# $e^-e^-$ Physics for ILC

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# Outline

- Introduction
  - Why $e^-e^-$?
  - What is different from $e^+e^-$?
- Physics of $e^-e^-$ collisions
  - Majorana Neutrino Search
  - s-electron Search/Study
  - And so on …
- Summary

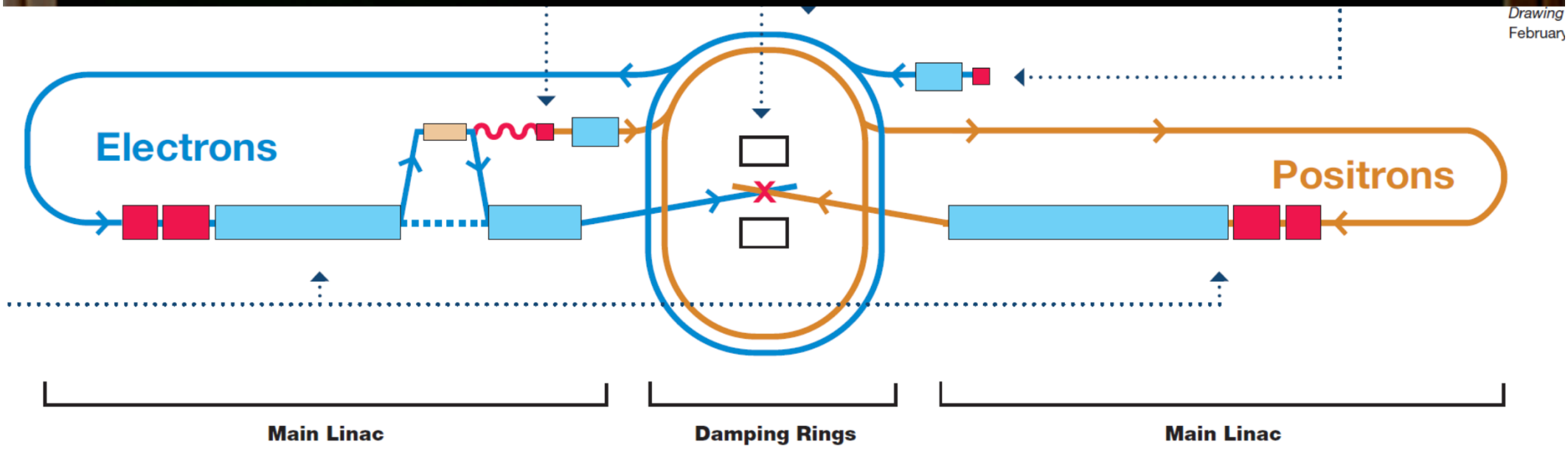

Introduction

# Introduction: Why $e^- e^-$?

- 電子•電子特有の物理があり、電子•陽電子実験と相補的な情報が得られる。
- (Higgsも作れる。)
- 加速器の変更は、ほとんどいらない。
- (電子源は安くて簡単。)
- 測定器/final focusの変更は、必要ない。

# Introduction

- An $e^-e^-$ option in ILC



# Introduction

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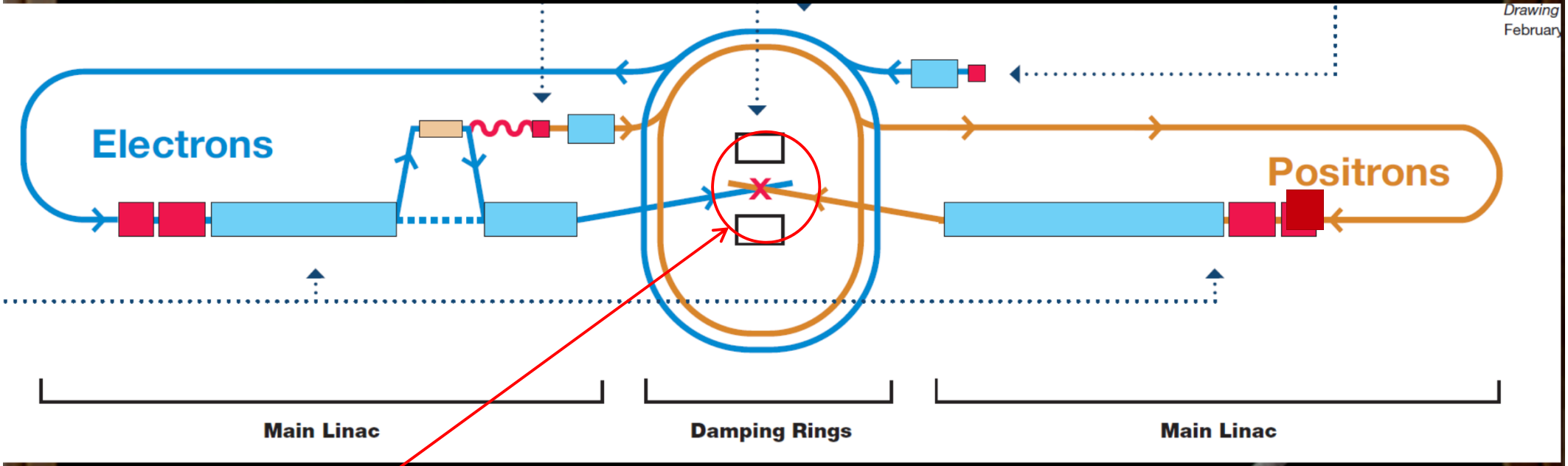


Final focus system(crossing angle) is the same as the $e^+e^-$ collider
Detector can be common to the $e^+e^-$ collider

# Introduction

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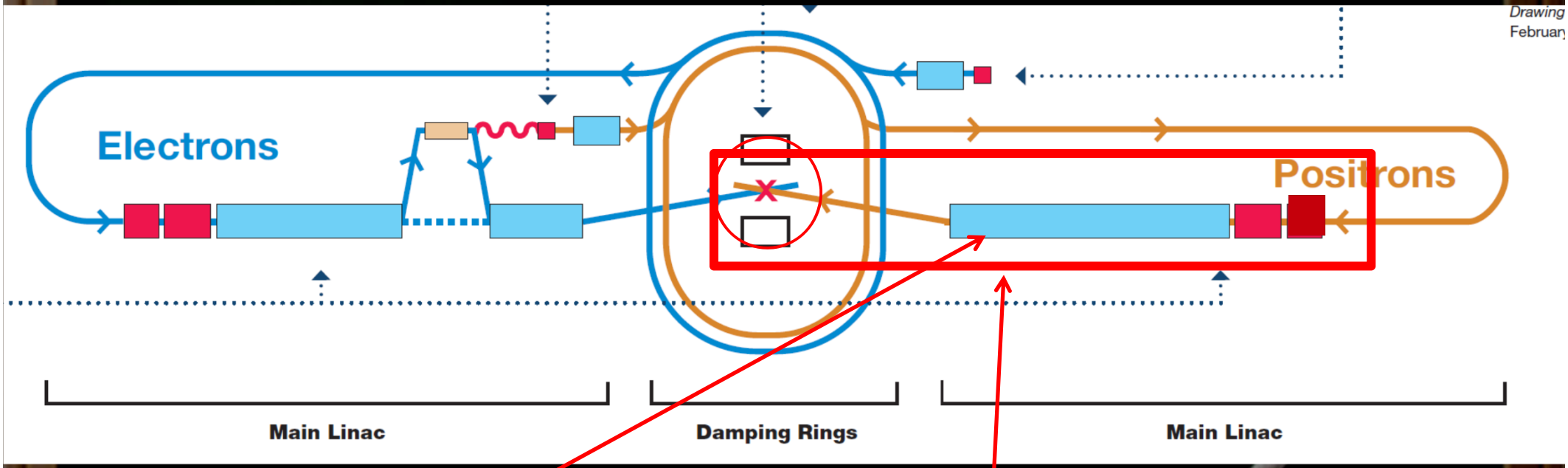
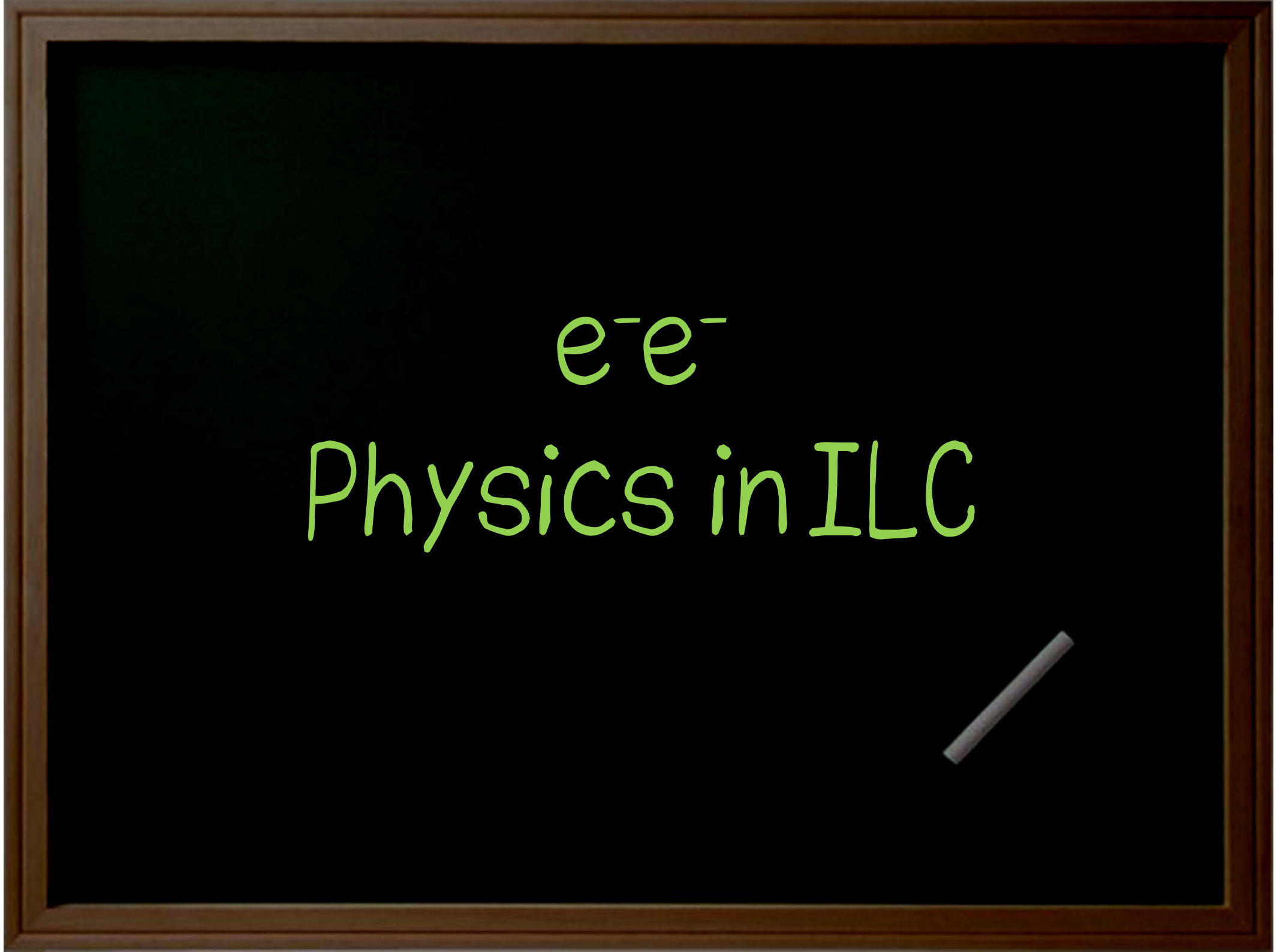


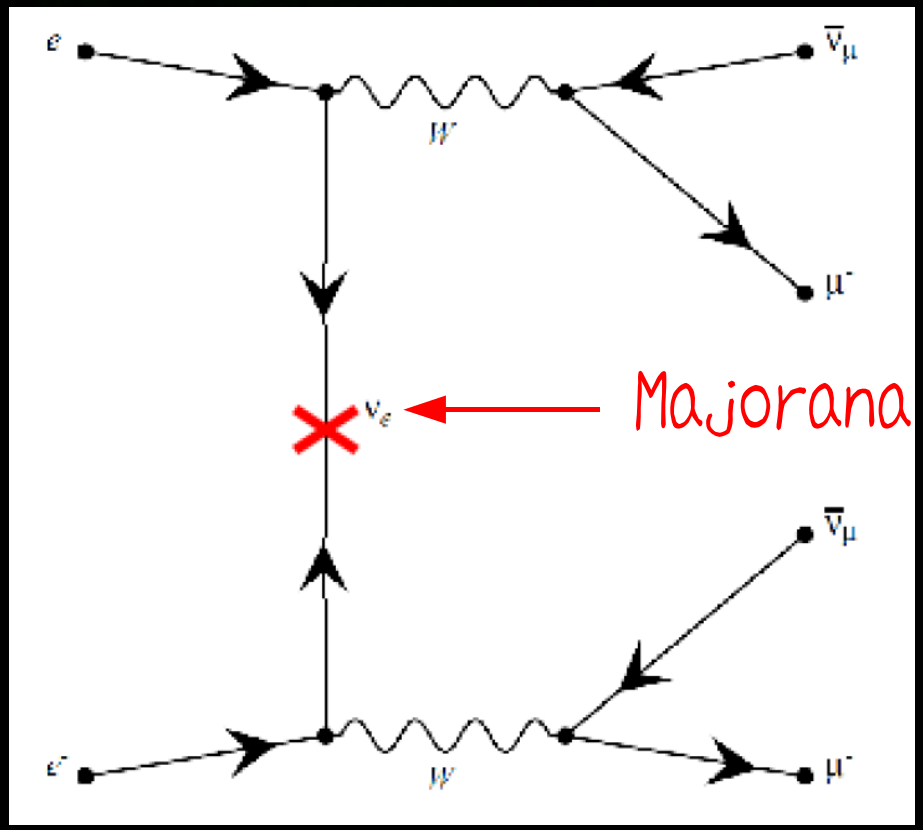

Acceleration Phase Change

Magnet Polarity Change

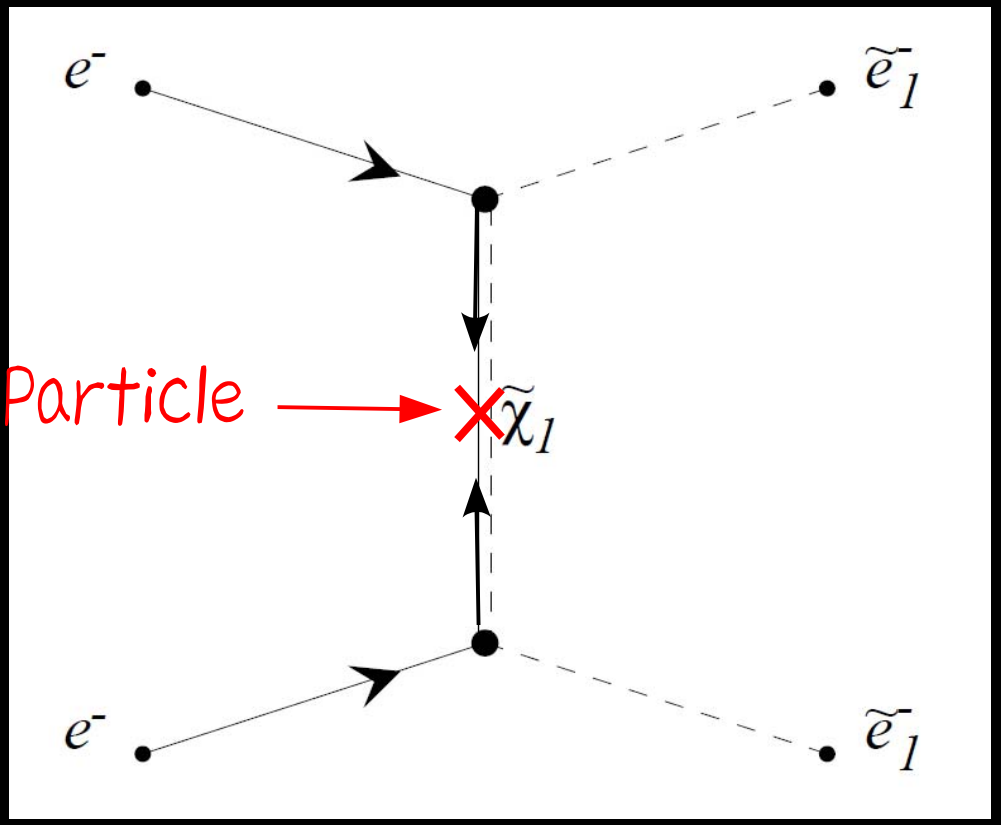

e⁻e⁻
Physics in ILC

# $e^-e^-$ Physics

- Majorana Fermion Productions



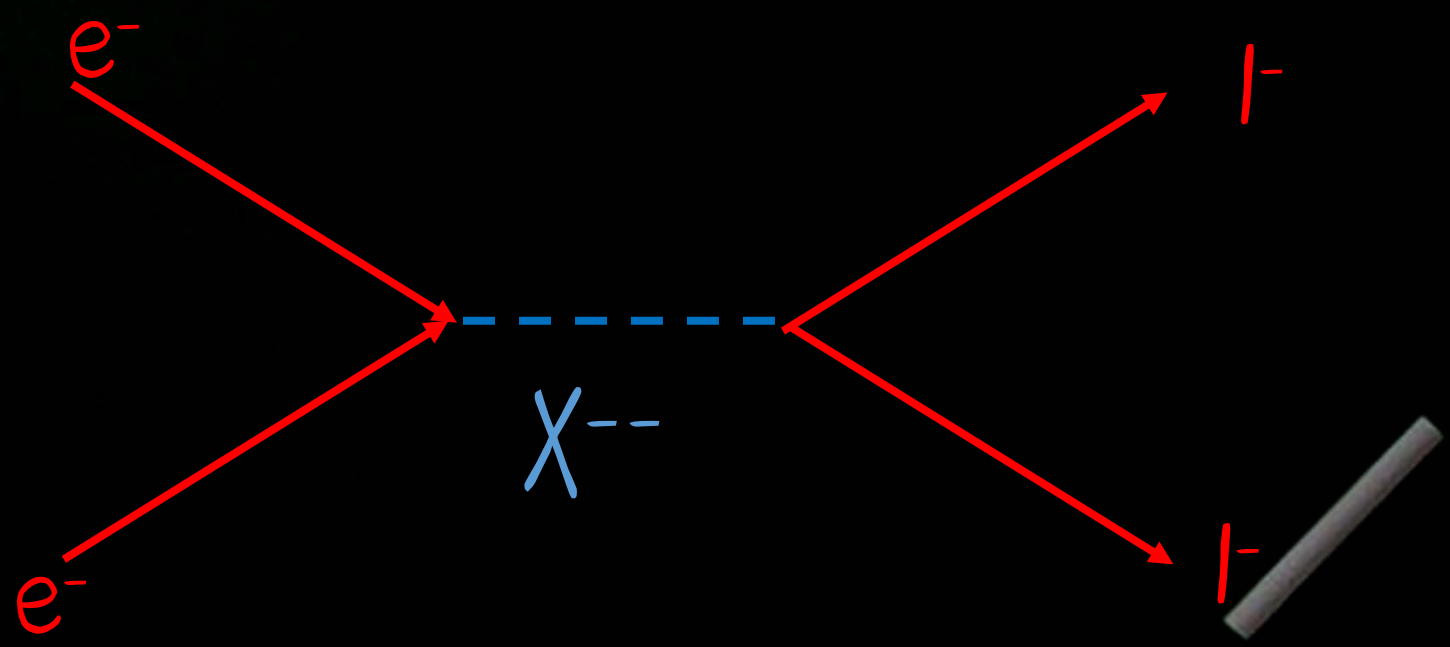

Majorana Neutrino Search




s-electon Search

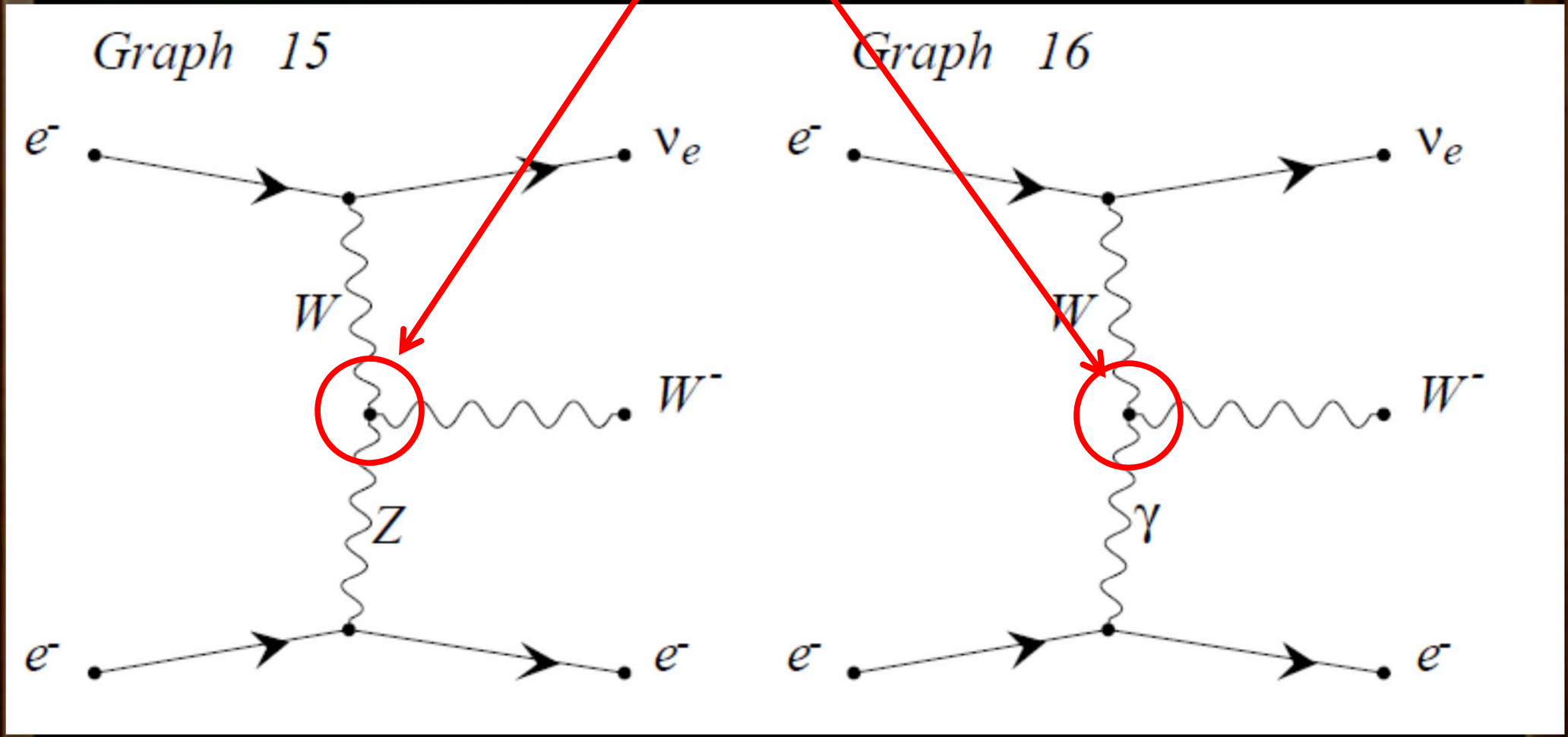
# $e^-e^-$ Physics

## Doubly charged particle



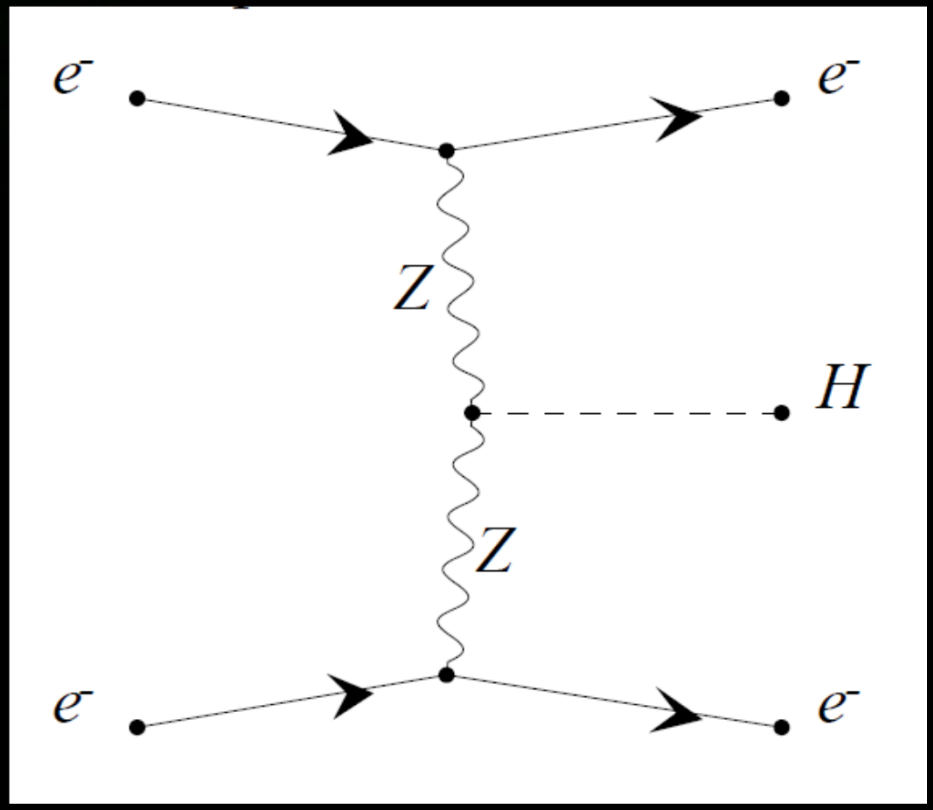
# $e^-e^-$ Physics

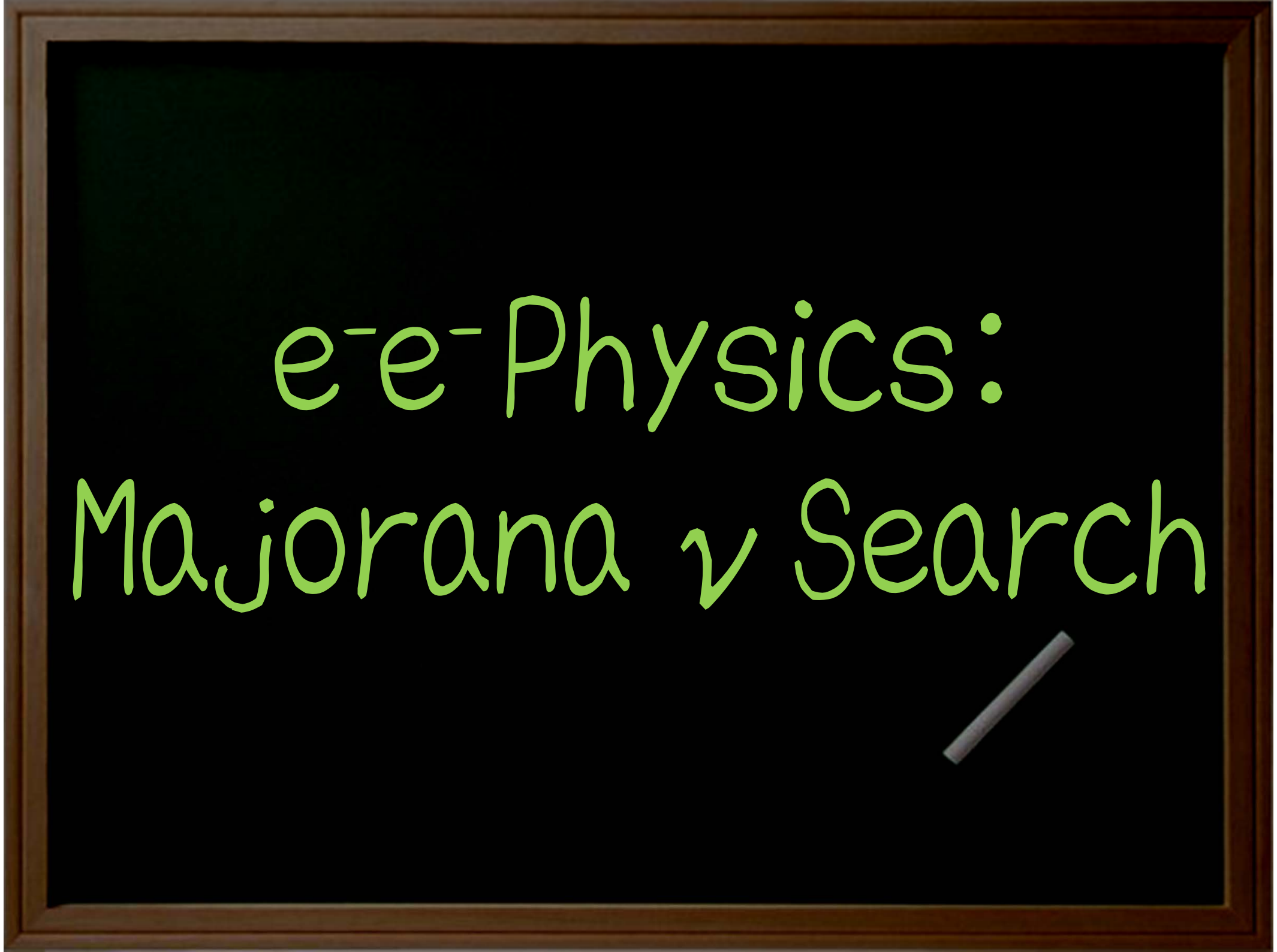
## Gauge boson couplings



# $e^-e^-$ Physics

## Higgs Production in $e^-e^-$ collider




e⁻e⁻ Physics:
Majorana ν Search

# Majorana Neutrino Search

Heavy Majorana-neutrino search
at future $e^-e^-$ colliders

J. Fujimoto and Y. Kurihara

November 14, 2011

# Majorana Neutrino Search

## 1 Model

- $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- Gauge boson masses on $SU(2)_L \times SU(2)_R$ are degenerated: $m_{W_L^\pm} = m_{W_R^\pm}$.
- Neutrinos are Majorana particles.
- A mass of a left-handed neutrino is light: $m_{\nu_L} \ll \mathcal{O}(\text{eV})$.
- A mass of a right-handed neutrino is heavy: $m_{\nu_R} \geq \mathcal{O}(\text{weak scale})$.
- Right-handed gauge-bosons, $W_R^\pm$, do not contribute to low energy experiment

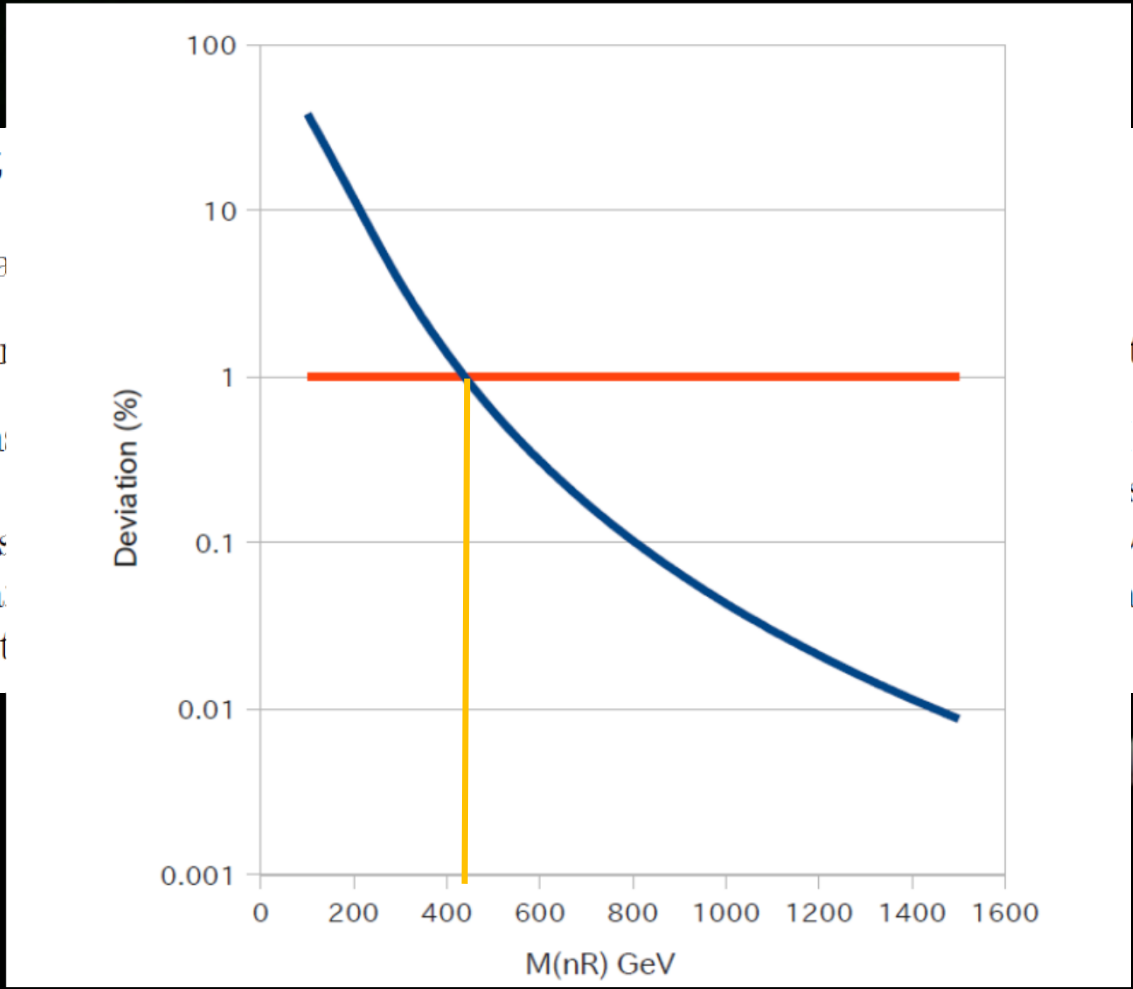
# Majorana Neutrino Search

## 2 Experiment

- Heavy neutrino ma
- An electron-neutri
- Total cross section
  of 1% level. A $\nu_{eR}$
  When the $\nu_{eR}$-mas
  diagram is less tha
  allowed experiment

ts.

experiments with accurac
s mass is not heavy enough
$_{eR}$ in a $t$-channel exchang
mass above 500 GeV is ti



# Majorana Neutrino Search

## 2 Experimental limit for $\nu_R$ mass

- Heavy neutrino masses must be grater then $m_Z/2$ from LEP-I experiments.
- An electron-neutrino mass has additional constraint from LEP-II experiments.
- Total cross sections of a $W$-pair production have bean measured by LEP-II experiments with accurac of 1% level. A $\nu_{eR}$ can contribute the $W$-pair production cross-sections, if its mass is not heavy enougl When the $\nu_{eR}$-mass is heavier than about 500 GeV, a contribution from $\nu_{eR}$ in a $t$-channel exchang diagram is less than 1% as shown in Figure 1. Then we assume a $\nu_{eR}$ with a mass above 500 GeV is ti allowed experimentally.

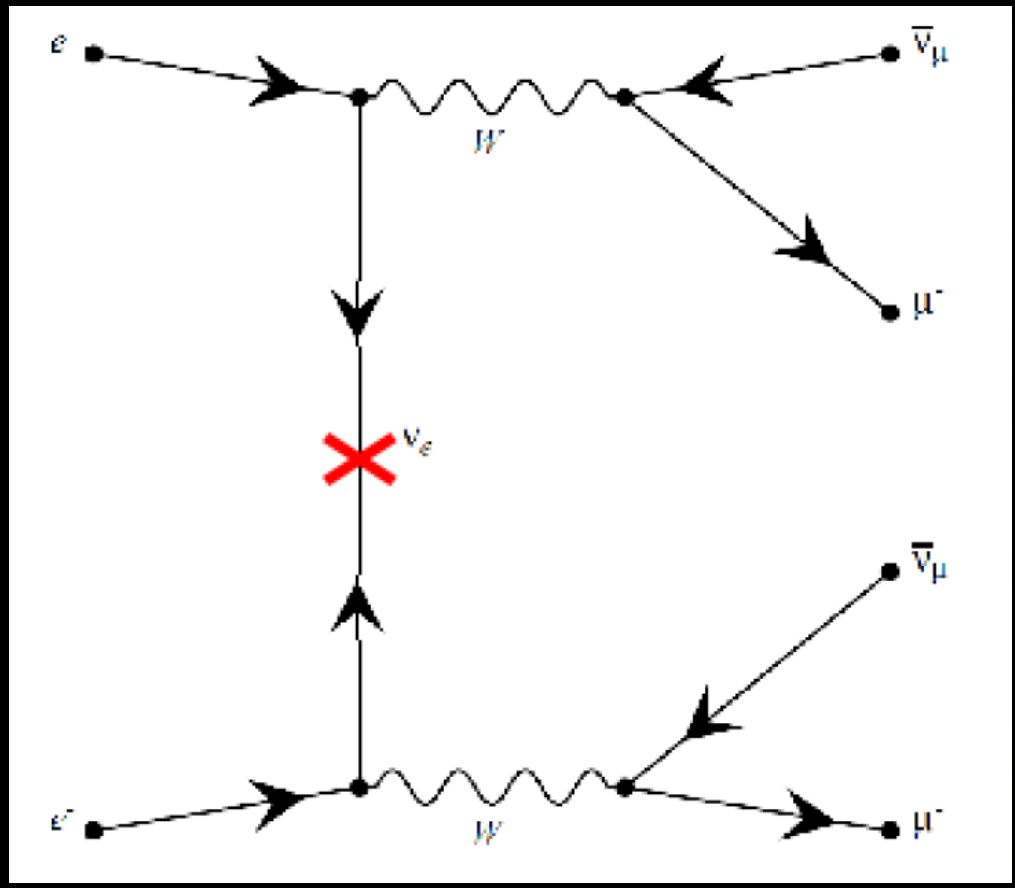
# Majorana Neutrino Search

## 3 Parameters

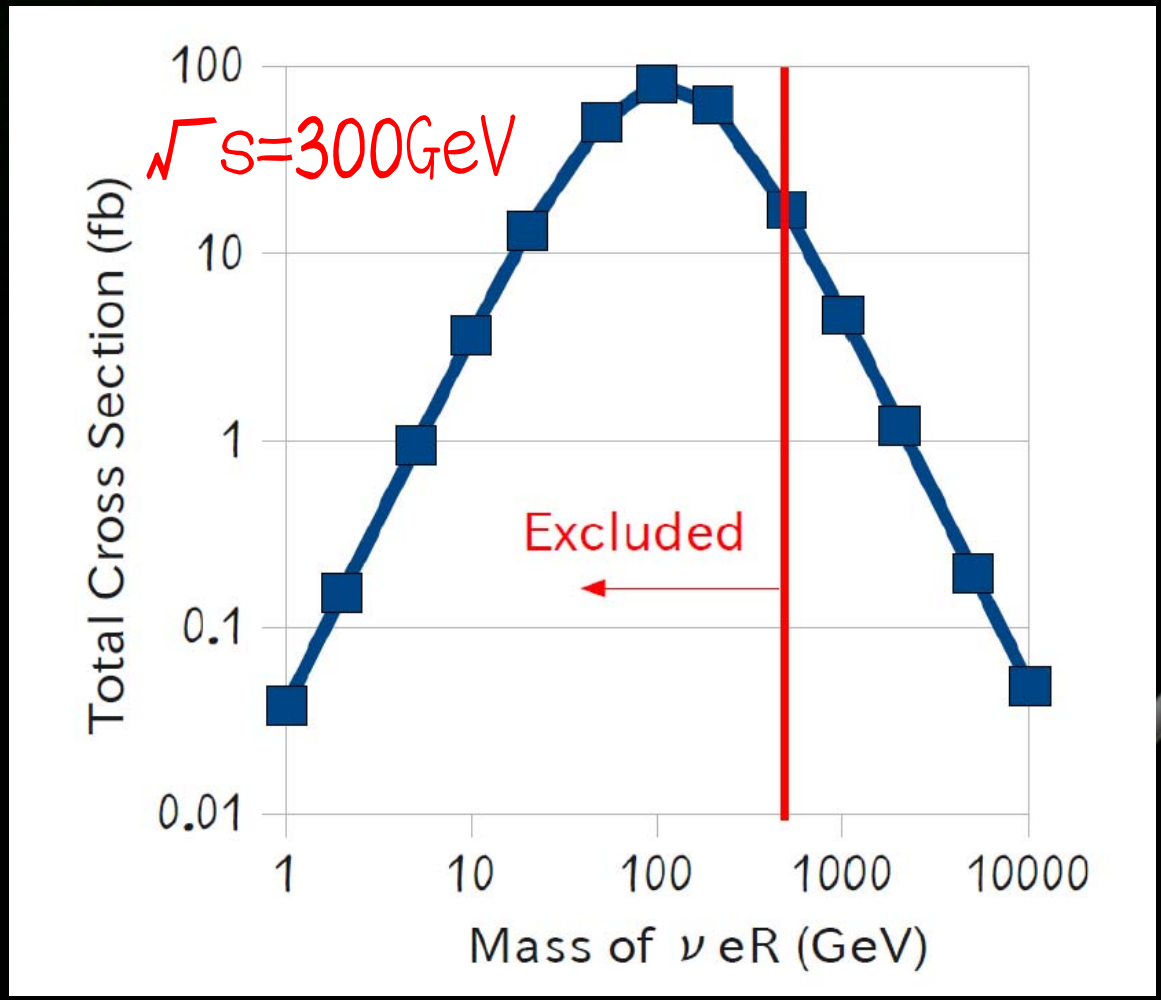
- Accelerator:a future $e^-e^-$ linear collider experiment.
- $\alpha$=1/137.036
- $m_W$=80.22 GeV
- $m_Z$=91.187 GeV
- $\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$
- $m_e = 0.511 \times 10^{-3}$ GeV

# Majorana Neutrino Search

Signal:
$\mu^- \mu^-$ pair+missing
B.G.: $\nu_e \nu_e W^- W^-$

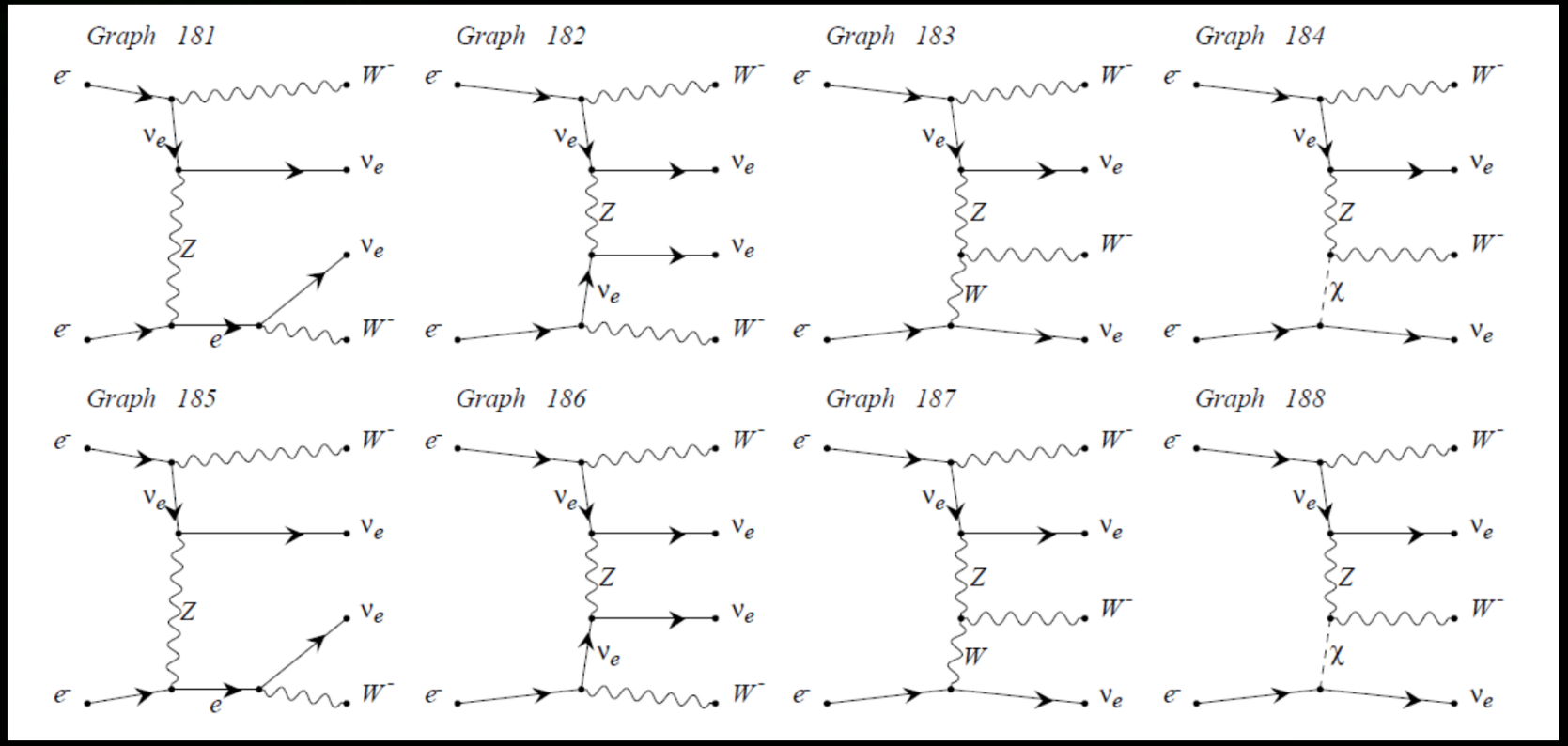


# Majorana Neutrino Search



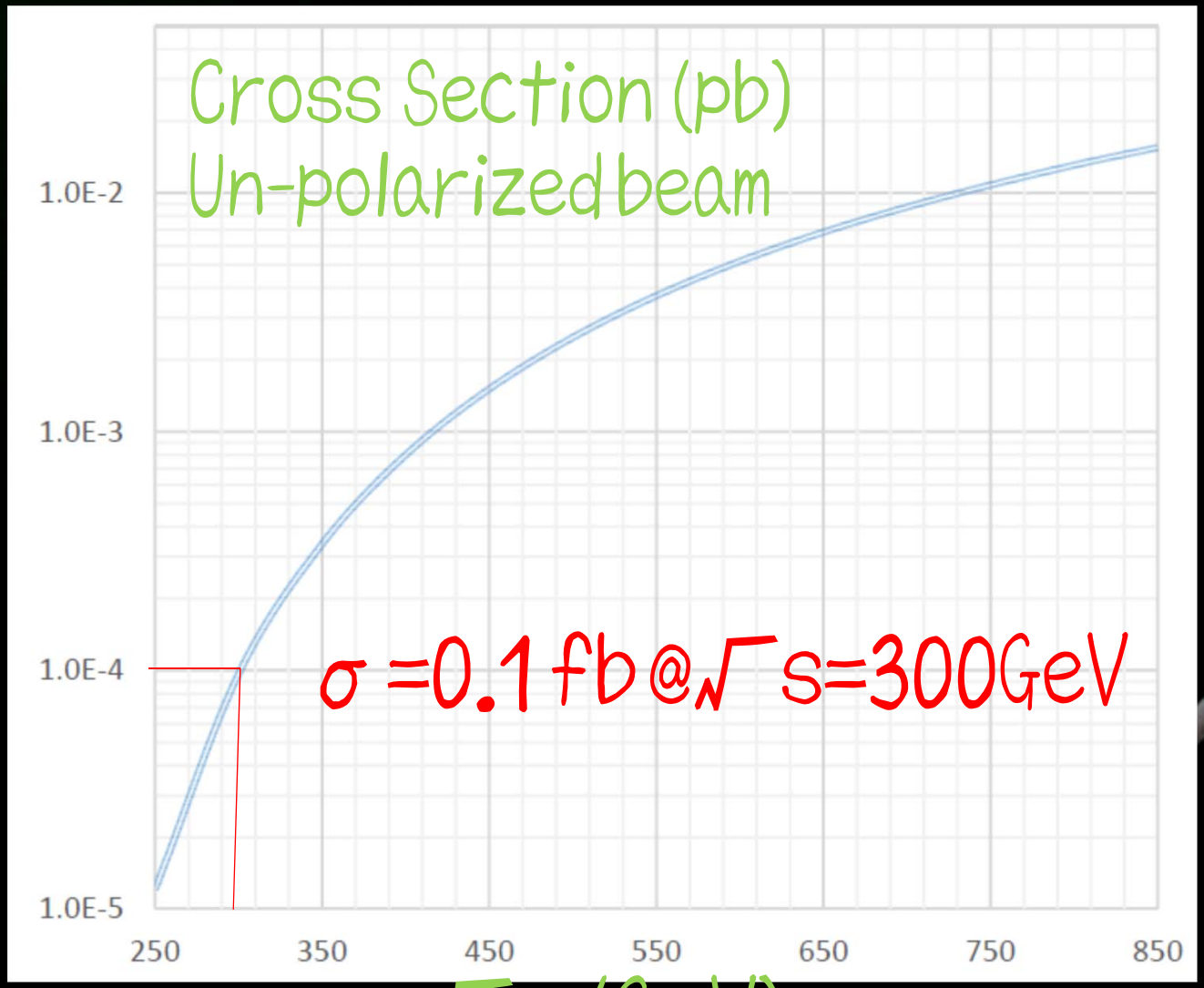
# W-W- Scattering

## BackGround




#Diagrams:286

# W-W- Scattering



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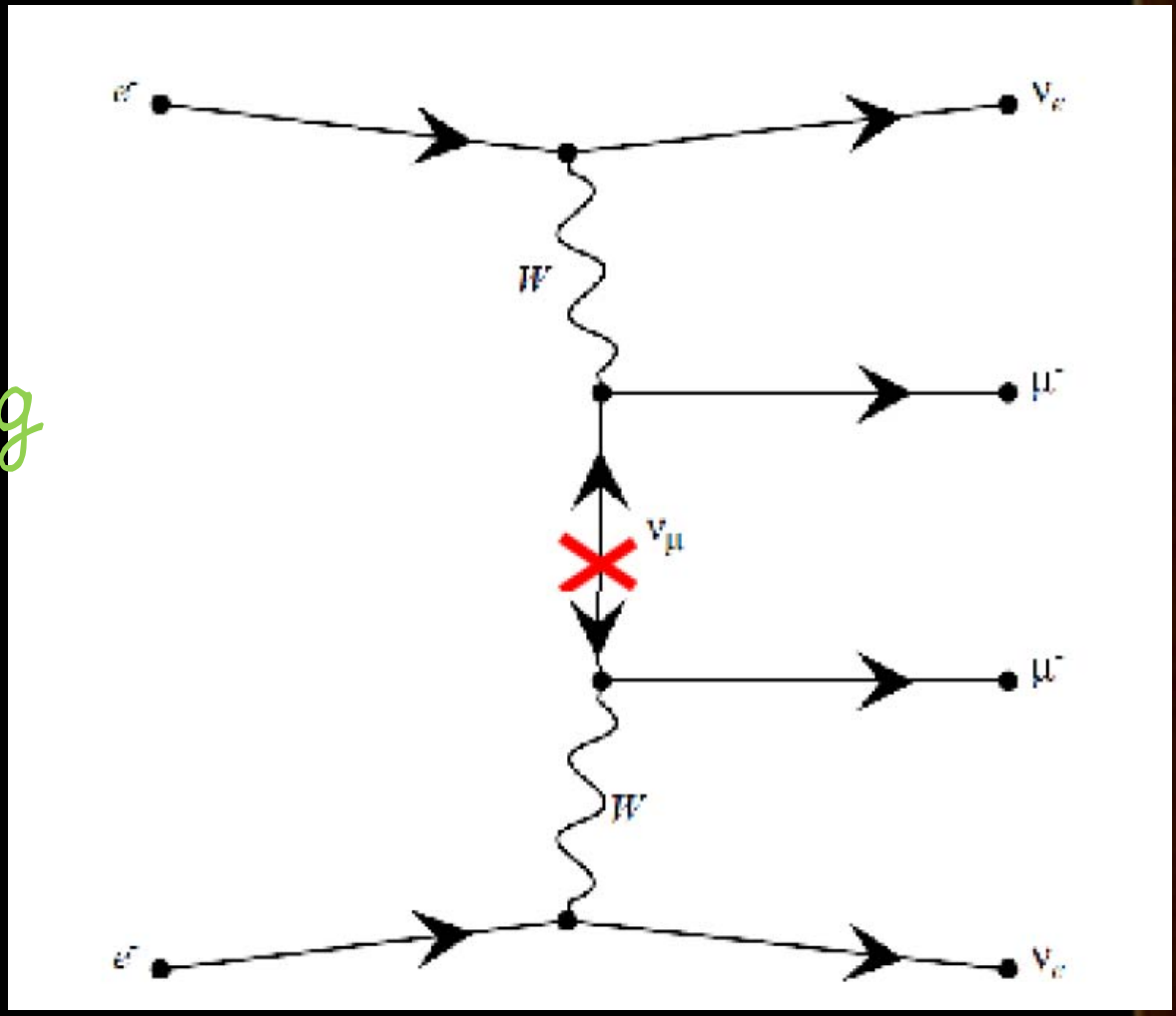

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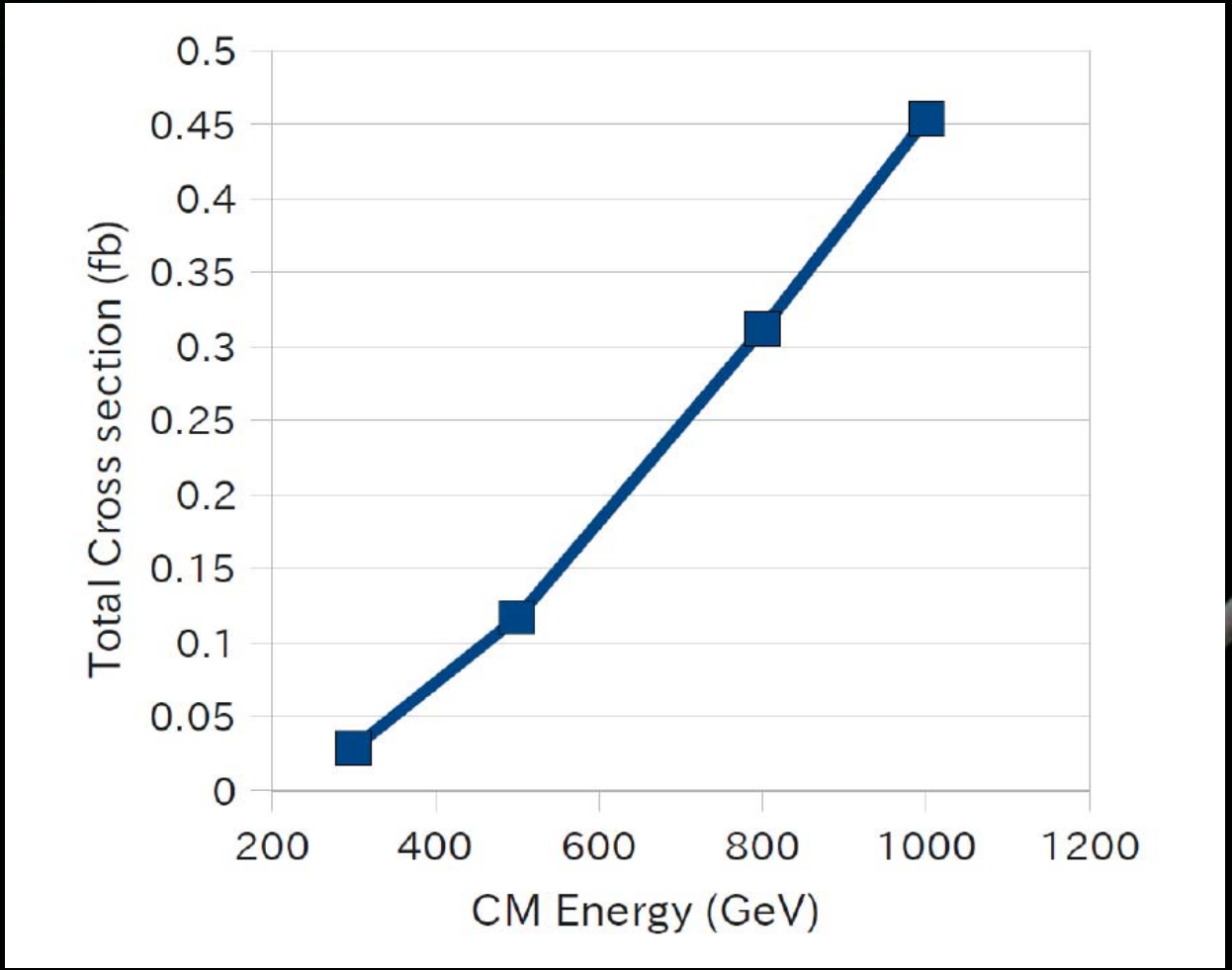

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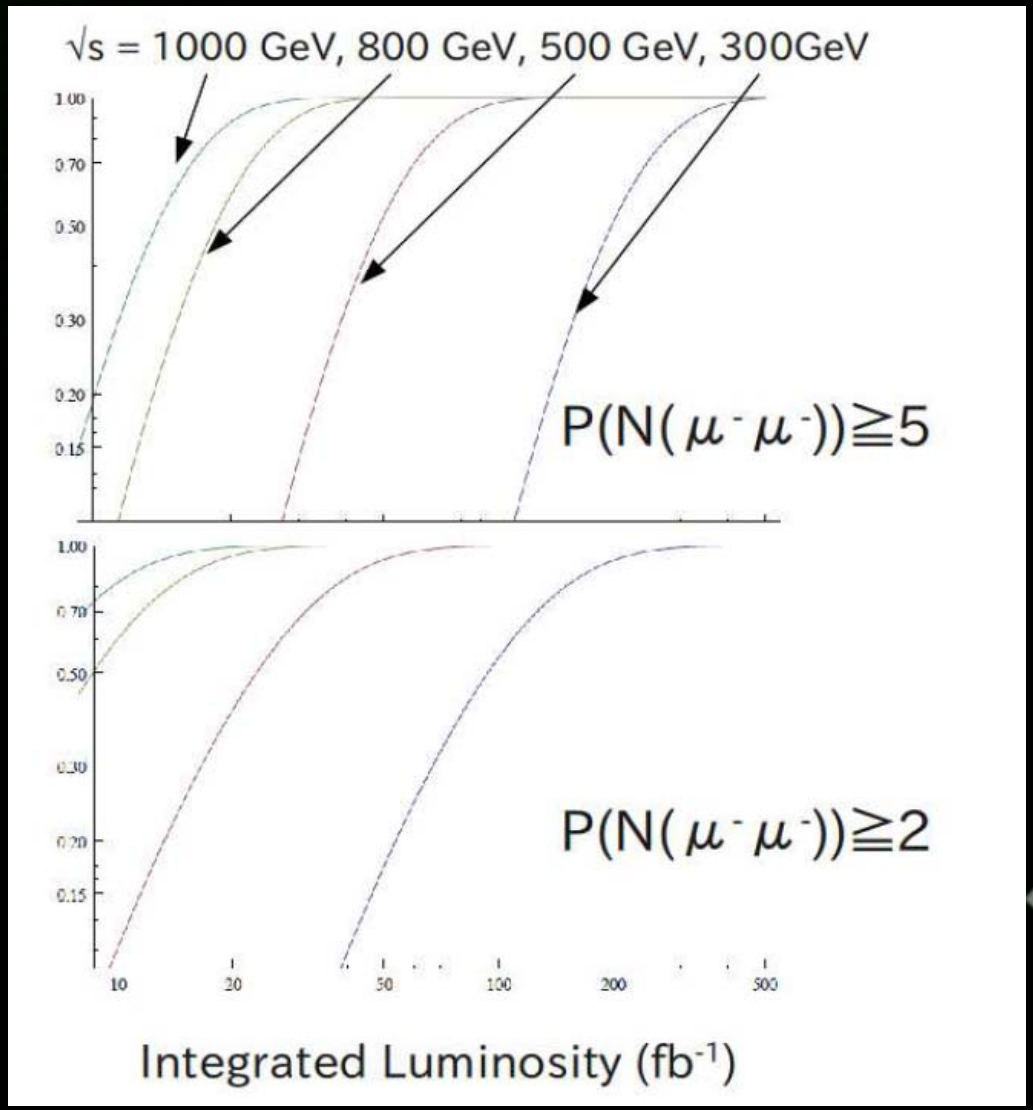

# Majorana Neutrino Search

PHYSICAL REVIEW D **81,** 114001 (2010)

## Inverse neutrinoless double beta decay revisited: Neutrinos, Higgs triplets, and a muon collider

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*Max-Planck-Institut für Kernphysik, Postfach 103980, D-69029 Heidelberg, Germany*

(Received 1 April 2010; published 1 June 2010)

We revisit the process of inverse neutrinoless double beta decay ($e^-e^- \to W^-W^-$) at future linear colliders. The cases of Majorana neutrino and Higgs triplet exchange are considered. We also discuss the processes $e^-\mu^- \to W^-W^-$ and $\mu^-\mu^- \to W^-W^-$, which are motivated by the possibility of muon colliders. For heavy neutrino exchange, we show that masses up to $10^6$ ($10^5$) GeV could be probed for $ee$ and $e\mu$ machines, respectively. The stringent limits for mixing of heavy neutrinos with muons render $\mu^-\mu^- \to W^-W^-$ less promising, even though this process is not constrained by limits from neutrinoless double beta decay. If Higgs triplets are responsible for inverse neutrinoless double beta decay, observable signals are only possible if a very narrow resonance is met. We also consider unitarity aspects of the process in case both Higgs triplets and neutrinos are exchanged. An exact seesaw relation connecting low energy data with heavy neutrino and triplet parameters is found.

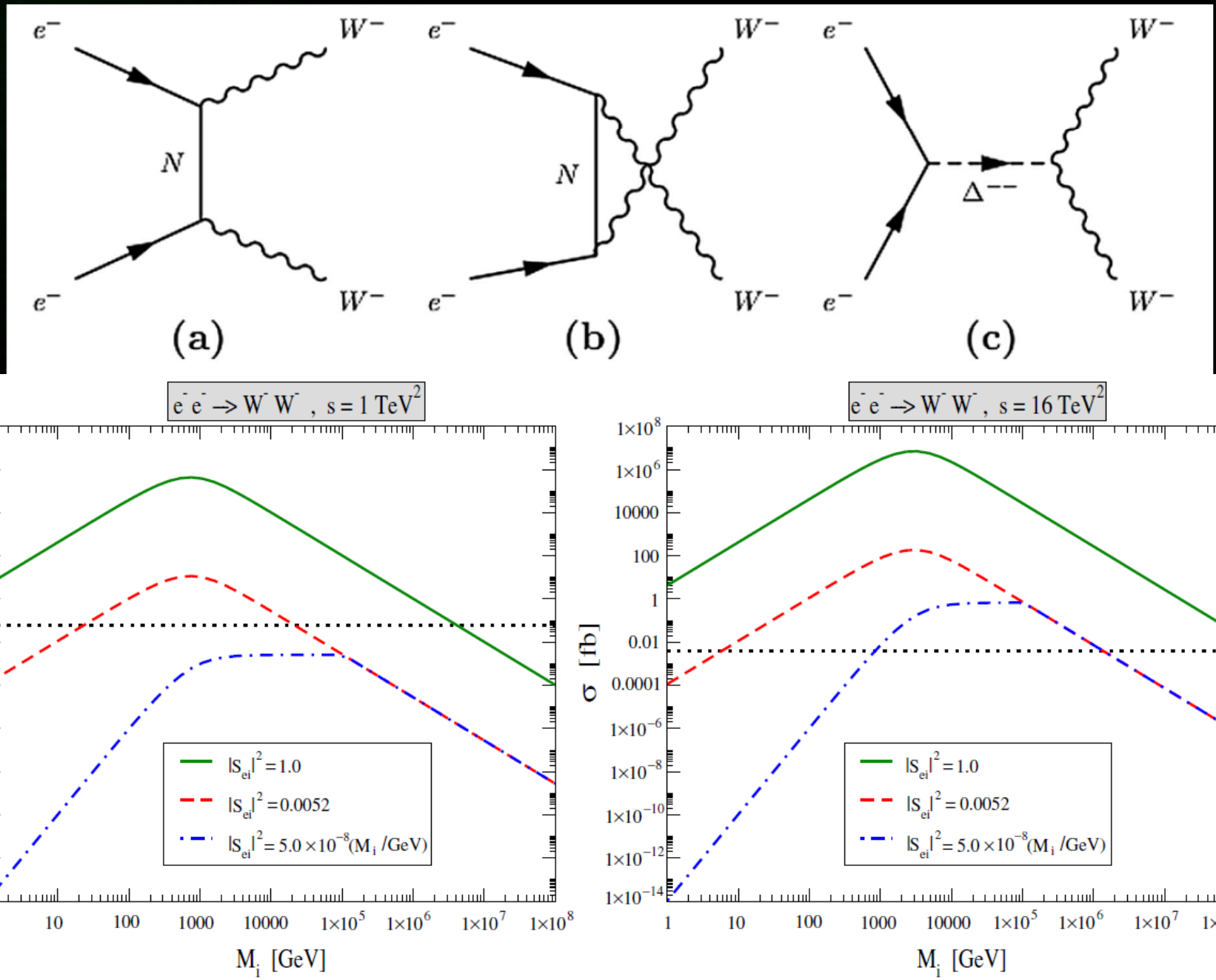


FIG. 2 (color online). Cross section for $e^-e^- \to W^-W^-$ with $\sqrt{s} = 1$ TeV (left panel) and $\sqrt{s} = 4$ TeV (right panel) and three limits for the mixing parameter $|S_{ei}|^2$. The dotted line corresponds to five events for an assumed luminosity of 80 (s/TeV$^2$) fb$^{-1}$.

ELSEVIER

Physics Letters B

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# Probing the Majorana nature of TeV-scale radiative seesaw models at collider experiments

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http://dx.doi.org/10.1016/j.physletb.2010.04.024, How to Cite or Link Using DOI

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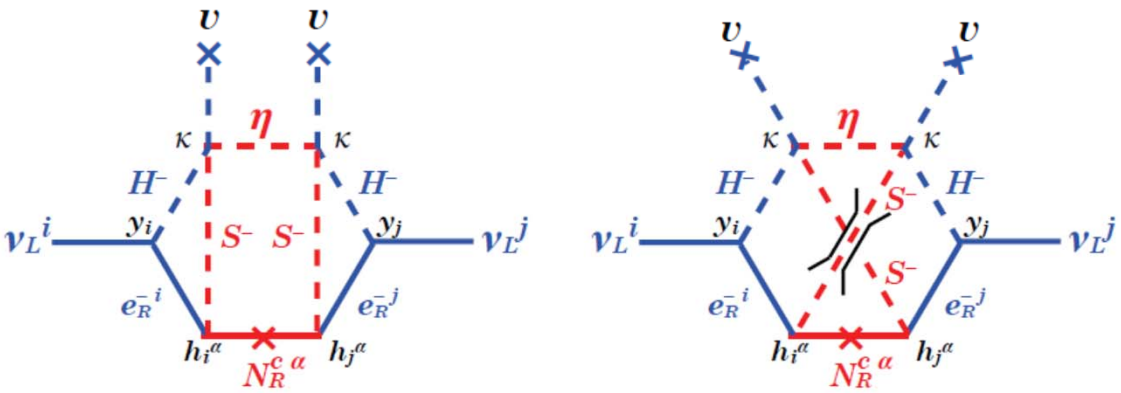
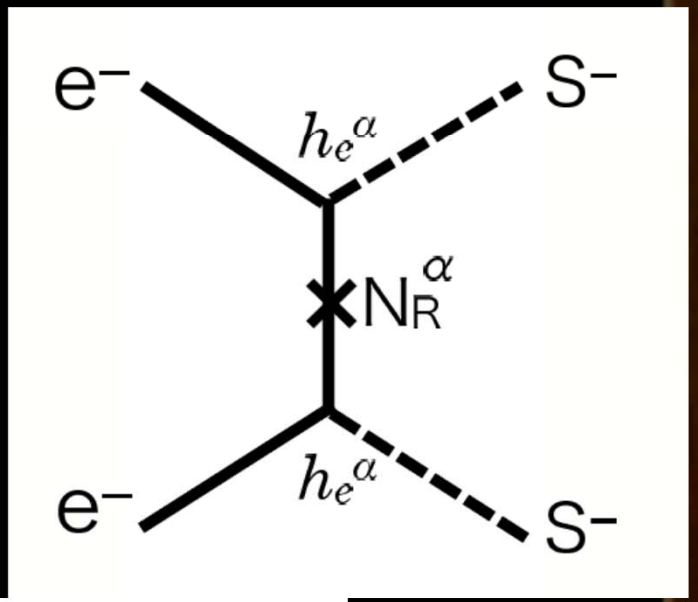
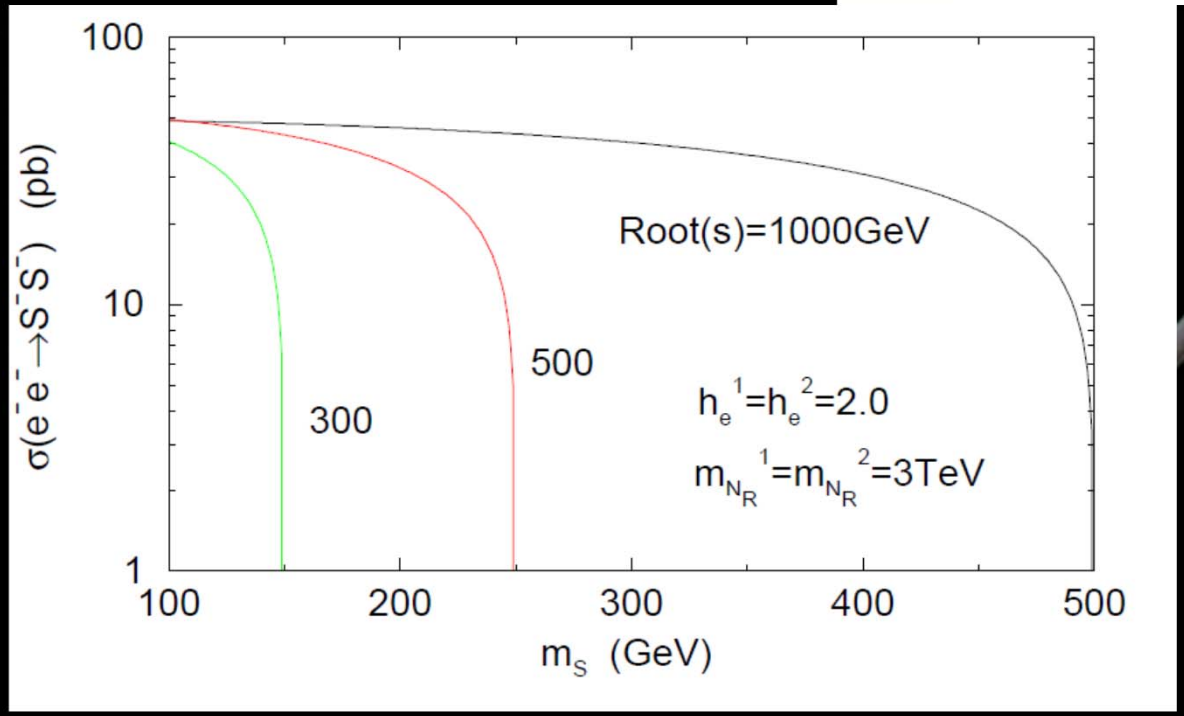


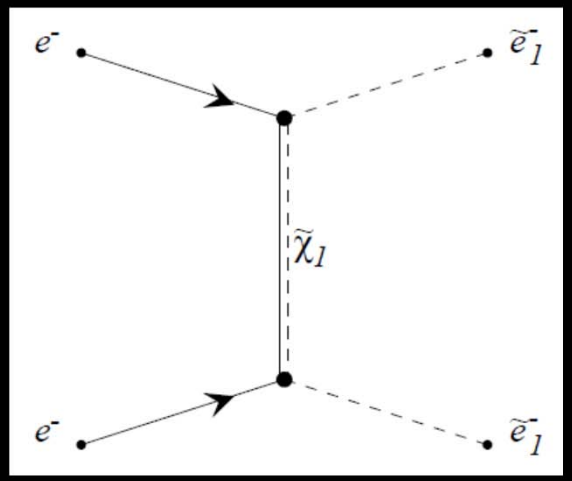

Figure 1: The diagrams for generating tiny neutrino masses.

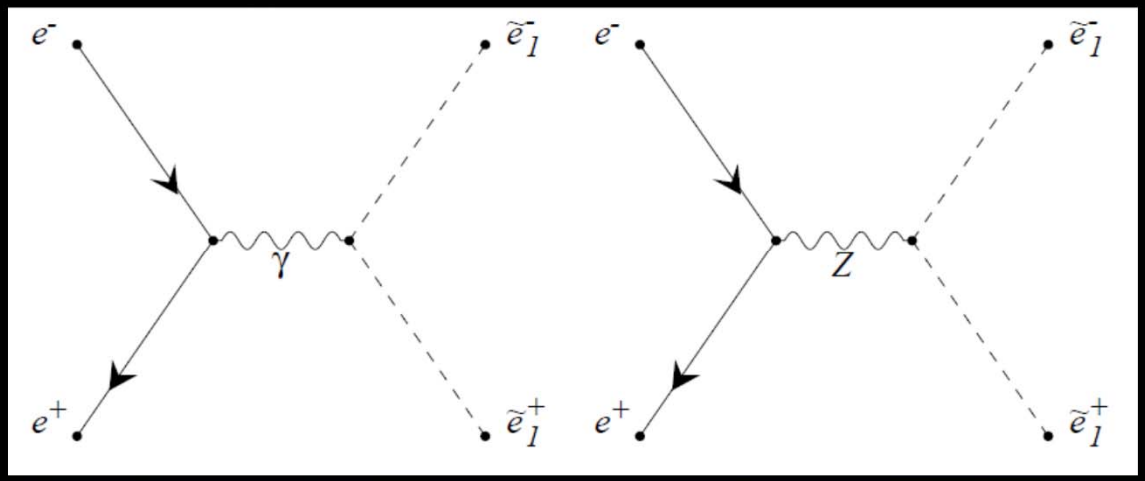


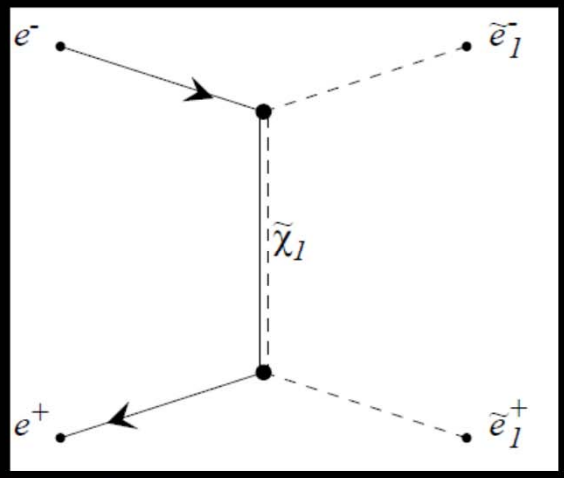



# s-electron Search/Study

$e^- e^{\pm} \rightarrow \tilde{e}_{1,2}^- \tilde{e}_{1,2}^{\pm}$



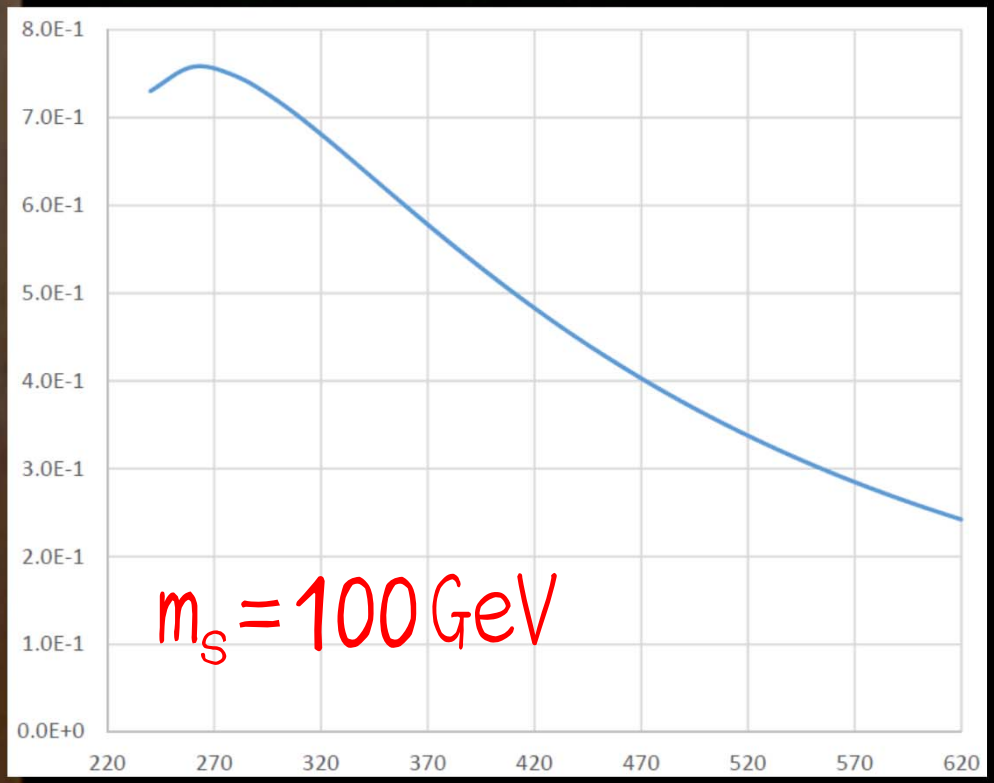



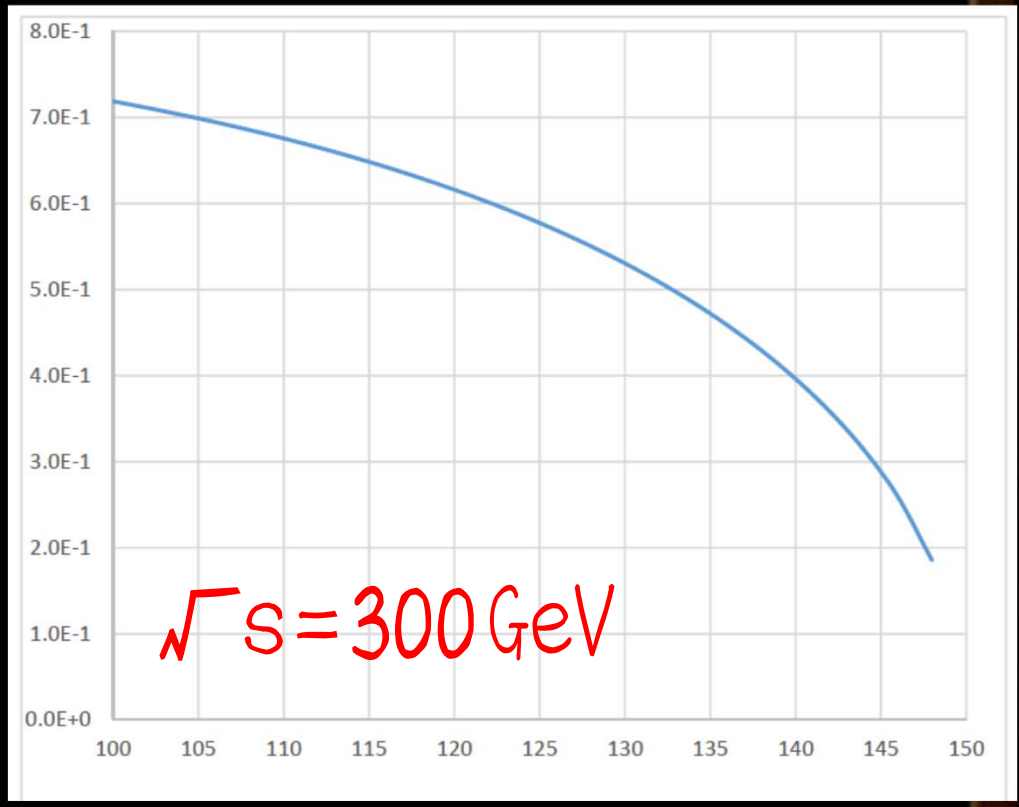
# s-electron Search/Study

## Cross Section (pb)
## Un-polarized beam

$m_{\chi_1}$=145.46 GeV
$m_{\chi_2}$= 294.09 GeV
$m_{\chi_3}$= 605.15 GeV
$m_{\chi_4}$= 611.65 GeV




$\sqrt{s}$ (GeV)




$m_s$ (GeV)

# s-electron Search/Study

## Beam Polarization

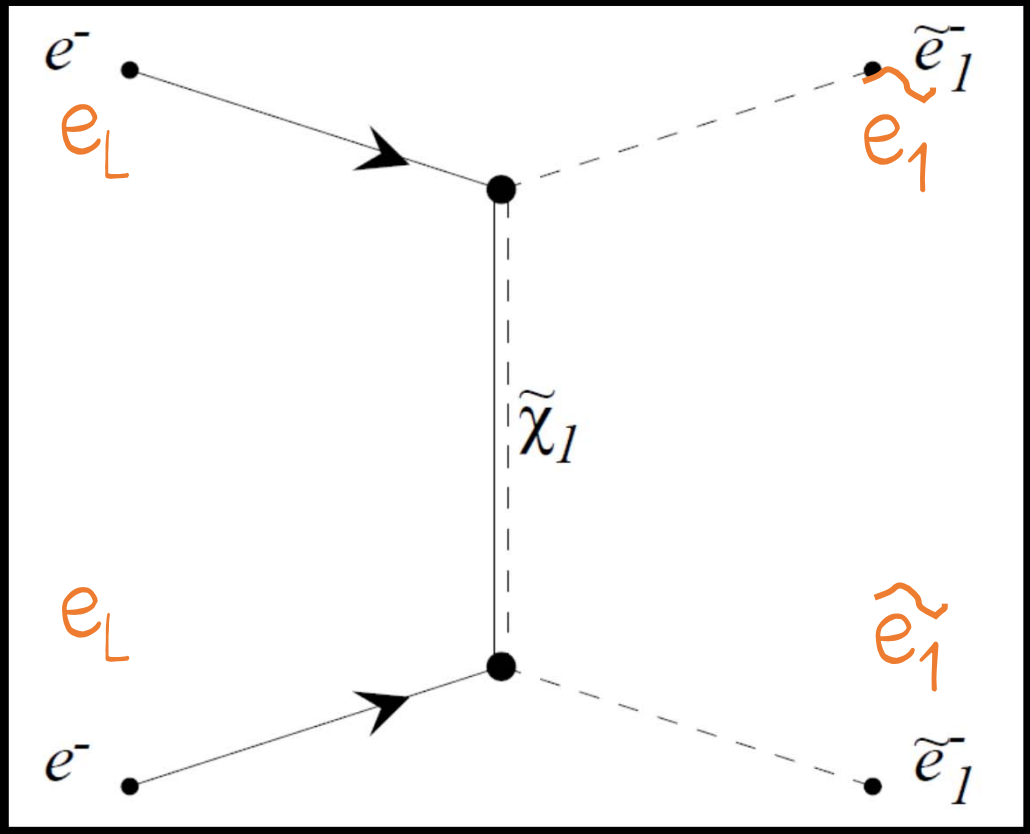
$e^-$ : 80%  $e^+$ : 30%

## Small Mixing

$e_L^{\pm} \rightarrow \tilde{e}_1^{\pm}$

$e_R^{\pm} \rightarrow \tilde{e}_2^{-\pm}$

$m_1 \doteqdot m_2$



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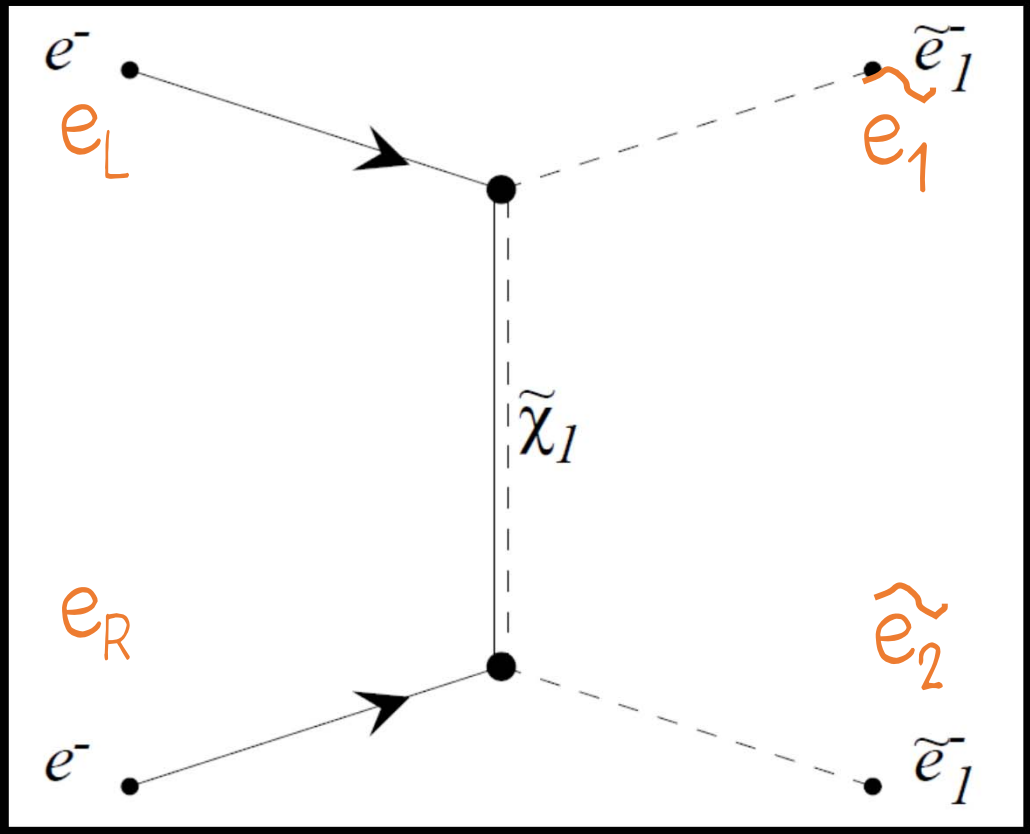

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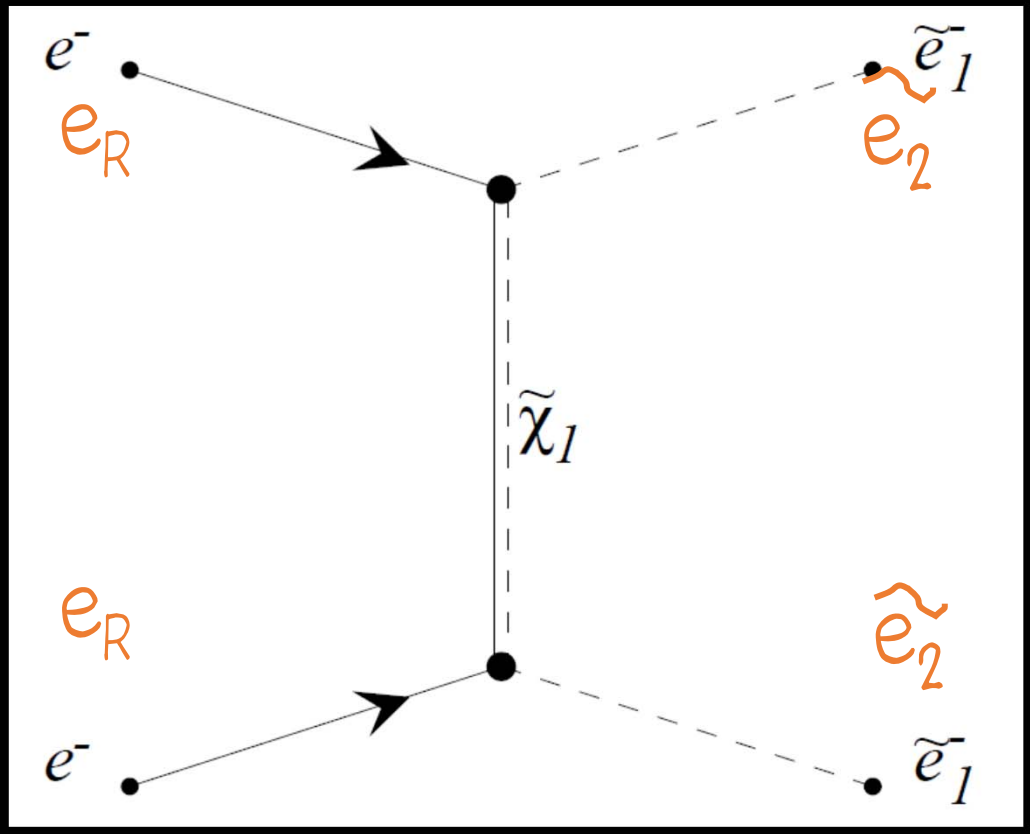
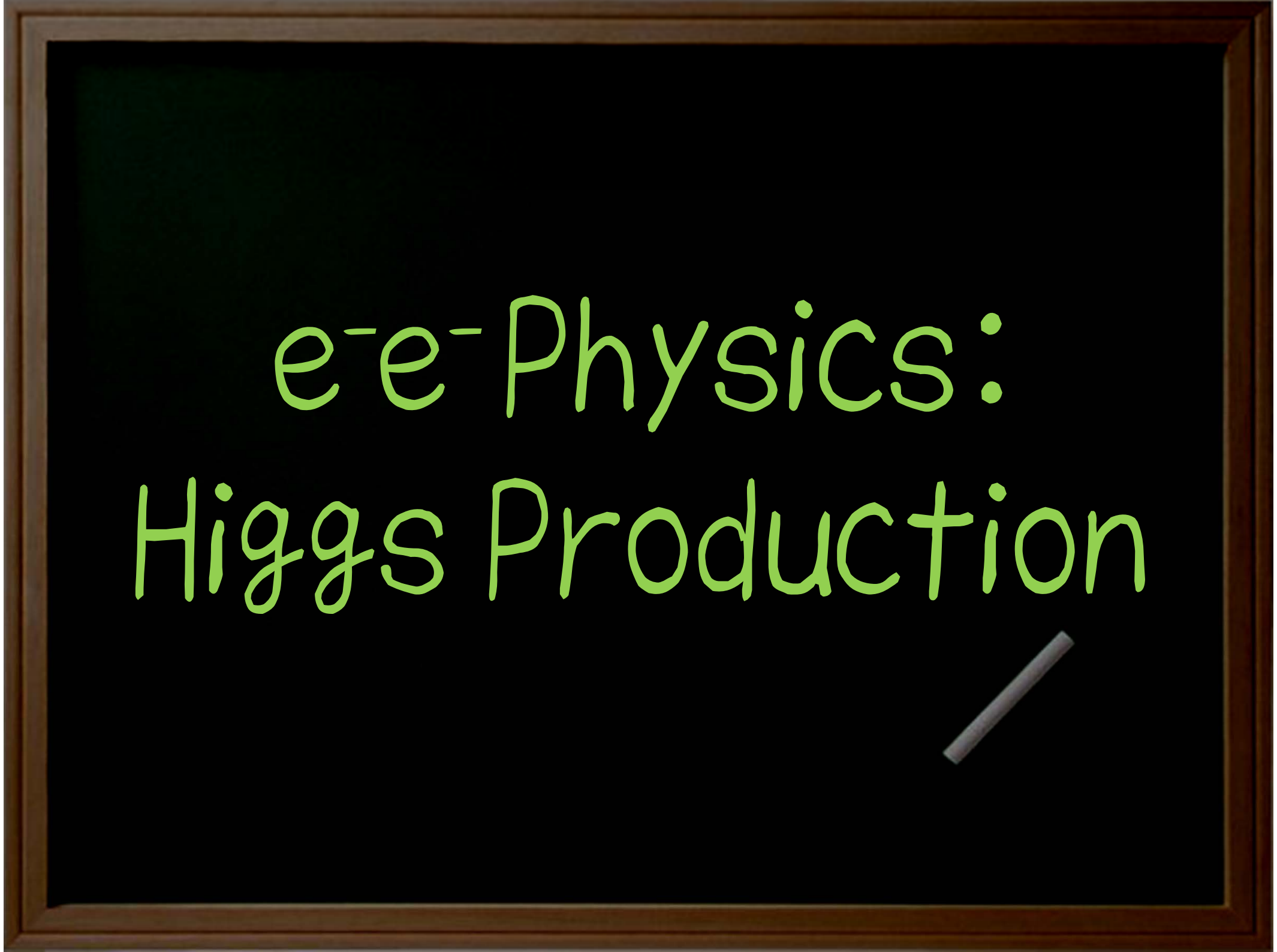
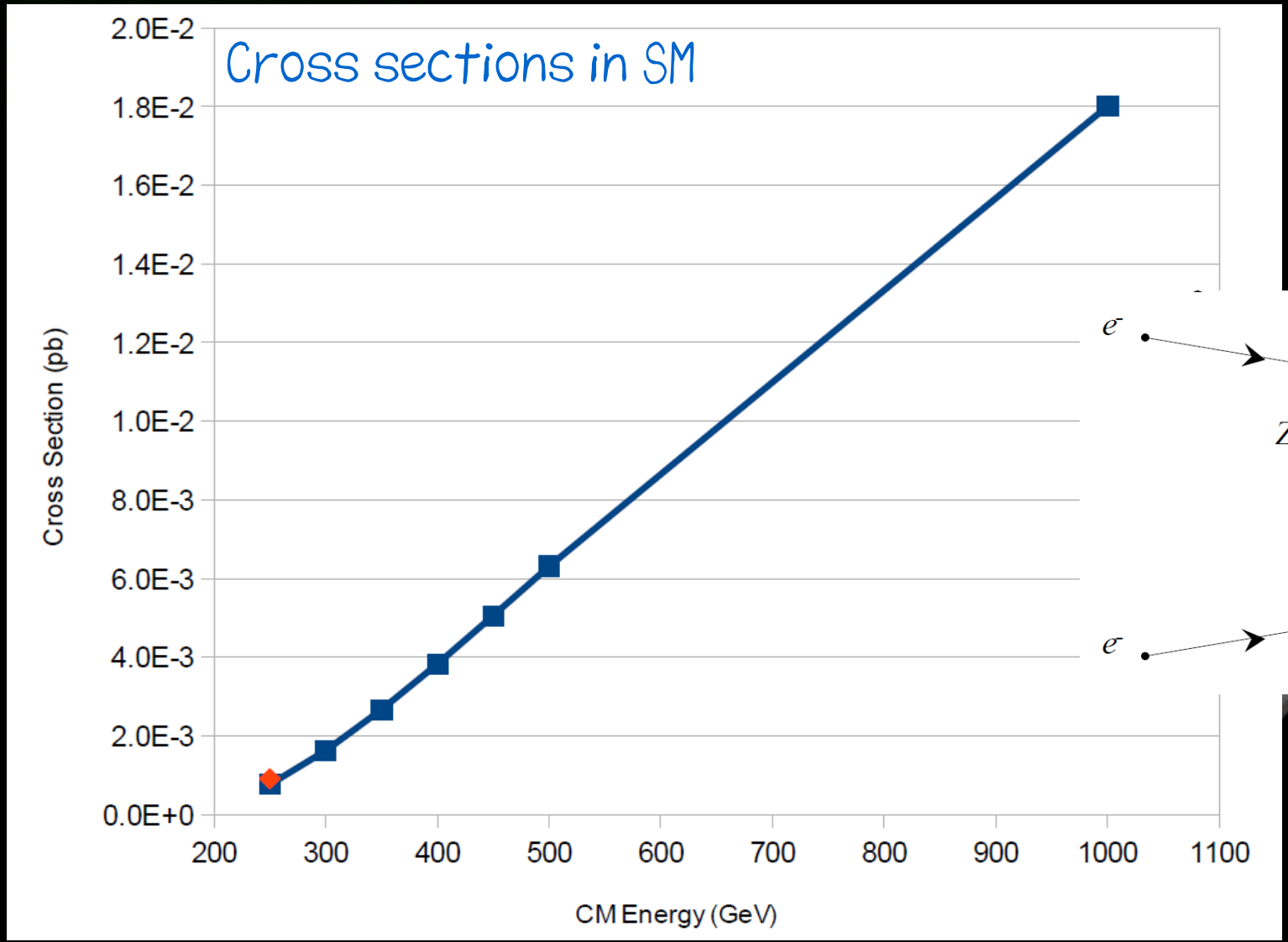
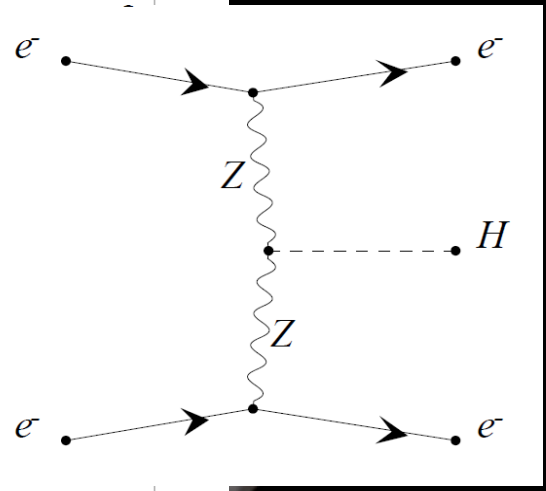


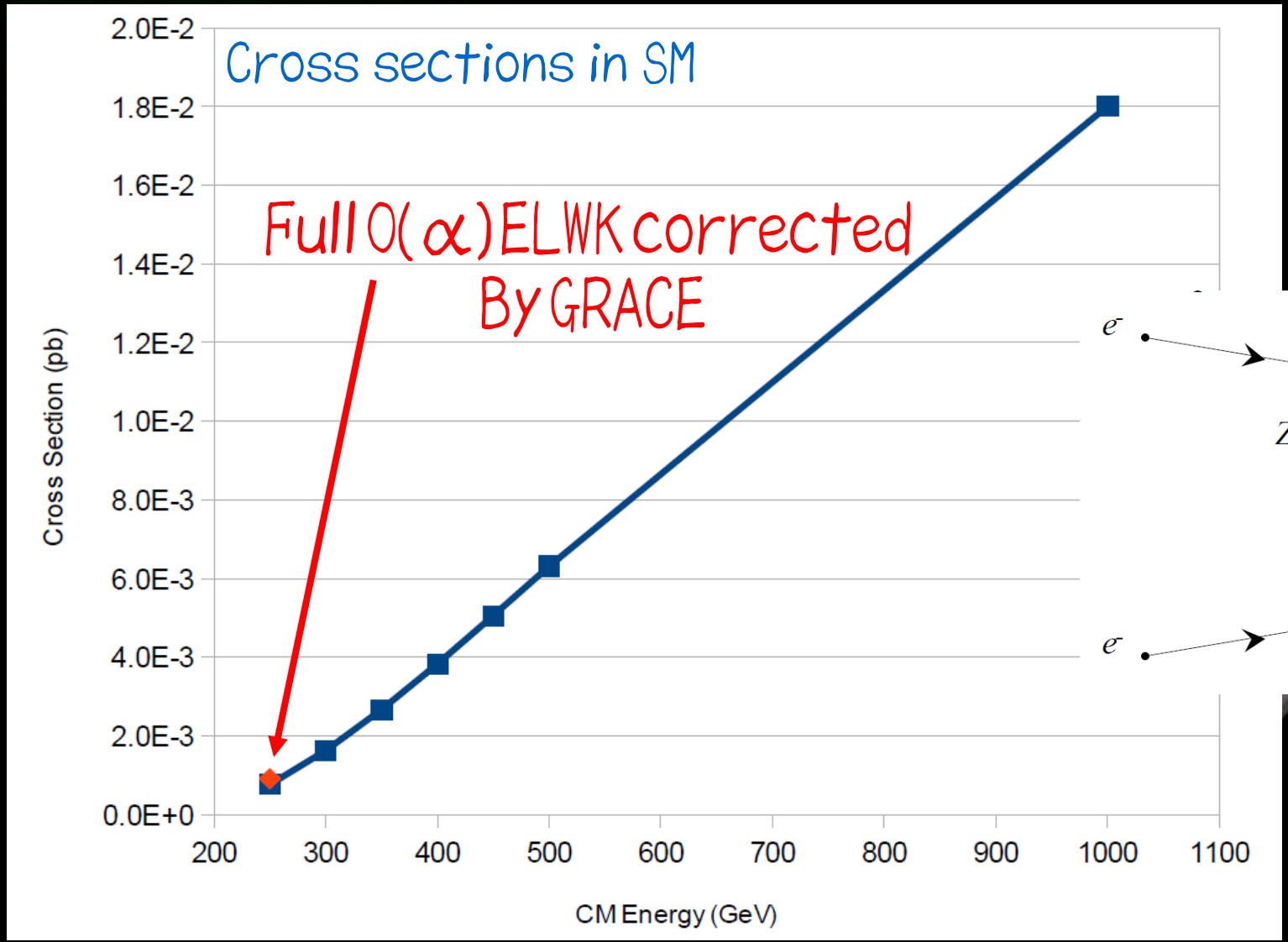

e⁻e⁻ Physics:
Higgs Production

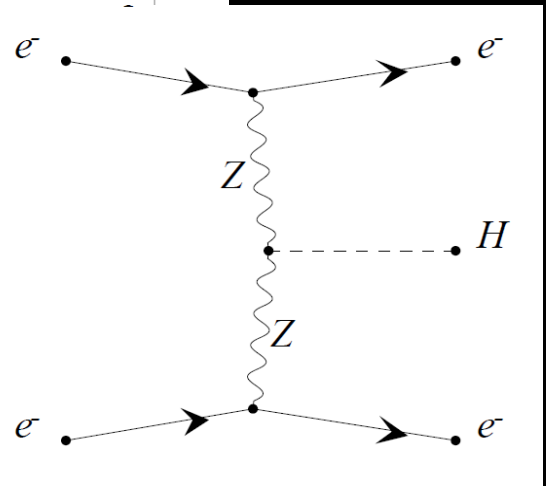
# BSM Signal Search in Higgs couplings



# BSM Signal Search in Higgs couplings




Summary

# Summary

$e^-e^-$ physics in ILC

- Majorana fermion search
  - Majorana neutrino
  - s-electron (beam pol.)
- X-- Search
- Higgs Physics

- An $e^-e^-$ option of ILC is interesting !!