FUTURE CIRCULAR COLLIDER

Physics potential for the measurement of Higgs to ZZ* at FCC

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Future Circular Collider

FCC is proposed future collider at CERN

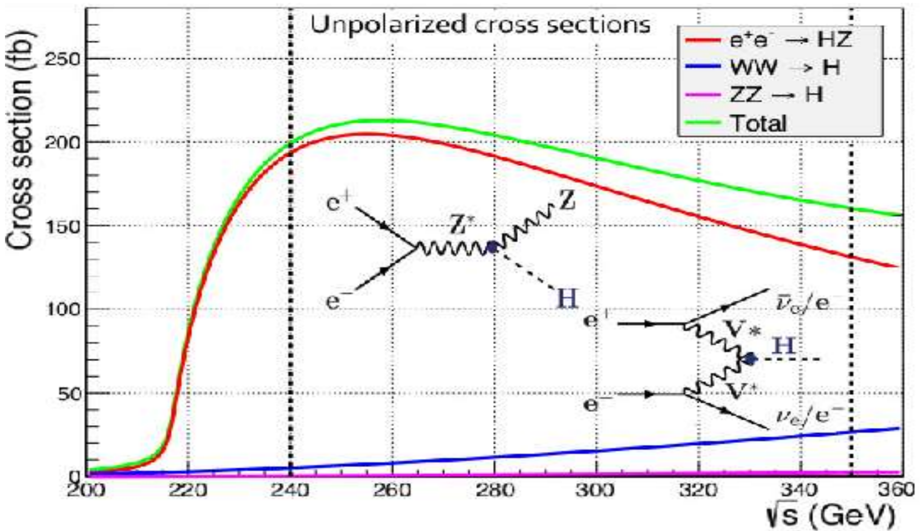
First phase: electron-positron collider FCCee

Foreseen physics runs:

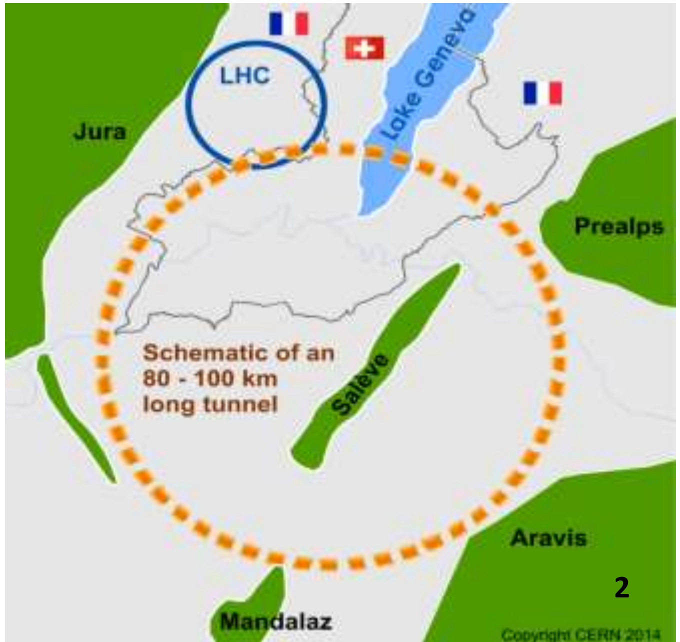
- 240 GeV operating as the Higgs boson factory
- Z-pole and WW threshold: electroweak, flavor precision physics
- $t\bar{t}$ threshold top quark physics

Second phase: FCC-hh ~ 84 GeV TeV **(pp & AA collisions; e-h option)**

FCCee “The Higgs factory”



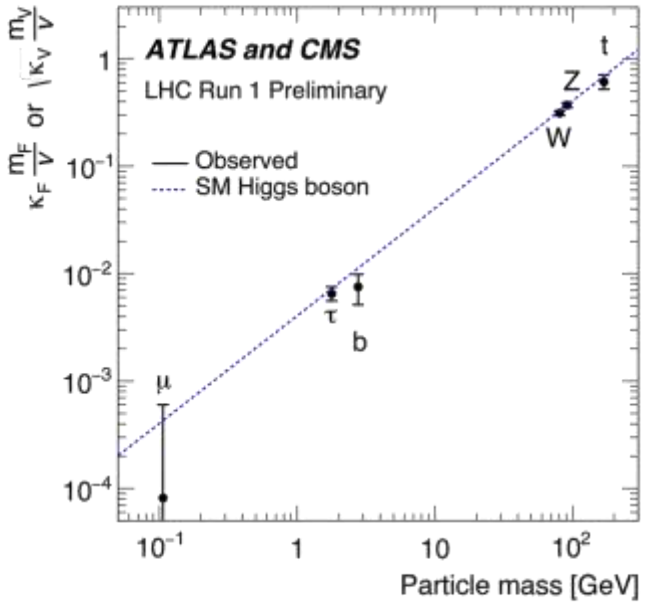
Parameter FCCee	Z	WW	H (ZH)	$t\bar{t}$
beam energy [GeV]	45.6	80	120	182.5
Run time (4IP)	4	2	3	4
synchrotron radiation/beam [MW]	100	100	100	100
beam current [mA]	1292	135	26.8	5.1
number bunches / beam	11200	1852	300	64
luminosity / per IP [10^{34} $cm^{-2}s^{-1}$]	140	20	7.5	1.4
total integrated luminosity / per 4 IP / year [ab^{-1} / yr]	68	9.6	3.6	0.68
beam lifetime [min]	21	13	9	10



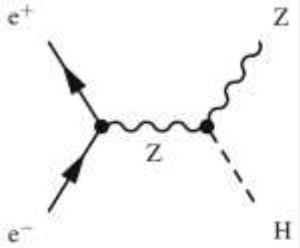
Motivation for the of H to ZZ measurement at FCCee

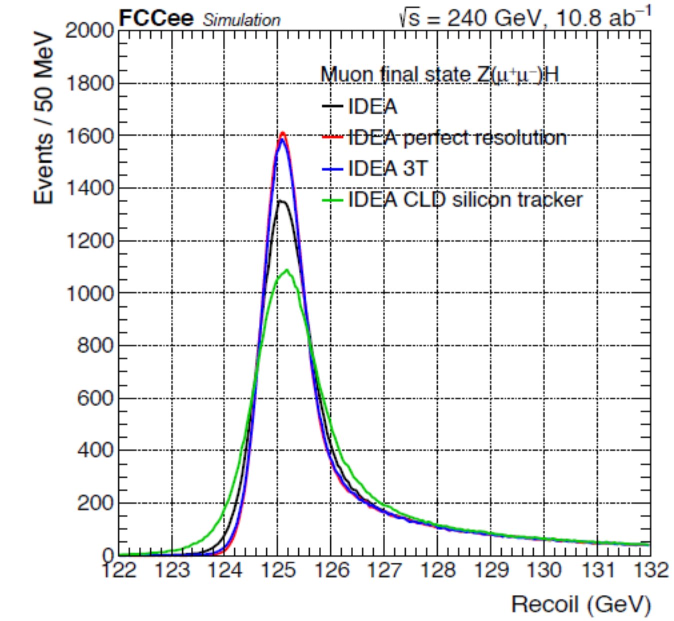
- The primary goal of FCCee, are high precision measurements of the fundamental properties of the Standard Model (SM) Higgs boson: mass, decay width and couplings to the Sandard model particles

- Precise measurements of the Higgs boson couplings, the strengths of its interactions to the SM particles, provide the test of SM since many BSM models predict their deviation from SM predictions



- Future e+e- colliders allow the measurement of the absolute Higgs boson couplings. The cornerstone is the determination of the absolute Higgs to Z boson coupling, by measuring total Higgsstrahlung (HZ) cross section using the recoil method $\sigma(e^-e^+ \rightarrow HZ) \propto g_{HZZ}$
- The total Higgs decay width (Γ_H^{SM}~4.1MeV) can also be accessed at the FCC-ee: extracted using the measurements of the branching fraction for the decay H → ZZ∗ in HZ:
- $\sigma(e^-e^+ \rightarrow HZ) \times B(H \rightarrow ZZ^*) \propto \frac{g_{HZZ}^4}{\Gamma_H}$
- g_{HZZ} and Γ_H all absolute couplings





Higgs decay to the Z boson

ZHZZ

The goal of the analysis is to obtain relative statistical uncertainty of $\boldsymbol{\sigma(\mathrm{HZ})\mathrm{xBR}(\mathrm{Z} \to qq, \mathrm{H} \to ZZ^* \to qqqq)}$

Analyzed fully hadronic decay H-ZZ in Higgstrahlung

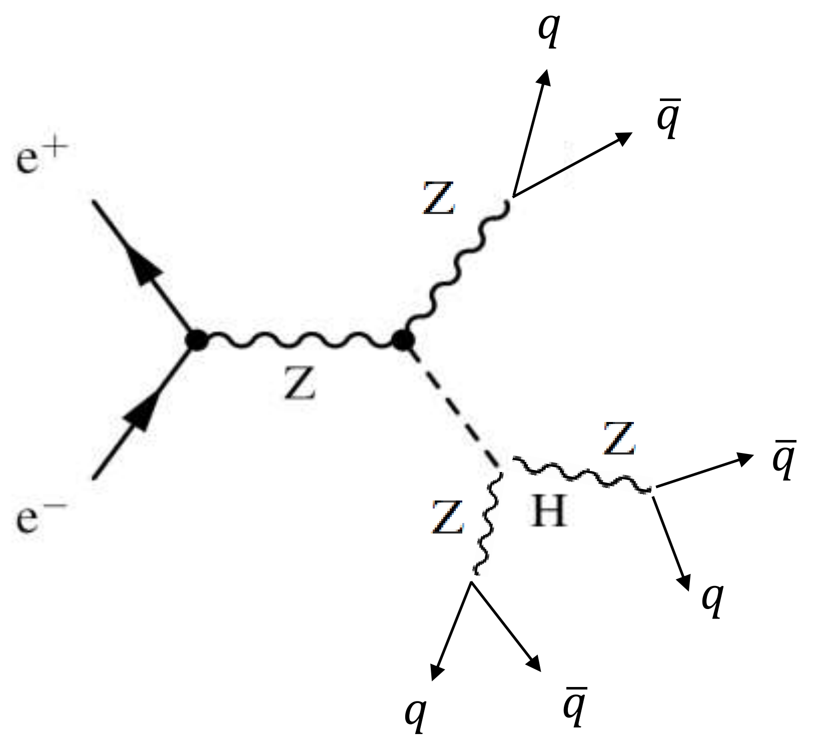
$e^+e^- \to HZ, Z \to qq, H \to ZZ^* \to qqqq$

$\mathrm{BR}_{H\to ZZ}$~2.5% , $\mathrm{BR}_{ZZ\to qqqq}$~0.476%

$\sigma_{(HZ,\ Z\to qq\ ,\ H\to WW^*\to qqqq\ )}$ ~ Xsec = 0.004 pb

Integral luminosity: 10.8 ab^{-1}

Signal signature: six central jets in the final state



Challenges:

- low $BR(H \to ZZ^*)$ **~2.5%**
- hadronic calorimeter resolution
- intrinsic overlap of Z/W invariant masses ⇒

- "Irreducible background" is coming from the similar H to WW decay $ee \to HZ, Z \to q\bar{q}, H \to WW^* \to q\bar{q}q\bar{q}$

Monte Carlo samples and detector simulation

Event generator: Whizard / Pythia8

Process	240 GeV	365 GeV
$e^+e^- \to HZ \to Z \to qq, H \to ZZ^*$	0.00357	0.00221
$e^+e^- \to HZ \to Z \to qq, H \to WW^*$	0.02914	0.01803
$e^+e^- \to WW$	16.44	10.72
$e^+e^- \to ZZ$	1.36	0.64
$e^+e^- \to q\bar{q}$	55.01	22.80

Centre of mass energy [GeV]	**240**	**365**
Luminosity [ab^{-1}]	10.8	3.0

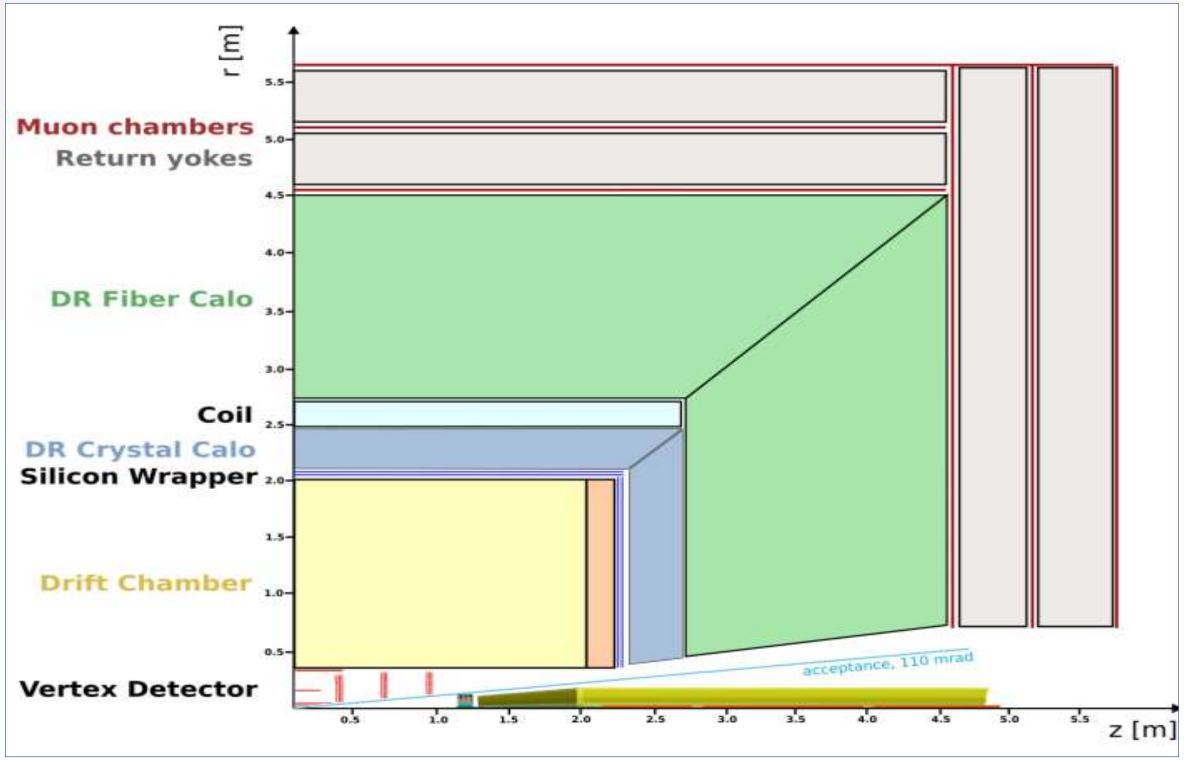
Detector simulation: Delphes

Reconstruction: Particle Flow

Detector model: IDEA Dual-readout based calorimetry

"Innovative Detector for an Electron-positron colliders"

All integrated into Key4HEP framework



Analysis strategy

- Due to the moderate hadronic energy resolution and the similarity of the W and Z boson masses, the reconstructed final states from these processes significantly overlap
- This overlap especially impacts the HZZ measurement, due to it lower branching fraction.
- Thus the analysis strategy is primarily targeted at the HWW background reduction

This analysis is designed to extract H(ZZ) and H(WW) simultaneously and proceeds in several steps:

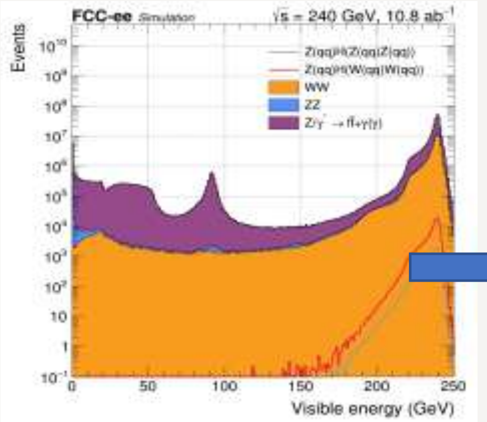
1. Veto leptons and visible mass
2. Exclusive jet clustering N=6 hypothesis, obtaining kt parameter jet transitions
3. Flavor tagging for each jet
4. Jet pairing to reconstruct Zreal, Z* and Z from HZ
5. ML1: multivariate analysis for the event categorization HZZ-like / HWW-like (Boosted decision tree BDT)
6. ML2: multivariate analyses HZZ-like vs all backgrounds (WW,ZZ,ff, other Higgs dcays)= BDT_{HZZ} response
7. ML3: multivariate analyses optimized for HWW-like events, BDT_{HWW} response
8. Simultaneous fit of the H(ZZ) and H(WW) signal strengths to obtain the final results the relative statistical uncertainties

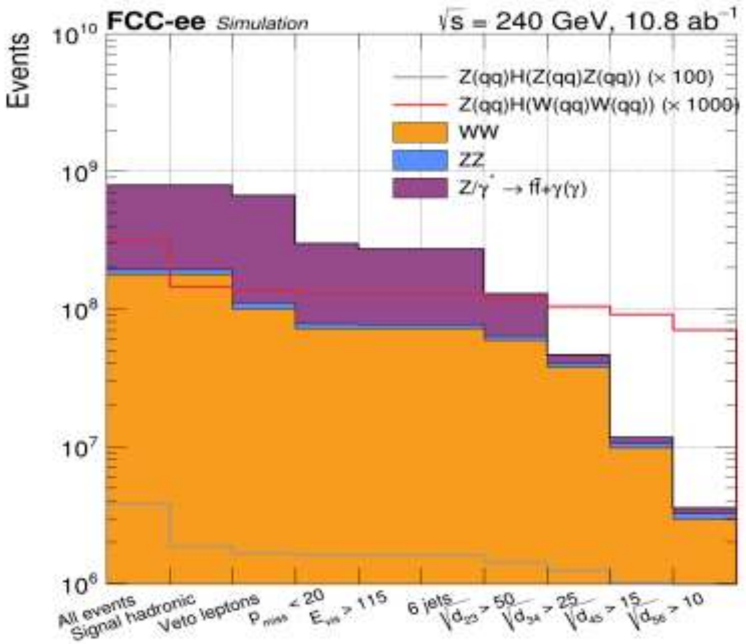
Lepton isolation/prior ML selection

Preslection Cut flow diagram

Prior to the event clustering, events are preselected to be pure in hadronic activity by imposing a cut on the missing

- momentum < 20 GeV
- visible mass > 10 GeV
- visible energy >115 GeV
- Energy e,**m** < 10 GeV





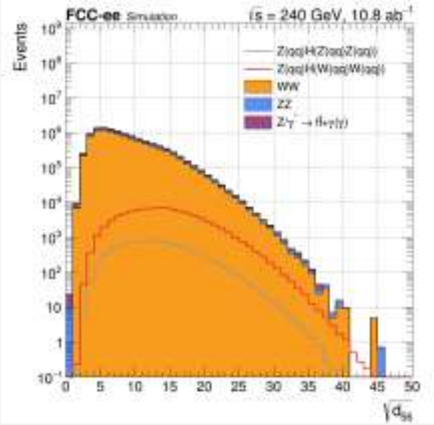
Jet Clustering

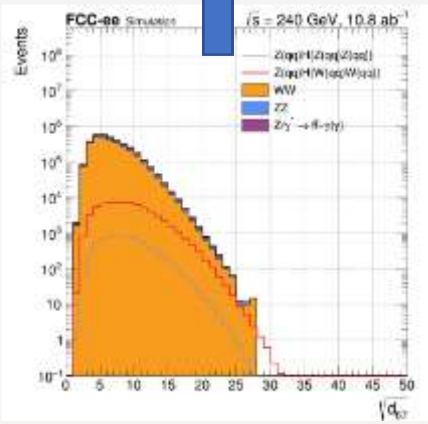
Remaining events are clustered into six jet usingDurham kT algorithm, implemented in FastJet

The distance parameters of the jet algorithm, dij,

when merging n + 1 to n jets

- $\sqrt{d23} > 50$
- $\sqrt{d34} > 25$
- $\sqrt{d45} > 15$
- $\sqrt{d56} > 10$

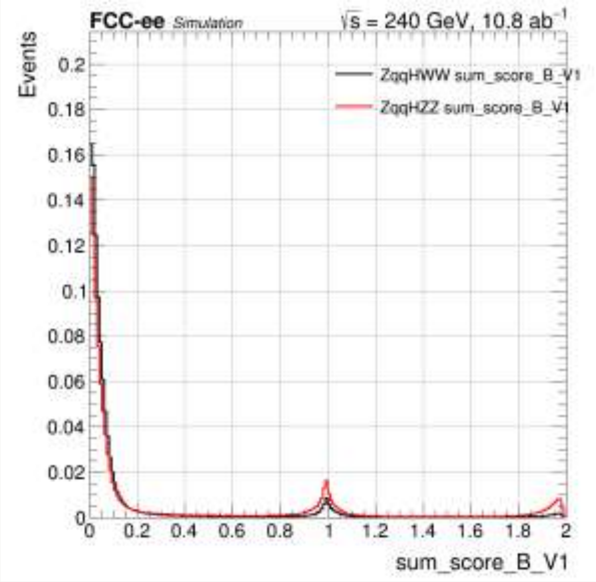




The events that could not be clustered into N=6 jets are discarded

Flavor tagging

- To each a flavor tag probability of originating from one of seven particle types: b,c,s,u,d,g, τ is assigned using a Graph Neural Network (GNN) jet flavor tagger
- The tagger uses kinematic information from particle-flow candidates within each jet
- Kinematic properties:
  - Displacement information: longitudinal/transverse impact parameters, ..
  - particle identification features:
    - particle charge
    - mass (time-of-flight measurements)
    - dN/dx cluster counting
    - displaced vertices and tracks…
  - Flavor tag is assigned before the event reconstruction



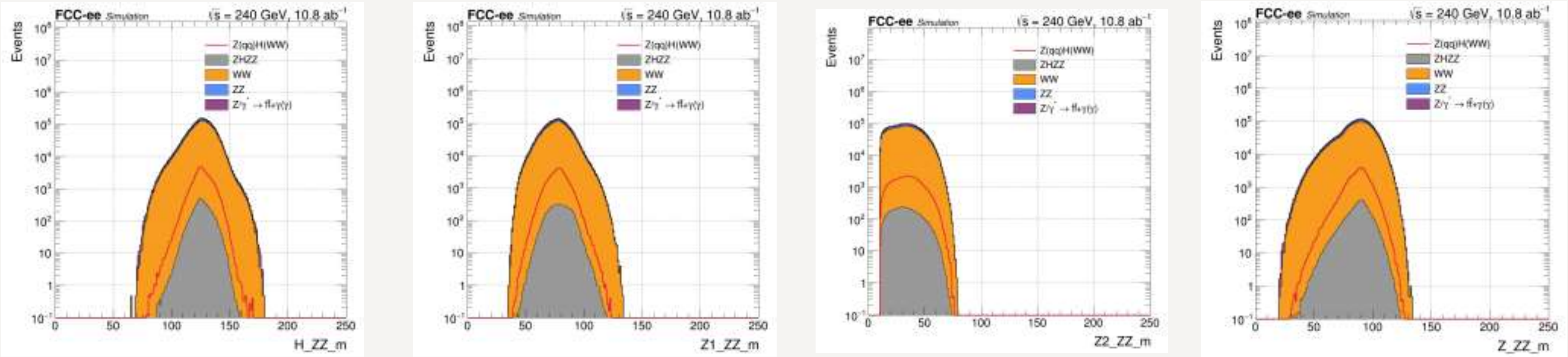
Bedeschi, F., Gouskos, L. & Selvaggi, M. Jet flavour tagging for future colliders with fast simulation. *Eur. Phys. J. C* **82**, 646 (2022). https://doi.org/10.1140/epjc/s10052-022-10609-1

Jet pairing and event reconstruction

- Reconstruction of the Higgs, real and virtual Z and the Z boson from HZ: event is forced into six jets
- Obtained jets are grouped into three pairs to form the Z, Z* and Z_{HZ} boson
- The combination which minimizes the χ^2 is chosen :

$$\chi^2_{HZZ} = \frac{\left(m_{ij} - m_Z\right)^2}{\sigma^2{}_Z} + \frac{\left(m_{kl} - m_Z\right)^2}{\sigma^2{}_Z} + \frac{\left(m_{ijmn} - m_H\right)^2}{\sigma^2{}_H}$$

Reconstructed invariant masses Higgs, real Z, Z*, Z



ML classification HZZ/HWW

HWW is the one of the main backgrounds. In order to separate the signal from the HWW background the multivariate analysis is firstly performed using HZZ as a signal and only HWW as a background.
The HWW is reconstructed independently using χ^2

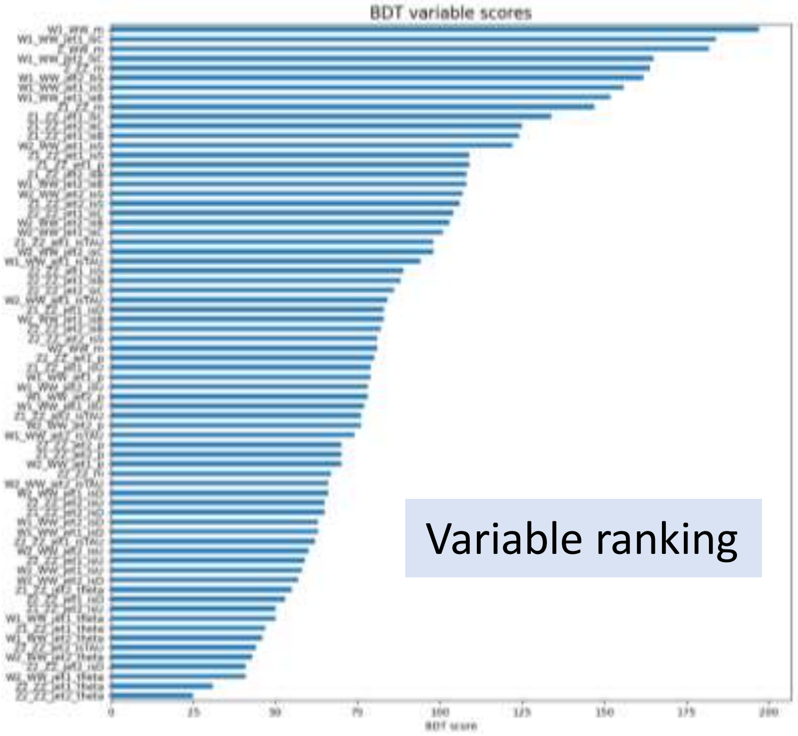
$$\chi^2_{HWW} = \frac{(m_{ij} - m_W)^2}{\sigma^2_Z} + \frac{(m_{kl} - m_Z)^2}{\sigma^2_Z} + \frac{(m_{ijmn} - m_H)^2}{\sigma^2_H}$$

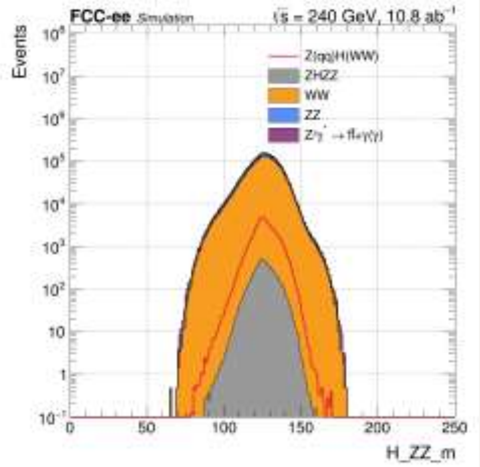
Boosted Decision Tree (BDT) is trained using HZZ reconstructed vs. HWW reconstructed events. The observables used for discrimination:

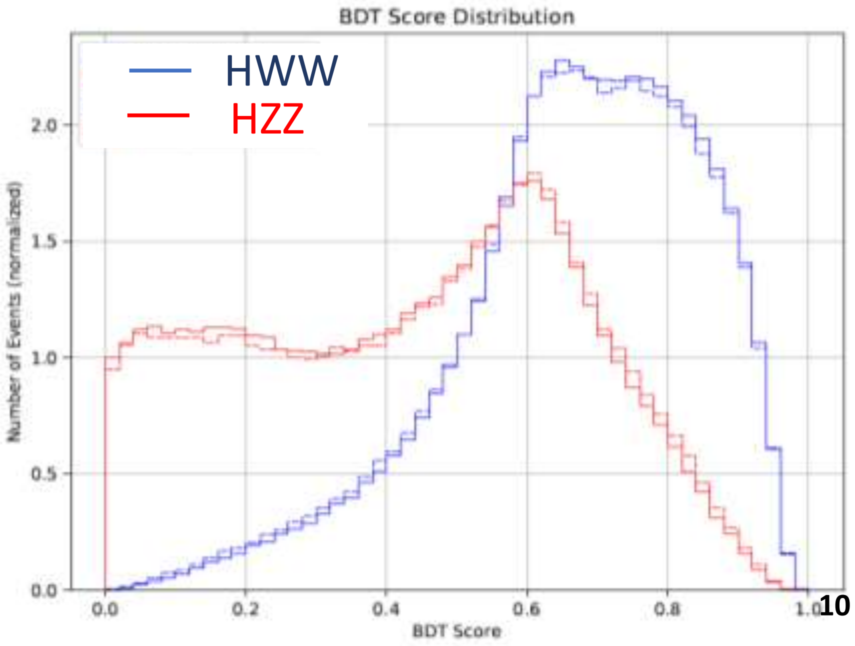
- $m_W, m_H, m_Z, m_{Z/ZH}$
- jet flavour tagging variables t, b, c, s, g, τ
- momentum of jets, angle

77% HZZ/HWW separation power obtained
Optimal classification of events obtained with:

MVA < 0.5 classified as HZZ
MVA > 0.5 classified as HWW







Final ML final selection HZZ

- ML2 HZZ: Boosted Decision Tree (BDT) is subsequently trained using:
- Signal: remaining HZZ-like events
- Backgrounds: four fermion ZZ, WW, two fermion and remaining HWW events. The background samples are mostly fully hadronic due to the applied preselection
- The most effective invariant mass is the mass of the real Z boson

Sensitive observables:

- masses of reconstructed bosons in the event for different reconstruction hypotheses
- kinematic variables
- jet flavor information
- jet variables
- angular variables

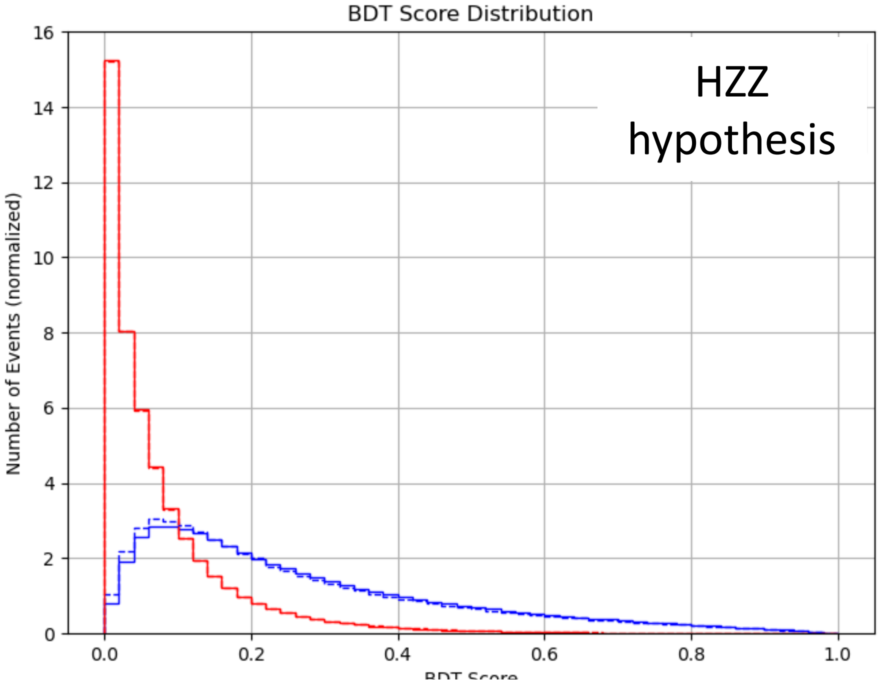
ML HWW selection

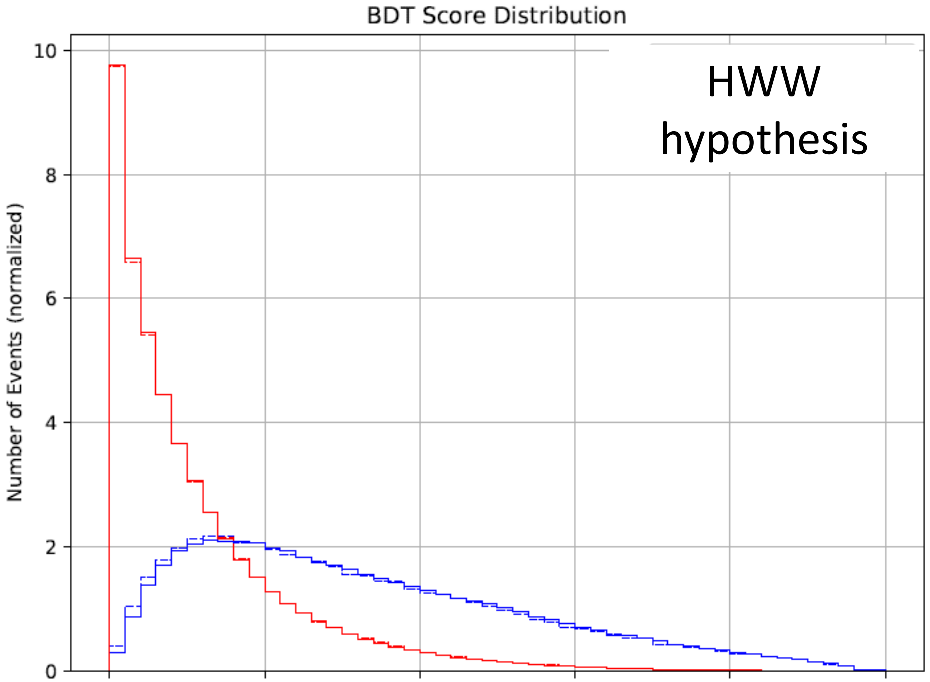
ML3: For the main background HWW, the analysis where HWW is treated like signal while the background contains the remaining HZZ sample and all other samples has been carried out. Optimization of the training variables set – the most effective is the p_H

RESULTS

Relative statistical uncertainty of the measurement is obtained by performing the simultaneous fit using the output discriminants from the HZZ and HWW analyses, $BDT_{HZZ}$and BDT_{HWW} with two signal strength parameters. Background processes are assigned a 1% normalization uncertainty.

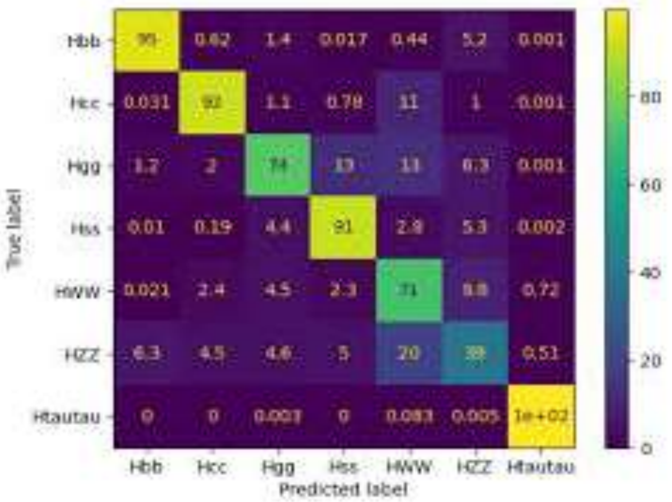
The resulting expected uncertainty obtained in the fully hadronic channel by the simultanious fit is 8.20% for σ(ZH) × B(H → ZZ∗)





The result entered FCC Feasibility study https://cds.cern.ch/record/2928193 and submitted to the European Strategy update https://indico.cern.ch/event/1439855/contributions/6461619/

Higgs to ZZ other channels



Determination of the uncertainties of the H→bb/cc/gg/ss/WW/ZZ/ττ

- ZZ is not the main goal in this study; obtained sensitivity is combined with the main analysis
- Besides Higgsstrahlung vector boson fusion is used ZH(+VBF)@240&365
- N = 2 exclusive kT clustering for Z(ll/$\nu\nu$)
- N = 4 for Z(qq)
- For WW and ZZ hadronic state is treated as “two jet”
- backgrounds WW, ZZ, Z/γ*, Zqq, ee, μμ, tt, $\nu\nu$Z, qq
- S/B optimization with kinematic selection
- Categorization using ParticleNet tagger output
- Simultaneous fit on all categories
- Combination of all Z decay channels

Expected precision on σ×BR(Z(H→XX)) at √s=240 GeV

Final state	Z($\nu\nu$)H(jj)	Z($\ell\ell$)H(jj)	Z(jj)H(jj)	Combination
H → bb	0.33	0.60	0.32	0.21
H → cc	2.27	3.47	3.52	1.61
H → gg	0.94	1.93	3.07	0.80
H → ss	140	220	410	120
H → WW*	1.28	1.49	8.74	1.17
H → ZZ*	11.4	7.65	50	9.94
H →$\tau\tau$	10.6	2.54	110	3.67

- Z boson decay that are considered
- Z→ll, l = e,μ BR(Z→ll) ~ 6.7 %
- Z→qq BR(Z→qq) ~ 67%
- Z→$\nu\nu$ BR(Z→$\nu\nu$) ~ 20%

A.Del Vecchio, J. Eysermans, L. Gouskos, G.Iakovidis, A. Maloizel, G.Marchiori, M.Selvaggi
Measurement of Higgs boson hadronic decays at FCC-ee, https://doi.org/10.17181/3jjdh-6fz97

Higgs to ZZ other analyses

ZH→Z(jj)ll$\nu\nu$ S. Aumiller, M. Sellvaggi

- S/B optimized using a BDT trained on lepton and jet kinematics
- One step multivariate analysis BDT
- A precision of 13.5 % Z(jj) Zreal(ll)Z*($\nu\nu$) of and a precision of 19.3 % for Z(jj) Zreal($\nu\nu$)Z*(ll) final state .

Z→jj,$\nu\nu$ & H→ZZ→4l

Y. Mahmoud, M. Sellvaggi, J. Eysermans, N. De Filippis

- S/B optimized using a BDT

  trained on lepton and jet kinematics

- One step multivariate analysis BDT
- Z(jj/vv)H(4l) combined: 10%

Z→ll & H→ZZ→4l

Uncertainty 30%

Channel	Uncertainty on (%)
vvjjjj	11%
lljjjj	7.6%
vvlljj	4.7%
llvvjj	5.0%
lljjvv	7.3%
jjllvv	13%
jjvvll	19%
jj/vv 4l	10 %
6l	30 %
6j	8.2%
Combination	2.5%

Combining all the channels

HWW and HZZ in the fully hadronicfinal states at the FCC-ee
https://doi.org/10.17181/jxx9k-b9z97

Measurement of Higgs boson hadronic decays at FCC-ee
https://repository.cern/records/3jjdh-6fz97

Measurements of the ZH→ZZZ*→qqllvv and qqvvll final states at FCC-ee
https://doi.org/10.17181/fnwcp-qfs39

Precision measurement of Higgs production cross section in the four-lepton final state at the FCC-ee
https://doi.org/10.17181/ey2ff-hqv83

HZ to six leptons analysis at FCC-ee
https://repository.cern/records/aaf59-q6v03

- Studies including τ final states not included yet
- The 365 GeV case on the way to finalization

Combination of all studied channels for 240 GeV case, deliver the sensitivity using samples of 10.8ab^{-1}

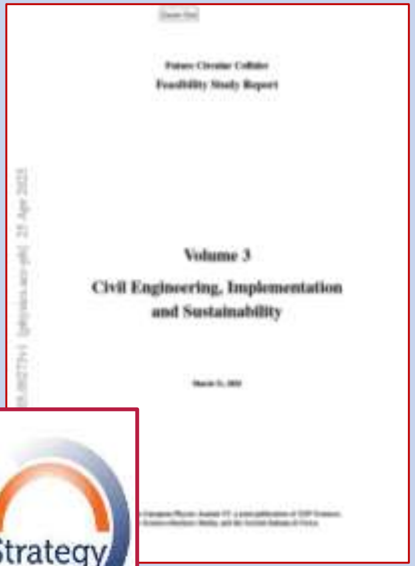
σxBR(H→ZZ) = 2.5 %

z

Feasibility study

European strategy update

2020 Update of European Strategy for Particle Physics:
"Europe, together with its international partners, should investigate technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage."
https://indico.cern.ch/event/1534205/
FCC Collaboration delivered 3 volumes of Feasibility Study

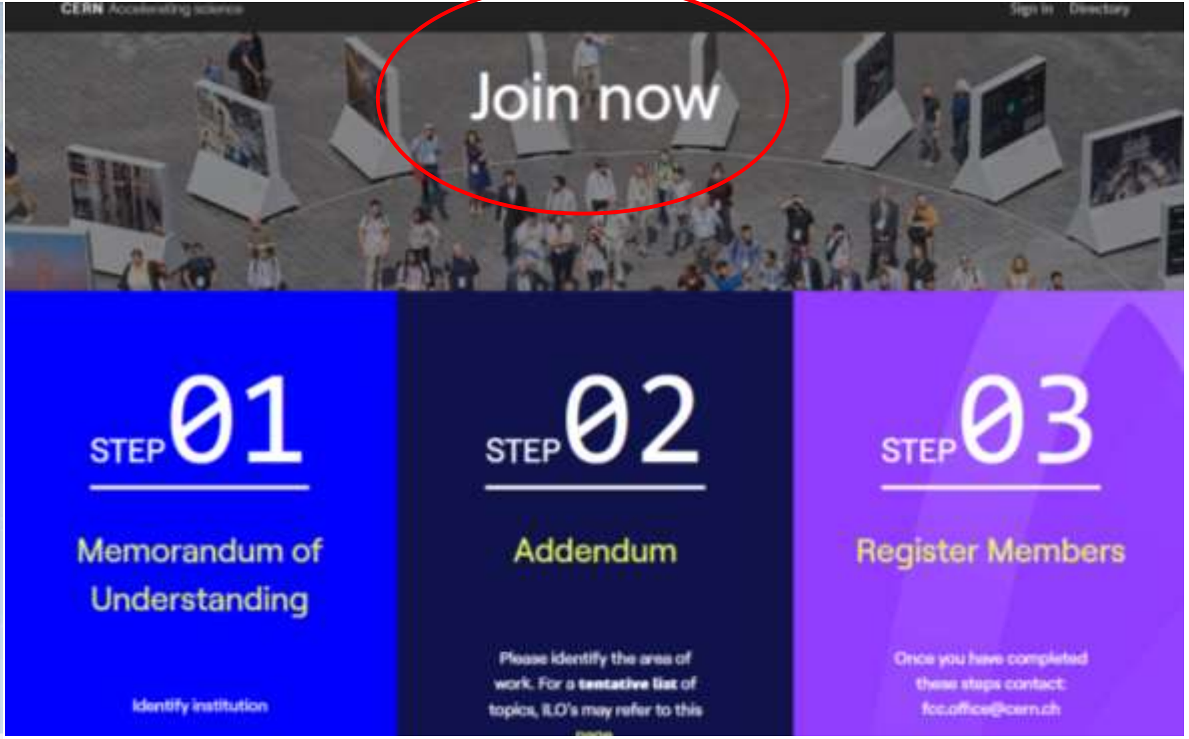


European Strategy Update

Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z ($\times 10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
σ_{had}^0 ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
N_ν($\times 10^3$)	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{\text{pol},\tau}$ ($\times 10^4$)	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2)$ ($\times 10^4$)	1 010	±	270	**2**	2	Combined R_ℓ^W, Γ_{tot}^W fit
N_ν ($\times 10^3$)	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
ttZ couplings		±	30%	**0.5–1.5 %**	small	From $\sqrt{s}$ = 365 GeV run

Feasibility Study: estimates of the systematic uncertainties encouraging!

FCC Collaboration



38 Participating Countries

Austria – Belgium – Brazil – Canada – Chile – Colombia – Czech Republic – Denmark – Estonia – Finland – France – Georgia – Germany – Greece – Hungary – India – Iran – Italy – Japan – Latvia – Malta – Mexico – Netherlands – Norway – Pakistan – Poland – Portugal – Republic of Korea – Romania – Serbia – Spain – Sweden – Switzerland – Thailand – Türkiye – Ukraine – United Kingdom – United States of America

162 Institutes

38 Countries + CERN

FUTURE CIRCULAR COLLIDER *Feasibility Study*

Summary

- FCC is a proposed future collider designed to be built an operated at CERN
- It will operate in two modes, as an electron- positron FCCee and a hadron- hadron collider FCChh
- It will be hosted by CERN in an ~ 90 km circumference ring
- FCCee will operate on several energy stages Z-pole, HZ 240 GeV, WW production 160 GeV and ttbar 365 GeV
- Primary target are precision measurments of the Higgs boson properties at 240 GeV mass, couplings and Γ_H
- We investigated fully hadronic final state of Higgs decay to ZZ in Higgsstrahlung using a multivariate analysis
- A simultaneous fit is performed using the output discriminants from the HZZ and HWW analyses, with two signal strength parameters extracted to determine their respective uncertainties.
- The obtained relative statistical uncertainty of the $\sigma(ZH) \times B(H \rightarrow ZZ*)$ is 8.2% at 240 GeV using Higgsstrahlung process and the integral luminosity of 10.8 ab^{-1}
- Combination of currently studied Higgs to ZZ decays channels in Higgstrahlung at 240 GeV the current relative statistical uncertainty of $\sigma(ZH) \times B(H \rightarrow ZZ*)$ amounts to 2.5% . Still large room for improvement!
- Results have entered The FCC Feasibility study and submitted to the European Strategy update
- Interested? Join the FCC Collaboration