Search for light scalar boson in minimal $U(1)_{L\mu\text{-}L\tau}$ model at ILC experiment

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(Miyazaki U.)

in collaboration with

Takaaki Nomura (KIAS, Korea)

"Light Z' boson from scalar boson decay at collider experiment in an $U(1)_{L\mu\text{-}L\tau}$ model"

arXiv:1803.00842

August 7th, 2018 @ PPP2018

Introduction

- The discrepancy of muon (g-2) is a long standing problem in particle physics.

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

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- Non-SM contributions are required to explain this discrepancy.

$$\Delta a_\mu^{NP} \sim \frac{f^2}{4\pi^2}\frac{m_\mu^2}{M^2} \sim 10^{-9}$$

M : mass of new particle
f : coupling const with muon

$$\rightarrow \quad \frac{f}{M} \sim 2 \times 10^{-3} \quad \text{(/GeV)}$$

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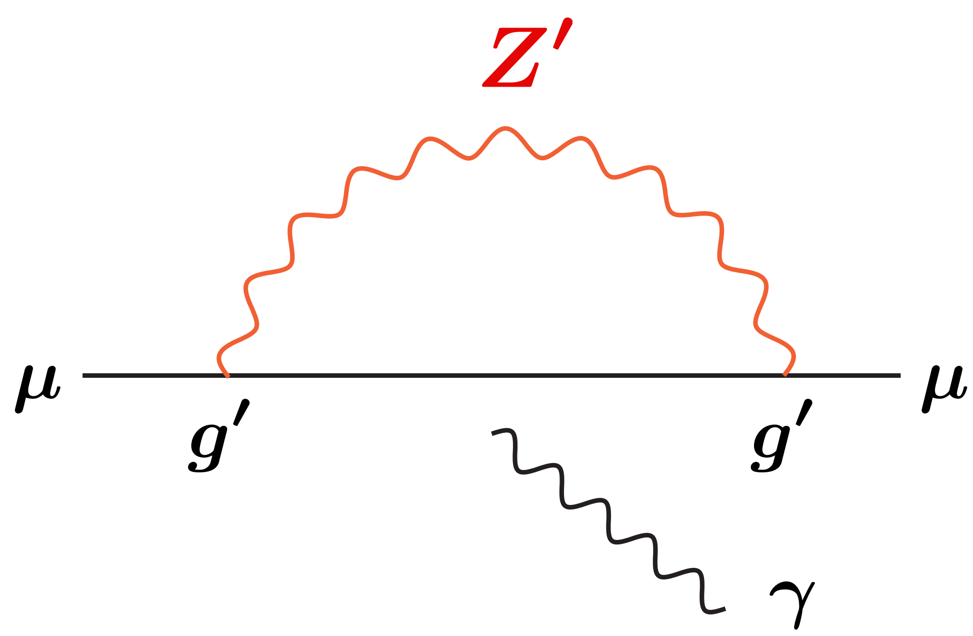
The scale of New Physics (NP)

- High scale NP, e.g. M=1 TeV and $f = O(1)$
- Low scale NP, e.g. M=100 MeV and $f = O(10^{-4})$

Introduction

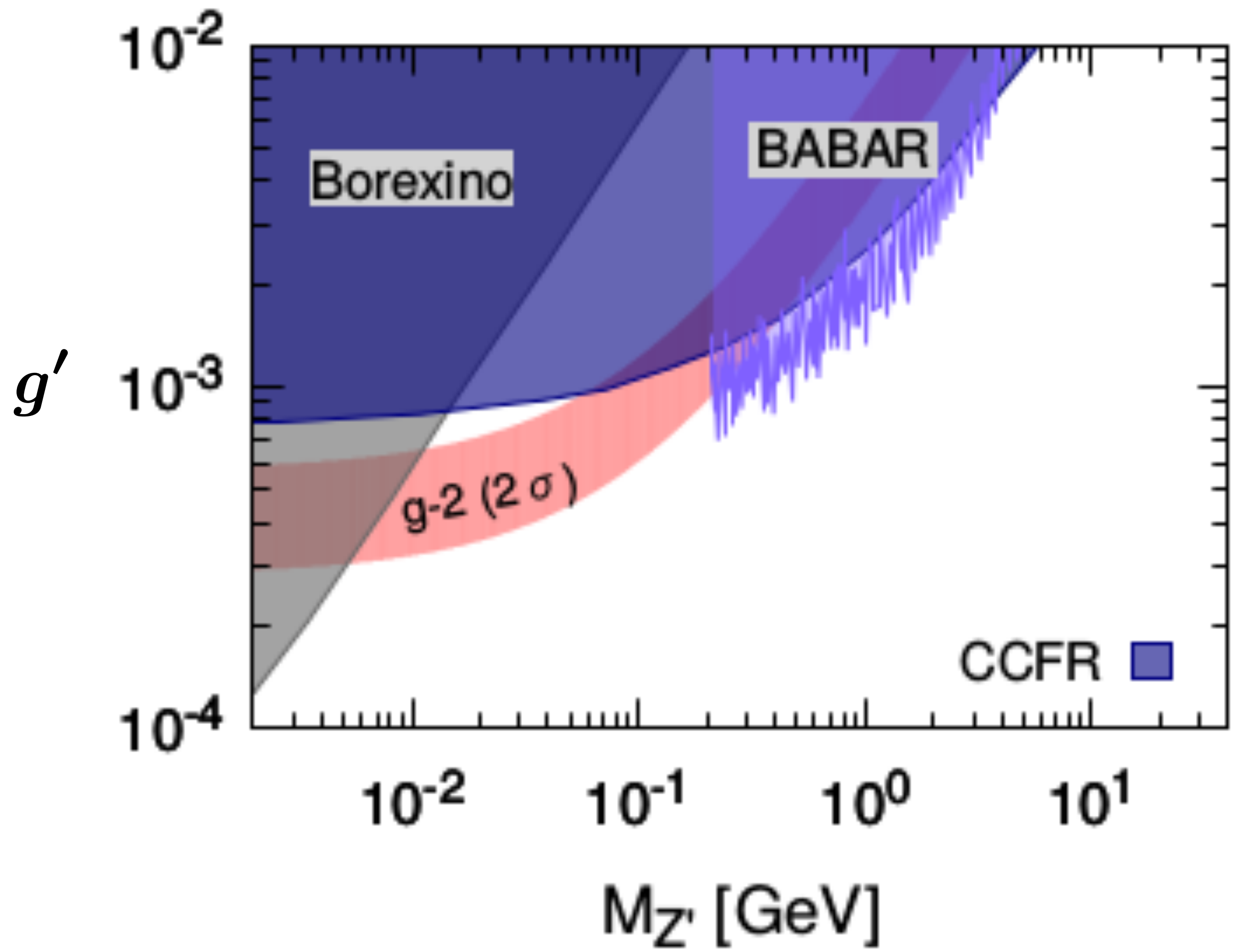
Gauged $U(1)_{L\mu\text{-}L\tau}$ model

Muon interacts with a gauge boson, *Z'*, of the symmetry



Introduction

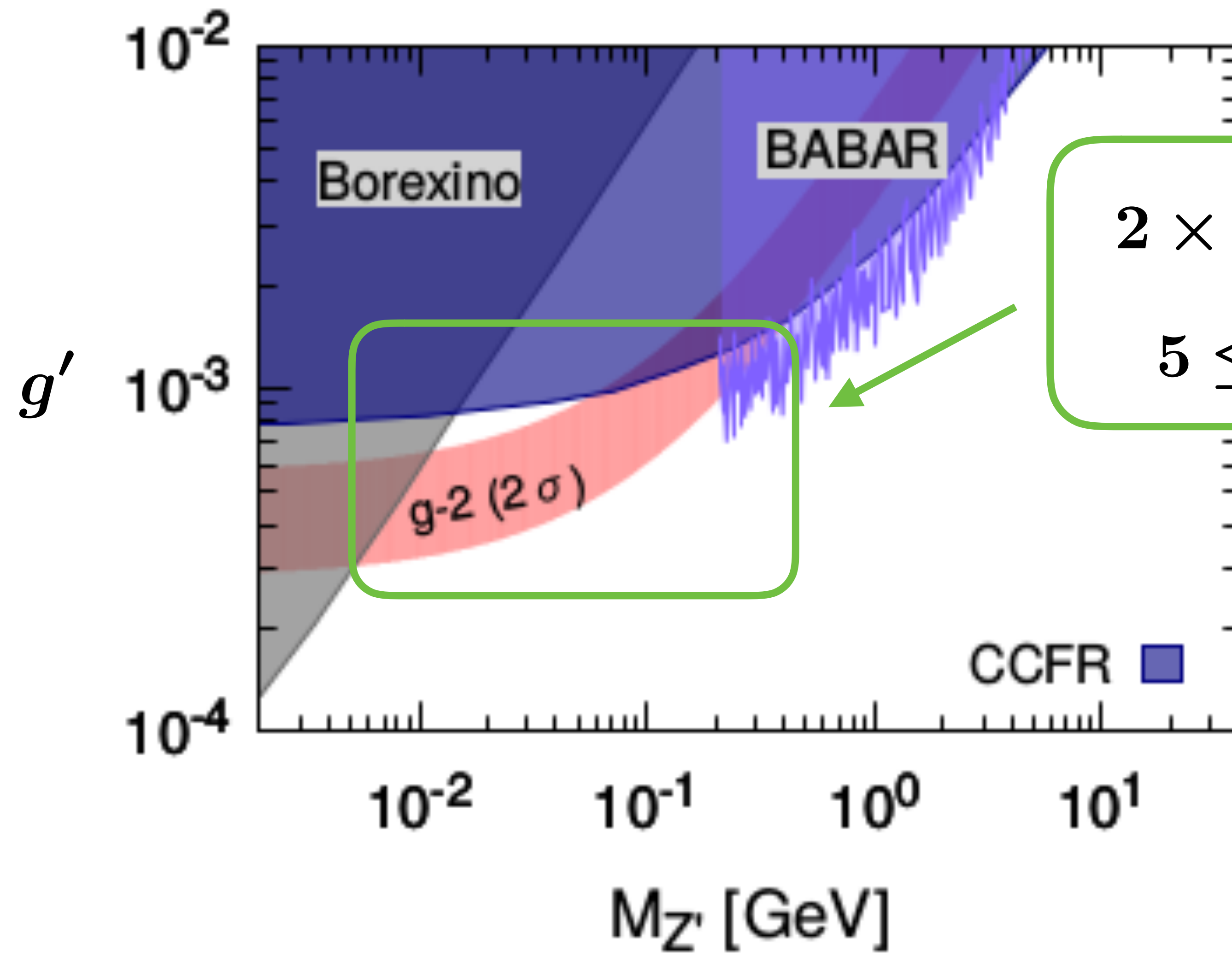
Gauged U(1)$_{L\mu-L\tau}$ model



Araki, Hoshino, Ota, Sato, T.S.
PRD95 (2017)

Introduction

Gauged $U(1)_{L\mu-L\tau}$ model



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

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

Araki, Hoshino, Ota, Sato, T.S.
PRD95 (2017)

Introduction

The $U(1)_{L\mu-L\tau}$ symmetry should be broken so that *Z'* acquires mass.

A new scalar boson must exist to break the symmetry spontaneously.

- 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

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

Purpose

There are two new particles at least

- Feebly int. gauge boson with mass < $\mathcal{O}(100)$ MeV

  Low energy with high luminosity, i.e. Belle-II

  - Araki, Hoshino, Ota, Sato, T.S. PRD95 (2017)
  - Kaneta, T.S. PTEP 2017

- Scalar boson with mass < $\mathcal{O}(100)$ GeV

  High energy with high luminosity, ILC!

Search for the symmetry breaking scalar at ILC

Table of Talk

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

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

We introduce one complex scalar to $U(1)_{L\mu\text{-}L\tau}$ model

- Anomaly free
- neutrino mass and mixing
- minimal setup

Choubey, Rodejohann, Eur.Phys.J, (2005)
Ota, Rodejohann, Phys.Lett. (2006)
Asai, Hamaguchi, Nagata, 1705.00419

	Scalar		Lepton					
	H	φ	L_e	L_μ	L_τ	e_R	μ_R	τ_R
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{2}$	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

The Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + |D_\mu \varphi|^2 - V - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} - \frac{\epsilon}{2} B_{\mu\nu} Z'^{\mu\nu} + g' Z'_\mu J^\mu_{Z'}$$

where gauge kinetic mixing

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

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

scalar mixing

* We omit RH neutrino sector. Neutrino mass generation is discussed in Asai, Hamaguchi, Nagata

Mass eigenstates

After the EW and $U(1)_{L\mu\text{-}L\tau}$ symmetry breaking,

scalar bosons:

$$h = \cos\alpha H + \sin\alpha\varphi, \qquad \tan 2\alpha = \frac{2\lambda_{H\varphi} v v_\varphi}{\lambda_H v^2 - \lambda_\varphi v_\varphi^2}$$
$$\phi = -\sin\alpha H + \cos\alpha\varphi,$$

where v and v_ϕ are the vev *of H* and ϕ, respectively.

gauge boson:

$$Z_3 = Z' - \epsilon \sin\theta_W Z$$

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The Yukawa and gauge int.

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

$$+\frac{m_{Z'}^2}{v_\varphi}\cos\alpha\phi Z'_\mu Z'^\mu + Z'_\mu(-e\epsilon\cos\theta_W J_{\mathrm{EM}}^\mu + g' J_{Z'}^\mu) + \mathcal{O}(\epsilon^2)$$

J_{EM} : Electromagnetic current

Decay of ϕ

Assuming $2m_t > m_\phi \gg m_{Z',f}$, the decay widths are

$$\Gamma_{\phi\to Z'Z'} \simeq \frac{g'^2 \cos^2\alpha}{32\pi} \frac{m_\phi^2}{m_{Z'}^2} m_\phi$$

$$\Gamma_{\phi\to f\bar{f}} \simeq \frac{\sin^2\alpha}{8\pi} \left(\frac{m_f}{v}\right)^2 m_\phi$$

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enhancement by *longitudinal mode*

$$\Gamma_{\phi\to f\bar{f}} \simeq \frac{\sin^2\alpha}{8\pi} \left(\frac{m_f}{v}\right)^2 m_\phi$$

To resolve $(g-2)_\mu$, $m_\phi/m_{Z'} \sim 10^3$ for m_ϕ=100 GeV and $m_{Z'}$=*100 MeV*

$$\Gamma_{\phi\to Z'Z'} \gg \Gamma_{\phi\to f\bar{f}}$$

Thus,

ϕ dominantly decays into *Z'* pair

Decay of Z'

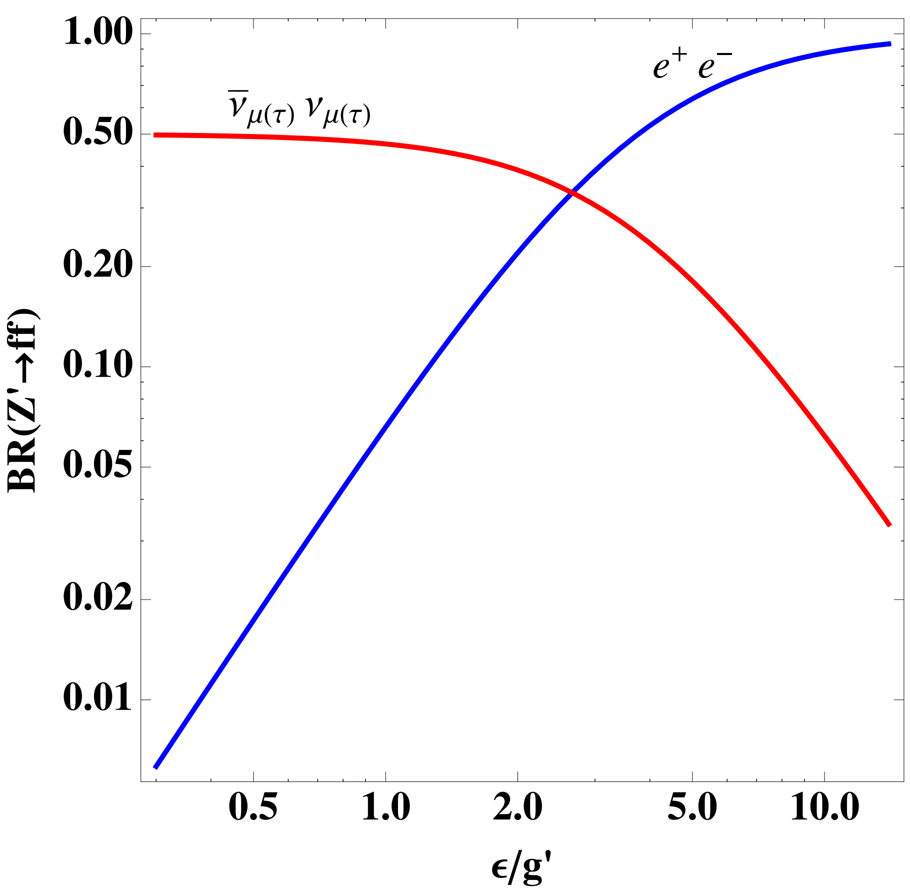
$$\Gamma_{Z' \to \nu\bar{\nu}} = \frac{g'^2}{24\pi} m_{Z'}$$

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

For *ε*/*g*' < 1,

Z' mainly decays into *ν*

$m_{Z'} = 100$ MeV



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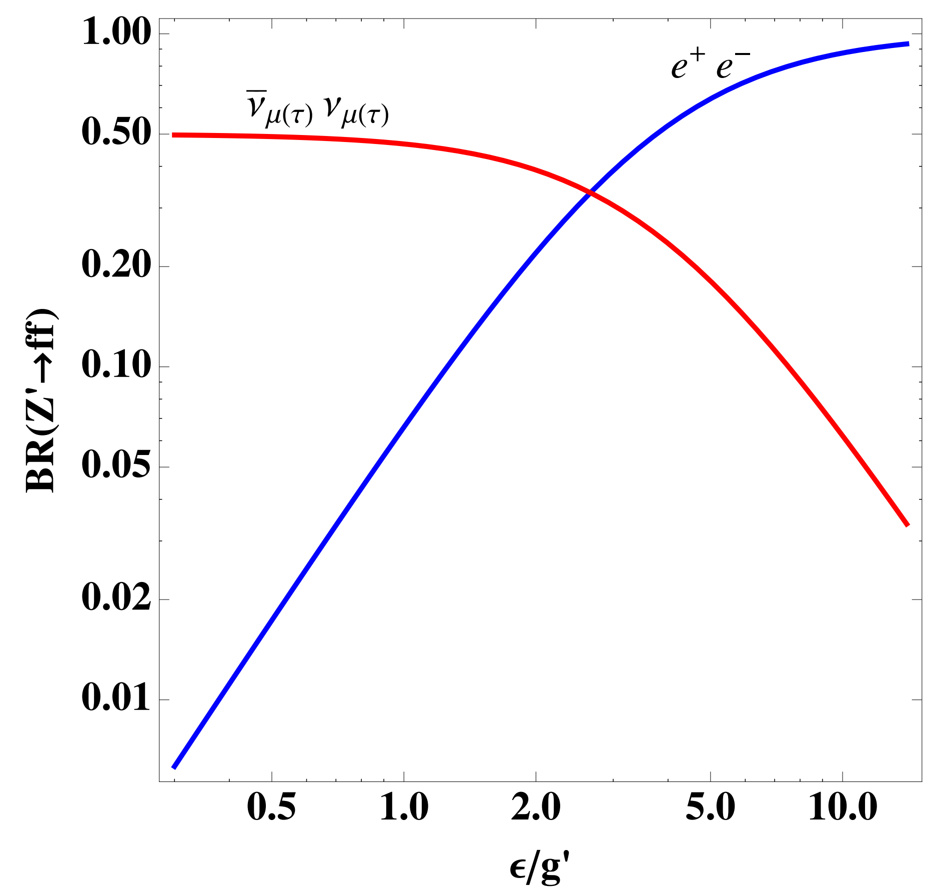


Therefore the main decay mode of ϕ is

$$\phi \to Z'Z' \to 4\nu$$

- Invisible at collider experiments
- different from the SM Higgs

Allowed Parameter Region

Allowed parameter region

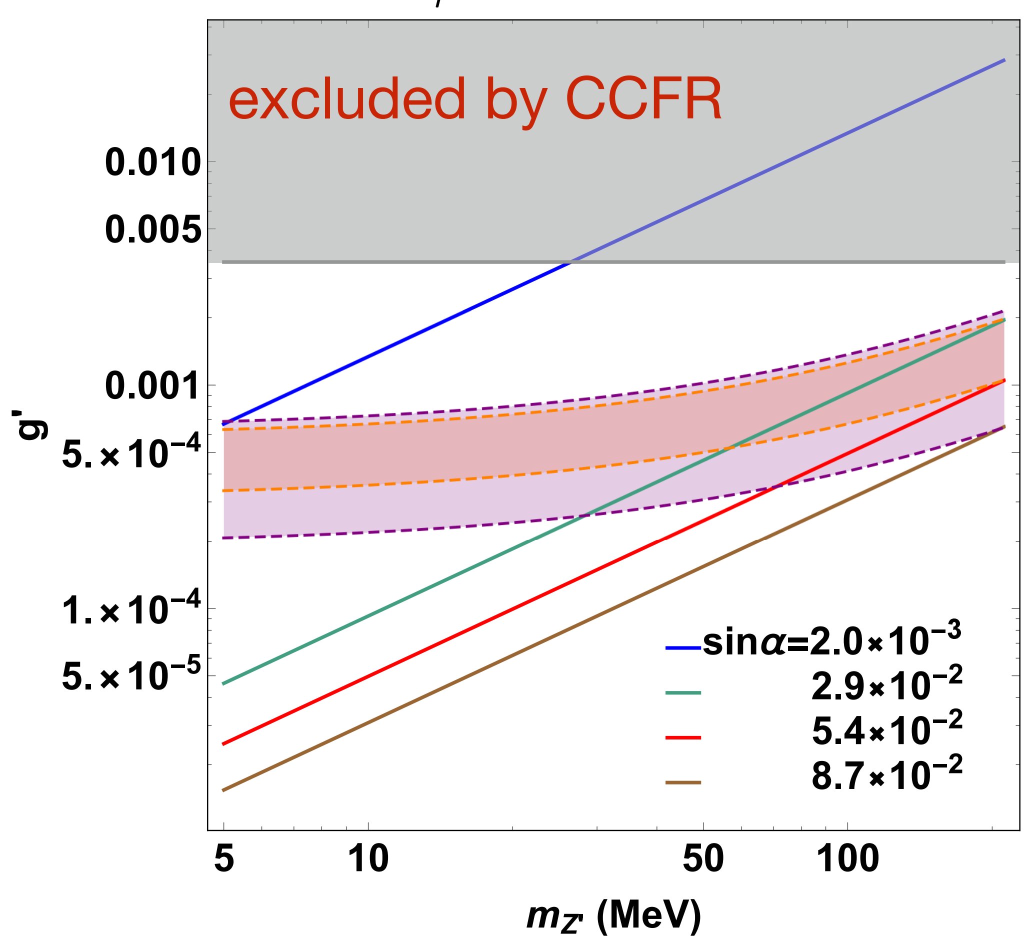
- Extra invisible decays of the SM Higgs into Z' and ϕ pairs,

$$h \to Z'Z',\ \phi\phi$$

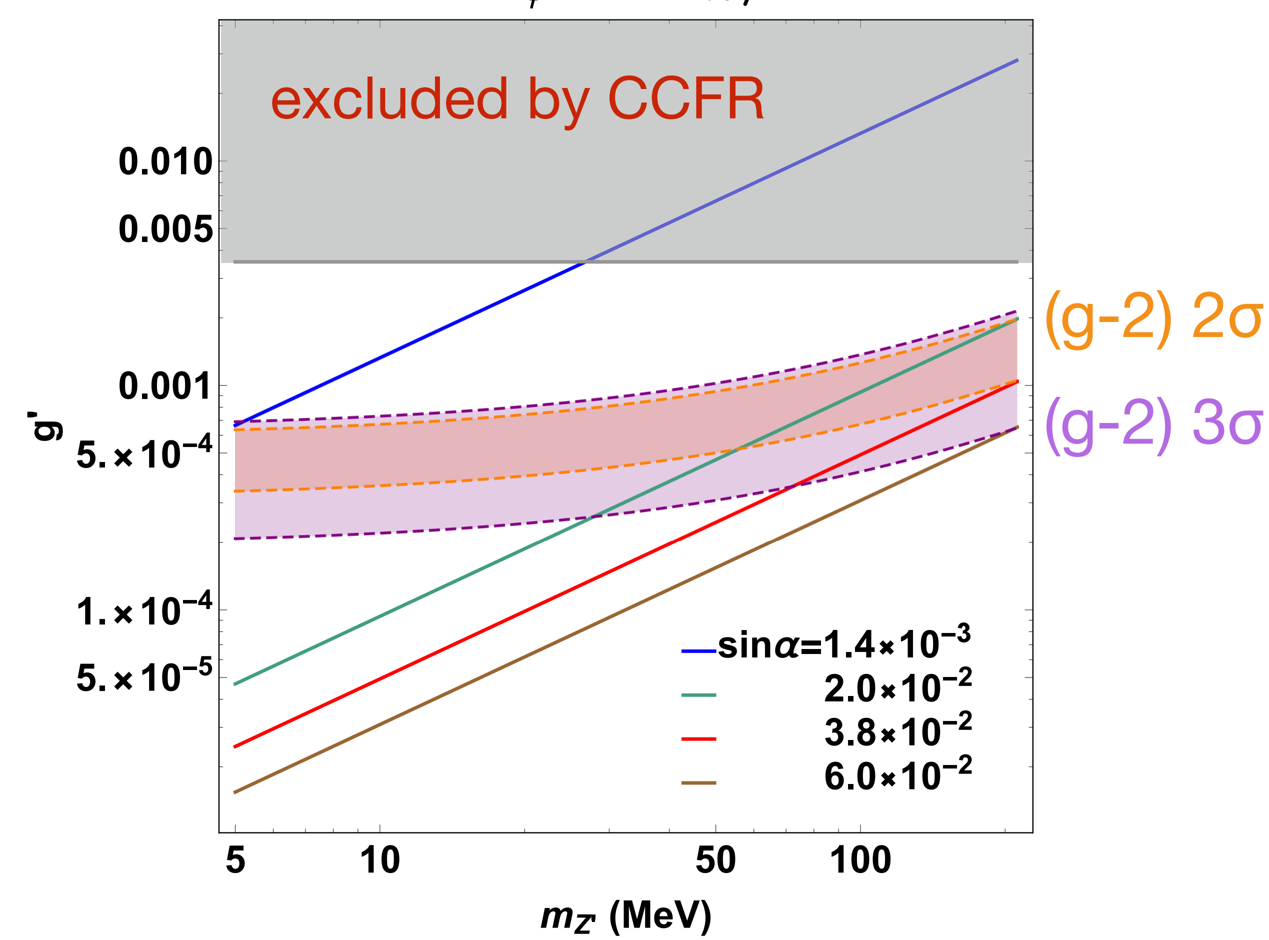
- Constraints from invisible Higgs decay measured at LHC,

$$\sin\alpha < 0.3, \quad BR_{\mathrm{invisible}} < 0.25$$

$m_\phi = 30\ \mathrm{GeV}$



$m_\phi > m_h/2$



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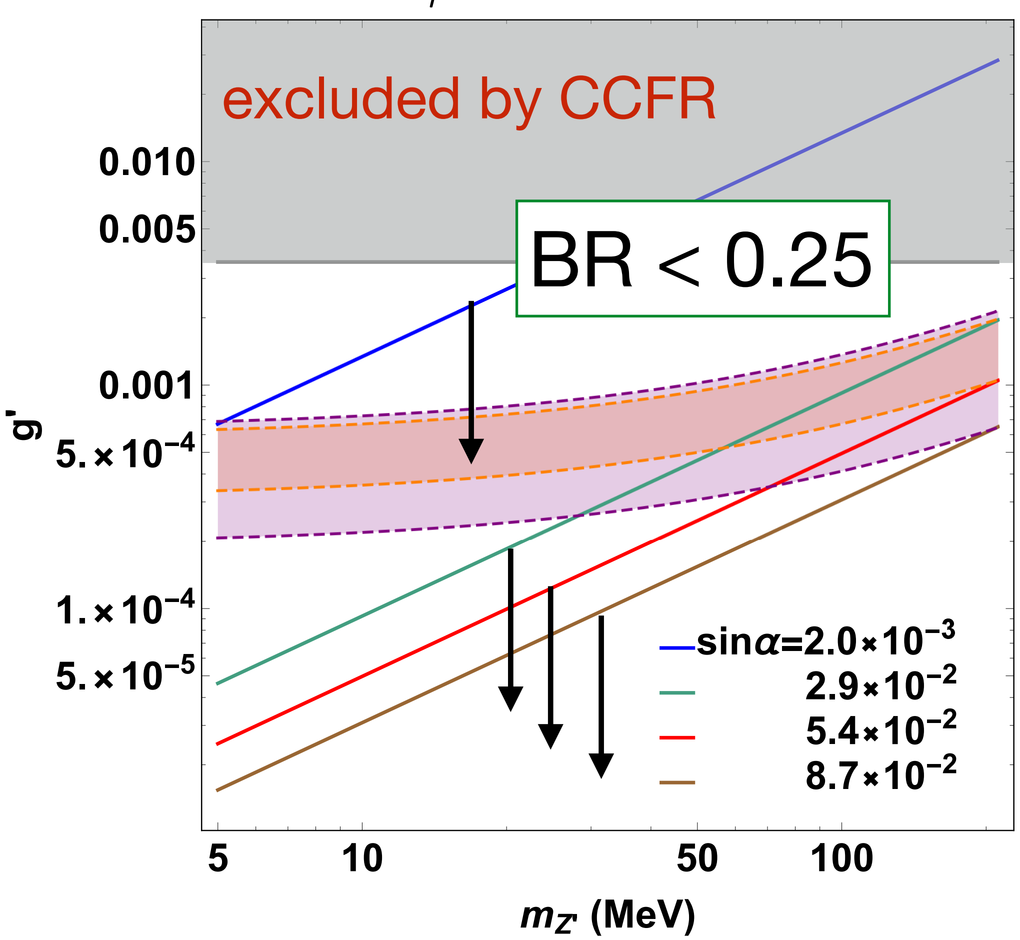

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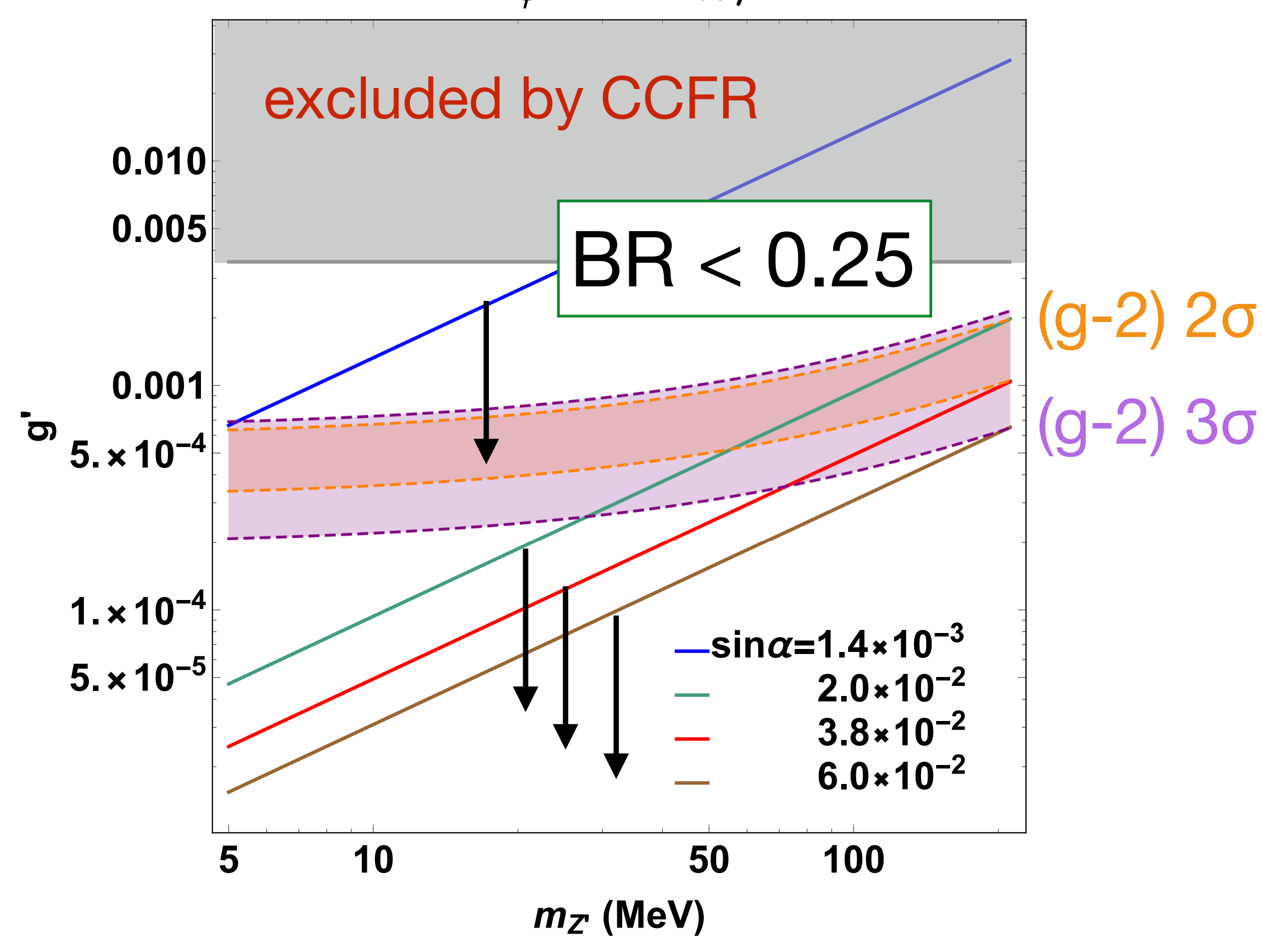

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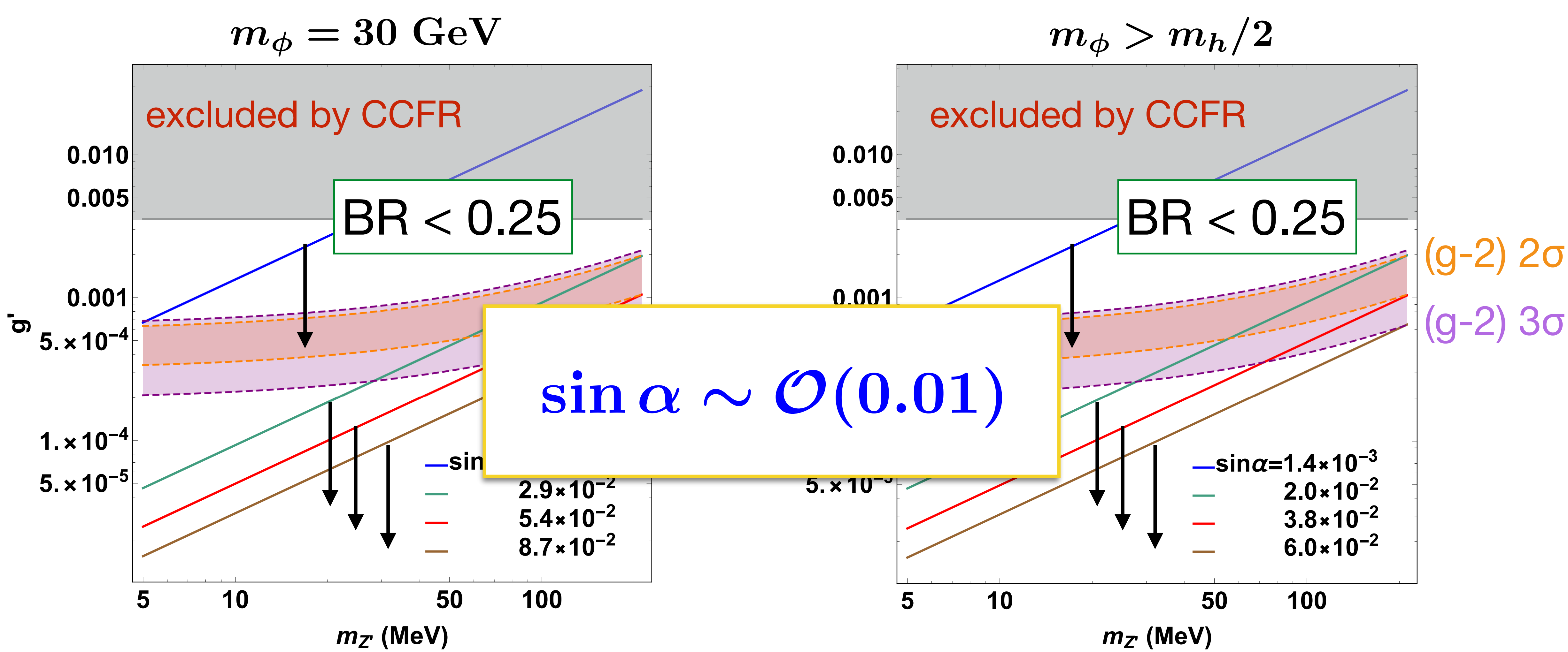

Allowed parameter region

- Z' search in meson decays at NA64: $Z' \to e^+e^-$

$$\epsilon/g' \leq 2\ (0.6) \quad \text{for} \quad m_{Z'} = 100\ (5)\ \mathrm{MeV}$$

- EW precision: ρ parameter

$$\epsilon \leq 7 \times 10^{-4}$$

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In the following discussion, we fix

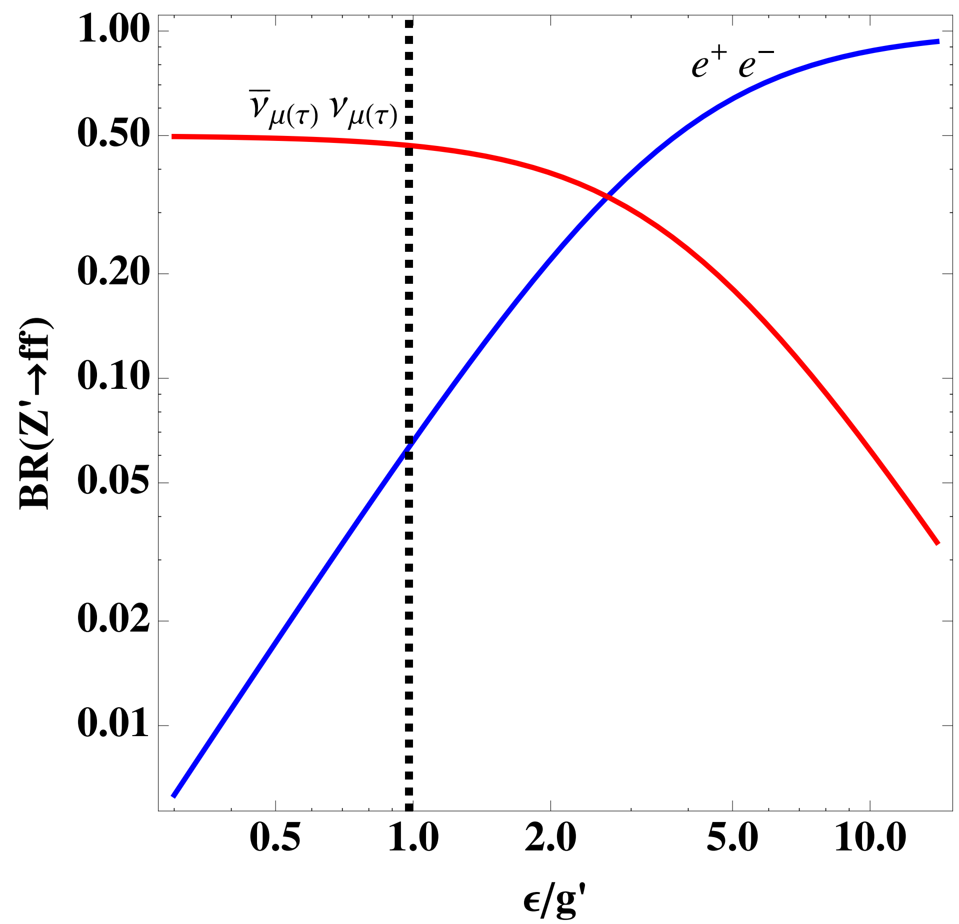
$$m_{Z'} = 100\ \text{MeV}$$

$$\sin\alpha = 0.05$$

$$\epsilon/g' = 1$$

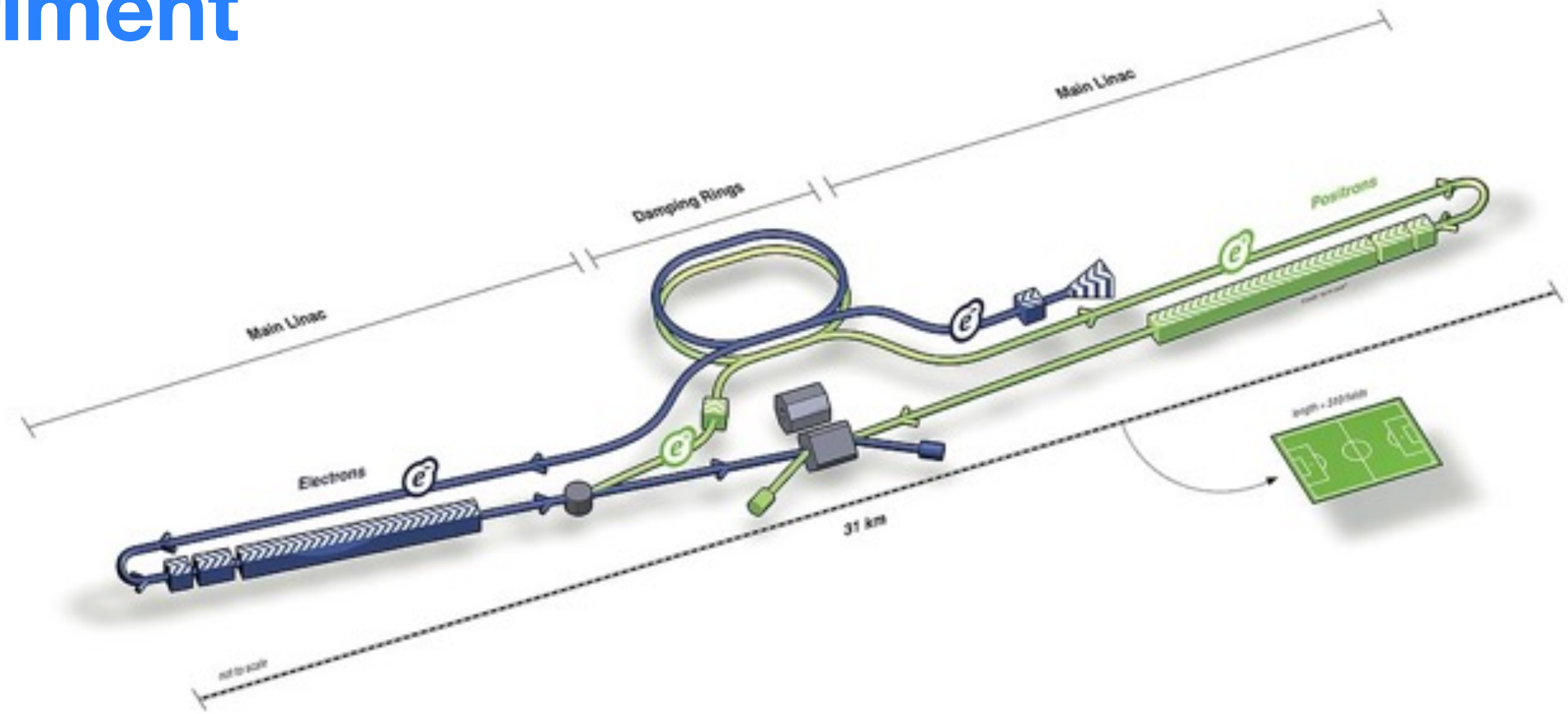
$$BR(Z' \to \nu\bar{\nu}) = 0.97$$

$$m_{Z'} = 100\ \text{MeV}$$



Search at ILC experiment

ILC experiment



- Electron-Positoron collider with $\sqrt{s}$=250 GeV
- Beam polarization (+−, −+, ++, −−) for (e^+,e^-)
- Total integrated luminosity, 2000 fb^{-1}, (45%,45%,5%,5%)
- Clean BG and invariant mass reconstruction available

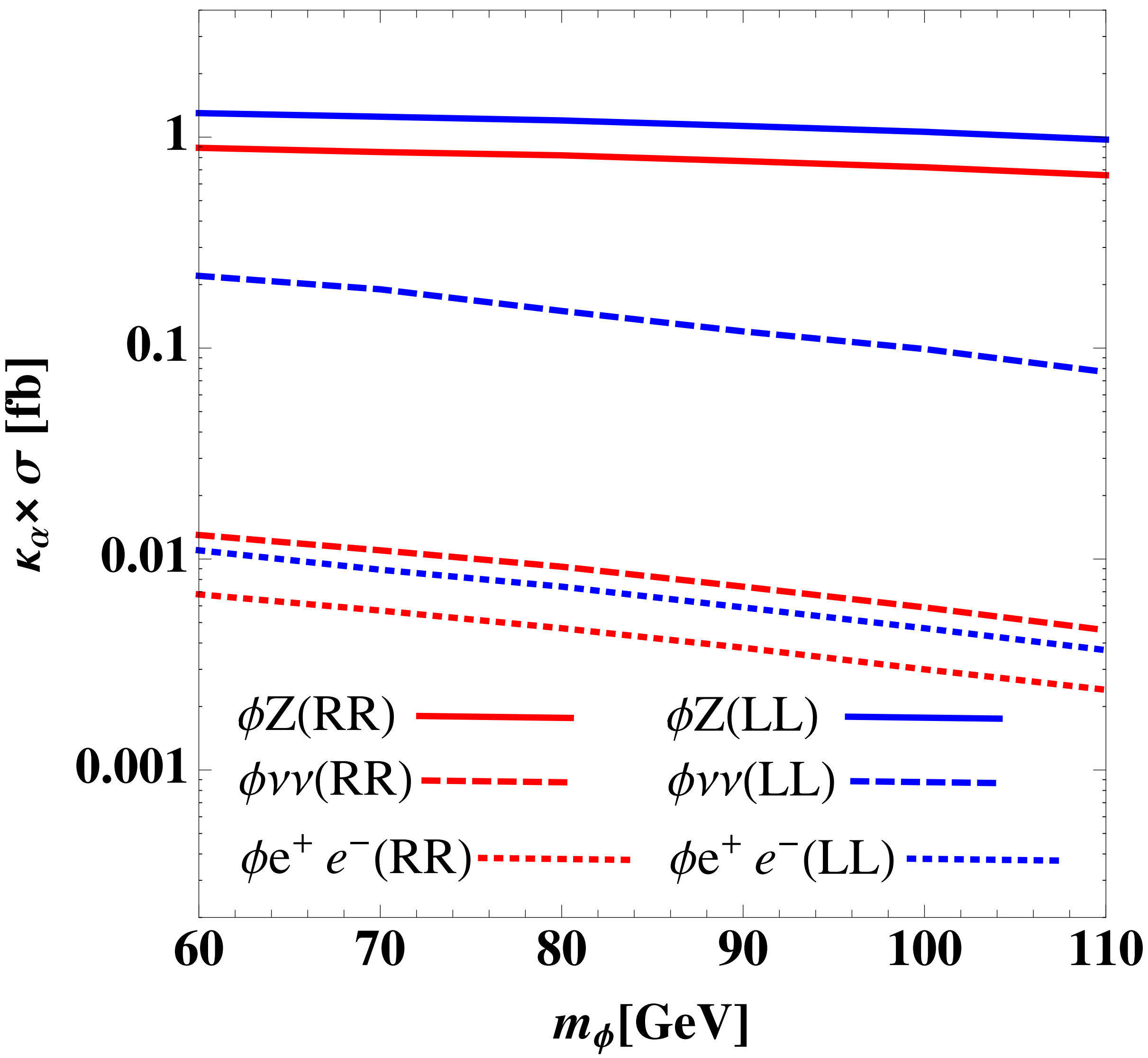
In the following analysis, we apply

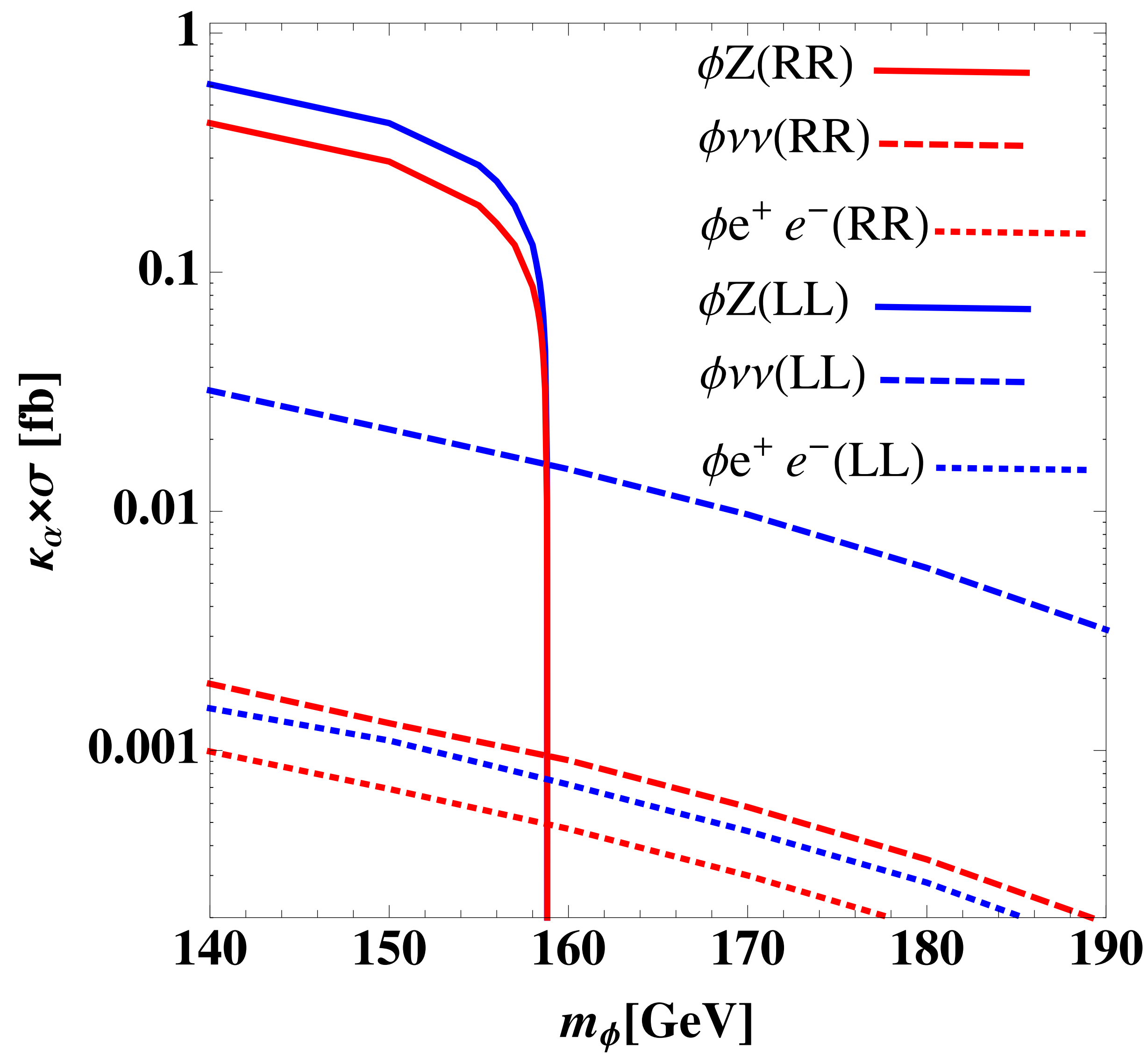
LL : $(e^-_L, e^+_R) = (-80\%, 30\%)$ with L=900fb^{-1}

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

ILC experiment

Production cross section of ϕ at ILC experiment





normalized by

$$\kappa_\alpha = \left(\frac{0.05}{\sin\alpha}\right)^2$$

ILC experiment

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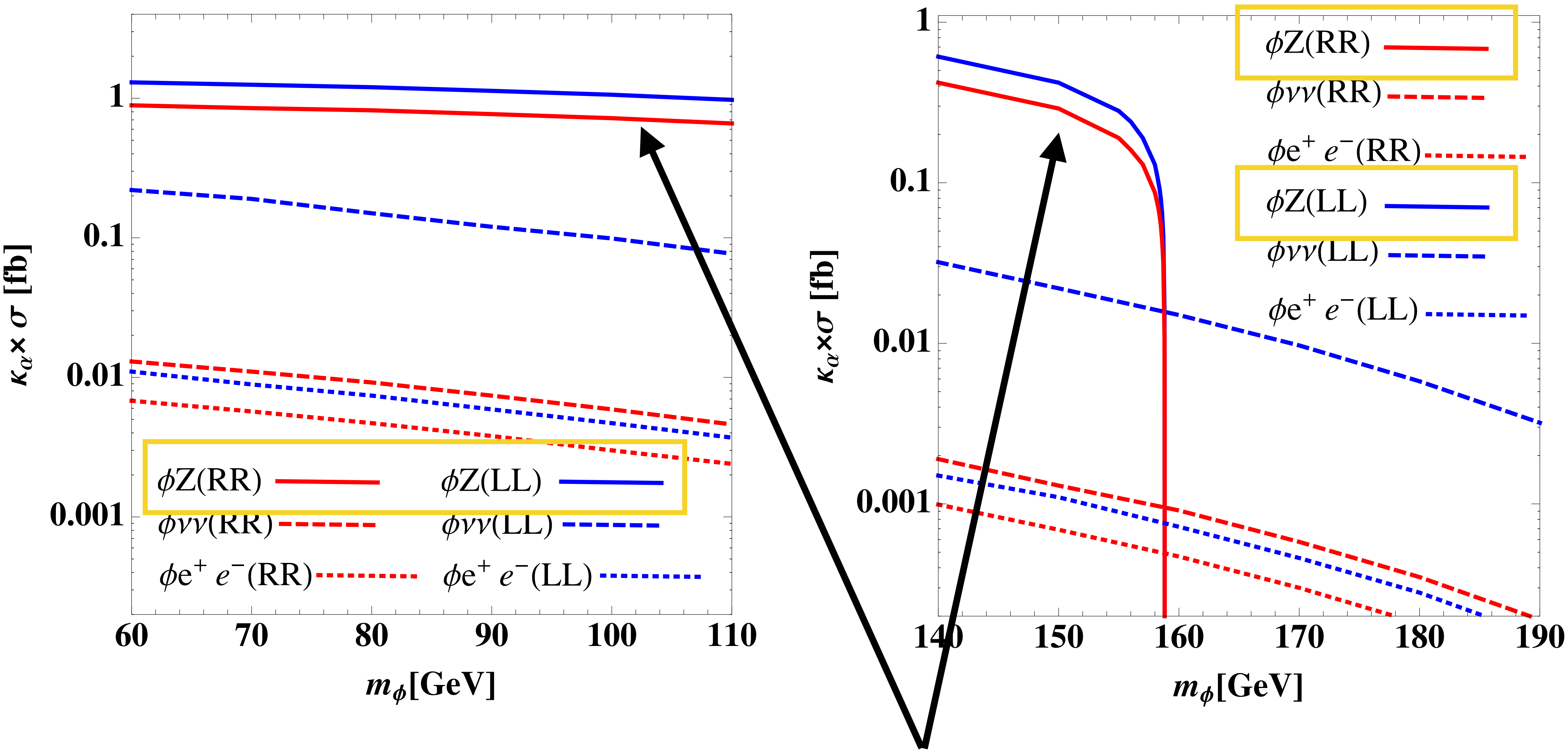


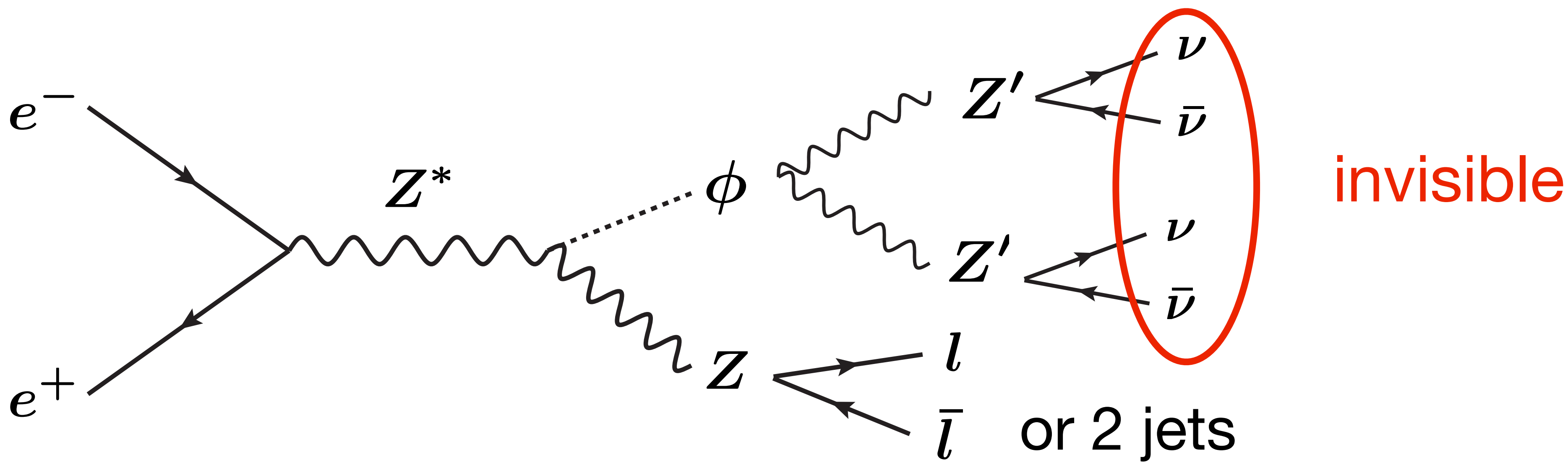
normalized by

$$\kappa_\alpha = \left(\frac{0.05}{\sin \alpha} \right)^2$$

For $m_\phi < 160$ GeV,
Higgs-Strahlung is dominat

ILC experiment

Main production process of ϕ at ILC with $\sqrt{s}$ = 250 GeV



The signal

1) $e^+e^- \to l^+l^- + \not{E}$

2) $e^+e^- \to jj + \not{E}$

The backgrounds

1) $e^+e^- \to l^+l^-\nu\bar{\nu},\ \tau^+\tau^-$ followed by leptonic decay

2) $e^+e^- \to jj\nu\bar{\nu},\ \tau^+\tau^-$ followed by hadronic decay

ILC experiment

We perform a simulation study by using MADGRAPH/MADEVENT with PYTHIA6, assuming L=900/fb and m_ϕ=30, 65 GeV.

Basic Cuts

Reduce BGs

1) $p_T(\ell^\pm) > 7$ GeV, $\eta(\ell^\pm) < 2.5$ for leptons

2) $p_T(j) > 20$ GeV, $\eta(j) < 5.0$ for jets

Invariant Mass Cuts

Reduce BGs in M^{rec} dist.

1) $m_Z - 10 \text{ GeV} < M_{\ell^+\ell^-} < m_Z + 10 \text{ GeV}$ for leptons

2) $m_Z - 20 \text{ GeV} < M_{jj} < m_Z + 5 \text{ GeV}$ for jets

reconstructed mass

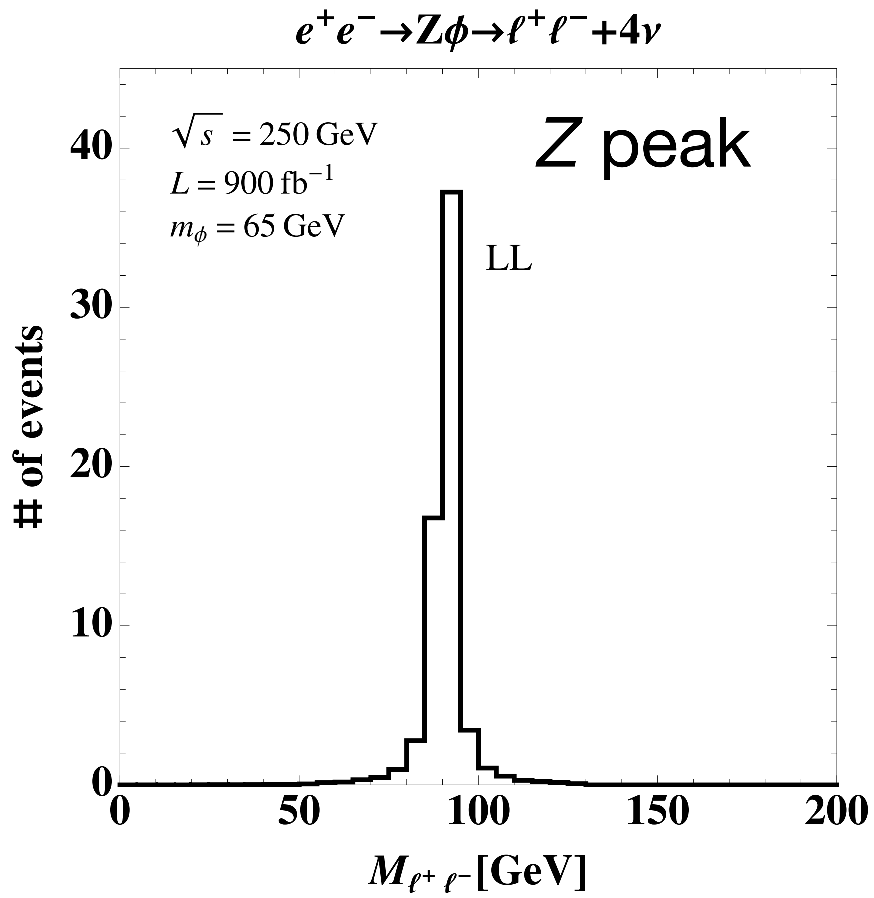
$$M_\phi^{rec} = \sqrt{s + m_Z^2 - 2(E_{l/j_1} + E_{l/j_2})\sqrt{s}}$$

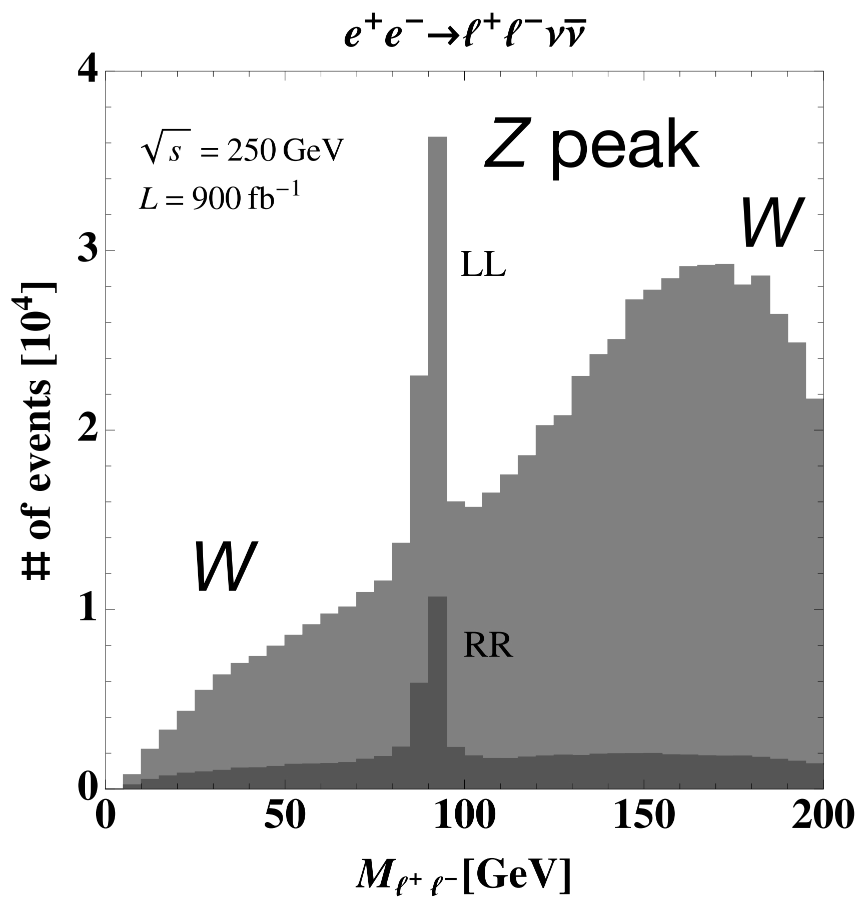
Kinematical Cuts

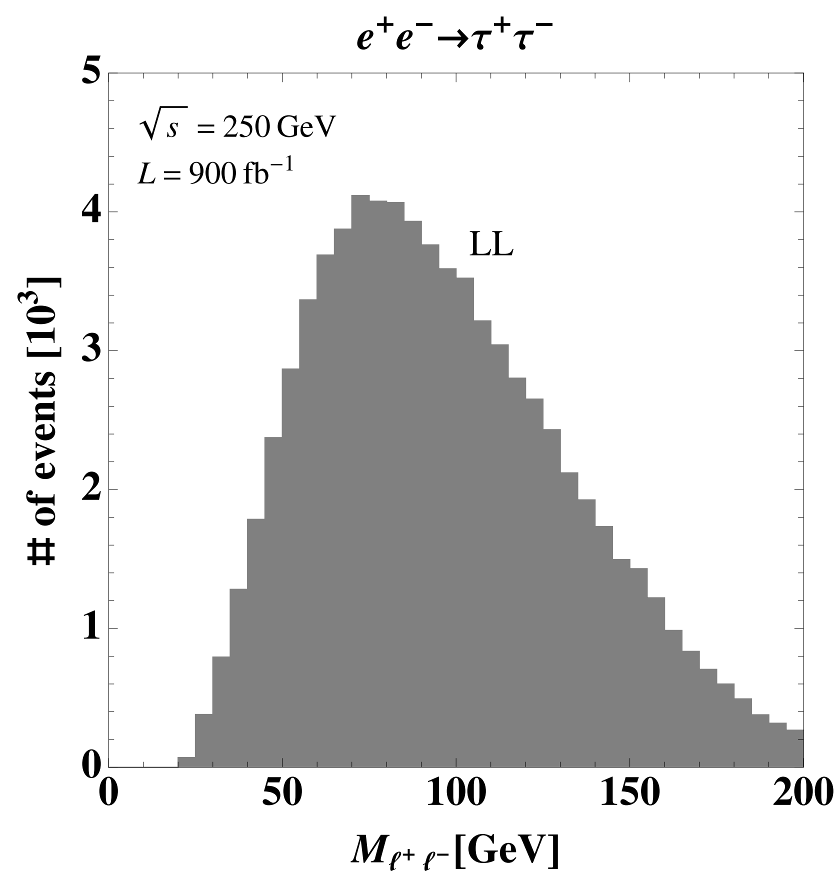
1) $m_\phi - 10 \text{ GeV} < M_{\phi_\ell}^{rec} < m_\phi + 10 \text{ GeV}$ for leptons

2) $m_\phi - 15(10) \text{ GeV} < M_{\phi_j}^{rec} < m_\phi + 25(50) \text{ GeV}$ for jets

Lepton signal lepton BG tau BG







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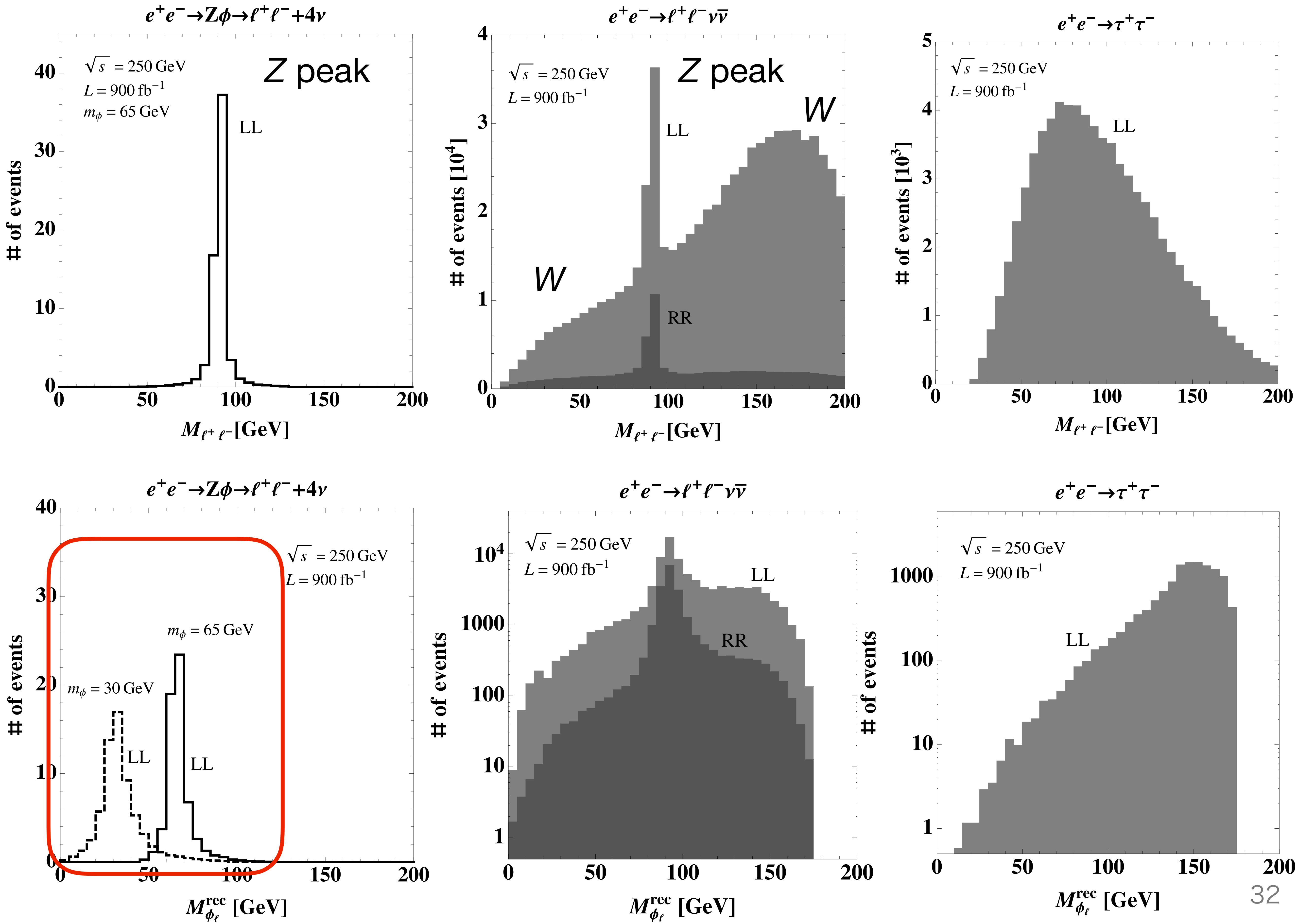
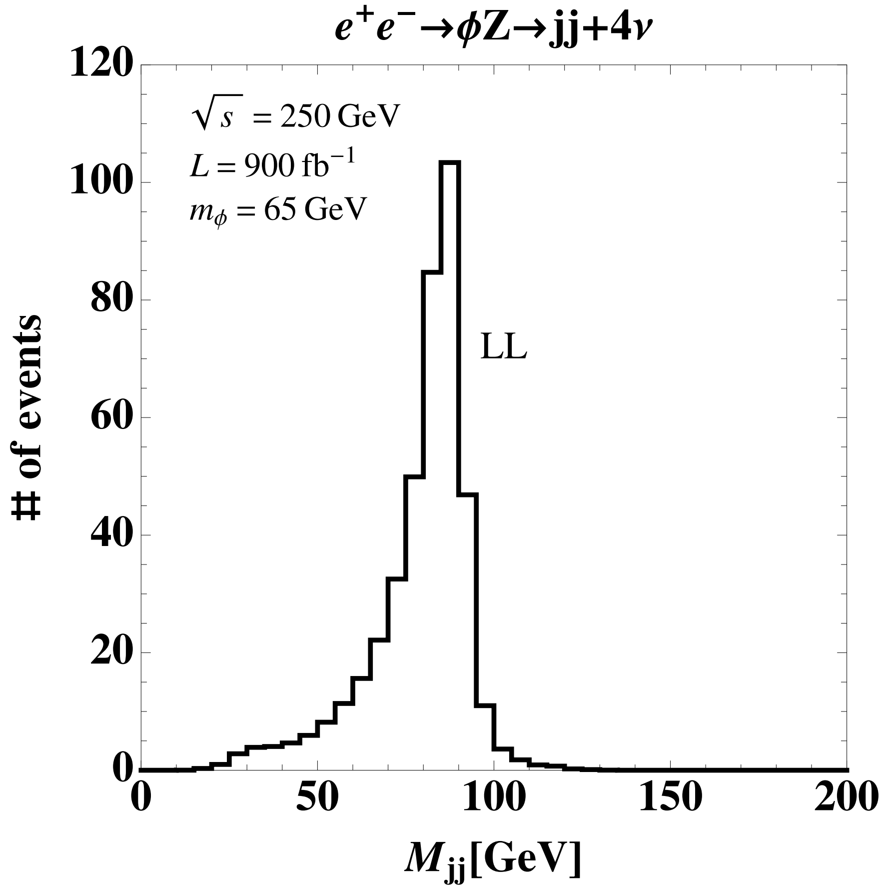
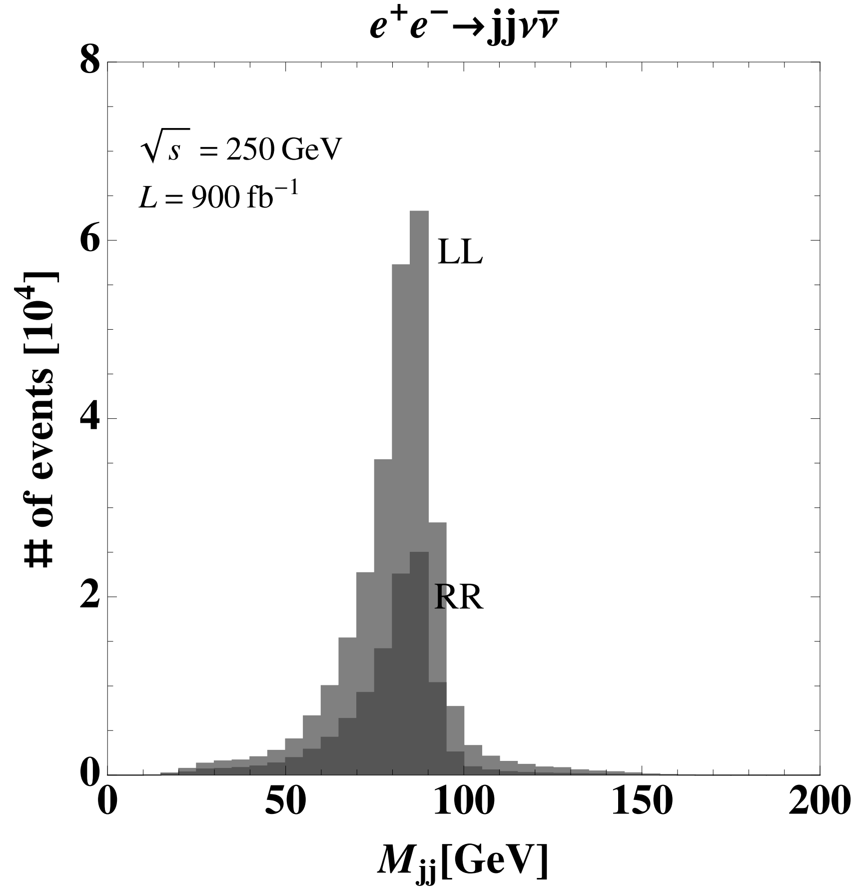
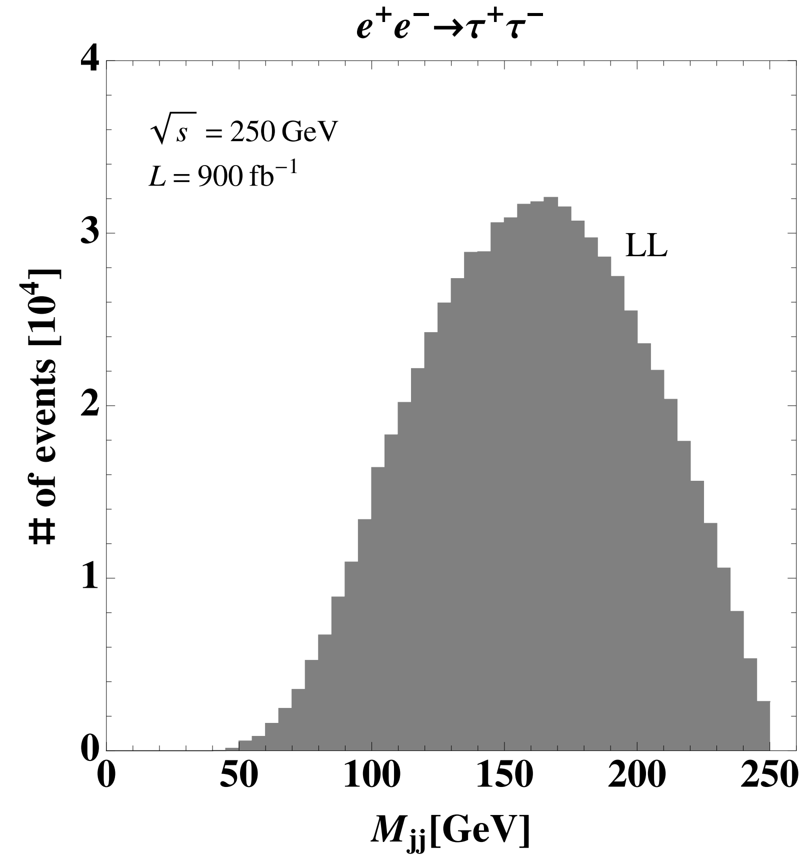


Jets signal lepton BG tau BG





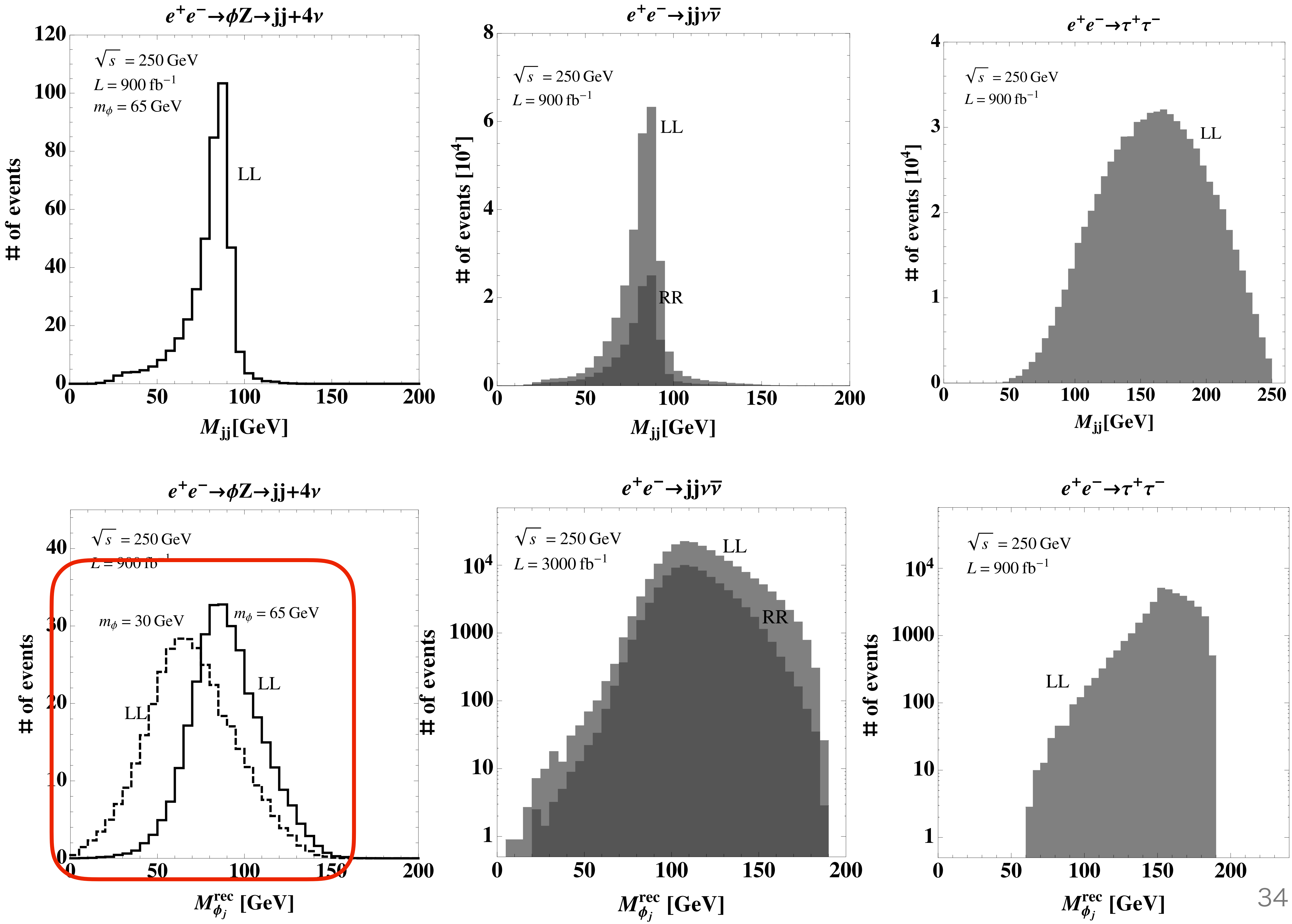


Slightly broader *Z* peak due to jet energy resolution

Continuous BG suppressed at low mass region

1. Lepton BG comes from *ZZ* followed by *Z* decays into jets/neutrinos.
2. Tau BG shifts to higher mass region due to miss-identification of τ-jet with missing energy.

Jets signal lepton BG tau BG



lepton pair event

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

	$\kappa_\alpha N_S^{\kappa_\alpha=1}$; $m_\phi = 65(30)$ 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)

jet event

	$\kappa_\alpha N_S^{\kappa_\alpha=1}$; $m_\phi = 65(30)$ 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

Summary

We have studied the scalar boson search which breaks gauged $U(1)_{L\mu-L\tau}$ symmetry spontaneously at ILC250.

From (g-2) and the invisible Higgs decay,

- The gauge boson mass and gauge coupling are $O(100)$ MeV and 10^{-4}, respectively.
- The scalar mass should be $<O(100)$ GeV, and its mixing should be $O(0.01)$
- The scalar boson is invisible because its main decay mode is $\phi \to Z'Z' \to 4\nu$.

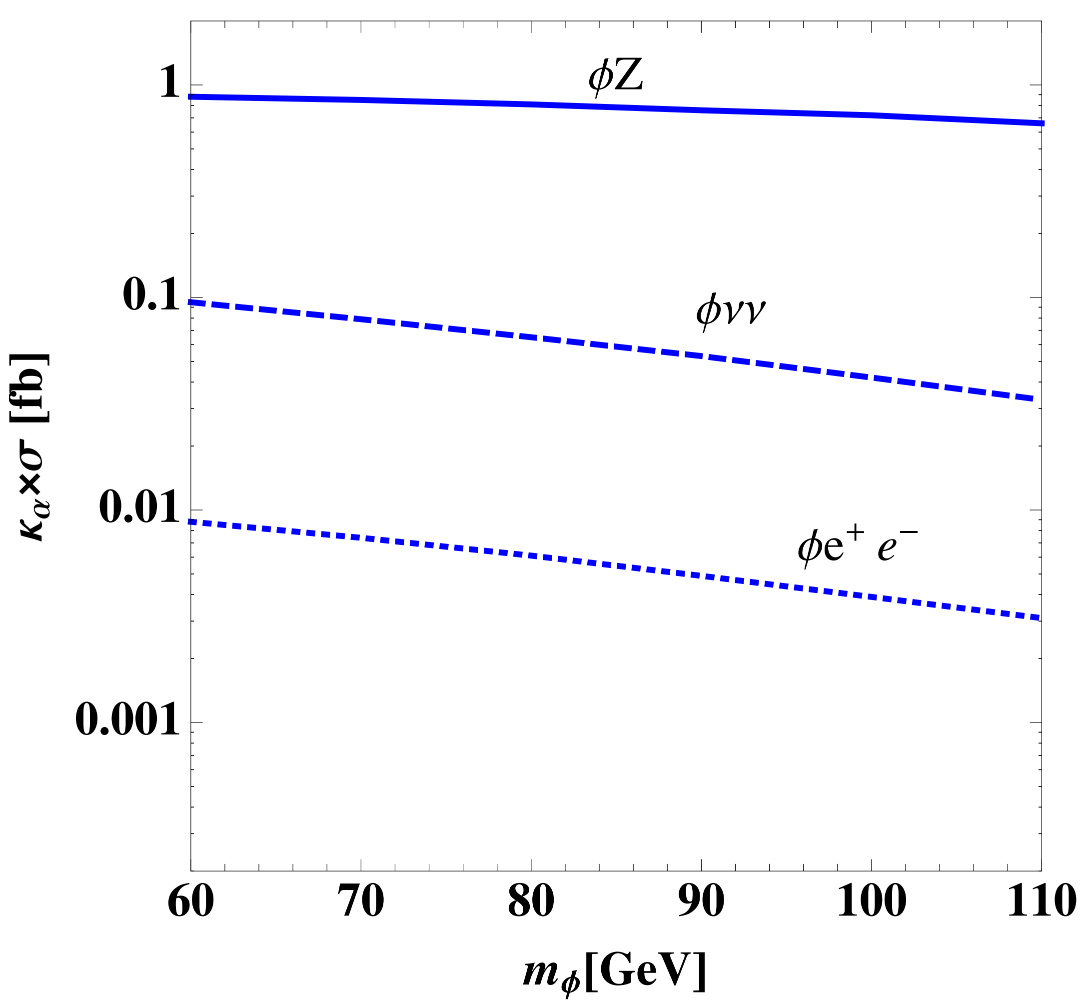
Then, at the ILC experiment,

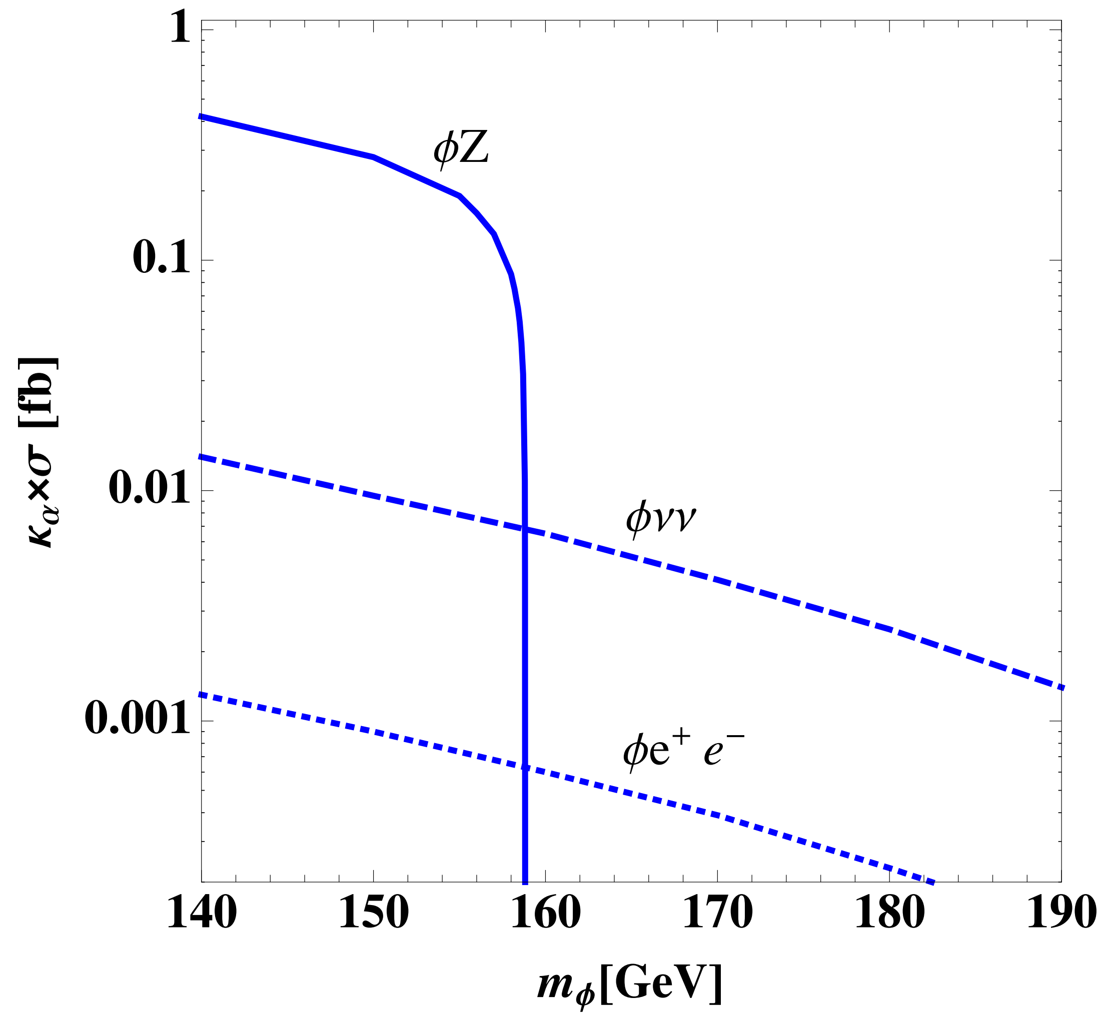
- ϕ mass can be reconstructed from lepton pair and jet events.
- Signal significance is obtained as 2.2 (2.5) for lepton pair in *RR*, and 2.1 (9.7) for jets in *LL*+*RR* with m_ϕ=65 (30) GeV after cuts.

Back-up

ILC experiment

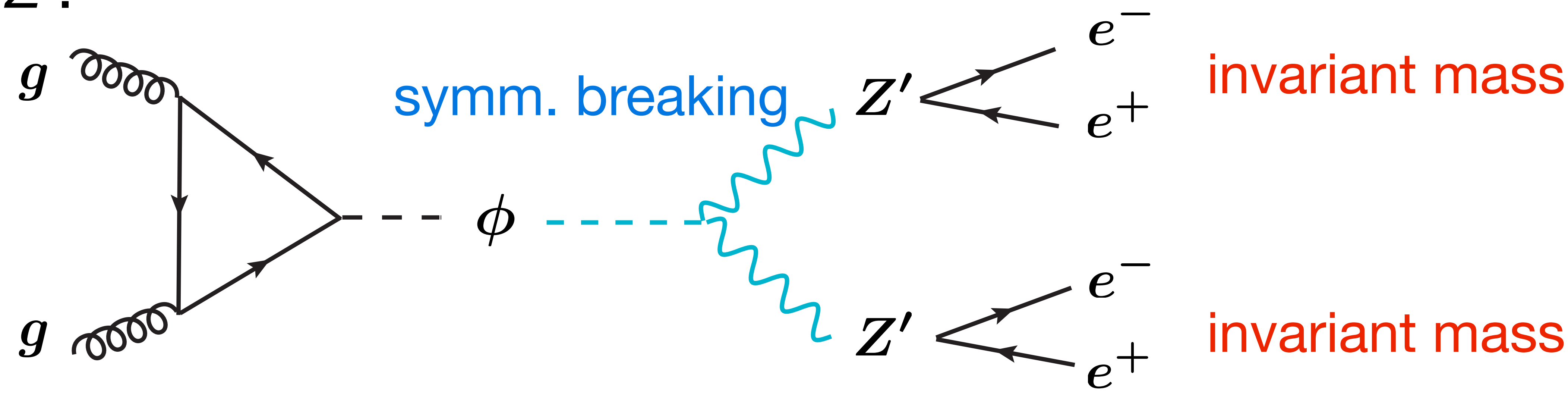
Production cross section at ILC250





LHC experiment

The main production mode of ϕ is gluon fusion, followed by decay into *Z'Z'*.



In principle, *Z'* and ϕ mass can be reconstructed by measuring e^+e^- energy and momentum.

$$m_{Z'} = \sqrt{M^2_{e^+e^-}}$$

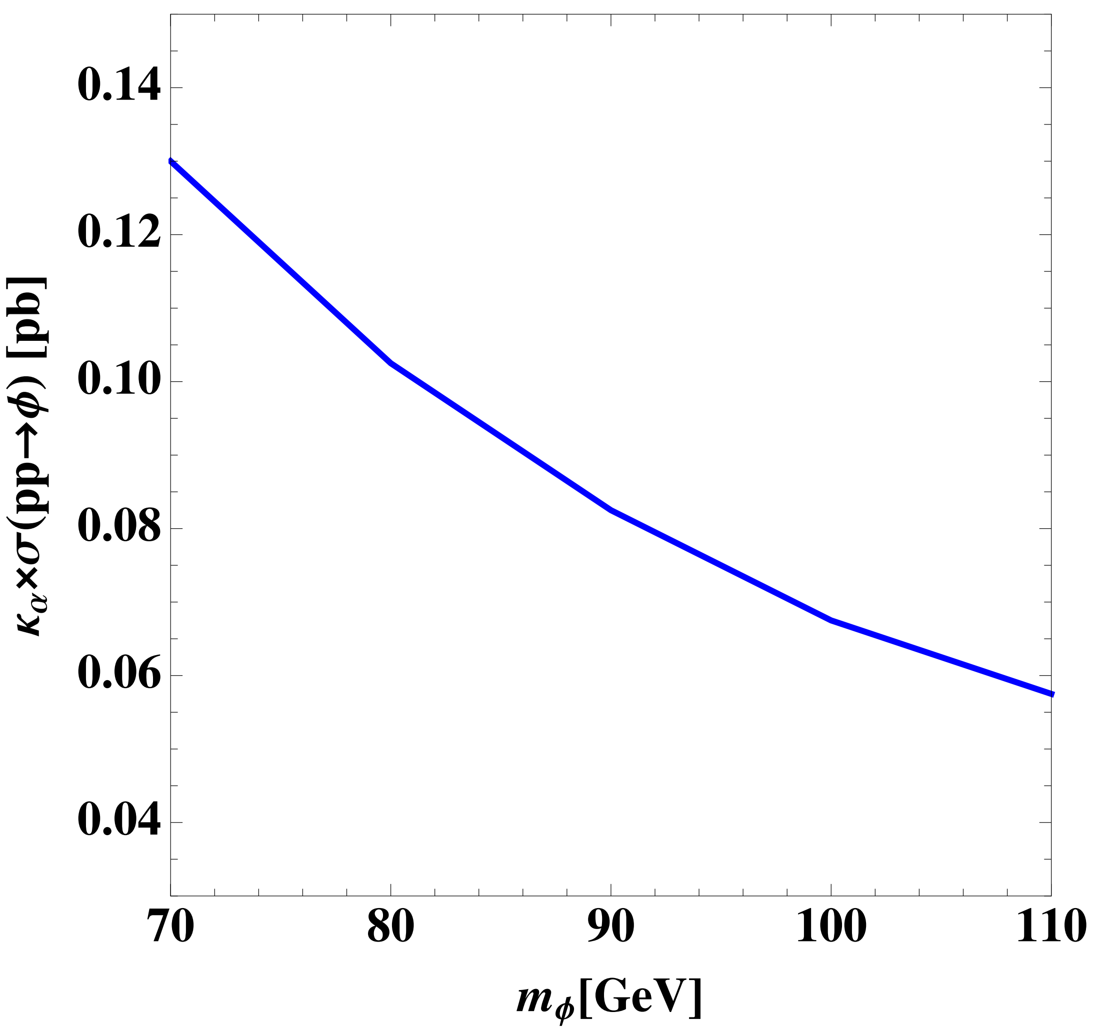
$$m_\phi = \sqrt{(p_{Z'} + p'_{Z'})^2}$$

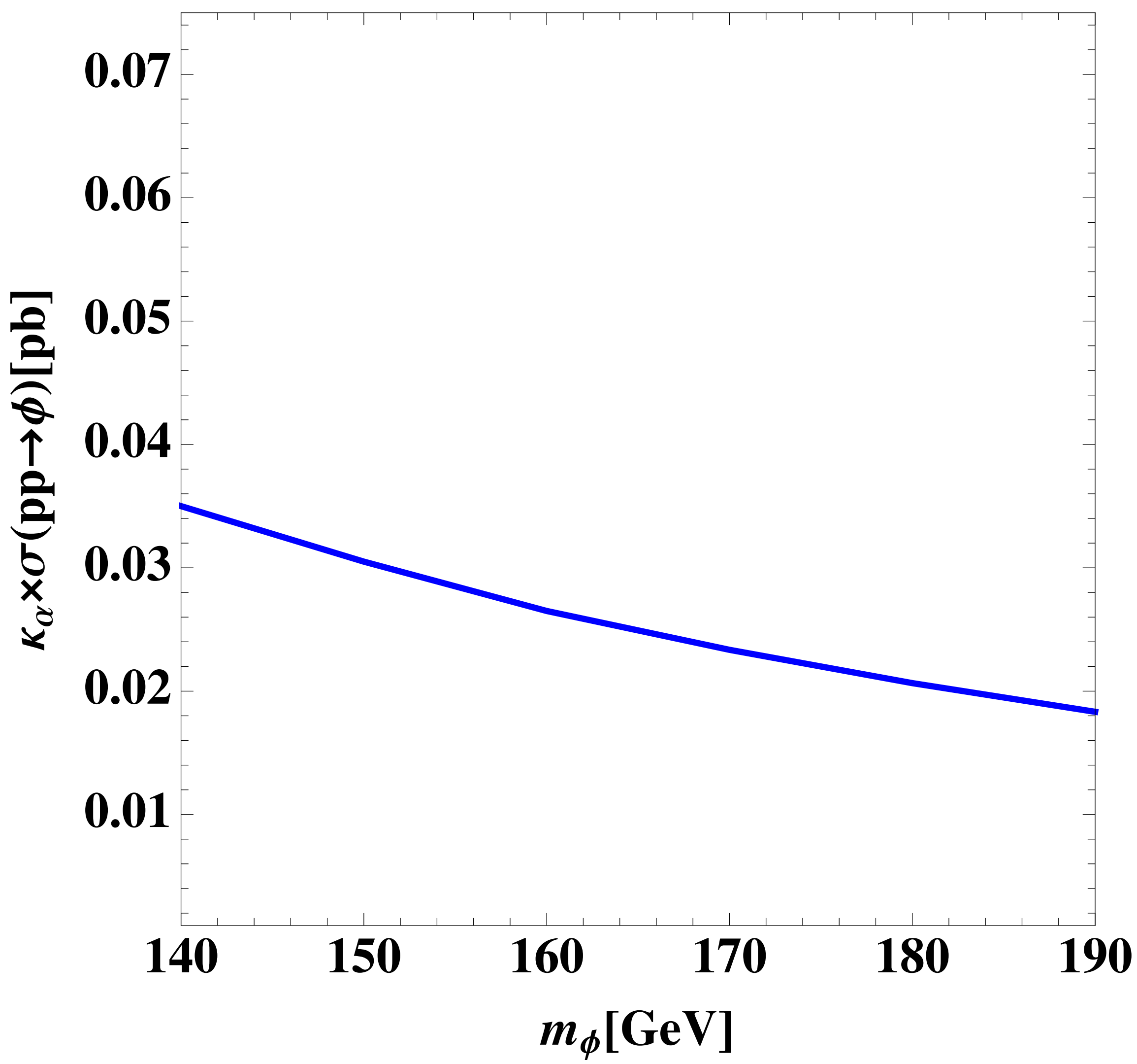
The SM BGs are *ZZ* production and Drell-Yang with ISR/FSR e^+e^-

The momentum distrib. of e^+e^- in BG are different from the signal. Kinematical cuts will reduce the BGs

LHC experiment

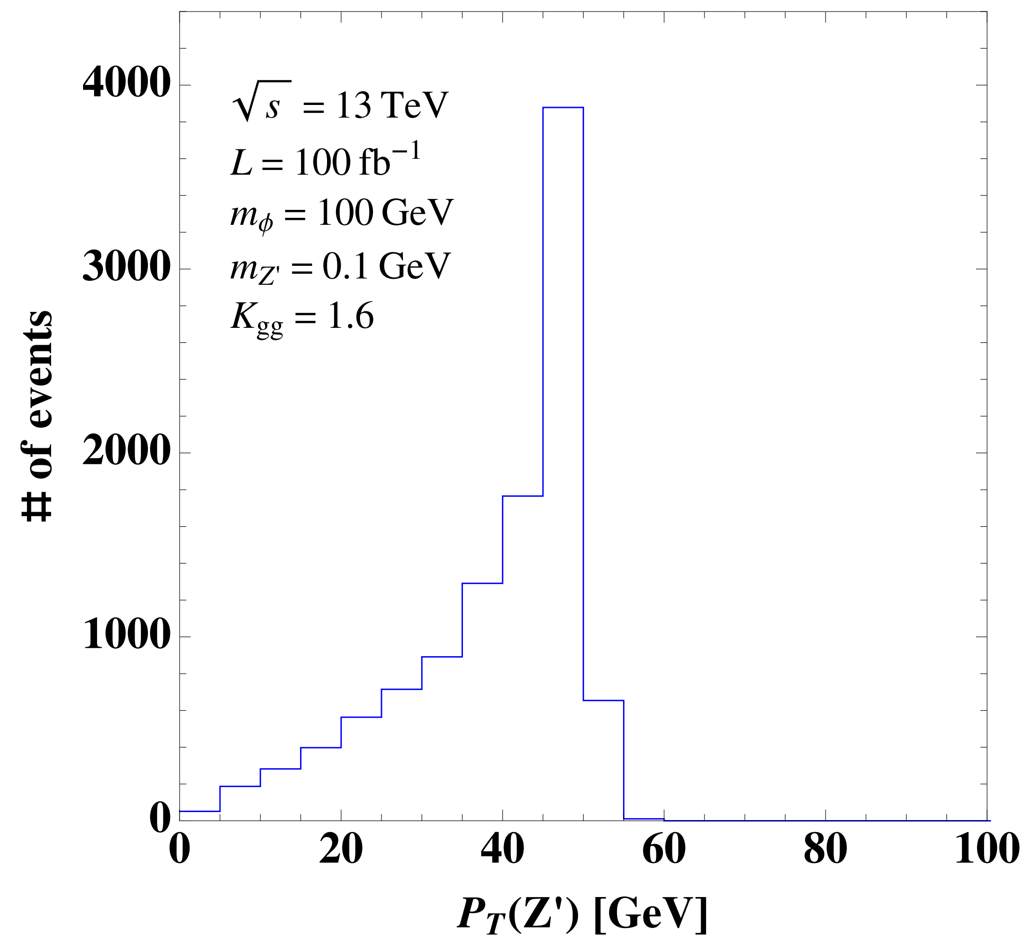
Production cross section at LHC13





LHC experiment

signal



$O(10^3)$ events expected even $BR(Z' \to e^+e^-)$ = 0.07

However, e+e- pair is highly collimated, with the angle θ ~ 0.5°

Analysis of such a collimated e^+e^- is challenging at present