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

Takashi Shimomura
(Miyazaki U.)

in collaboration with

Takaaki Nomura (KIAS, Korea)

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

arXiv:1803.00842

May 29th, 2018 @ ALCW2018

Introduction

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

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

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

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

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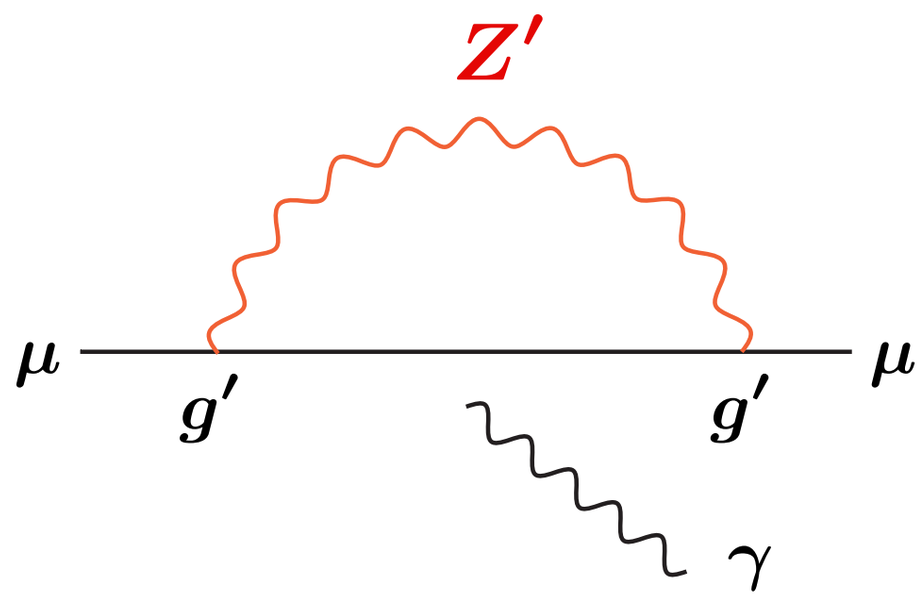
The scale of New Physics (NP)

- 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



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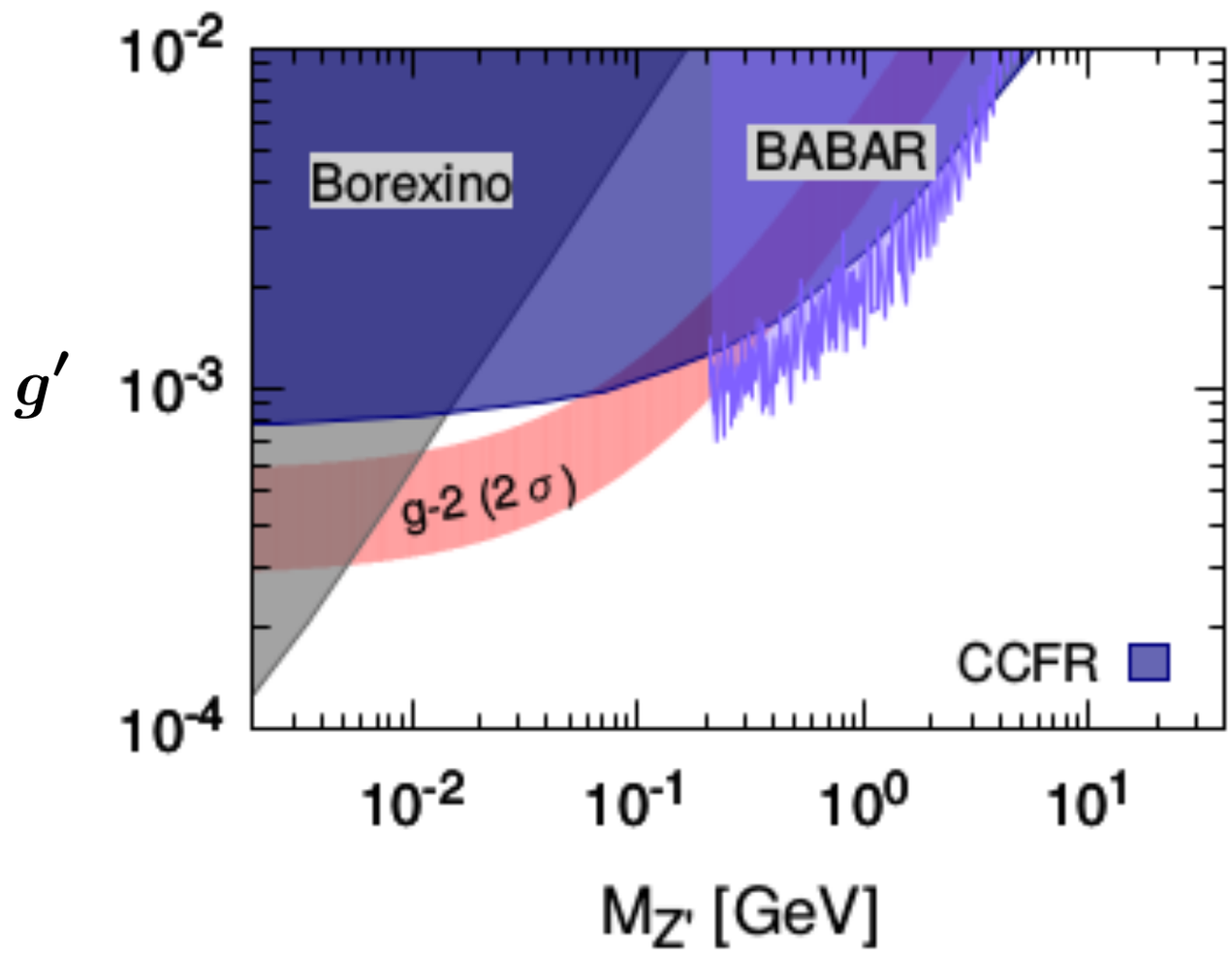

Araki, Hoshino, Ota, Sato, T.S.
PRD95 (2017)

Introduction

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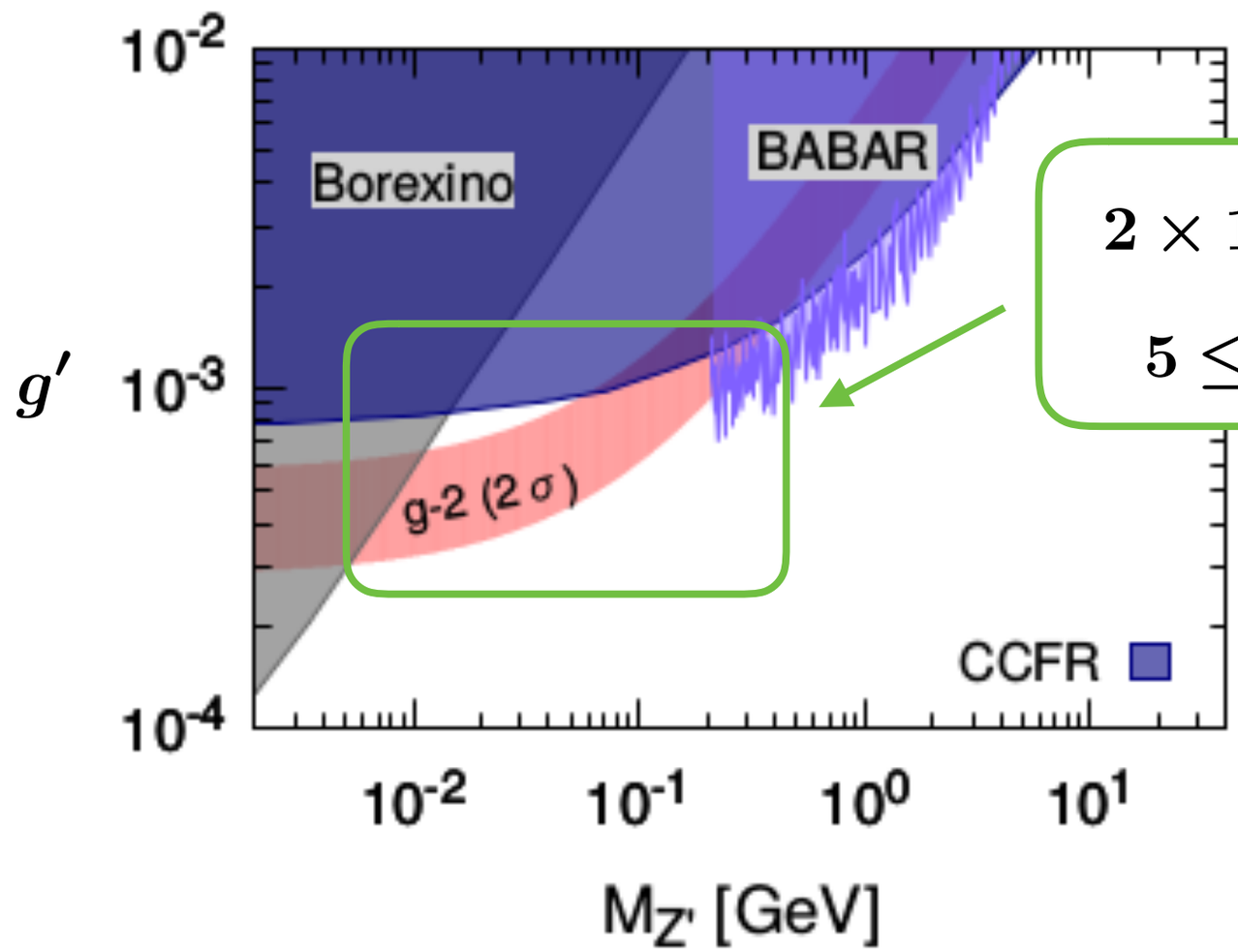

$$2 \times 10^{-4} \leq g' \leq 10^{-3}$$

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

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 < $O(100)$ 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 < $O(100)$ GeV

  High energy with high luminosity, ILC!

Search for the symmetry breaking scalar at ILC

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
$SU(2)_L$	**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

The Lagrangian

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

gauge kinetic mixing

where

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

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

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:

$$h = \cos\alpha H + \sin\alpha\varphi,$$
$$\phi = -\sin\alpha H + \cos\alpha\varphi,$$

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

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.

$$\mathcal{L} \supset \sin\alpha\phi \left[\sum_f \frac{m_f}{v} \bar{f} f + \frac{m_Z^2}{v} Z_\mu Z^\mu + \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} \right]$$
$$+ \frac{m_{Z'}^2}{v_\varphi} \cos\alpha\phi Z'_\mu Z'^\mu + Z'_\mu(-e\epsilon\cos\theta_W J^\mu_{\rm EM} + g' J^\mu_{Z'}) + \mathcal{O}(\epsilon^2)$$

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 $(g\text{-}2)_\mu$, $m_\phi/m_{Z'} \sim 10^3$ 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'*

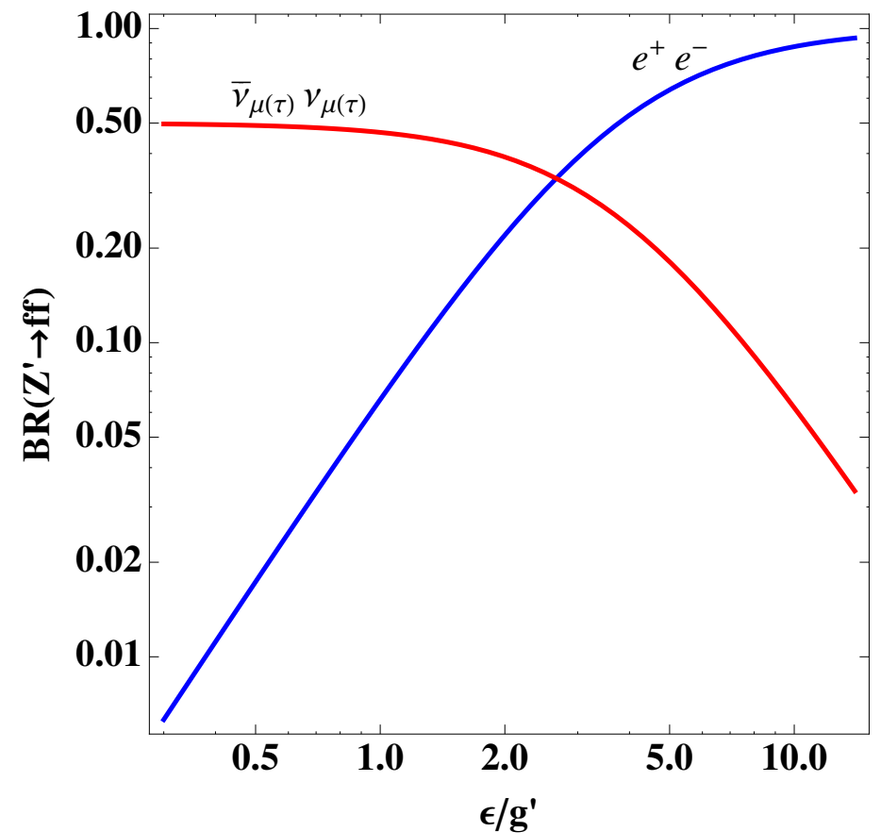
$$\Gamma_{Z'\to\nu\bar{\nu}} = \frac{g'^2}{24\pi} m_{Z'}$$

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

For $\varepsilon/g' < 1$,

Z' mainly decays into *ν*

$m_{Z'} = 100$ MeV



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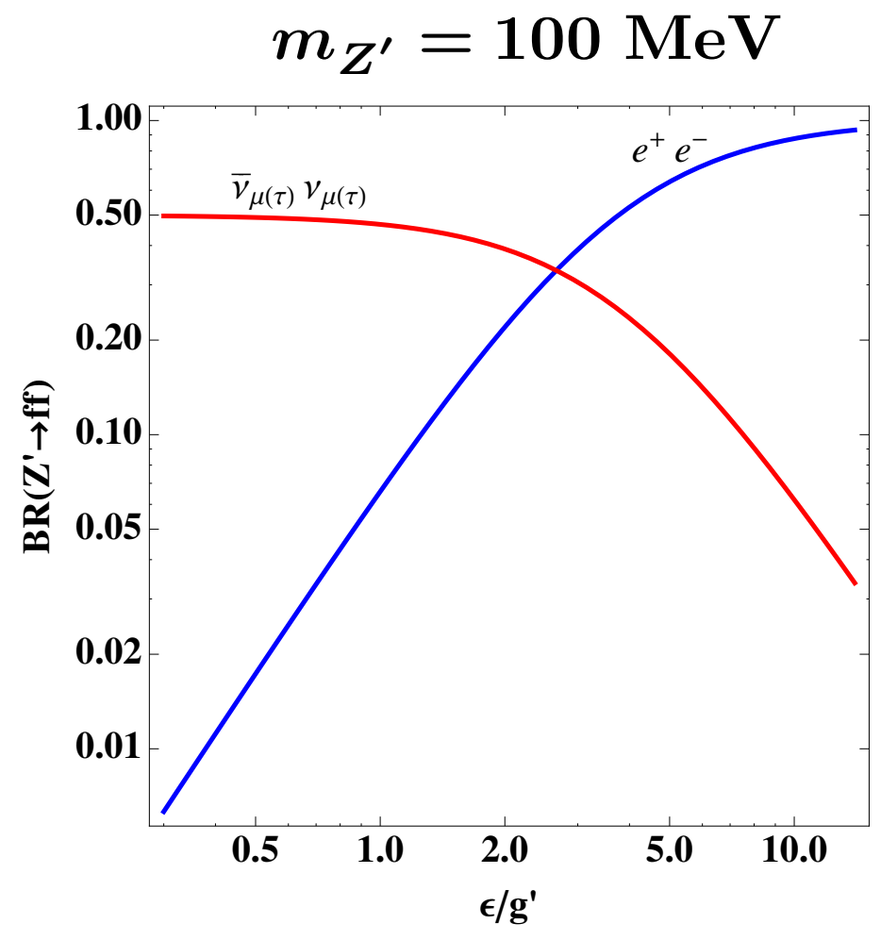


For $\varepsilon/g' < 1$,

Z' mainly decays into *ν*

Therefore the main decay mode of ϕ is

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

- Invisible at collider experiments
- different from the SM Higgs

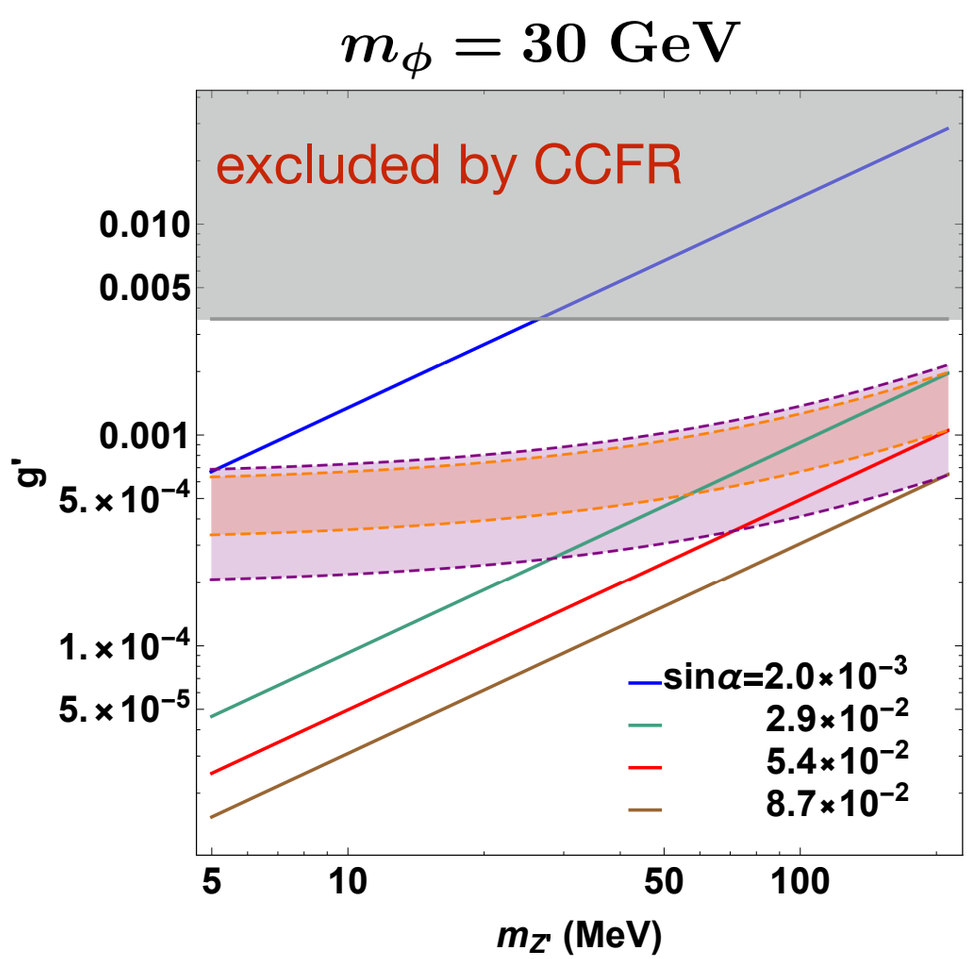
Allowed parameter region

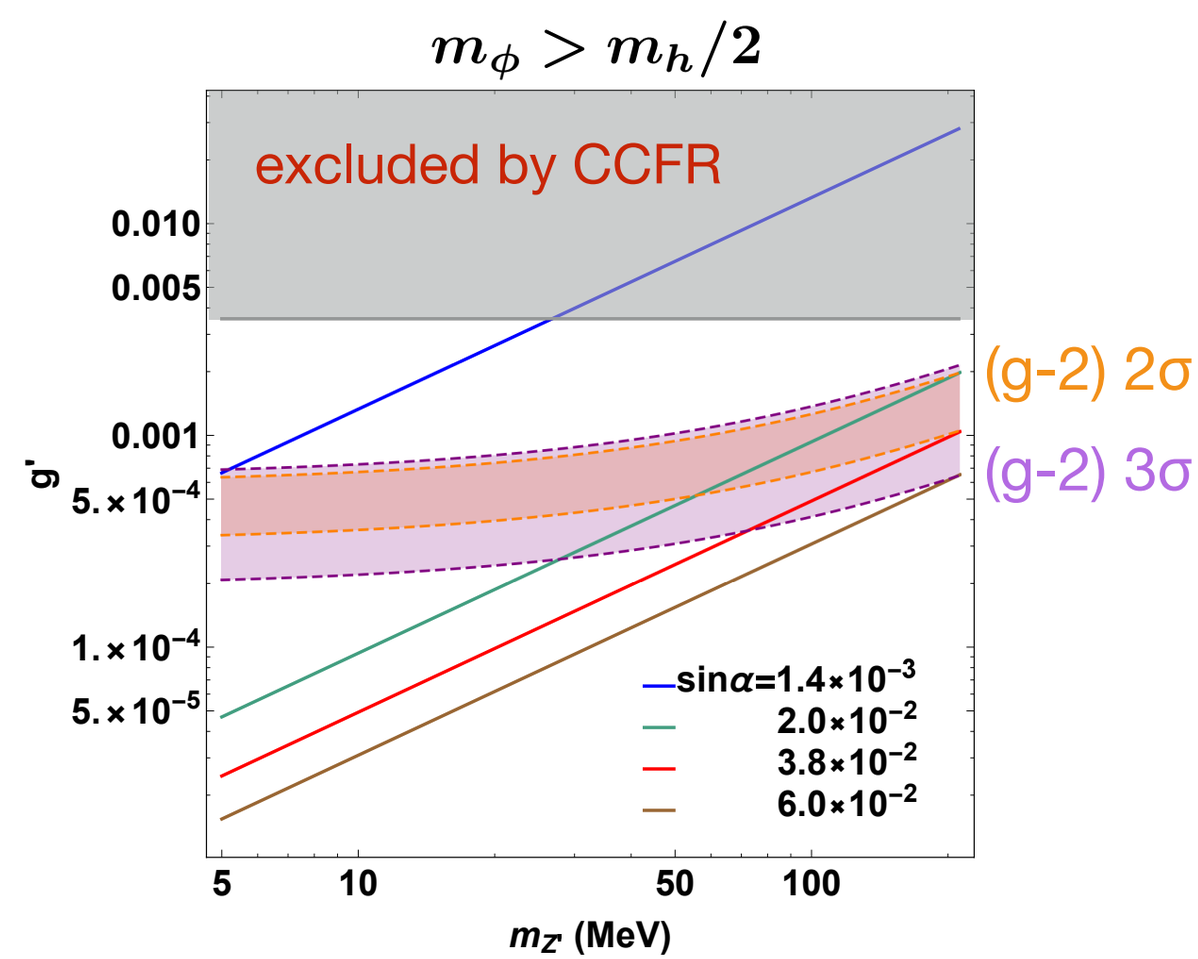
- Extra invisible decays of the SM Higgs into Z' and ϕ pairs,

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

- Constraints from invisible Higgs decay measured at LHC,

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





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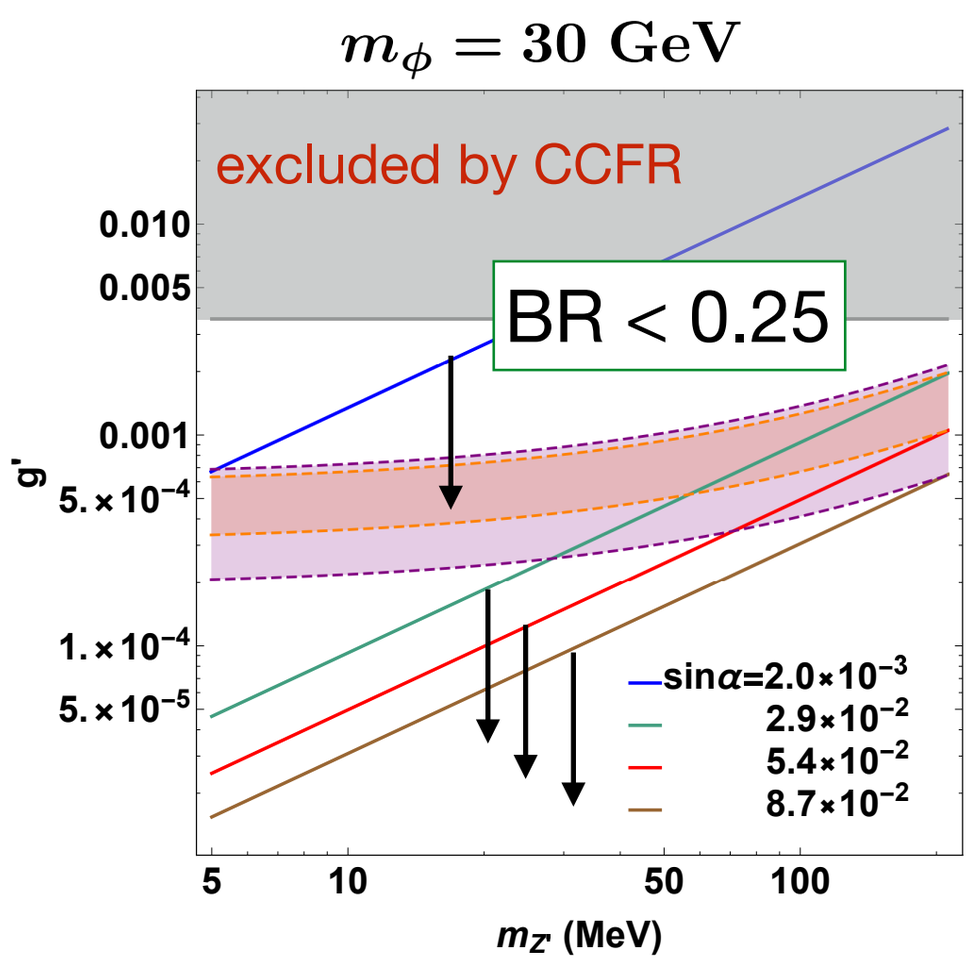

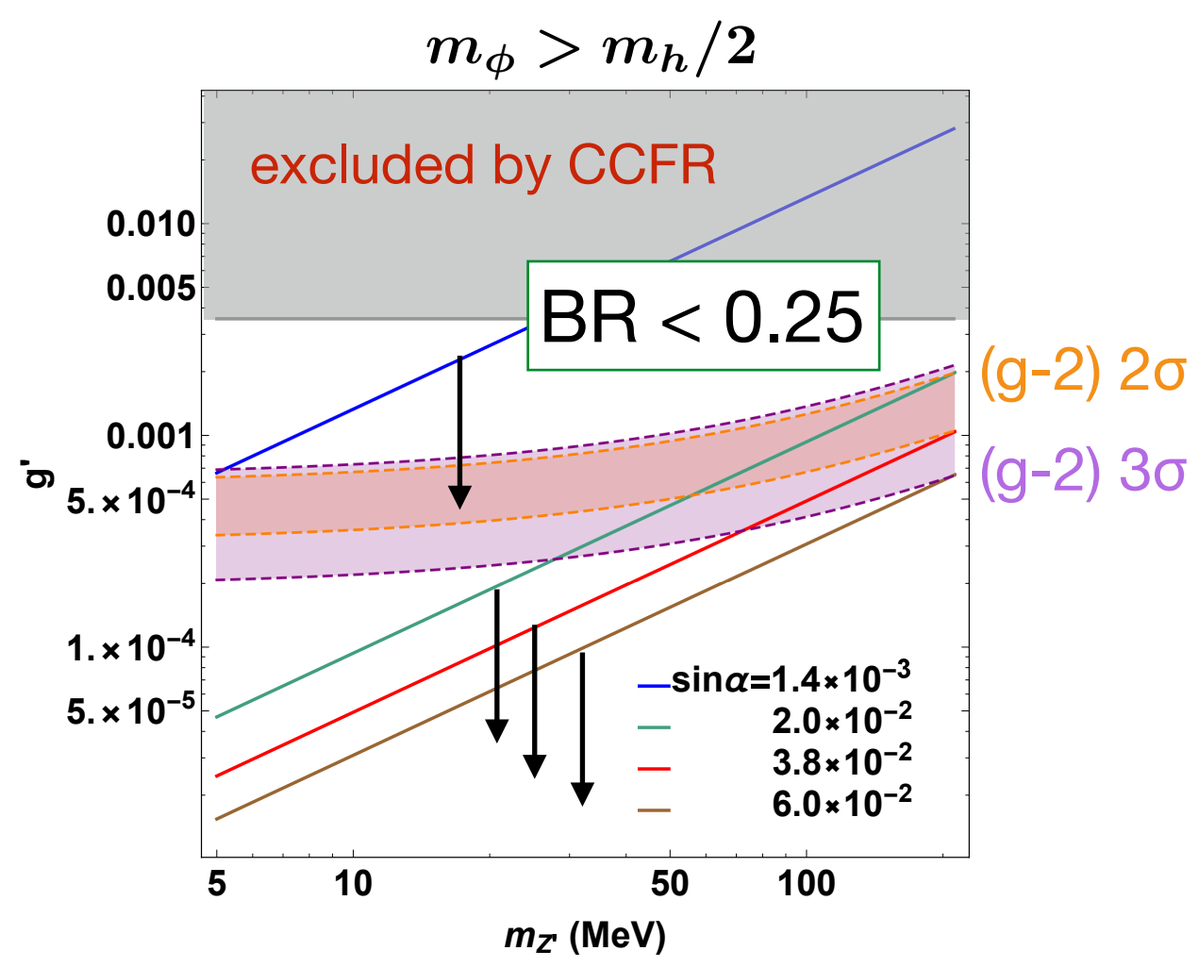

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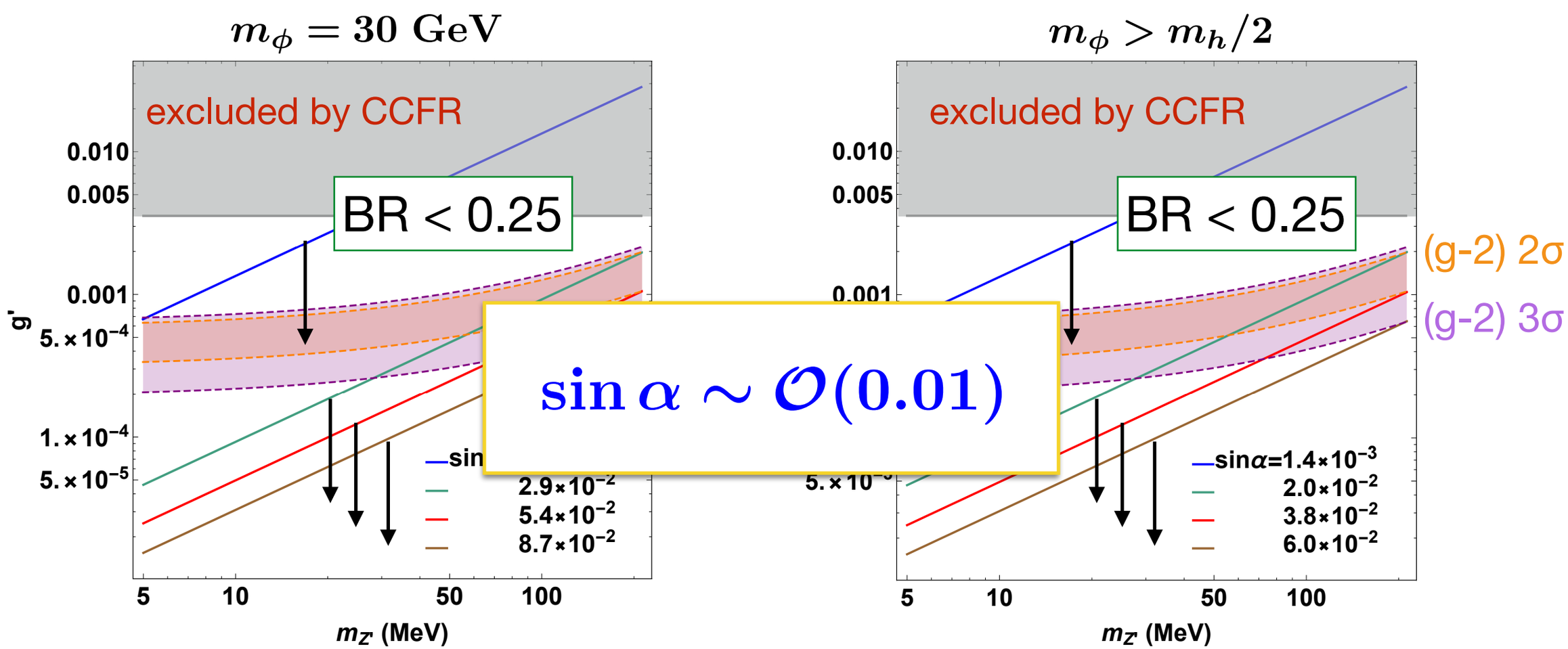

Allowed parameter region

- *Z'* search in meson decays at NA64: *Z'* → 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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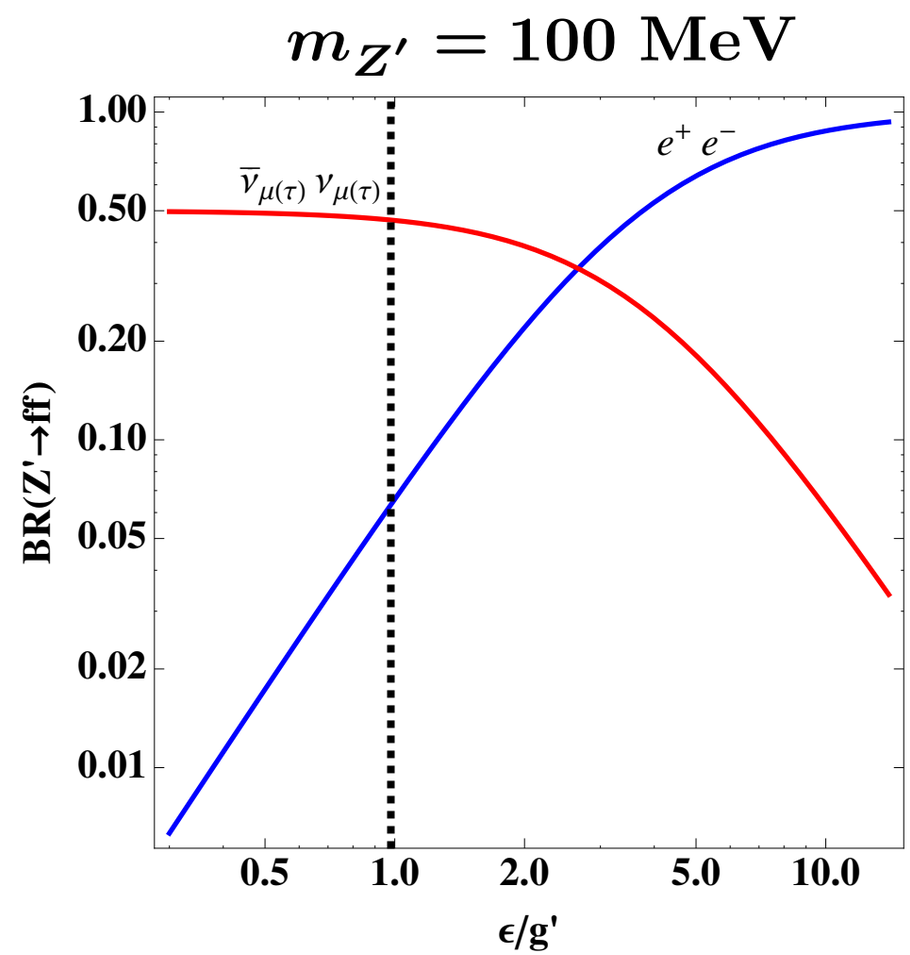
In the following discussion, we fix

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

$$\sin\alpha = 0.05$$

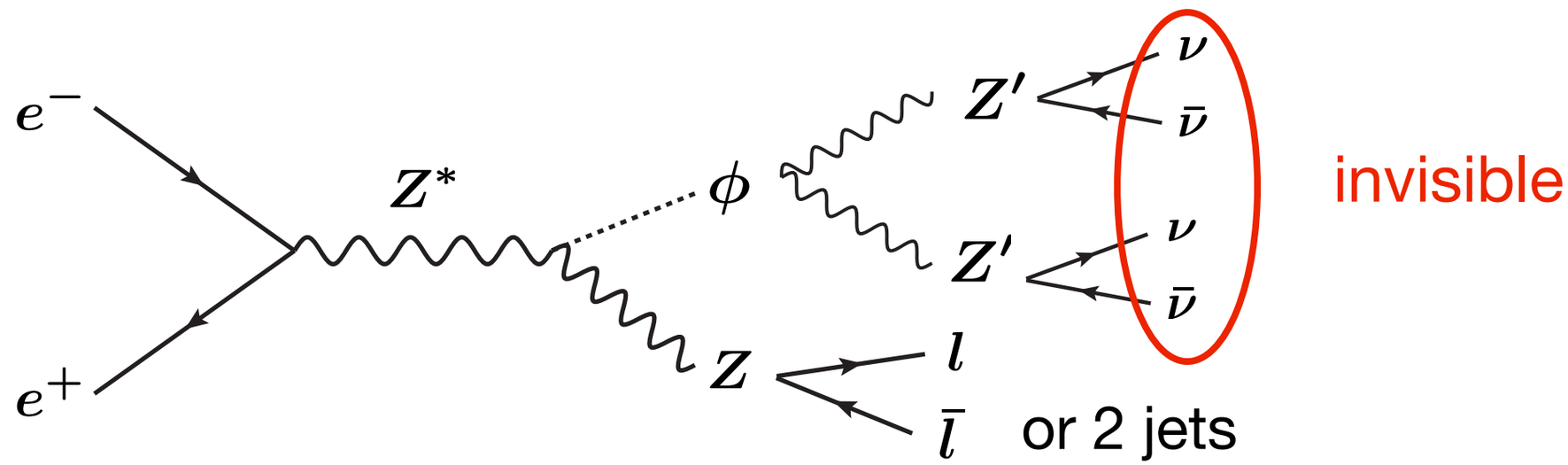
$$\epsilon/g' = 1$$

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



ILC experiment

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



<u>The signal</u>

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

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

<u>The backgrounds</u>

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*=3000/fb and m_ϕ=30, 65 GeV.

Basic Cuts

Reduce BGs

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

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

Invariant Mass Cuts

Reduce BGs in M^{rec} dist.

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

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

reconstructed mass

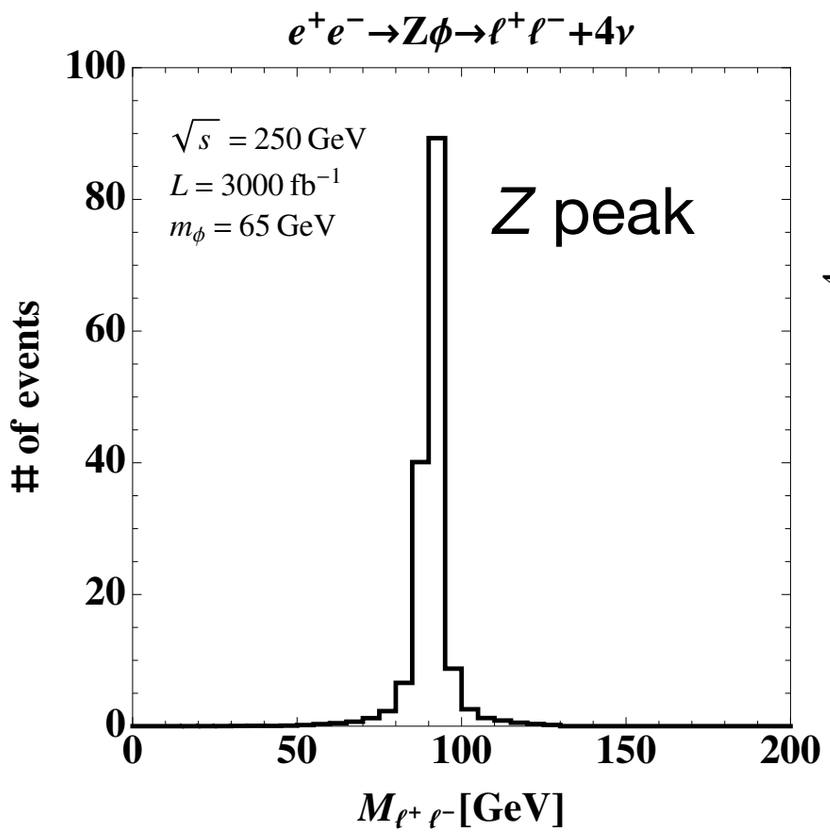
$$M_\phi^{rec} = \sqrt{s + m_Z^2 - 2(E_{l/j_1} + E_{l/j_2})\sqrt{s}}$$

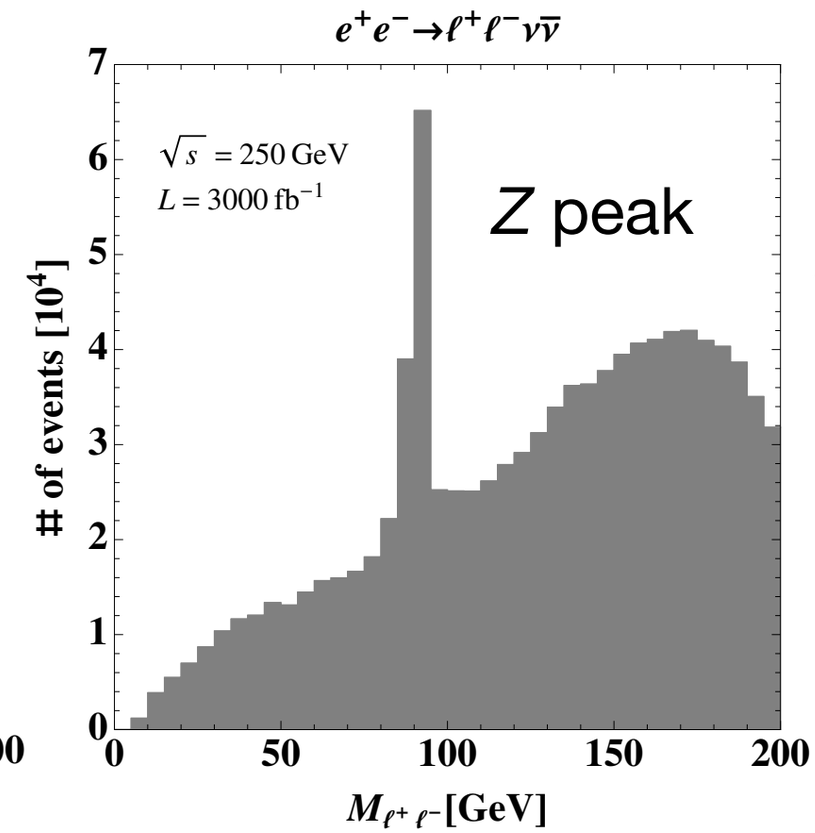
Kinematical Cuts

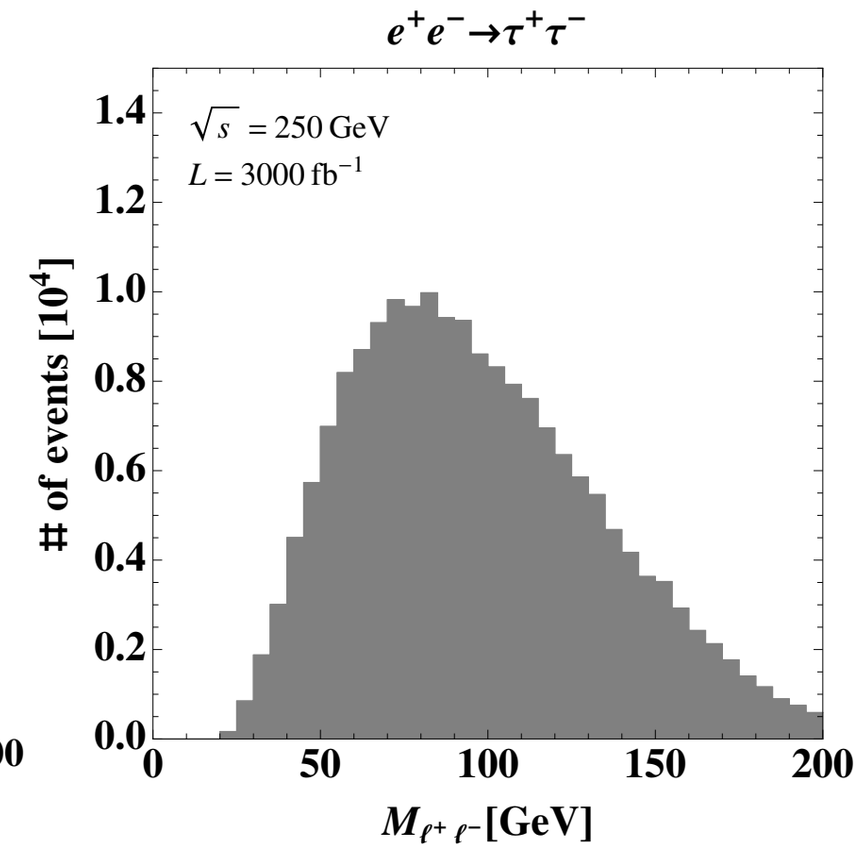
1) $m_\phi - 10\ \mathrm{GeV} < M_{\phi_\ell}^{rec} < m_\phi + 10\ \mathrm{GeV}$ for leptons

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

Lepton signal lepton BG tau BG

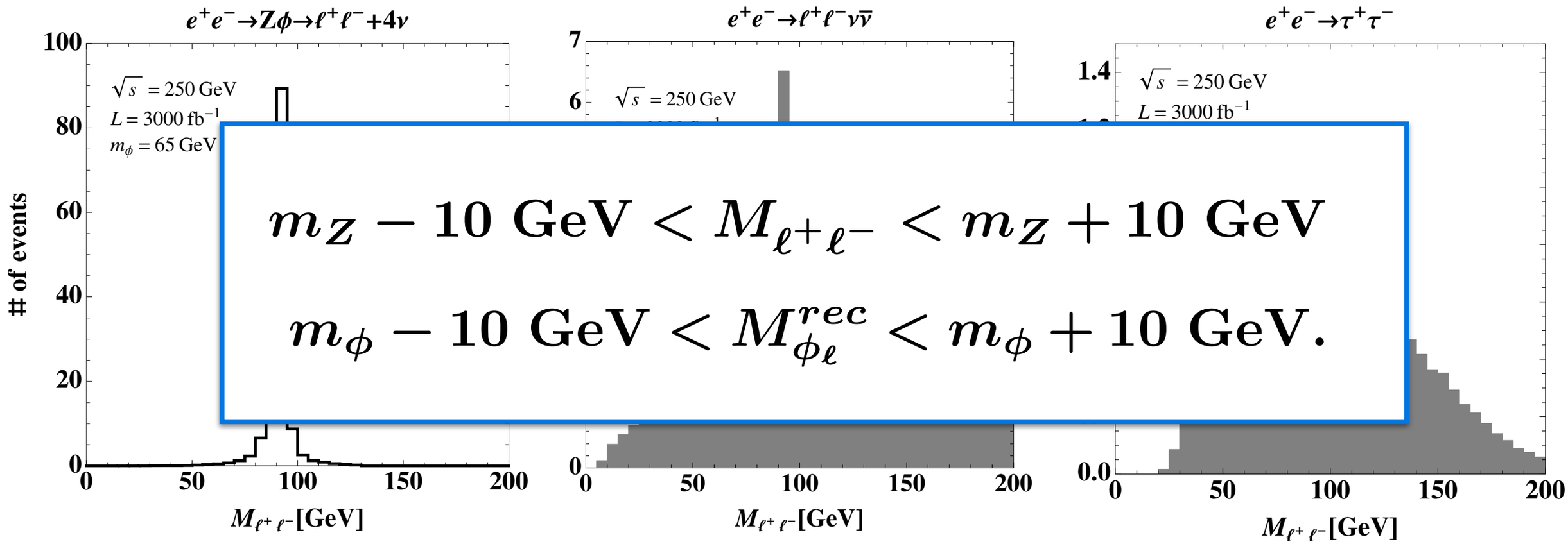






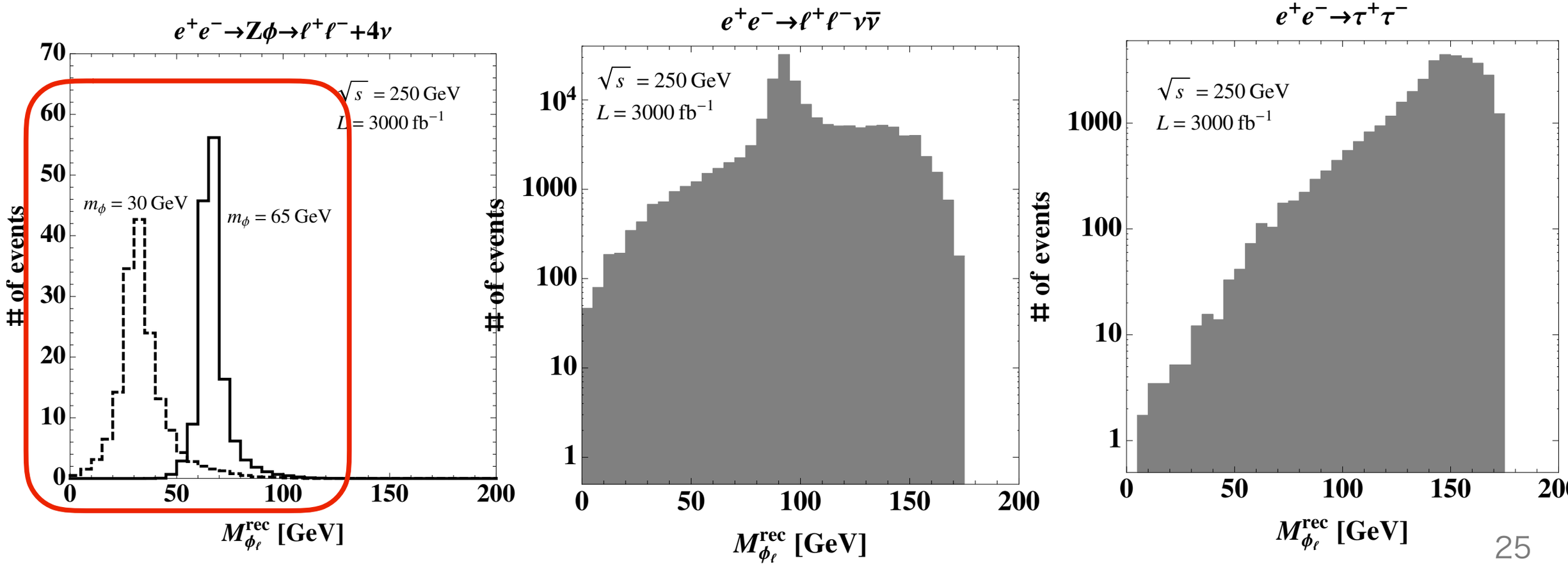
Lepton

signal | lepton BG | tau BG

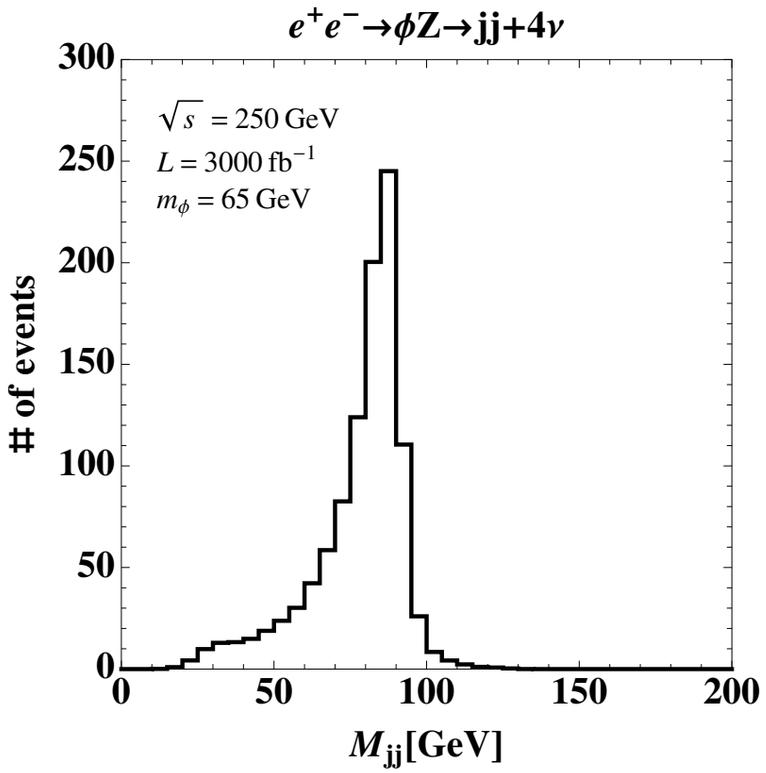


$$m_Z - 10\ \text{GeV} < M_{\ell^+\ell^-} < m_Z + 10\ \text{GeV}$$

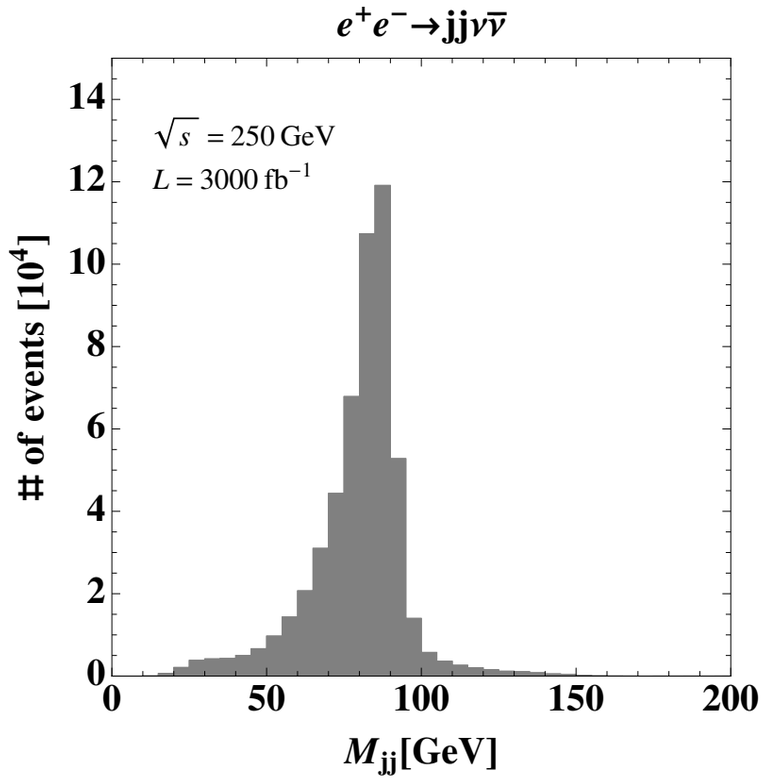
$$m_\phi - 10\ \text{GeV} < M^{rec}_{\phi_\ell} < m_\phi + 10\ \text{GeV}.$$



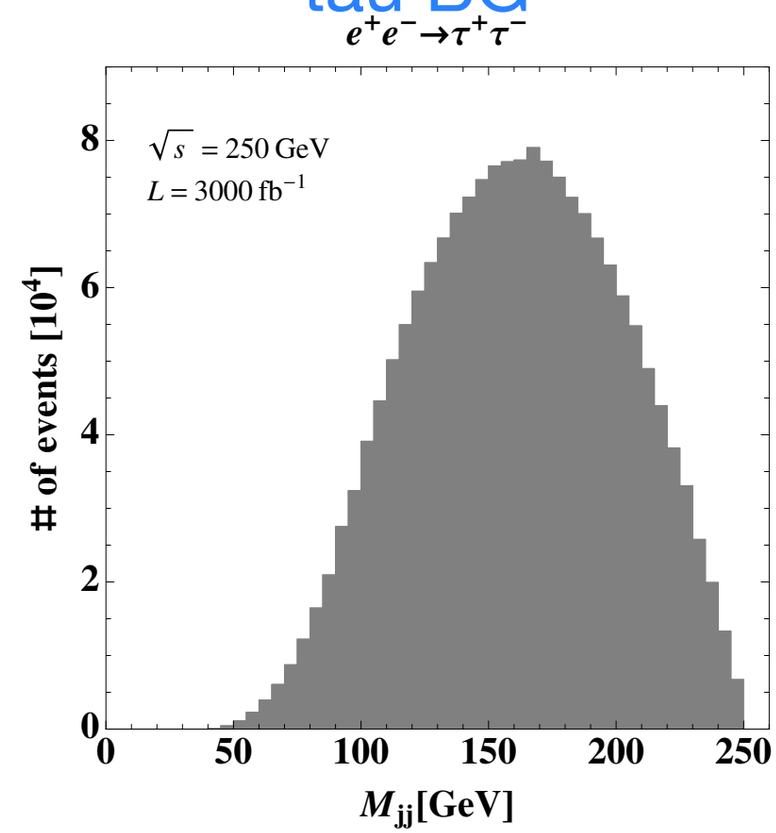
Jets signal



lepton BG



tau BG

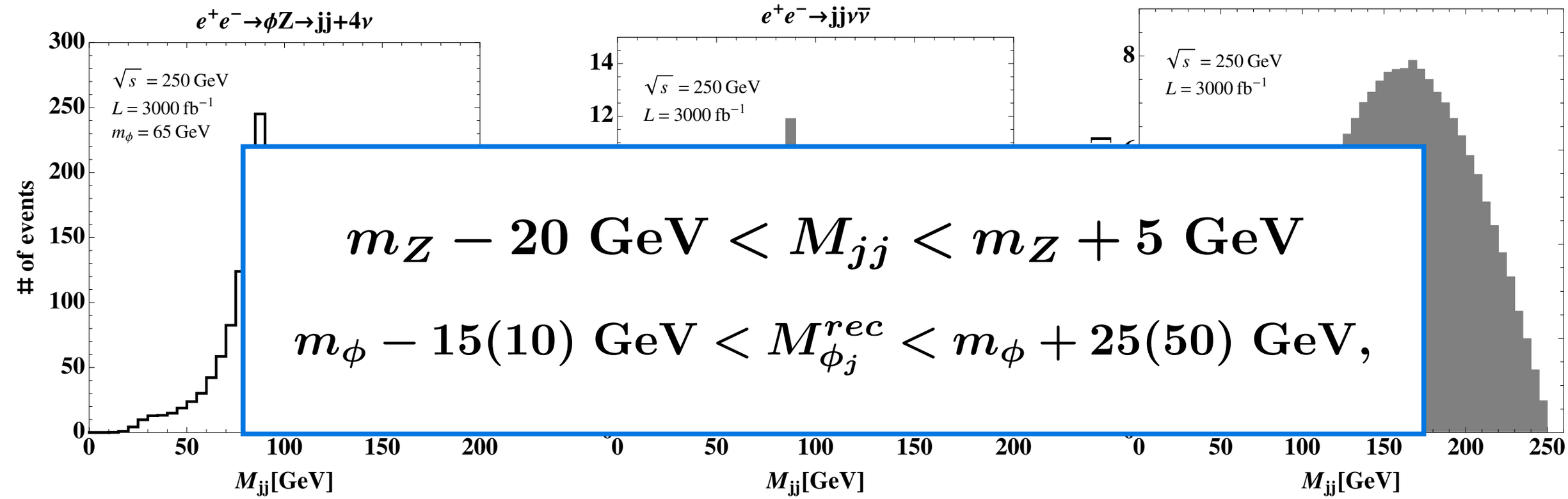


Jets

signal

lepton BG

tau BG



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

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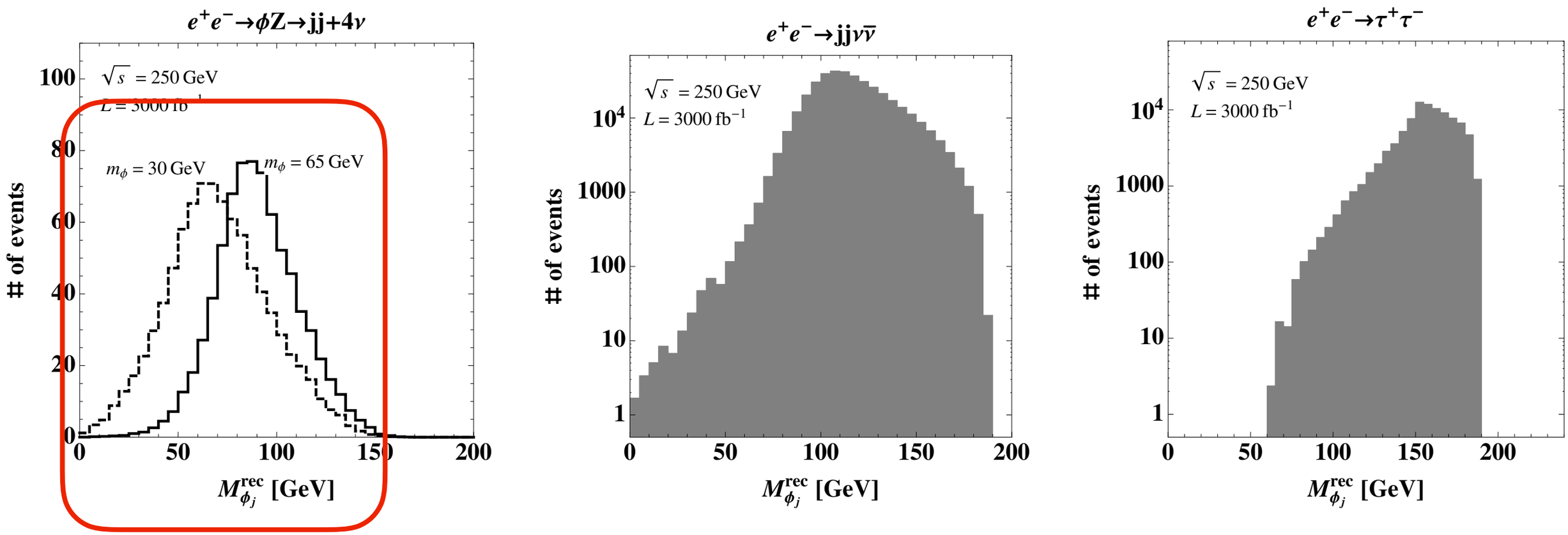


lepton pair event

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

	$\kappa_\alpha N_S$; $m_\phi = (65, 30)$ GeV	$N_{BG}^{\ell^+\ell^-\nu\bar{\nu}}$	$N_{BG}^{\tau\tau}$	$\kappa_\alpha S_c$
Only basic cuts	$(1.6 \times 10^2,\ 1.8 \times 10^2)$	1.1×10^6	1.9×10^5	(0.14, 0.16)
$+\ M_{\ell^+\ell^-}$ cut	$(1.5 \times 10^2,\ 1.7 \times 10^2)$	1.5×10^5	3.7×10^4	(0.35, 0.39)
$+\ M_{\phi_\ell}^{rec}$ cut for $m_\phi = 65$ GeV	$(1.3 \times 10^2, \cdots)$	7.5×10^3	4.6×10^2	$(1.5, \cdots)$
$+\ M_{\phi_\ell}^{rec}$ cut for $m_\phi = 30$ GeV	$(\cdots,\ 1.2 \times 10^2)$	2.8×10^3	42.	$(\cdots,\ 2.2)$

jet event

	$\kappa_\alpha N_S$; $m_\phi = (65, 30)$ GeV	$N_{BG}^{jj\nu\bar{\nu}}$	$N_{BG}^{\tau\tau}$	$\kappa_\alpha S_c$
Only basic cuts	$(1.1 \times 10^3,\ 1.2 \times 10^3)$	5.3×10^5	1.8×10^6	(0.69, 0.83)
$+\ M_{jj}$ cut	$(7.7 \times 10^2,\ 9.3 \times 10^2)$	3.9×10^5	9.1×10^4	(1.1, 1.3)
$+\ M_{\phi_j}^{rec}$ cut for $m_\phi = 65$ GeV	$(3.8 \times 10^2, \cdots)$	2.5×10^4	3.4×10^2	$(2.4, \cdots)$
$+\ M_{\phi_j}^{rec}$ cut for $m_\phi = 30$ GeV	$(\cdots,\ 4.7 \times 10^2)$	1.7×10^3	19.	$(\cdots,\ 11)$

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 and10^{-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 $\phi \to Z'Z' \to 4\nu$.

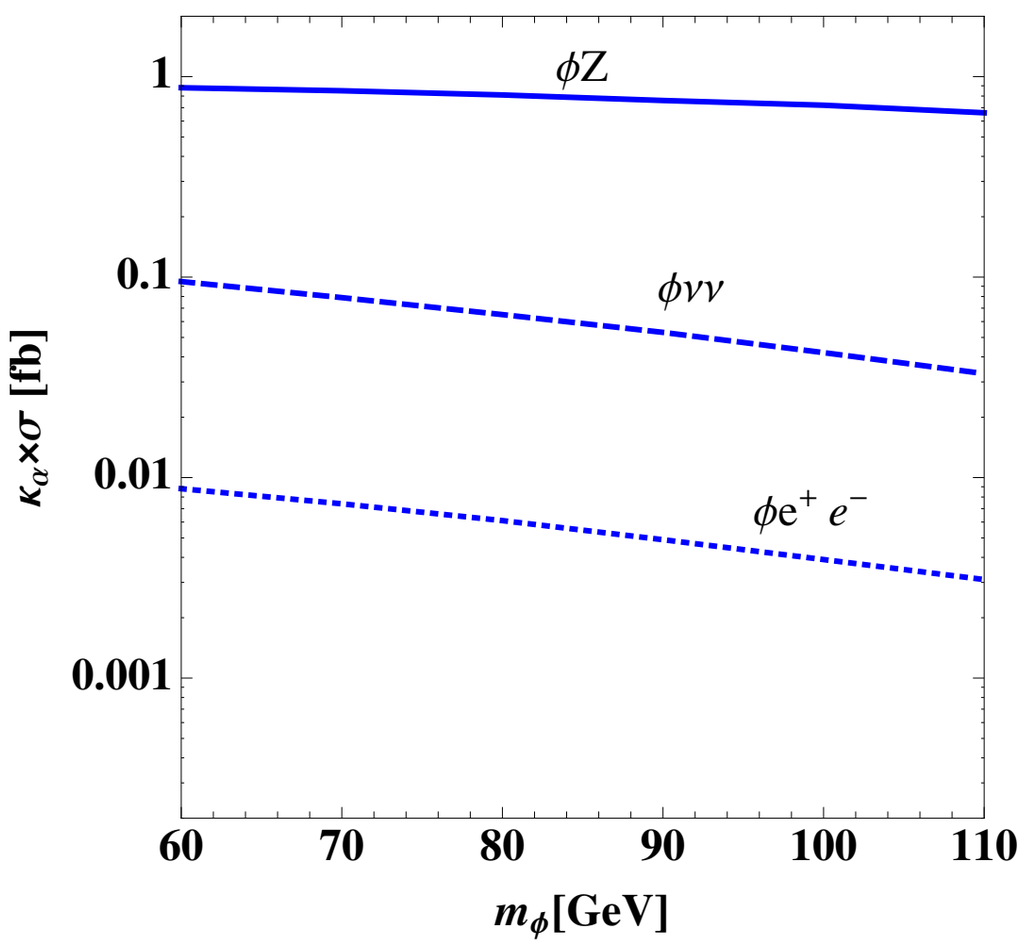
Then, at the ILC experiment,

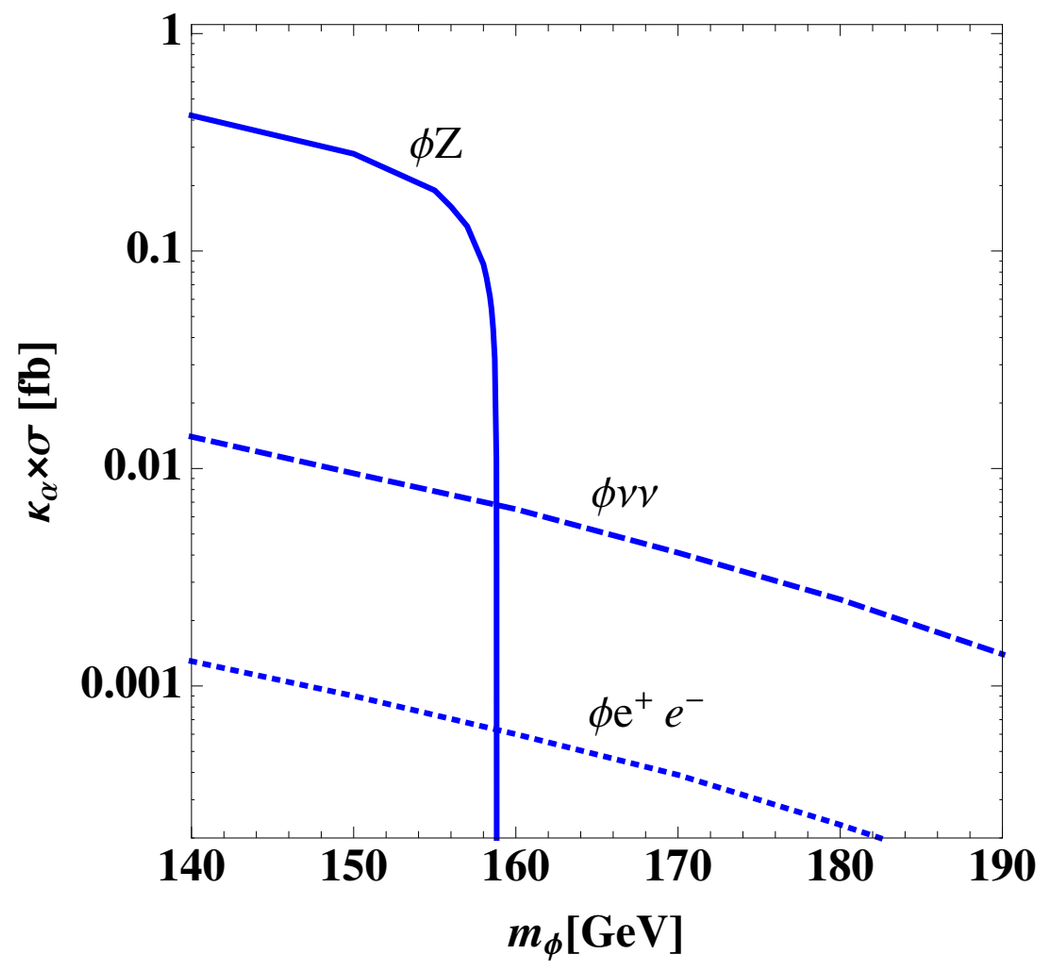
- ϕ mass can be reconstructed from lepton pair and jet events.
- Signal significance is obtained as 1.5 (2.2) for lepton pair, and 2.4 (11) for jets with m_ϕ=65 (30) GeV after cuts.

Back-up

ILC experiment

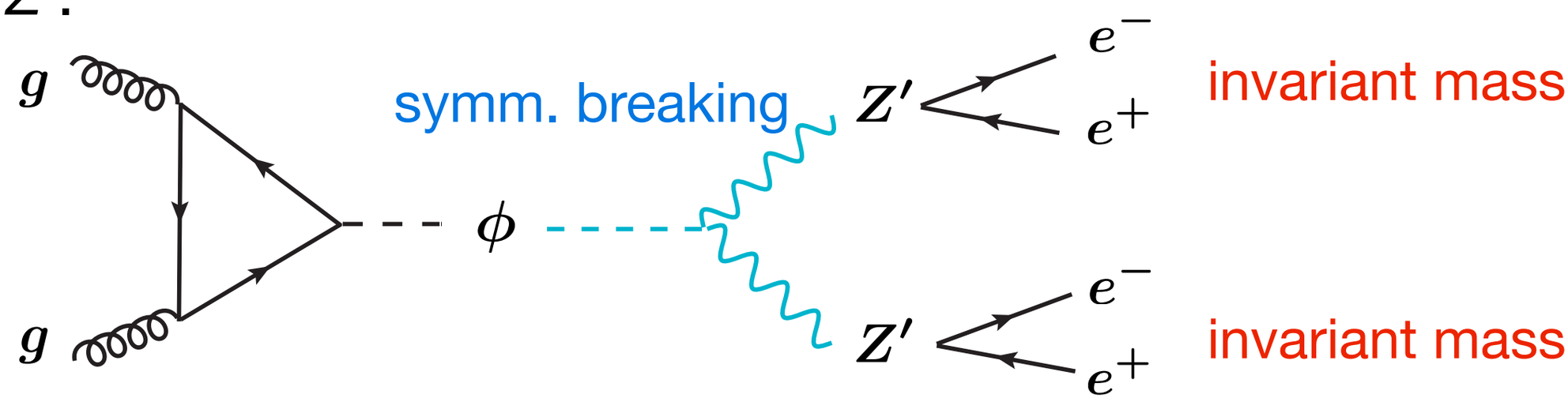
Production cross section at ILC250





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.

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

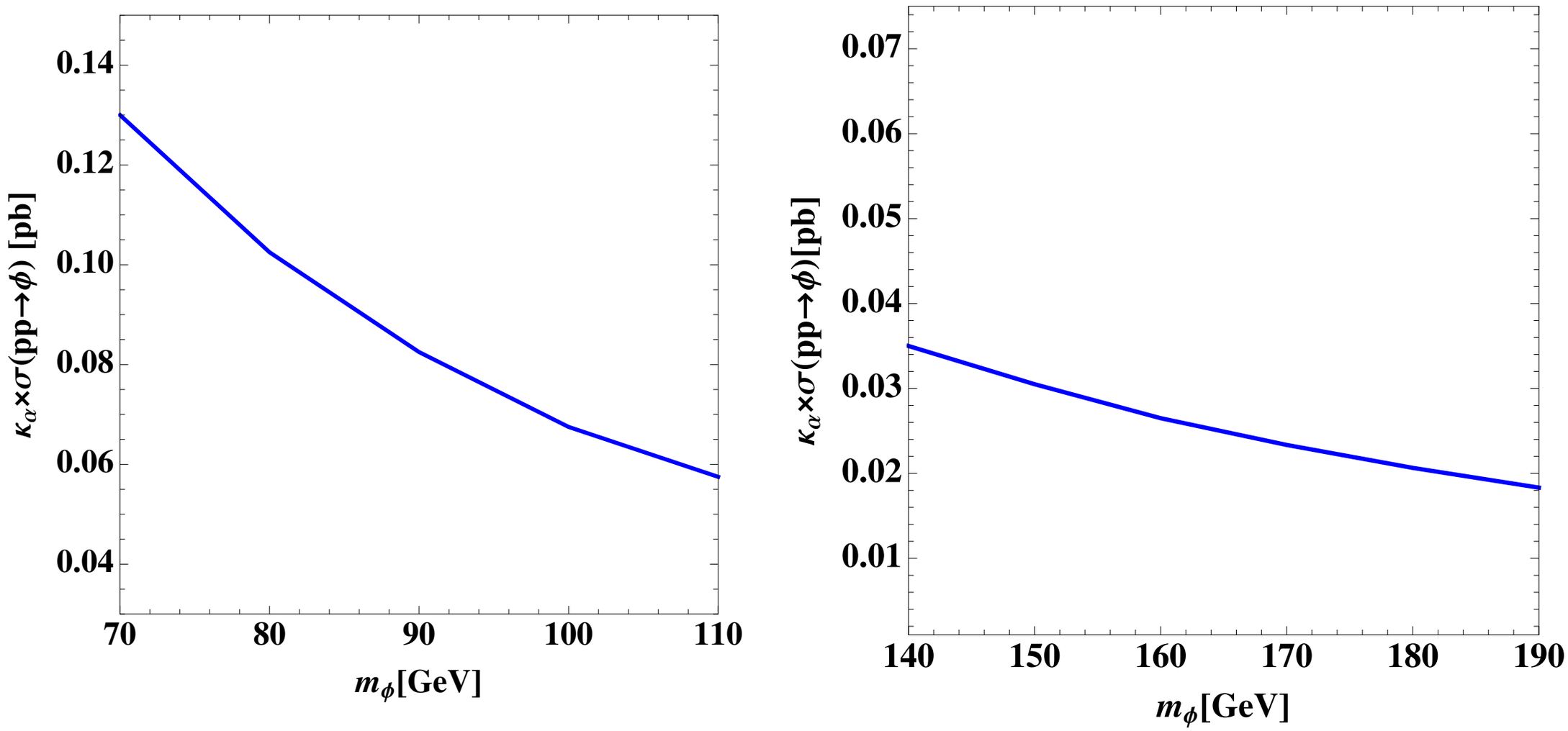
$$m_\phi = \sqrt{(p_{Z'} + p'_{Z'})^2}$$

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

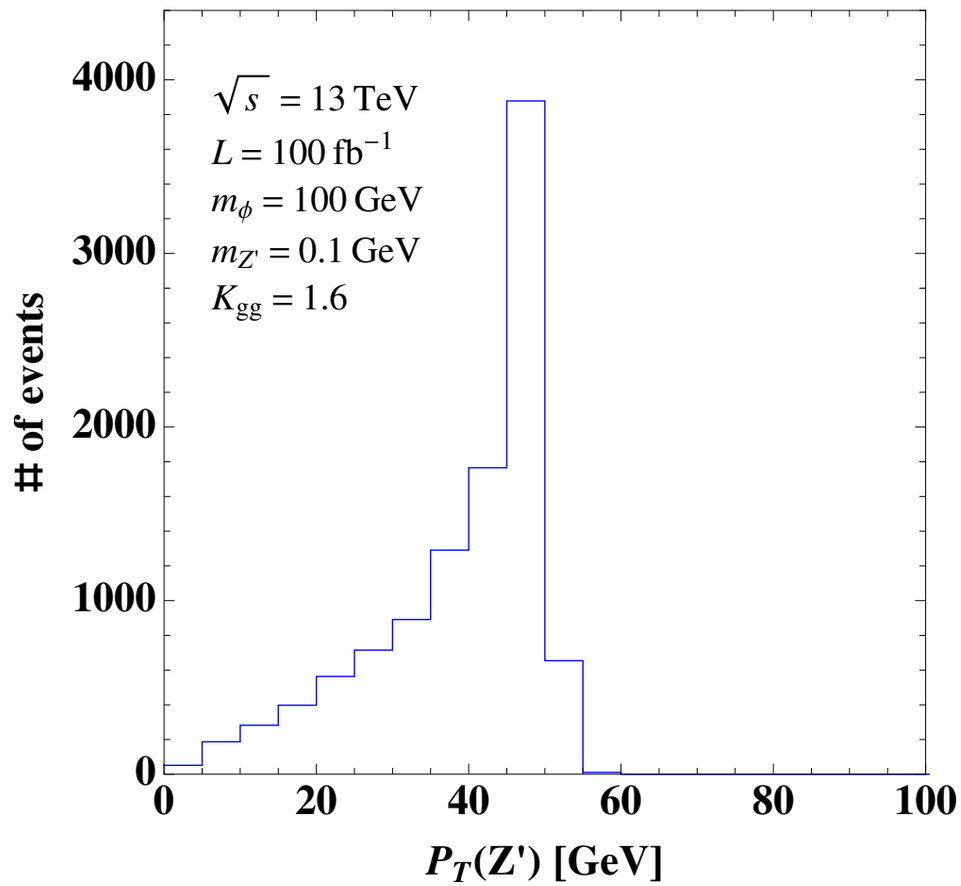
LHC experiment

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