Signature of light Z’ boson from scalar boson decay in local $L_\mu - L_\tau$ model at the ILC

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(Based on arXiv: 1803.00842)

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Out line of the talk

1. Introduction
2. Model and constraint
3. Signal at the ILC
4. Summary

1. Introduction

Local U(1)$_{L\mu\text{-}L\tau}$ symmetry model

He, Joshi, Lew, Volkas PRD 43 (1991)
He, Lew, Volkas PRD 50 (1994)

μ(ν_μ) and τ(ν_τ) have opposite charge

- Motivated by resolving muon (g-2) anomaly

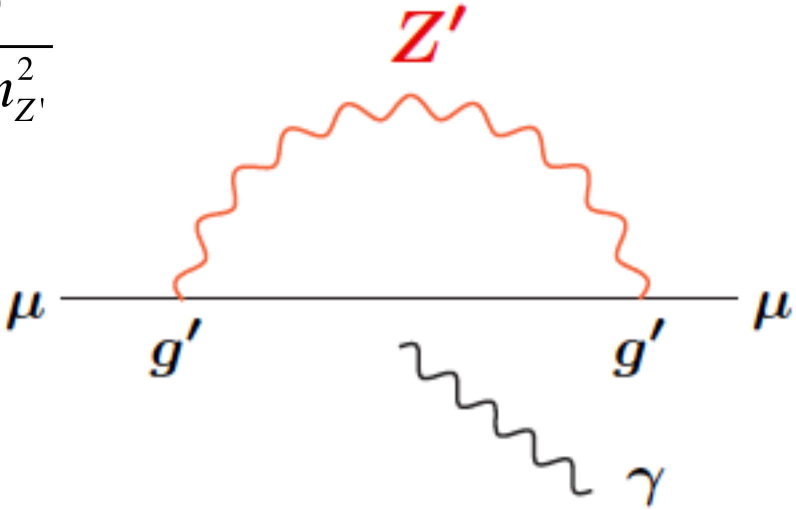
$$\Delta a_\mu \equiv \Delta a_\mu^{\rm exp} - \Delta a_\mu^{\rm th} = (28.8 \pm 8.0) \times 10^{-10},$$

~3.3σ – 3.6σ deviation

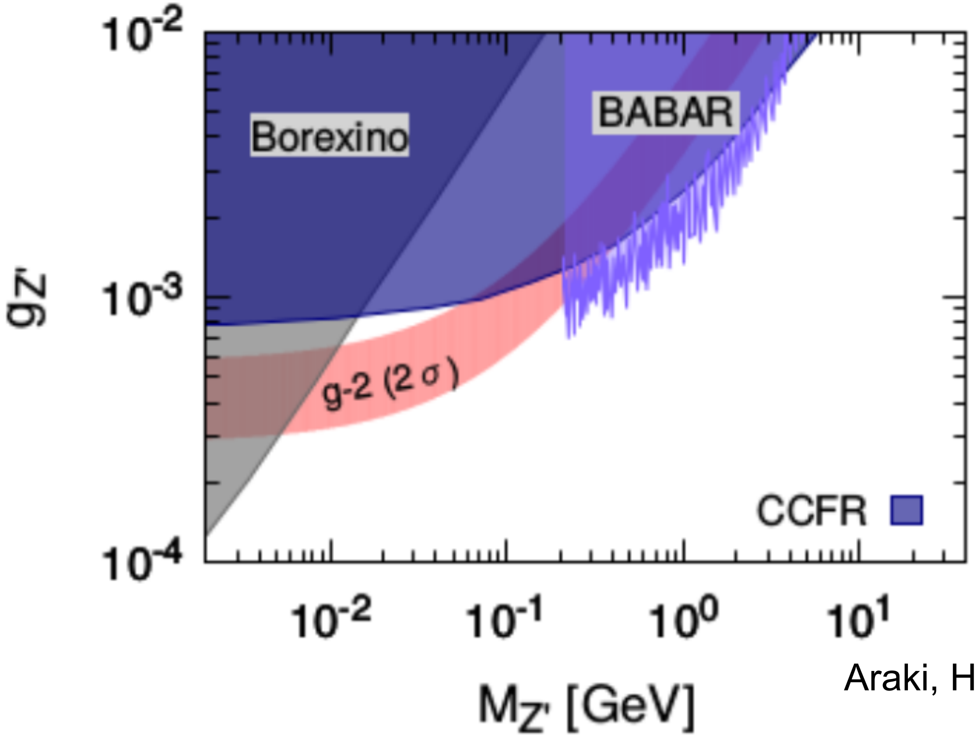
- Light Z' boson can contribute to muon (g-2)

$$\Delta a_\mu = \frac{g'^2}{8\pi}\int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)m_{Z'}^2}$$

∗ g': new gauge coupling



Allowed parameter region explaining g-2



Araki, Hoshino, Ota, Sato, Shimomura (2017)

$$2 \times 10^{-4} \leq g' \leq 2 \times 10^{-3},$$

$$5 \leq m_{Z'} \leq 210 \text{ MeV}.$$

Light Z’ with small coupling

Z’ decay into neutrinos
with small kinetic mixing

1. Introduction

We also have new scalar boson

⇨ From scalar field breaking U(1)$_{L\mu\text{-}L\tau}$

- The vev of the scalar can be estimated as

$$v_\phi = \frac{m_{Z'}}{g'} \sim \mathcal{O}(10 - 100)\ \mathrm{GeV}$$

- The mass of the scalar will be the same order or less

$$m_\phi = \sqrt{\lambda} v_\phi \leq \mathcal{O}(100)\ \mathrm{GeV}$$

It can be produced via new scalar-Higgs mixing

Its decay into Z' bosons indicate symmetry breaking

⇨ Search for the signal at the ILC

Out line of the talk

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Minimal local U(1)$_{L\mu\text{-}L\tau}$ model

	Scalar		Lepton					
	H	φ	L_e	L_μ	L_τ	e_R	μ_R	τ_R
$SU(2)_L$	**2**	**1**	**2**	**2**	**2**	**1**	**1**	**1**
$U(1)_Y$	$\frac{1}{2}$	0	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1
$U(1)_{L_\mu - L_\tau}$	0	1	0	1	-1	0	1	-1

- ➢ Anomaly free
- ➢ VEV of φ breaks U(1)$_{L\mu\text{-}L\tau}$

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \tilde{H} + iG^0) \end{pmatrix}, \quad \varphi = \frac{1}{\sqrt{2}}(v_\varphi + \tilde{\phi} + iG_{Z'})$$

Lagrangian of the model

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + |D_\mu \varphi|^2 - \underbrace{V}_{\text{Scalar potential}} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} - \underbrace{\frac{\epsilon}{2} B_{\mu\nu} Z'^{\mu\nu}}_{\text{Kinetic mixing}} + g' Z'_\mu J^\mu_{Z'},$$

$$J^\mu_{Z'} = \bar{L}_\mu \gamma^\mu L_\mu + \bar{\mu}_R \gamma^\mu \mu_R - \bar{L}_\tau \gamma^\mu L_\tau - \bar{\tau}_R \gamma^\mu \tau_R,$$

$$V = -\mu_H^2 H^\dagger H - \mu_\varphi^2 \varphi^* \varphi + \frac{\lambda_H}{2}(H^\dagger H)^2 + \frac{\lambda_\varphi}{2}(\varphi^* \varphi)^2 + \lambda_{H\varphi}(H^\dagger H)(\varphi^* \varphi),$$

Mass eigenstates/eigenvalues after symmetry breaking

- Scalar bosons

$$h = \cos\alpha \tilde{H} + \sin\alpha \tilde{\phi}$$

$$\phi = -\sin\alpha \tilde{H} + \cos\alpha \tilde{\phi}$$

$$\left(\tan 2\alpha = \frac{2\lambda_{H\varphi} v v_\varphi}{\lambda_H v^2 - \lambda_\varphi v_\varphi^2} \right)$$

$$m_{h,\phi}^2 = \frac{\lambda_H v^2 + \lambda_\varphi v_\varphi^2}{4} \pm \frac{1}{4}\sqrt{\left(\lambda_H v^2 - \lambda_\varphi v_\varphi^2\right)^2 + 4\lambda_{H\varphi}^2 v^2 v_\varphi^2},$$

- gauge boson

$$Z_{L\mu - L\tau} \approx Z' - \varepsilon \sin\theta_W Z \qquad m_{Z'} = g' v_\varphi$$

Yukawa and gauge interactions

$$L \supset \sin\alpha\phi\left[\sum_f \frac{m_f}{v}\bar{f}f + \frac{m_Z^2}{v}Z_\mu Z^\mu + \frac{2m_W^2}{v}W_\mu^+ W^{-\mu}\right]$$

$$+\cos\alpha h\left[\sum_f \frac{m_f}{v}\bar{f}f + \frac{m_Z^2}{v}Z_\mu Z^\mu + \frac{2m_W^2}{v}W_\mu^+ W^{-\mu}\right]$$

$$+\frac{m_{Z'}^2}{v_\varphi}\cos\alpha\phi Z'^\mu Z'_\mu + \frac{m_{Z'}^2}{v_\varphi}\sin\alpha h Z'^\mu Z'_\mu$$

$$+Z'_\mu(-e\varepsilon\cos\theta_W J_{EW}^\mu + g' J_{Z'}^\mu) + O(\varepsilon^2)$$

- New scalar interact with SM particles via mixing between SM Higgs
- Z’ interact with μ and τ type leptons
- Z’e+e- interaction via kinetic mixing

Decay mode of new particles

- Scalar boson (dominant modes)

$$\Gamma_{\phi\to Z'Z'} = \frac{g'^2\cos^2\alpha}{8\pi}\frac{m_{Z'}^2}{m_\phi}\sqrt{1-\frac{4m_{Z'}^2}{m_\phi^2}}\left(2+\frac{m_\phi^4}{4m_{Z'}^4}\left(1-\frac{2m_{Z'}^2}{m_\phi^2}\right)^2\right)$$

$$\Gamma_{\phi\to f\bar{f}} = \frac{m_\phi}{8\pi}\left(\frac{m_f}{v}\right)^2\sin^2\alpha\left(1-\frac{4m_f^2}{m_\phi^2}\right)^{\frac{3}{2}}$$

To resolve muon g-2,

$$\frac{m_\phi}{m_{Z'}}\sim 10^3 \quad \left(m_{Z'}\sim 0.1\,GeV, m_\phi\sim 100\,GeV\right)$$

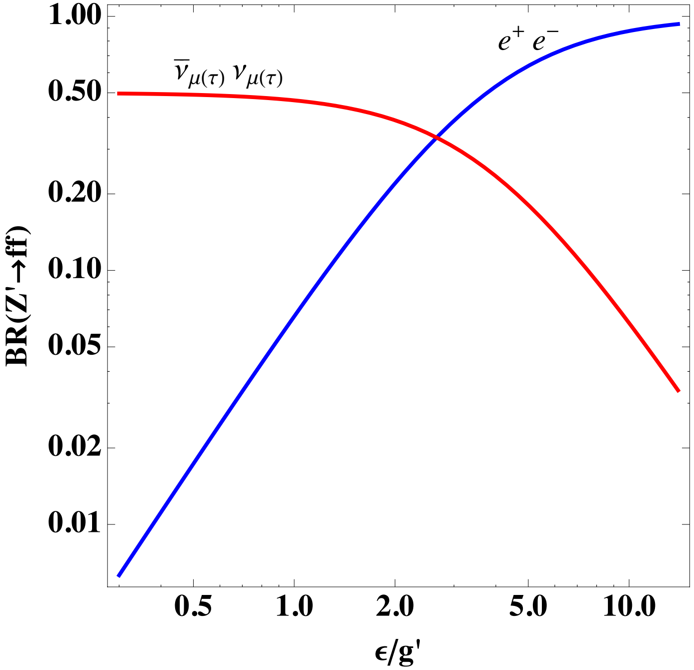
➡ Z’Z’ model is dominant: BR(Φ→Z’Z’) > 0.99

Decay mode of new particles

- Z’ boson (dominant modes)

$$\Gamma_{Z'\to\nu\bar{\nu}} = \frac{g'^2}{24\pi} m_{Z'}$$

$$\Gamma_{Z'\to e^+e^-} \approx \frac{e^2\varepsilon^2\cos^2\theta_W}{12\pi} m_{Z'}$$



We consider ε/g’ = 1 ⇨ Z’ mainly decay into neutrinos

Thus decay chain on new scalar is

$$\phi \to Z'Z' \to \nu\bar{\nu}\nu\bar{\nu}$$

- ➢ Missing energy at detector
- ➢ Different from SM Higgs decay

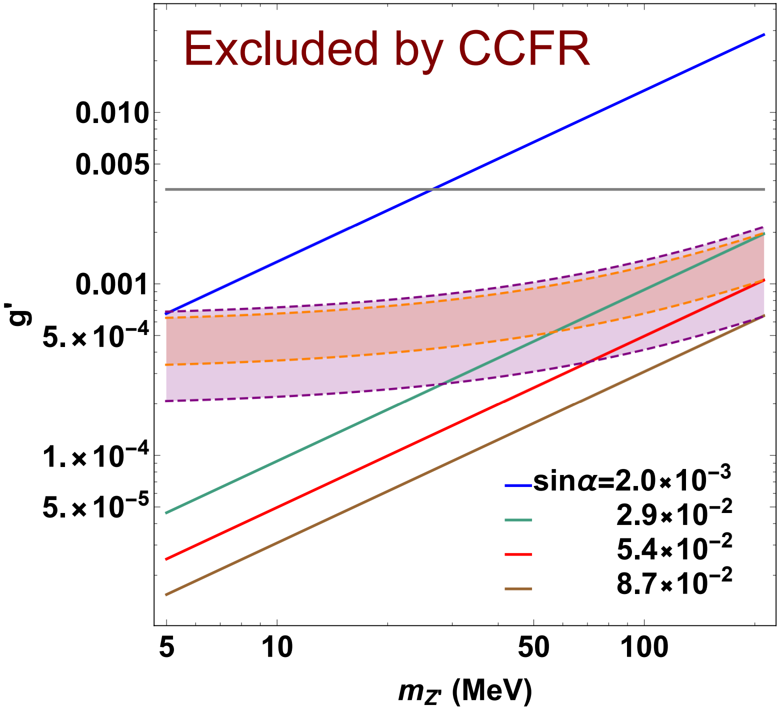
Constraints from invisible Higgs decay and scalar mixing

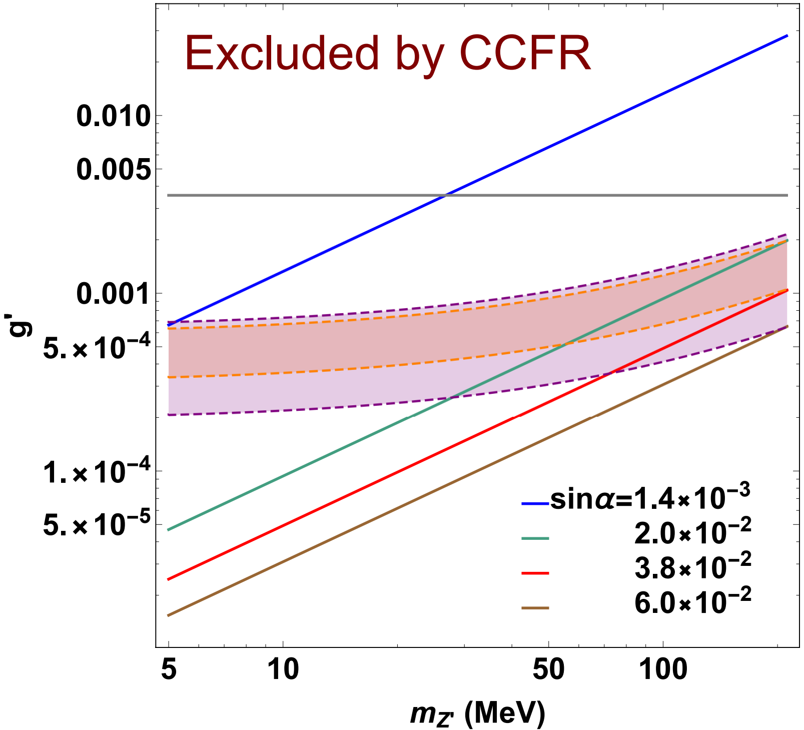
SM Higgs can decay into new particles $H \rightarrow Z'Z', \phi\phi$

⇨ Invisible Higgs decay

In addition, we apply constraints from scalar mixing

$$BR(H \rightarrow invisible) < 0.25, \quad \sin\alpha < 0.3$$





Other constrains

- Z’ search in meson decays at NA64: Z’ → e^+e^-

NA64 collaboration (2017)

⇨ $\varepsilon / g' \leq 2(0.6)$ For $m_{Z'}$ = 100 (5) MeV

Mostly Z’ decays into neutrinos

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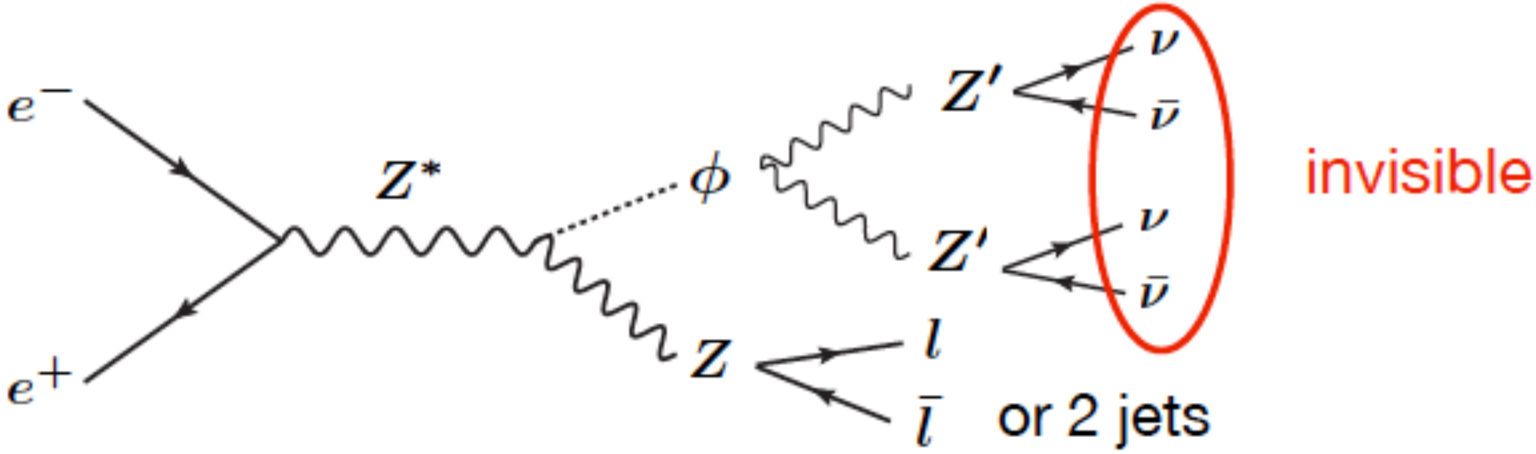
The Signal from hidden scalar production at the ILC



Signal processes

$$e^+e^- \rightarrow l^+l^- + E_{mis} \quad (l = e, \mu)$$

$$e^+e^- \rightarrow jj + E_{mis}$$

Background processes

$$e^+e^- \rightarrow l^+l^-\nu\nu, \quad \tau^+\tau^-$$ (with leptonic decay of tau)

$$e^+e^- \rightarrow jj\nu\nu, \quad \tau^+\tau^-$$ (with hadronic decay of tau)

Numerical analysis for signals/BGs at the ILC

- We carry out simulation study using MADGRAPH/MADEVENT
- Applying PYTHIA6 for ISR/FSR and hadronization
- Detector simulation applying DELPHES

(ILD card based on arXiv:1306.6329)

We also apply polarized beam at the ILC 250 GeV

(e^+, e^-) polarization (+,-) → LL polarization

(e^+, e^-) polarization (-,+) → RR polarization

Max integrated luminosity is taken as 900 fb^{-1} each polarization

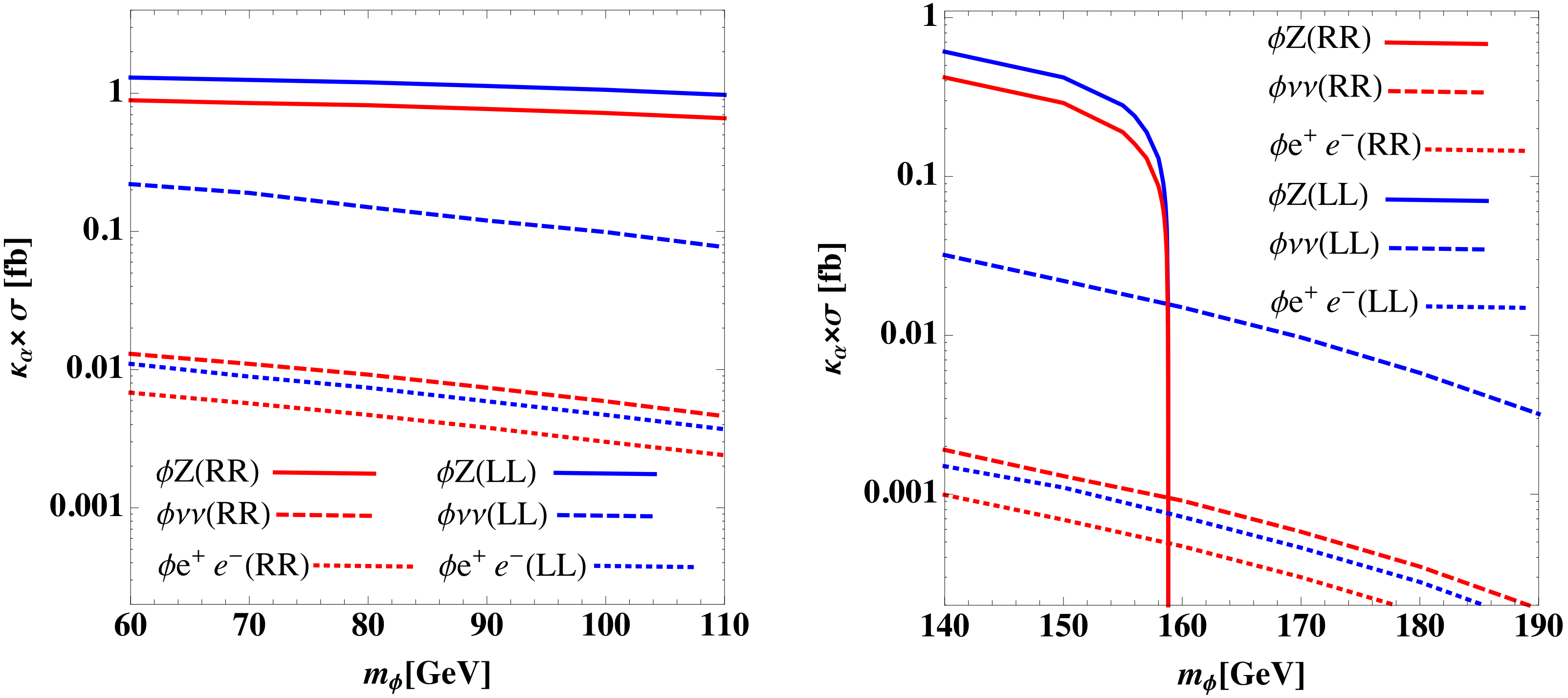
LL: (e^+, e^-) polarization (+30%,-80%) with L=900 fb^{-1}

RR: (e^+, e^-) polarization (-30%,+80%) with L=900 fb^{-1}

With more realistic polarization ratio

3. Signal at the ILC

The cross section for scalar production



($\kappa_\alpha=(0.05/\sin\alpha)^2$)

The cross section for SM backgrounds

$$\sigma(e^+e^- \to l^+l^-\nu\nu) \sim 1.99(0.186)\ pb, \quad \sigma(e^+e^- \to \tau^+\tau^-) \sim 2.36(1.94)\ pb$$

$$\sigma(e^+e^- \to jj\nu\nu) \sim 0.398(0.158)\ pb$$

For LL(RR) polarization

Kinematical cuts and mass reconstruction

- **Basic cuts**

$p_T(l^\pm) > 7\,GeV, \quad |\eta(l^\pm)| < 2.5$ For charged leptons

$p_T(j) > 20\,GeV, \quad |\eta(j)| < 5.0$ For jets

- **Invariant mass cuts**

$m_Z - 10\,GeV < M_{l^+l^-} < m_Z + 10\,GeV$ For charged leptons

$m_Z - 20\,GeV < M_{jj} < m_Z + 5\,GeV$ For jets

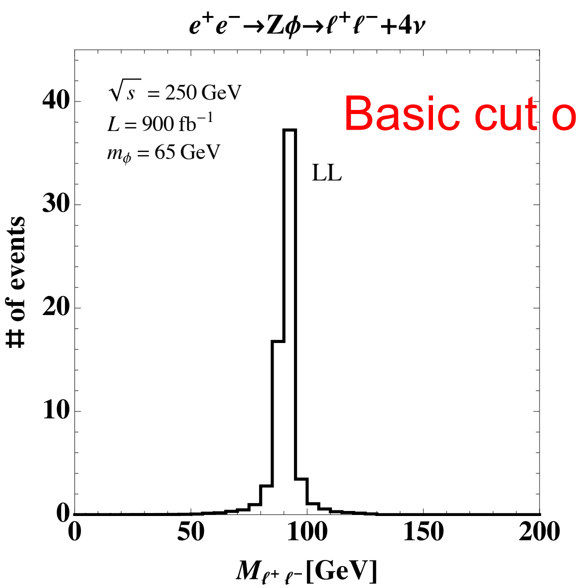
- **Scalar mass reconstruction**

$$M_\phi^{rec} = \sqrt{s + m_Z^2 - 2\left(E_{l^+/j_1} + E_{l^-/j_2}\right)\sqrt{s}}$$

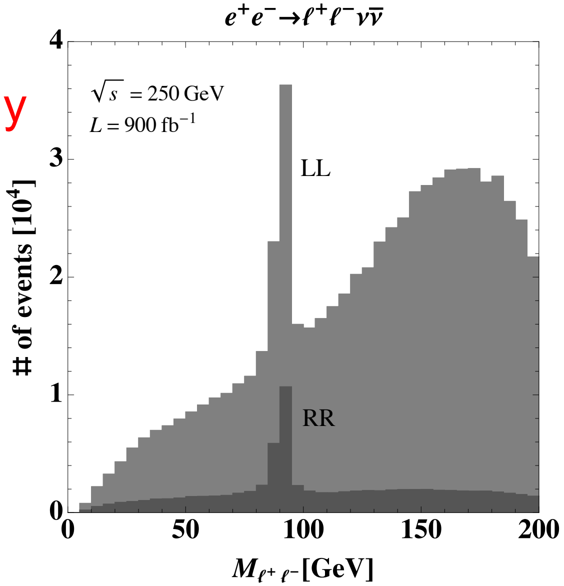
3. Signal at the ILC

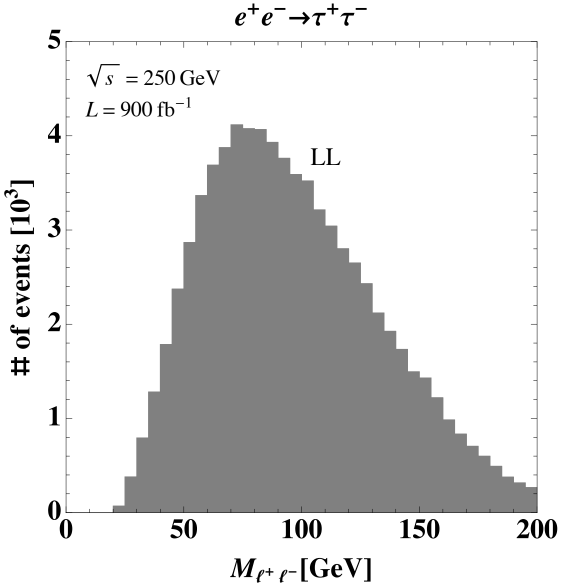
Signal

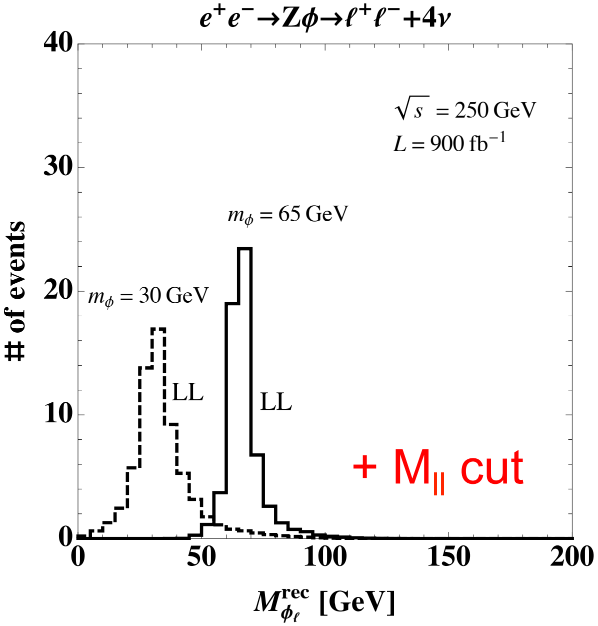
Distributions for leptonic signal/BGs



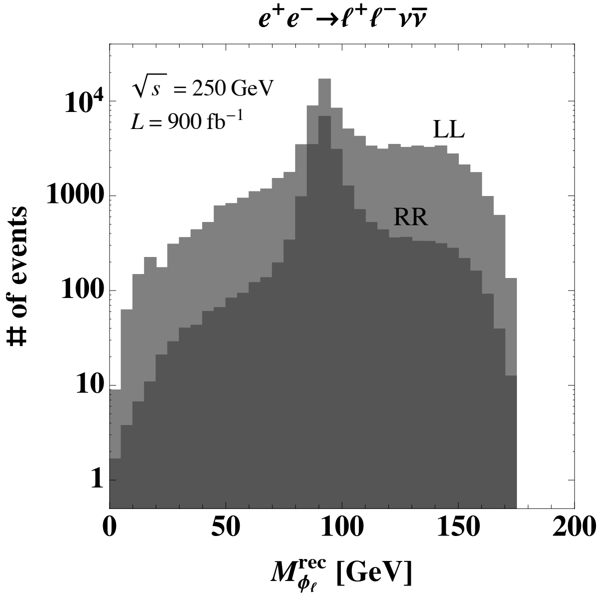
Basic cut only

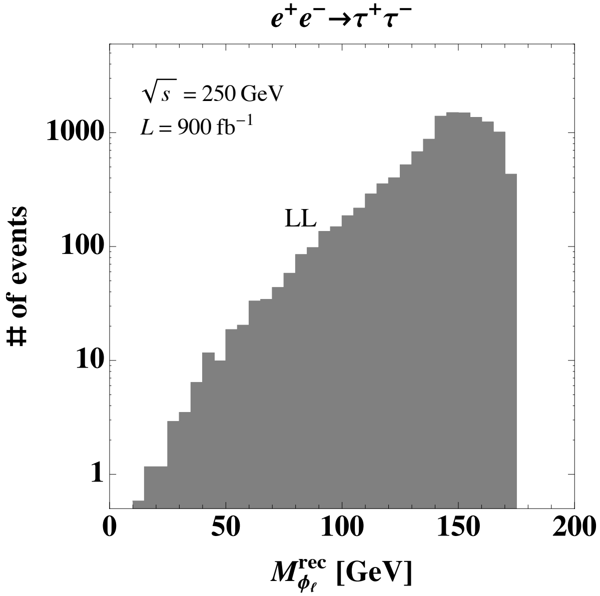






+ M_{ll} cut

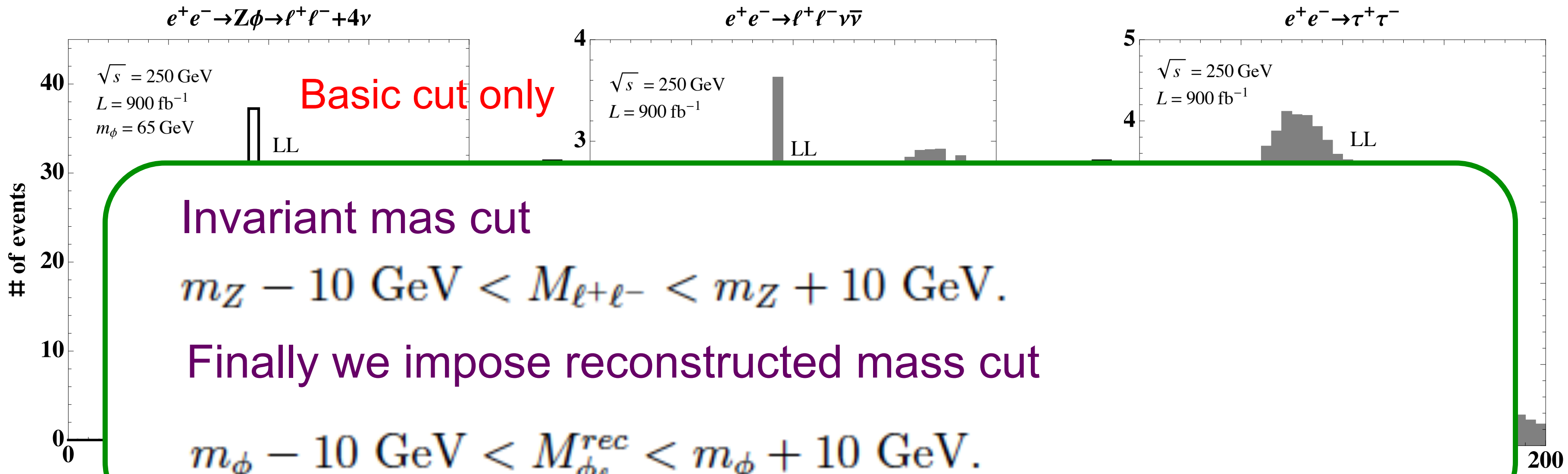




3. Signal at the ILC

Distributions for leptonic signal/BGs

Signal



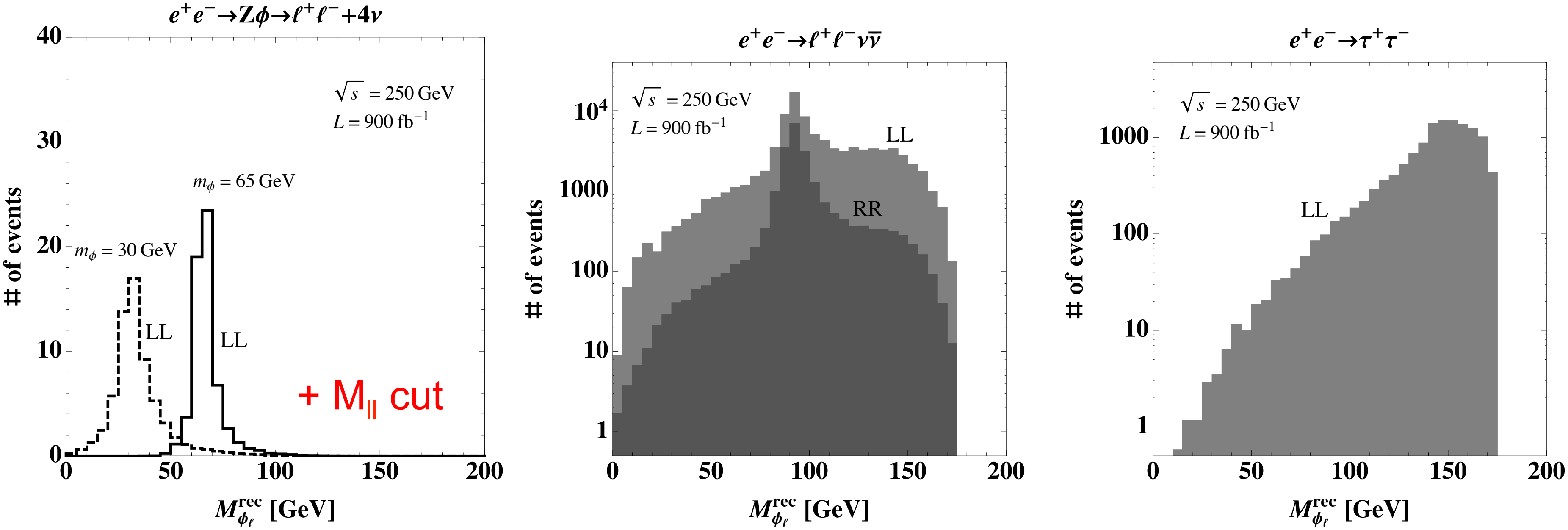
Basic cut only

Invariant mas cut

$$m_Z - 10\ \text{GeV} < M_{\ell^+\ell^-} < m_Z + 10\ \text{GeV}.$$

Finally we impose reconstructed mass cut

$$m_\phi - 10\ \text{GeV} < M^{rec}_{\phi_\ell} < m_\phi + 10\ \text{GeV}.$$



+ M_{ll} cut

3. Signal at the ILC

of events before/after kinematical cuts

	$\kappa_\alpha N_S^{\kappa_\alpha=1}$; $m_\phi = (65, 30)$ GeV	$N_{BG}^{\ell^+\ell^-\nu\bar{\nu}}$	$N_{BG}^{\tau\tau}$	$\kappa_\alpha S_{cl}^{\kappa_\alpha=1}$
Only basic cuts	(51., 53.)	7.7×10^4	6.3×10^4	(0.14, 0.14)
+ $M_{\ell^+\ell^-}$ cut	(48., 49.)	2.1×10^4	1.3×10^4	(0.25, 0.27)
+ $M_{\phi\ell}^{rec}$ cut for $m_\phi = 65$ GeV	(42., $\cdots$)	2.2×10^2	1.3×10^2	(2.2, $\cdots$)
+ $M_{\phi\ell}^{rec}$ cut for $m_\phi = 30$ GeV	($\cdots$, 34.)	1.7×10^2	14.	($\cdots$, 2.5)

Comparing different polarizations

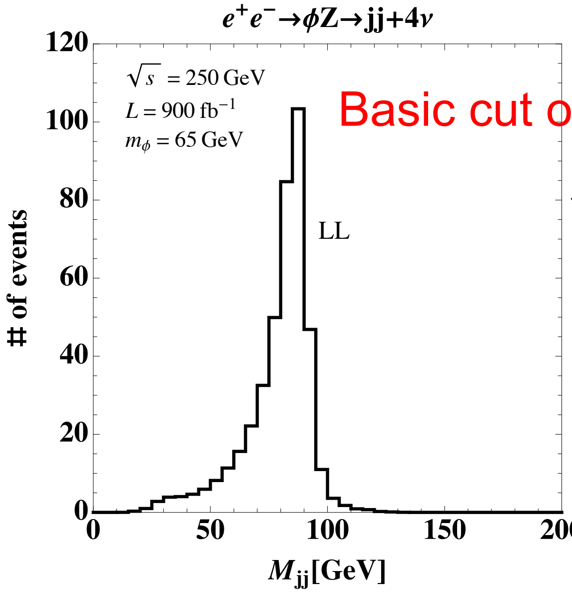
	$\kappa_\alpha N_S^{\kappa_\alpha=1}$; $m_\phi = 65(30)$ GeV	$N_{BG}^{\ell^+\ell^-\nu\bar{\nu}}$	$N_{BG}^{\tau\tau}$	$\kappa_\alpha S_{cl}^{\kappa_\alpha=1}$
RR	42.(34.)	$2.2(1.7) \times 10^2$	$1.3(0.14) \times 10^2$	2.2(2.5)
LL	53.(47.)	$4.7(1.7) \times 10^3$	$1.6(0.15) \times 10^2$	0.75(1.1)
$LL + RR$	95.(81.)	$4.9(1.9) \times 10^3$	$2.9(0.29) \times 10^2$	1.3(1.8)

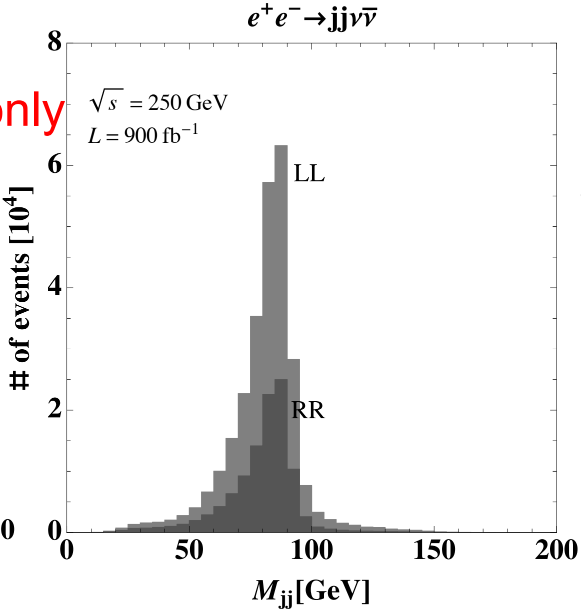
$$\left(S_{cl} = \frac{N_S}{\sqrt{N_{BG}}}, \right)$$

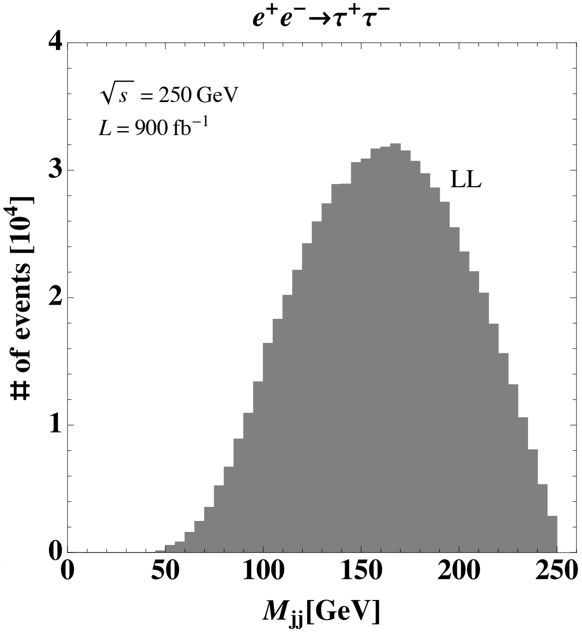
Distributions for hadronic signal/BGs

Signal

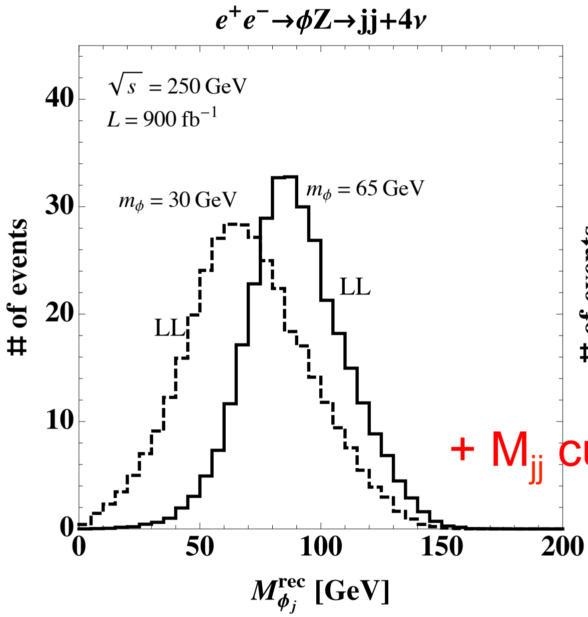
Basic cut only

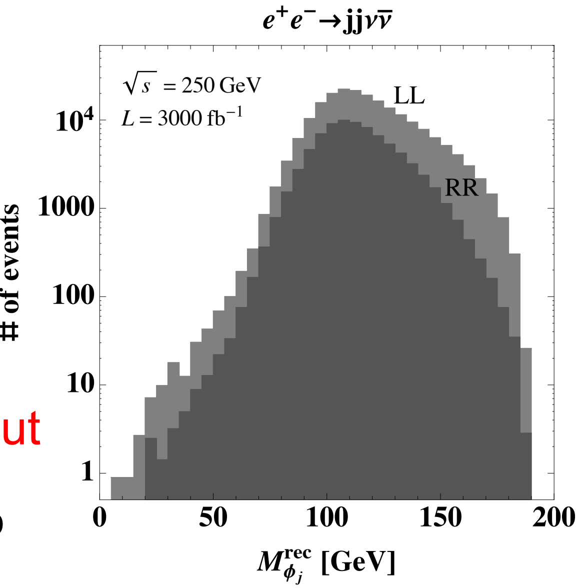


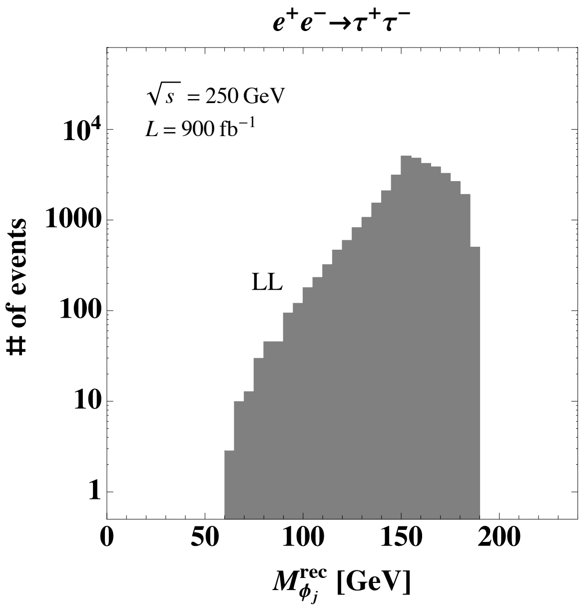




+ M_{jj} cut





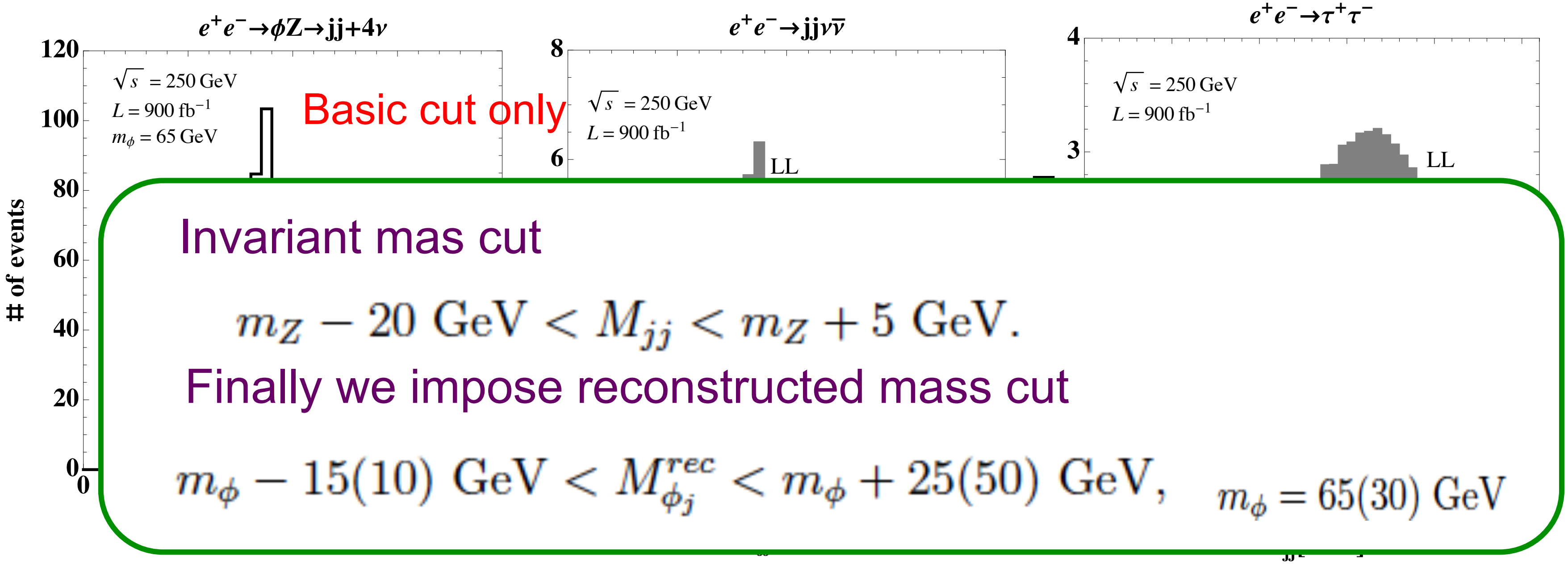


3. Signal at the ILC

Distributions for hadronic signal/BGs

Signal

Basic cut only

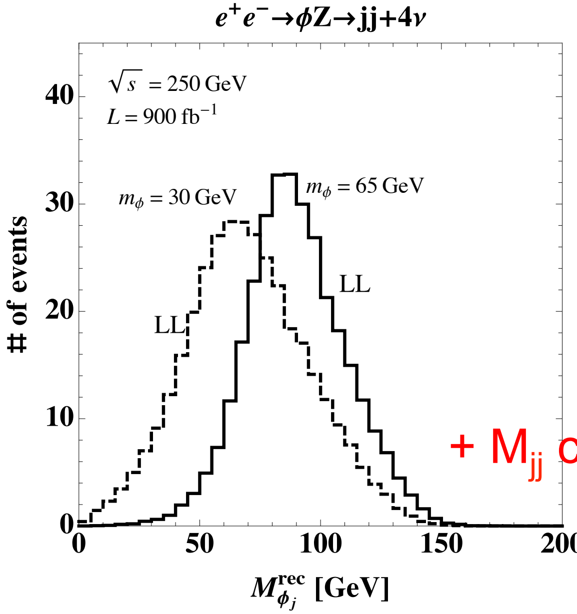


Invariant mas cut

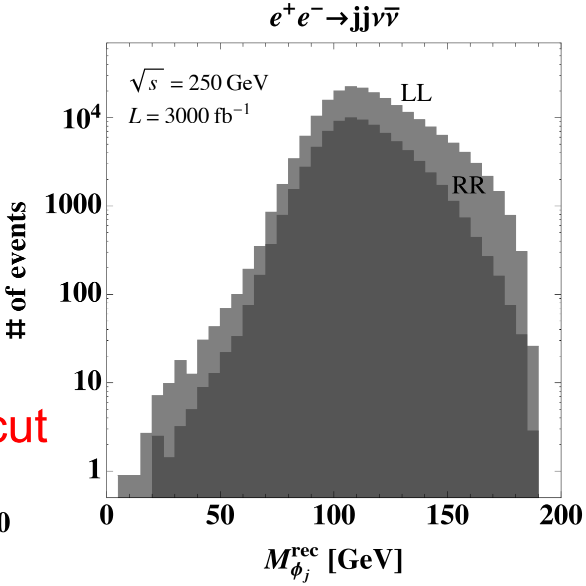
$$m_Z - 20\ \mathrm{GeV} < M_{jj} < m_Z + 5\ \mathrm{GeV}.$$

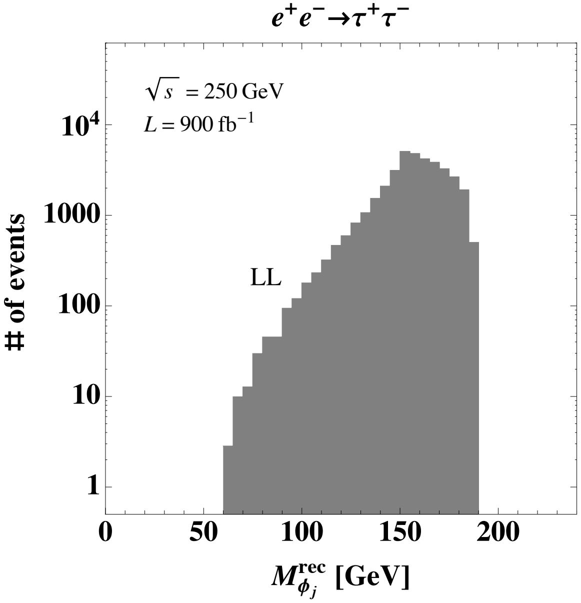
Finally we impose reconstructed mass cut

$$m_\phi - 15(10)\ \mathrm{GeV} < M_{\phi_j}^{rec} < m_\phi + 25(50)\ \mathrm{GeV}, \quad m_\phi = 65(30)\ \mathrm{GeV}$$



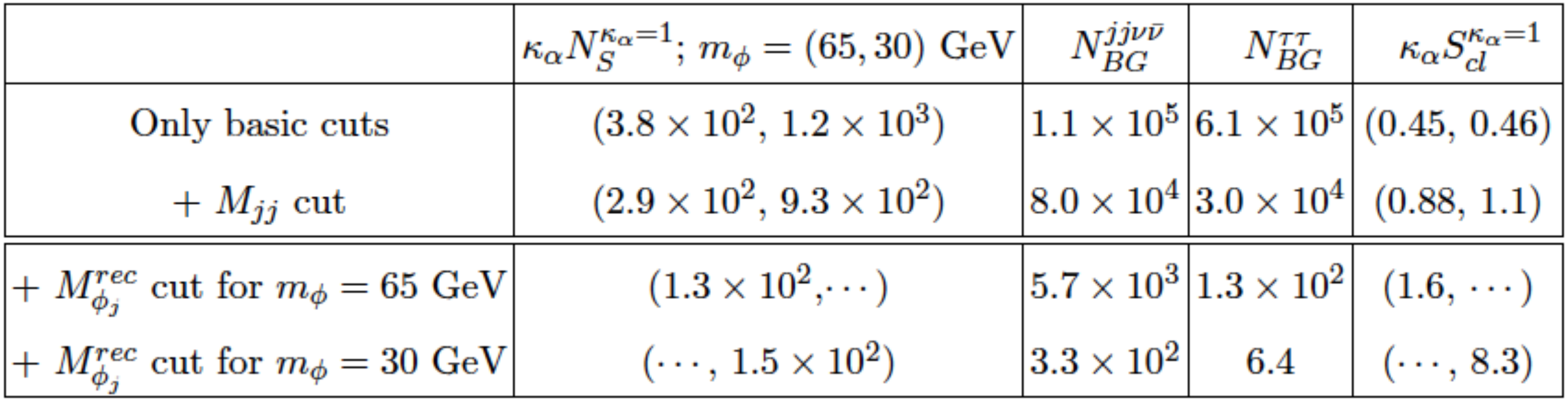
+ M_{jj} cut





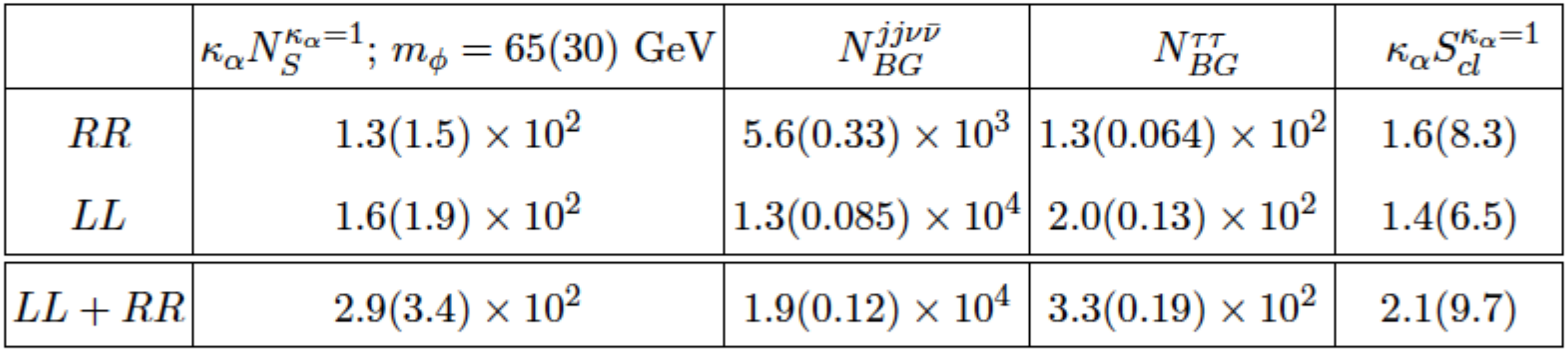
3. Signal at the ILC

of events before/after kinematical cuts



	$\kappa_\alpha N_S^{\kappa_\alpha=1}$; $m_\phi = (65, 30)$ GeV	$N_{BG}^{jj\nu\bar{\nu}}$	$N_{BG}^{\tau\tau}$	$\kappa_\alpha S_{cl}^{\kappa_\alpha=1}$
Only basic cuts	$(3.8 \times 10^2,\ 1.2 \times 10^3)$	1.1×10^5	6.1×10^5	$(0.45,\ 0.46)$
+ M_{jj} cut	$(2.9 \times 10^2,\ 9.3 \times 10^2)$	8.0×10^4	3.0×10^4	$(0.88,\ 1.1)$
+ $M_{\phi_j}^{rec}$ cut for $m_\phi = 65$ GeV	$(1.3 \times 10^2, \cdots)$	5.7×10^3	1.3×10^2	$(1.6,\ \cdots)$
+ $M_{\phi_j}^{rec}$ cut for $m_\phi = 30$ GeV	$(\cdots,\ 1.5 \times 10^2)$	3.3×10^2	6.4	$(\cdots,\ 8.3)$

Comparing different polarizations



	$\kappa_\alpha N_S^{\kappa_\alpha=1}$; $m_\phi = 65(30)$ GeV	$N_{BG}^{jj\nu\bar{\nu}}$	$N_{BG}^{\tau\tau}$	$\kappa_\alpha S_{cl}^{\kappa_\alpha=1}$
RR	$1.3(1.5) \times 10^2$	$5.6(0.33) \times 10^3$	$1.3(0.064) \times 10^2$	1.6(8.3)
LL	$1.6(1.9) \times 10^2$	$1.3(0.085) \times 10^4$	$2.0(0.13) \times 10^2$	1.4(6.5)
$LL + RR$	$2.9(3.4) \times 10^2$	$1.9(0.12) \times 10^4$	$3.3(0.19) \times 10^2$	2.1(9.7)

Summary and Discussions

☐ Minimal U(1)$_{L\mu\text{-}L\tau}$ model

- ✓ Anomaly free model
- ✓ Resolve anomalous muon magnetic moment
- ✓ We have new Z' and scalar bosons

☐ Signal at the ILC

- ✓ Scalar production via mixing between the SM Higgs
- ✓ New scalar dominantly decay into Z'Z' followed by Z' →νν
- ✓ Signal: Dilepton or Dijet + missing energy
- ✓ Testable at the ILC experiment

Thanks for listening !