Search for dark matter and precision Higgs measurements at Future Lepton Colliders

Presented By:

Yehia Mahmoud

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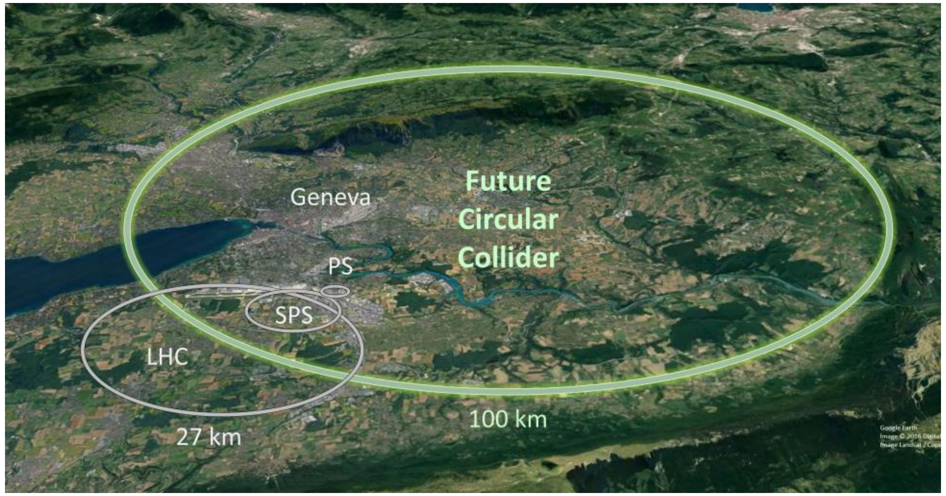
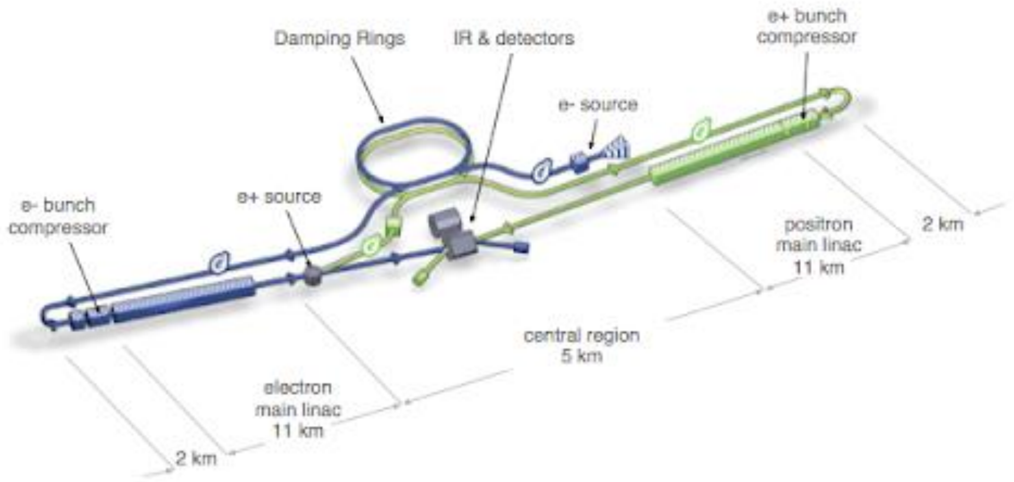
- Summary

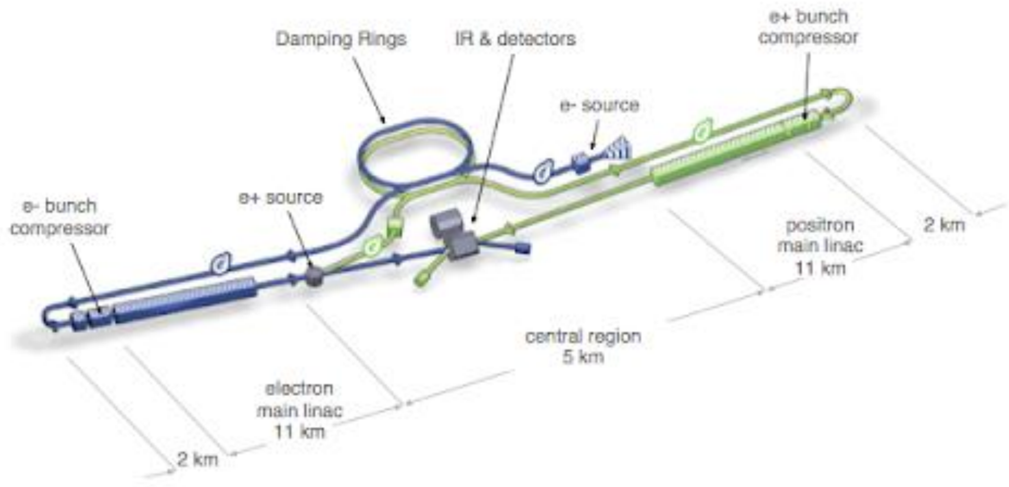
Future Particle Accelerators

- After Higgs discovery in 2012, No new physics discovered.
- New Particle colliders are designed for higher center of mass energy, luminosity and precision.
- Future hadron colliders: HL-LHC, FCC-hh.
- Future electron-positron colliders: FCC-ee, ILC, CLIC CEPC.
- Future electron-hadron colliders: FCC-eh.
- Future Muon colliders are also proposed.
- Monte Carlo studies on these future projects are ongoing.





Lepton Collider Physics



- Electrons are point-like, initial state is known.
- Clean environment, no QCD background.
- Ideal for precision measurements but can also be used for searches of new physics
- **International Linear Collider (ILC)** designed to operate at $\sqrt{s}$ = 250,350 and 500 GeV and possible upgrade to 1 TeV
- Expected to deliver L=2ab^{-1} at 250 GeV and 4ab^{-1} at 500 GeV and 200 fb^{-1} at 350 GeV
- **Future Circular Collider (FCC-ee)** designed to operate at $\sqrt{s}$ = 240, 350 GeV with L=10.8 and 3 ab^{-1} respectively

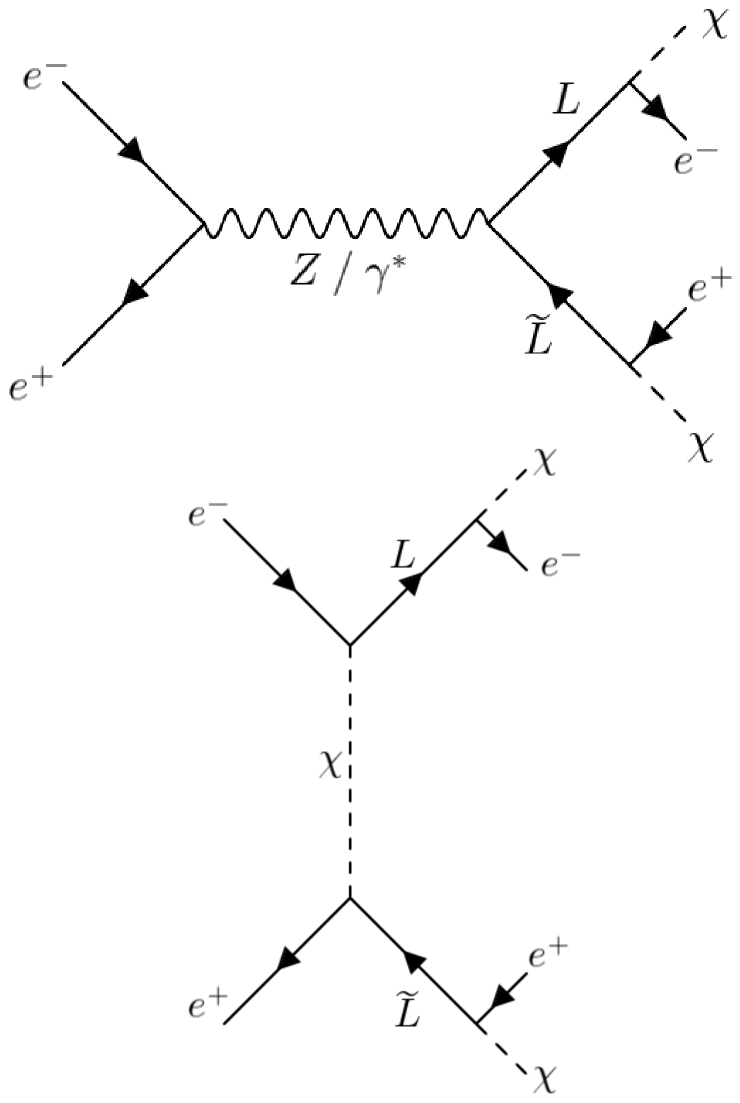
Y. Mahmoud, J. Kawamura, H. Abdallah, M.T. Hussein and S. Elgammal

Lepton Portal Dark Matter (LPDM)

- BSM theory where Dark Matter is a singlet scalar under SM.
- Interacts with SM through yukawa couplings with new extra leptons: **Vector-Like Leptons (L).**
- VLLs are particles whose left- and right-handed components transform the same way under SU(2).
- VLLs can explain many BSM problems like the discrepancy between the measured and predicted muon g-2 and the mass hierarchy between different generations.
- **Lagrangian**:

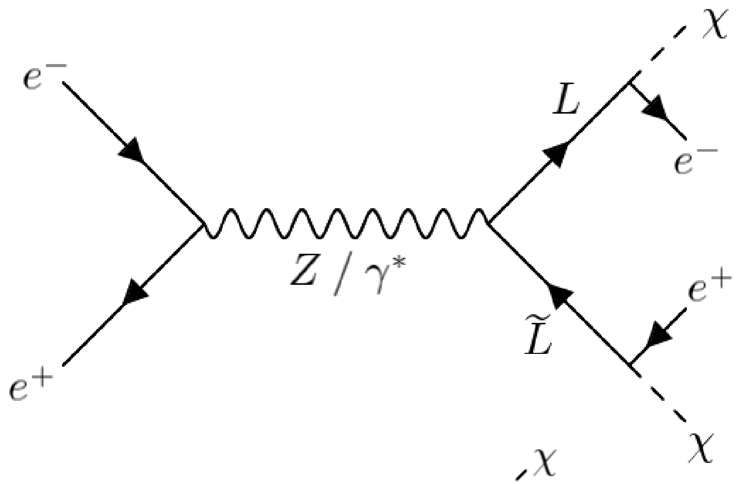
$$-\mathcal{L} = M_L \bar{L}_L L_R + \lambda_L^i X \bar{\ell}_{L_i} L_R.$$

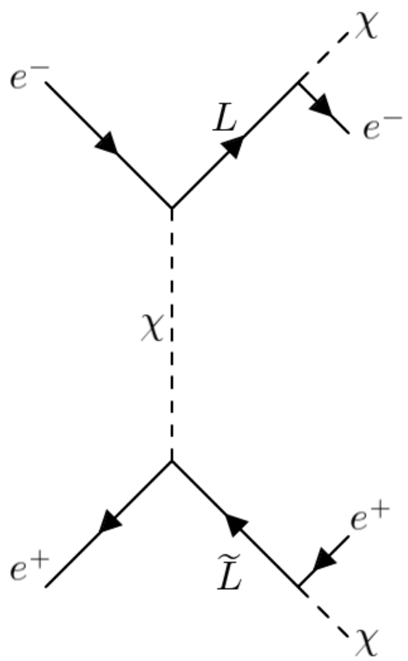
- VLLs can be pair produced at electron-positron colliders in two ways: **s-channel** and **t-channel** exchange.
- The s-channel contribution is mediated by **Z/γ** , while the t-channel is mediated by **χ**.



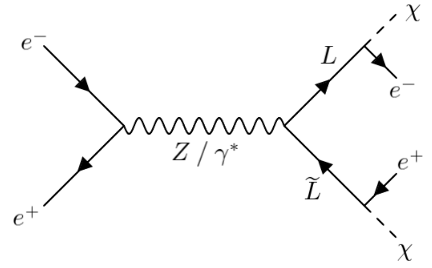
Lepton Portal Dark Matter (LPDM)

- Contribution for t-channel is significant only for **large** Yukawa coupling.
- Vector-Like leptons can decay into DM χ and SM charged lepton with a **branching ratio of unity**.
- As a result, **production rate** is not affected by $M\chi$, except for the t-channel case where the process is mediated by χ.
- We study the case were the **SM charged lepton is an electron** (Electrophilic case).
- Cases where the SM charged particle is Muon or Tauon would yield similar results .
- Free Parameters: Yukawa coupling λ^{i}_{L} - Mass of scalar DM $M\chi$ - Mass of vector-like lepton M_L.
- Final state: Dilelectron + Missing transverse momentum
- Generate electron-positron collisions with beam energy of 250 GeV using **WHIZARD,** showering and hadronization with **PYTHIA6** and fast simulation of International Large Detector (ILD) at ILC with **DELPHES**





Lepton Portal Dark Matter (LPDM)



- Samples were generated for different masses of L and χ and a coupling λ^i_L of 0.1 and 1.
- We studied the conservative case of **λ^i_L =0.1**.
- Three cases of the mass splitting **$\Delta M = M_L - M\chi$** were considered:
  - Wide mass splitting: ΔM = 100 GeV
  - Mass splitting of ΔM = 10 GeV
  - Narrow mass splitting ΔM = 5 GeV
- Selecting events two oppositely charged electrons and missing E_T.
- Pseudorapidity of the leading electron

$$|\eta_1^e| < 0.7$$

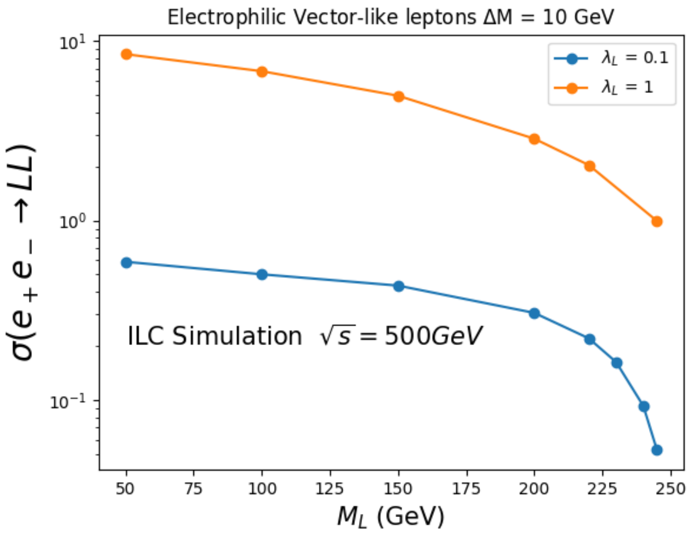
- Relative difference between dielectron p_T^{ee} and missing transverse energy E_T^{miss}

$$\frac{|p_T^{ee} - E_T^{miss}|}{p_T^{ee}} < 0.2$$

- Delta R between the dielectron:

$$\Delta R^{ee} < 3.2$$

- Cuts were successful In rejecting most of the background.



Y.Mahmoud et.al JHEP03(2025)001

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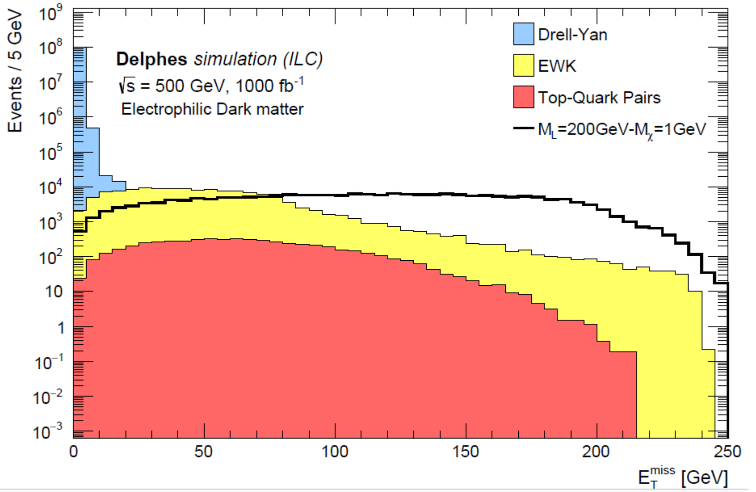
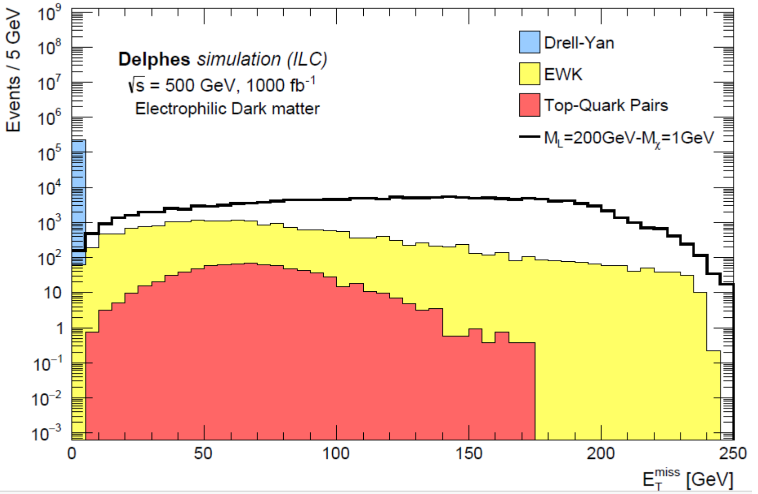




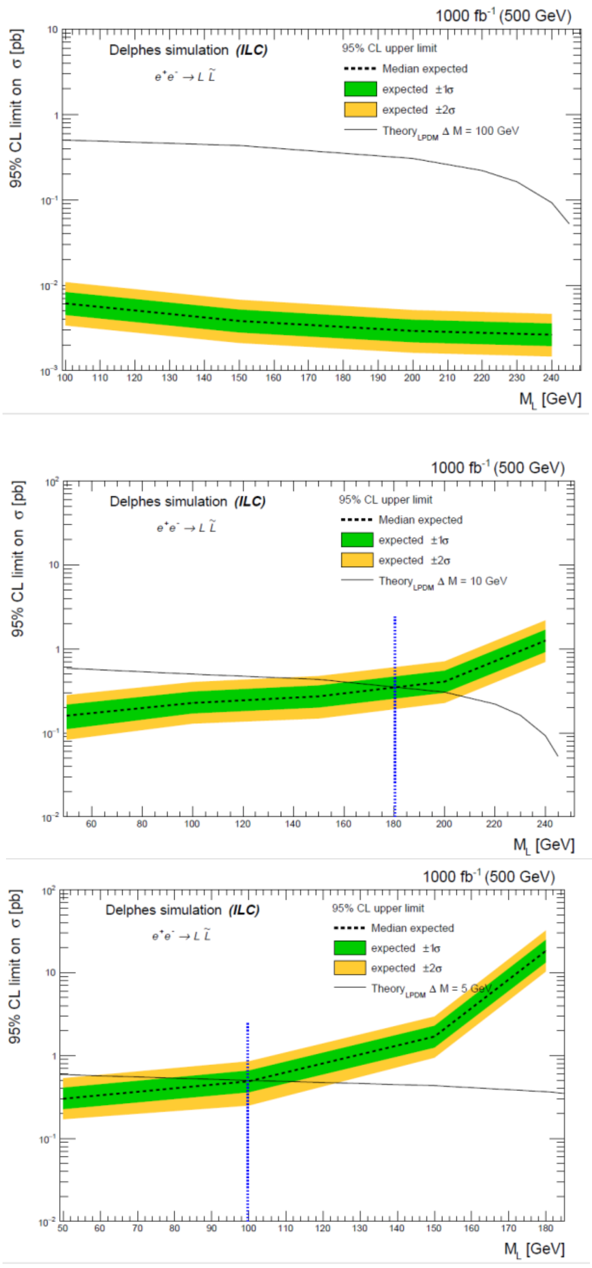
Lepton Portal Dark Matter (LPDM)

Results and Conclusion

- Study was concluded for an integrated luminosity of 1000 fb^{-1}.
- In case of no discovery, an exclusion limit on the model parameters at **95% CL** is computed.
- A statistical test was performed based on the likelihood ratio test statistic.
- For the case of the wide mass splitting , ΔM = 100 GeV it is possible to exclude the whole parameter space. While for the case of ΔM = 10 GeV, it is possible to exclude M_L up to 180 GeV and the narrow mass splitting ΔM = 5 GeV up to 100 GeV.
- Degenrate case of ΔM < 100 GeV not accessible by LHC!

- **Publication:**

Y.Mahmoud, J.Kawamura, M.T.Hussein, and S.Elgammal "**Investigating vector-like leptons decaying into an electron and missing transverse energy in $e^+ e^-$ collisions with $\sqrt{s}$ = 500 GeV at the ILC**", JHEP03(2025)001



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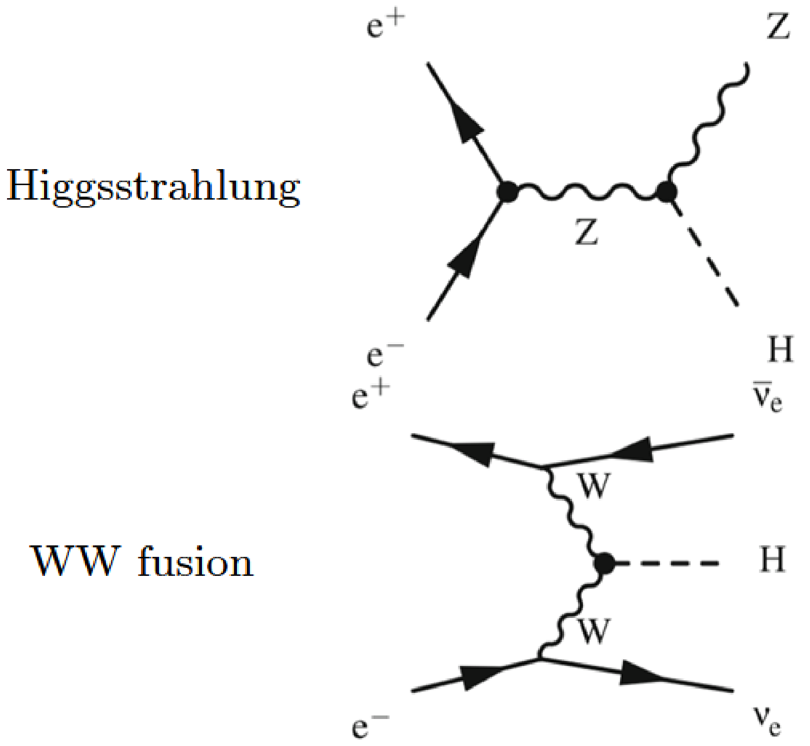
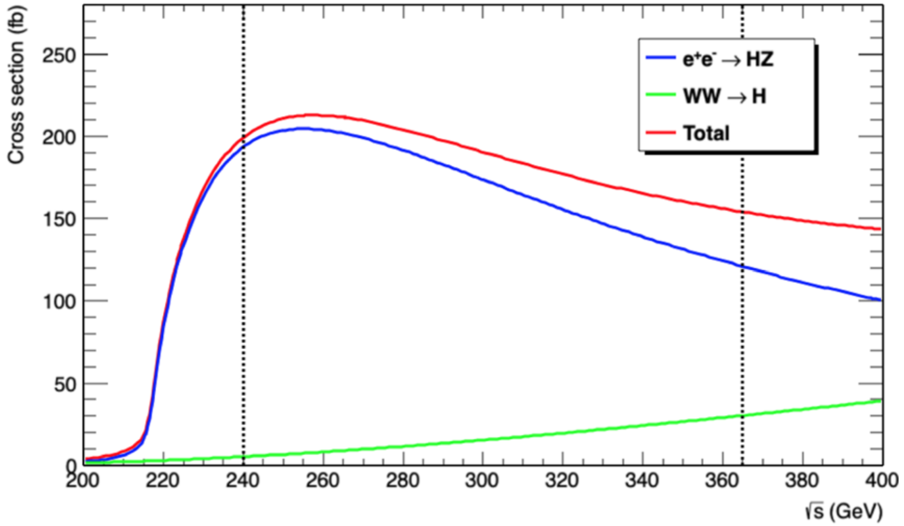
Yehia Mahmoud, Nicola De Filippis, Michele Selvaggi and Jan Eysermans

Precision Higgs at FCC-ee

- Measurement of Higgs boson properties with high precision
- Constraints contribution from BSM physics
- **Higgs physics at LHC**: Large center of mass energy but weak statistics due to very large hadronic background
- LHC has a limited reach on Higgs physics even for high luminosity upgrade.
- **Lepton colliders** offer a promising and unique ways of Higgs measurements due its **clean background** and **known initial state**
- Higgs production at lepton colliders proceeds in two mechanisms: **Higgstrahlung (e- e+ → ZH)** and Vector boson fusion (e- e+ → Hνν)
- FCC-ee is expected to work as a Higgs factory at $\sqrt{s}$ = 240 GeV with **≈ 2 million** Higgs from ZH production
- **Absolute** measurement of the total ZH production cross section σ_{HZZ} is allowed in a **model independent** way without knowledge of any specific decay of the Higgs





Precision Higgs at FCC-ee

- Since initial state is known, Higgs boson can be reconstructed as a recoil particle.
- For example, in the case where $Z \rightarrow ll$, the recoil mass is given by:

$$m_{recoil}^2 = s + m_{ll}^2 - 2\sqrt{s}\, E_{ll}$$

- This method, known as "**Recoil mass**" is unique only to lepton colliders !
- Measurment of $\boldsymbol{\sigma_{HZZ}}$ allows for direct measurement of $\mathbf{g_{HZZ}}$ since

$$\boldsymbol{\sigma_{HZZ} \propto g_{HZZ}^2}$$

- Recoil mass peak gives an accurate measurement of the **Higgs mass**.
- Measurment of $\mathbf{g_{HZZ}}$ gives access to all other **SM Higgs couplings**

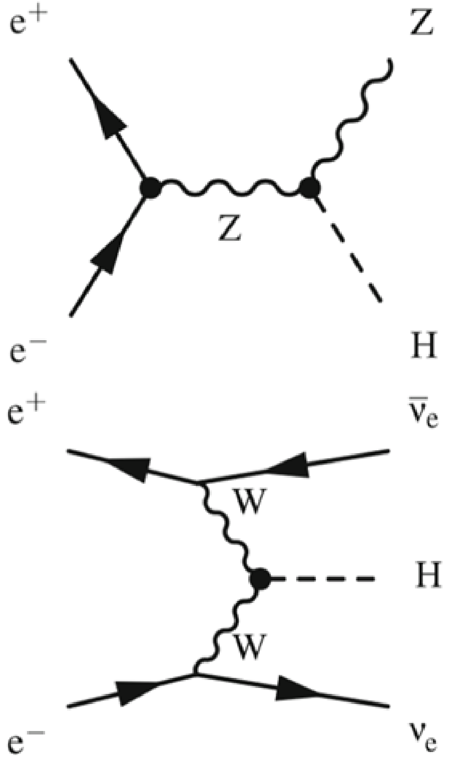
$$\sigma_{HZZ} \times \mathcal{B}(H \rightarrow XX) \propto \frac{\sigma_{HZZ} \times g_{HXX}^2}{\Gamma_H}$$

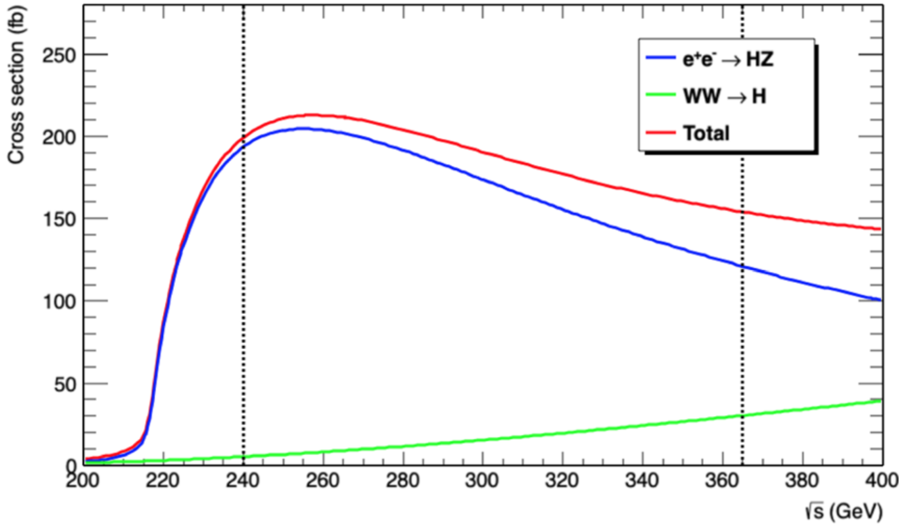
- Total width of the Higgs boson can be determined from the measurement of Higgs → ZZ* decays

$$\sigma_{HZZ} \times \mathcal{B}(H \rightarrow ZZ^*) \propto \frac{\sigma_{HZZ}^2}{\Gamma_H}$$

Higgsstrahlung

WW fusion

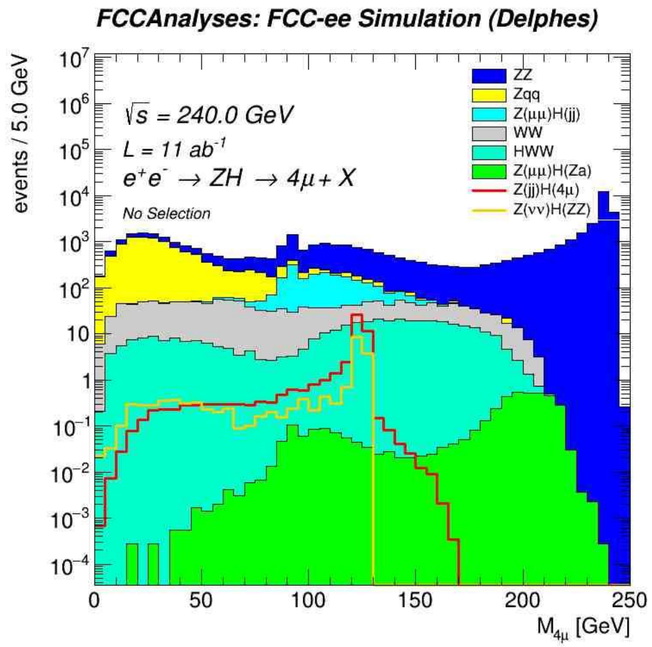


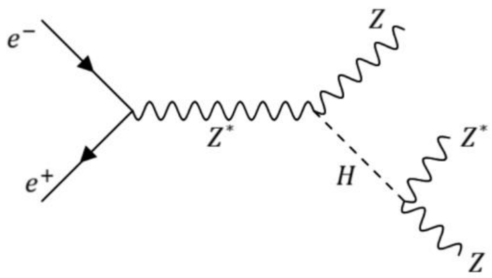


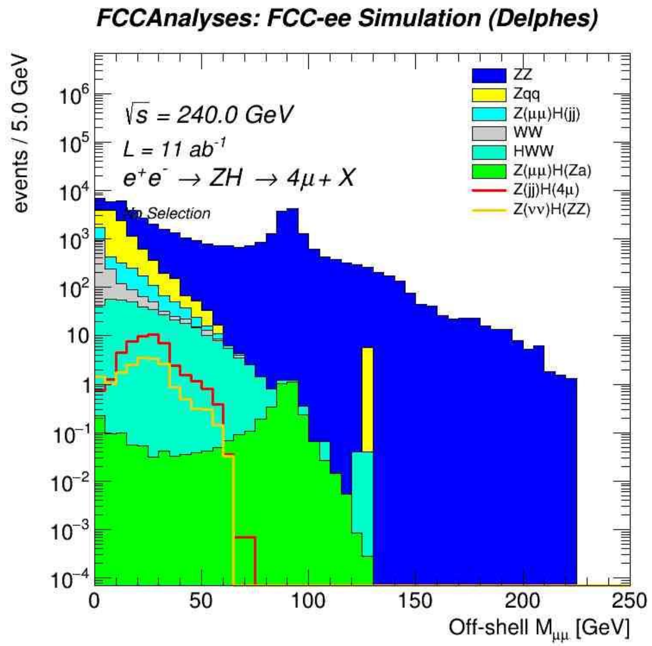
Precision Higgs at FCC-ee

- We performed a study on the final state of **H** $\rightarrow ZZ^* \rightarrow$ **4l**
- Cases with **4l = 4e,4μ,2e2μ** were considered
- Cases with ZH where Z decays to dijet or invisible states.
- Expected Background: **ZZ, Zqq, Z(ll) H(jj), Z(jj) H(ll), ZH(Za), ZH(WW)**
- Centrally produced Winter 2023 samples at √s = 240 GeV generated with Delphes
- **Lepton selection criteria:**
    - First pair of leptons (From On-shell Z)
        - Oppositely charged leptons
        - The pair which minimises $|M_{ll} - M_Z|$
    - Second Pair of leptons (From Off-shell Z)
        - Oppositely charged leptons
        - Highest momentum oppositely charged pair of the remaining
    - Additional cut for 2e2μ: **M_{ll} (On-Shell) > 60 GeV**.

  This is to remove contribution from Off-Shell Z leptons.







Analysis Strategy

- Rectangular cuts were applied to to discriminate the signal from the background
- Most dominant background is ZZ
- Signal is characterized by a resonance in the 4-lepton invariant mass distribution corresponding to 125 GeV (Higgs mass)
- Z(jj)H(4l) signal is characterized by additional energy above the 4-lepton energy (ZZ can have only 4-leptons)
- Z(vv)H(jj) signal is characterized by large missing momentum

Z(jj) H(4l)	Z(vv) H(4l)
Momentum of the softest lepton of the reconstructed 4 lepton: **$P_{min} > 5$ GeV**	Momentum of the softest lepton of the reconstructed 4 lepton: **$P_{min} > 5$ GeV**
Missing momentum cut: **$P_{miss} < 40$ GeV**	Missing momentum cut: **$P_{miss} > 100$ GeV**
Visible energy of all reconstructed Particles excluding the four leptons **$E_{vis} > 30$ GeV**	
Invariant mass of dilepton pair from the Off-Shell Z **$10 < M_{Z*} < 65$ GeV**	Invariant mass of dilepton pair from the Off-Shell Z **$10 < M_{Z*} < 65$ GeV**
Invariant mass of the 4 leptons: **$124 < M_{4l} < 125.5$ GeV**	Invariant mass of the 4 leptons: **$124 < M_{4l} < 125.5$ GeV**

Cuts	Bckg (4μ)	Z(jj) H(4μ)	Bckg (4e)	Z(jj) H(4e)	Bckg (2e2μ)	Z(jj) H(4e)
No selection	50514	47	121755	49	48513	80
$P_{min} > 5$ GeV	36048	44	46564	44	43851	74
$P_{miss} < 40$ GeV	26890	39	30891	39	37651	70
$E_{vis} > 30$ GeV	2327	37	6365	37	1470	66
$10 < M_{Z*} < 65$ GeV	1184	37	2472	37	537	66
$124 < M_{4l} < 125.5$ GeV	3	26	8	19	5	40

Cuts	Bckg (4μ)	Z(vv) H(4μ)	Bckg (4e)	Z(vv) H(4e)	Bckg (2e2μ)	Z(vv) H(4e)
No selection	50514	18	121755	19	48513	26
$P_{min} > 5$ GeV	36048	15	46564	15	43851	24
$P_{miss} > 100$ GeV	1146	14	2944	13	175	22
$10 < M_{Z*} < 65$ GeV	683	13	969	13	97	22
$124 < M_{4l} < 125.5$ GeV	4	9	2	6	3	14

Event yield for the signal and background processes normalized to their cross sections and $\mathcal{L} = 10.8\text{ab}^{-1}$

Results

- Cuts were successful in rejecting most of the background
- It is possible to reach a significance $s/\sqrt{(s+b)}$ of 6 for the Z(jj)H(ZZ*) channel and 4.7 for the Z(vv)H(ZZ*) with a total of 9.674
- Statistical test is performed with the parameter of interest being the signal strength μ
- Best-fit value of the signal strength is obtained with the uncertainty on its value at 68% Confidence Level.
- It is possible to reach a precision of 12% for the Z(jj)H(ZZ*) channel and 22% for the Z(vv)H(ZZ*) with a total of **10%** at 68% CL.
- Systematic uncertainty on the estimation of ZZ and Hjj processes were considered with 10% on each.
- Possible upgrade to the sensitivity can be achieved with Deep neural networks or Boosted decision trees
- Study of all possible decay channels of ZH, HZZ must be performed.
- Results documented in an analysis note on the CERN document server, DOI:**10.17181/ey2ff-hqv83**

Signal	$s/\sqrt{(s+b)}$	Precision at 68% CL
Z(jj)H(4μ)	4.828	1± 0.2075
Z(jj)H(4e)	3.656	1± 0.2755
Z(jj)H(2e2μ)	5.9628	1± 0.2505
Z(jj) combined	8.45	1± 0.122
Z(vv)H(4μ)	2.49	1± 0.403
Z(vv)H(2e)	2.12	1± 0.4735
Z(vv)H(2e2μ)	3.39	1± 0.4535
Z(vv) combined	4.71	1± 0.222
Total	9.674	**1± 0.107**

Summary

- Future lepton colliders offer a clean environment and a known initial state which can provide high precision measurements of the Standard Model
- Future lepton colliders can also be used for BSM searches in low energy regions due to its clean environment
- A study of BSM physics at the International Linear Collider in Japan was proposed.
- We studied Dark matter at the ILC in the context of LPDM at a center of mass energy of 500 GeV and a total integrated luminosity of 1000 fb^{-1}.
- The study demonstrates the potential of studying vector-like leptons nearly degenerate with dark matter $\Delta M < 100$ GeV which is not accessible at the LHC.
- A study of Higgs precision measurements at the Future Circular Collider FCC-ee to calculate the expected precision on the Higgs total width
- We studied the ZH production with Z(jj) and H $\rightarrow ZZ^* \rightarrow$ 4l and calculated the expected precision on this decay channel
- A precision of 10% on the Z(jj)H($ZZ^* \rightarrow$ 4l) is reached at 68% CL.
- Input from other H $\rightarrow ZZ^*$ decay channels are required to calculate the expected total uncertainty on the Higgs total width

Thank you!