Higgs mass, cross sections, CP, self-coupling

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On behalf of the FCC Higgs/Top performance working group

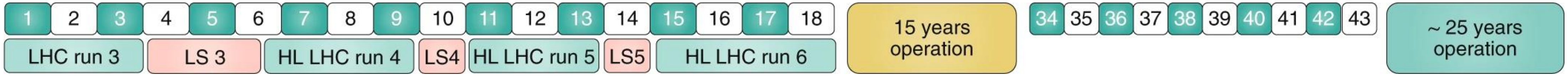
FCC Physics Workshop 2025, CERN, Jan. 14, 2025

@BrookhavenLab

Outline

- Introduction
- Higgs mass
- ZH cross-section
- CP
- Self-coupling
- Conclusion

Higgs: Introduction



FCC-ee

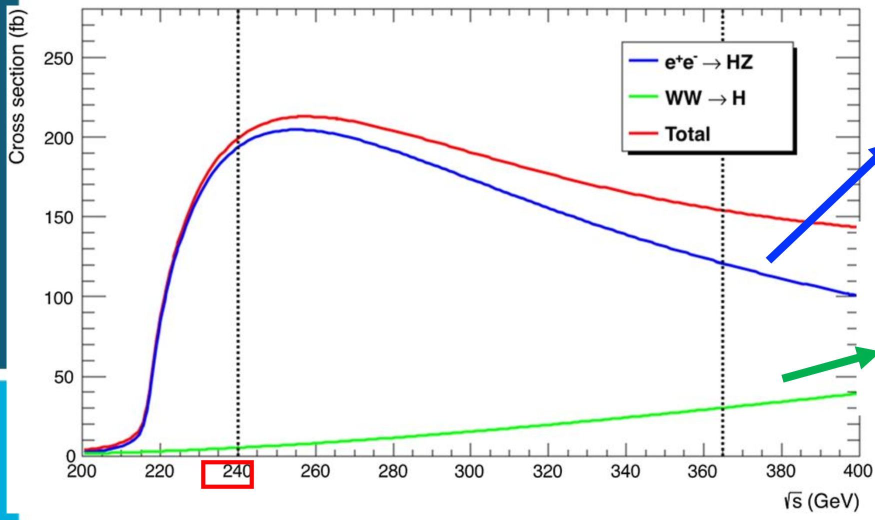
FCC-hh

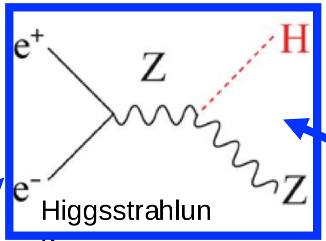
Baseline:

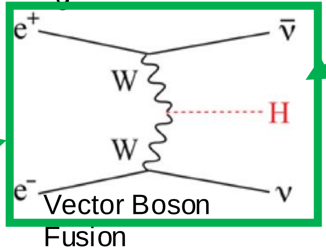
Higgs Physics at FCC-ee

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	$6\,10^{12}$ Z		$2.4\,10^{8}$ WW		$1.45\,10^{6}$ HZ + 45k WW → H	$1.9\,10^{6}$ $t\bar{t}$ +330k HZ +80k WW → H	

Main energy point for Higgs studies







Main Production Mechanisms at 240 and 365 GeV

- ZH production "Higgs-strahlung"
- Vector Boson Fusion (VBF): WW dominant

Optional run at 125 GeV s-channel

$e^+e^- \rightarrow H$

- Direct Probe of electron-Yukawa coupling
- Requires beam monochromatization

Higgs mass

$\sqrt{s} = 240$ GeV
$L = 10.8\ ab^{-1}$

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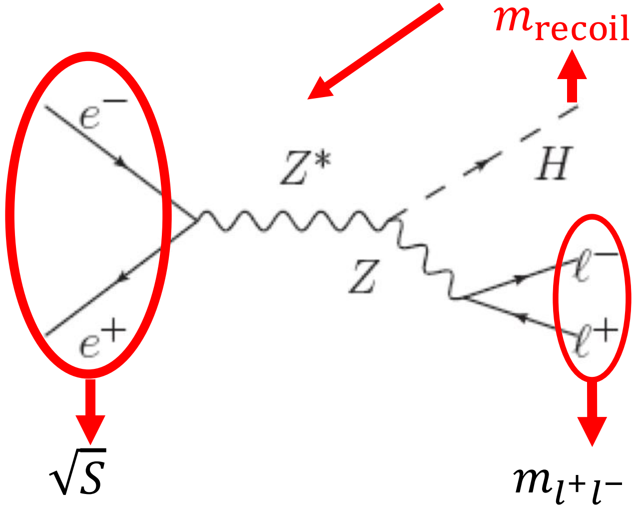
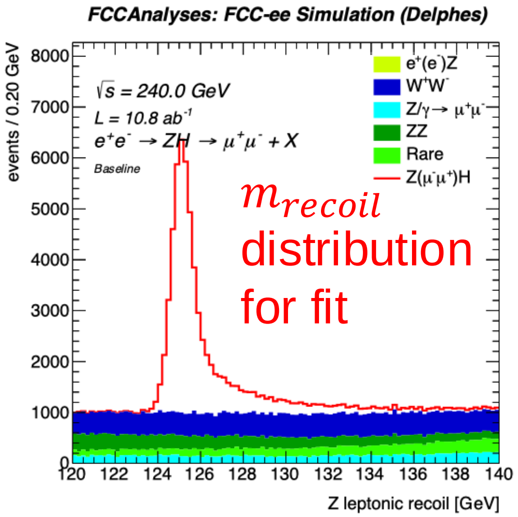
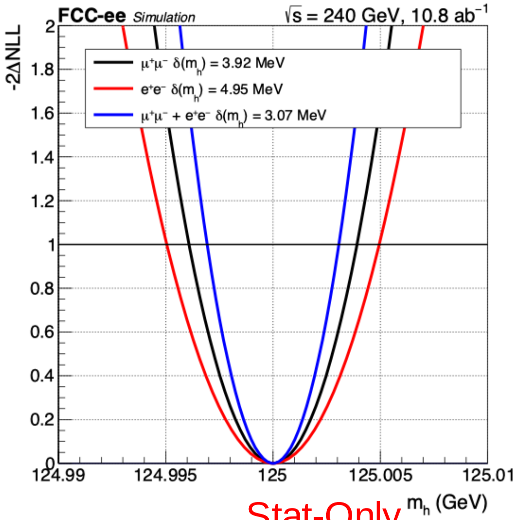
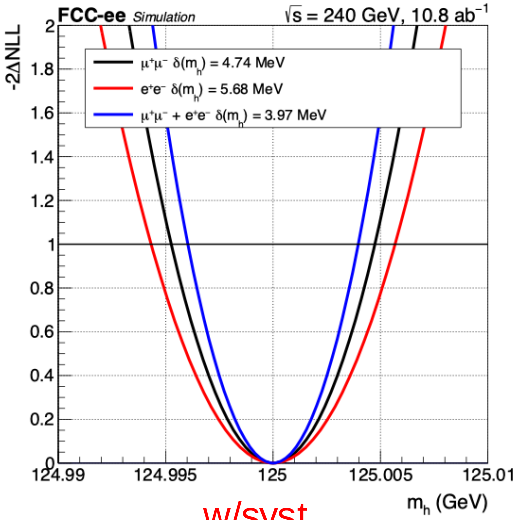
- Current best from LHC $\delta m_H \sim 100$ MeV
- At FCC-ee, Higgs mass will reach **MeV level** accuracy, ($\Gamma_H \sim 4.1$ MeV)
- Electron and Muons final states: $e^+e^- \to ZH \to l^+l^- + XX$, $(Z \to \mu^+\mu^-, e^+e^-)$
- M_{recoil} from the Z production without measuring the Higgs production final state

$$m^2_{\text{recoil}} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$









Higgs mass, Fit with analytic shape

- Signal Shape: 2 Crystal-Ball with Gaussian core
- Backgrounds modelled as polynomial (3rd order)
- Signal and background injected in Combine, m_H as POI

Uncertainty Stat-Only, and w/ systematics:

- Higgs mass: **3.07 MeV → 3.97 MeV**

Dominant Syst. Unc. :

Centre-of-mass with ~ 2 MeV

Higgs mass

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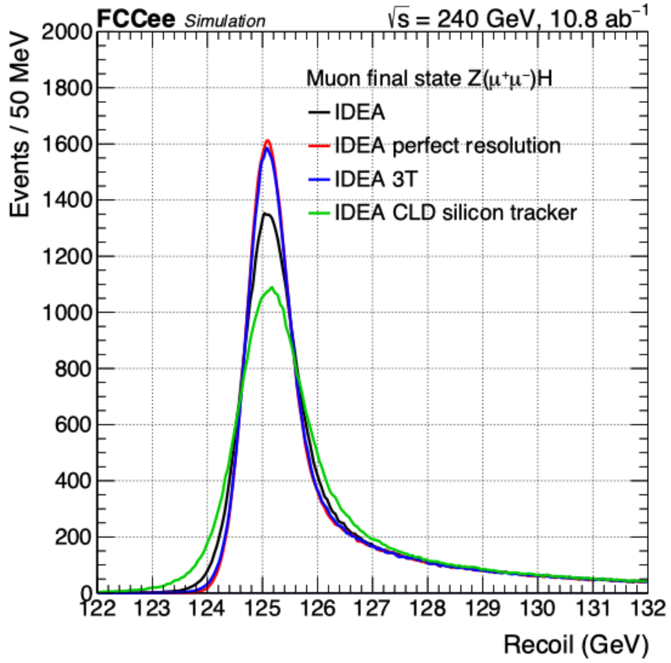
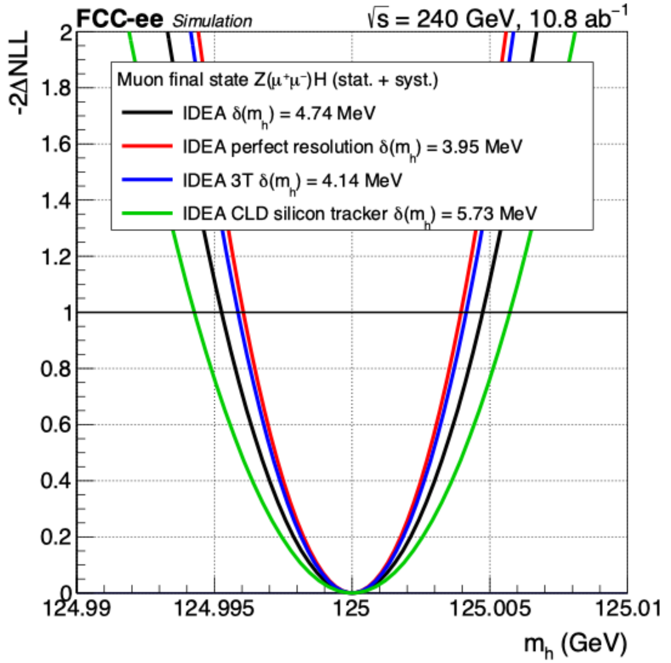
Some extended studies performed regarding detector effects

- Assuming "perfect" (generator-level) momentum resolution
- Nominal 2 T magnetic field → 3 T (stronger field → better tracking)
- IDEA drift chamber → CLD silicon tracker

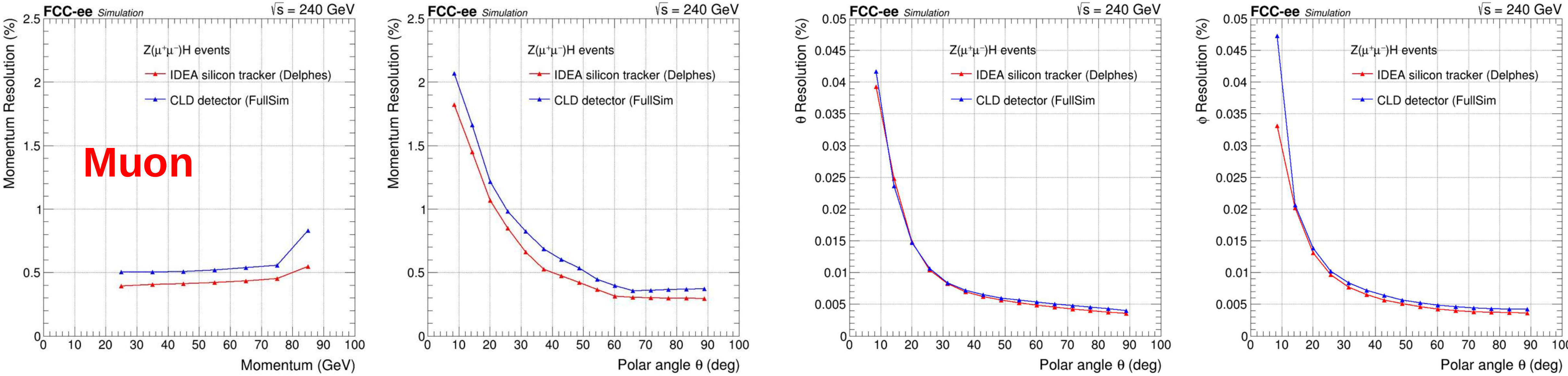
	Combined
Nominal	3.07 (3.97)
Ideal resolution	2.42 (3.40)
Magnetic Field 3T	2.54 (3.52)
CLD 2T (silicon tracker)	3.86 (4.55)



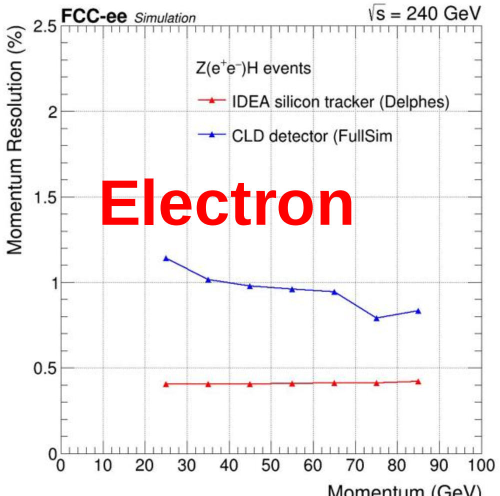


Feedbacks to the Detector Design from Analysis

FullSim: Momentum and Angular resolution



- **Muon resolutions based on Z($\mu\mu$)H events**
  - Slightly worse momentum in FullSim (residual difference in material budget, smearing)
  - Angular resolutions OK



Electron resolutions based on Z(ee)H events

- Visibly worse momentum in FullSim
- No Bremsstrahlung recovery in CLD reconstruction
  - Some work already done
  - Emmanuel/Michele: Detector requirements for ECAL (Link)
  - BNL attempt for MVA-based brem recovery (Link)

Higgs mass with Full Sim (Muon)

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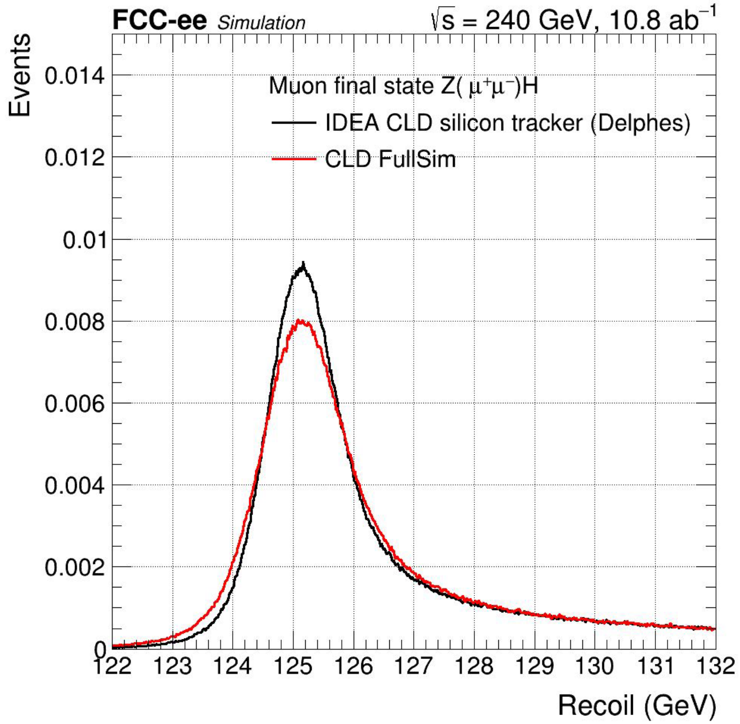
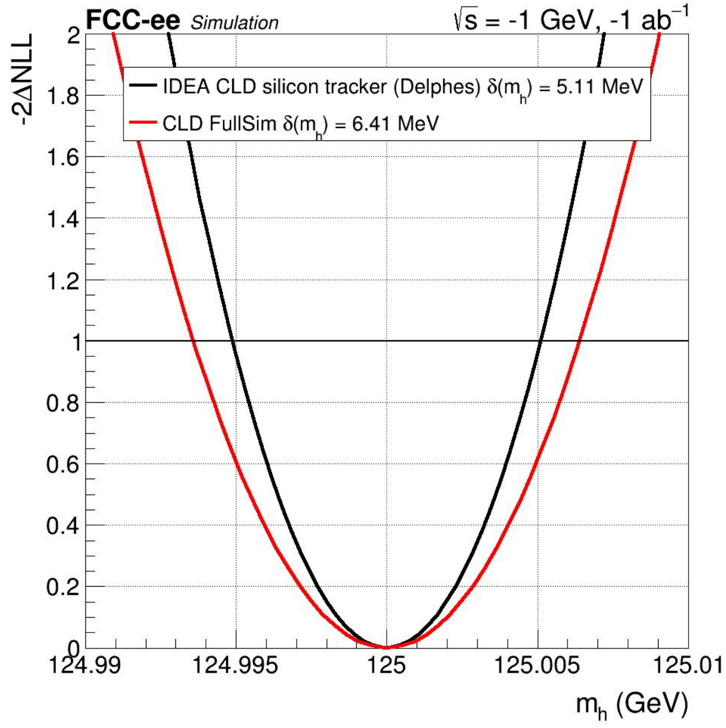
- **FullSim recoil distribution slightly worse than Delphes**
- **Repeat the fit producer as for the Delphes analysis**
  - Fit recoil distributions with Crystal Ball and Gauss
  - Statistical-only fit, no systematics

	Uncertainty
Delphes	5.11 MeV
FullSim	6.41 MeV

- **FullSim is 25% worse than Delphes**





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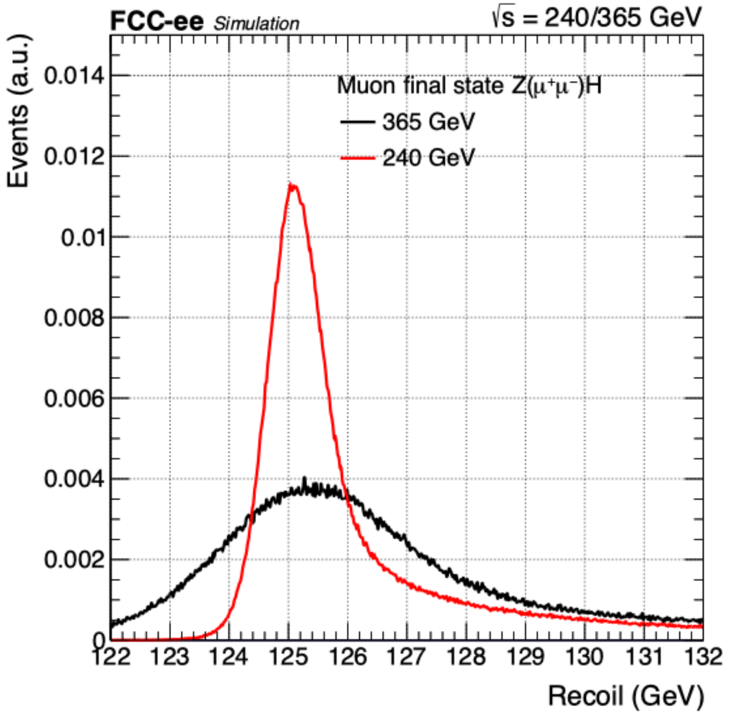
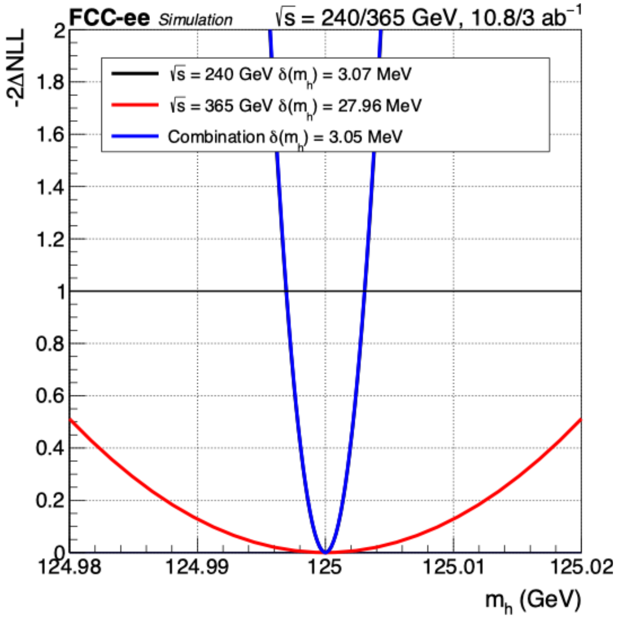
Higgs mass at 365 GeV

- **At $\sqrt{s} = 365$ GeV**
  - Reduced statistics
  - Broadened recoil distribution
  - 365 GeV only: 27.96(28.79) MeV uncertainty on Higgs mass on Electron (Muon) channel
  - Combined with 240 GeV brings it down from **3.07** MeV **3.05** MeV (Stat-Only) **~1%** improvement





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Total ZH production cross-section

Measure the ZH cross-section in a Model-Independent way

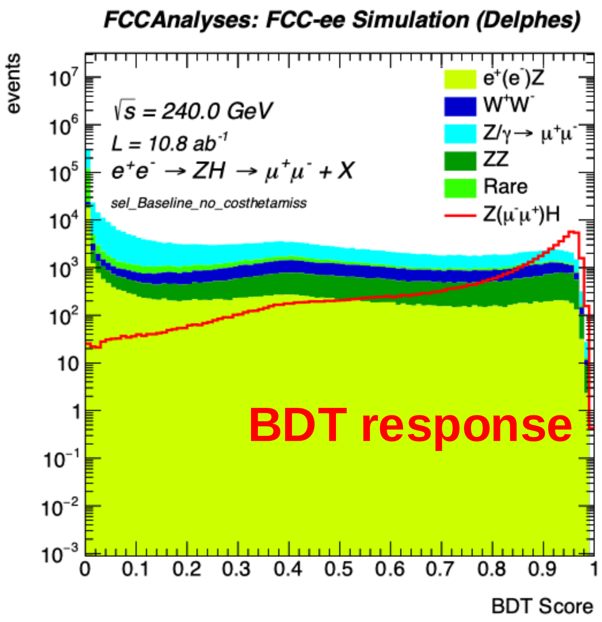
- Unique to electron-positron colliders because of known initial state
- Challenge to ensure model-independent
- Once know, determine couplings to $H \to XX$ in a model independent way

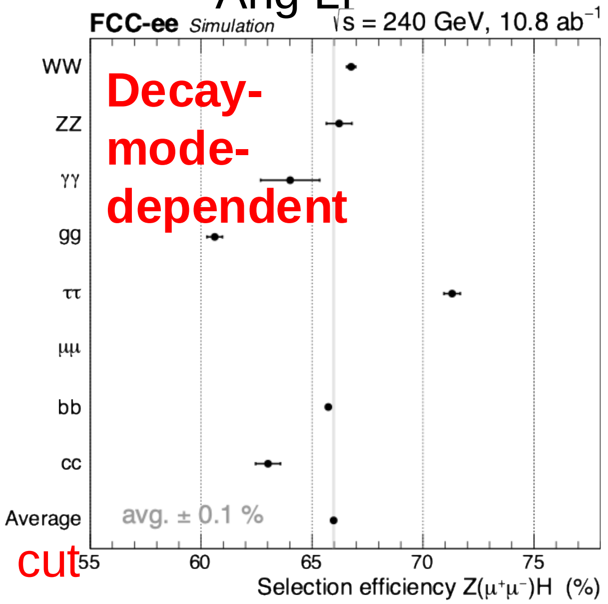
$$\sigma_{ZH} \times Br(H \to X\bar{X}) \propto \frac{g_{HZZ}^2 \times g_{HXX}^2}{\Gamma_H}$$

At FCC-ee ZH cross-section is expected to ~0.5 % accuracy

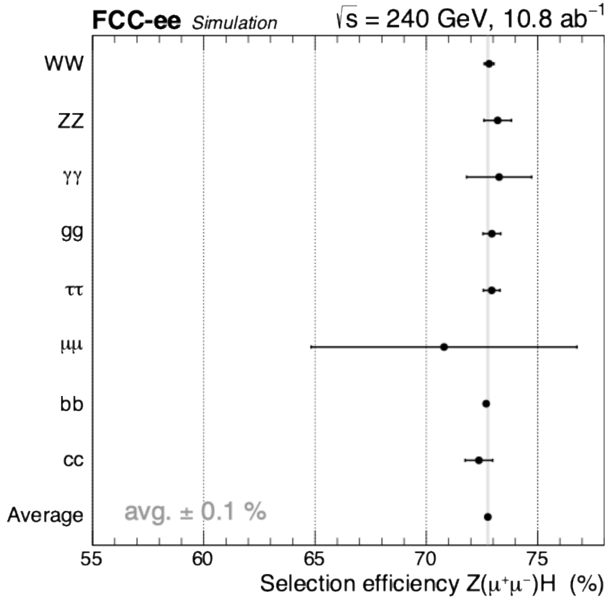
- $e^+e^- \to ZH \to l^+l^- + XX, (Z \to \mu^+\mu^-, e^+e^-)$

- Remove Decay-Mode dependent event selection → $\cos\theta_{miss}$
- Introduce BDT approach to keep decay-mode independency
- Fit BDT distribution





Remove $\cos\theta_{miss}$ cut



Total ZH production cross-section

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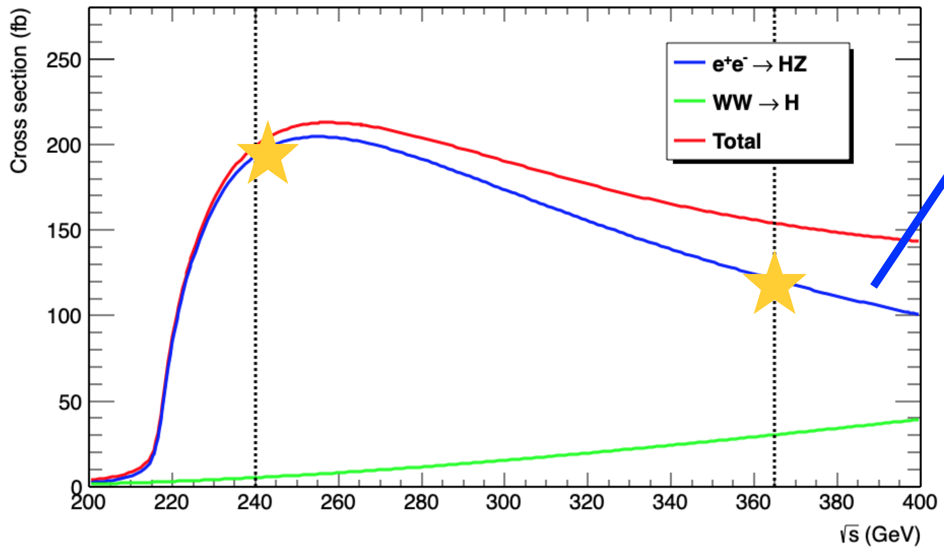
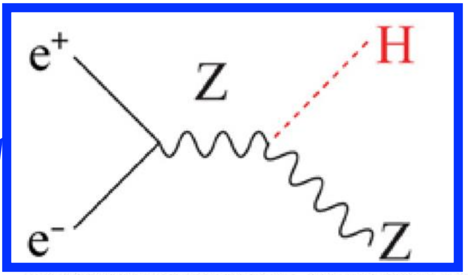
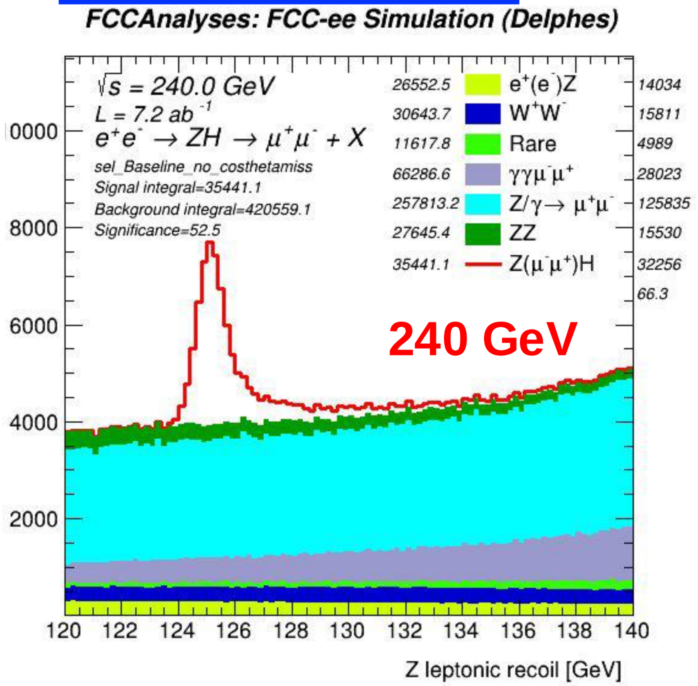
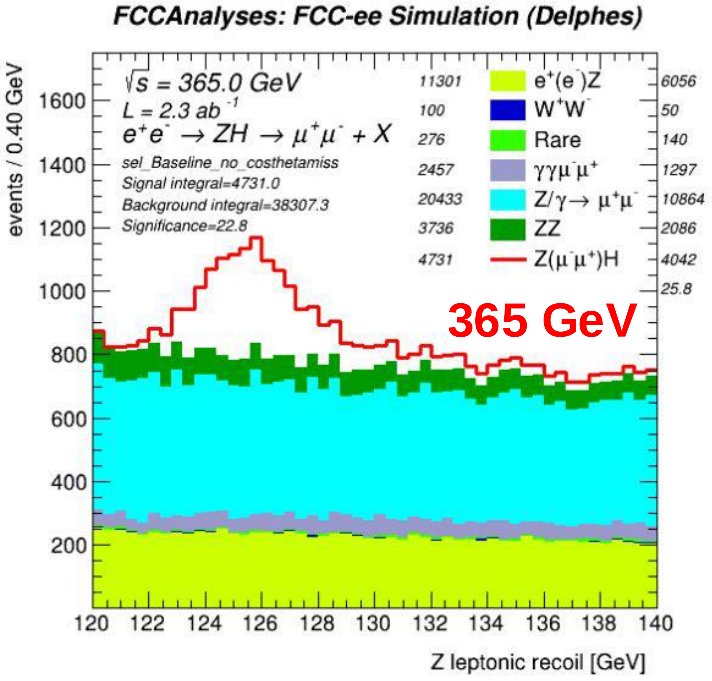
240 GeV 365 GeV









365 GeV has

- Worse resolution
- But Negligible WW background

ZH cross-section @$\sqrt{s} = 240$ GeV

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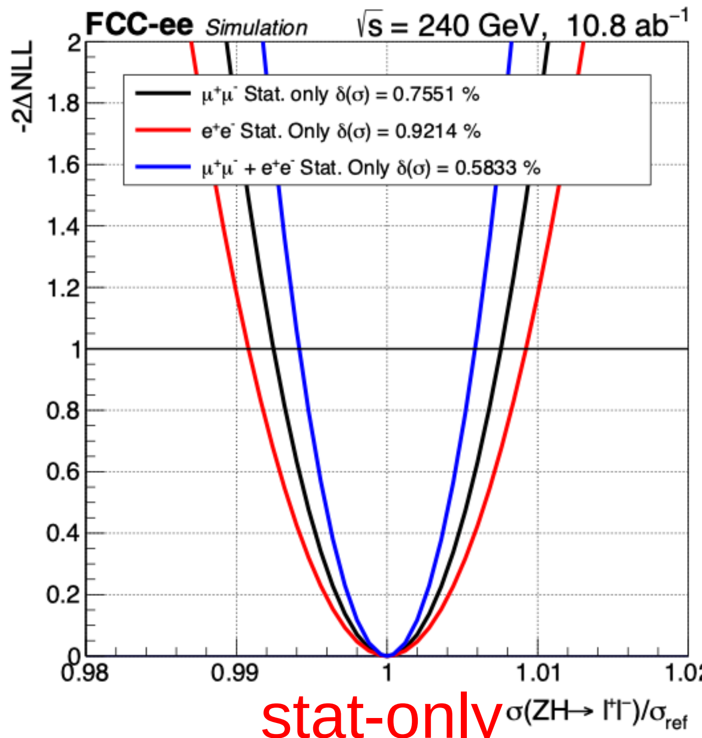
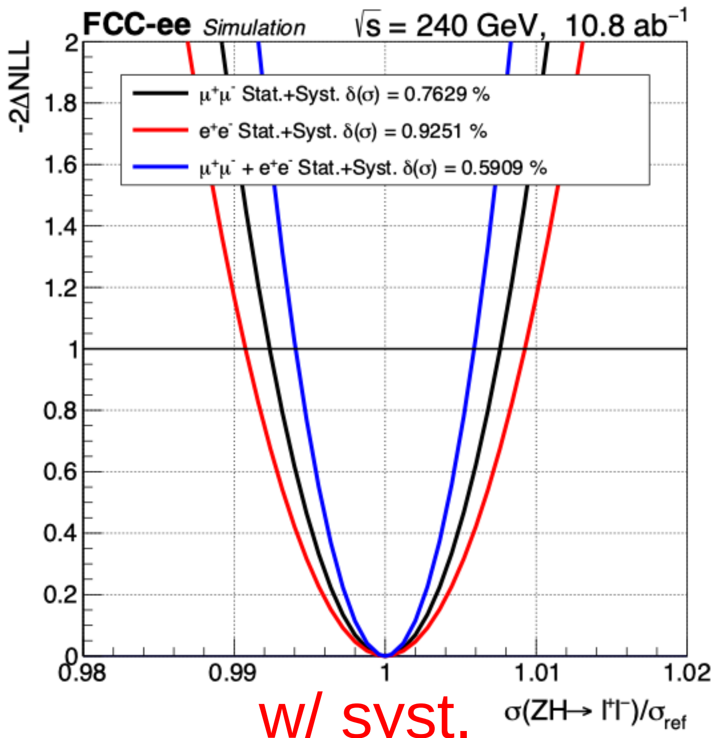
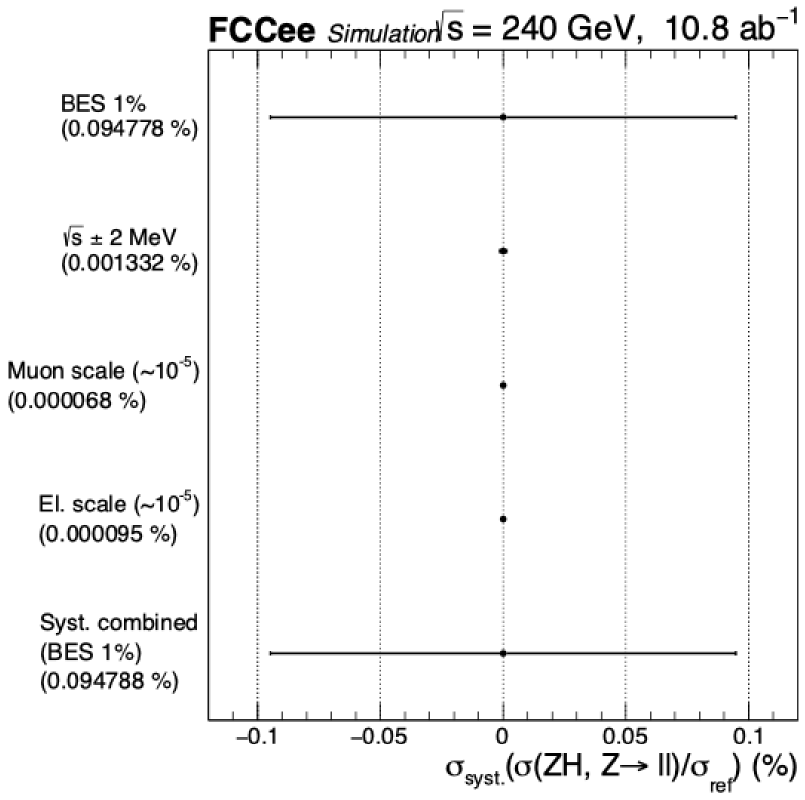


stat-only



w/ syst.



- **Likelihood scan to extract ZH cross−section uncertainty**
  - Muon channel 0.76%
  - Electron channel 0.92%
- **Combined uncertainty 0.58% (stat. only)**
  - Sensitivity driven by muon channel; electrons gain ~ 24%
- **Systematics are negligible (0.58%→0.59%)**
  - Leading Systematic is BES

ZH cross-section @$\sqrt{s} = 365$ GeV

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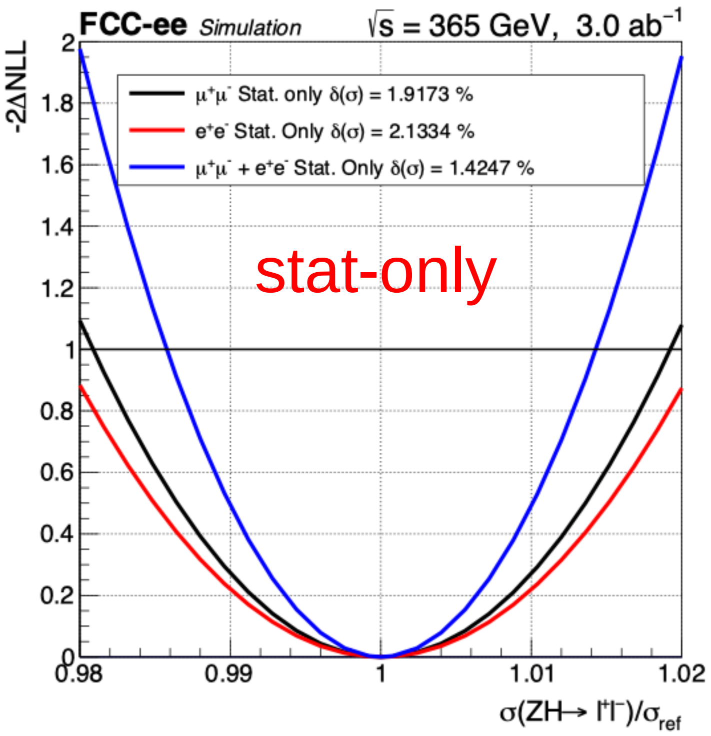

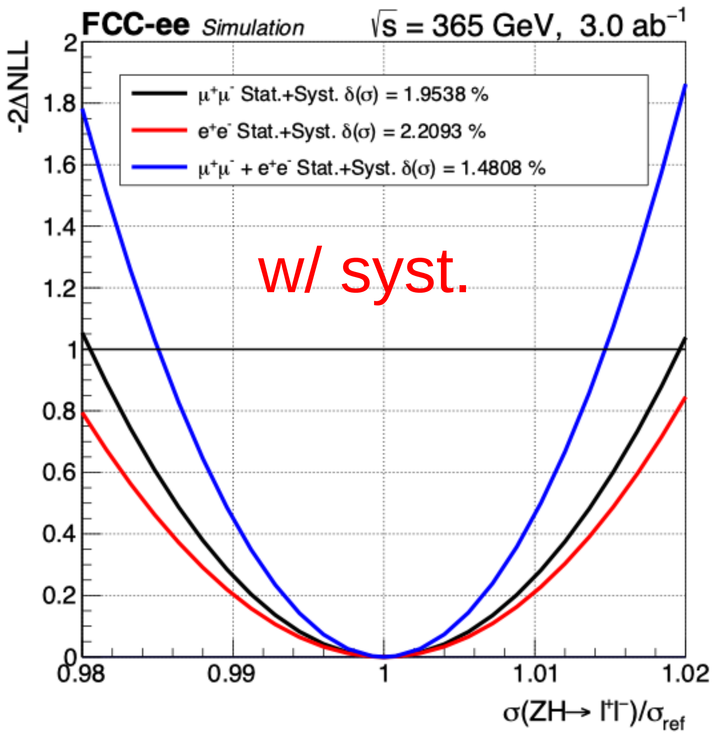

$\delta\sigma_{ZH}/\sigma_{ZH}$	stat-only	w/ syst.
$\sqrt{s} = 240$ GeV, $10.8\ ab^{-1}$	0.58%	0.59%
$\sqrt{s} = 365$ GeV, $3.0\ ab^{-1}$	1.42%	1.48%

Higgs CP studies

$\sqrt{s} = 240$ GeV
$L = 7.2\ ab^{-1}$

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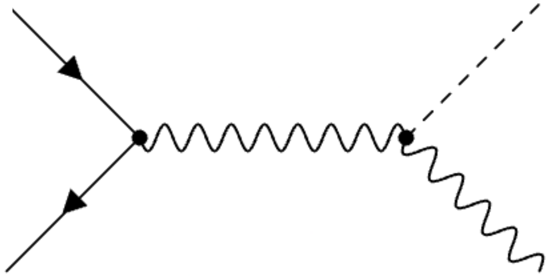
Nicholas Pinto,
Valdis Slokenbergs

Link



- **Include $H \to X$,**
  - $Z \to ee, \mu\mu$
  - $Z \to qq \quad (uu, dd, ss, cc)$ and
  - $Z \to bb$

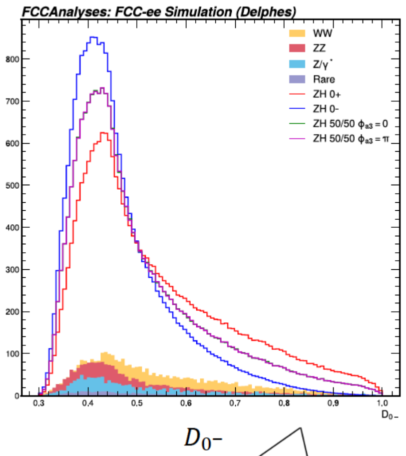
$$f_{CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{\text{CP odd}}}{\Gamma_{H\to X}^{\text{CP odd}} + \Gamma_{H\to X}^{\text{CP even}}}$$

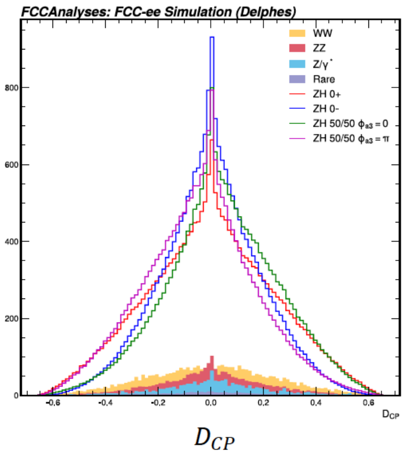
- **Optimal observables in leptonic final state**

$$D_{0^-} = \frac{P(0^-)}{P(0^+)+P(0^-)}$$

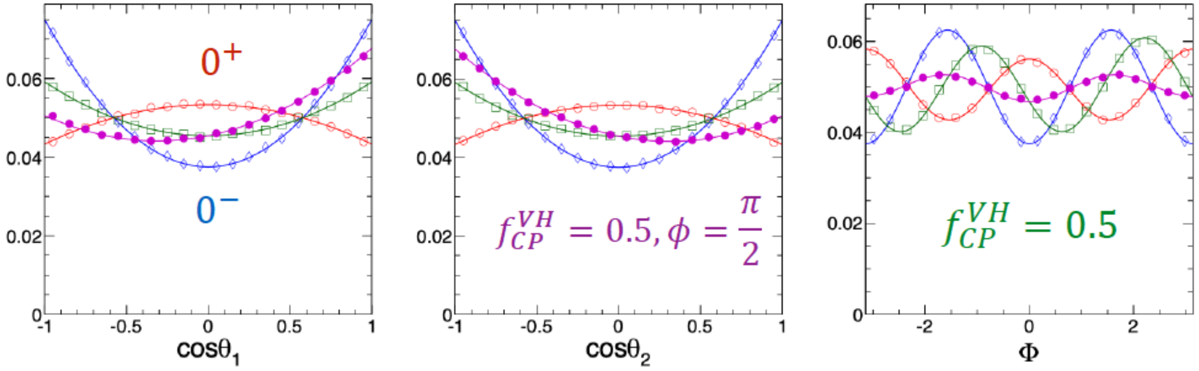
$$D_{CP} = \frac{P(int)}{2\sqrt{P(0^+)*P(0^-)}}$$

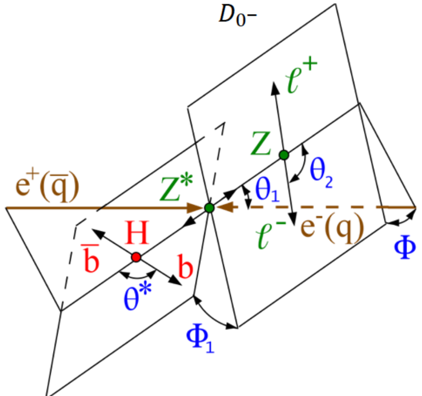
  - D_{0^-} : Separate CP-even distribution from CP-odd.
  - D_{CP} : Separate two equal mixtures of CP-even and CP-odd with different phases of the CP-odd coupling.





- **$cos\theta_1, cos\theta_2$ and ϕ in hadronic final states**





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Higgs CP studies

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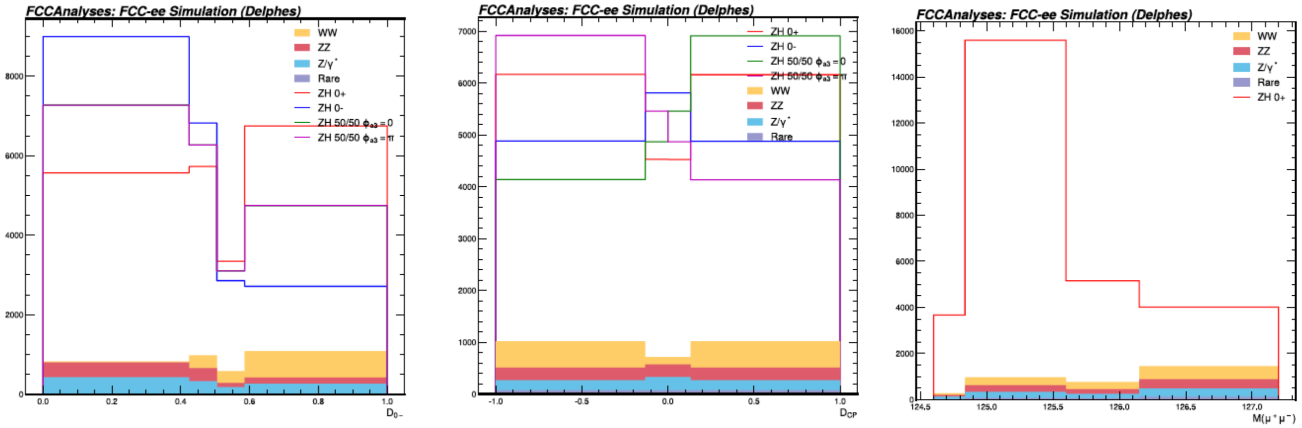
Link

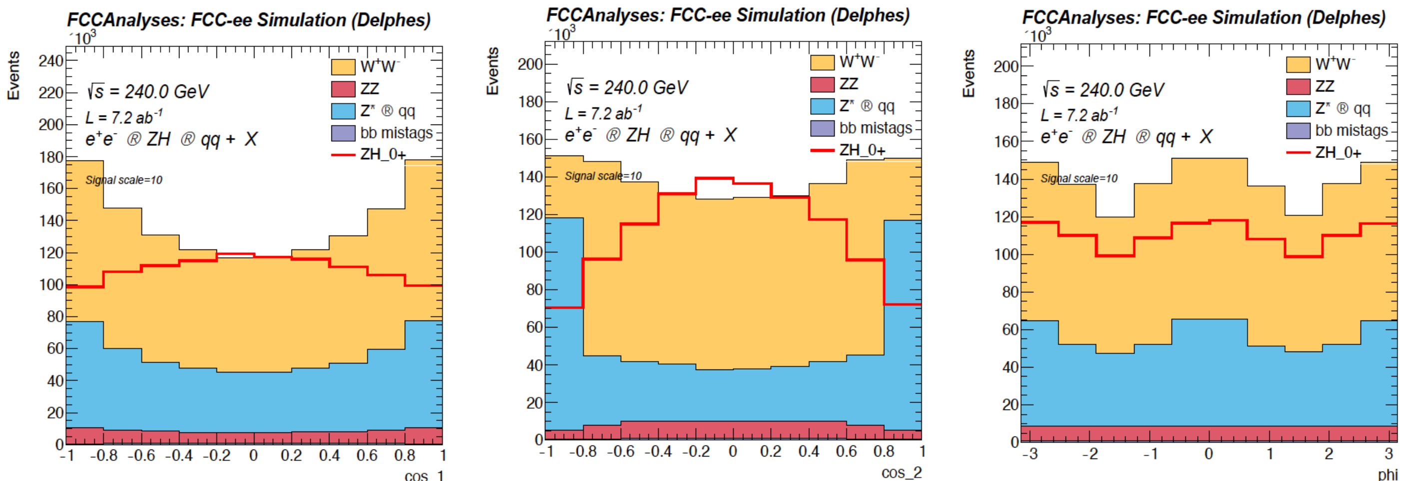
❖ Lepton channel:

Fit on 3D Histogram formed from D_{0^-}, D_{CP} and M_{recoil}



❖ Hadronic channel:

Fit on $\cos\theta_1, cos\theta_2$ and ϕ



Higgs CP studies

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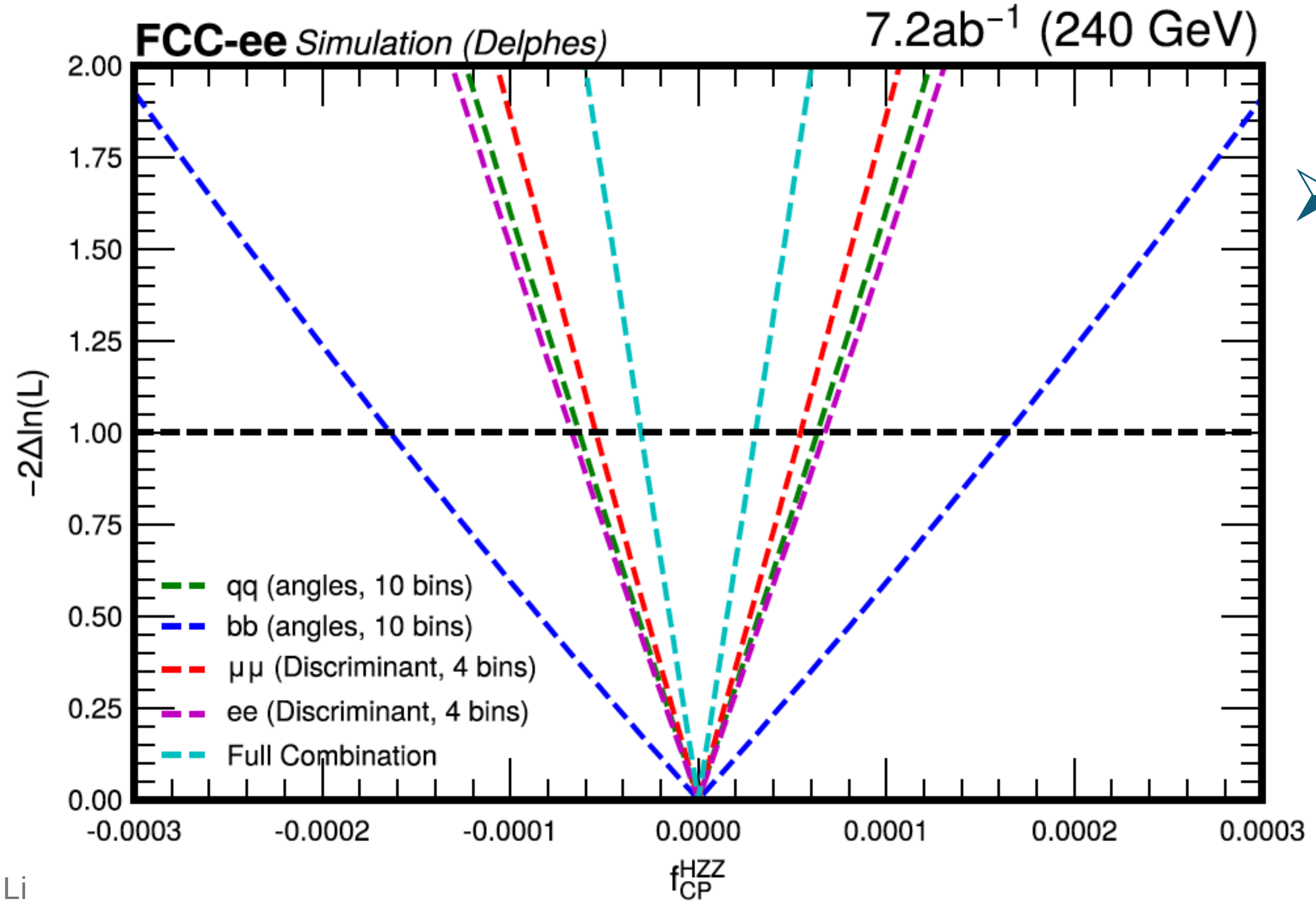
Link

- **Fits with Reconstructed Signal,** $\mathrm{Z} \longrightarrow qq, \;\; bb, \;\; ee, \;\; \mu\mu$:

$$f_{\mathrm{CP}}^{HX} \equiv \frac{\Gamma_{H\to X}^{\mathrm{CP\,odd}}}{\Gamma_{H\to X}^{\mathrm{CP\,odd}} + \Gamma_{H\to X}^{\mathrm{CP\,even}}}$$



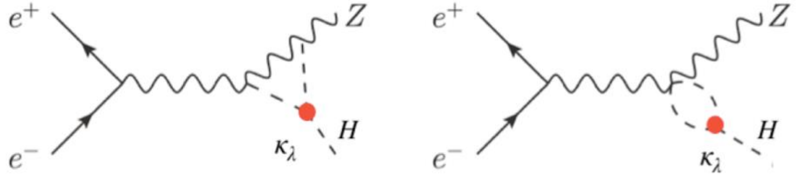
- **f_{CP}^{HZZ} at 68% Confidence Level**
  - $qq \sim \pm 6.3 \times 10^{-5}$
  - $bb \sim \pm 1.6 \times 10^{-5}$
  - $\mu\mu \sim \pm 5.5 \times 10^{-5}$
  - $ee \sim \pm 6.7 \times 10^{-5}$
  - Combined $\sim \pm 3.0 \times 10^{-5}$

- **Combined result represents ~79% of Z decays**

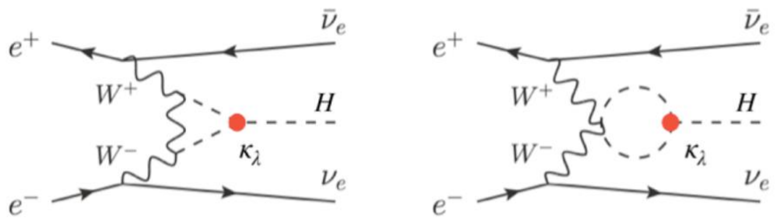
Self-coupling

Probe trilinear Higgs self-coupling λ_3 (λ_{HHH}) through single Higgs boson cross section

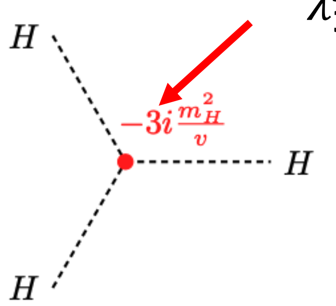
- Higgs-strahlung: $e^+e^- \to ZH$



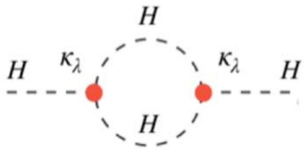
- WW-fusion: $e^+e^- \to \nu\bar{\nu}_e H$



$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{SM}}$



- Higgs self-energy



$$\Sigma_{NLO} = Z_H \Sigma_{LO}(1 + \boldsymbol{\kappa_\lambda} C_1)$$

NLO ZH cross-section **LO ZH cross-section**

Higgs self-coupling can be measured through the NLO variations on the total ZH cross-section thanks to sufficient statistics

Self-coupling

Elizabeth Brost,
Robert Szafron,
Abraham Tishelman-Charny
DOI 10.17181/gtesb-a8354

- 2409.11466 shows how to rewrite κ_λ in terms of C_ϕ:
  A dim-6 operator which affects the Higgs self-coupling vertex

- Using κ_λ parameterization equation derived in JHEP02 (2018) 178, but replacing κ_λ with SMEFT definition:

$$\kappa_\lambda \longrightarrow 1 - \frac{2v^4}{m_H^2\Lambda^2}C_\phi = 1 - 0.47\,C_\phi\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- Assuming a scale of Λ = 1 TeV, can approximate to:

$$\kappa_\lambda \longrightarrow 1 - 0.47\,C_\phi$$

Self-coupling

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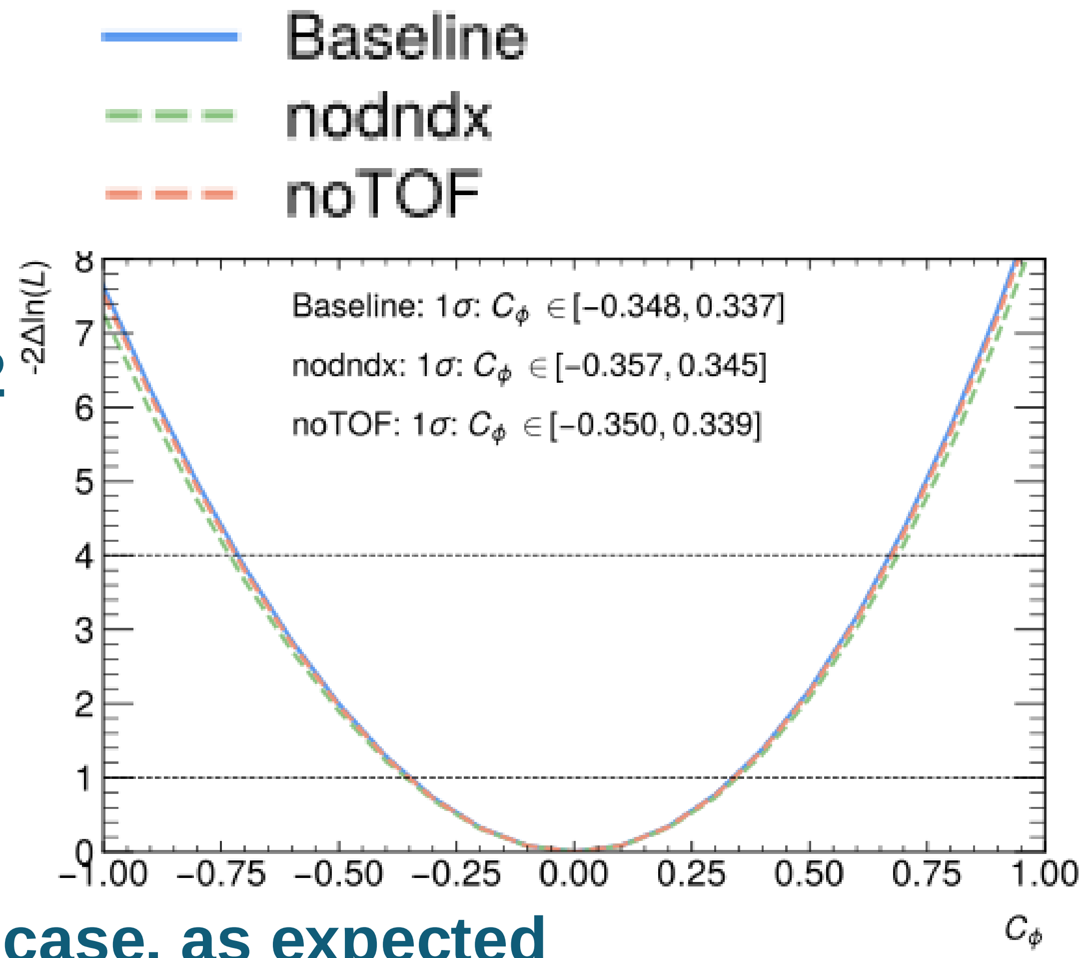
- **Fully-hadronic ZH analysis**

- **Vary C_ϕ from -1 to 1 (valid range without including higher-order contributions)**

- **Do this for baseline IDEA (Delphes) and 2 detector variations:**
  Nodndx: No cluster counting information
  noTOF: No time-of-flight information

- **Centered at $C_\phi = 0$ ($\kappa_\lambda = 1$)**
  Makes sense as this is the SM value

- **Slightly less sensitivity from the Nodndx case, as expected**

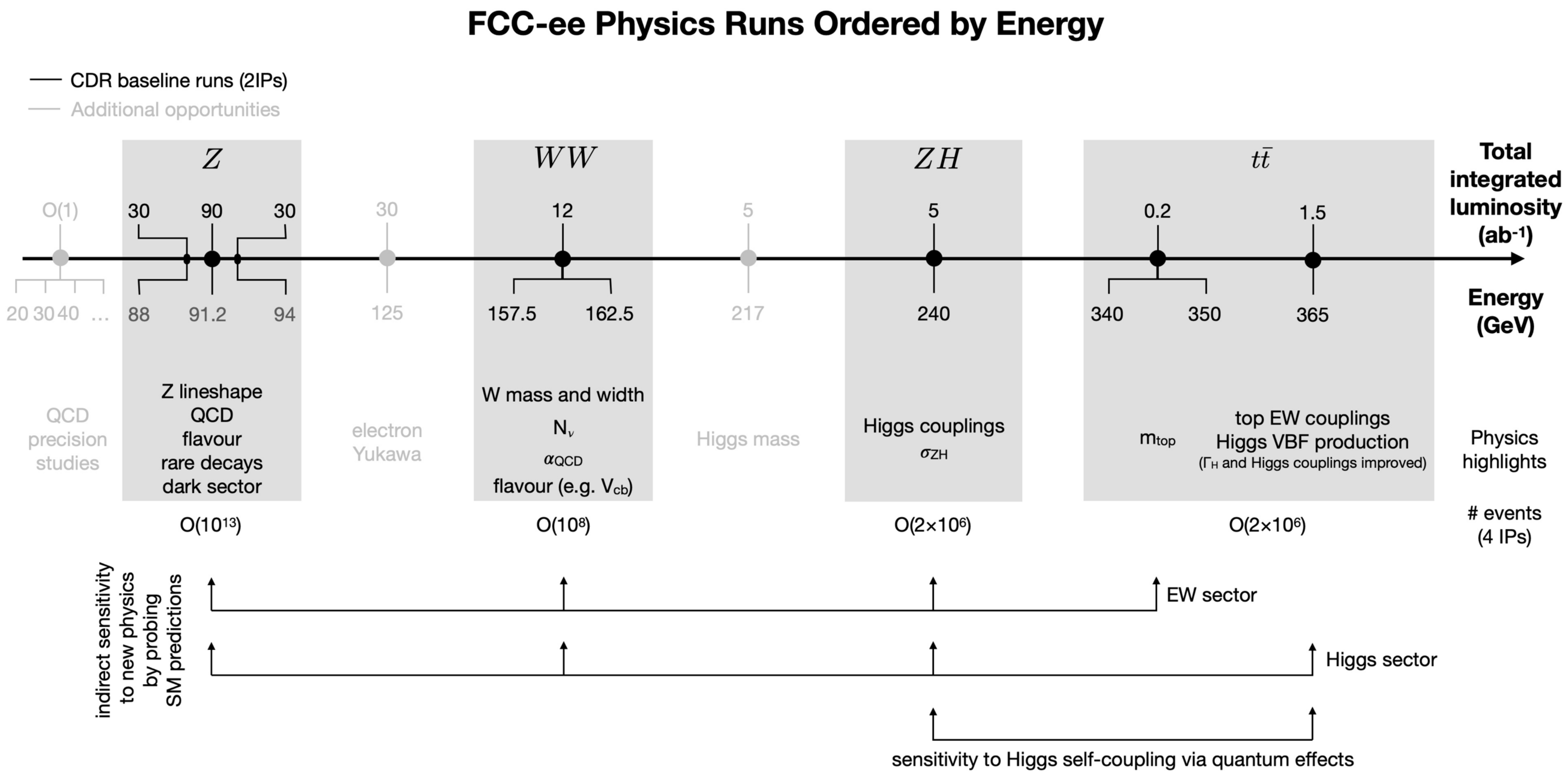


Summary

- **Higgs mass**
  - At 240 GeV, Higgs mass uncertainty reach 3.07 (3.97) MeV
  - Including 365 GeV, Higgs mass uncertainty improved ~ 1%
  - For FullSim, in the muon channel, reached 6.41 MeV uncertainty, 25% worse than Delphes-based analysis (5.11 MeV)
- **ZH cross section**
  - ZH cross-section reach ~0.59% (at 240 GeV), ~1.48% (at 365 GeV)
- **CP**
  - Combined $f_{CP}^{HZZ} \sim \pm 3 \times 10^{-5}$
  - Combined result represents ~79% of Z decays
- **Self-coupling**
  - Cross-section in terms of SMEFT parameter C_ϕ
  - Constraint on $C_\phi \in [-0.348, 0.337]$

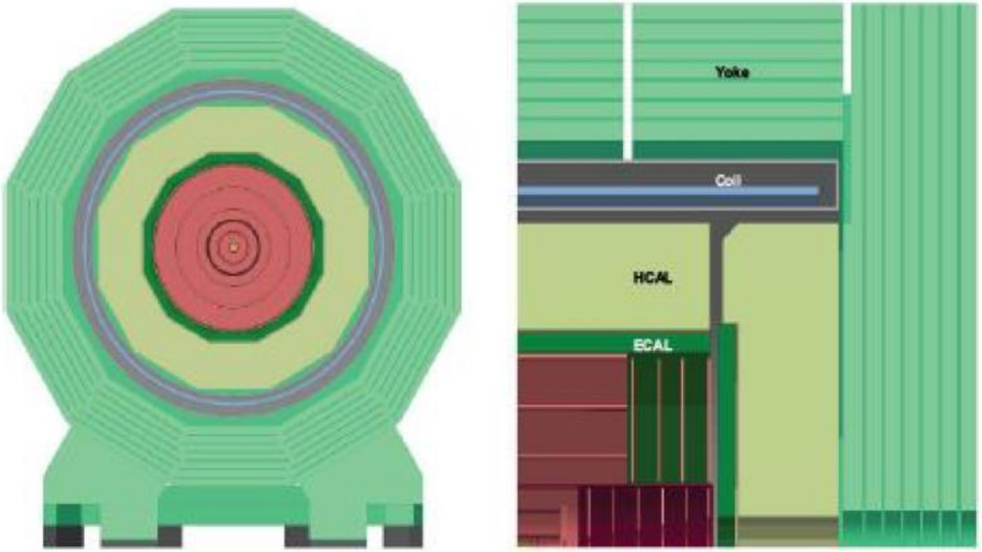
Backup

FCC-ee


FCC-ee Physics Runs Ordered by Energy
CDR baseline runs (2IPs)
Additional opportunities
Z
WW
ZH
tt̄
Total integrated luminosity (ab-1)
O(1)
30
90
30
30
12
5
5
0.2
1.5
20 30 40 …
88
91.2
94
125
157.5
162.5
217
240
340
350
365
Energy (GeV)
QCD precision studies
Z lineshape
QCD
flavour
rare decays
dark sector
electron Yukawa
W mass and width
Nν
αQCD
flavour (e.g. Vcb)
Higgs mass
Higgs couplings
σZH
mtop
top EW couplings
Higgs VBF production
(ΓH and Higgs couplings improved)
Physics highlights
O(1013)
O(108)
O(2×106)
O(2×106)
# events (4 IPs)
indirect sensitivity to new physics by probing SM predictions
EW sector
Higgs sector
sensitivity to Higgs self-coupling via quantum effects

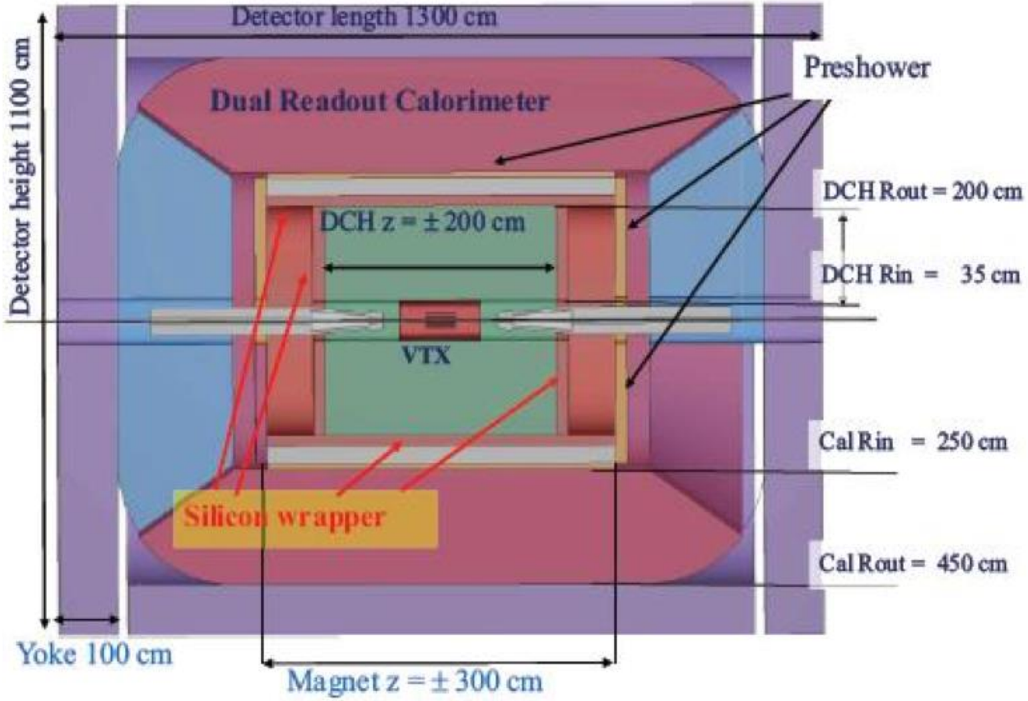
Detectors

CLD



- conceptually extended from the CLIC detector design
  - full silicon tracker
  - 2T magnetic field
  - high granular silicon-tungsten ECAL
  - high granular scintillator-steel HCAL
  - instrumented steel-yoke with RPC for muon detection

IDEA



- explicitly designed for FCC-ee/CepC
  - silicon vertex
  - low X_0 drift chamber
  - drift-chamber silicon wrapper
  - MPGD/magnet coil/lead preshower
  - dual-readout calorimeter: lead-scintillating/cerenkhov fibers
- µRwell for muon detection

Higgs mass

Some extended studies performed regarding detector effects

Nominal configuration → Nominal

Crystal ECAL to Dual Readout → Degradation electron resolution

Nominal 2 T → field 3 T → Magnetic field 3T

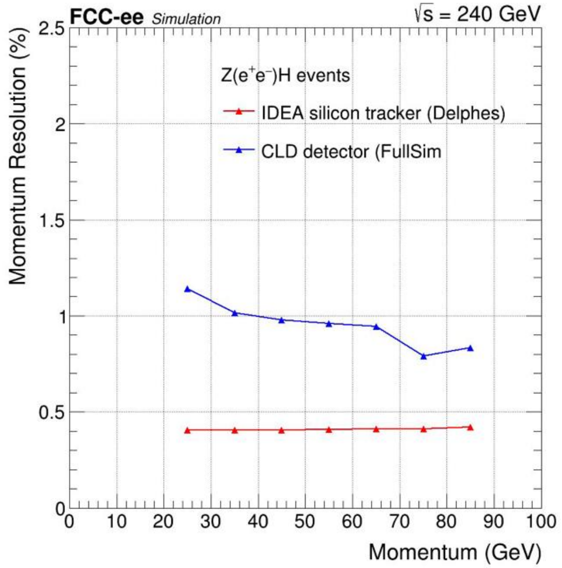
IDEA drift chamber → CLD Si tracker → Silicon tracker

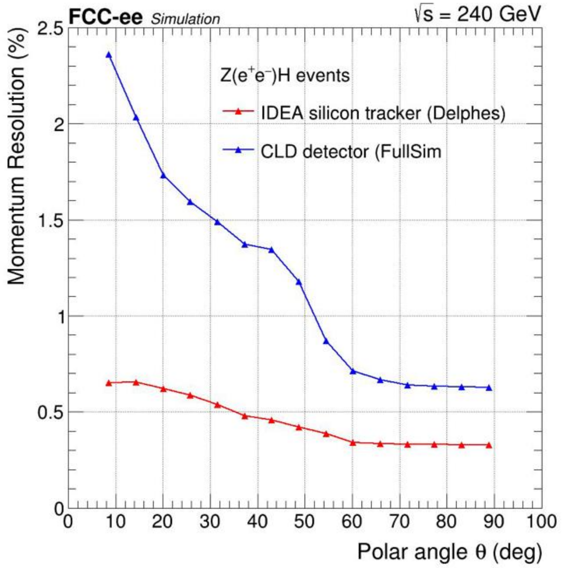
Impact of Beam Energy Spread → BES 6% uncertainty, Disable BES

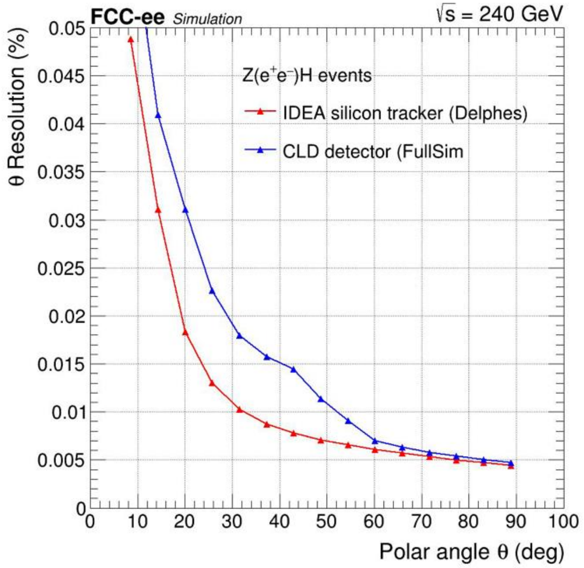
Perfect (=gen-level) momentum resolution → Ideal resolution

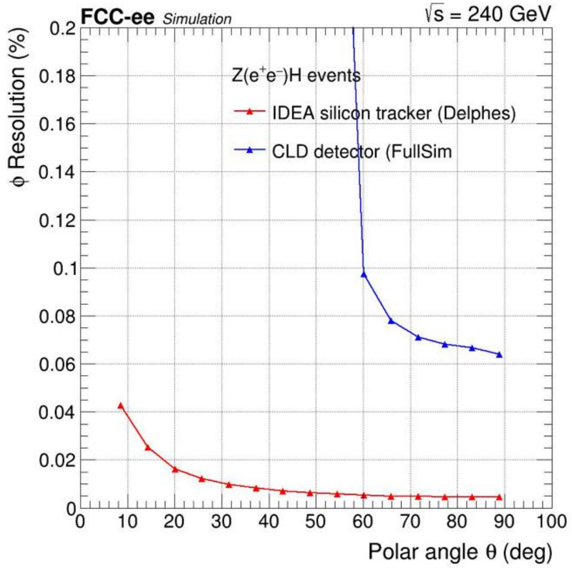
Final state	Muon	Electron	Combination
Nominal	3.92(4.74)	4.95(5.68)	3.07(3.97)
Inclusive	3.92(4.74)	4.95(5.68)	3.10(3.97)
Degradation electron resolution	3.92(4.74)	5.79(6.33)	3.24(4.12)
Magnetic field 3T	3.22(4.14)	4.11(4.83)	2.54(3.52)
Silicon tracker	5.11(5.73)	5.89(6.42)	3.86(4.55)
BES 6% uncertainty	3.92(4.79)	4.95(5.92)	3.07(3.98)
Disable BES	2.11(3.31)	2.93(3.88)	1.71(2.92)
Ideal resolution	3.12(3.95)	3.58(4.52)	2.42(3.40)
Freeze backgrounds	3.91(4.74)	4.95(5.67)	3.07(3.96)
Remove backgrounds	3.08(4.13)	3.51(4.58)	2.31(3.45)

Momentum and Angular resolution









Electron resolutions based on Z(ee)H events
- Visibly worse momentum in FullSim
- No Bremsstrahlung recovery in CLD reconstruction