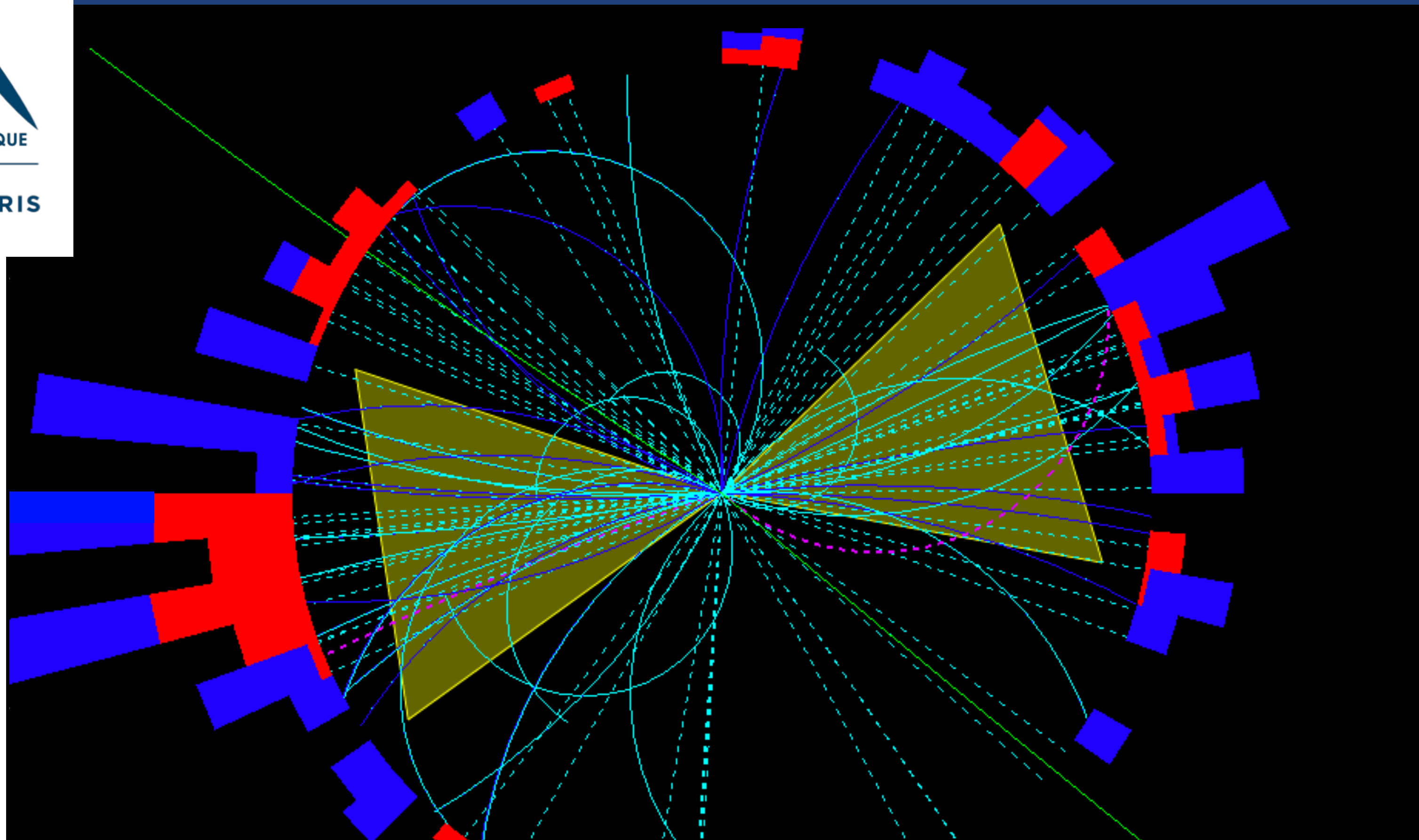


Precision measurements of the Higgs Boson properties and trilinear self-coupling at the FCC-ee

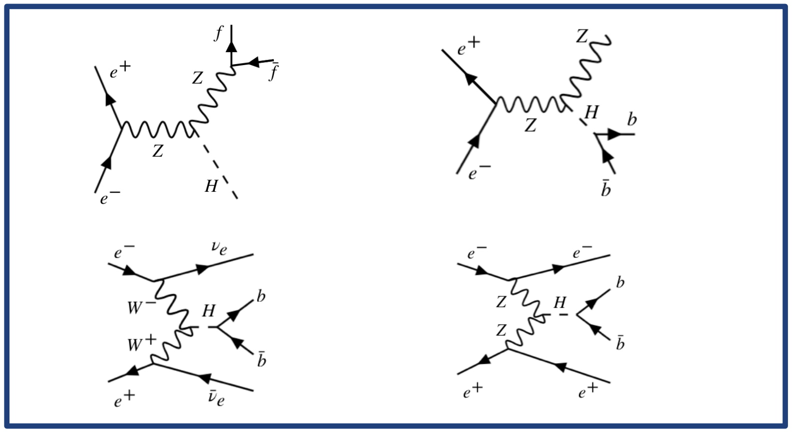
Cesare Cazzaniga and Roberto Salerno

MC SIMULATIONS AND ANALYSES

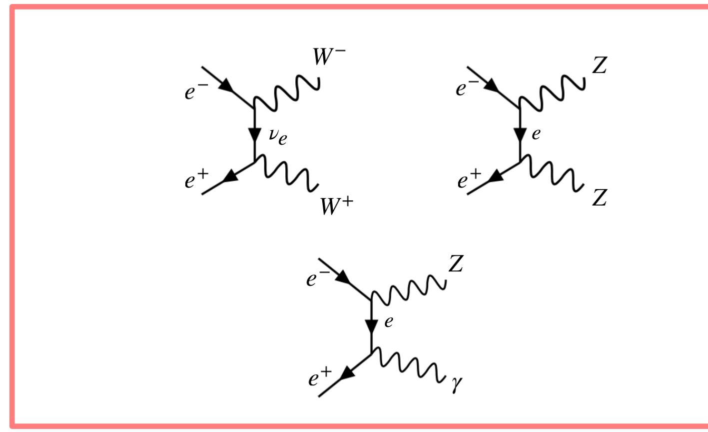
Event generation: MadGraph5_aMC@NLO + pythia

Fast simulations: Delphes / IDEA detector

Two energy points (2 IPs): 240 GeV ($5\ \text{ab}^{-1}$) / 365 GeV ($1.5\ \text{ab}^{-1}$)



Signal: ZH (recoil and decay), VBF (WW, ZZ)



Backgrounds considered: WW, ZZ, Z/γ

Measurements: Higgs Boson mass, signal strengths, HWW/HZZ couplings and κ_λ

Use of 6 orthogonal analyses: inclusive in ZH, ZH with $H \to b\bar{b}$, and VBF with $H \to b\bar{b}$

SELECTIONS - SUMMARY

Inclusive analyses	Individual decays
$Z \to \mu^+\mu^-$ (240/365 GeV) • $\mu^+\mu^-$ with $p_{T\mu1} > 20$ GeV, $p_{T\mu2} > 5$ GeV • Minimum $\lvert M_{\mu^+\mu^-} - M_Z \rvert$ • $80 < M_{\mu^+\mu^-} < 100$ GeV • $120/110 < M_{rec} < 150$ GeV	$Z \to e^+e^-$ $H \to b\bar{b}$ (240 GeV) • e^+e^- with $p_{Te1} > 10$ GeV, $p_{Te2} > 5$ GeV • Minimum $\lvert M_{e^+e^-} - M_Z \rvert$ • ≥ 2 b-jets • $110 < M_{rec} < 150$ GeV
$Z \to e^+e^-$ (240 GeV) • e^+e^- with $p_{Te1} > 10$ GeV, $p_{Te2} > 5$ GeV • Minimum $\lvert M_{e^+e^-} - M_Z \rvert$ • $60 < M_{e^+e^-} < 120$ GeV • $110 < M_{rec} < 150$ GeV	VBF : WW fusion (365 GeV) • ≥ 2 b-jets + $\lvert \Delta\eta_{jj} \rvert < 3$ • $H_T > 10$ GeV • MET > 10 GeV • BDT (17 variables): M_{jj}, n_j, acol$_{jj}$, E_j, p_{Tj}, p_{Tjj}, H_T, MET, η_j,...
$Z \to b\bar{b}$ (240 GeV) • ≥ 2 b-jets + $p_{Tjj} > 60$ GeV • $M_{jj} > 45$ GeV • $H_T > 10$ GeV • BDT (17 variables): n_j, $acol_{jj}$, n_{bj}, E_j, η_j, H_T, MET, M_{jj},...	VBF : ZZ fusion (365 GeV) • ≥ 2 b-jets + $p_{Te1} > 15$ GeV, $p_{Te2} > 5$ GeV • $M_{e^+e^-} > 80$ GeV • BDT (25 variables): $M_{e^+e^-}$, acol$_{e^+e^-}$, acol$_{jj}$, n_{bj}, M_{jj}, η_e, E_j, η_j,...

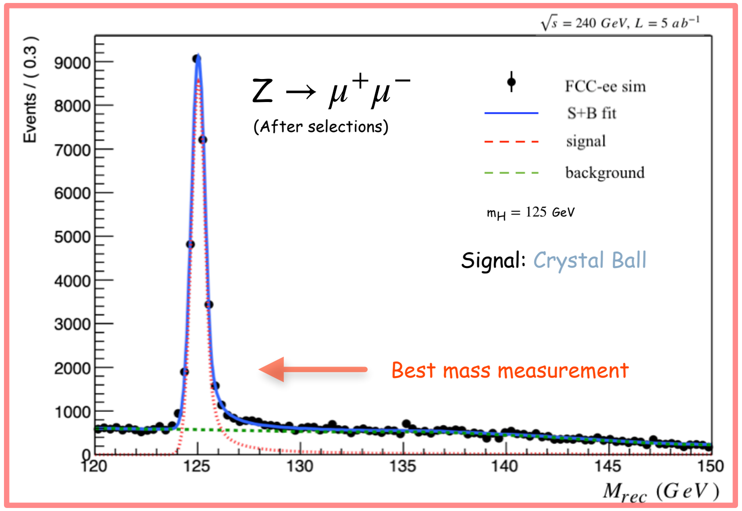
Orthogonal set/s

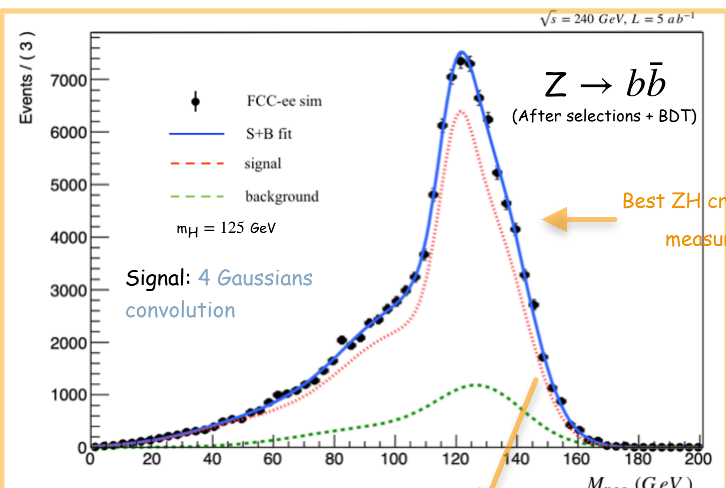
$\sqrt{s}$ (GeV)	Production	Z decay	H Decay
240	ZH	$\mu^+\mu^-$	-
240	ZH	$b\bar{b}$	-
240	ZH	e^+e^-	$b\bar{b}$
365	ZH	$\mu^+\mu^-$	-
365	WWF	-	$b\bar{b}$
365	ZZF	-	$b\bar{b}$

⟷ recoil: $Z \to e^+e^-$ (240 GeV)

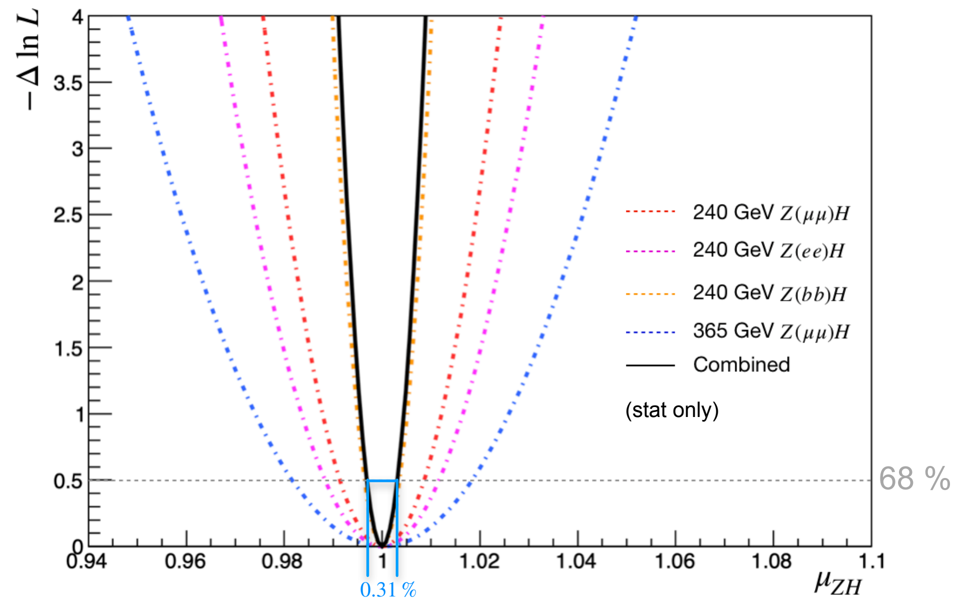
HIGGS BOSON MASS AND μ_{ZH} SIGNAL STRENGTH

Fits to the inclusive M_{rec} spectrum: extract m_H and μ_{ZH} signal strength (model independent)





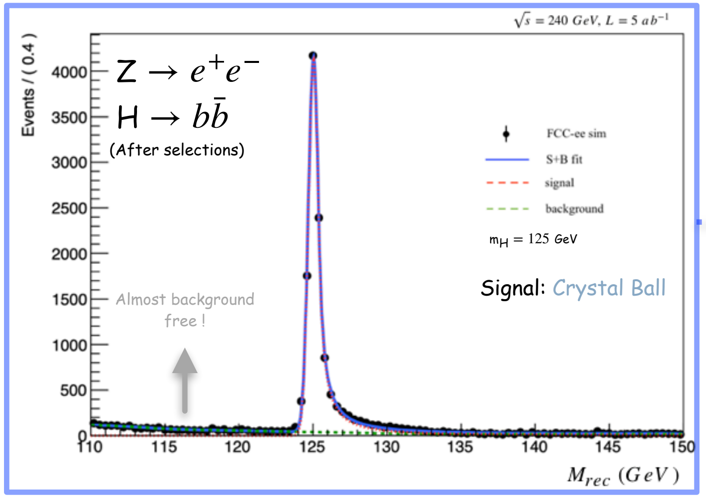
Jet energy resolution and detector smearing spoils mass measurement

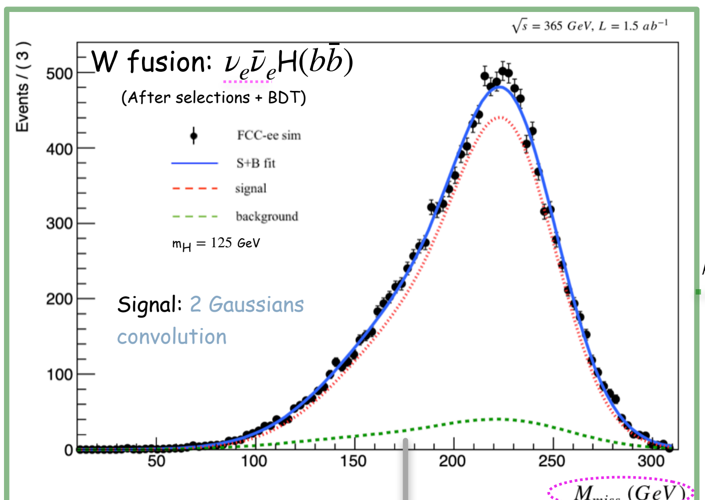


Z decay mode	$\sqrt{s}$ (GeV)	δm_H^{rec} (MeV)	$\delta\mu_{ZH}$ %
$\mu^+\mu^-$	240	3	0.86
$\mu^+\mu^-$	365	-	1.84
e^+e^-	240	4.2	1.1
$b\bar{b}$	240	-	0.36
combination		2.4	0.31

INDIVIDUAL DECAY MODES

Study of the individual decay modes: disentangle production and decay signal strengths



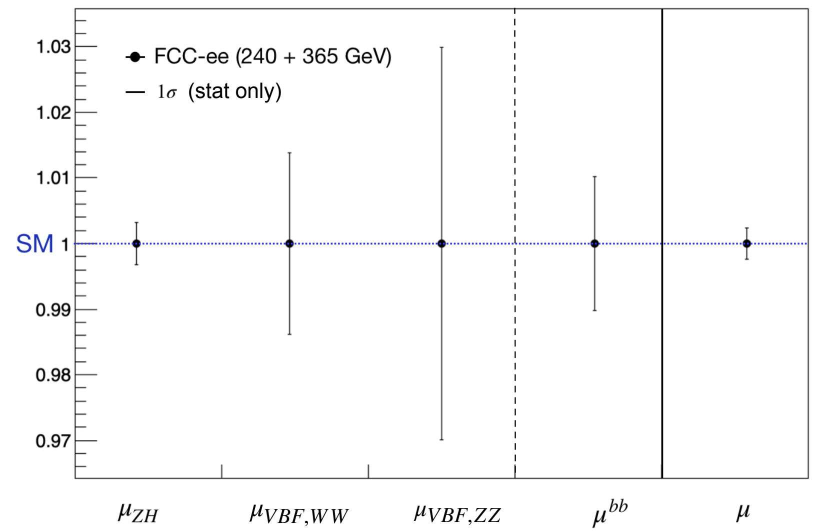


Irreducible background from $Z(\nu\bar{\nu})H(b\bar{b})$

$\mu_{ZH} \times \mu^{bb}$

$\mu_{VBF,WW} \times \mu^{bb}$

$+M_{rec}$

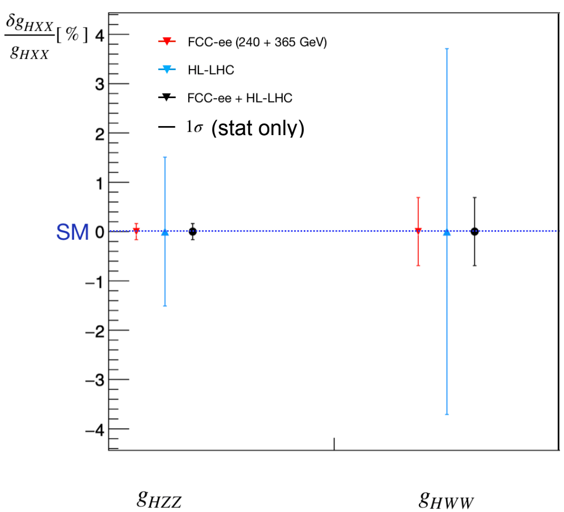


Property	Estimated precision
μ_{ZH}	0.33%
$\mu_{VBF,WW}$	1.4%
$\mu_{VBF,ZZ}$	3%
μ^{bb}	1%
μ	0.23%

Much smaller x-section

PRECISION ON ABSOLUTE COUPLINGS TO VECTOR BOSONS

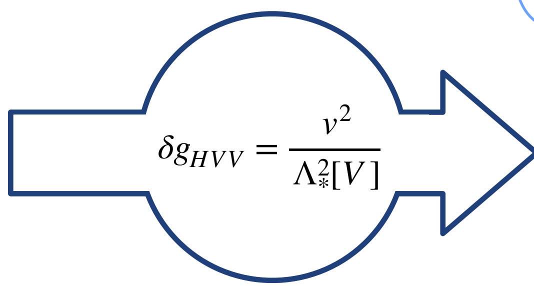
Production signal strengths → sensitivity to the absolute couplings to vector bosons



Collider	⋆HL-LHC	FCC-ee (240 + 365 GeV)	Combined
Lumi (ab^{-1})	3	$5_{240} \oplus 1.5_{365}$	
Years	10	$3_{240} + 4_{365}$	
$\delta g_{HZZ}/(g_{HZZ})_{SM}(\%)$	1.5	0.16	0.16
$\delta g_{HWW}/(g_{HWW})_{SM}(\%)$	3.7	0.69	0.68

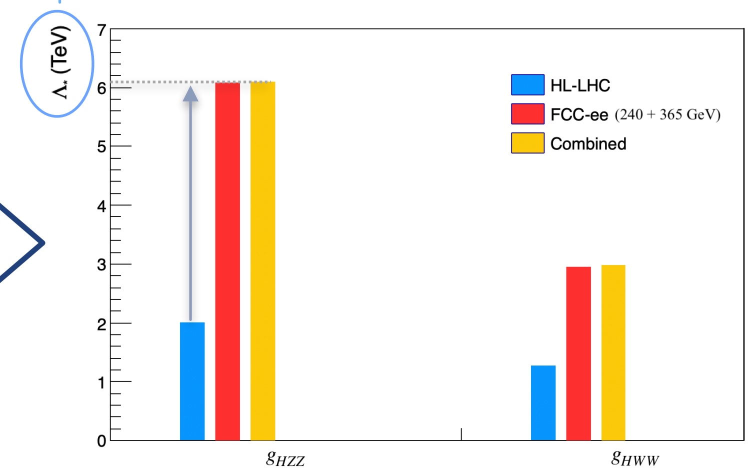
⋆ arXiv:1809.10041
arXiv:1902.00134

Indirect reach of NP scale



arXiv:1403.7191

Effective NP scale Λ_* proportional to Λ_{NP}

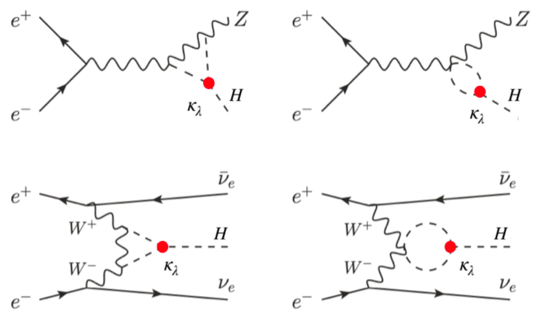


Superior sensitivity to deviations in the Higgs sector → FCC-ee can probe NP up to multi-TeV scale

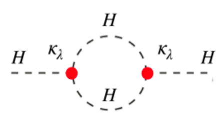
PROBING THE TRILINEAR SELF-COUPLING @ FCC-ee

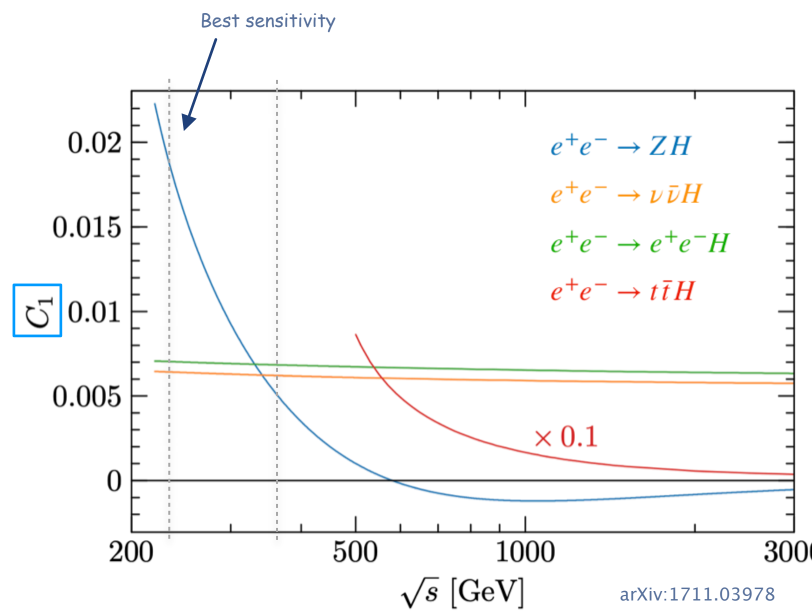
FCC-ee cannot probe directly κ_λ by HH → loop corrections to single Higgs x-sections

Linear vertex corrections



Quadratic corrections
(wave function renormalization)





NLO corrections to the single Higgs production* x-section

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

↳ universal coefficient due to wave function renormalisation

$$Z_H = \frac{1}{1 - \delta Z_H \kappa_\lambda^2}$$ → Expected a degeneracy in the minima

↳ ≈ -0.00154

* No NLO corrections in decay considered here: small, linear and symmetric around SM value in κ_λ for fermions ($C_1(f\bar{f}) = 0$) arXiv:1607.04251

ONE-DIMENSIONAL EFT FIT TO $\delta\kappa_\lambda$

Maximum potential to probe the trilinear self-coupling → 1D fit with only $\delta\kappa_\lambda$ floating

EFT parametrization

$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}} \quad \Rightarrow \quad \delta\kappa_\lambda = \kappa_\lambda - 1$$

arXiv:1711.03978

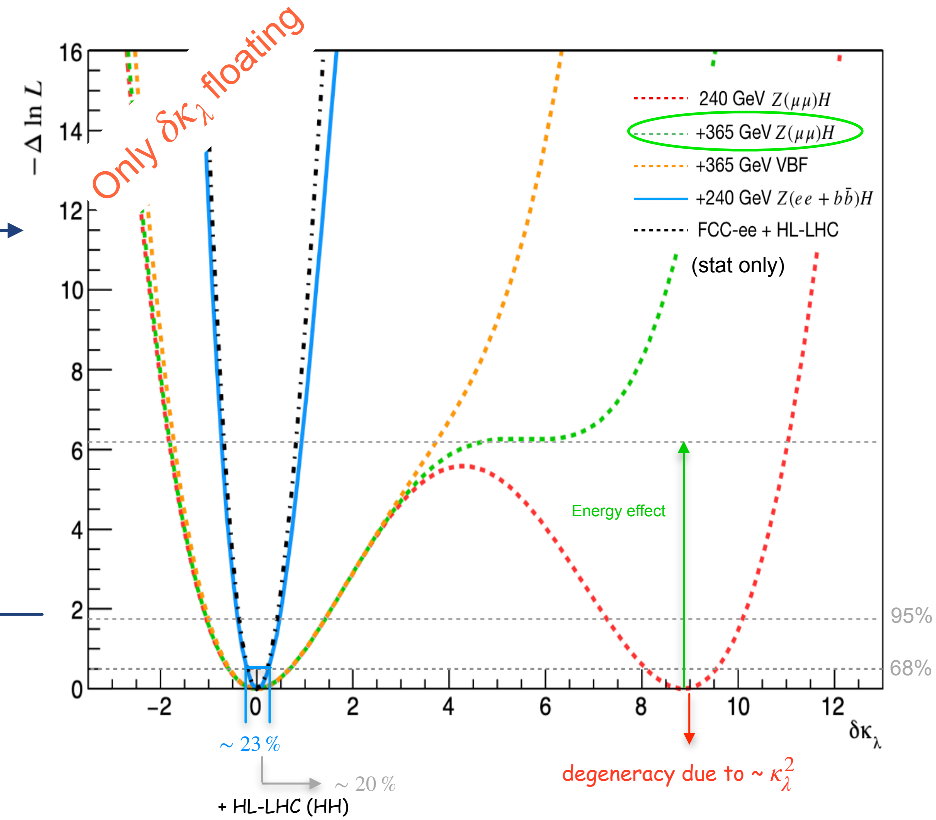
$$V^{dim-6}(\Phi) = V_{SM}(\Phi) + \frac{c_6}{v^2}(\Phi^\dagger\Phi)^3$$

arXiv:1607.04251

Sensitivity to NP scale

$$\delta\kappa_\lambda = \frac{v^4}{\Lambda_*^2 \cdot m_H^2} \rightarrow \Lambda_* \sim 1.1 \text{ TeV}$$

arXiv:1905.07489



Constraint by the FCC-ee on the Higgs trilinear self-coupling of $-0.2 < \delta\kappa_\lambda < 0.25$ @ 68% CL

The secondary minimum excluded at more then 5σ adding different energies and productions

A MORE GLOBAL VIEW ON κ_λ

More "realistic" scenarios → more scale factors κ are left free in the fits

$\sqrt{s}$ (GeV)	Production	Z decay	H Decay	Couplings
240	ZH	$\mu^+\mu^-$	-	κ_λ, κ_Z
240	ZH	$b\bar{b}$	-	κ_λ, κ_Z
240	ZH	e^+e^-	$b\bar{b}$	κ_λ, κ_Z, ${}^*\bar{\kappa}_b$
365	ZH	$\mu^+\mu^-$	-	κ_λ, κ_Z
365	WWF	-	$b\bar{b}$	κ_λ, κ_W, $\bar{\kappa}_b$
365	ZZF	-	$b\bar{b}$	κ_λ, κ_Z, $\bar{\kappa}_b$

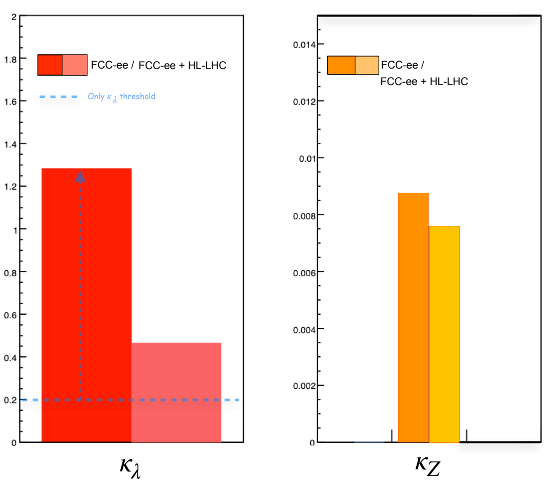
$\star$ $\bar{\kappa}_f = \kappa_b/\kappa_H$

Linear expansion around SM value

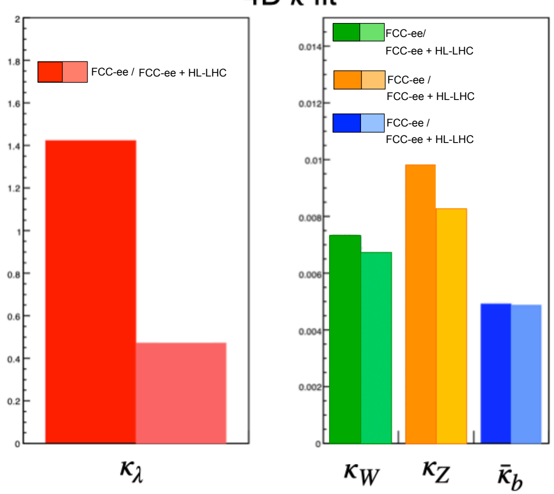
$$\frac{\delta\sigma_{NLO}(i \to H \to f)}{\sigma_{LO}(i \to H \to f)} \approx 2\sum_i \delta\kappa_i + 2\bar{\kappa}_f + (C_1 + 2\delta Z_H)\delta\kappa_\lambda$$

arXiv:1312.3322

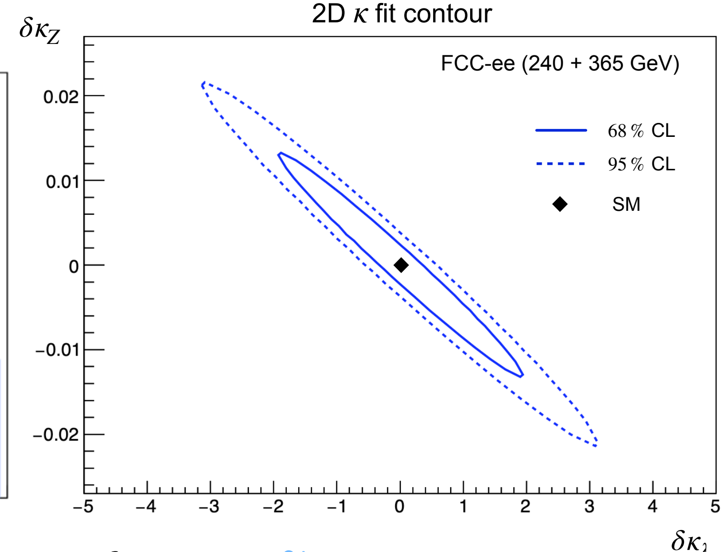
2D κ fit



4D κ fit



2D κ fit contour



→ weaker constraint on κ_λ: need to combine with HL-LHC for ~ 45 % precision

→ decrease the precision on κ_Z : most sensitive to variations in κ_λ (C_1 factor larger)

CONCLUSIONS AND OUTLOOKS

The Higgs Boson properties can be measured with high precision

→ ~ MeV precision on the Higgs Boson mass

→ ZH production x-section can measured in a model independent way with ~ 0.3 % precision

→ VBF production x-section and decay branching ratio to b quarks with percent level accuracy

→ More extended studies on the Higgs Boson decays are needed

Possibility to disentangle production and decay of the Higgs Boson

→ measurement of the absolute couplings to vector bosons with sub-percent accuracy

→ possible to probe NP up to Multi-TeV energy scale

→ measurement of the Higgs Boson width is needed to access absolute couplings in decay

No need to reach HH production threshold to access κ_λ : quantum loops

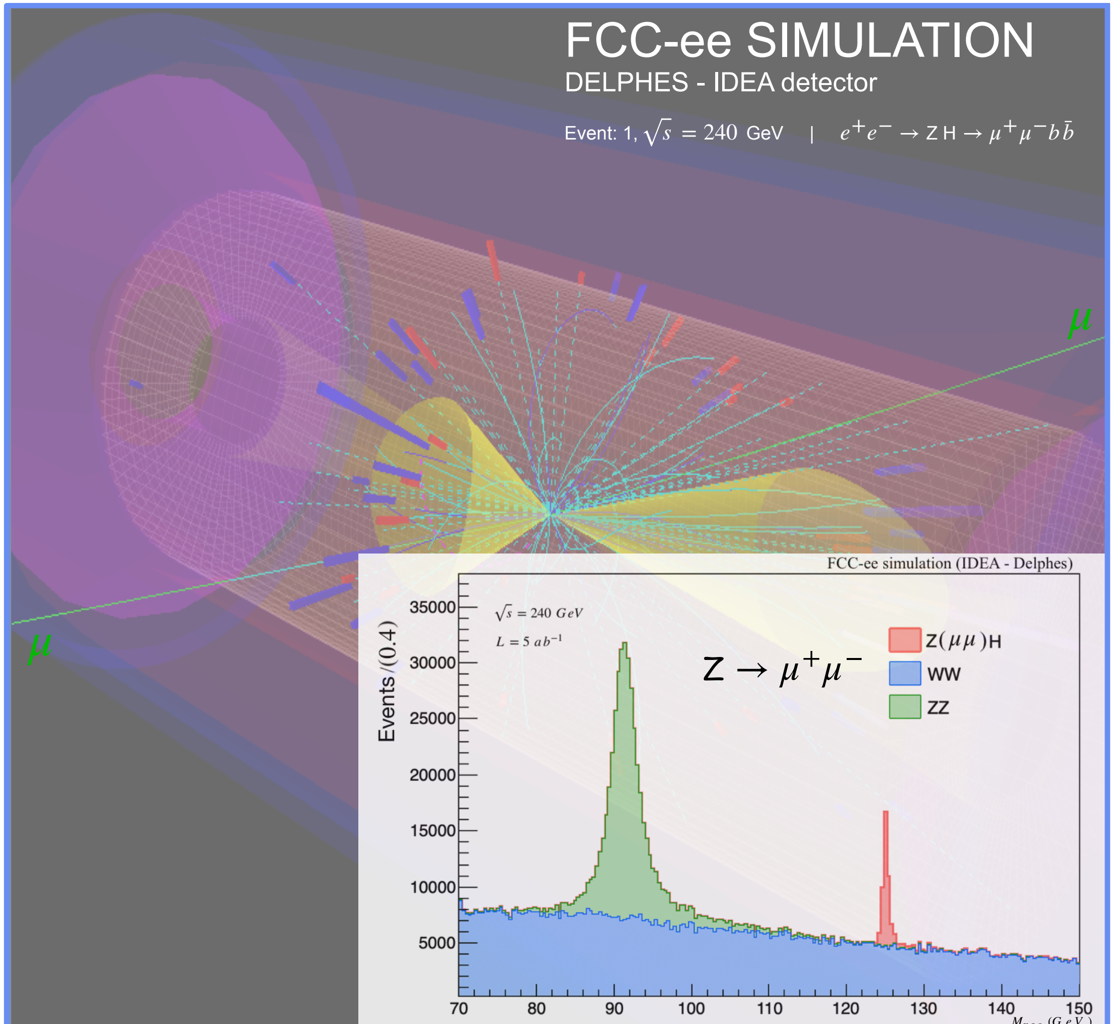
→ one-dimensional EFT fit: maximum sensitivity on κ_λ ~ 20 % (in production)

→ sensitivity on κ_λ in the Higgs Boson decays can be included

→ a full global EFT analysis is needed to have a more robust estimate

Backup

RECOIL MASS TECHNIQUE



The Higgs Boson can be tagged by a $Z \rightarrow f\bar{f}$ without looking at its decays

Momentum conservation → Recoil mass

$$M_{rec}^2 = s + M_{f\bar{f}}^2 - 2E_{ff}\sqrt{s}$$

Cleanest channel (no MVA) : $Z \rightarrow \mu^+\mu^-$

Two opposite sign muons with $p_{T1} > 20$ GeV, $p_{T2} > 5$ GeV and minimum $|M_{\mu^+\mu^-} - M_Z|$

Cut on the invariant mass: $80 < M_{\mu^+\mu^-} < 100$ GeV

Cut on the recoil mass: $120 < M_{rec} < 150$ GeV