Exploring Right Handed Neutrinos at ILC

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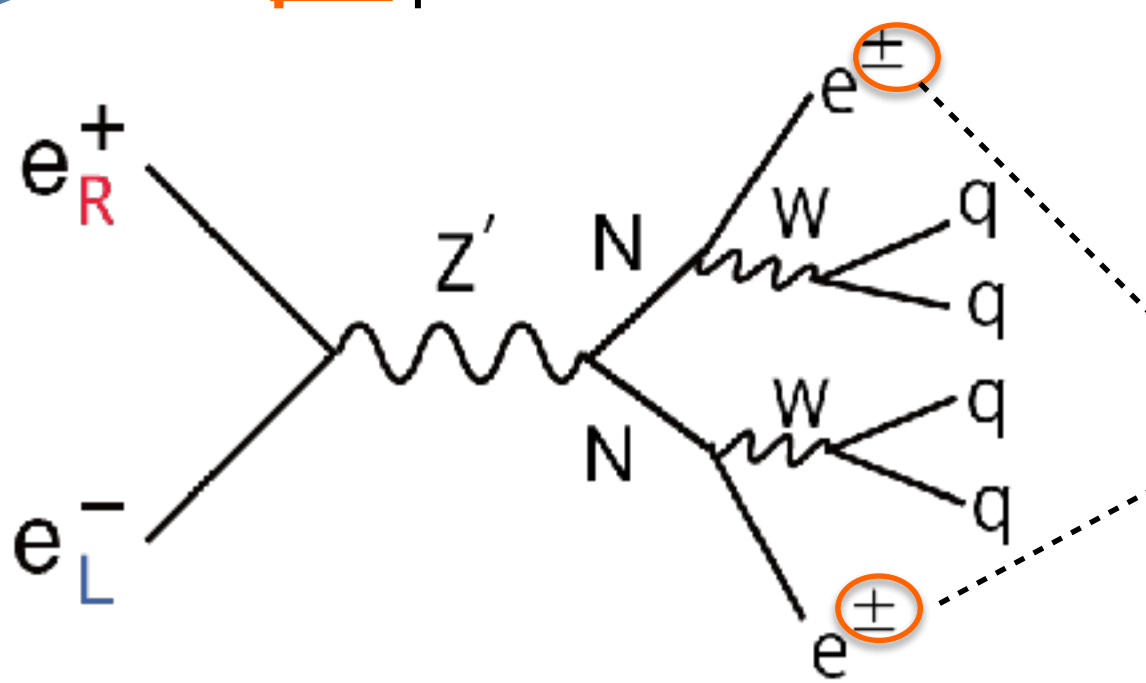
Motivation and Introduction

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

WHIZARD ver 2.8.5
Make Events

↓

Slow

Full Simulation

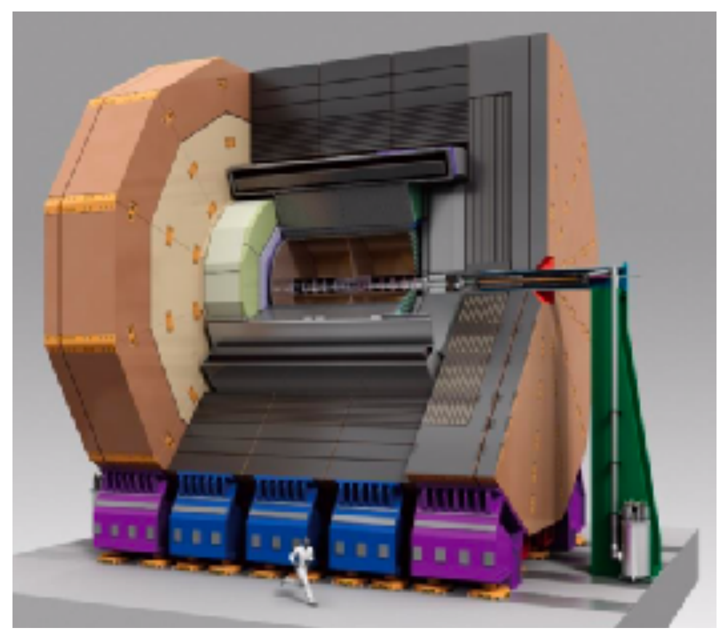
precise

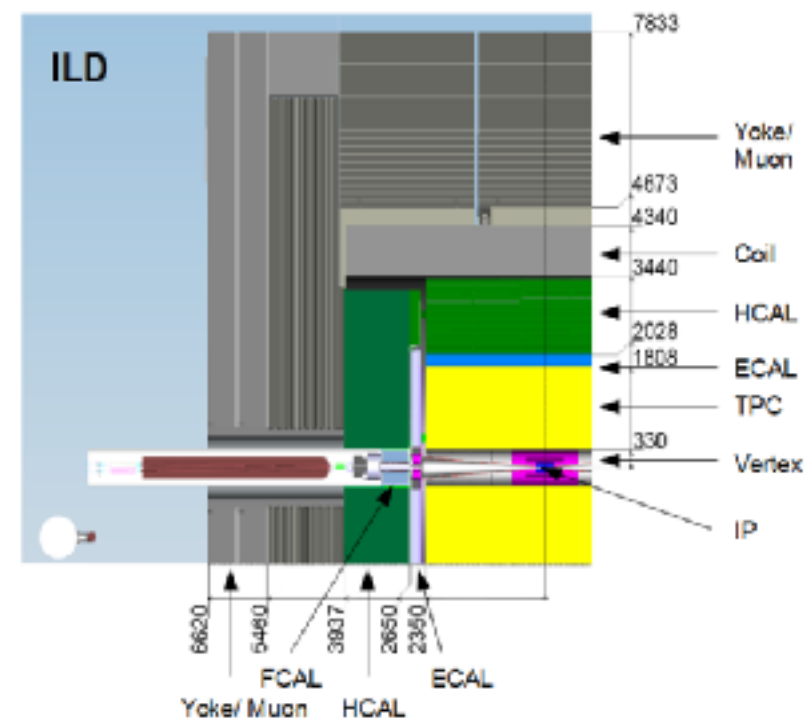
↓

miniDST
Events format

<u>**Full** simulation</u>

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





We prepared full simulation signal samples.

Benchmark points

Not excluded by LHC

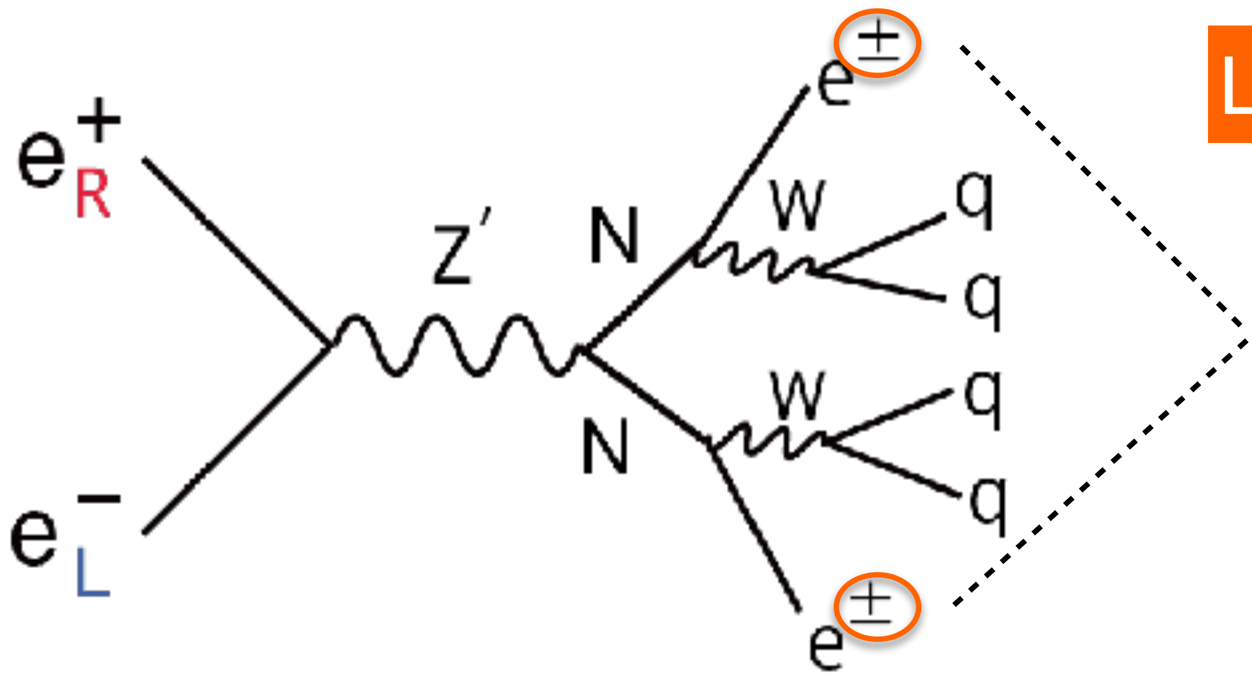
M_N [GeV]	$M_{Z'}$ [TeV]	g1’	$\|V_{eN}\|^2$	σ_{LR} (ee→NN) [fb]	Event # [$4000fb^{-1}$]
100	7	1	0.001	7.08E-01	**1261**
200	7	1	0.005	1.63E-01	**131**

- minimal $U(1)_{B-L}$ 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’ : $U(1)_{B-L}$ coupling constant
V_{eN} : mixing angle

Backgrounds



Lepton # violation is possible!

↓

Same sign leptons possible

↓

No SM BG!

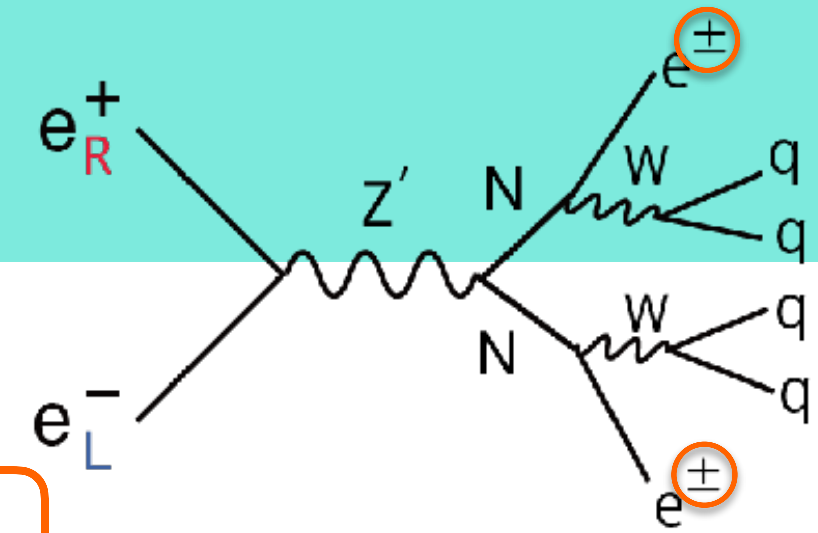
However… We need to consider

Choosing the wrong particle as an electron

Add to <u>full</u> simulation background samples.

- eeqqqq
- 6f_ttbar
  → 2 electrons, 1 electron, 0 electron (in final state)
- 4f_singleW_semileptonic
- 4f_singleZee_semileptonic

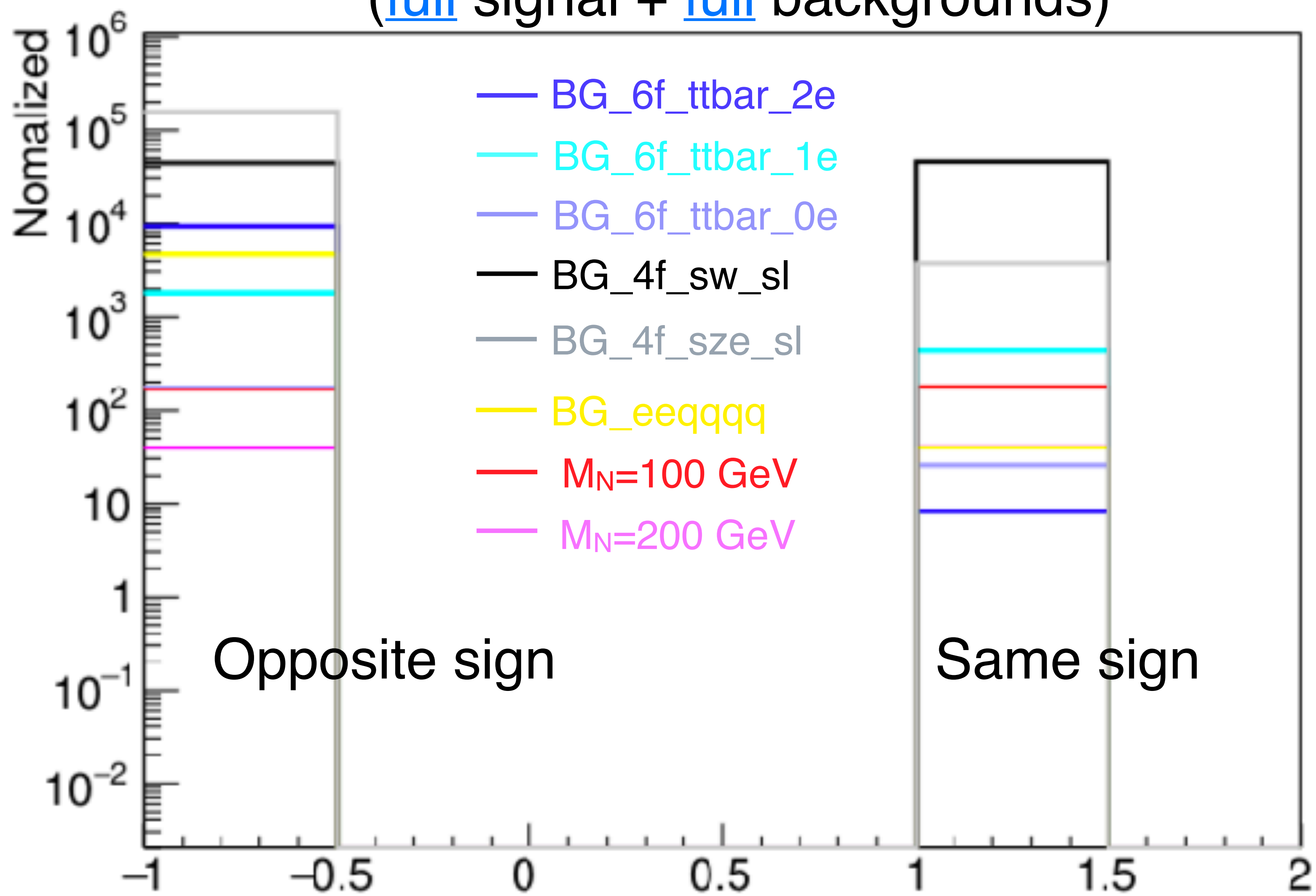
Electron Charge



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

Isolated electrons charge

(full signal + full backgrounds)



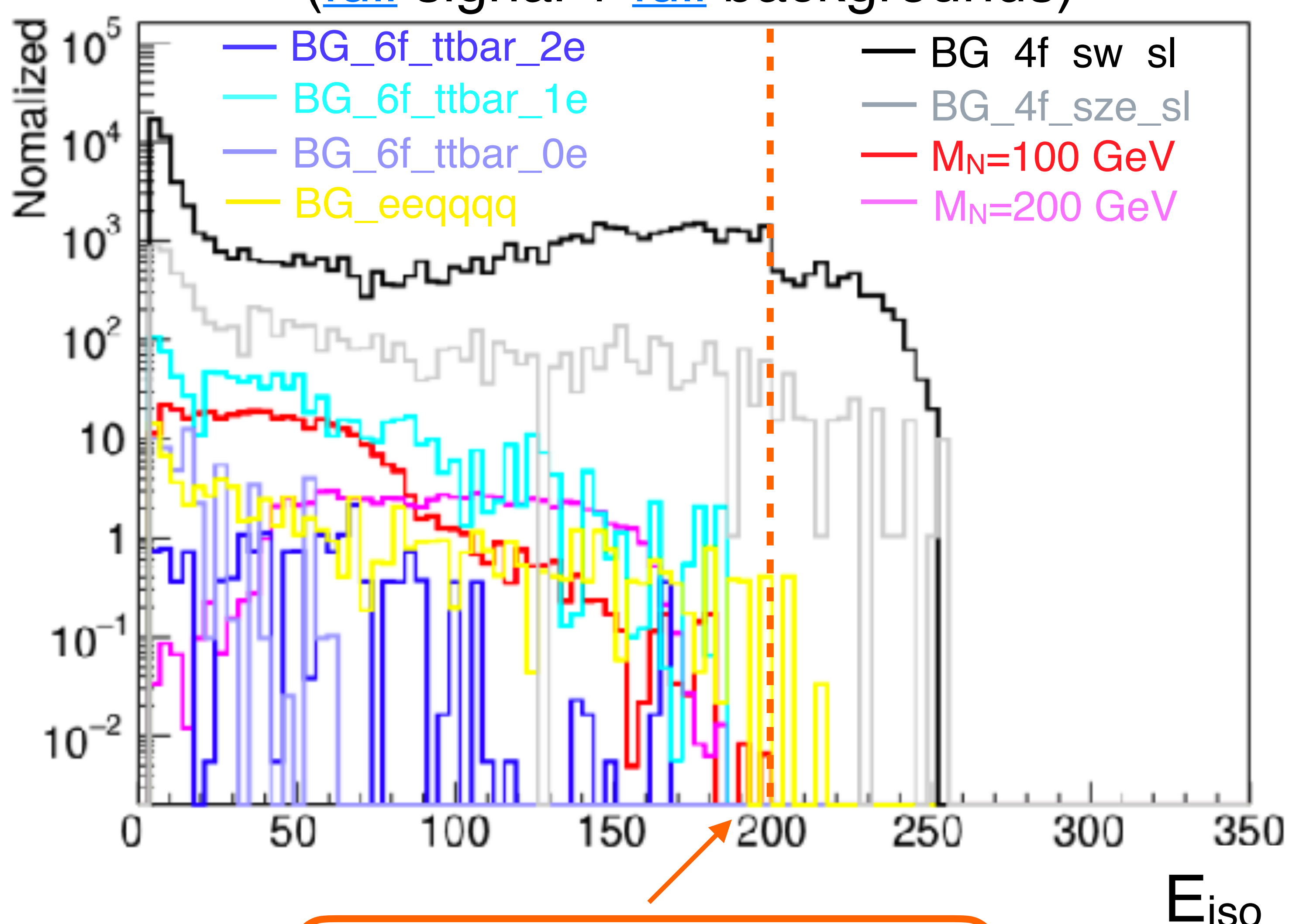
We use only same sign samples **Charge == 1**

Distribution of Isolated electron energy

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

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

Isolated electron energy
(full signal + full backgrounds)



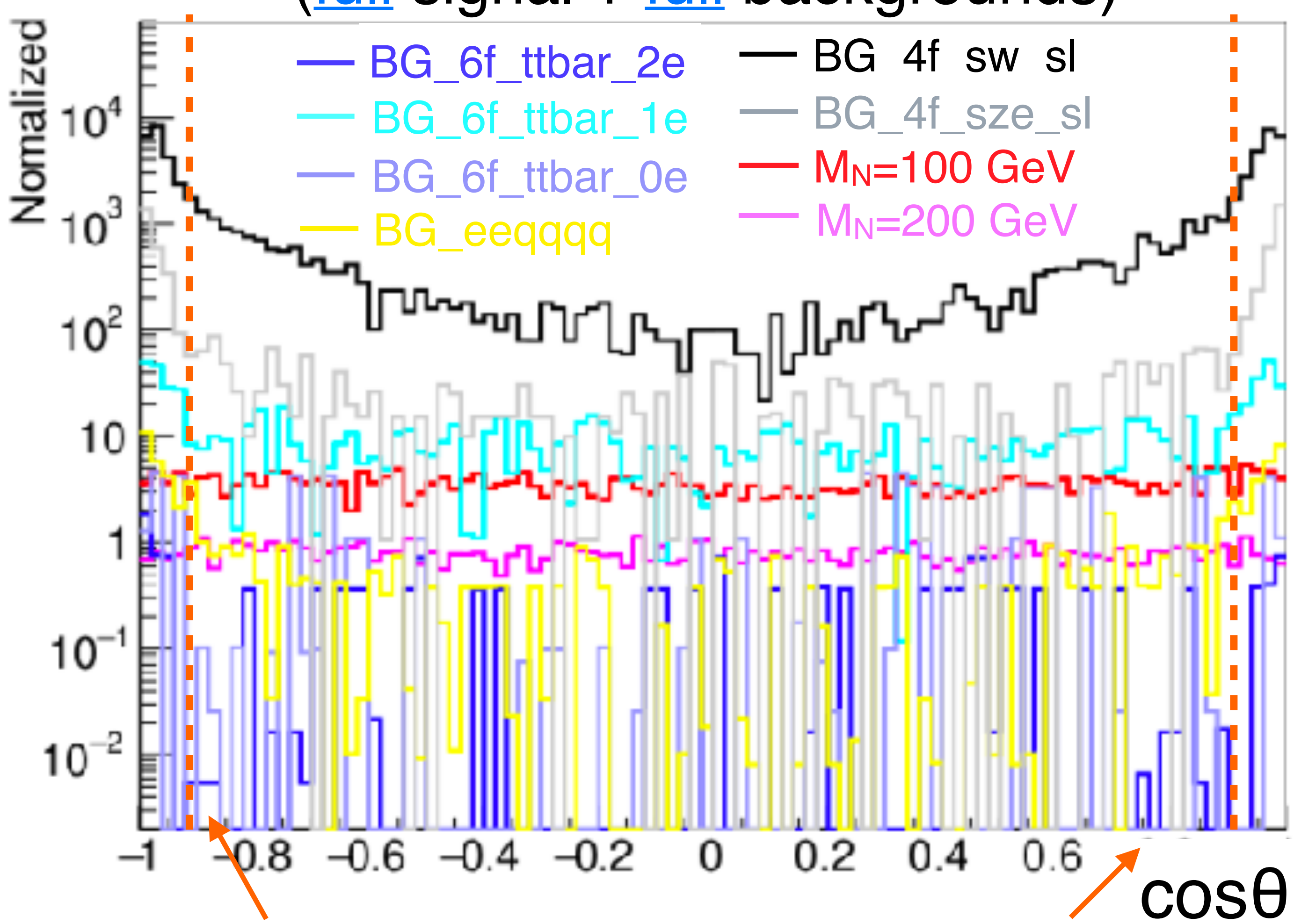
E_{iso} < 200 [GeV]

Distribution of $\cos\theta_{isoe}$

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

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

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



$\cos\theta_{isoe}$

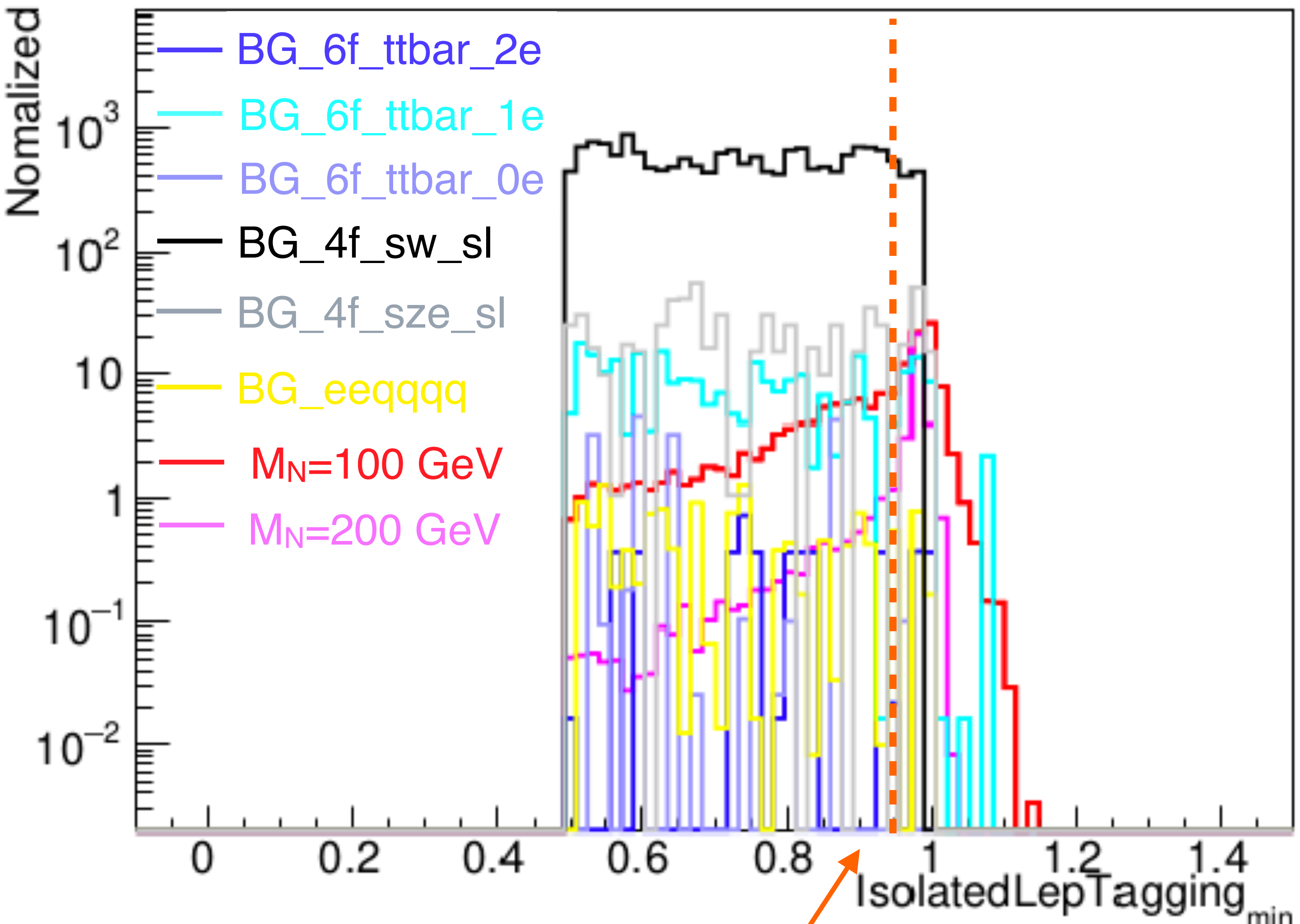
-0.95< $\cos\theta_{isoe}$ < 0.95

Distribution of IsolatedLepTagging

- 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

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



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

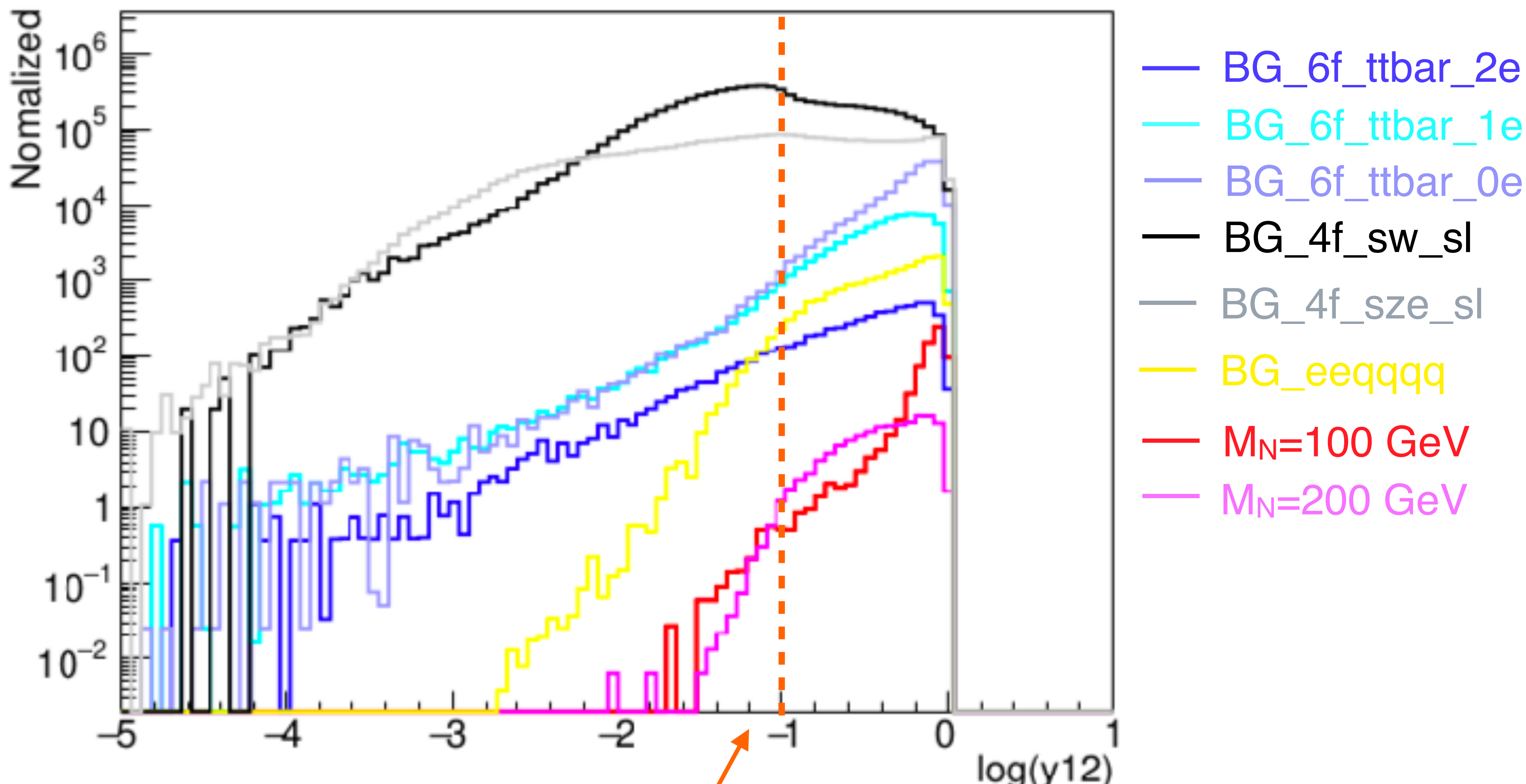
→ Output for e is **near 1**

IsolatedLepTagging$_{min}$ > 0.9

Distribution of y12 (Durham)

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

y12 (full signal + full backgrounds)

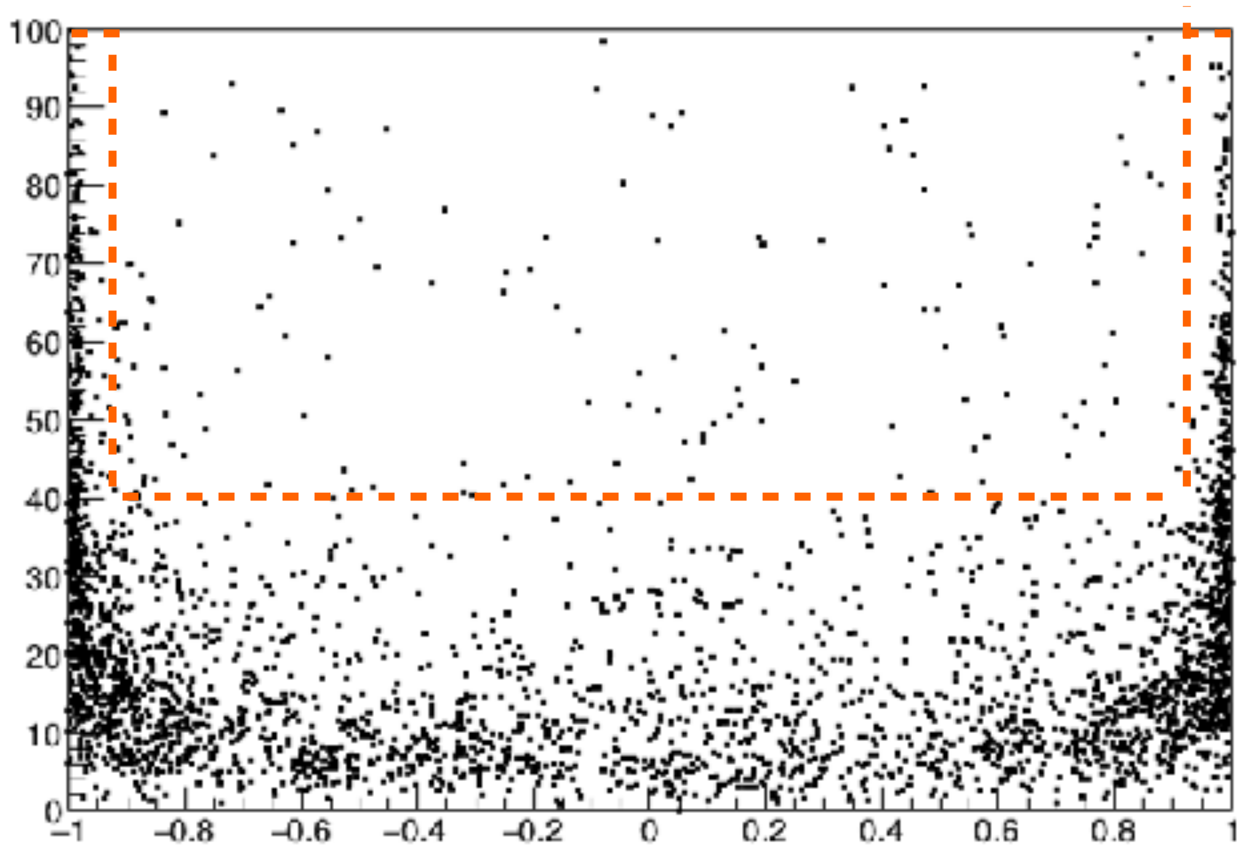


$\log_{10}$(y12) > -1

$\cos\theta_{total}$ vs Magnitude of total momentum

M_N=200GeV(LR)
(full **signal**)

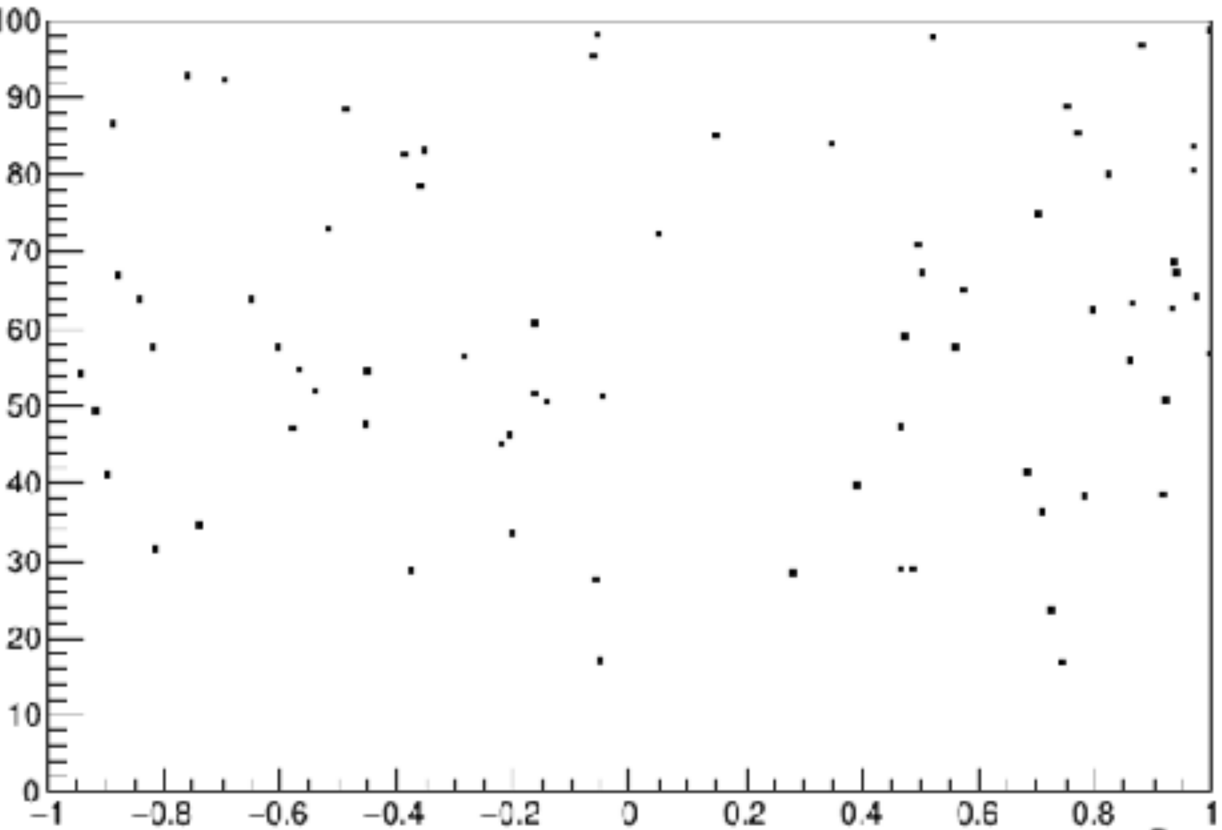
P_{total}



$\cos\theta_{total}$

4f_sw_sl(LR)
(full **backgrounds**)

P_{total}



$\cos\theta_{total}$

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

Cut flow (eLpR)

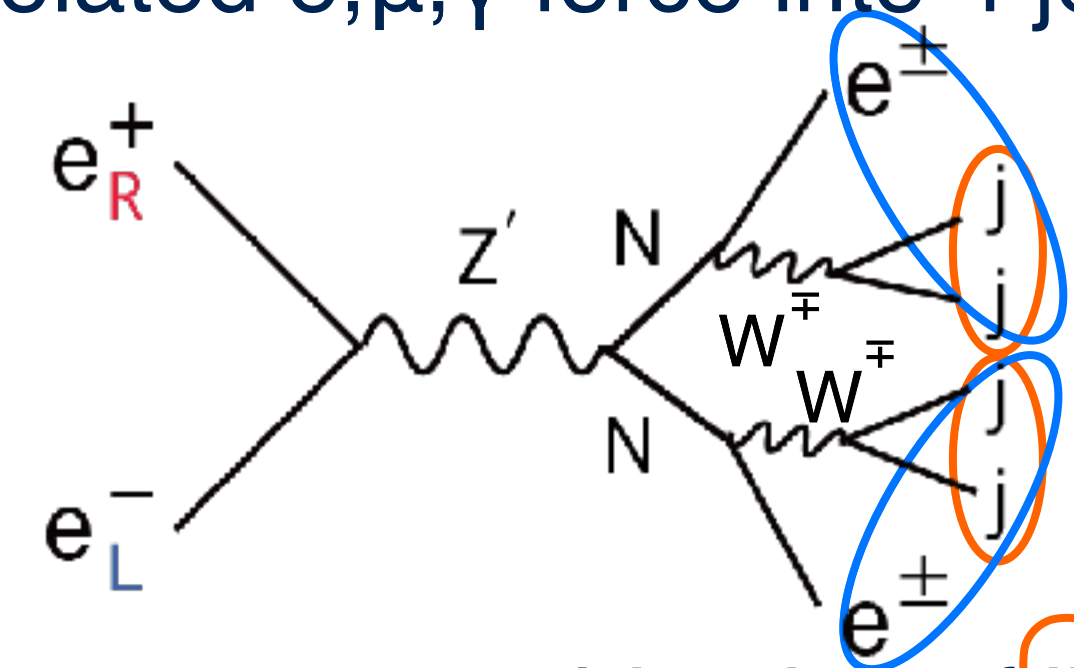
	Signal Entries		Background Entries					
	M_N=100	M_N=200	eeqqqq	4f_singleW _semileptonic	4f_singleZee _semileptonic	6f_ttbar 2electrons	6f_ttbar 1electron	6f_ttbar 0electron
No cut	1109	286	2.37E+04	5.65E+06	1.39E+06	3.28E+04	2.58E+05	2.20E+04
e_{iso} #=2 && e_γ #=0 && e_μ #=0	694	158	9.44E+03	1.81E+05	3.25E+05	1.88E+04	4.54E+03	402
Same sign ($e_{iso1} \times e_{iso2} = 1$)	352	79	78	9.22E+04	7.60E+03	16	879	51
$E_{iso} < 200$ [GeV]	351	79	78	8.26E+04	7.11E+03	16	879	51
$-0.95 < \cos\theta_{isoe} < 0.95$	312	72	26	3.50E+04	1.24E+03	8	532	31
$IsolatedLepTagging_{min} > 0.9$	189	63	4.5	5.26E+03	257	2	101	0.19
$\log_{10}(y12) > -1$	186	63	4.5	2.63E+03	256	2	101	0.19
$P_{total} < 100$ && ($P_{total} < 40$ || $\|\cos\theta_{total}\| > 0.95$)	169	57	2	158	61	0	19	0

Cut flow (eRpL)

	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	1116	287	7.851E+03	5.17E+05	1.22E+06	1.42E+04	1.12E+05	9.78E+04
e_{iso} #=2 && e_γ #=0 && e_μ #=0	692	162	2.46E+03	1.44E+04	2.80E+05	7.82E+03	1.74E+03	188
Same sign ($e_{iso1} \times e_{iso2} = 1$)	343	82	29	7.48E+03	6.58E+03	5	354	38
$E_{iso} < 200$ [GeV]	342	82	29	6.77E+03	6.16E+03	5	354	38
$-0.95 < \cos\theta_{isoe} < 0.95$	316	74	7	2.68E+04	951	2	227	25
$\text{IsolatedLepTagging}_{min} > 0.9$	192	65	1	397	202	0.68	30	3
$\log_{10}(y12) > -1$	173	60	1	15	94	0	5	9
$P_{total} < 100$ && ($P_{total} < 40$ || $\|\cos\theta_{total}\| > 0.95$)	173	60	1	14	30	0	5	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}

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

Best jet pair 1 + iso e→M_{jje1}

Best jet pair 2 + iso e→M_{jje2}

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

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

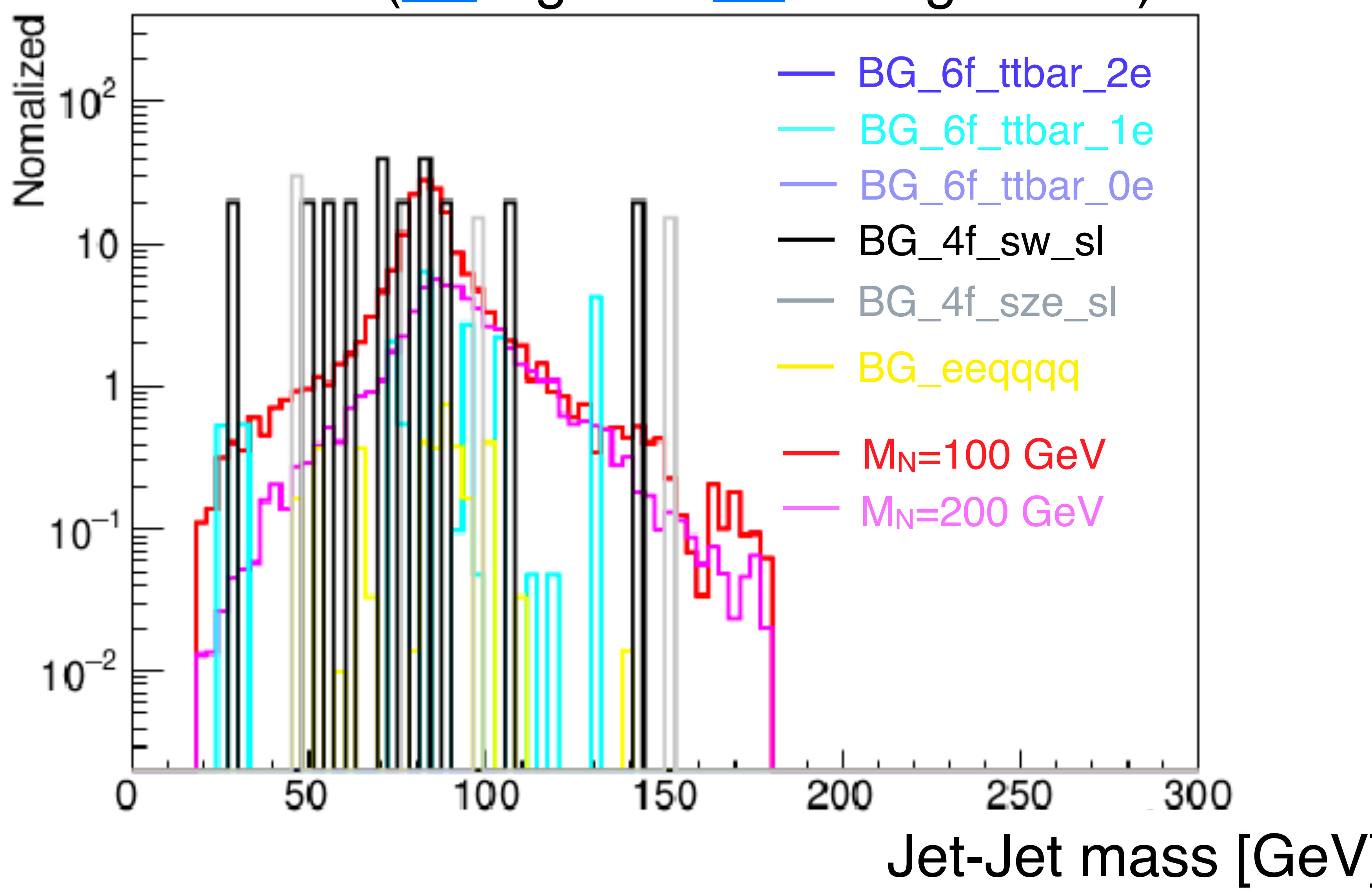
Choose combination with minimum F

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]
- $-0.95 < \cos\theta_{isoe} < 0.95$
- $\text{IsolatedLepTagging}_{min} > 0.9$
- $P_{total} < 100$ &&($P_{total} < 40$ || $|\cos\theta_{total}| > 0.95$)
- $\log_{10}(y12) > -1$

W mass (full signal + full backgrounds)

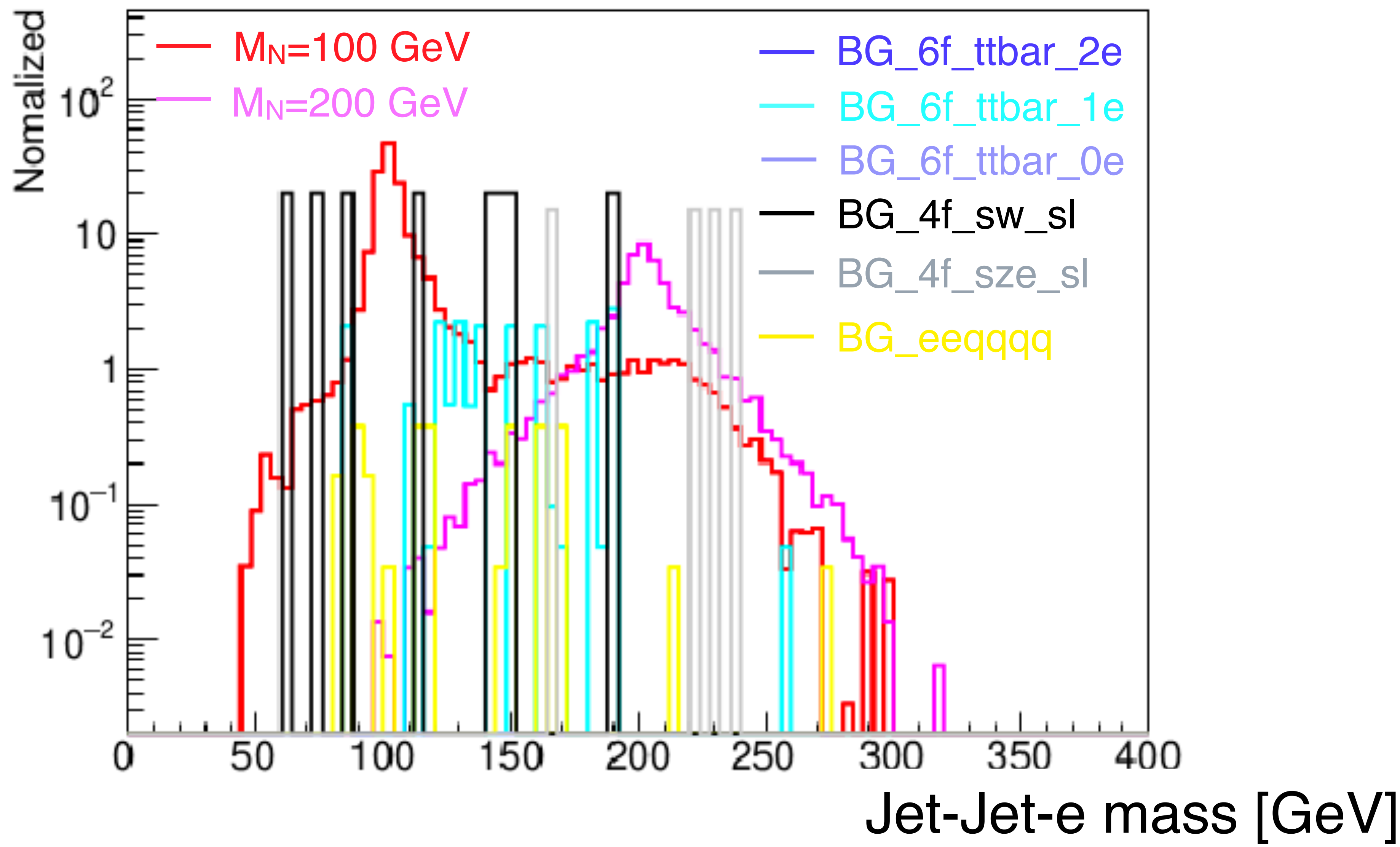


Reconstructed RHN mass

- 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]
- $-0.95 < \cos\theta_{isoe} < 0.95$
- $\text{IsolatedLepTagging}_{min} > 0.9$
- $\log_{10}(y12) > -1$
- $P_{total} < 100$ &&($P_{total} < 40$ || $|\cos\theta_{total}| > 0.95$)

RHN mass (full signal + full backgrounds)



Summary

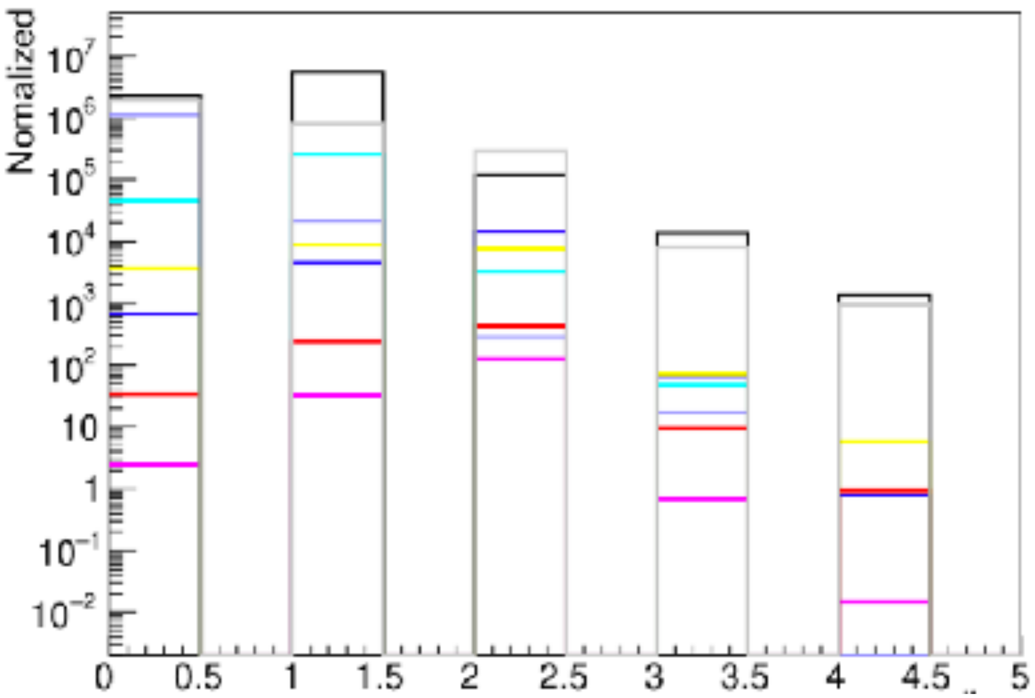
- We analyze “RHN **pair** production” by full simulation

- 4f_sw_sl and 4f_sze_sl are dominant backgrounds.
  -> we need to consider additional cut condition

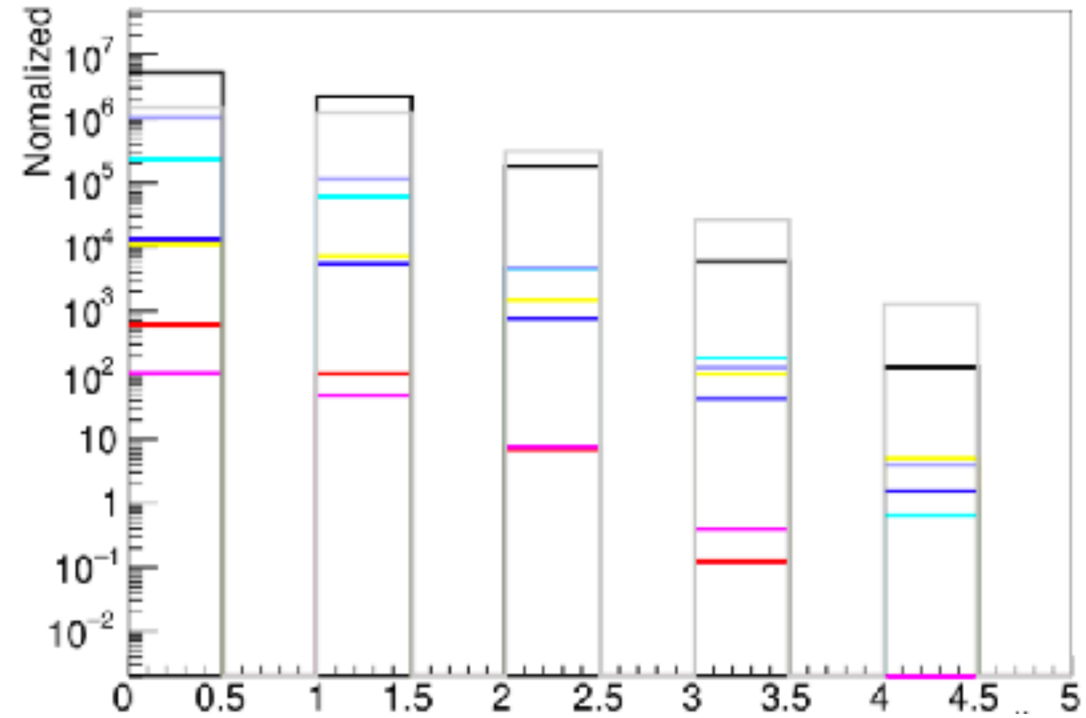
Backup

Isolated e,γ,μ

Number of isolated e

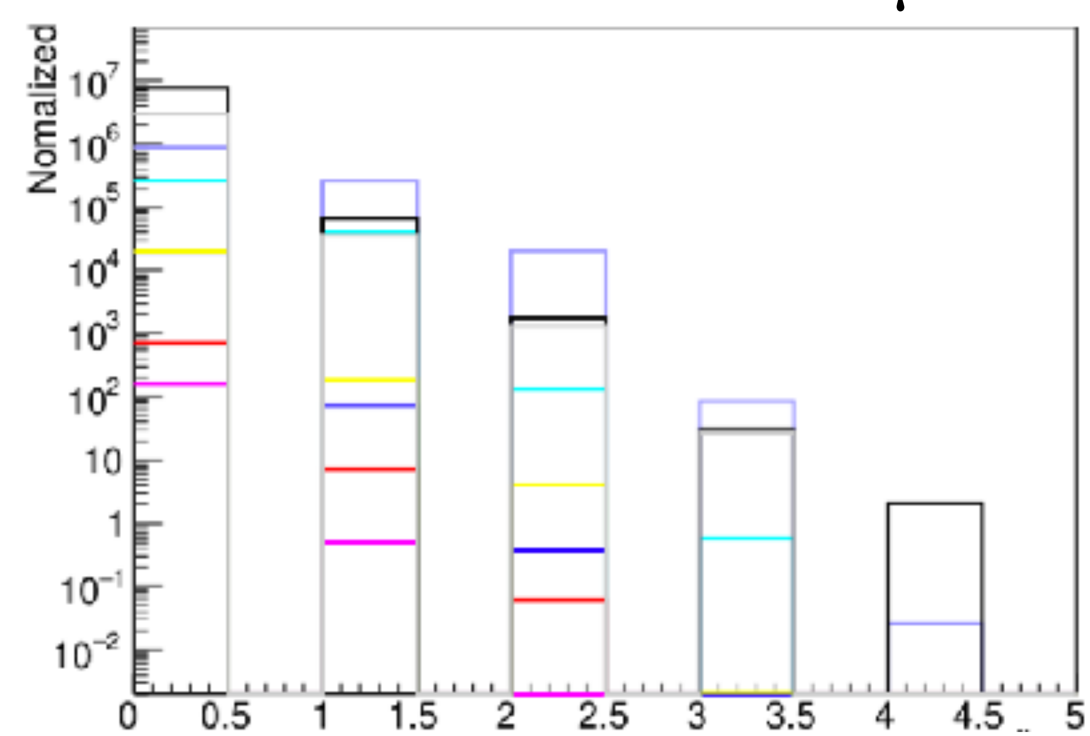


Number of isolated γ



— 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

Number of isolated μ

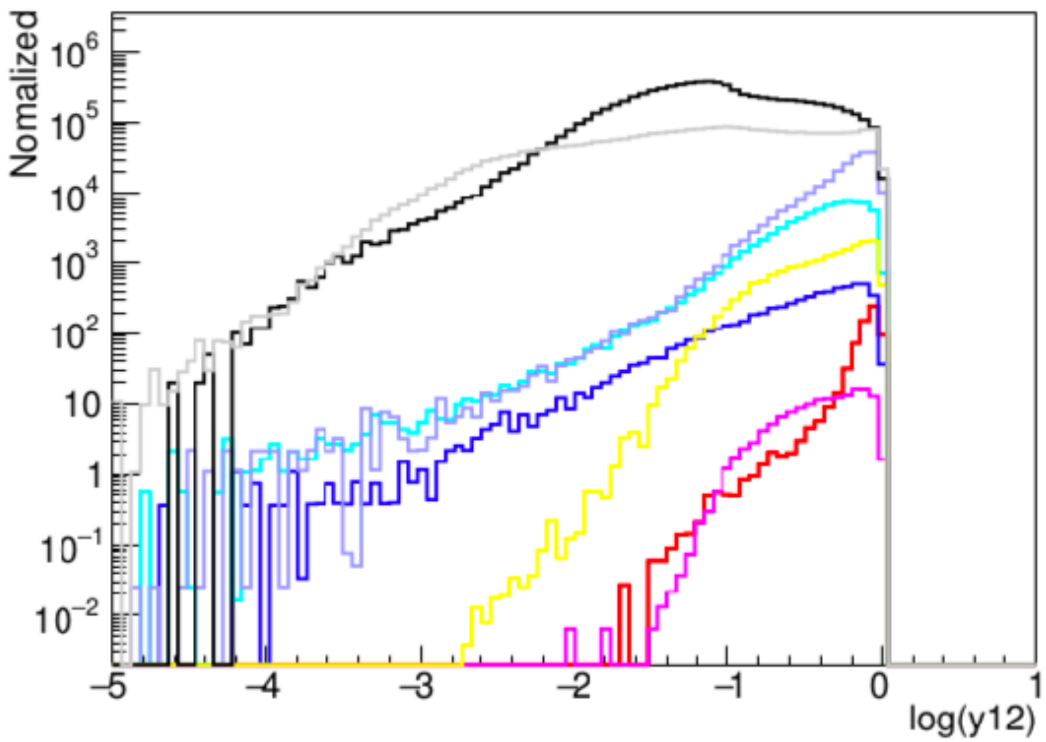


- Isolated e # = 2 && Isolated γ, **μ = 0**

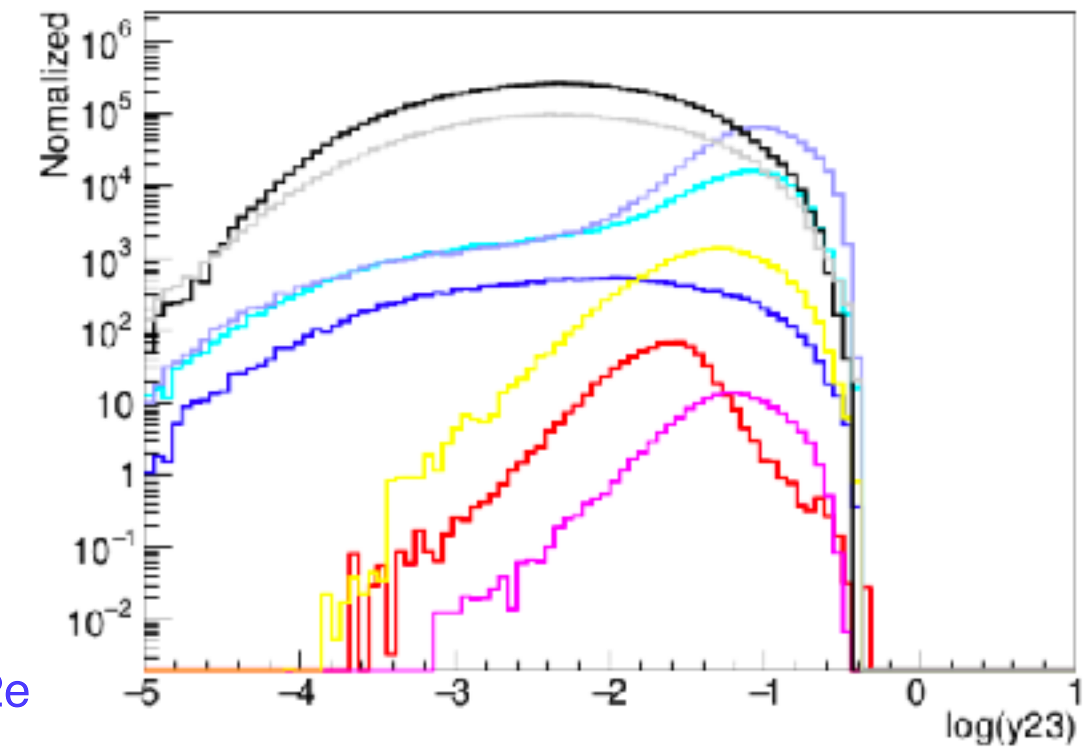
Distribution of y12,y23, y34, y45 (Durham)

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

y12 (full signal + full backgrounds)

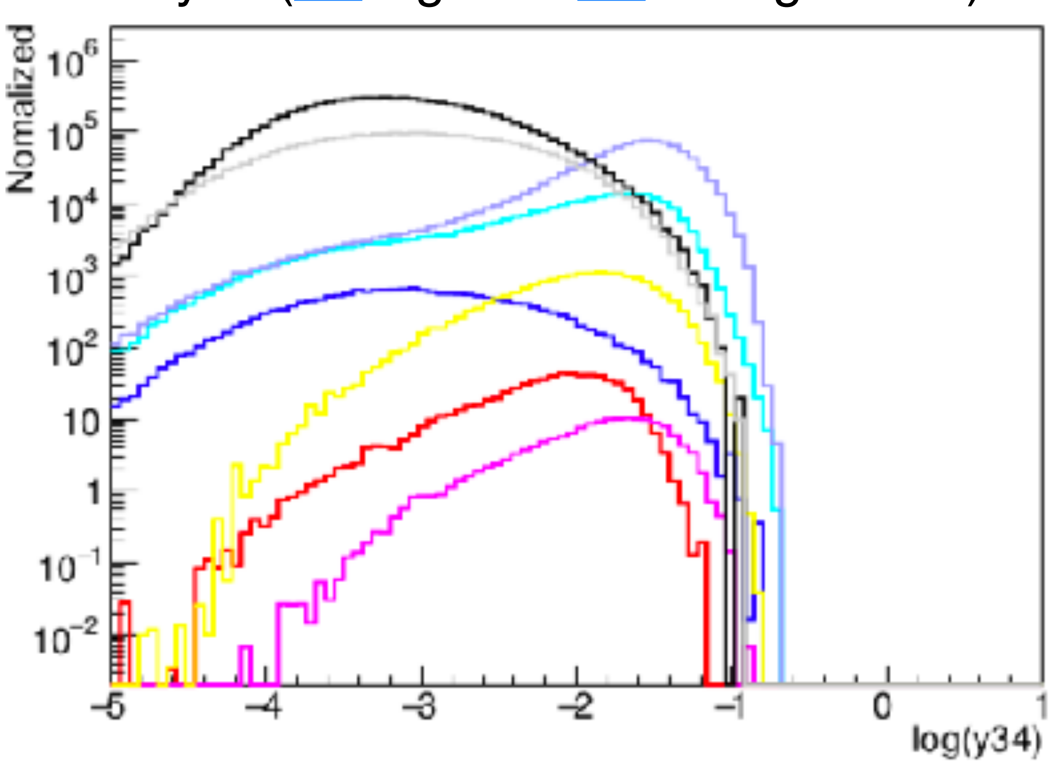


y23 (full signal + full backgrounds)

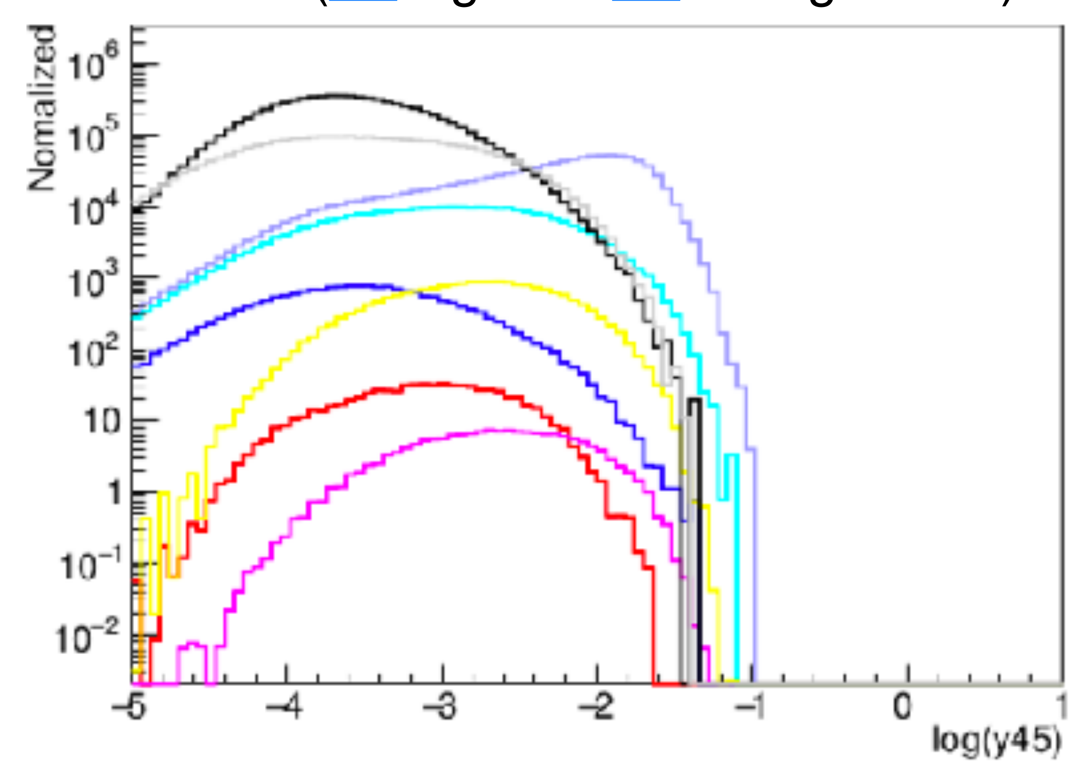


- M_N=100 GeV
- M_N=200 GeV
- BG_6f_ttbar_2e
- BG_6f_ttbar_1e
- BG_6f_ttbar_0e
- BG_4f_sw_sl
- BG_4f_sze_sl
- BG_eeqqqq

y34 (full signal + full backgrounds)



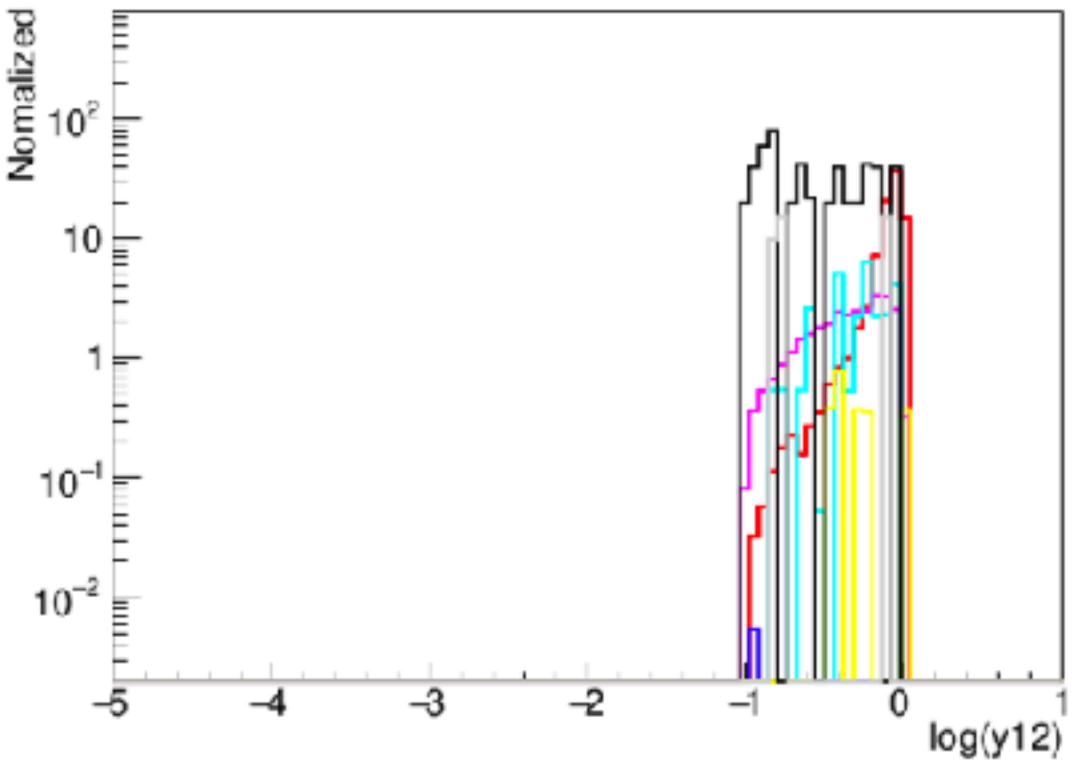
Y45 (full signal + full backgrounds)



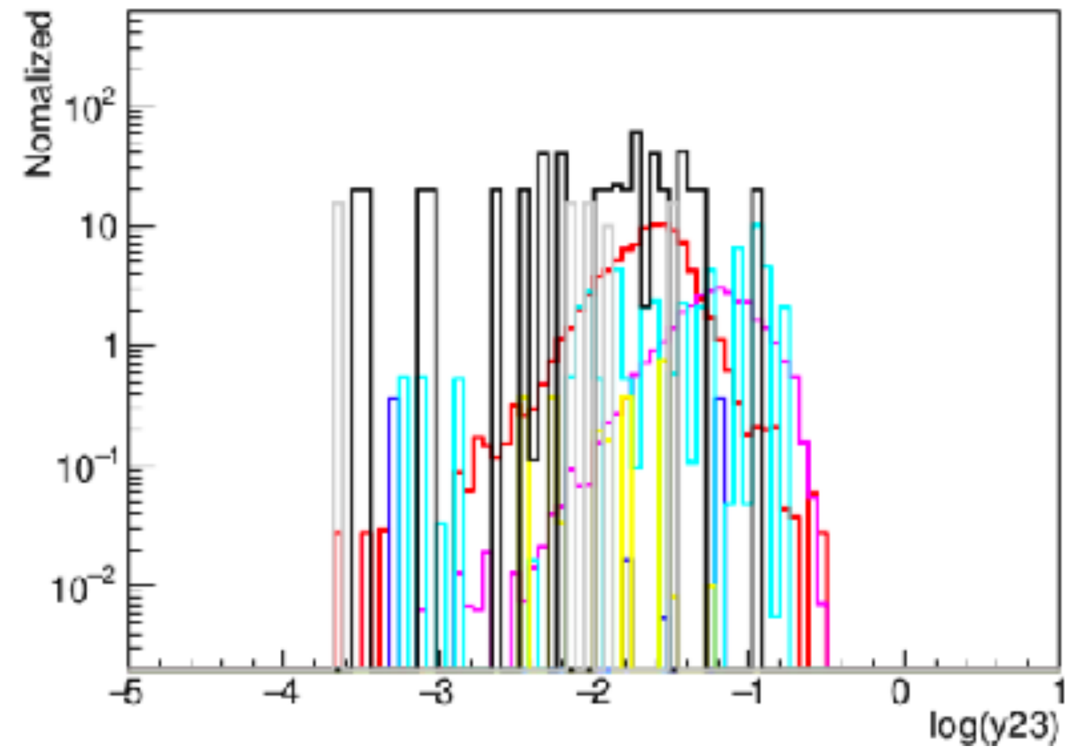
Distribution of y12,y23, y34, y45 (Durham) after y12 cut

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

y12 (full signal + full backgrounds)

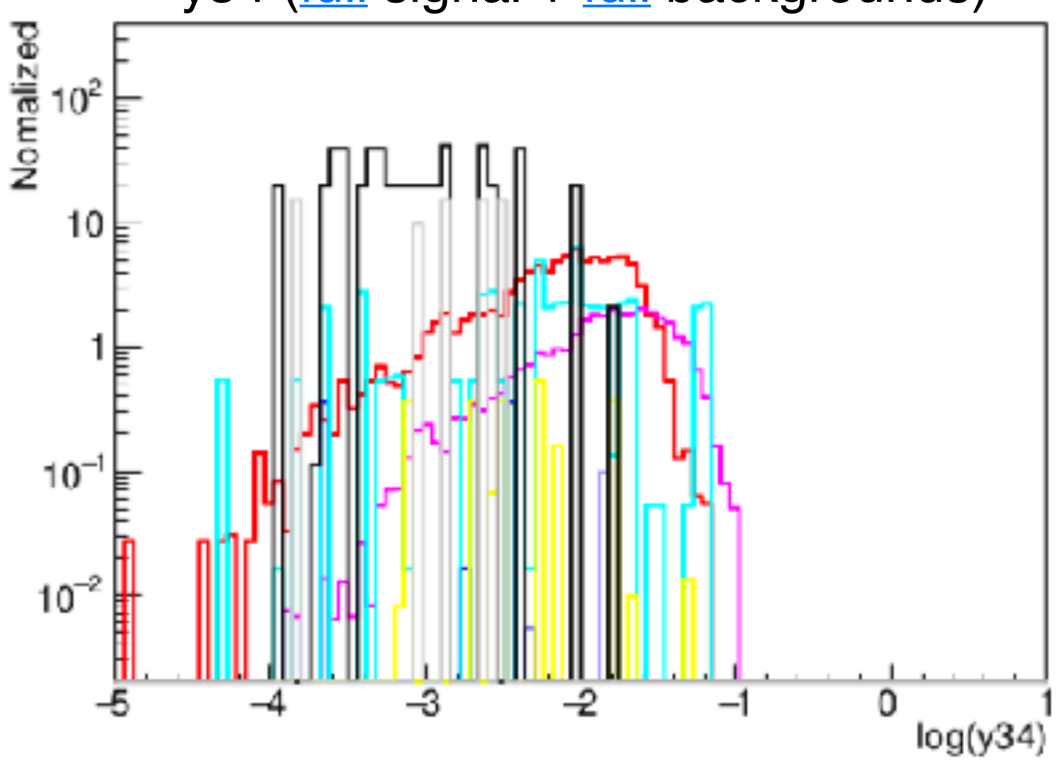


y23 (full signal + full backgrounds)

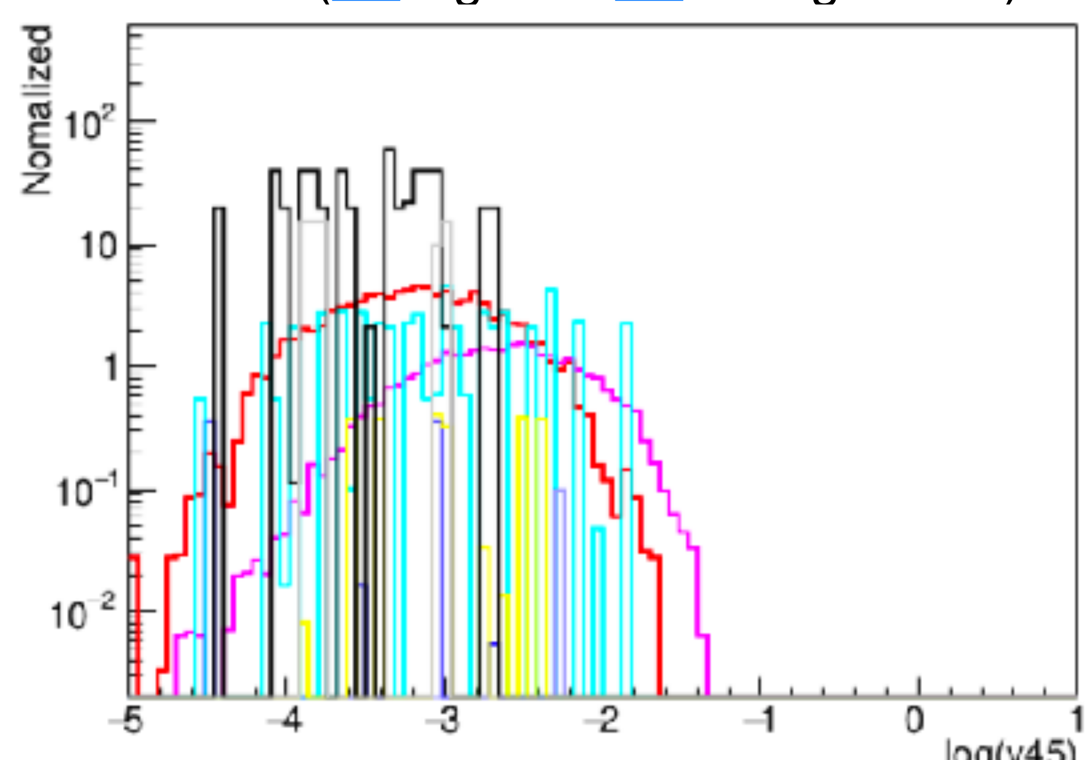


- M_N=100 GeV
- M_N=200 GeV
- BG_6f_ttbar_2e
- BG_6f_ttbar_1e
- BG_6f_ttbar_0e
- BG_4f_sw_sl
- BG_4f_sze_sl
- BG_eeqqqq

y34 (full signal + full backgrounds)



Y45 (full signal + full backgrounds)

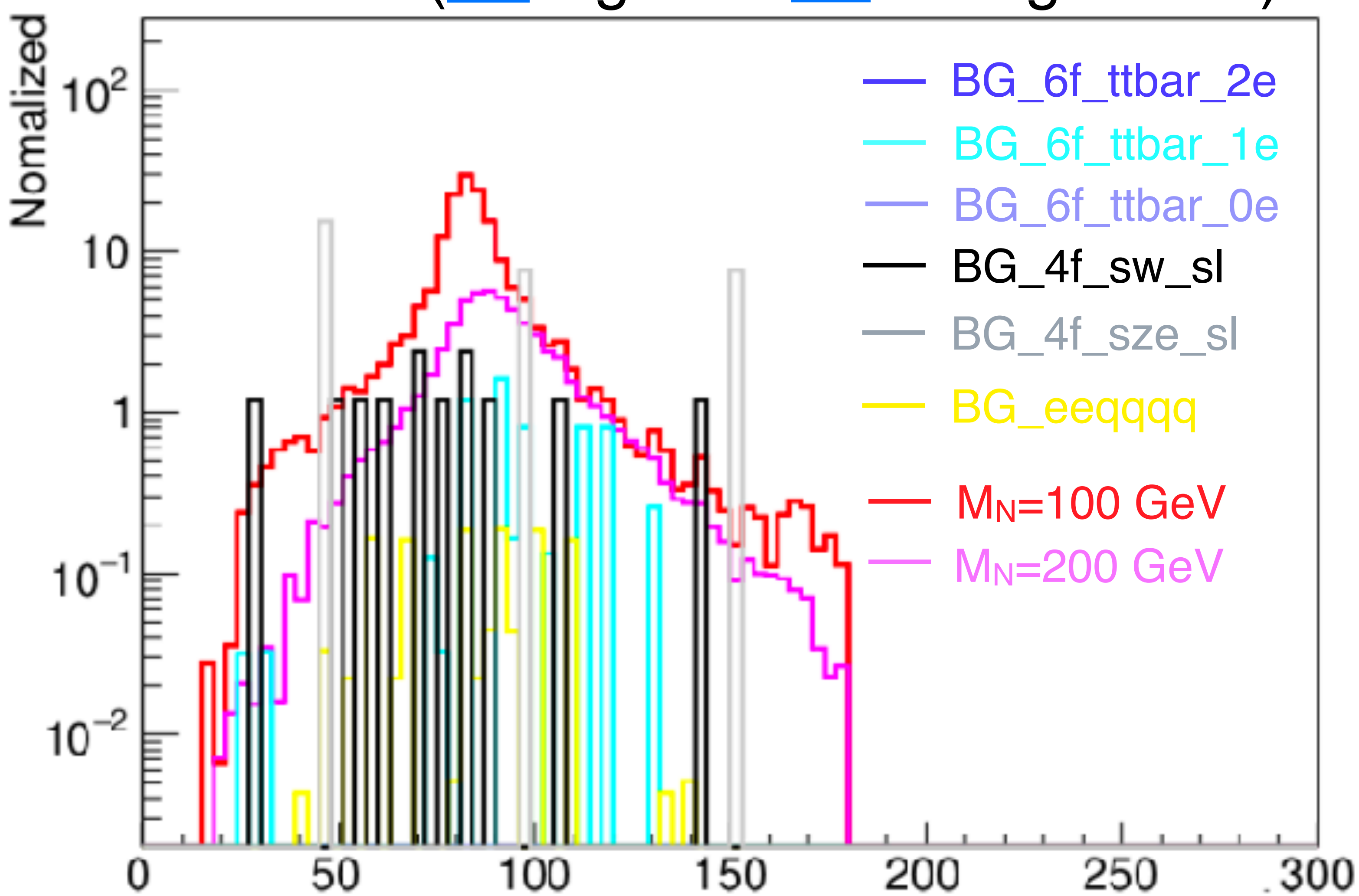


Reconstructed W mass

- 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_{total} < 100 &&(P_{total} < 40 || $|\cos\theta_{total}|$ > 0.95)
- $\log_{10}$(y12) > -1

W mass (full signal + full backgrounds)



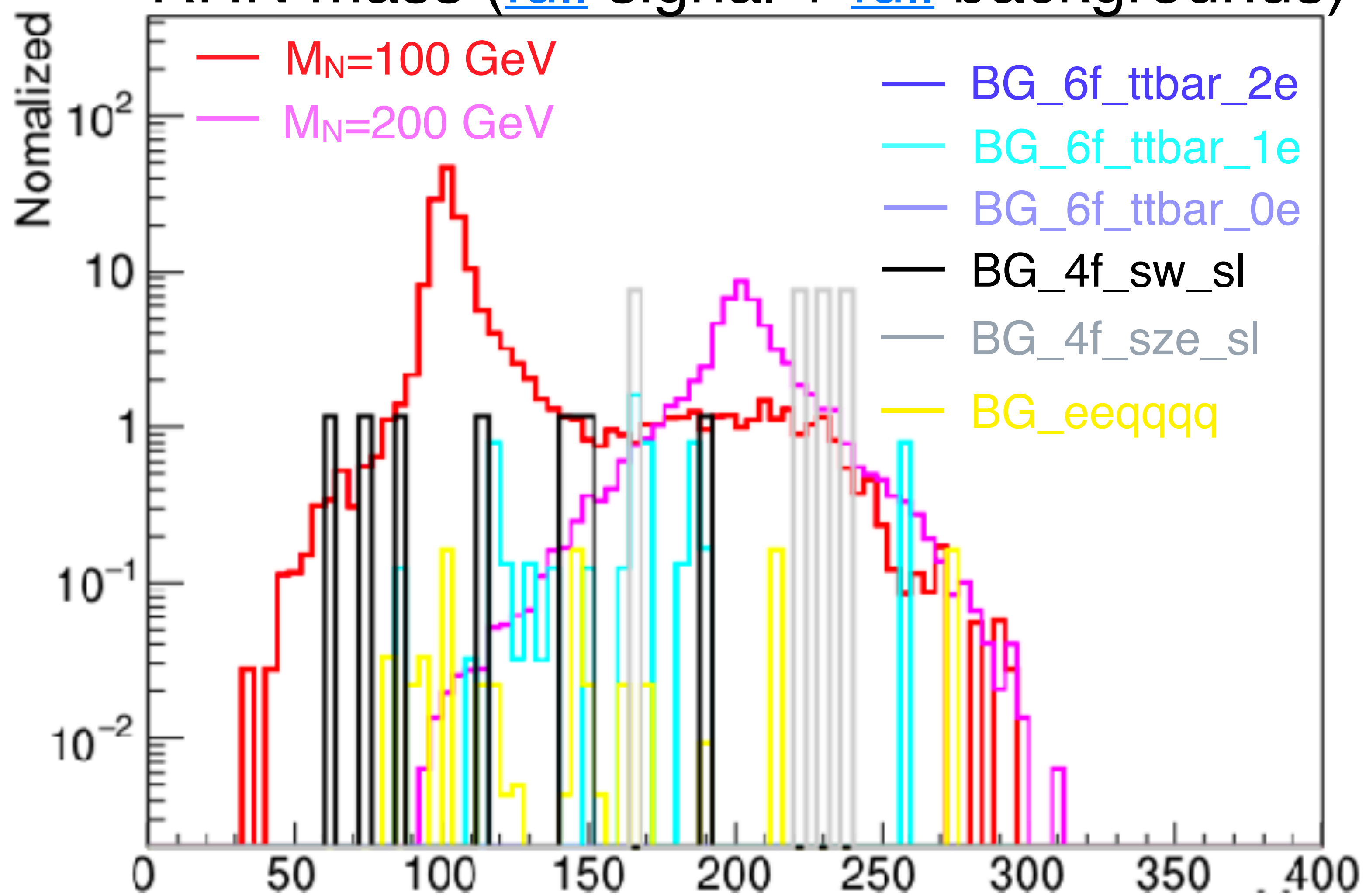
Jet-Jet mass [GeV]

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_{total} < 100 &&(P_{total} < 40 || $|\cos\theta_{total}|$ > 0.95)
- $\log_{10}(y12)$ > -1

RHN mass (full signal + full backgrounds)



Jet-Jet-e mass [GeV]

Cross section — BG

(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

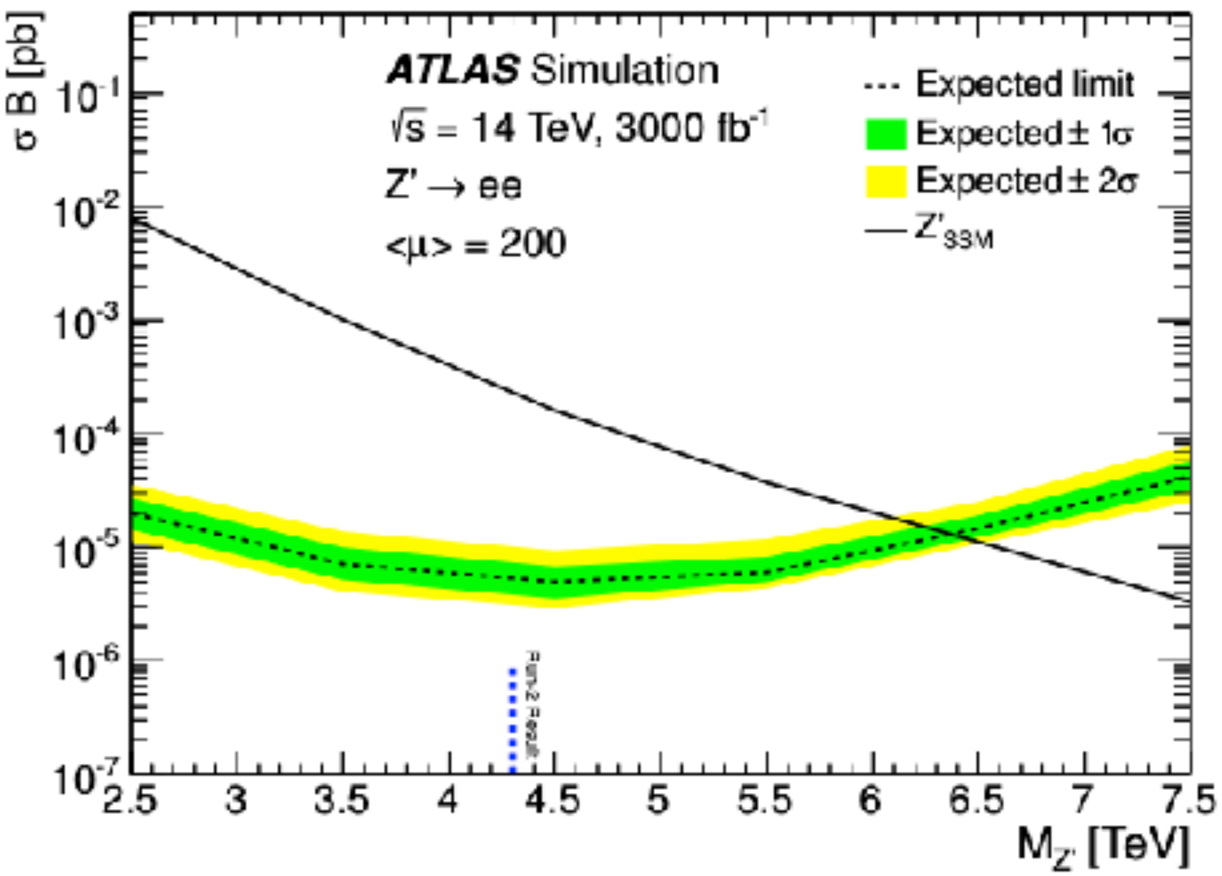
(100%, 100%)	6f_ttbar											
	yyveev	yyvelv	yyvlev	yyveyx	yyxyev	yyvllv	yyvlyx	yyxylv	yyuyyu	yyuyyc	yycyyu	yycyyc
eLpR	2.01E+01	3.96E+01	3.96E+01	1.17E+02	1.17E+02	7.87E+01	2.32E+02	2.31E+02	1.67E+02	1.64E+02	1.65E+02	1.63E+02
eRpL	7.56E+00	1.50E+01	1.50E+01	4.45E+01	4.45E+01	3.01E+01	8.91E+01	8.89E+01	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							

Cut flow (eLpR)

	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#	24000	24000	61112	368881	132424	52139	239403	326573

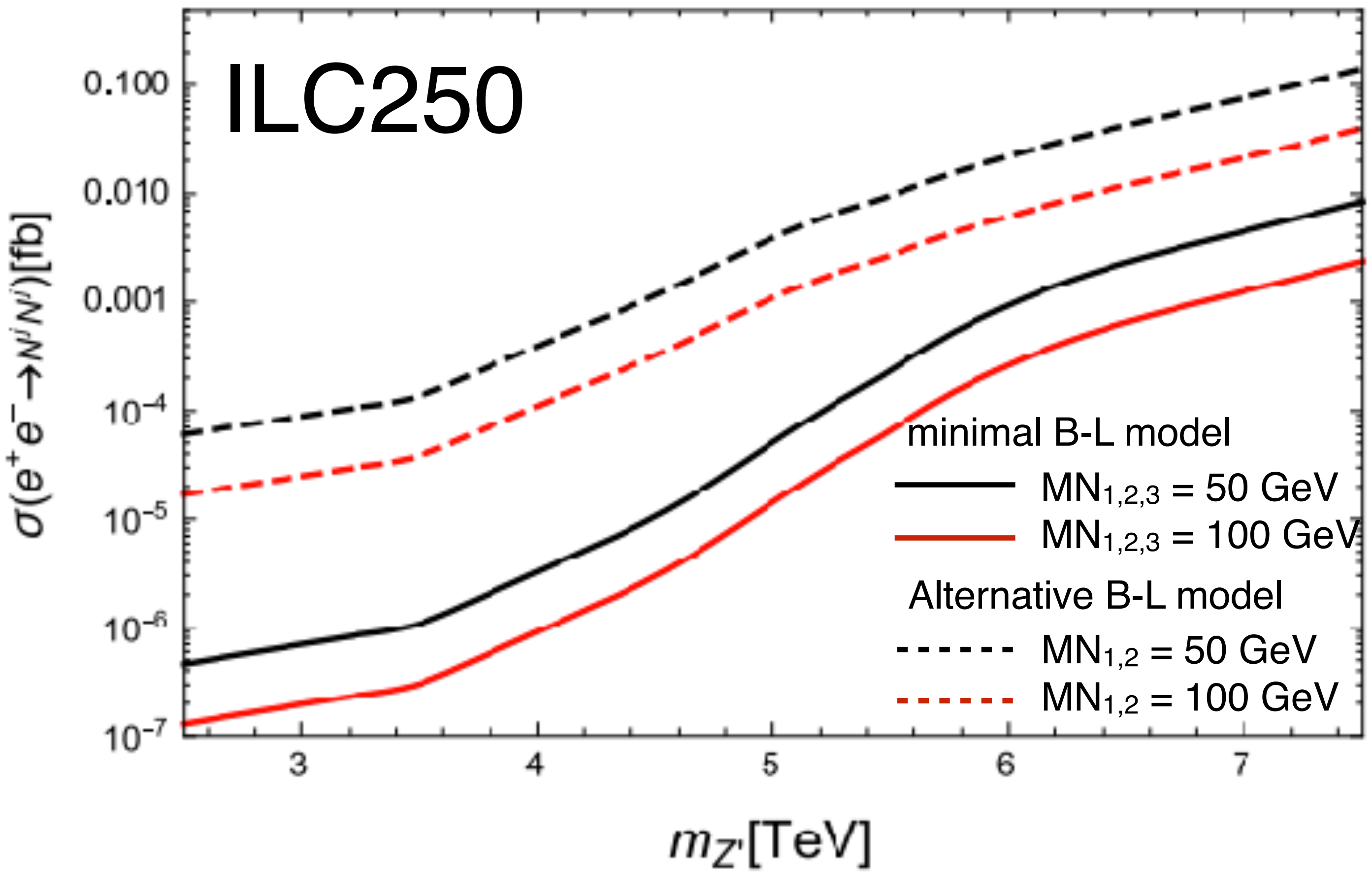
Current limits - Z’ mass

SM like Z’ coupling



ATLAS-TDR-LHCC2017-2018

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

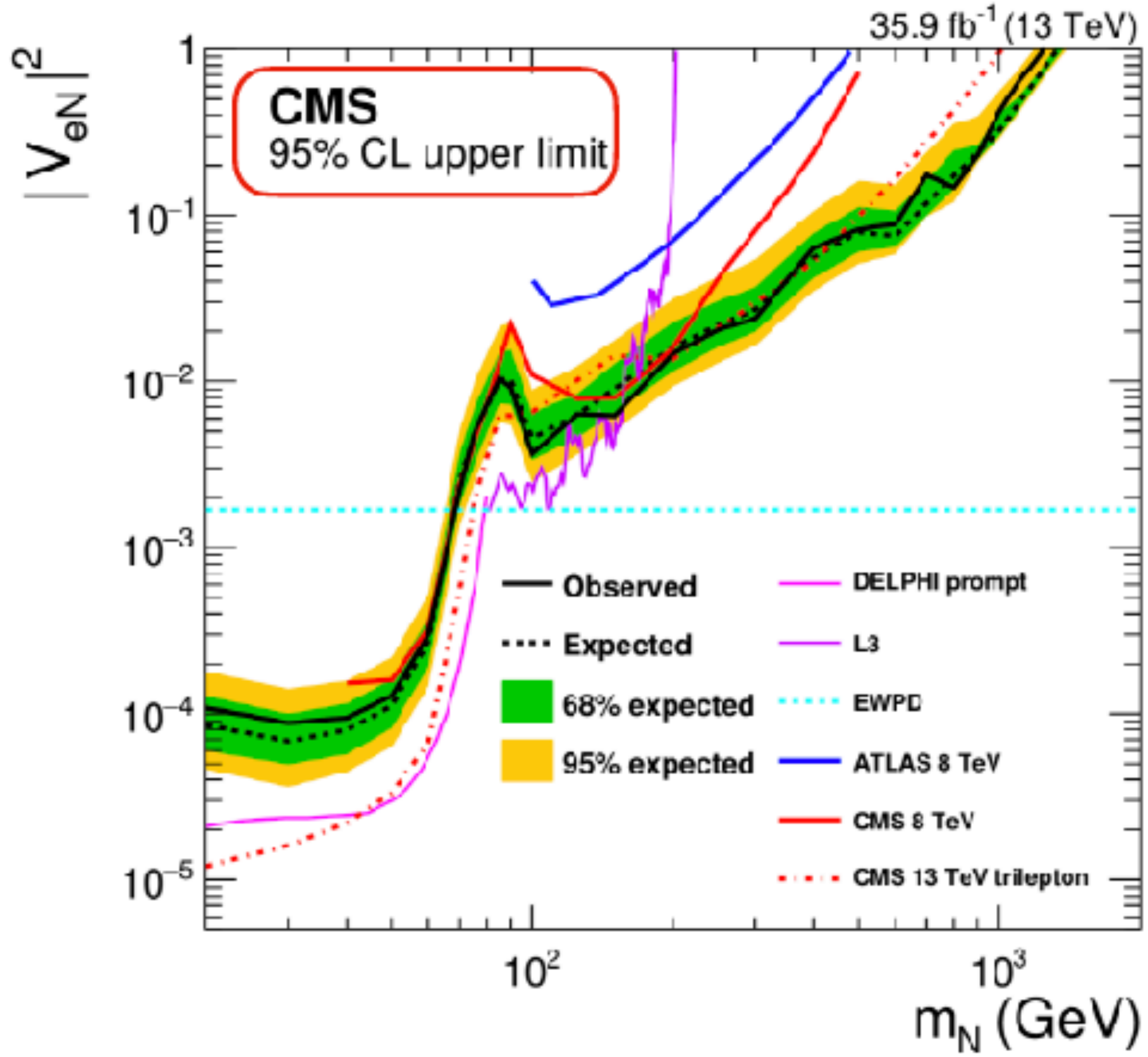


arXiV[1812.11931]

The heavier Z’ mass less constrained by LHC

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

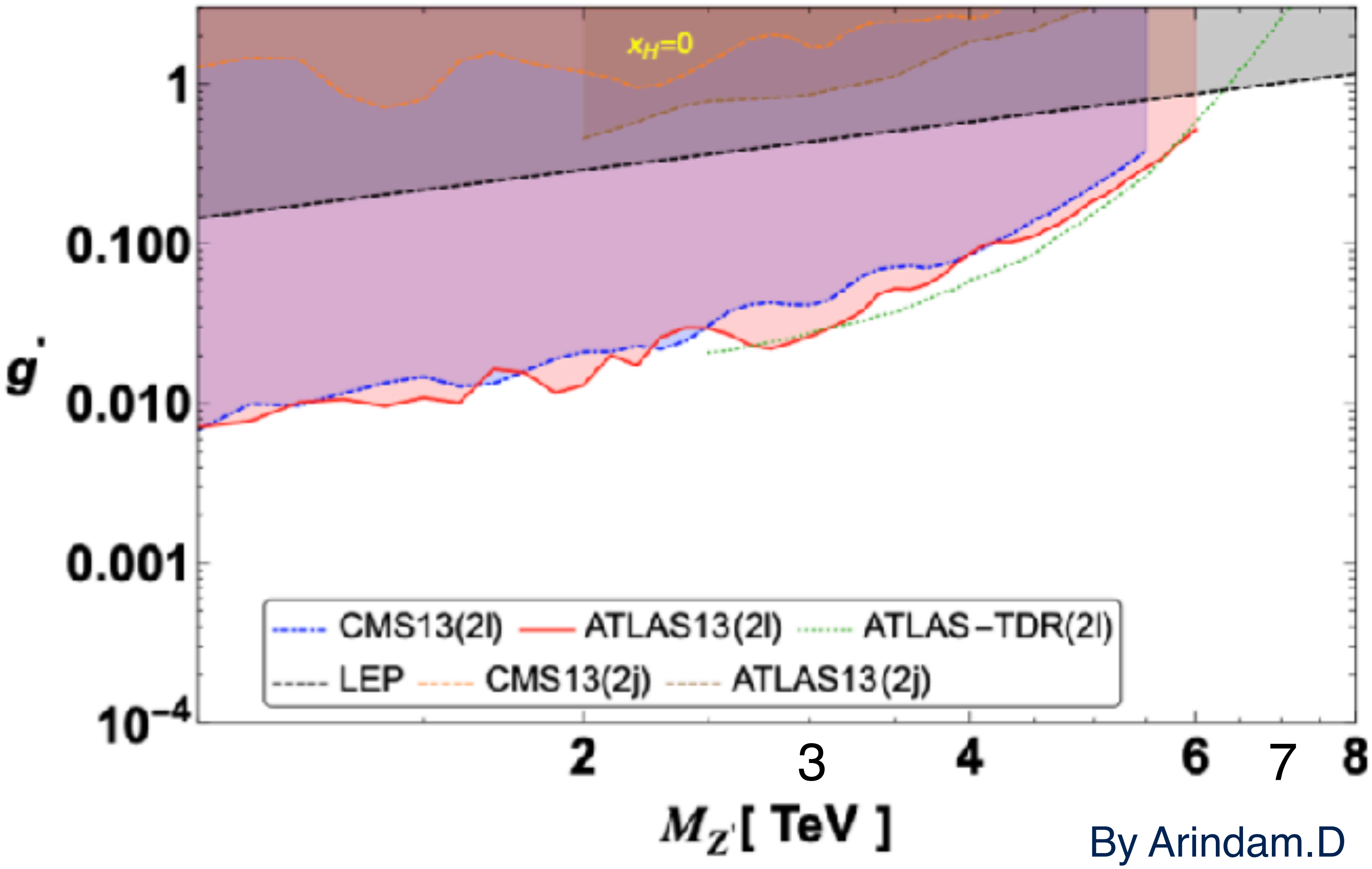
$|V_{eN}|^2$: the “light-heavy” neutrino mixing matrix



CMS PAS EXO-19-019

Current Limits and prospects - Z’ mass,g1’

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



By Arindam.D

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