Measuring the electron Yukawa coupling via Higgs production at FCC-ee

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Outline

Introduction

- The Standard Model of Particle Physics:

  1- Higgs mechanism
  2- electron Yukawa coupling

$$\mathcal{L}_e = -m_e \bar{e}e - \frac{y_e}{\sqrt{2}} \nu \bar{e}eh \tag{1}$$

with $y_e = \sqrt{2}\frac{m_e}{\nu}$ and $\bar{e}e = \bar{e}_L e_R + \bar{e}_R e_L$

Introduction

- Future Circular Collider (FCC):

  1- a proposed particle accelerator with an energy significantly above circular colliders, such as the Super Proton Synchrotron, the Tevatron, and the Large Hadron Collider (LHC)

  2- Has three scenarios: FCC-hh, for hadron-hadron collisions, including proton-proton and heavy ion collisions, FCC-ee, for electron-positron collisions, and FCC-eh, for electron-hadron collisions.

Introduction

- FCC-ee:

  1- With centre-of-mass collision energies between 90 and 350 GeV is an intermediate step towards the realization of the hadron facility.

  2- Clean experimental conditions, High luminosity and improved handling of lepton beams make e^+e^- a strong record both for measuring known particles and their interactions with the highest precision and for exploring the unknown.

  3- The FCC-ee could collect 10^{12} Z bosons,10^8 W pairs, 10^6 Higgs bosons and 4×10^5 top-quark pairs per year.

Introduction

- FCC-ee:

  4- search for new particles coupling to the Higgs and electroweak bosons up to scales of $\Lambda = 7$ and 100 TeV.

  5- Measurements of invisible or exotic decays of the Higgs and Z bosons offer discovery potential for dark matter or heavy neutrinos.

  6- It enables profound investigations of electroweak symmetry breaking and open a broad indirect search for new physics over several orders of magnitude in energy or couplings.

Future Circular Collider (FCC-ee)

- Electron Yukawa coupling at FCC-ee:

  1- Unique opportunity of studying the Higgs Yukawa coupling to the electron, y_e, via resonant s -channel, $e^+e^- \to H$, in $\sqrt{s} = m_H$.

  2- Higgs mechanism for elementary particles is only valid for the heaviest SM particles: W and Z bosons, quarks and leptons of the third family (t, b, and τ), experimentally.

  3- Not only all neutrino masses remain a mystery, at the end of the LHC lifetime only a fraction of the Higgs Yukawa couplings to the second-family fermions (the muon and, the charm quark) will have been probed.

Future Circular Collider (FCC-ee)

- Electron Yukawa coupling at FCC-ee:

  1- Due to low masses and small Yukawa couplings to the Higgs field, the mass generation mechanism for the stable matter of the visible universe, composed of u and d quarks plus the electron and neutrinos (ν), remain experimentally untested

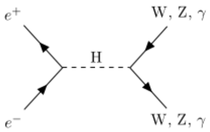
  2- The smallest Yukawa coupling, is that of the electron: $y_e = \sqrt{2} m_e/\nu = 2.9 \times 10^{-6}$ for $m_e = 0.511 \times 10^{-3}$ GeV and $\nu = 246.22$ GeV

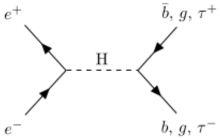
  3- Measuring the Higgs coupling to the electron is impossible at hadron colliders because the $H \to e^+e^-$ decay has a tiny branching fraction of $B(H \to e^+e^-) = 5.22 \times 10^{-9}$, and is completely swamped by a Drell–Yan ($pp \to e^+e^-$) continuum whose cross section is many orders of magnitude larger.

Future Circular Collider (FCC-ee)

- The prospects of FCC-ee measurement of the direct Higgs boson production via resonant s-channel, $e^+e^- \to H$, in a dedicated run at $\sqrt{s} = m_H$.

- A means to determine the Higgs Yukawa coupling of the electron, y_e.





Future Circular Collider (FCC-ee)

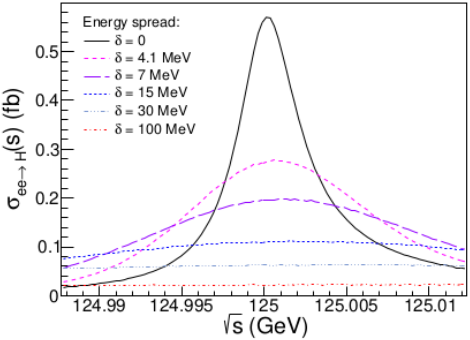
- Three main challenges of such a measuremen:

  1- The need to accurately know (within MeV's) beforehand the value of the Higgs boson mass where to operate the collide

  2- The smallness of the resonant Higgs boson cross section, due to ISR and beam energy spread ($\delta_{\sqrt{s}}$) requires to monochromatize the beams, still delivering large (few ab^{-1}) $\mathcal{L}_{int}$.

  3- The existence of multiple backgrounds with orders-of-magnitude larger cross sections than the Higgs signal decay channels themselves

- Resonant Higgs production cross section, including ISR effects:



Future Circular Collider (FCC-ee)

- Previous studies:

1- At FCC-ee: Benchmark $(\delta_{\sqrt{s}}, \mathcal{L}_{int} = (4.1 MeV, 10 ab^{-1}))$,
peak s-channel cross section of $\sigma_{e^+e^- \to H} = 0.28 fb$,
$Z = S/\sqrt{B} = 1.3\sigma$, $\sigma < 2.6\sigma_{(e^+e^- \to H)_{SM}}$, $y_e < 1.6\ y_e^{SM}$,
per FCC-ee IP and per year.
$\Lambda_{BSM} \approx \nu^{3/2}(\sqrt{2}m_e.(y_e/y_e^{SM}))^{-1/2} \gtrsim 110\,TeV$

2- At LHC: $y_e < 260\ y_e^{SM}$, $\Lambda_{BSM} \gtrsim 8.8\,TeV$

3- At HL-LHC: $y_e < 120\ y_e^{SM}$, $\Lambda_{BSM} \gtrsim 13\,TeV$

4- Bound (1) is about $\times 100$ ($\times 30$) times better than that reachable at HL-LHC (FCC-hh)

Future Circular Collider (FCC-ee)

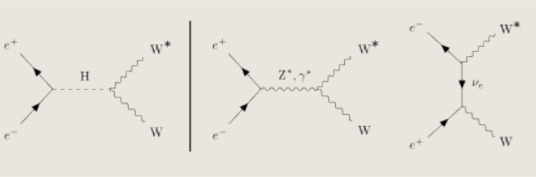
- The strategy to observe the resonant production of the Higgs boson, identifying final states in e^+e^- collisions at $\sqrt{m_H}$, consistent with H decay modes,

- Analyze two Higgs decay channels in FCC-ee.
  1- $H \longrightarrow WW^* \longrightarrow \ell\nu_\ell qq$
  2- $H \longrightarrow WW^* \longrightarrow qq\ell\nu_\ell$

- Our Tools in this analysis:
  1- Python developed Codes
  2- C developed Codes
  3- Root CERN Package
  4- FCCSW Package

Future Circular Collider (FCC-ee)

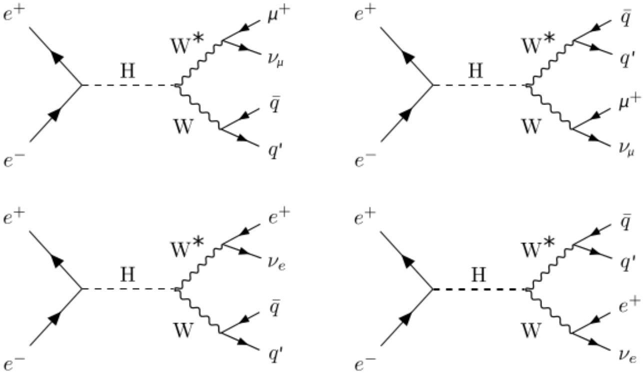
- Signal process of the Higgs decay and backgrounds:



Process	Cross Section (pb)
Semileptonic Processes	
$H \to W(\ell\nu)W^*(jj)$	2.626×10^{-5}
$H \to W(jj)W^*(\ell\nu)$	2.624×10^{-5}
$e\nu_e jj$	1.382×10^{-2}
$eejj$	5.065×10^{-1}
$\mu\nu_\mu jj$	6.711×10^{-3}
$\mu\mu jj$	1.505×10^{-1}
$\tau\nu_\tau jj$	6.761×10^{-3}
Fully Hadronic Processes	
$H \to gg$	7.384×10^{-5}
$H \to bb$	1.685×10^{-3}
jj	3.631×10^{2}
Fully Leptonic Processes	
$H \to \tau\tau$	1.011×10^{-4}
$H \to ll\nu\nu$	3.187×10^{-5}
$ee\nu\nu$	3.364×10^{-1}
$\mu\mu\nu\nu$	2.202×10^{-1}
$\tau\tau\nu\nu$	4.265×10^{-2}
$l_1 l_2 \nu\nu$	5.799×10^{-3}
$\tau\tau$	2.5939×10^{1}

Future Circular Collider (FCC-ee)

- Final states of the Signal processes:



Future Circular Collider (FCC-ee)

- Analysis stages:

  1- Calculating analysis variables (Kinematics of signal and backgrounds processes)

  2- Pre-selection Cuts (depend on Kinematics)

  3- MultiVariate Analysis (MVA) (based on Machine Learning)

  4- Determining the the overall significance and the impact on the electron Yukawa coupling

Future Circular Collider (FCC-ee)

- Kinematic and global topological variables used in analysis:

Category	Variables
Missing Energy / Momentum	Missing_P, Missing_Pt, Missing_Phi, Missing_Eta, Missing_Theta, Missing_Rapidity, Missing_M, Missing_Mt, Missing_E, Missing_Et, Missing_CosTheta, Missing_CosPhi
Isolated Photons	Iso_Photon_P, Iso_Photon_Pt, Iso_Photon_Eta, Iso_Photon_Phi, Iso_Photon_Theta, Iso_Photon_Rapidity, Iso_Photon_M, Iso_Photon_Mt, Iso_Photon_E, Iso_Photon_Et, Iso_Photon_CosTheta, Iso_Photon_CosPhi, Iso_Photons_No
Isolated Leptons	Iso_Lepton_P, Iso_Lepton_Pt, Iso_Lepton_Eta, Iso_Lepton_Phi, Iso_Lepton_Theta, Iso_Lepton_Rapidity, Iso_Lepton_M, Iso_Lepton_Mt, Iso_Lepton_E, Iso_Lepton_Et, Iso_Lepton_CosTheta, Iso_Lepton_CosPhi, Iso_Leptons_No
Jets (General)	Jets_InMa, d23, d34
Jet 1	Jet1_P, Jet1_Pt, Jet1_E, Jet1_Et, Jet1_Eta, Jet1_Rapidity, Jet1_Phi, Jet1_M, Jet1_Mt, Jet1_Theta, Jet1_CosTheta, Jet1_CosPhi
Jet 2	Jet2_P, Jet2_Pt, Jet2_E, Jet2_Et, Jet2_Eta, Jet2_Rapidity, Jet2_Phi, Jet2_M, Jet2_Mt, Jet2_Theta, Jet2_CosTheta, Jet2_CosPhi
Jet–Lepton / Jet–Jet Relations	Jets_delR, ILjet1_delR, ILjet2_delR, Jets_delphi, ILjet1_delphi, ILjet2_delphi, Jets_deleta, ILjet1_deleta, ILjet2_deleta, Jets_delrapi, ILjet1_delrapi, ILjet2_delrapi, Jets_deltheta, Jets_angle, ILjet1_angle, ILjet2_angle, Jets_cosangle, ILjet1_cosangle, ILjet2_cosangle

Future Circular Collider (FCC-ee)

- Kinematic and global topological variables used in analysis:

Category	Variables
Event-level Scalars	HT, Higgs_IM
Mass Combinations	LJJ_M, LJJ_Mt, LJ1_M, LJ1_Mt, LJ2_M, LJ2_Mt, Lnu_M, JJ_M, JJ_Mt, JJ_E
Transverse Momentum / Rapidity	lj1_PT, lj2_PT, jj_PT, ljj_y, jj_y, lj1_y, lj2_y
Angles / Phi	ljj_Phi, jj_Phi, Wl_M, Wl_Theta, Shell_M, Off_M, CosTheta_MaxjjW, CosTheta_MinjjW, expD
Jet Extremes	Max_JetsPT, Min_JetsPT, Max_JetsE, Min_JetsE, Max_DelRLJets, Min_DelRLJets, Max_DelPhiLJets, Min_DelPhiLJets, Max_DelEtaLJets, Min_DelEtaLJets, Max_DelyLJets, Min_DelyLJets, Max_CosLJets, Min_CosLJets
Global Event Shapes	Phi, CosPhi, Phi1, CosPhi1, PhiStar, CosPhiStar, ThetaStar, CosThetaStar, Theta1, Costheta1, Theta2, Costheta2, Planarity, APlanarity, Sphericity, ASphericity
Jet Constituents	Jet_nconst1, Jet_nconst2
Displacements	displacementdz0, displacementdxy0, displacementdz1, displacementdxy1
Jet Scores	scoreB1, scoreB2, scoreS1, scoreS2, scoreC1, scoreC2, scoreG1, scoreG2, scoreQ1, scoreQ2
Score Aggregates (Sum)	scoreSumB, scoreSumG, scoreSumS, scoreSumC, scoreSumQ, scoreSumSC, scoreSumCS
Score Aggregates (Product)	scoreMultiplyB, scoreMultiplyG, scoreMultiplyS, scoreMultiplyC, scoreMultiplyQ, scoreMultiplySC, scoreMultiplyCS

Future Circular Collider (FCC-ee)

- Preselection cuts:
- The criteria applied to all signal and backgrounds events aiming at a first preselection of final- state topologies consistent with each considered Higgs decay channel:

  1- To remove reducible backgrounds as much as possible

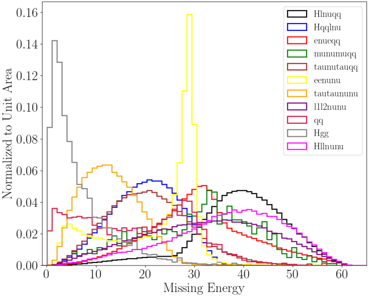
  2- While keeping the largest possible signal efficiency

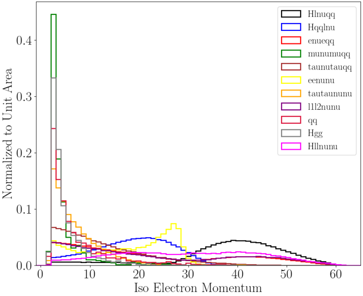
Future Circular Collider (FCC-ee)

- For example for the signal process: $H \longrightarrow WW^* \longrightarrow e\nu_e qq$, we used the following preselection cuts:

  1- isolated $e^{\pm}$,
  2- 2 (excl.) jets,
  3- $Iso\_Electron\_P > 3$,
  4- $Missing\_E > 2$
  5- $n\_jet1\_constituent > 5$
  6- $n\_jet2\_constituent > 5$
  7- $Jet1\_P > 10$
  7- $Jet2\_P > 2$
  9- $Lnu\_E > 60$

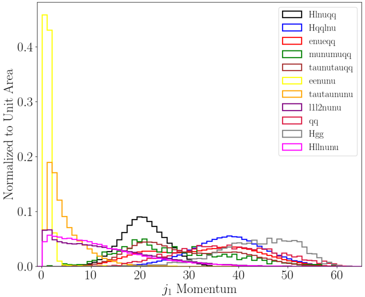
- some electron signal ($H \longrightarrow WW^* \longrightarrow e\nu_e qq$) variables:

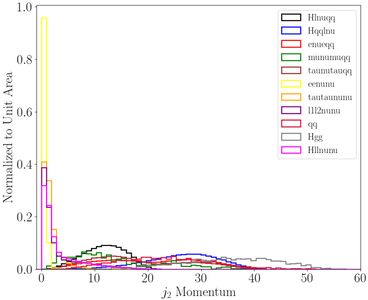




Future Circular Collider (FCC-ee)

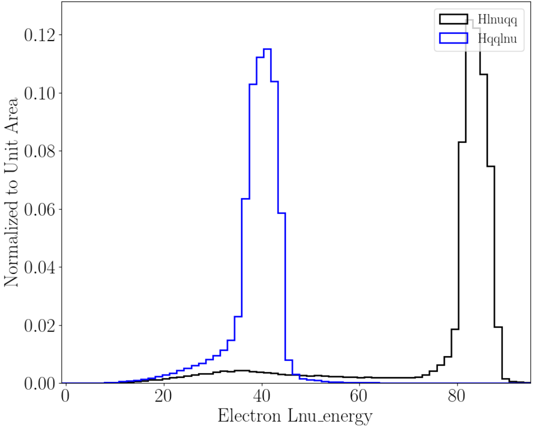
- some electron signal ($H \longrightarrow WW^* \longrightarrow e\nu_e qq$) variables:





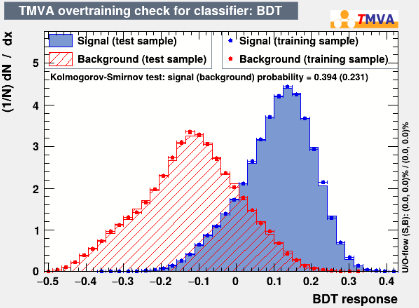
Future Circular Collider (FCC-ee)

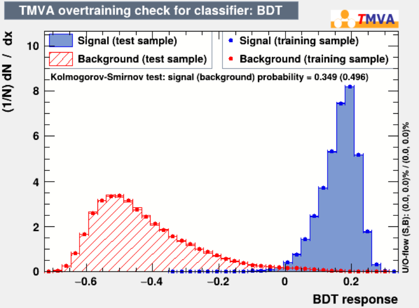
- Orthogonality cut ($Lnu\_E > 60$):



Future Circular Collider (FCC-ee)

- MultiVariate Analysis (MVA) (based on Machine Learning- BDT)
  1- For $(H \longrightarrow WW^* \longrightarrow e\nu_e qq)$
  2- For $(H \longrightarrow WW^* \longrightarrow qqe\nu_e)$





Conclusion

- The Significance Formula:

$$\text{Significance} = \frac{(\mathcal{L} \cdot \sigma \cdot \epsilon)_{\text{sig}}}{\sqrt{\sum_i (\mathcal{L} \cdot \sigma \cdot \epsilon)_{\text{bkg},i}}} \tag{2}$$

- The Significance for each processes:
  $Z_{e-on} = 1.08$, $Z_{e-off} = 0.65$, $Z_{\mu-on} = 1.19$ and $Z_{\mu-off} = 0.59$

  combined Significance:
  $Z_{combined} = \sqrt{(1.08)^2 + (0.65)^2 + (1.19)^2 + (0.59)^2} = 1.83$

- Better than a similar study for this channel: 0.52
- In a study for 11 Higgs decay channels: $Z = 1.3\sigma$,

Greetings

Thanks For Your Attention

References

1 F. Englert, R. Brout. Broken symmetry and the mass of gauge vector mesons. Phys. Rev. Lett., 13(9):321, 1964.

2 Higgs, P. W. Broken symmetry and the masses of gauge bosons. Phys. Rev. Lett., 13(16):508, 1964.

3 G. Aad, et al. [ATLAS]. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. Phys. Lett. B, 716:1–29, 2012.

4 S. Chatrchyan, et al. [CMS,]. Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC. Phys. Lett. B, 716:30–61, 2012.

5 H. Gray, P. Janot. Higgs Physics. Comptes Rendus. Physique, 21(1):23–43, 2020.

References

6 D. d'Enterria, A. Poldaru, G. Wojcik. Measuring the electron Yukawa coupling via resonant s-channel Higgs production at FCC-ee. Eur. Phys. J. Plus, 137(2):201, 2022.

7 L. Baudis, et al. Review of Particle Physics. Progress of Theoretical and Experimental Physics, 8:083C01, 2020.