

# Searching for Right Handed Neutrinos using same sign leptons at ILC

*Work in progress*

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# Motivation and Introduction

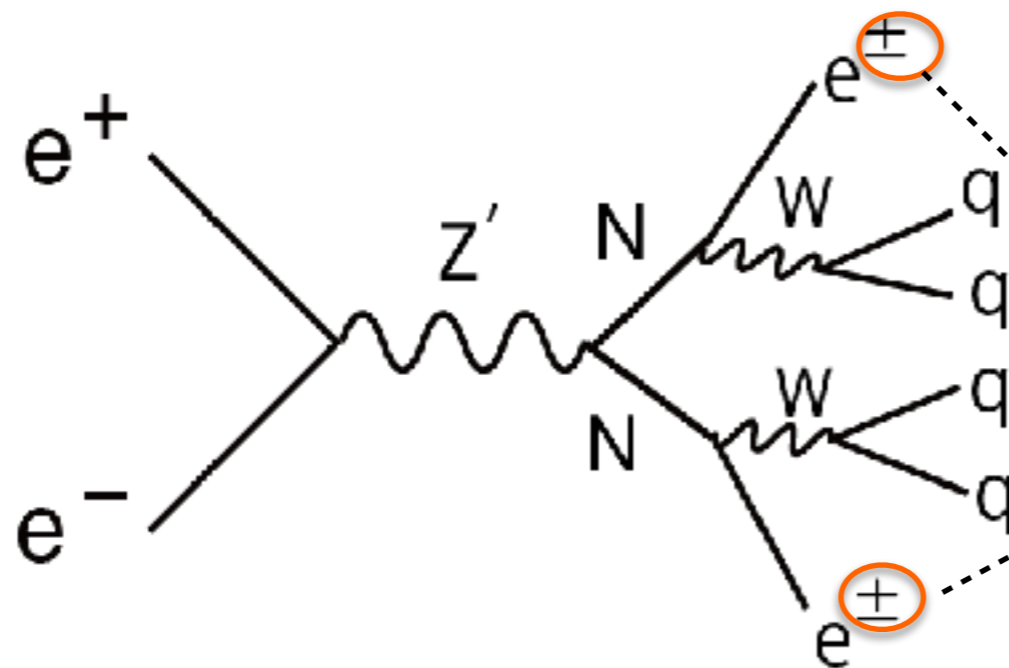
The right handed neutrino (RHN) can address the following big questions

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

## Gauged B-L extension of Standard Model (SM)

The unique anomaly free global symmetry in the SM

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

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

Gauge boson :  $Z'$

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

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

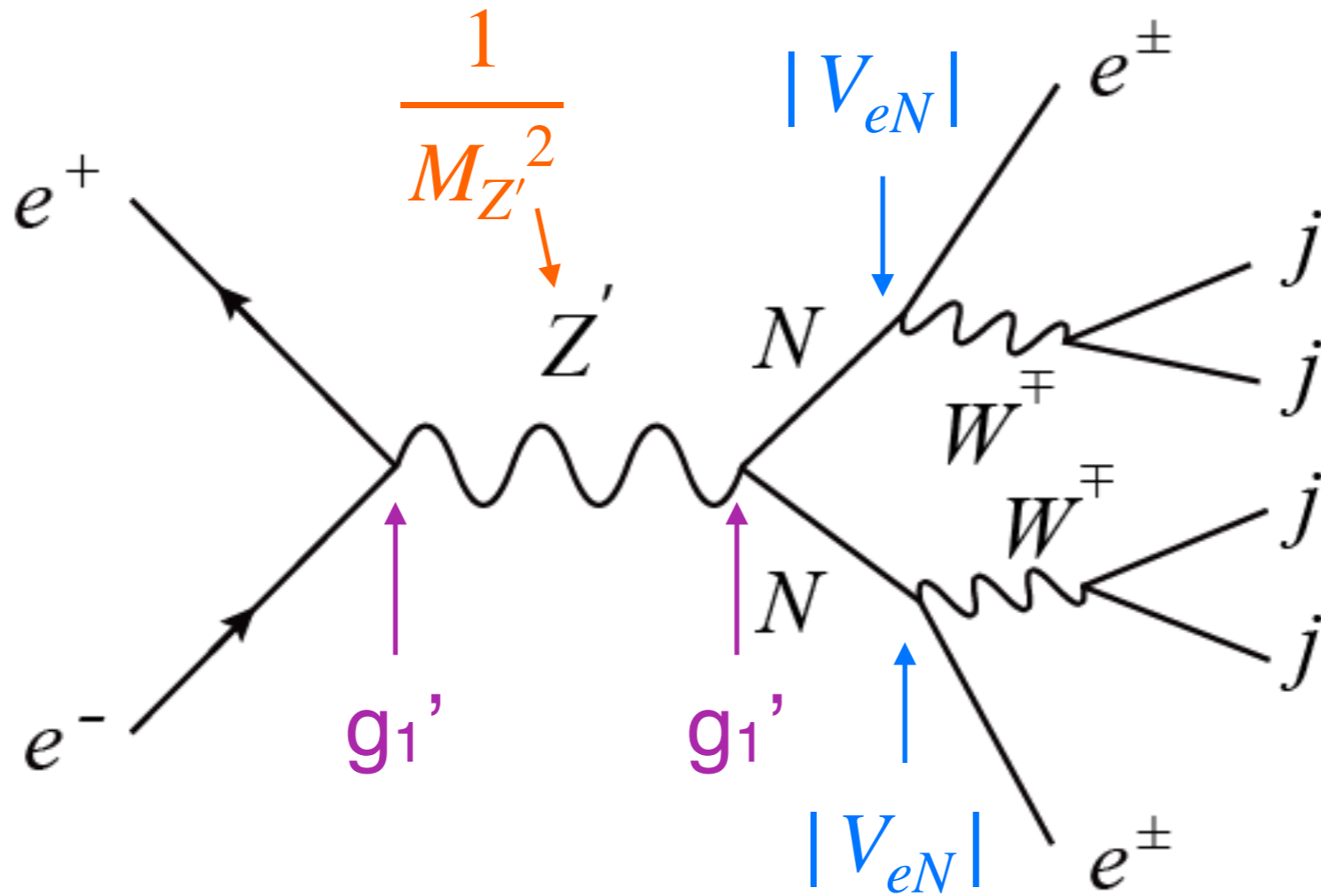
		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
RHN	$N_R^i$	1	1	0	-1
New Higgs field	$\Phi$	1	1	0	2

$i=1,2,3$

[arXiv\[1812.11931\]](https://arxiv.org/abs/1812.11931)

Arindam Das, Nobuchika Okada, Satomi Okada, Digesh Raut

# Model parameters



$$\sigma \propto \alpha \equiv \left| g_1'^4 \frac{1}{M_{Z'}^4} |V_{eN}|^4 \right| [\text{TeV}^{-4}]$$

# Benchmark points

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

$M_N$ [GeV] RHN mass	$M_{Z'}$ [TeV] Z' mass	$g_1'$ U(1) <sub>B-L</sub> coupling constant	$ V_{eN} ^2$ mixing angle	$\sigma(e_L^- e_R^+ \rightarrow NN)$ [fb]	Event # at ILC500 [4000fb <sup>-1</sup> ]
100	7	1	0.001	0.71	<b>1261</b>
150	7	1	0.001	0.45	<b>229</b>
200	7	1	0.001	0.16	<b>131</b>
225	7	1	0.001	0.052	<b>18</b>

► minimal U(1)<sub>B-L</sub> model

$$\blacklozenge \sigma_{LR} = \sigma_{RL}$$

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

# Analysis tool for signal samples

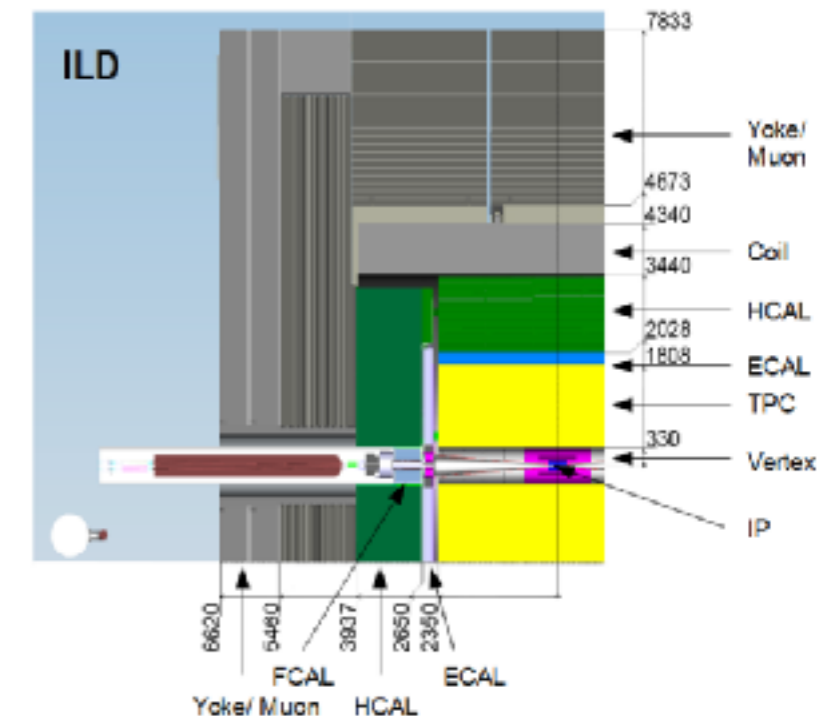
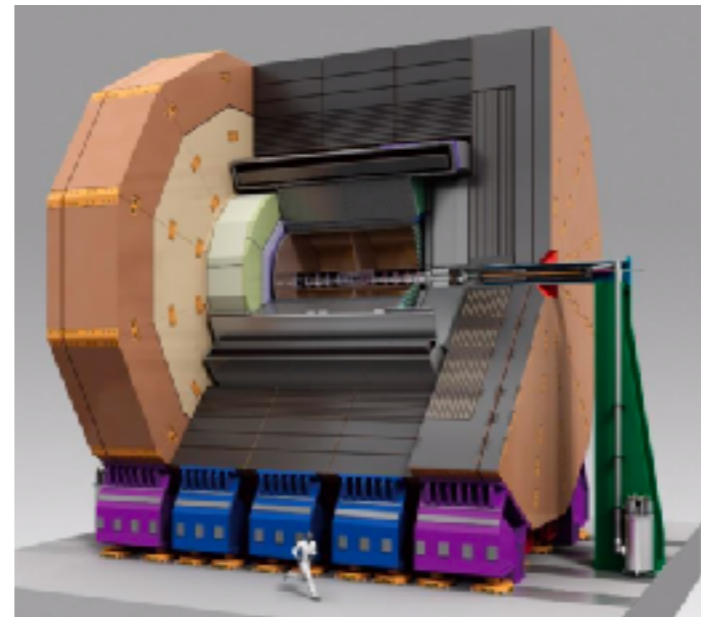
**WHIZARD** ver 2.8.5  
Make Events

**ILD Full Simulation  
&  
Reconstruction**

**miniDST**  
Events format

## Full simulation

Full geant4 simulation of ILD  
Realistic reconstruction



**We prepared full simulation signal samples.**

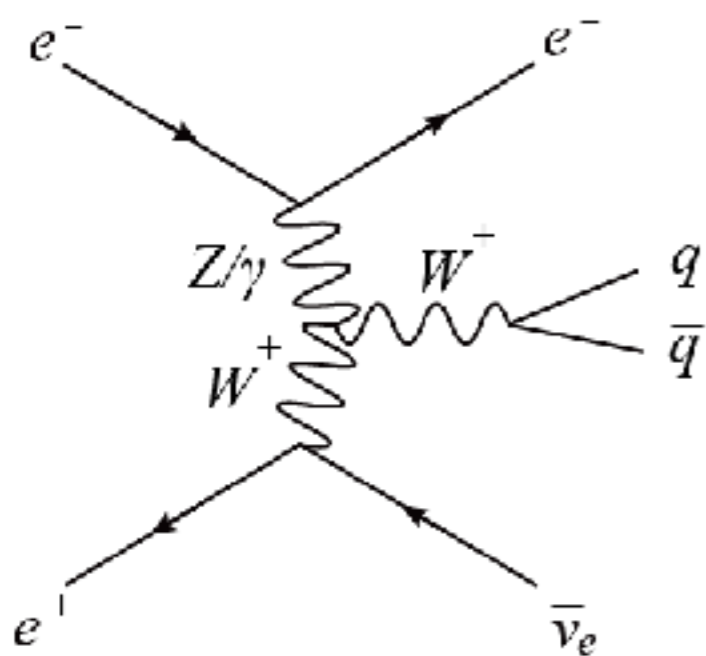
# Background samples

We consider 6f and 4f background samples

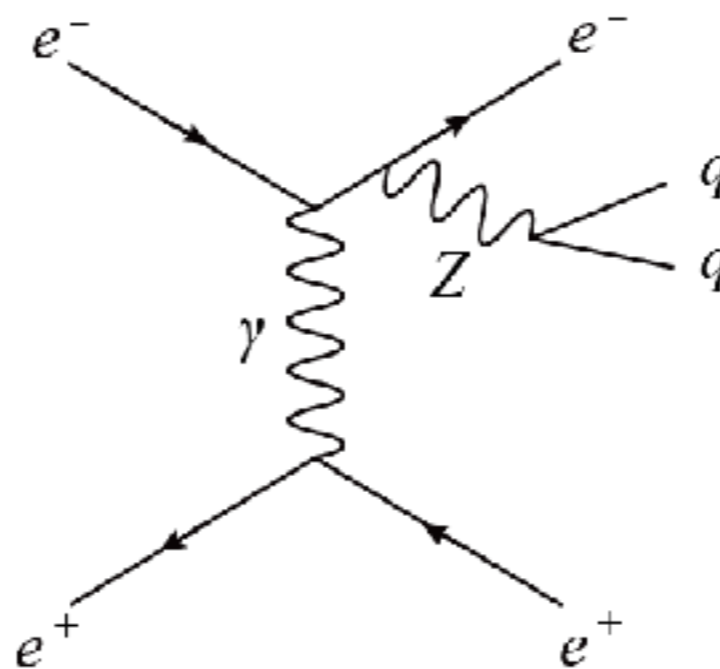
- eeqqqq
- 6f\_ttbar
- 4f\_singleW\_semileptonic
- 4f\_singleZee\_semileptonic

IDR samples  
ILC500  
miniDST

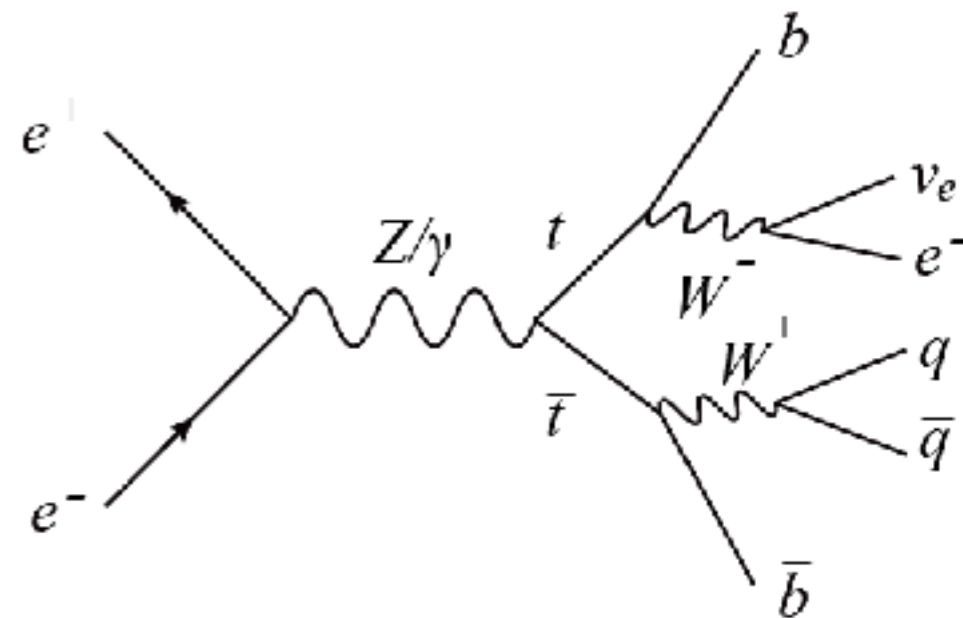
4 fermions singleW  
semileptonic



4 fermions singleZee  
semileptonic



6 fermions ttbar  
1electron



# Cut Conditions to select signal events

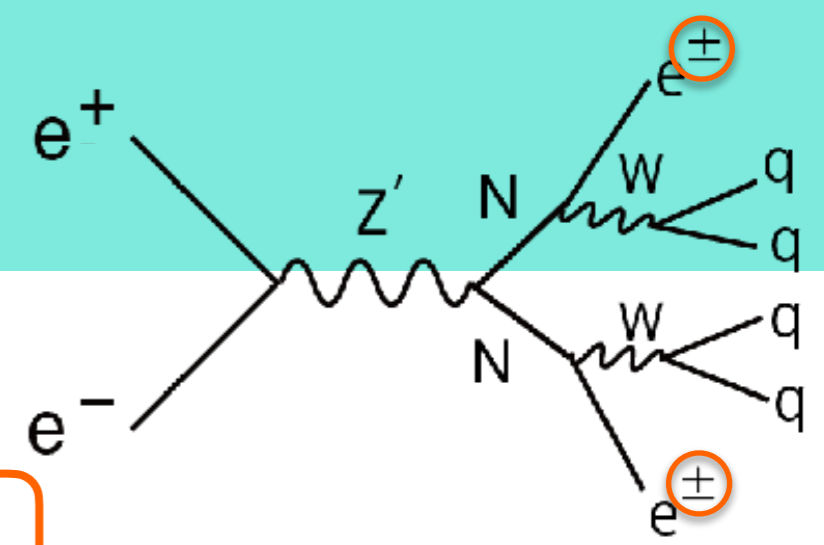
- Isolated  $e \# = 2$  && Isolated  $\gamma, \mu \# = 0$
- Same sign isolated electrons
- Isolated electron energies  $E_{\text{iso}} < 200$  [GeV]
- Isolated electron angles  $|\cos\theta_{\text{isoel}}| < 0.95$
- IsolatedLepTagging(min) > 0.9
- Jet clustering with Durham  $\log_{10}(y_{12}) > -1$
- $P_{\text{miss}} < 100$  [GeV] && (  $P_{\text{miss}} < 40$  [GeV] ||  $|\cos\theta_{P_{\text{miss}}}| > 0.95$  )

**I focus on three cut conditions.**

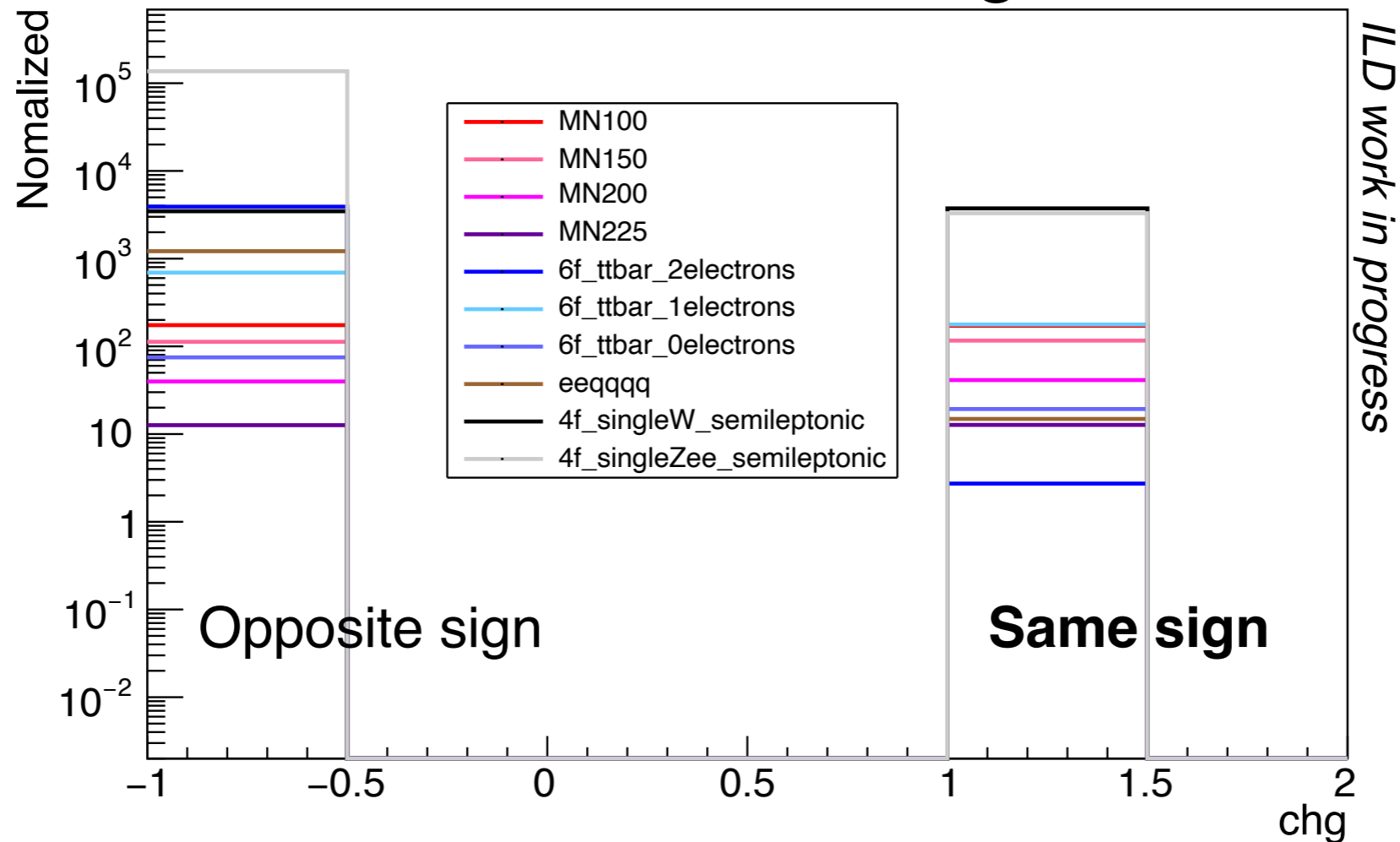


# Electron Charge

- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (+0.8, -0.3)$
- Isolated  $e^- \# = 2$  && Isolated  $\gamma \# = 0$  && Isolated  $\mu \# = 0$



## Isolated electrons charge $e_1 \times e_2$

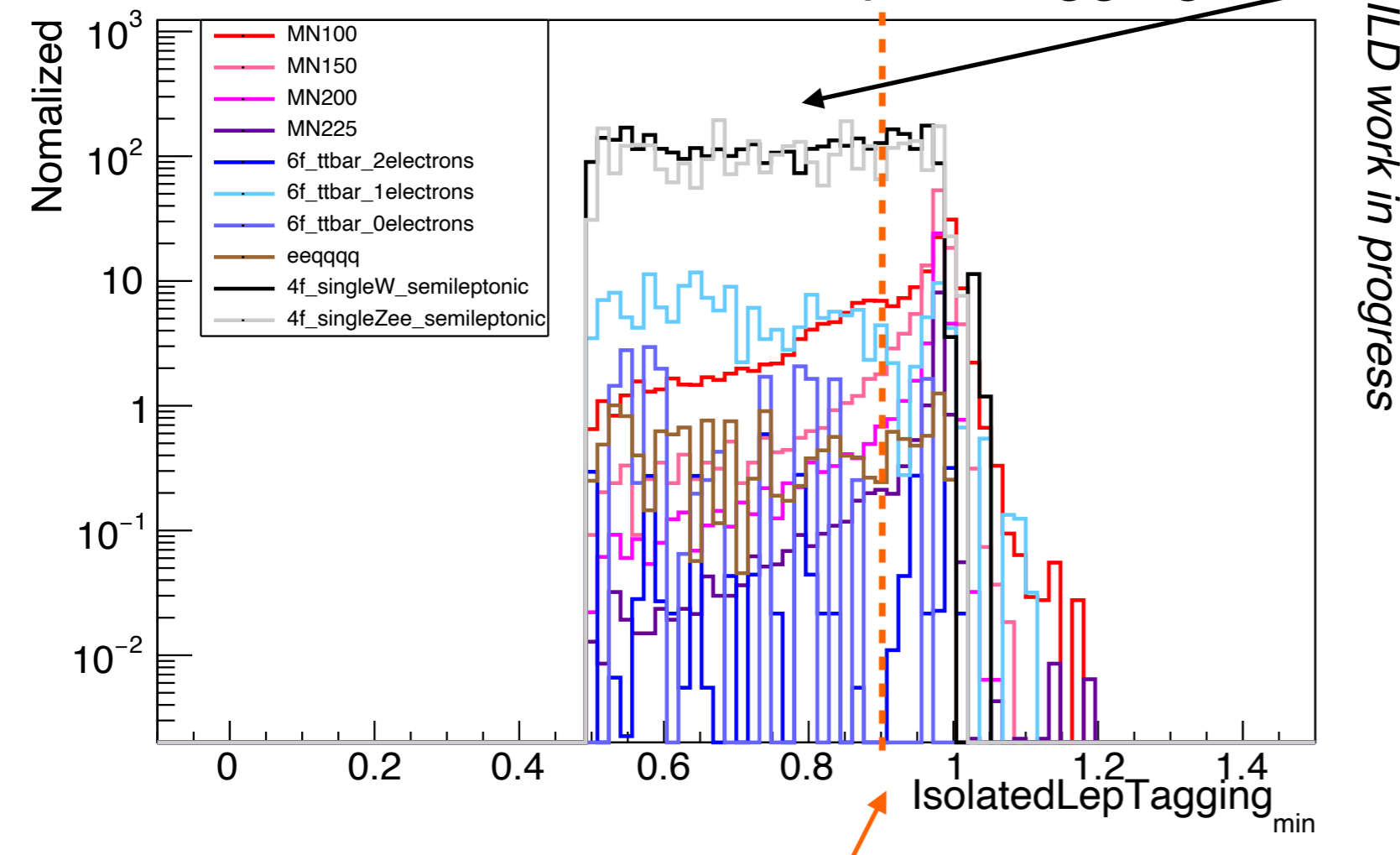


We use only same sign samples  $e_1 \times e_2 = 1$

# Distribution of IsolatedLepTagging

- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (+0.8, -0.3)$
- Isolated  $e \# = 2$  && Isolated  $\gamma \# = 0$  && Isolated  $\mu \# = 0$
- Isolated  $e$  is same sign ( $e_1 \times e_2 = 1$ )

## Minimum of isolated lepton tagging



Usually second background electron is misidentified.

### Isolated lepton tagging

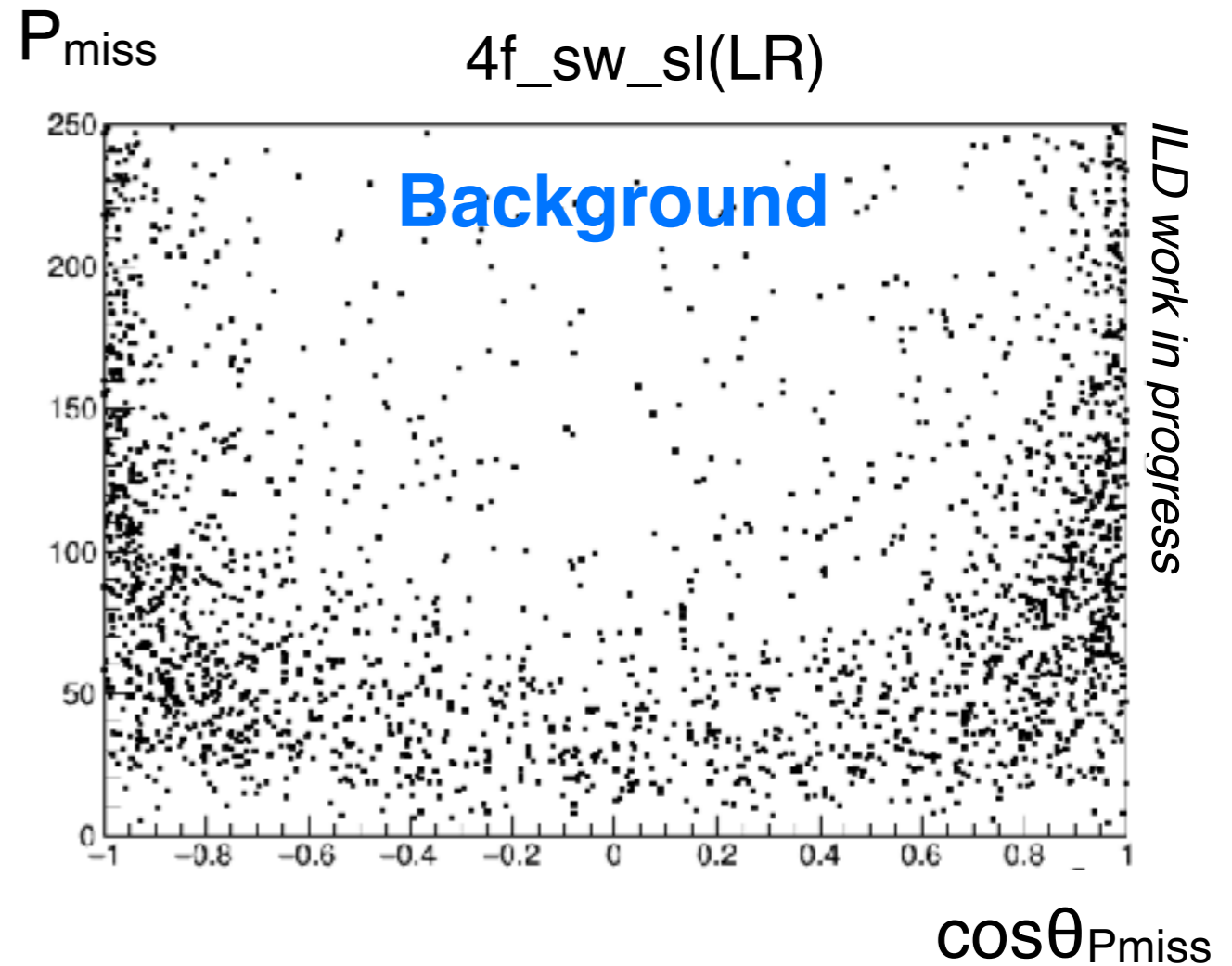
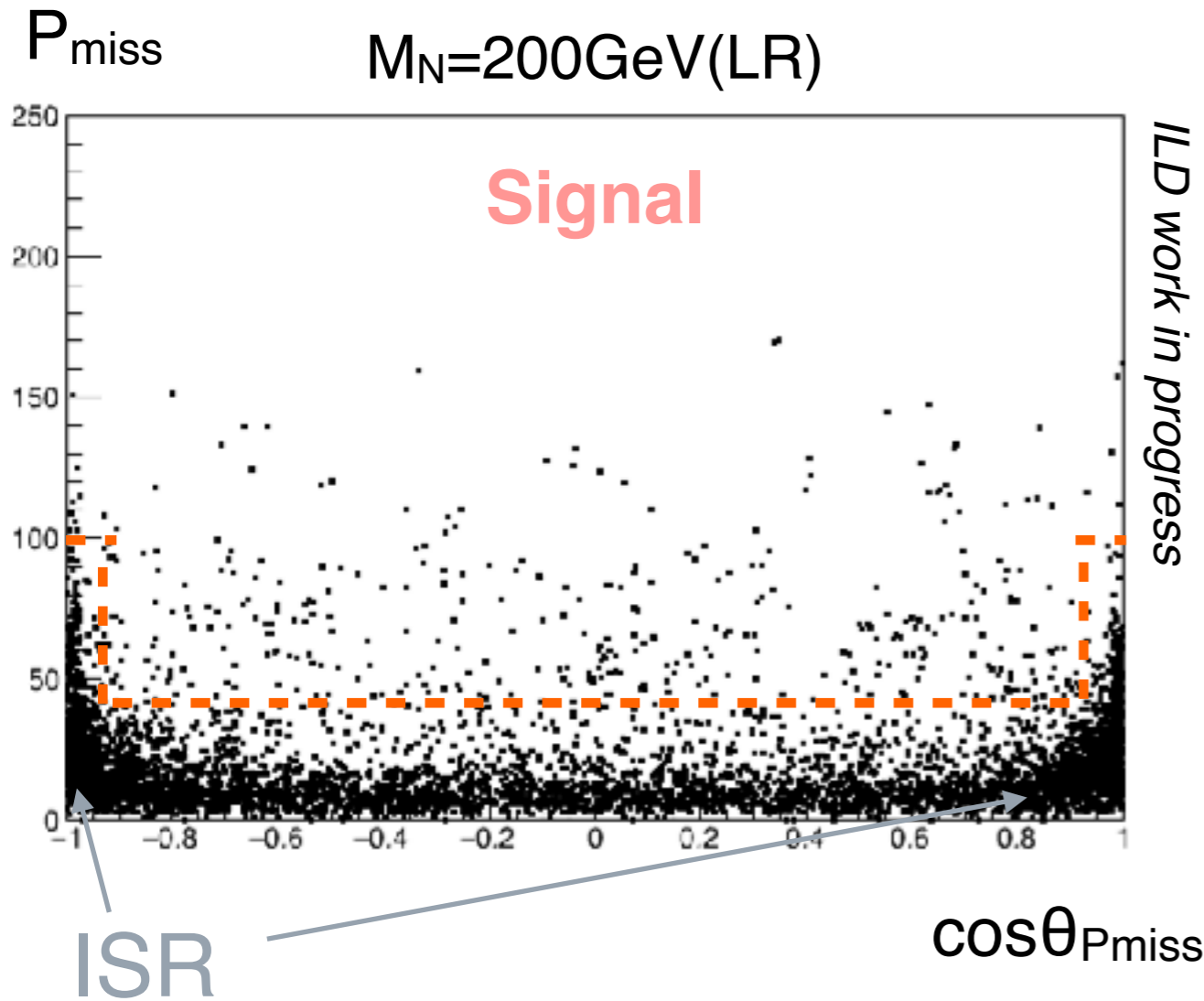
... “output” parameter of MVA to identify isolated lepton

→ Output for  $e$  is **near 1**

**IsolatedLepTagging<sub>min</sub> > 0.9**

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

- ILC 500 with ISR / BS



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

# Cut flow (eRpL)

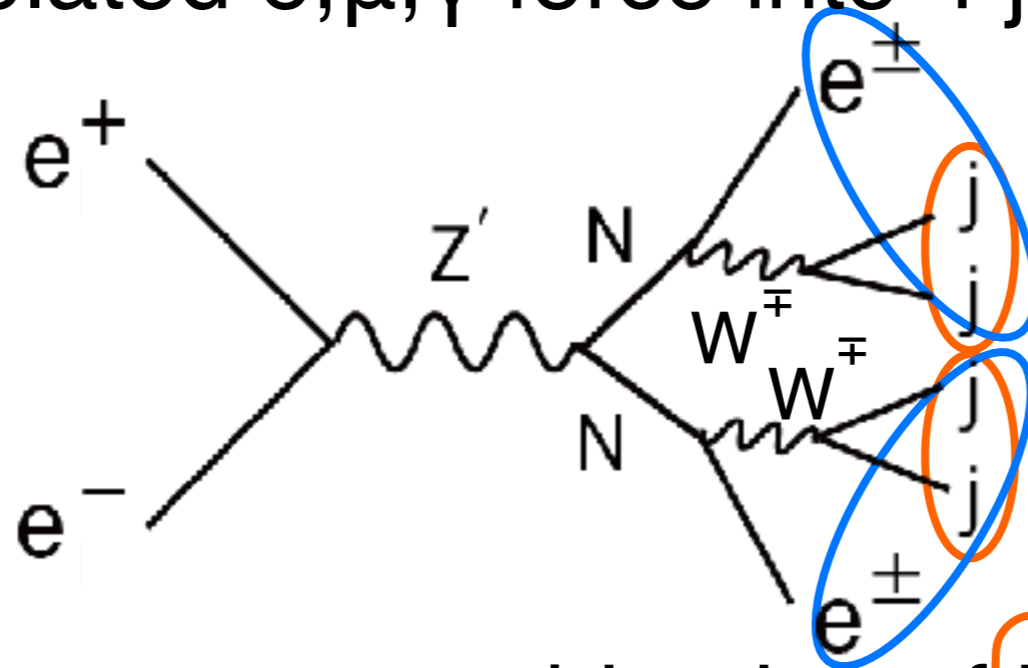
- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (+0.8, -0.3)$   $\mathcal{L} = 1600 [\text{fb}^{-1}]$

*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
$e_{\text{iso}} \# = 2 \ \&\&$ $\gamma_{\text{iso}} \# = 0 \ \&\&$	420	343	126	40	1935	9426	249000	6142	1295	127
Same sign ( $e_{\text{iso}1} \times e_{\text{iso}2} = 1$ )	346	115	81	12	1231	7210	140176	3911	870	94
$E_{\text{iso}} < 200$ [GeV]	171	114	41	12	14	3741	3294	2	177	19
$-0.95 <$ $\cos\theta_{\text{isoe}} < 0.95$	158	103	37	11	3	1324	475	1	113	12
IsolatedLepTa gging <sub>min</sub> > 0.9	96	91	32	10	0	198	101	0	15	1
$\log_{10}(y_{12}) > -1$	88	90	30	9	0	199	86	0	6	0
$P_{\text{miss}} < 100 \ \&\&$ ( $P_{\text{miss}} < 40 \ \parallel$ $ \cos\theta_{P_{\text{miss}}}  >$ 0.95)	86	84	29	9	0	4	15	0	2	0

# Reconstruction methods

After removing isolated  $e, \mu, \gamma$  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 " $M_{jje1} = M_{jje2}$ "

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

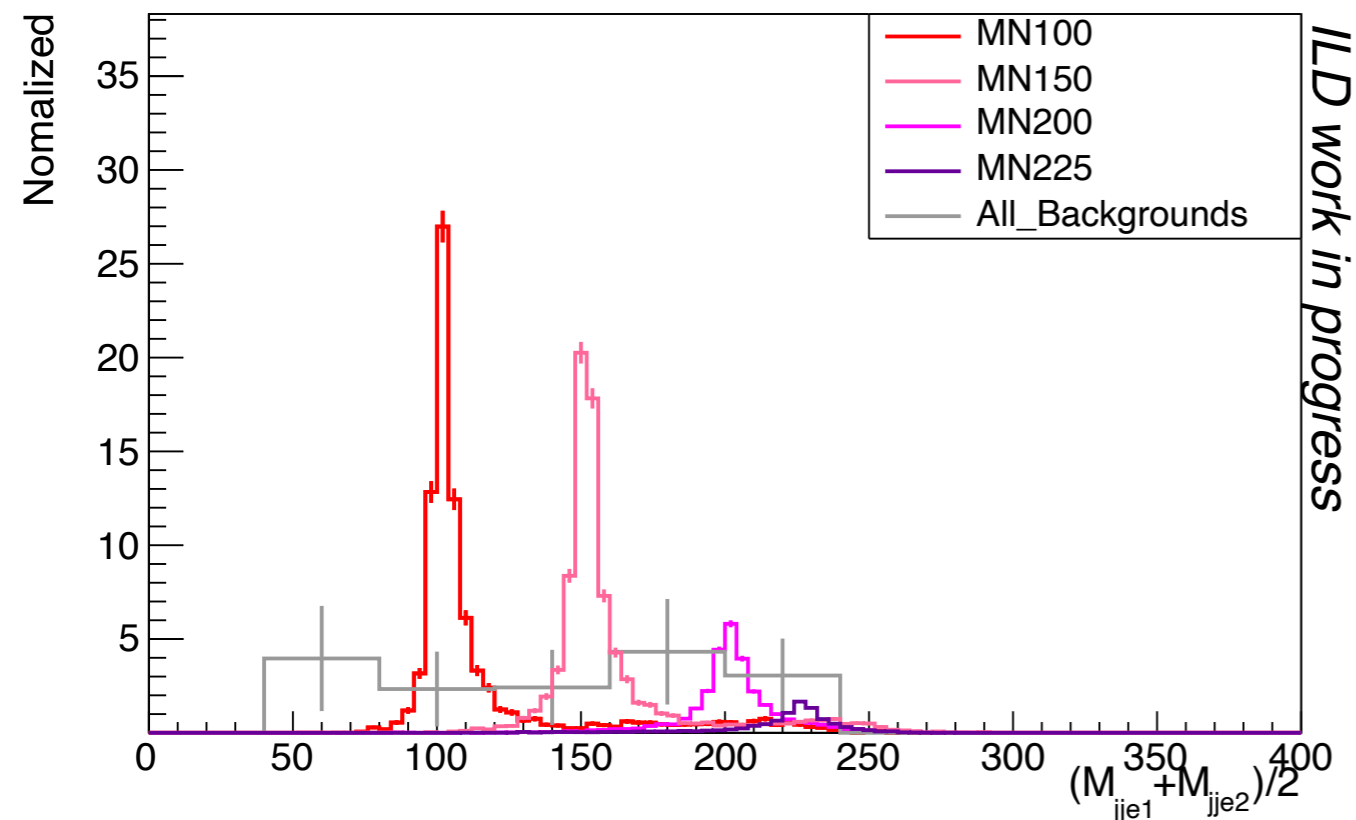
**Choose combination with minimum  $F_1, F_2$**

# Reconstructed RHN mass

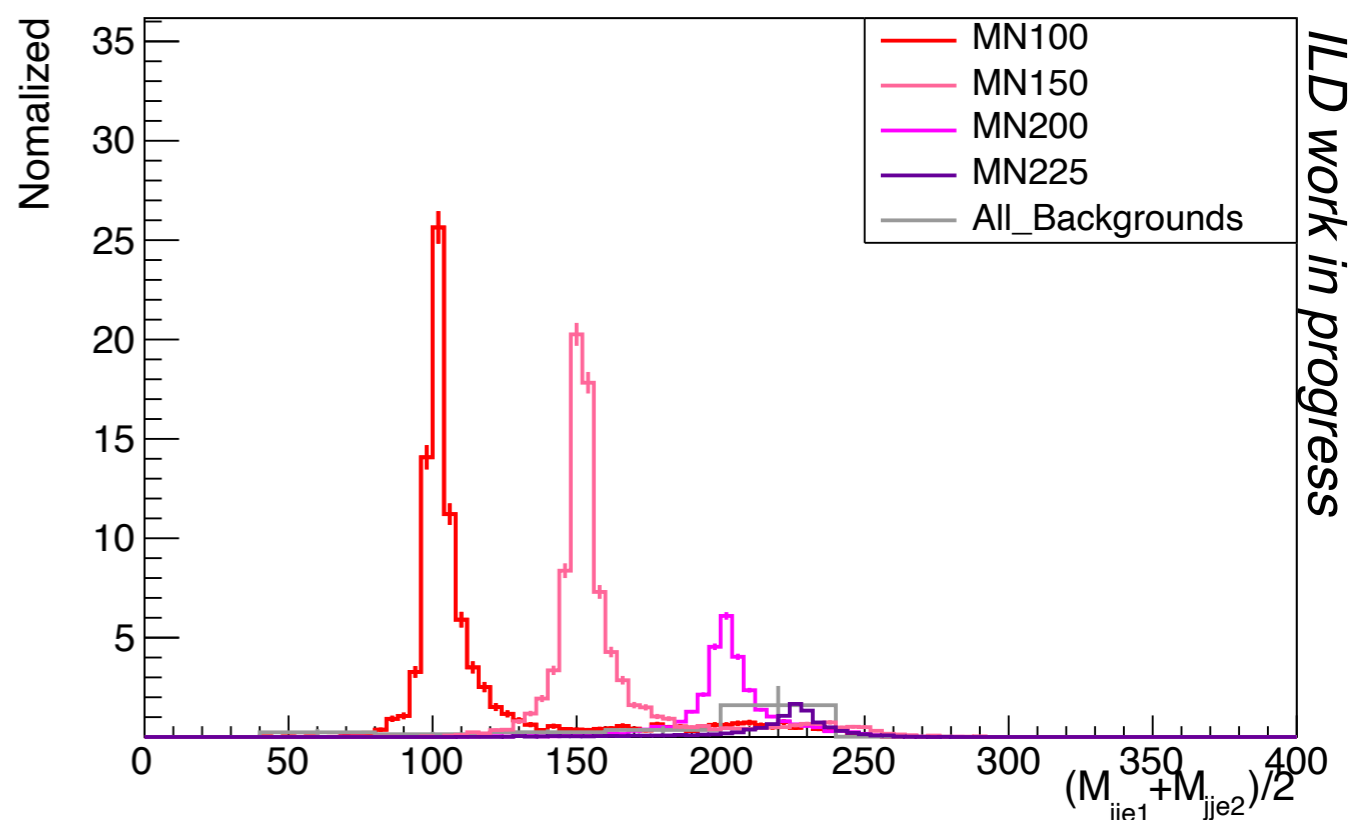
- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (\pm 0.8, \mp 0.3)$   
 $\mathcal{L} = 1600 [\text{fb}^{-1}]$

- Isolated  $e \# = 2$  && Isolated  $\gamma, \mu \# = 0$
- Isolated  $e$  is same sign ( $e_1 \times e_2 = 1$ )
- $E_{\text{iso}} < 200 [\text{GeV}]$
- $-0.95 < \cos\theta_{\text{iso}e} < 0.95$
- IsolatedLepTagging<sub>min</sub>  $> 0.9$
- $P_{\text{miss}} < 100$  && ( $P_{\text{miss}} < 40 \parallel |\cos\theta_{P_{\text{miss}}}| > 0.95$ )
- $\log_{10}(y_{12}) > -1$

RHN mass (Pol(-0.8,+0.3))



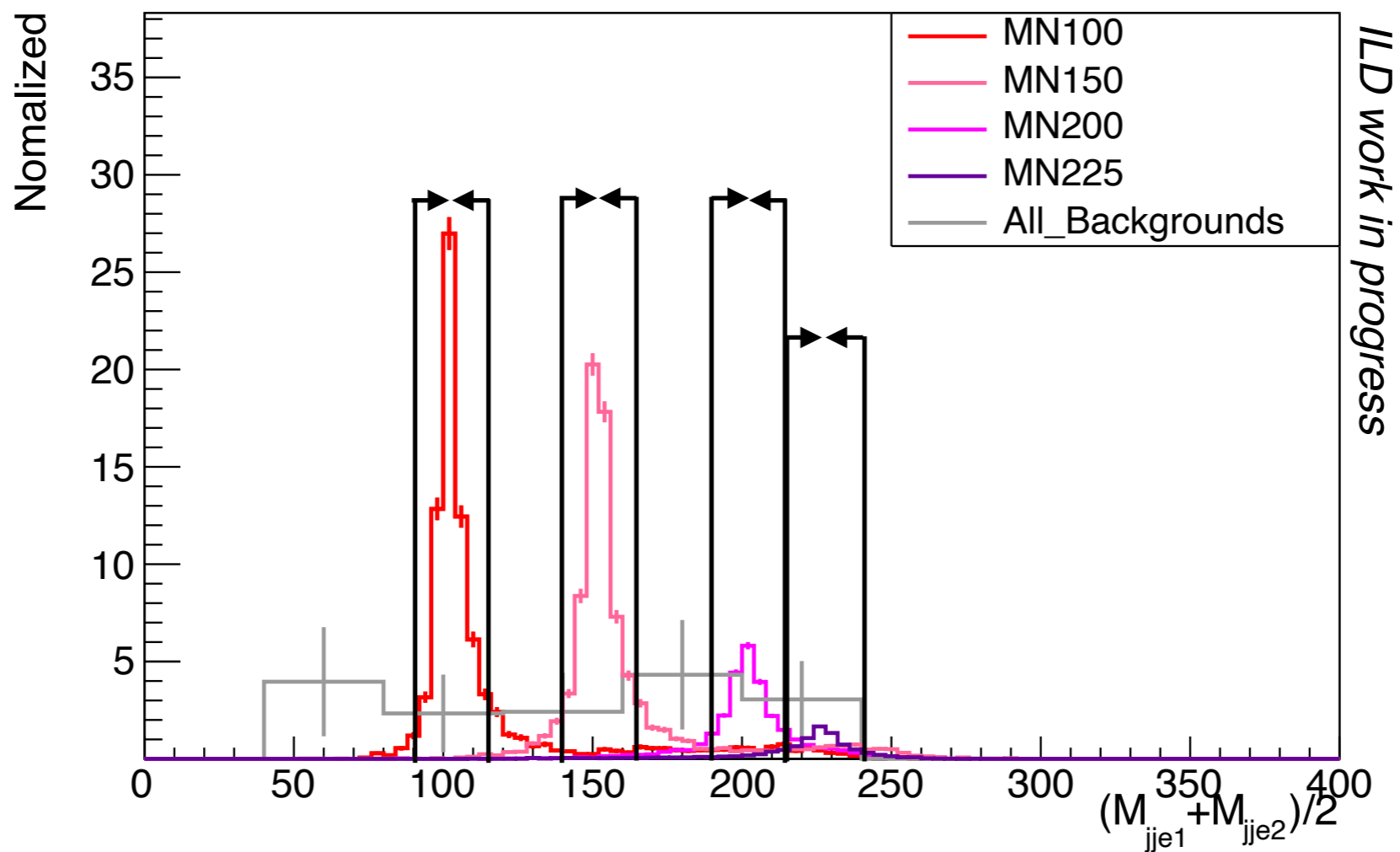
RHN mass (Pol(+0.8,-0.3))



**Background is mostly removed!**

# Signal mass cut

RHN mass (Pol(-0.8,+0.3))



For each MN, mass window MN-10, MN+15 [GeV]

**Assume background distribution is flat.**

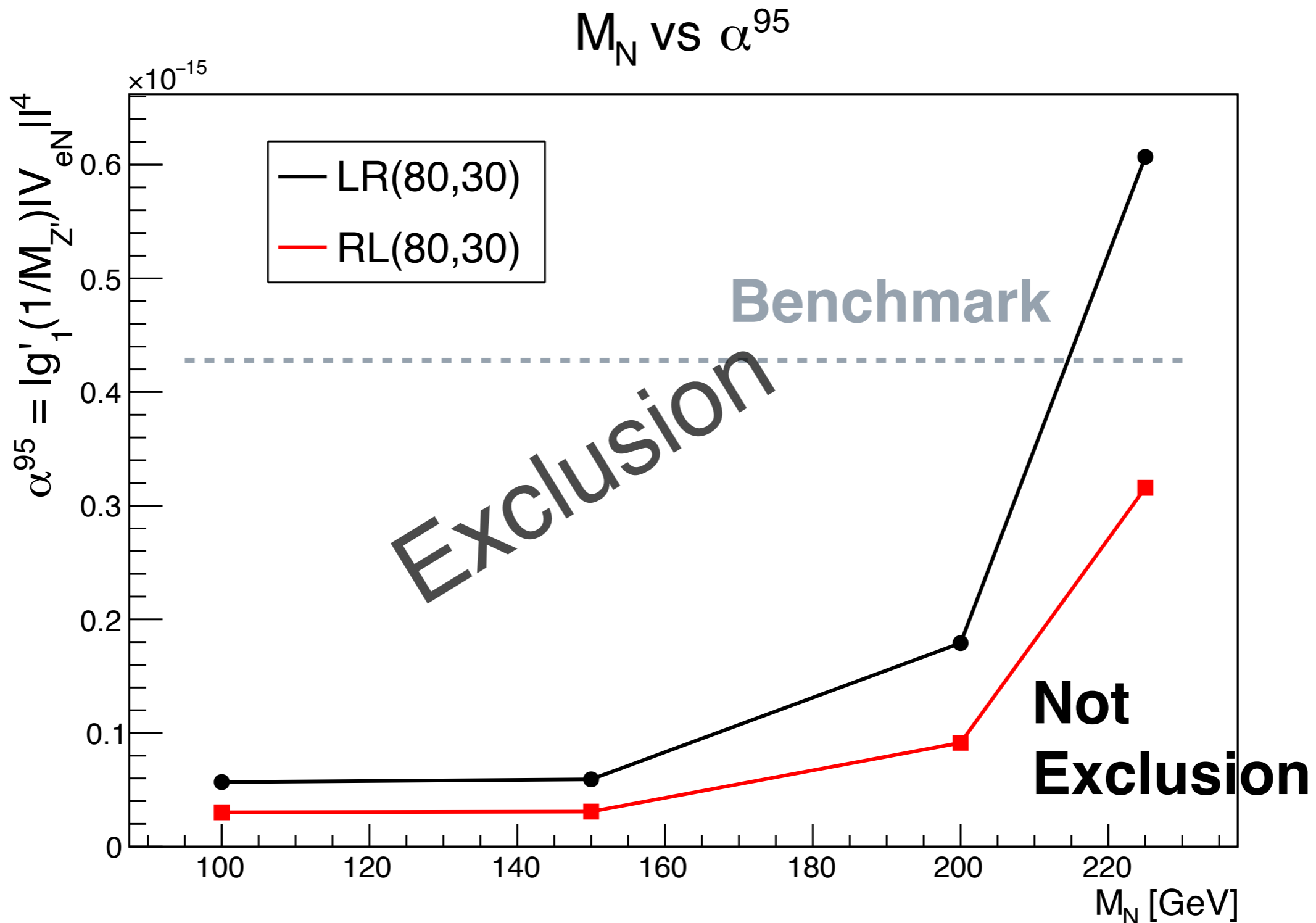
**Calculate 95% UL on cross-section and**  $\sigma \propto \alpha \equiv \left| g_1'^4 \frac{1}{M_{Z'}^4} |V_{eN}|^4 \right|$

# Results

	$M_N$ [GeV]	# of Signal After cut	# of BG After cut	Signal Significance	$\sigma_0$ [fb] Initial benchmark	$\sigma^{95}$ [fb] 95% exclusion limit	$\frac{\sigma^{95}}{\sigma_0}$	$\alpha^{95}$ [TeV <sup>-4</sup> ]
LR 80,30	100	64.73	20.12	14.43	0.71	0.097	0.14	5.68E-17
	150	62.11		13.8	0.45	0.063	0.14	5.92E-17
	200	20.52		4.57	0.16	0.070	0.43	1.80E-16
	225	6.05		1.35	0.052	0.075	1.46	6.07E-16
RL 80,30	100	63.39	3.24	35.12	0.71	0.051	0.072	3.02E-17
	150	62.11		34.49	0.45	0.033	0.074	3.08E-17
	200	20.93		11.62	0.16	0.036	0.22	9.13E-17
	225	6.05		3.36	0.052	0.039	0.76	3.16E-16



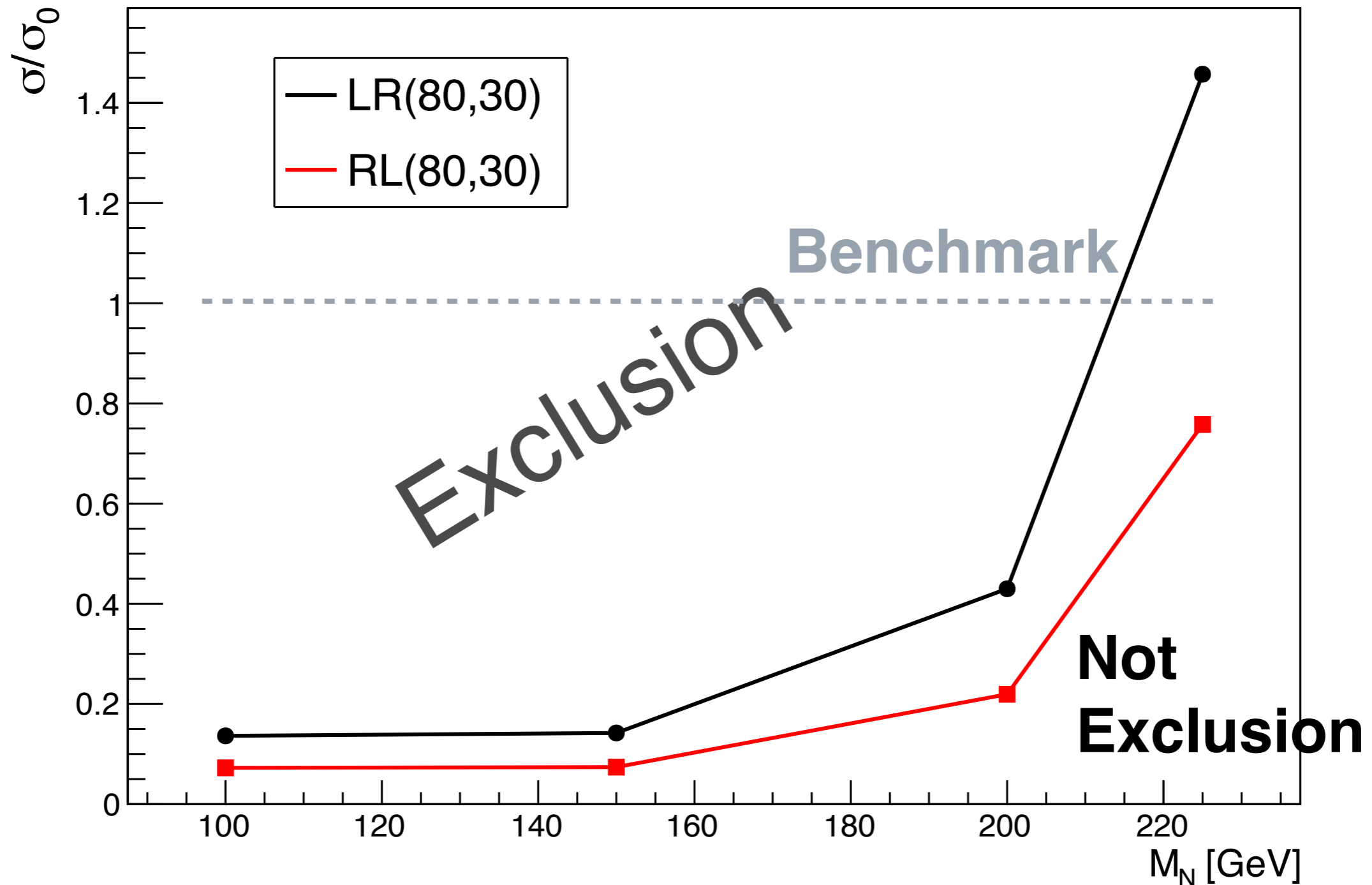
# Exclusion plot



**Exclude benchmark points**

# Exclusion plot

$M_N$  vs  $\sigma/\sigma_0$



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

# Summary

- ▶ 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 at ILC500.
- ▶ 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.**
- ▶ Exclude benchmark points and cross-sections up to 10x smaller

## Next step

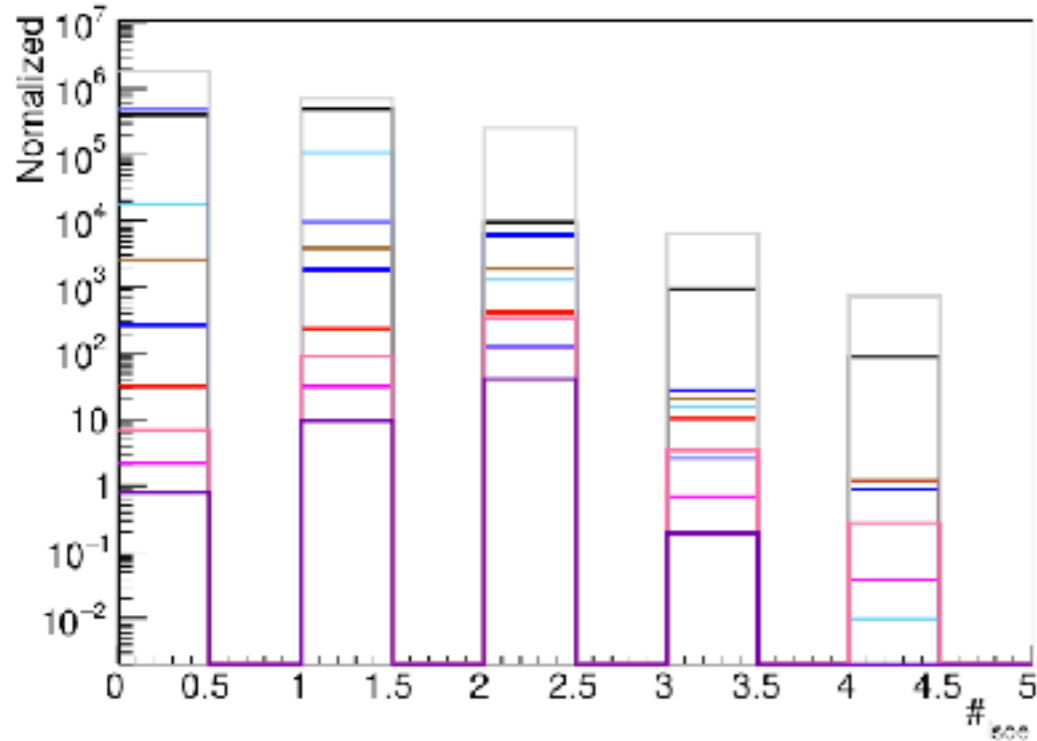
- ▶ Write Master thesis!

Backup

# Isolated e, $\gamma$ , $\mu$

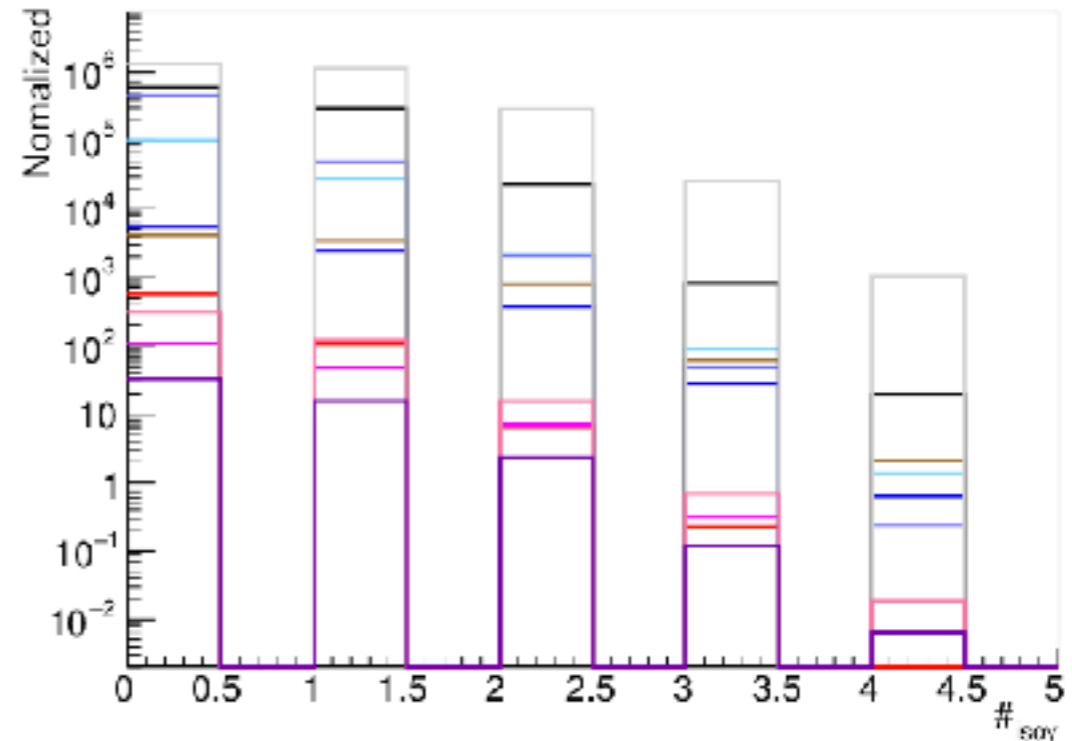
- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (+0.8, -0.3)$

Number of isolated e



ILD work in progress

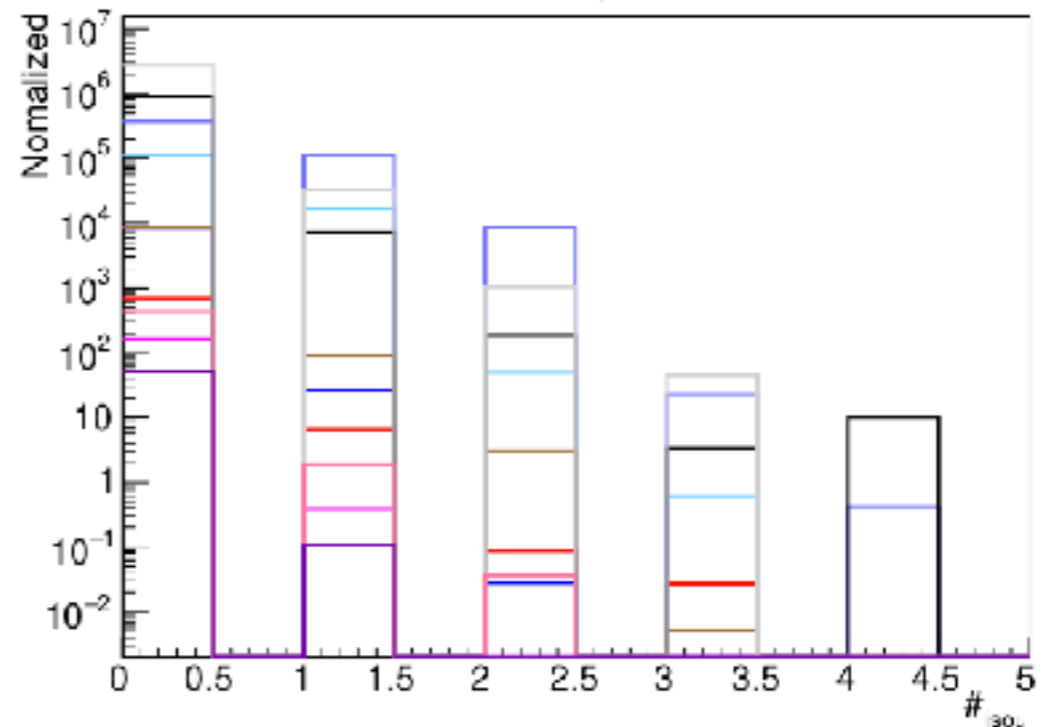
Number of isolated  $\gamma$



ILD work in progress

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

Number of isolated  $\mu$

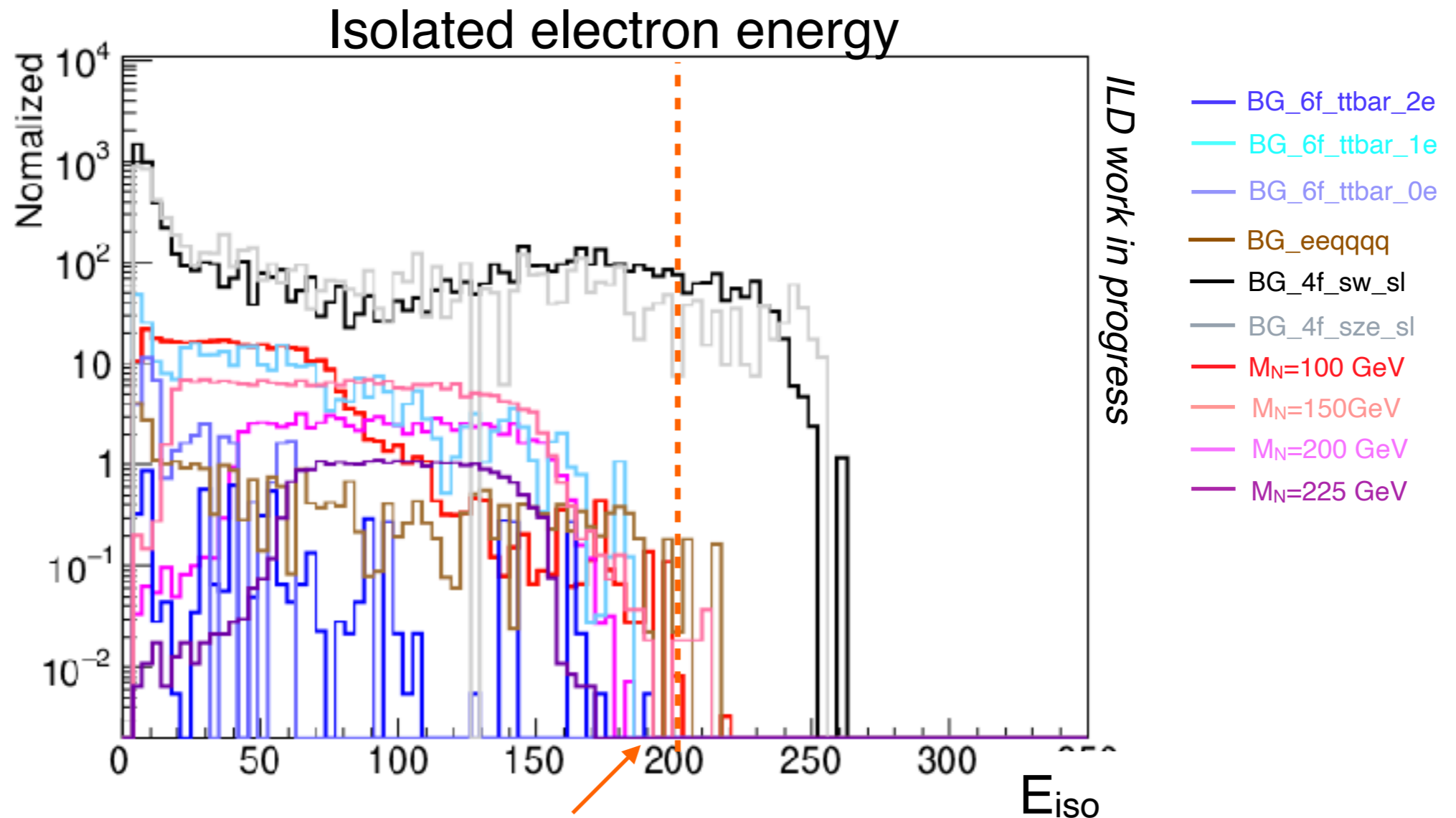


ILD work in progress

- Isolated e # = 2 && Isolated  $\gamma$ ,  $\mu = 0$

# Distribution of Isolated electron energy

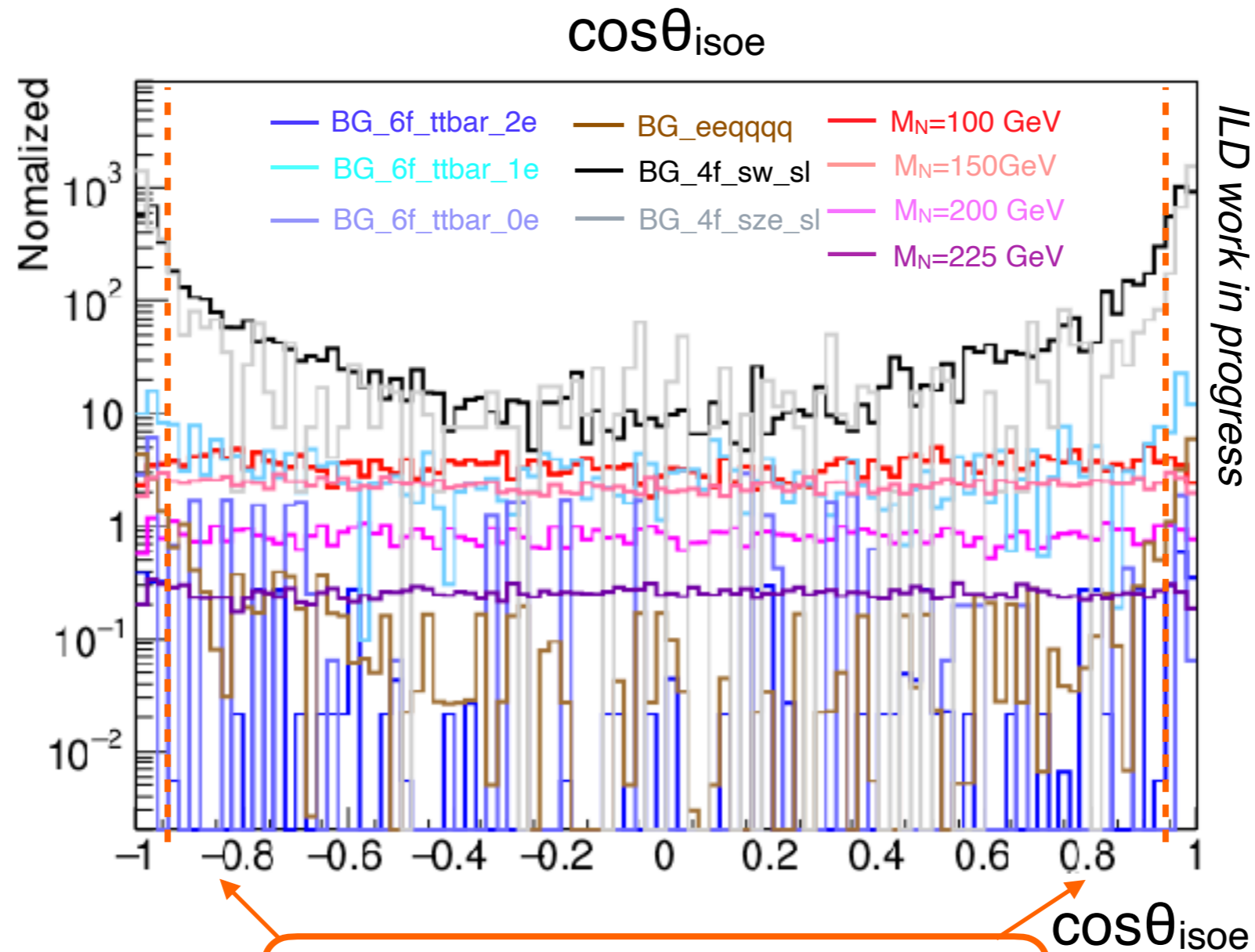
- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (+0.8, -0.3)$
- Isolated  $e^- \# = 2$  && Isolated  $\gamma \# = 0$  && Isolated  $\mu \# = 0$
- Isolated  $e^-$  is same sign ( $e_1 \times e_2 = 1$ )



$E_{\text{iso}} < 200$  [GeV]

# Distribution of $\cos\theta_{\text{isoe}}$

- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (+0.8, -0.3)$
- Isolated  $e \# = 2$  && Isolated  $\gamma \# = 0$  && Isolated  $\mu \# = 0$
- Isolated  $e$  is same sign ( $e_1 \times e_2 = 1$ )

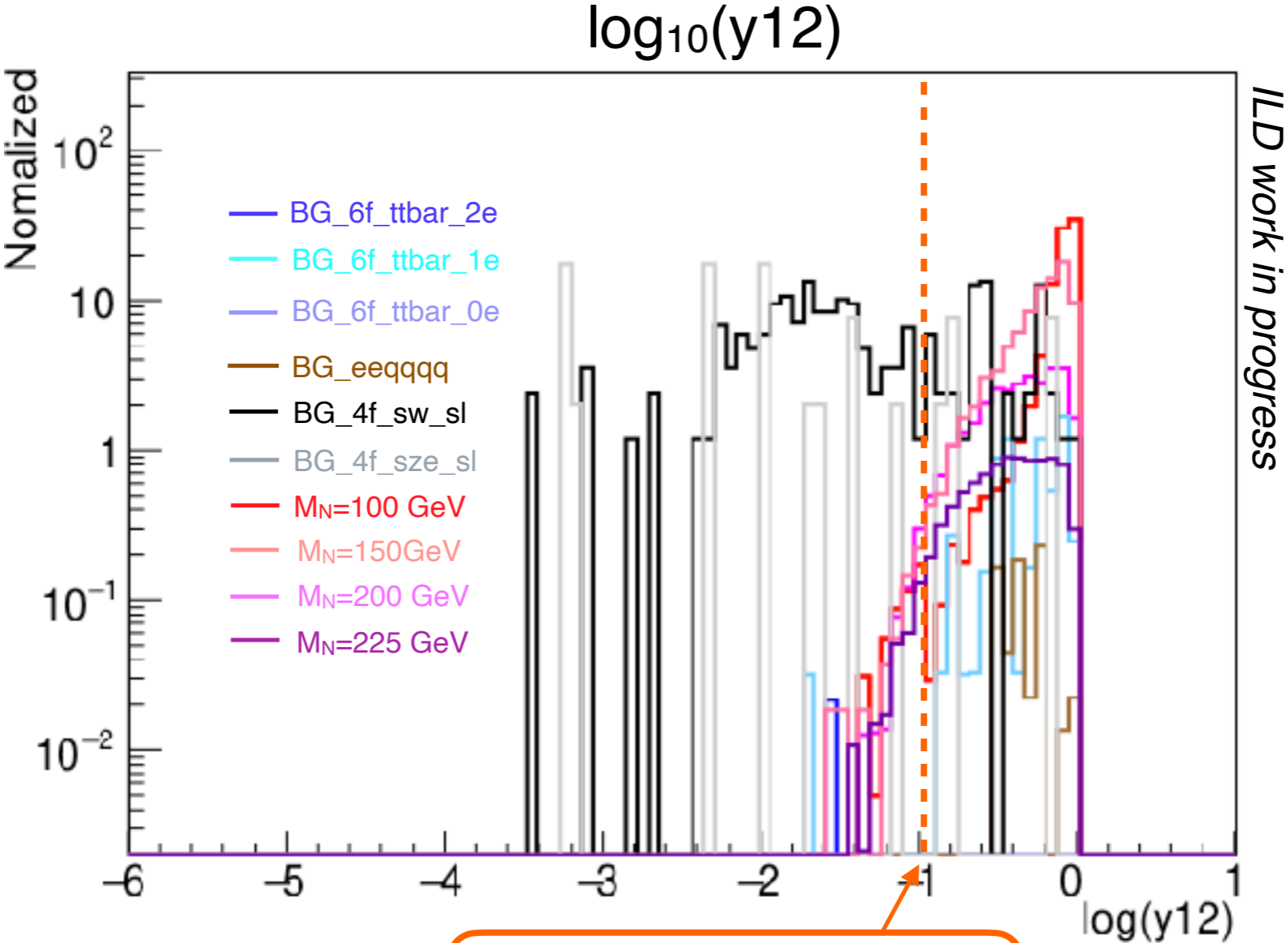


**$-0.95 < \cos\theta_{\text{isoe}} < 0.95$**

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

# Distribution of $y_{12}$ (Durham)

- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (+0.8, -0.3)$
- Isolated  $e \# = 2$  && Isolated  $\gamma \# = 0$  && Isolated  $\mu \# = 0$
- Isolated  $e$  is same sign ( $e_1 \times e_2 = 1$ )



$\log_{10}(y_{12}) > -1$



eLpR case

# Cut flow (eLpR)

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

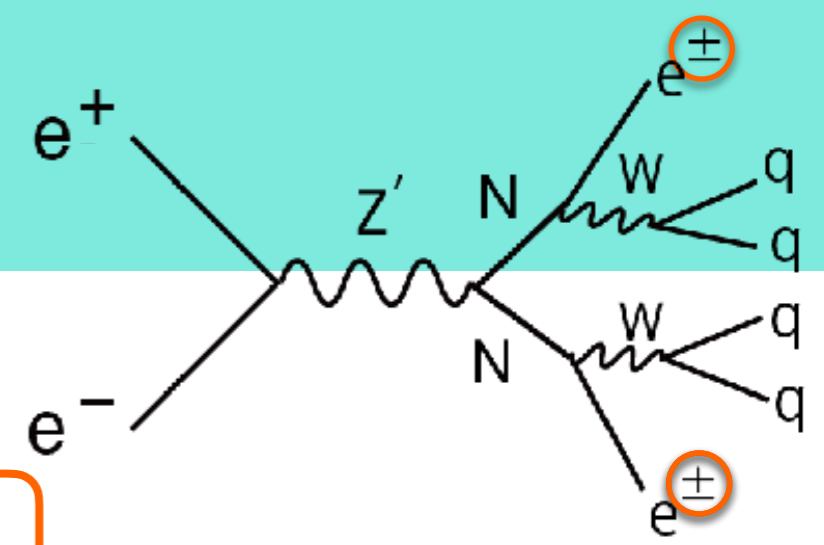
*ILD work in progress*

	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
$e_{\text{iso}} \# = 2 \ \&\&$ $\gamma_{\text{iso}} \# = 0 \ \&\&$	347	343	79	40	4721	90818	162774	9422	2271	201
Same sign ( $e_{\text{iso}1} \times e_{\text{iso}2} = 1$ )	176	115	39	12	39	46138	3800	8	439	25
$E_{\text{iso}} < 200$ [GeV]	175	114	39	12	39	41319	3557	8	439	25
$-0.95 <$ $\cos\theta_{\text{iso}e} < 0.95$	156	103	36	11	13	17506	623	4	266	15
IsolatedLepTa gging <sub>min</sub> > 0.9	94	91	31	10	2	2632	128	1	50	0
$\log_{10}(y_{12}) > -1$	94	90	31	9	2	2632	128	1	50	0
$P_{\text{miss}} < 100 \ \&\&$ ( $P_{\text{miss}} < 40 \ \parallel$ $ \cos\theta_{P_{\text{miss}}}  >$ 0.95)	84	84	28	9	1	79	30	0	9	0

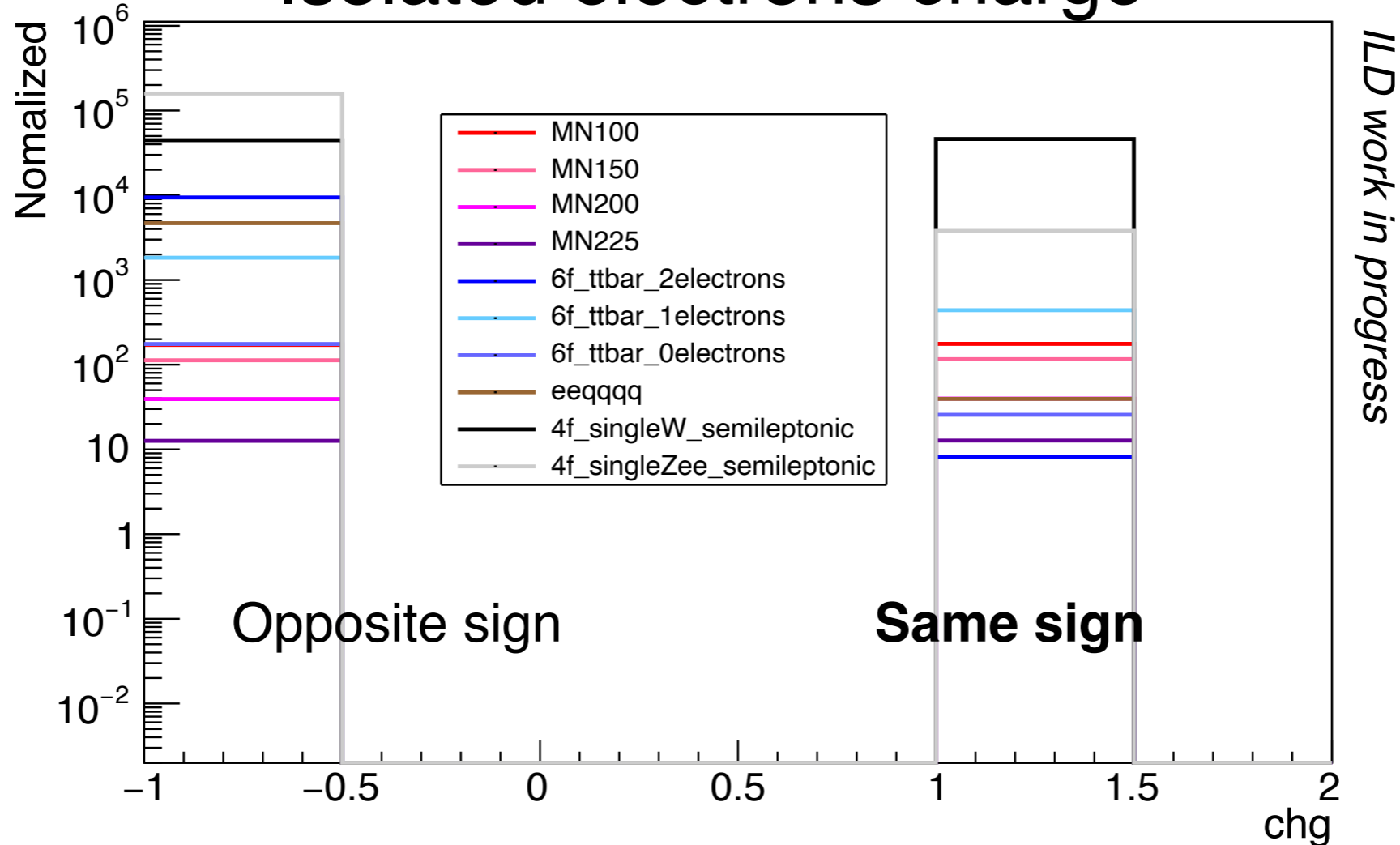
# Electron Charge

- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (-0.8, +0.3)$

- Isolated  $e^- \# = 2$  && Isolated  $\gamma \# = 0$  && Isolated  $\mu \# = 0$



## Isolated electrons charge

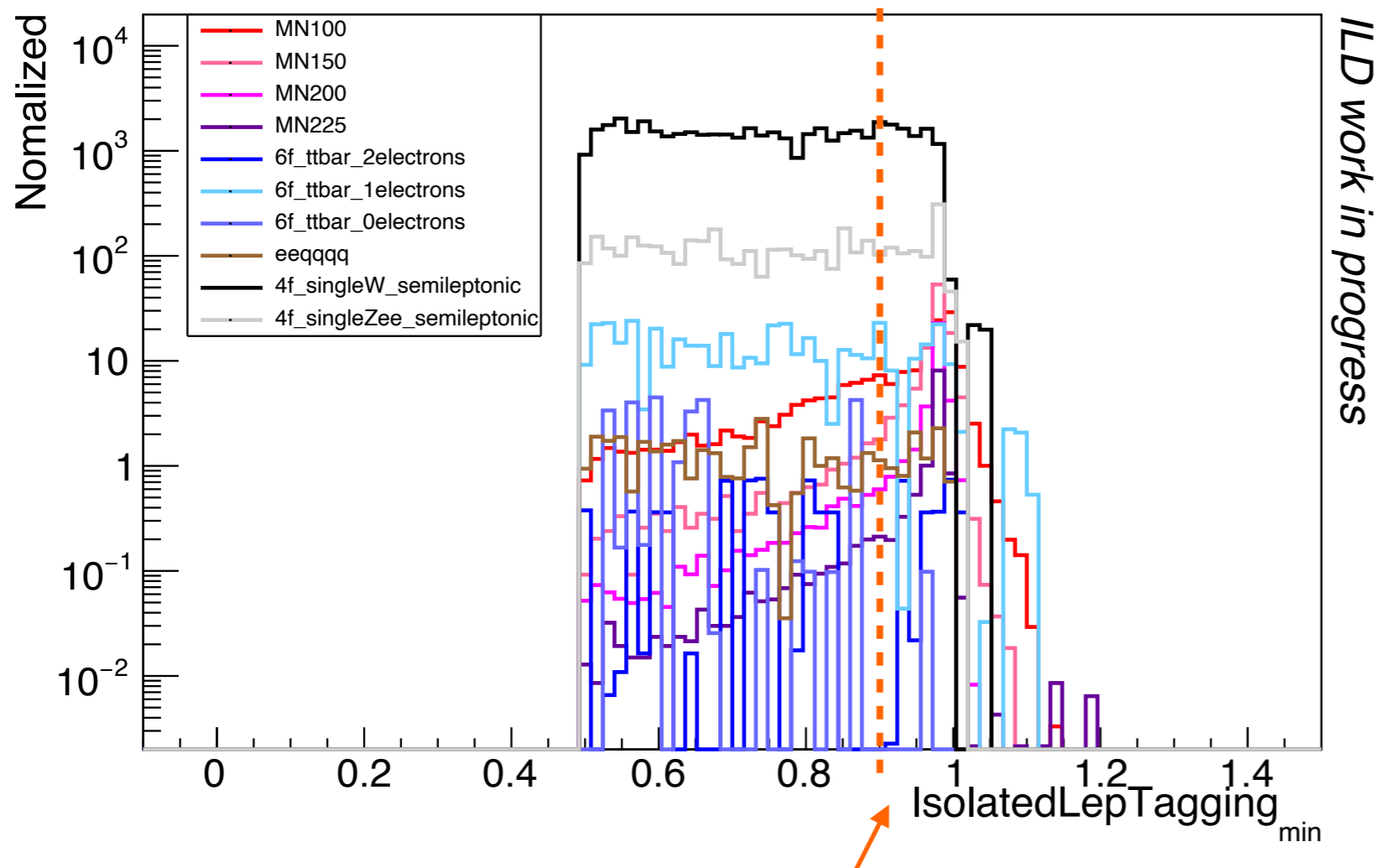


We use only same sign samples  $e_1 \times e_2 = 1$

# Distribution of IsolatedLepTagging

- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (-0.8, +0.3)$
- Isolated  $e \# = 2$  && Isolated  $\gamma \# = 0$  && Isolated  $\mu \# = 0$
- Isolated  $e$  is same sign ( $e_1 \times e_2 = 1$ )

## Minimum of isolated lepton tagging



ILD work in progress

Isolated lepton tagging  
... “output” parameter of MVA  
to identify isolated lepton

→ Output for  $e$  is **near 1**

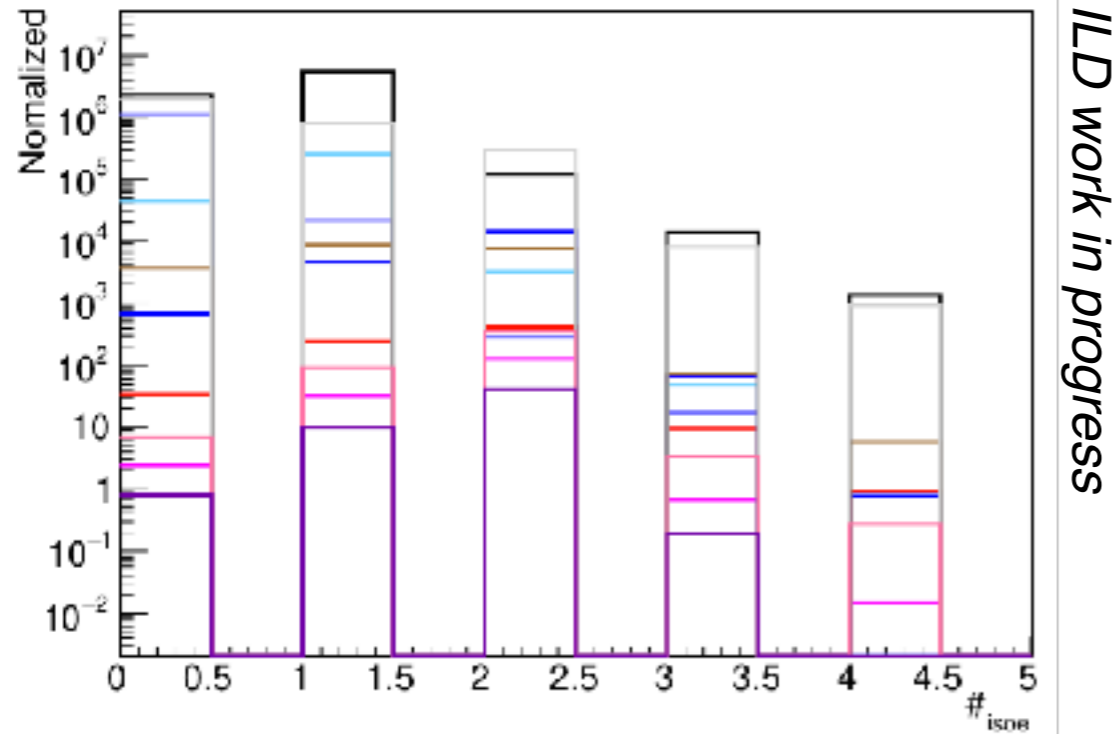
**Usually second background  
electron is fake**

**IsolatedLepTagging<sub>min</sub> > 0.9**

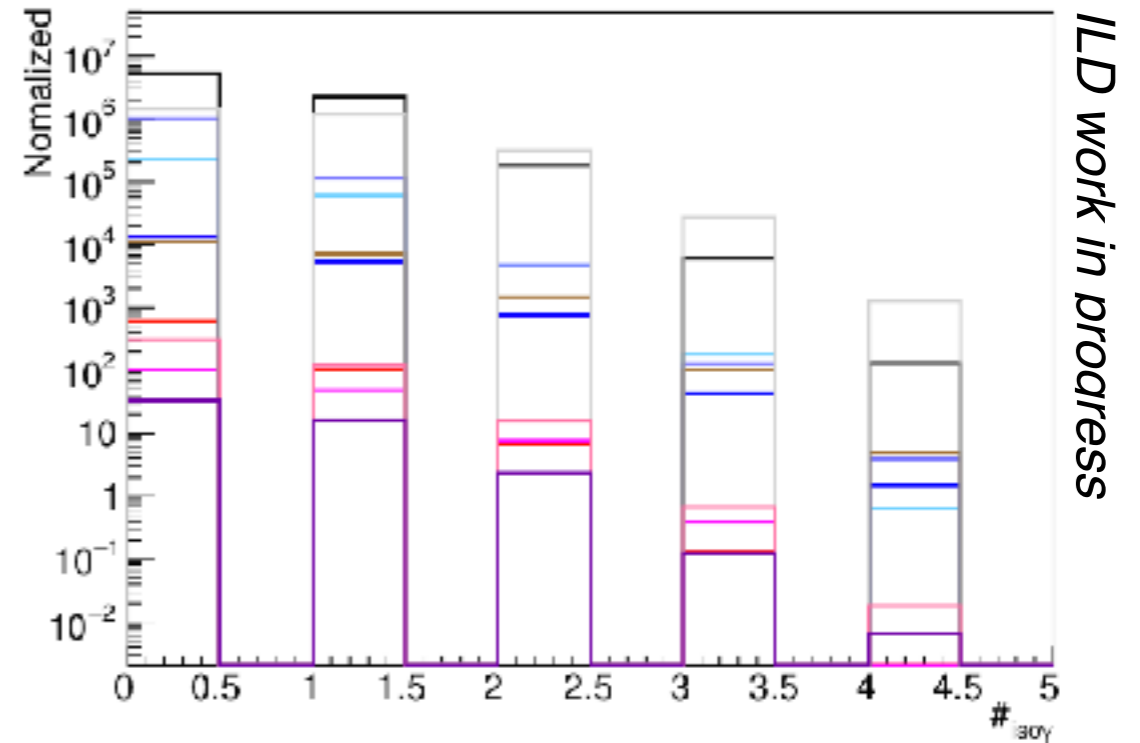
# Isolated $e, \gamma, \mu$

- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (-0.8, +0.3)$

Number of isolated  $e$

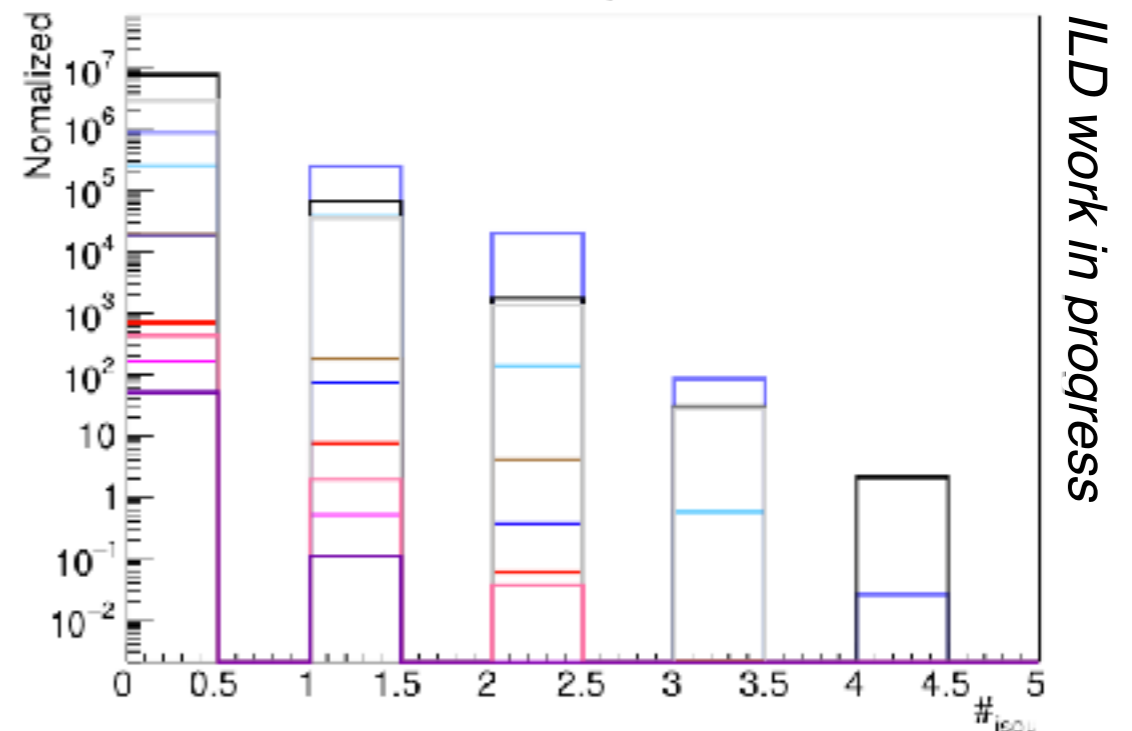


Number of isolated  $\gamma$



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

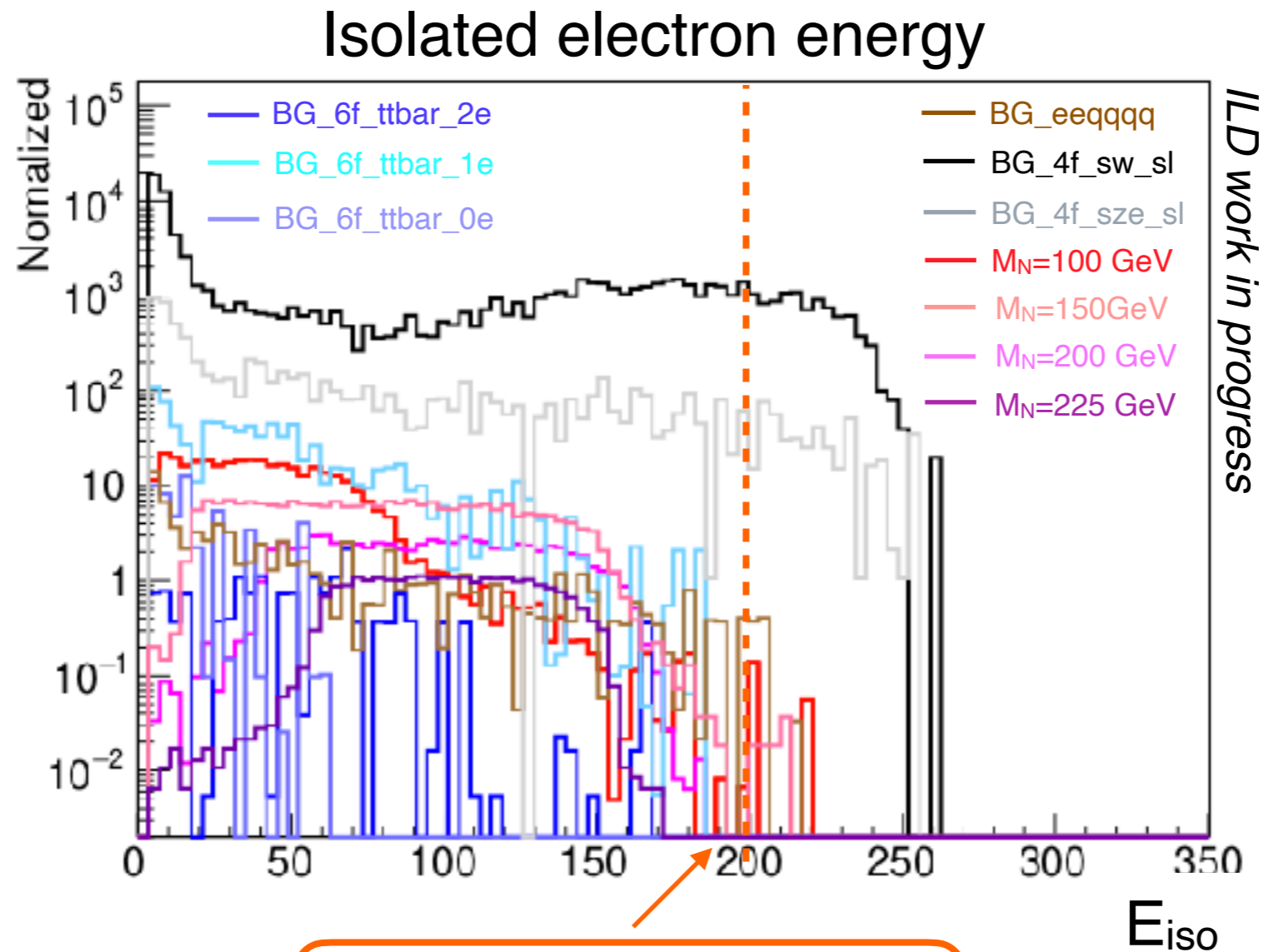
Number of isolated  $\mu$



- Isolated  $e$  # = 2 && Isolated  $\gamma, \mu = 0$

# Distribution of Isolated electron energy

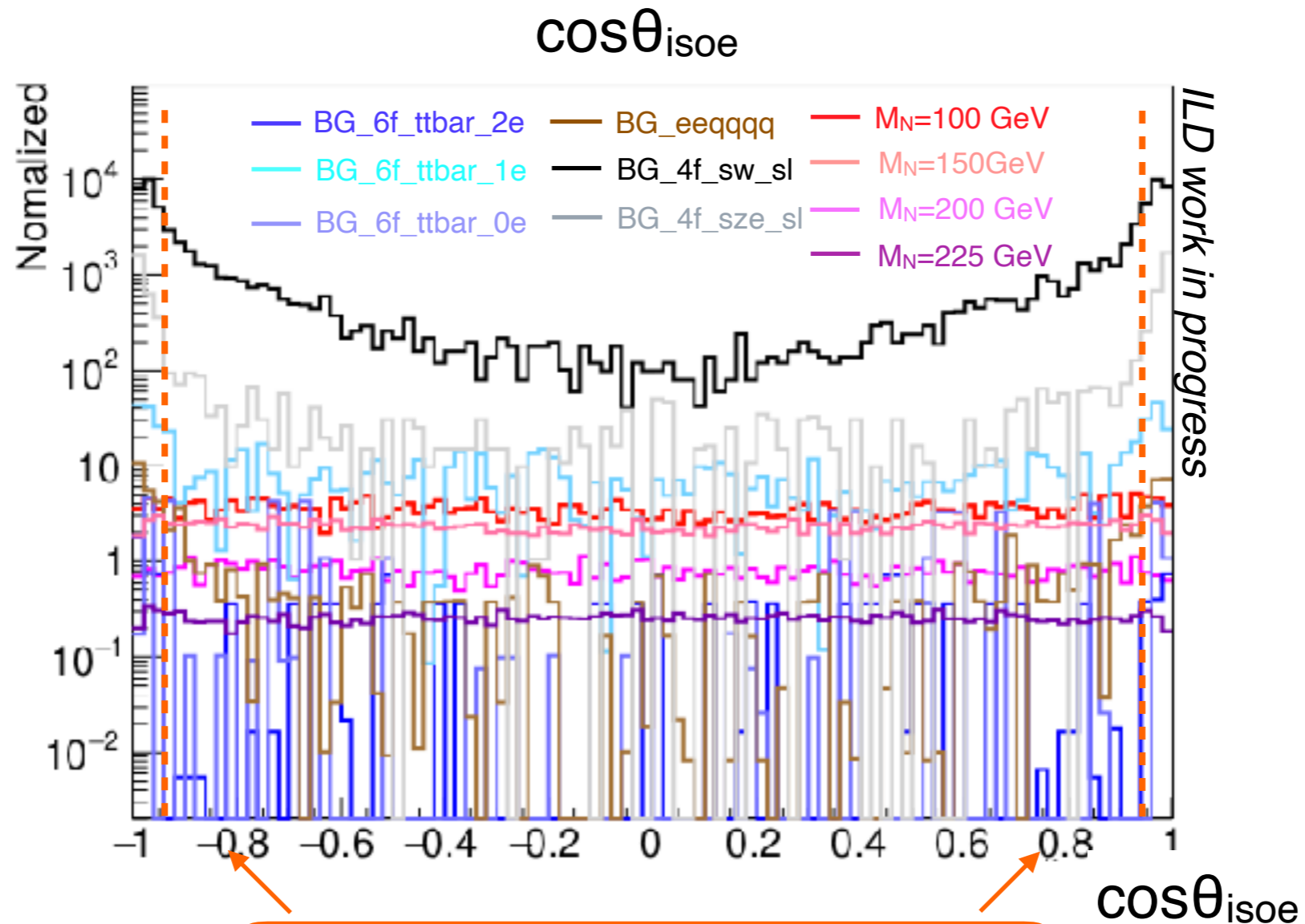
- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (-0.8, +0.3)$
- Isolated  $e^- \# = 2$  && Isolated  $\gamma \# = 0$  && Isolated  $\mu \# = 0$
- Isolated  $e^-$  is same sign ( $e_1 \times e_2 = 1$ )



$E_{\text{iso}} < 200$  [GeV]

# Distribution of $\cos\theta_{\text{isoe}}$

- ILC 500 with ISR / BS
- $\text{Pol}(e^-, e^+) = (-0.8, +0.3)$
- Isolated  $e \# = 2$  && Isolated  $\gamma \# = 0$  && Isolated  $\mu \# = 0$
- Isolated  $e$  is same sign ( $e_1 \times e_2 = 1$ )

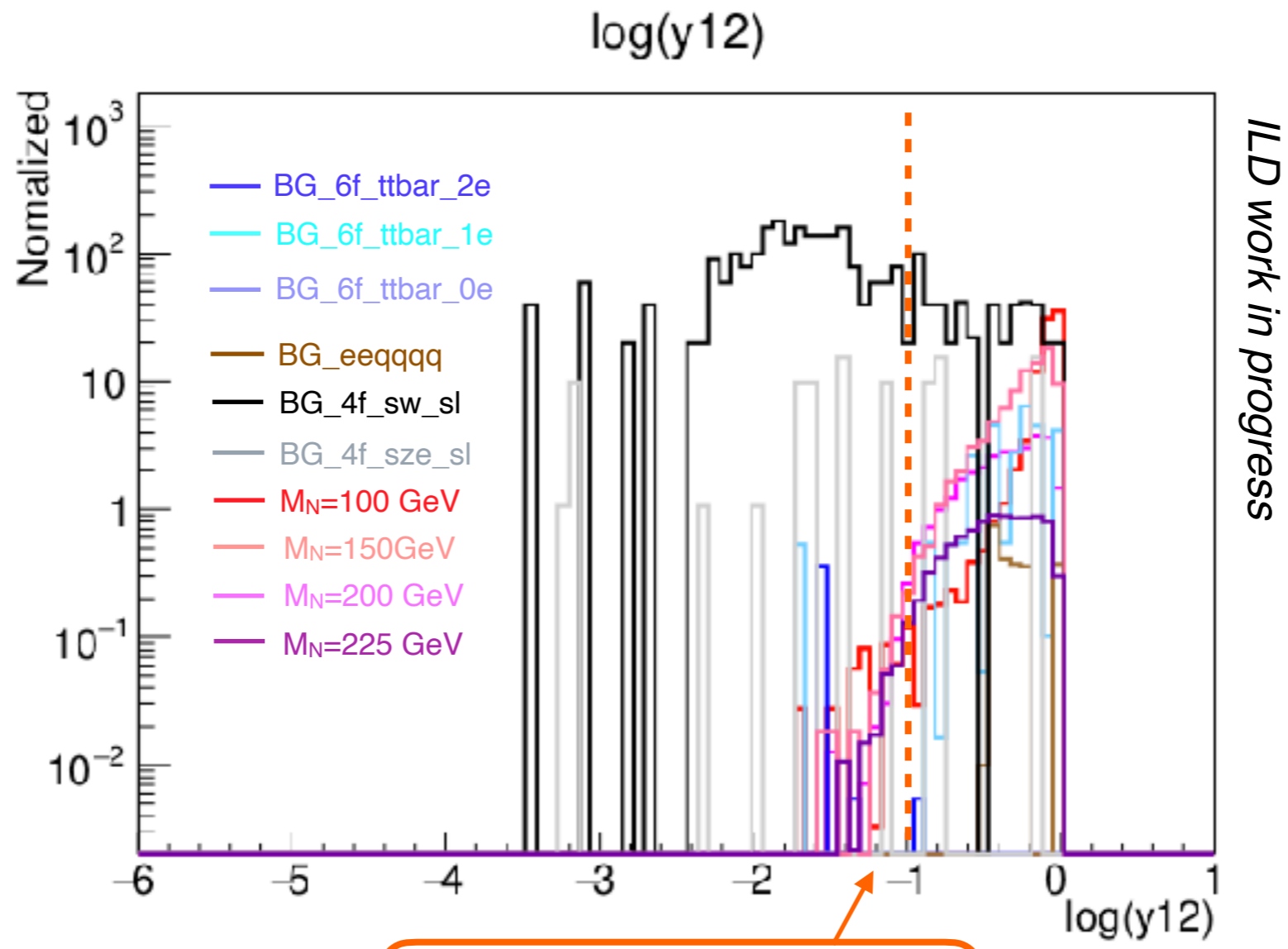


$$-0.95 < \cos\theta_{\text{isoe}} < 0.95$$

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

# Distribution of $y_{12}$ (Durham)

- ILC 500 with ISR / BS
- **Pol( $e^-$ ,  $e^+$ ) = (-0.8, +0.3)**
- Isolated  $e$  # = 2 && Isolated  $\gamma$  # = 0 && Isolated  $\mu$  # = 0
- Isolated  $e$  is same sign ( $e_1 \times e_2 = 1$ )



**$\log_{10}(y_{12}) > -1$**



4f and 6f background information

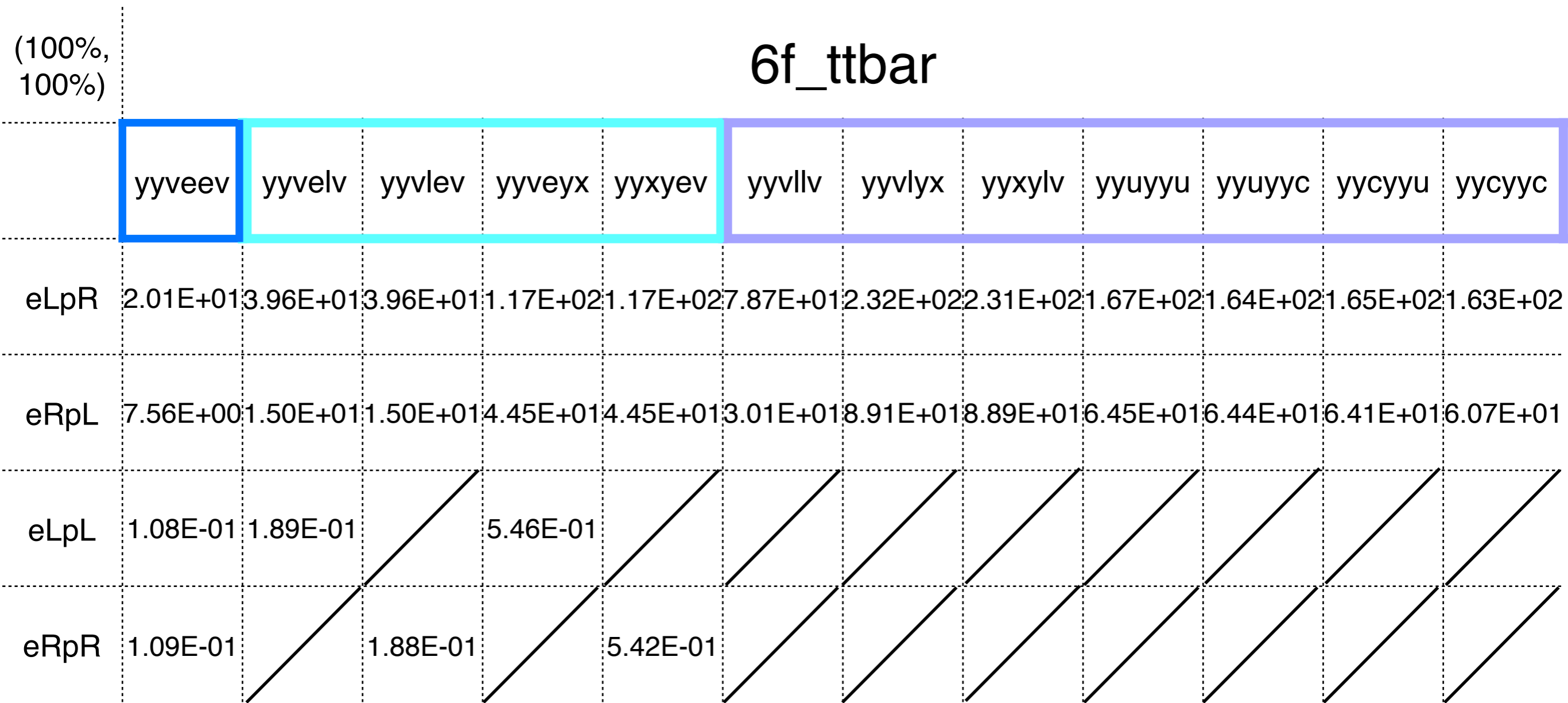
# Cross section — BG

- 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

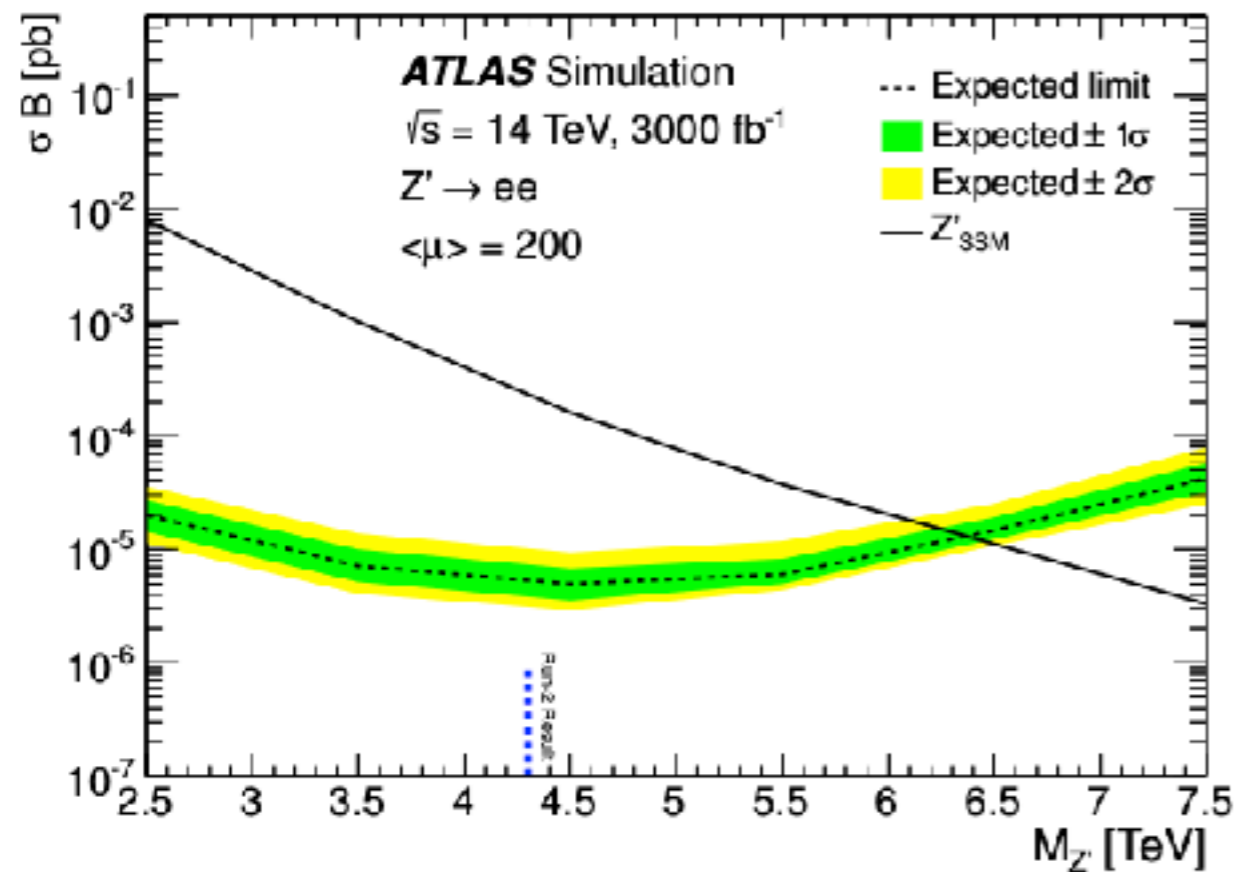
- ILC 500 with ISR / BS



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

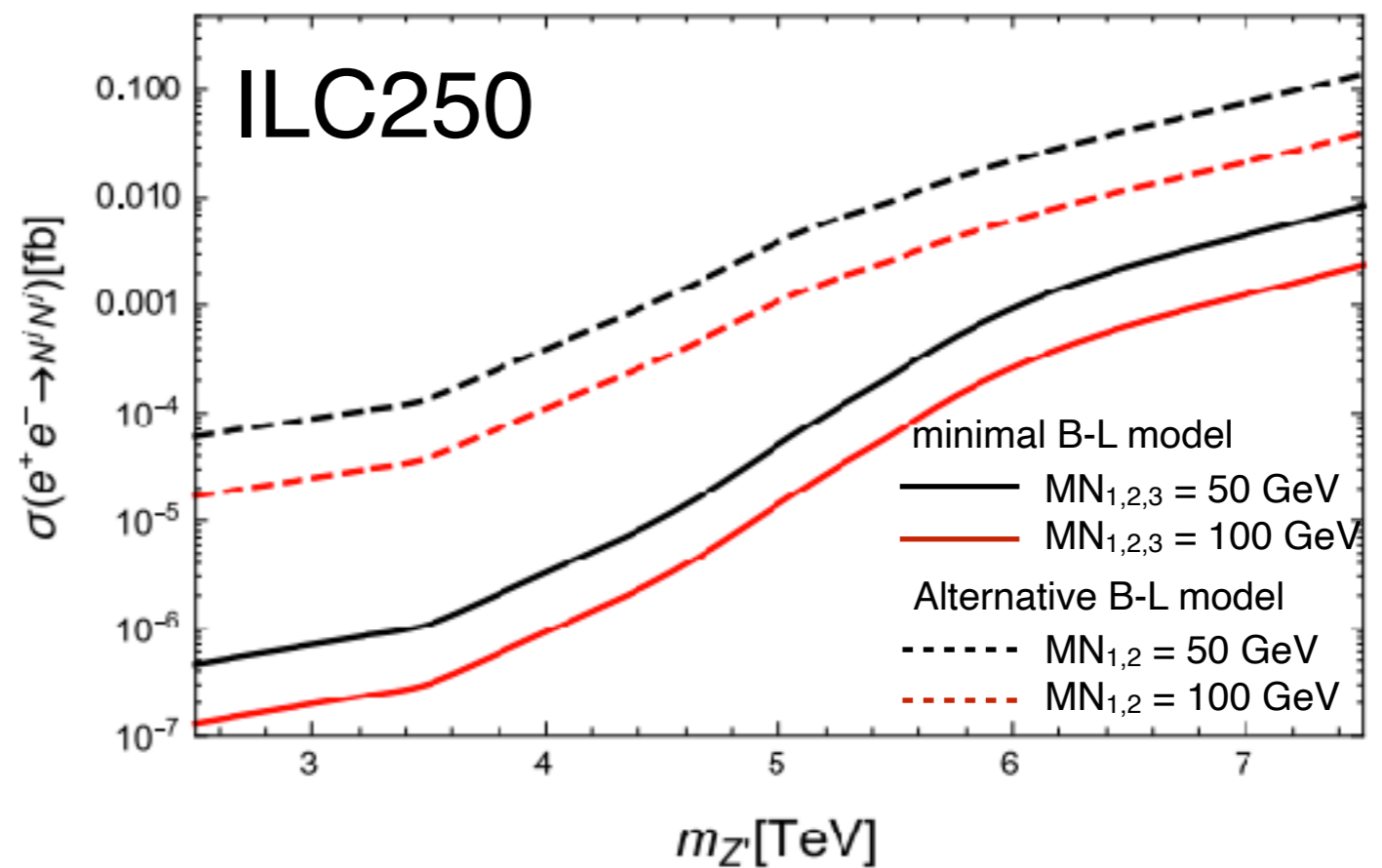
# Current limits - Z' mass

SM like Z' coupling



ATLAS-TDR-LHCC2017-2018

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

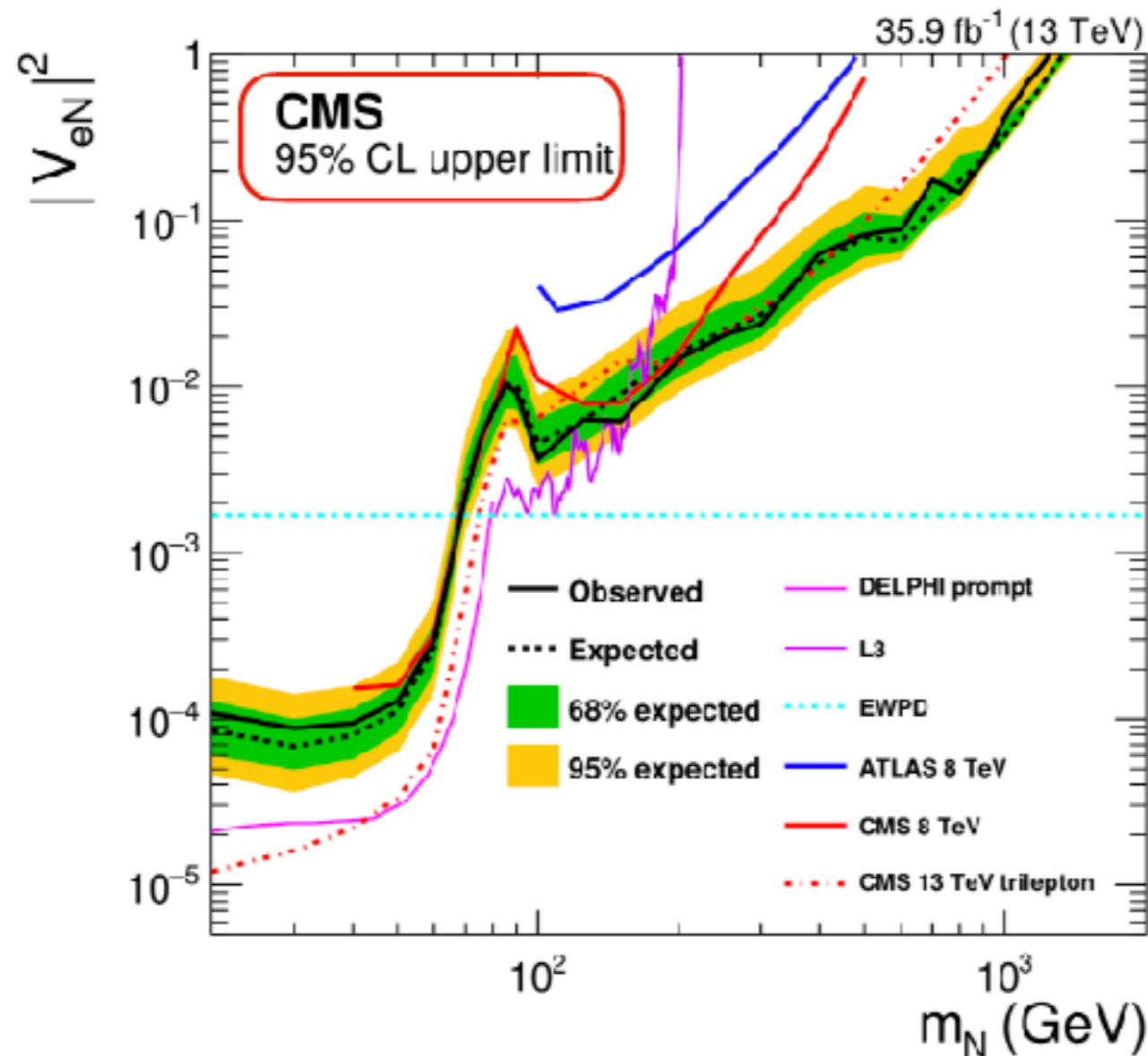


[arXiv\[1812.11931\]](https://arxiv.org/abs/1812.11931)

**The heavier Z' mass less constrained by LHC**

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

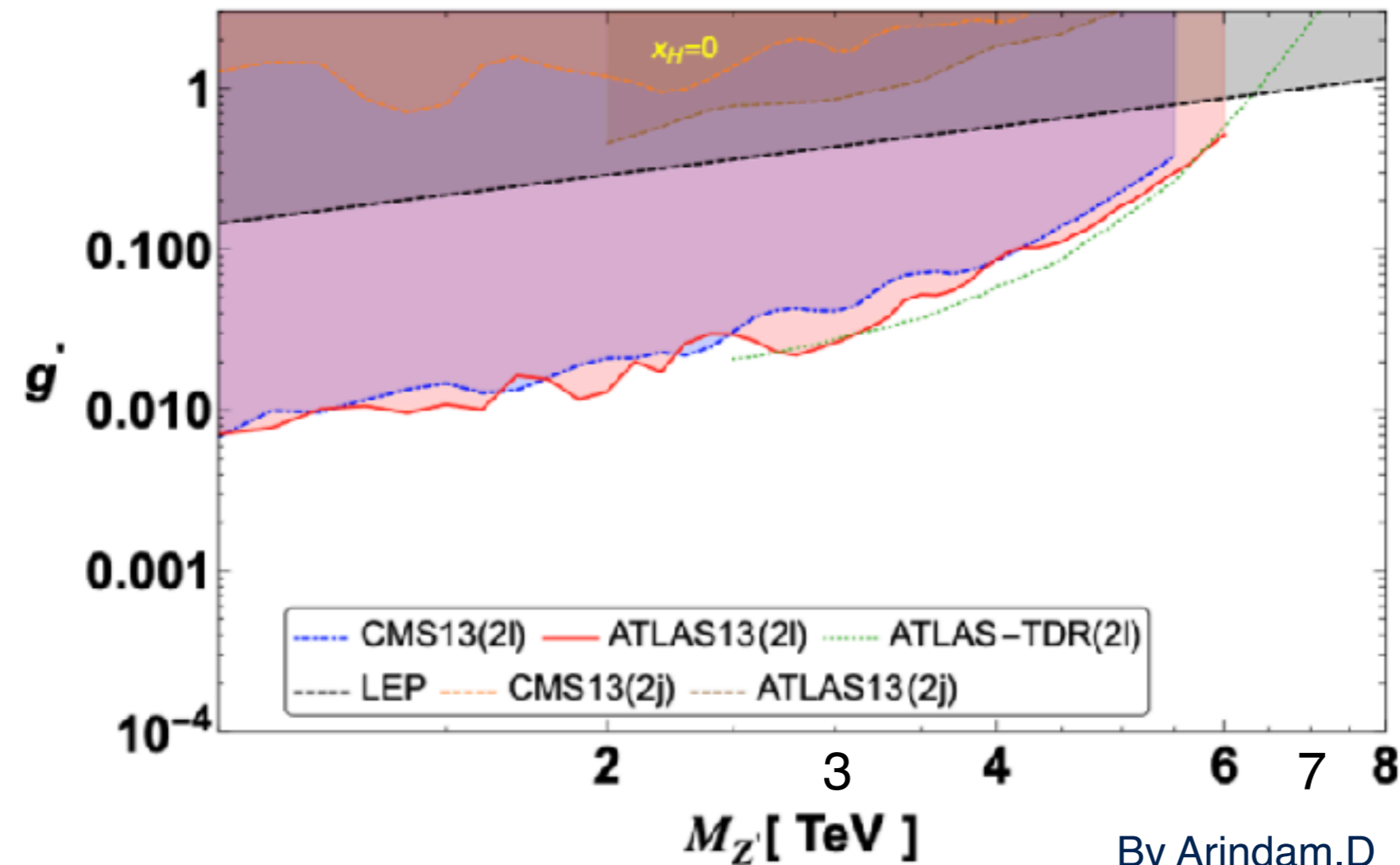
$|V_{eN}|^2$  : the “light-heavy” neutrino mixing matrix



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

# Current Limits and prospects - $Z'$ mass, $g_1'$

$G_1'$  :  $U(1)_{B-L}$  gauge coupling constant



$M_N$ [GeV]	$M_{Z'}$ [TeV]	$g_1'$
100	7	1
200	7	1