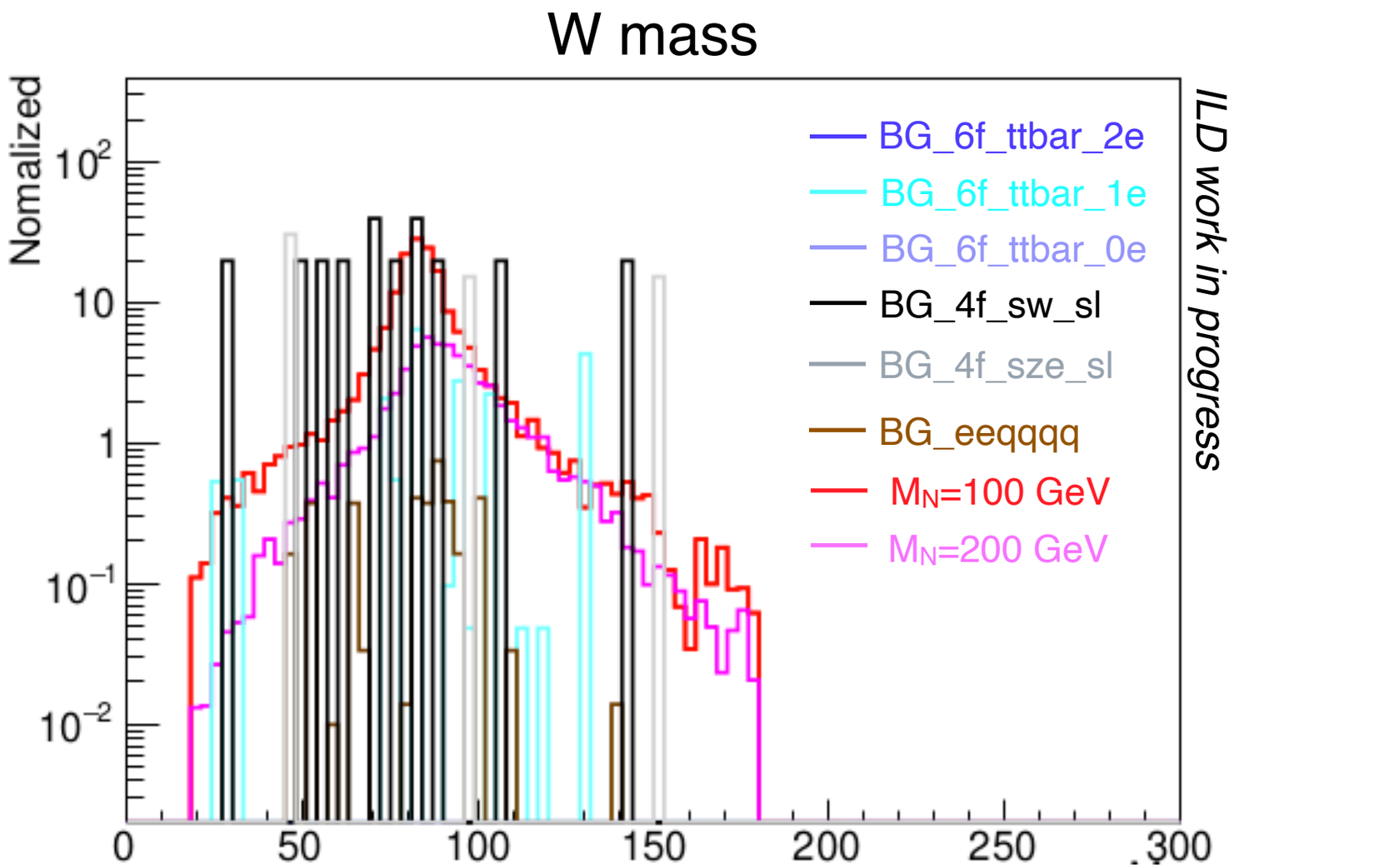
Usually second background electron is fake

IsolatedLepTagging$_{min}$ > 0.9

Reconstructed W mass

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

- Isolated e # = 2 && Isolated γ, μ # = 0
- Isolated e is same sign ($e_1 \times e_2 = 1$)
- $E_{iso} < 200$ [GeV]
- $-0.95 < \cos\theta_{isoe} < 0.95$
- $\text{IsolatedLepTagging}_{min} > 0.9$
- $P_{miss} < 100$ && ($P_{miss} < 40$ || $|\cos\theta_{Pmiss}| > 0.95$)
- $\log_{10}(y12) > -1$



Reconstructed RHN mass

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

- Isolated e # = 2 && Isolated γ, μ # = 0
- Isolated e is same sign ($e_1 \times e_2 = 1$)
- $E_{iso} < 200$ [GeV]
- $-0.95 < \cos\theta_{isoe} < 0.95$
- $\text{IsolatedLepTagging}_{min} > 0.9$
- $P_{miss} < 100$ && ($P_{miss} < 40$ || $|\cos\theta_{Pmiss}| > 0.95$)
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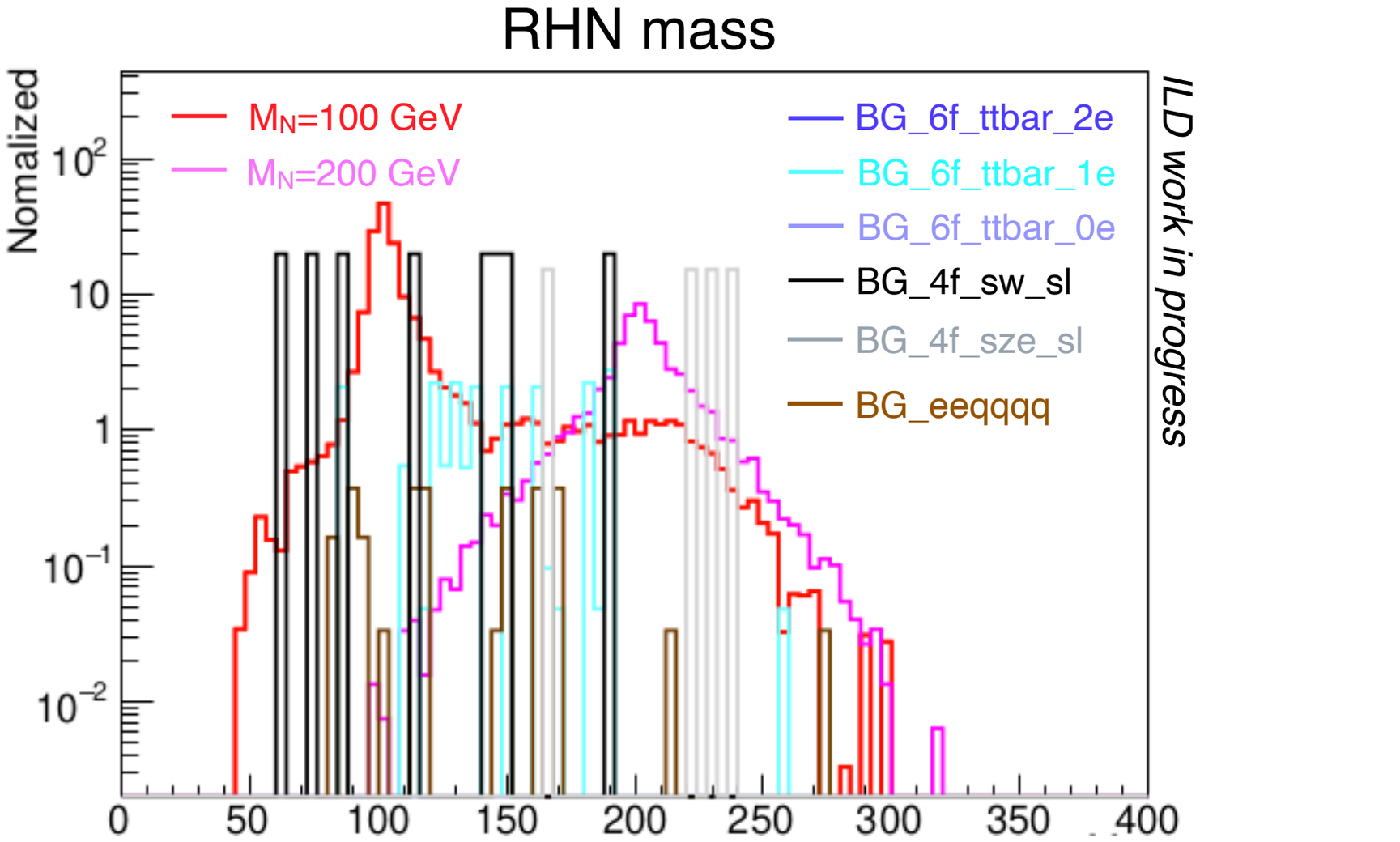
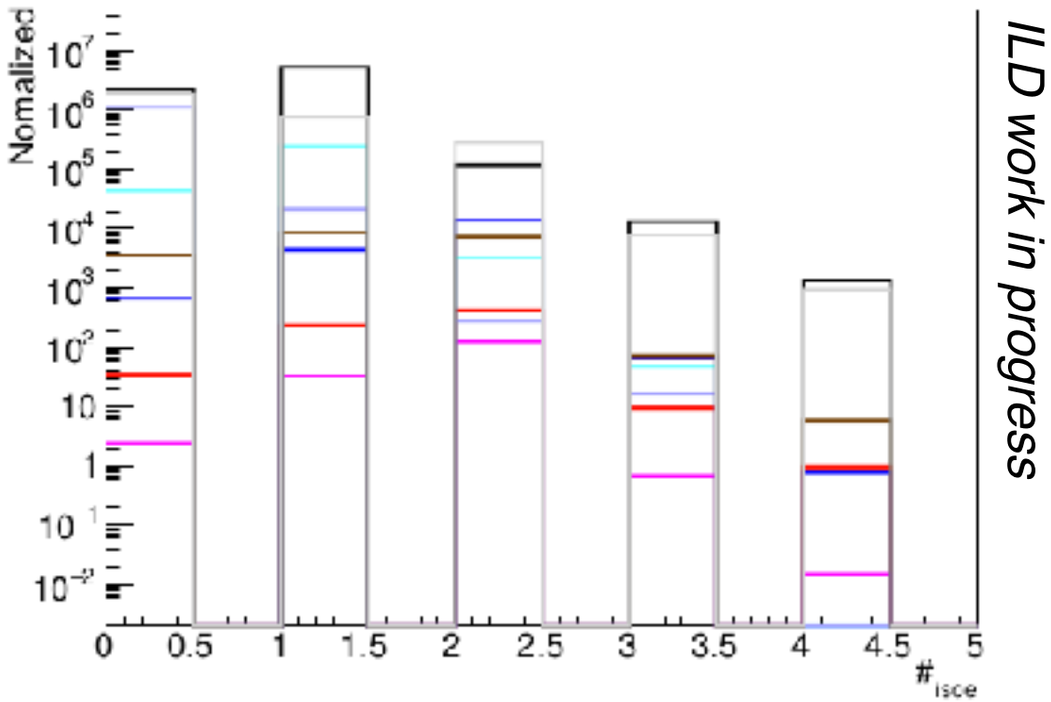


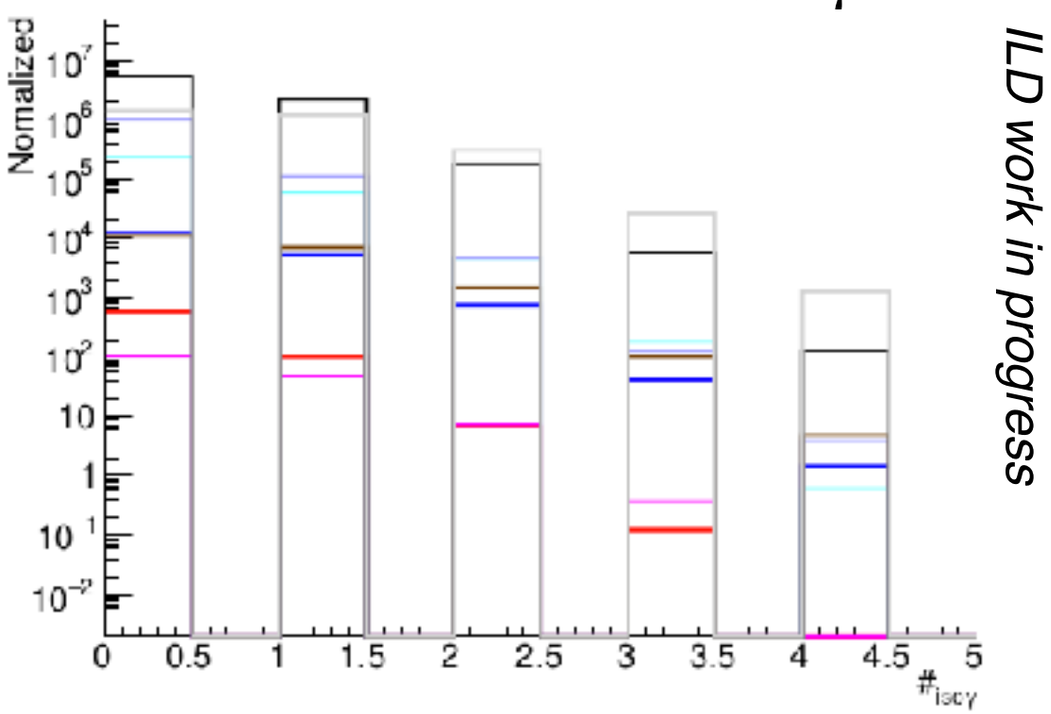
Isolated e,γ,μ

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

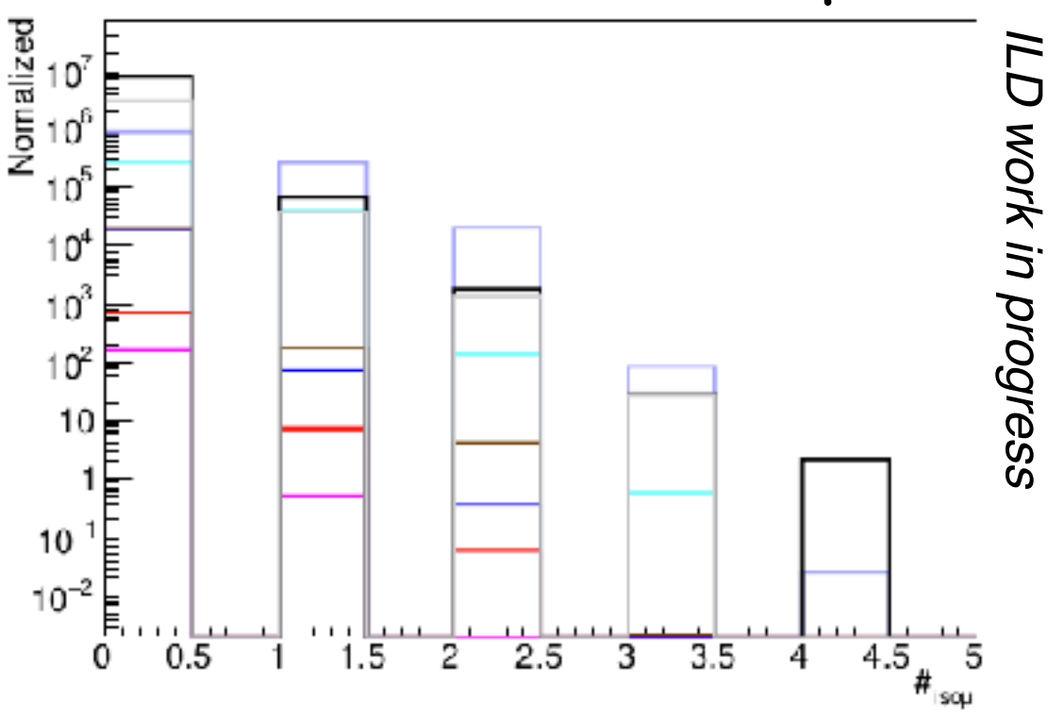
Number of isolated e



Number of isolated γ



Number of isolated μ



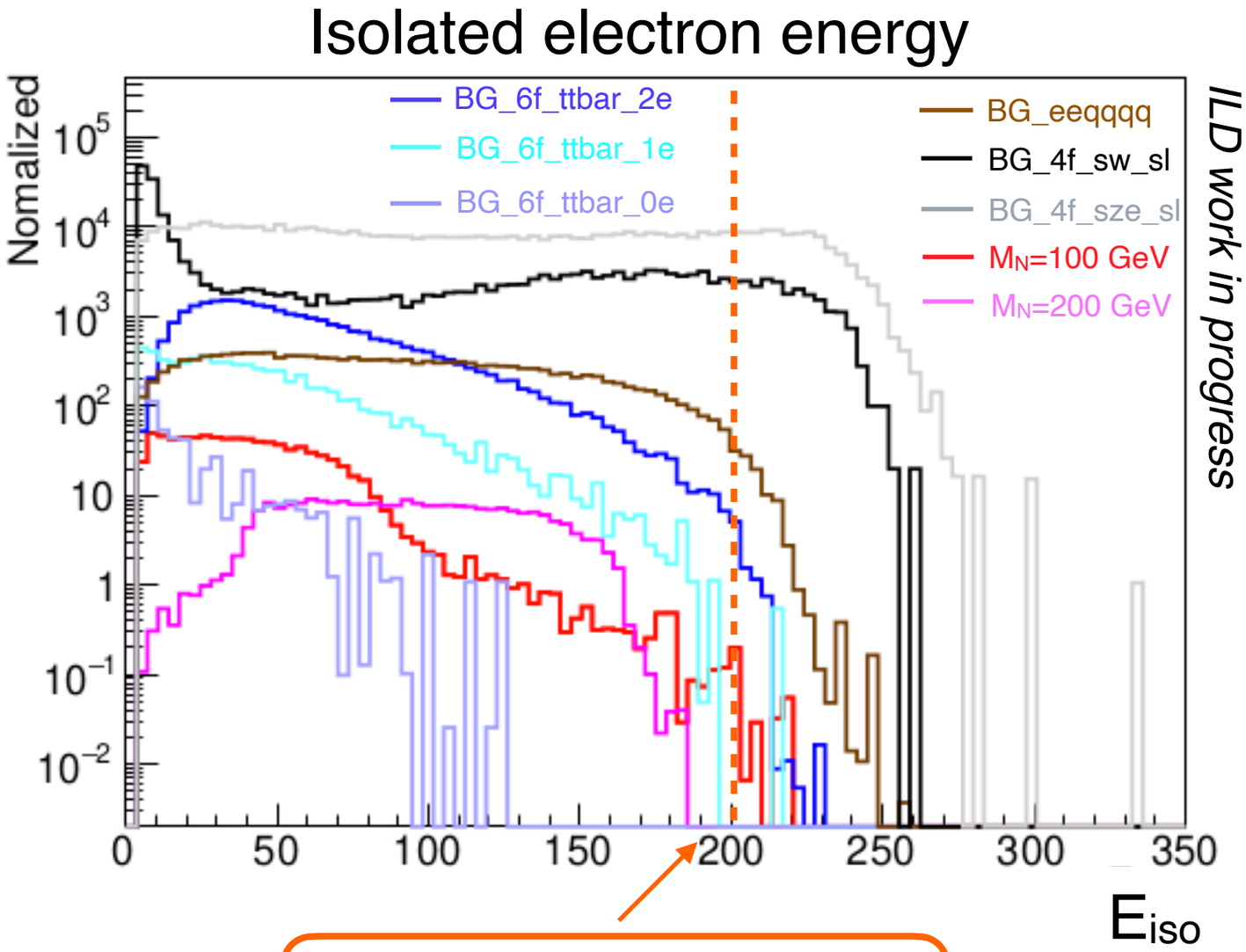
— M_N=100 GeV
— M_N=200 GeV
— BG_6f_ttbar_2e
— BG_6f_ttbar_1e
— BG_6f_ttbar_0e
— BG_4f_sw_sl
— BG_4f_sze_sl
— BG_eeqqqq

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

Distribution of Isolated electron energy

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

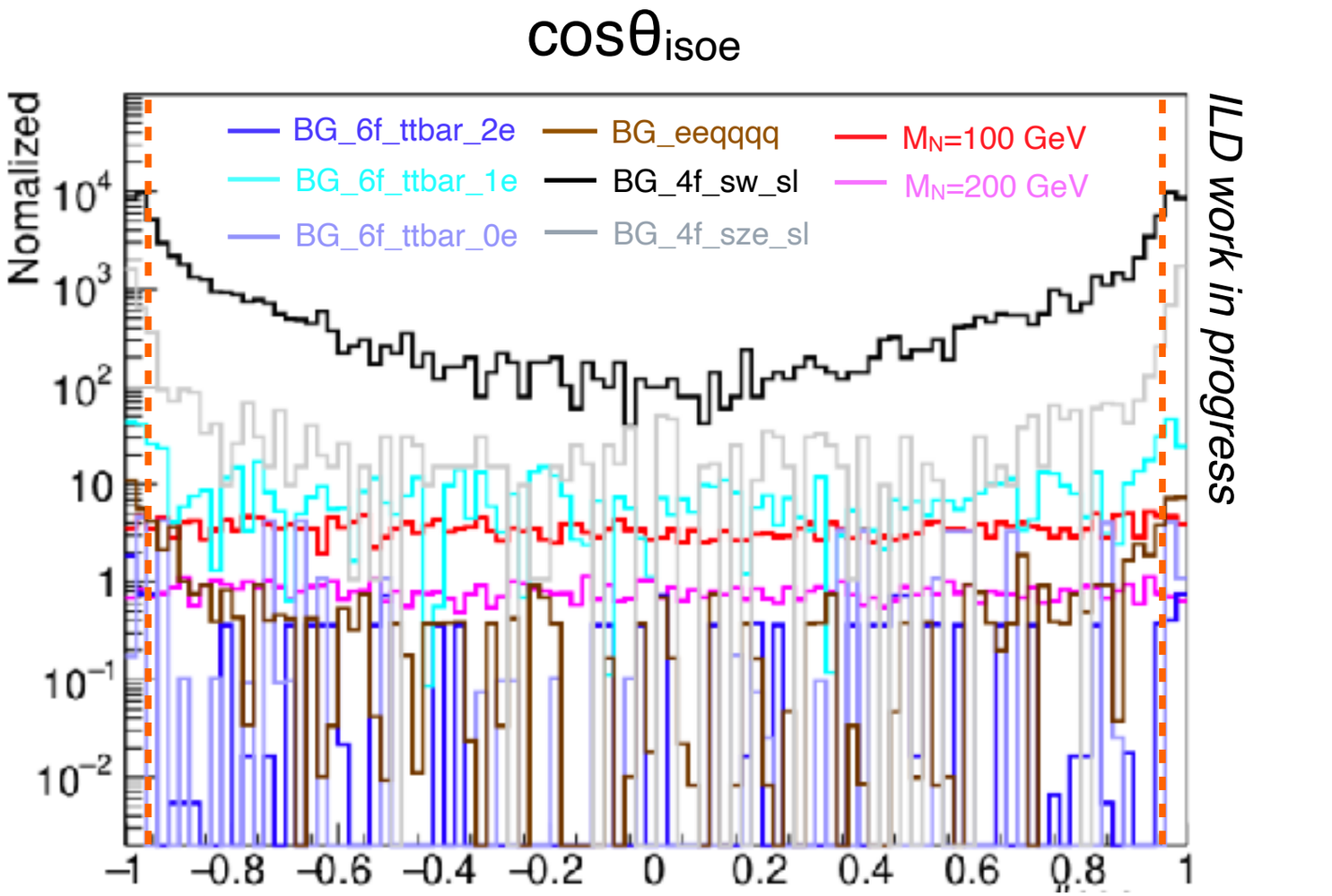
- Isolated e # = 2 && Isolated γ # = 0 && Isolated μ # = 0
- Isolated e is same sign ($e_1 \times e_2 = 1$)



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 ($e_1 \times e_2 = 1$)



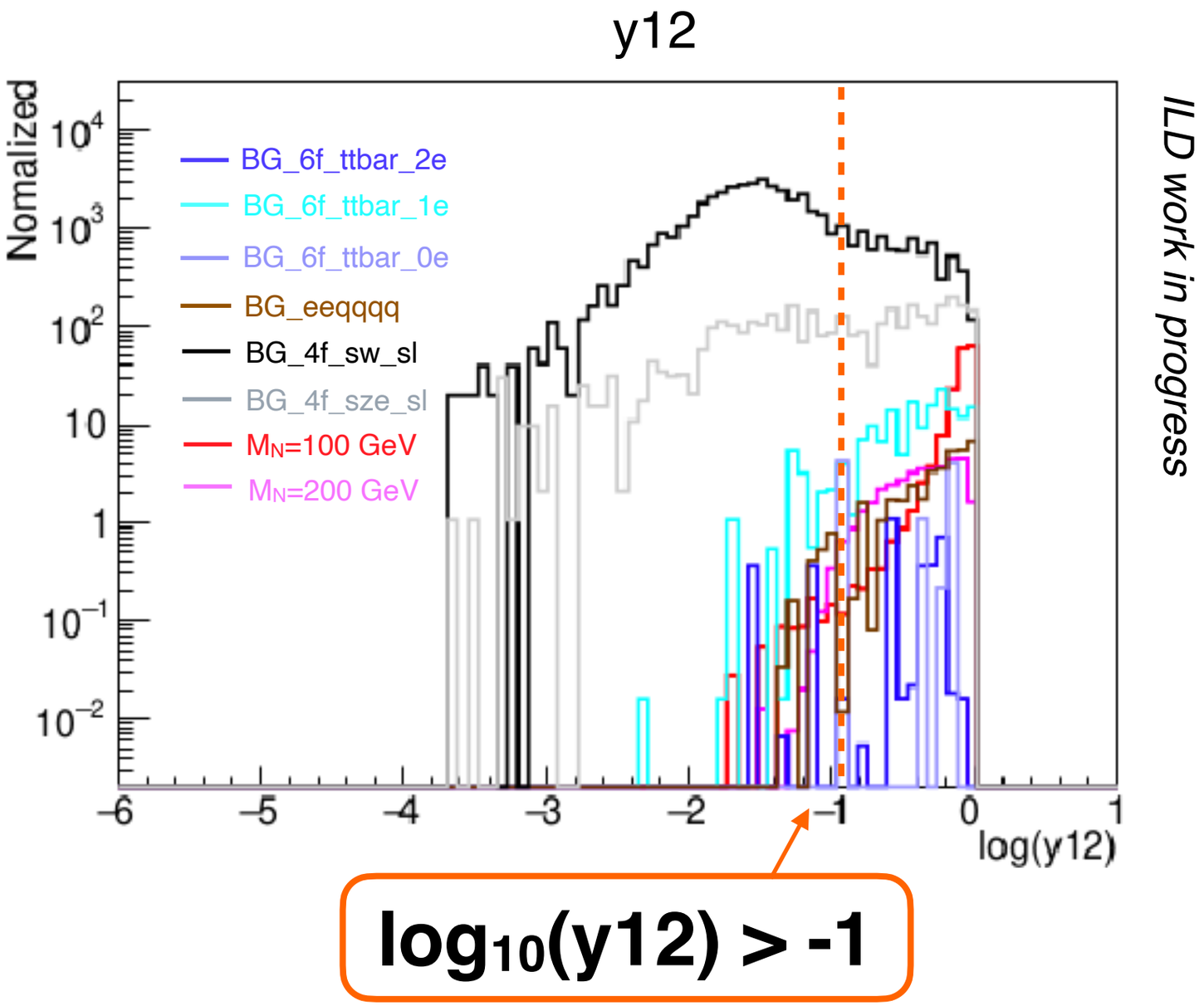
-0.95< $\cos\theta_{isoe}$ < 0.95

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 ($e_1 \times e_2 = 1$)



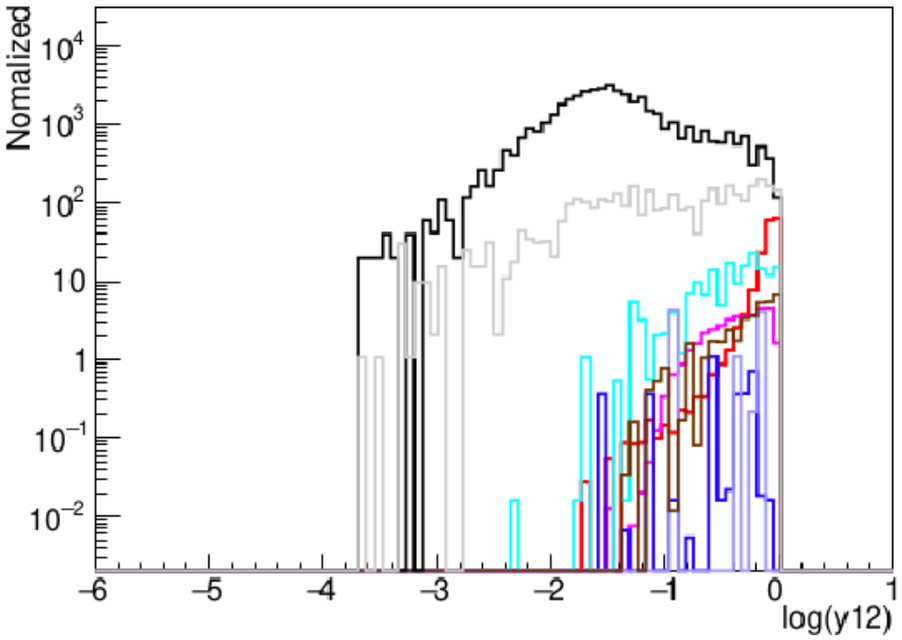
$\log_{10}$(y12) > -1

Distribution of y12,y23, y34, y45 (Durham)

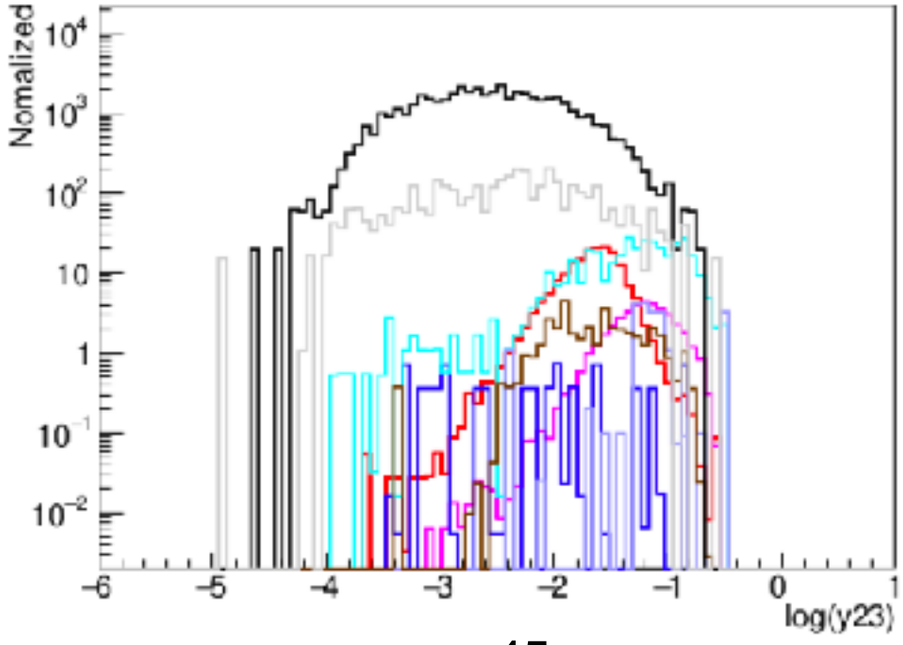
- ILC 500 with ISR / BS
- **Pol(e^-, e^+) = (–0.8, +0.3)**

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

y12

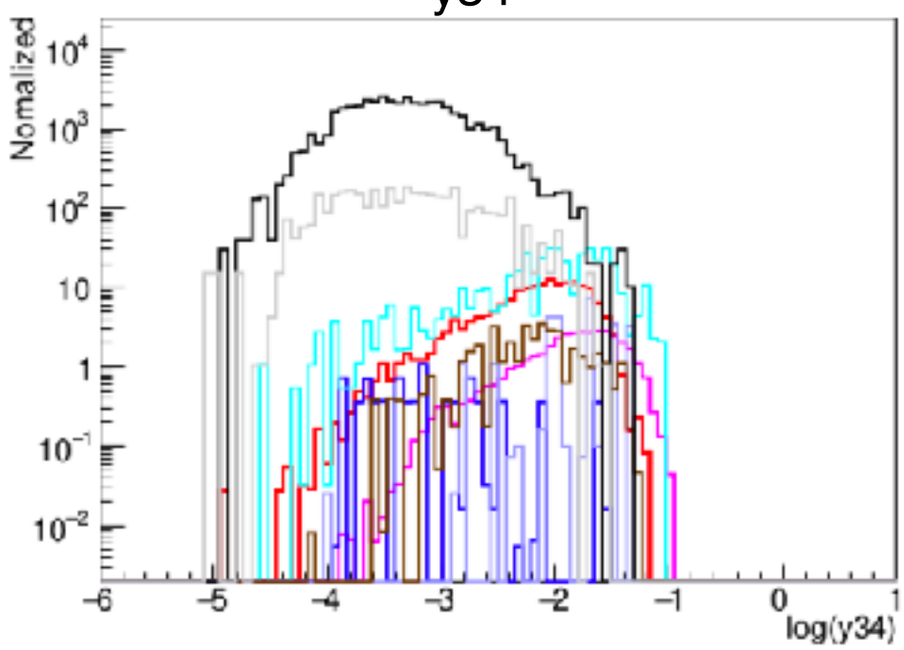


y23

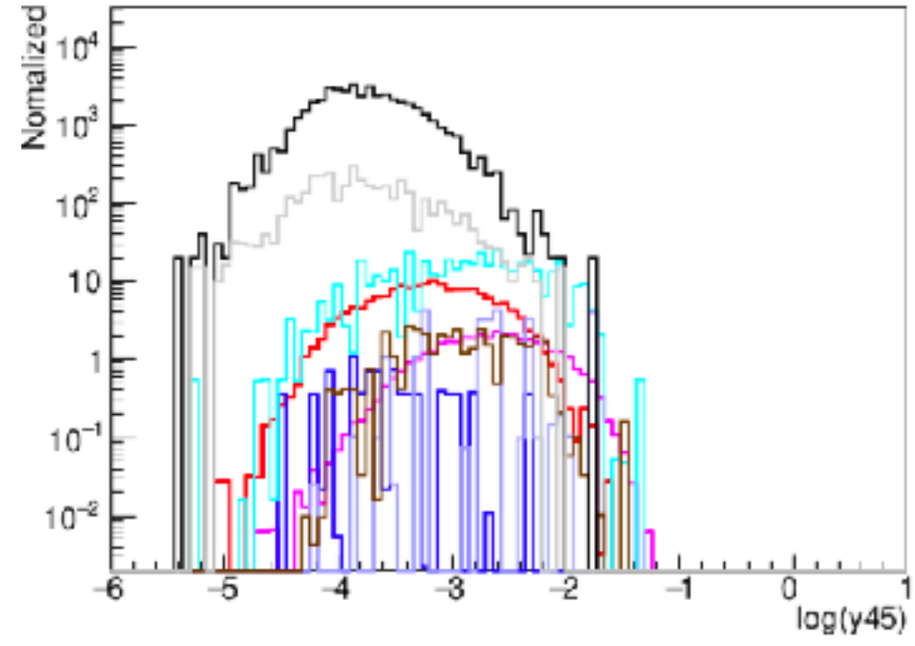


BG_6f_ttbar_2e
BG_6f_ttbar_1e
BG_6f_ttbar_0e
BG_eeqqqq
BG_4f_sw_sl
BG_4f_sze_sl
M_N=100 GeV
M_N=200 GeV

y34



y45



ILD work in progress

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							

MC event

- ILC 500
- Pol(e^-, e^+) = (∓0.8, ±0.3)

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

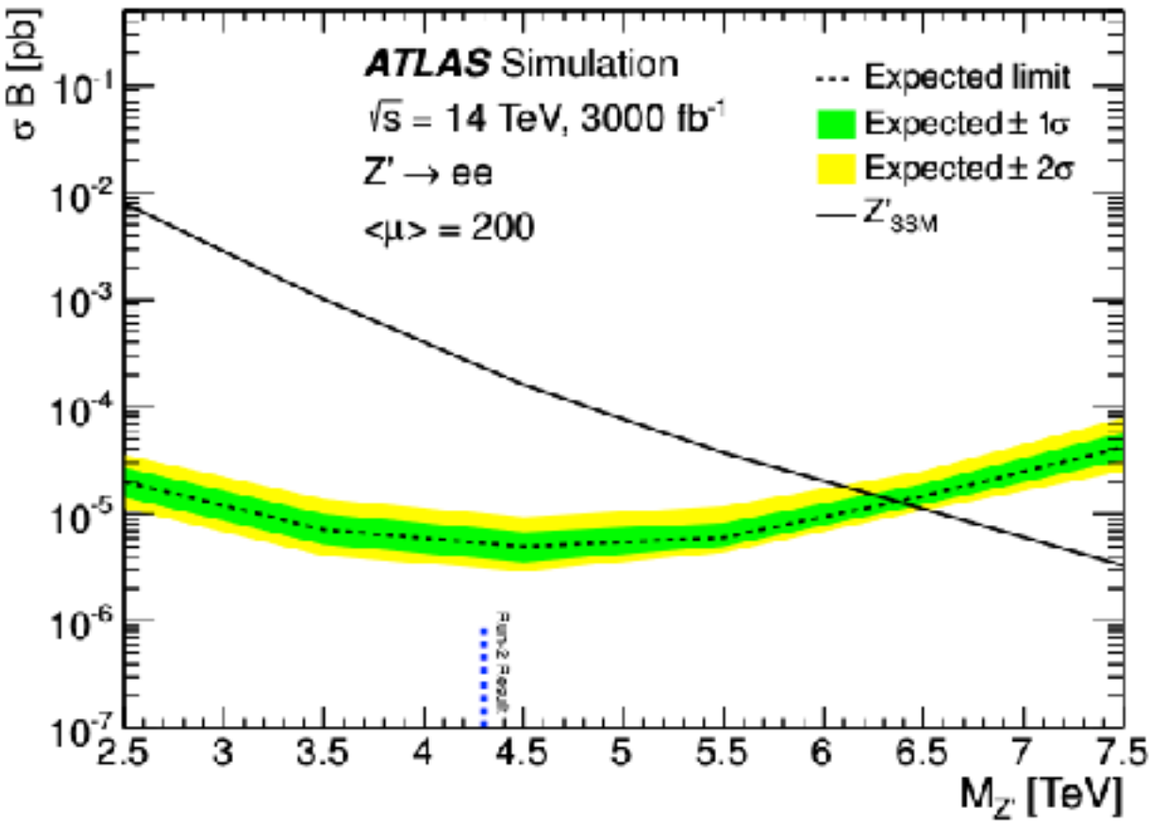
ILD work in progress

	Signal Entries		Background Entries					
	M_N=100	M_N=200	eeqqqq	4f_singleW _semileptonic	4f_singleZee_ semileptonic	6f_ttbar 2electrons	6f_ttbar 1electron	6f_ttbar 0electron
MC evt# (eLpR)	24000	24000	61112	368881	132424	52139	239403	326573
MC evt# (eRpL)	24000	24000	40533	11413	91754	25824	201643	524380

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

Current limits - Z' mass

SM like Z' coupling



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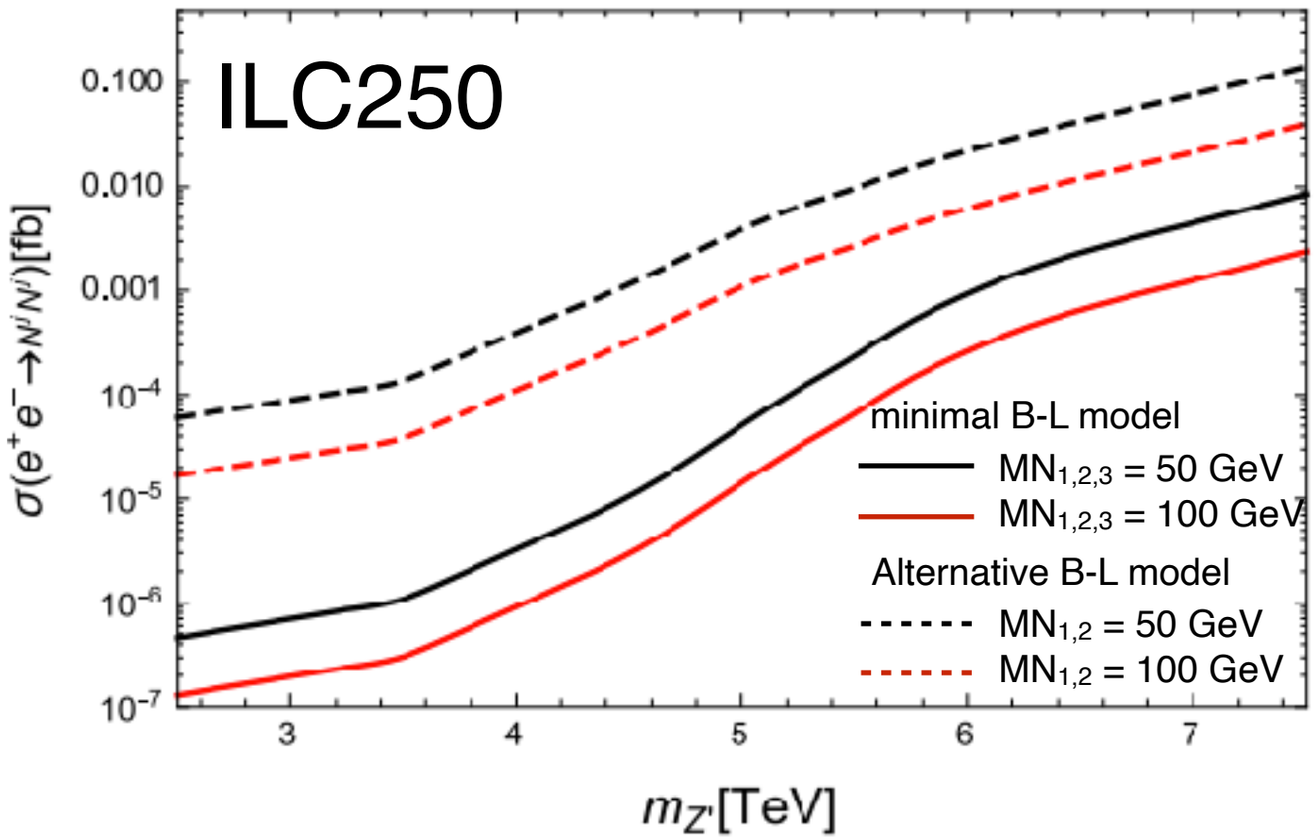
HL-LHC prospects limit for $U(1)_{B-L}$ model

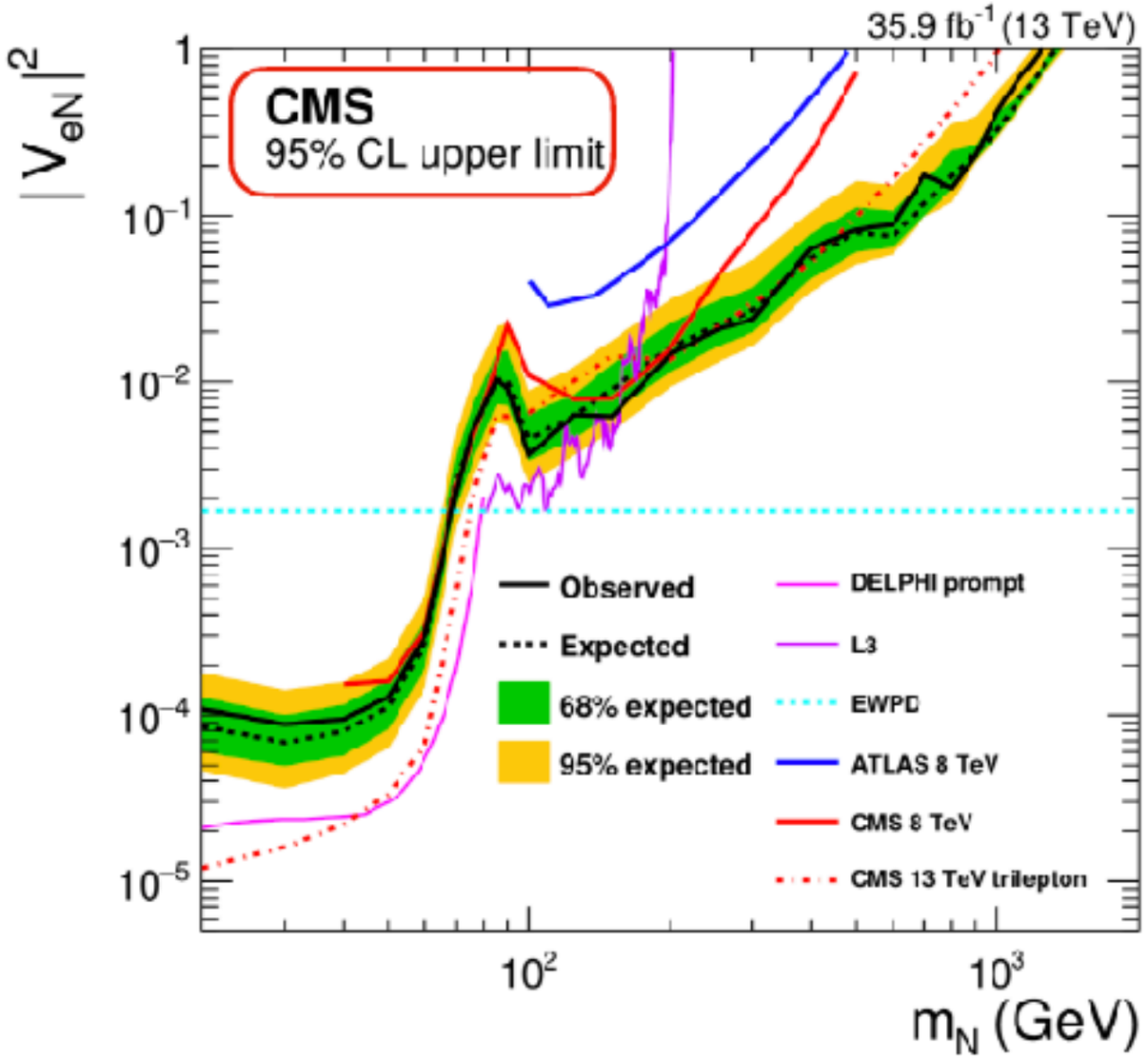


arXiV[1812.11931]

The heavier Z' mass less constrained by LHC

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

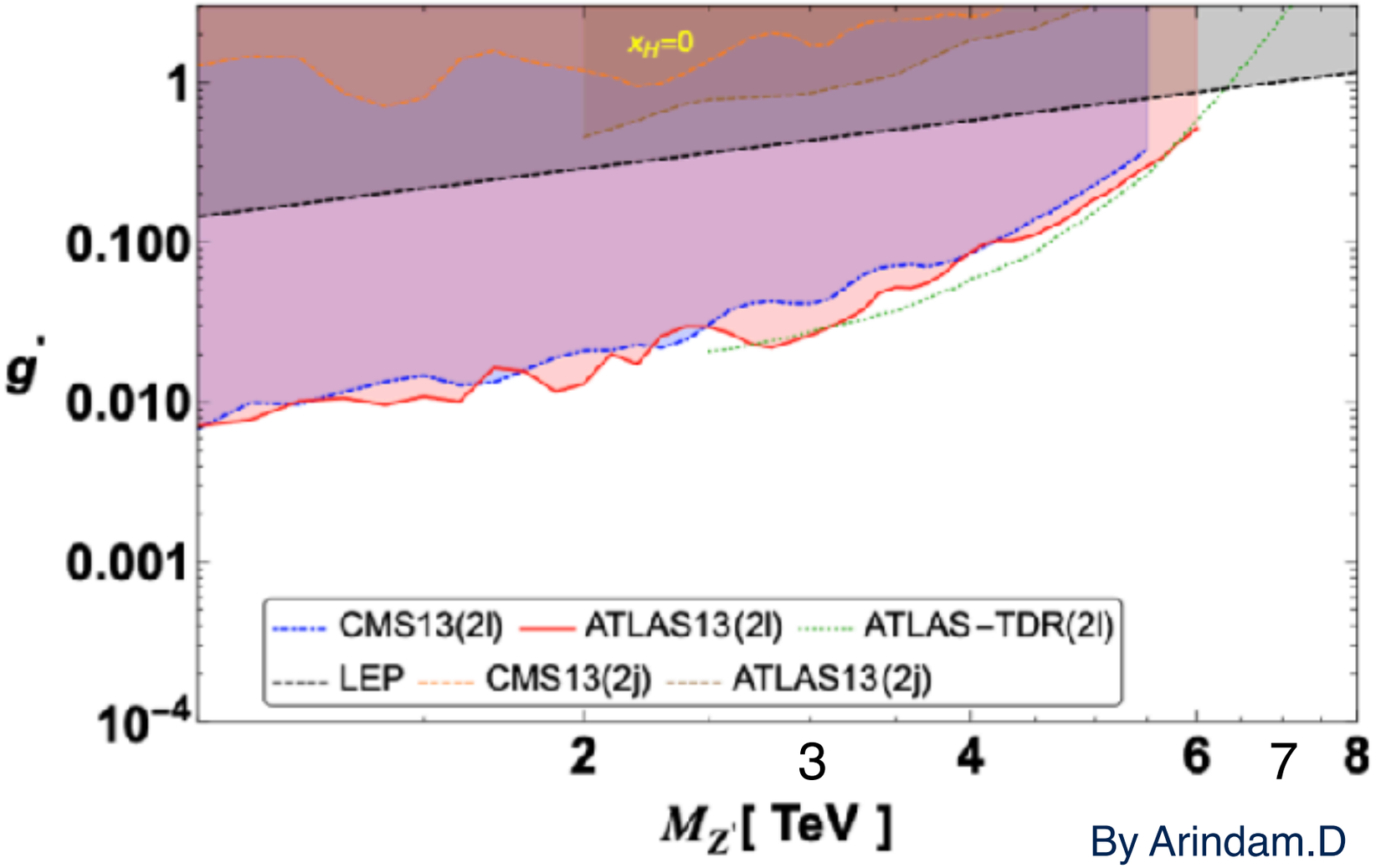
$|V_{eN}|^2$: the "light-heavy" neutrino mixing matrix



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