Higgs physics at FCC-ee

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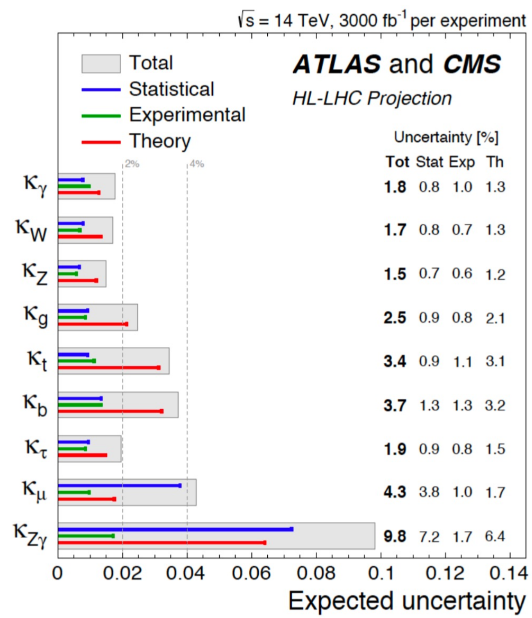
Landscape of the Higgs physics

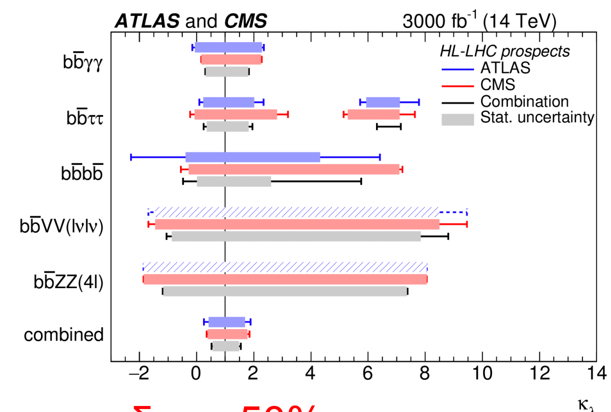
So far many questions still open for Higgs physics:

- ✓ How well the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?
- ✓ How do precision electroweak observables provide us information about the Higgs boson properties and/or BSM physics?
- ✓ What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?
- ✓ What is the best path towards measuring the Higgs potential ?
- ✓ To what extent can we tell whether the Higgs is fundamental or composite?

- ➢ **HL-LHC and future colliders would explore in detail the Higgs properties:** understand the deep origin of EWSB

- ➢ **Beyond HL-LHC measurements:**
  - ✓ Couplings to fermions to %-level, to bosons to per-mil
  - ✓ self-coupling
  - ✓ Invisible decays
  - ✓ BSM Higgses





$\delta\kappa_\lambda \sim 50\%$

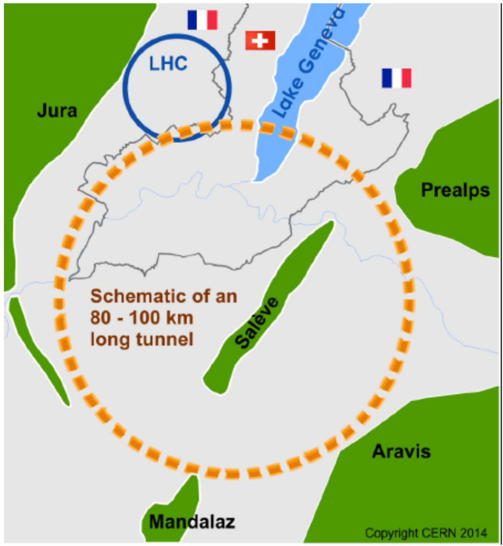
2020 update of European Strategy for Particle Physics

*"**An electron-positron Higgs factory is the highest priority next collider**. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."*

"Europe, together with its international partners, should investigate the 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. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

FCC project @ CERN: a new 100 km tunnel in the Geneva region, for two complementary machines covering the largest phase space in the high energy frontier:

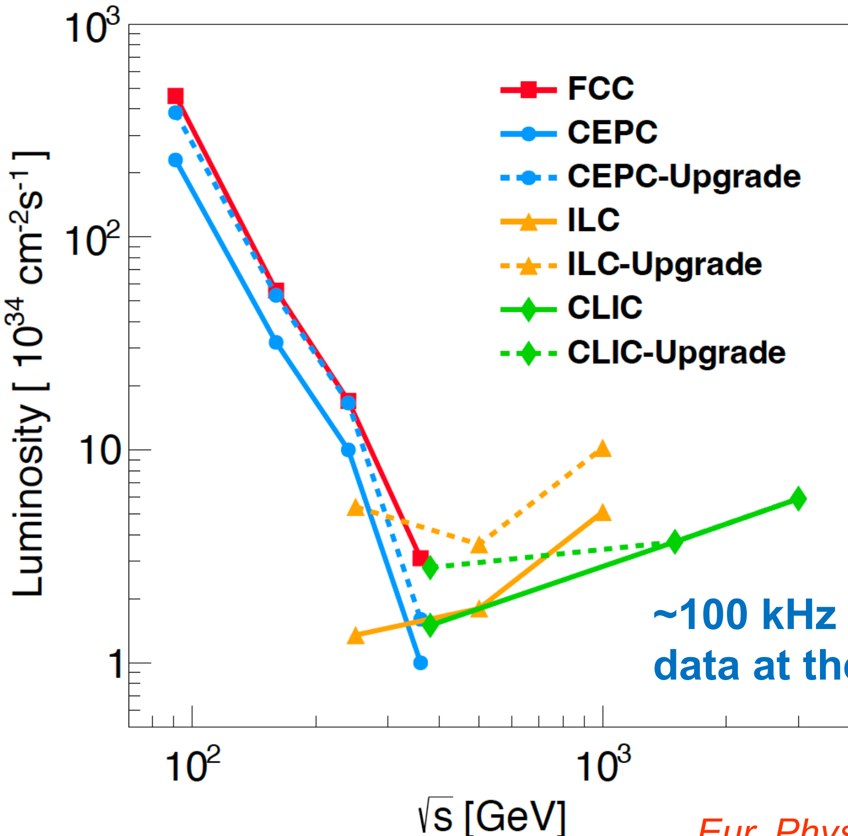
- **extreme precision circular e+e-collider (FCC-ee) with** variable collision energy from 90-360 GeV
- **highest energy reach in pp collisions (FCC-hh)**: 100 TeV



FCC Feasibility Study (FS) launched in 2021:

- To be carried out in 2021-2025 ➔ input to the next Strategy update
- Mid-term review in Autumn 2023

Machine luminosity for physics at e^+e^- colliders



- Higgs factory:
  - 10^6 $e^+e^- \rightarrow HZ$
- EW & Top factory:
  - 3×10^{12} $e^+e^- \rightarrow Z$
  - 10^8 $e^+e^- \rightarrow W^+W^-$
  - 10^6 $e^+e^- \rightarrow tt$
- Flavor factory:
  - 5×10^{12} $e^+e^- \rightarrow bb, cc$
  - 10^{11} $e^+e^- \rightarrow \tau^+\tau^-$

Eur. Phys. J. Special Topics volume 228, pages 261–623 (2019)

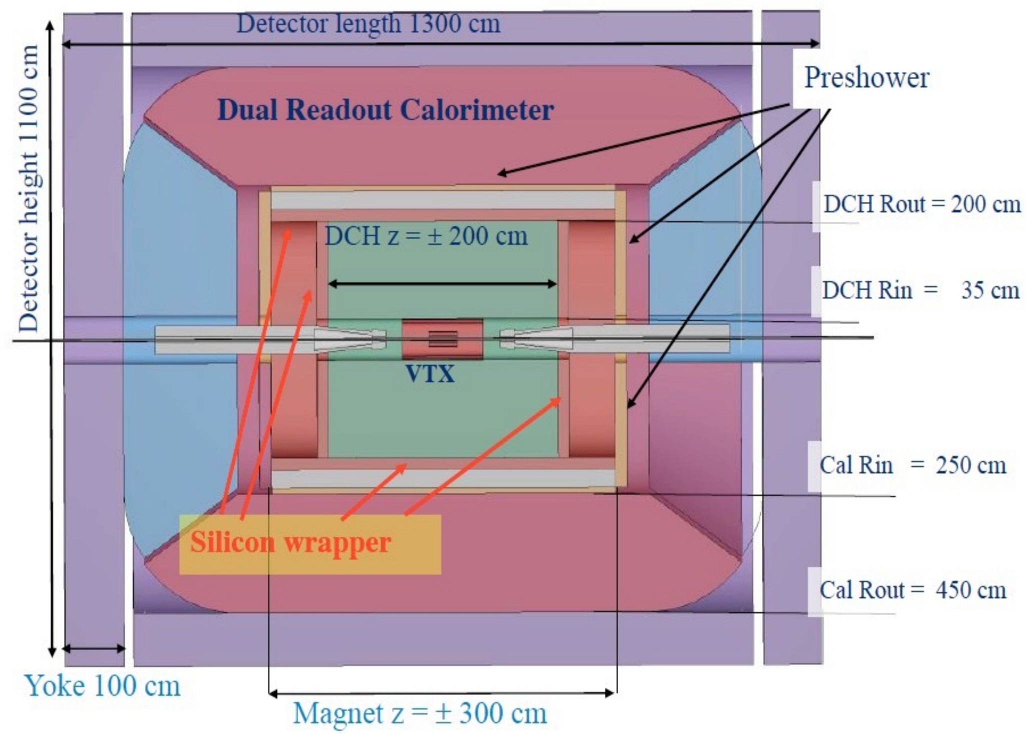
Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics	Extracted from FCC CDR
FCC-ee-Z	4	88-95 ± <100 KeV	150	3×10^{12} visible Z decays	LEP * 10^5
FCC-ee-W	2	158-162 <200 KeV	12	10^8 WW events	LEP * 2.10^3
FCC-ee-H	3	240 ± 2 MeV	5	10^6 ZH events	Never done
FCC-ee-tt	5	345-365 ± 5 MeV	1.5	10^6 $t\bar{t}$ events	Never done
s channel H	?	125 ± 2 MeV	10?	5000 events	Never done

Detector requirements for an experiment at FCC-ee

Critical Detector	Required Performance
Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5} \oplus 1 \times 10^{-3}/(p_T \sin\theta)$
Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu m$
ECAL, HCAL	$\sigma_E^{\mathrm{jet}}/E \sim 3-4\%$
ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

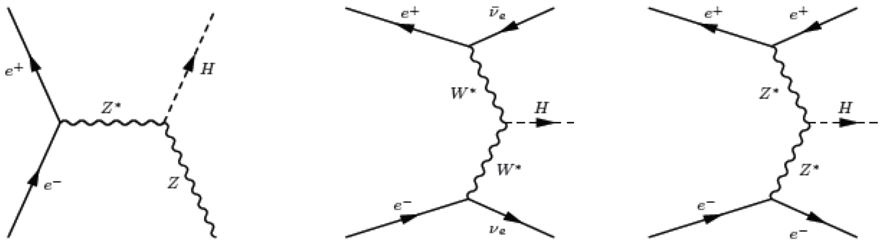
As an example: **IDEA** proposal

- a silicon pixel vertex detector
- a large-volume extremely-light drift wire chamber
- surrounded by a layer of silicon micro-strip detectors
- a thin low-mass superconducting solenoid coil
- a preshower detector
- a dual read-out calorimeter
- muon chambers inside the magnet return yoke



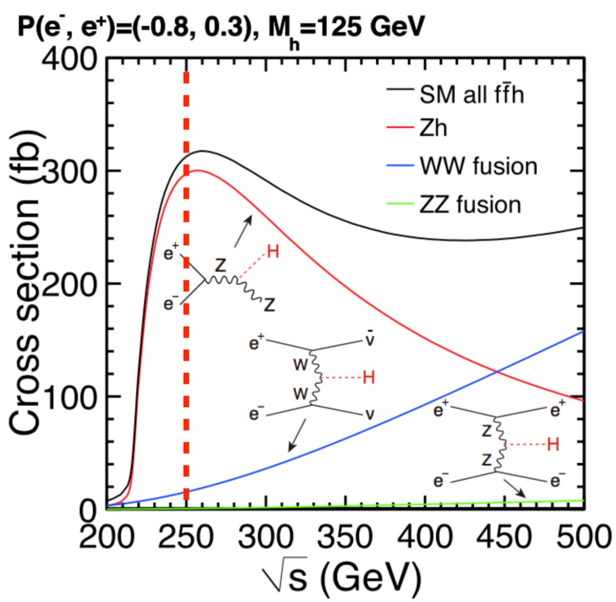
Higgs production at FCC-ee

Higgs-strahlung or $e^+e^- \rightarrow ZH$

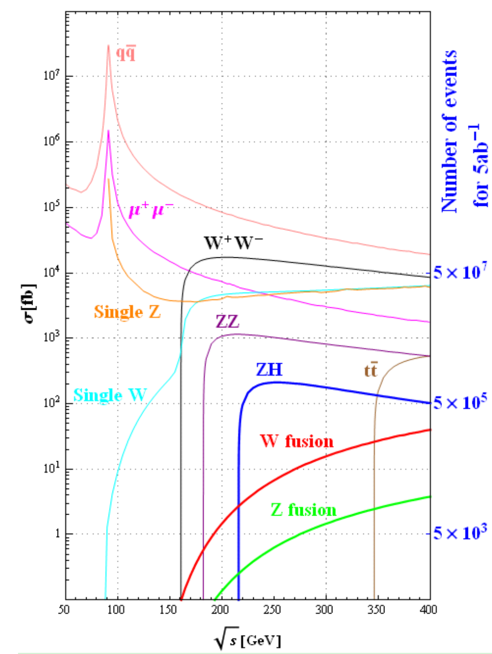


Higgs production @ FCC-ee		
Threshold	ZH production	VBF production
240 GeV / 5 ab^{-1}	1e6	2.5e4
365 GeV / 1.5 ab^{-1}	2e5	5e4

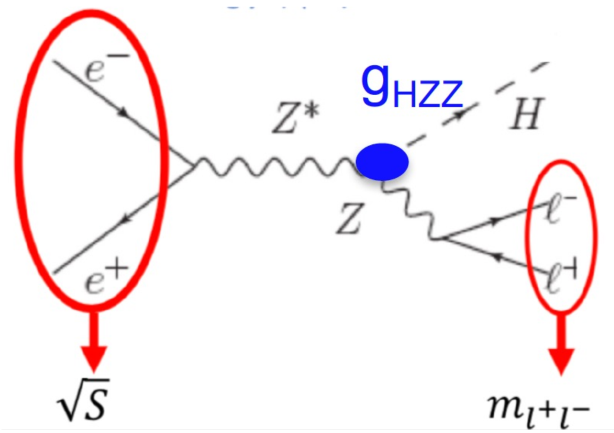
VBF production: $e^+e^- \rightarrow \nu\nu H$ (WW fus.), $e^+e^- \rightarrow He^+e^-$ (ZZ fus.)



Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6
Background processes, cross section in pb		
$e^+e^- \to e^+e^-$ (Bhabha)	25.1	1.3×10^8
$e^+e^- \to q\bar{q}$	50.2	2.5×10^8
$e^+e^- \to \mu\mu$ (or $\tau\tau$)	4.40	2.2×10^7
$e^+e^- \to WW$	15.4	7.7×10^7
$e^+e^- \to ZZ$	1.03	5.2×10^6
$e^+e^- \to eeZ$	4.73	2.4×10^7
$e^+e^- \to e\nu W$	5.14	2.6×10^7

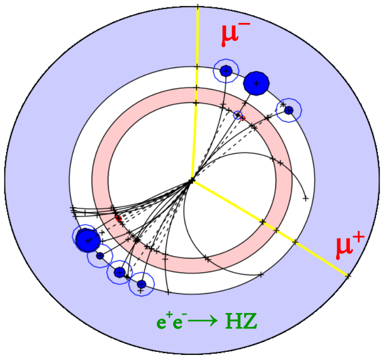


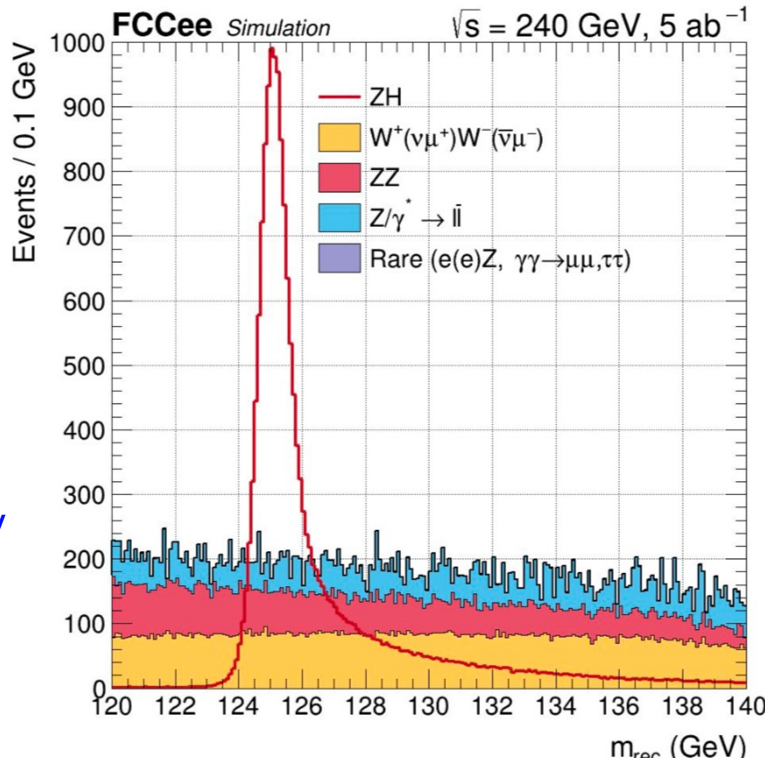
Global strategy for Higgs studies



$\sigma(e^+e^- \to HZ) \propto g^2_{HZZ}$

ZH events tagged by the Z, without reconstructing the Higgs decay. Unique to lepton colliders.





e.g. when Z → leptons :

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

A fit to the recoil mass distribution allows:

- measurement of σ(ZH) independent of the Higgs decay mode with O(%) uncertainty. Hence an absolute determination on g_{HZZ}

  → **$\delta g_{HZZ}/g_{HZZ}$ ~ 0.2 %** (also including Z→had)

- a precise meas. of the **Higgs mass → $\delta m_H/m_H$ ~ O(MeV)**

Easiest case: Z → lep.

• Z → had: more careful design of the analysis

Model-independent Higgs couplings measurements

Known g_{HZZ} it is possible to measure σ x BR for specific Higgs decays

$$\sigma_{ZH} \times \mathcal{B}(H \to X\overline{X}) \propto \frac{g^2_{HZZ} \times g^2_{HXX}}{\Gamma_H}$$

- H → ZZ* provides Γ_H
- H → XX provides g_{HXX}

H → ZZ* provides Γ_H : $\frac{\sigma(e^+e^- \to ZH)}{BR(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{SM} \times \Gamma_H$

→ **$\delta\Gamma_H / \Gamma_H$ ~ several %**

Select events with H → bb, cc, gg, WW, tt, γγ, μμ, Zγ, …

Deduce g_{Hbb} , g_{Hcc} , g_{Hgg} , g_{HWW} , g_{Htt} , $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, $g_{HZ\gamma}$, …

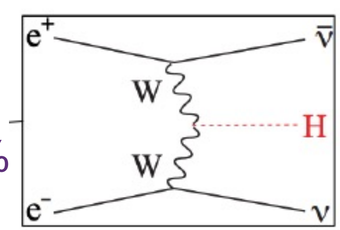
Select events with H → "nothing" → deduce Γ(H→invisible)

→ **$\delta g_{xx}/g_{xx}$ ~ 1 %**

a model-indep determination of Higgs couplings.

Data at higher energy bring important additional observables:

$$\sigma_{H\nu_e\bar{\nu}_e} \times \mathcal{B}(H \to X\overline{X}) \propto \frac{g^2_{HWW} \times g^2_{HXX}}{\Gamma_H}$$



First vvH → vvbb ~ $g_{HWW}^2\, g_{Hbb}^2 / \Gamma_H$

- vvbb / (ZH(bb) ZH(WW) ~ g_{HZZ}^4 / Γ_H = R → Γ_H precision at 1%

Then do vvH →vvWW ~ g_{HWW}^4 / Γ_H

- R / vvWW ~ g_{HWW}^4 / g_{HZZ}^4
- g_{HWW} precision to few permil

At the end: Higgs couplings and Γ_H extracted from a global fit to all σ x BR (Kappa framework, SMEFT framework)

Analyses overview

HZ cross section and mass measurement (1)

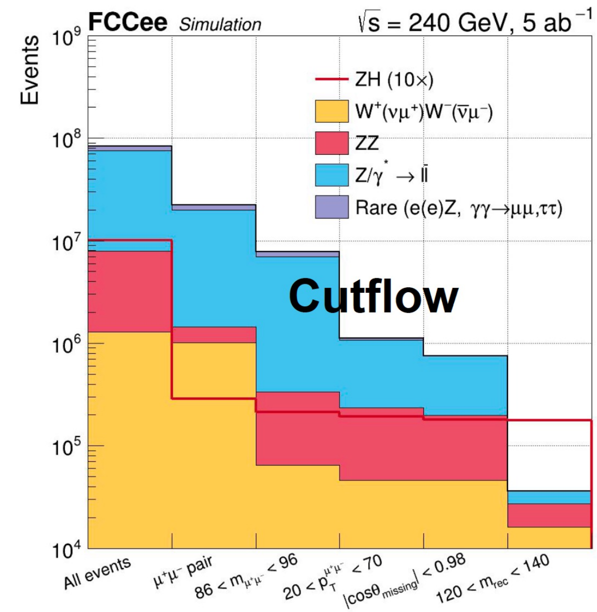
Details at link

MC simulation based on Whizard:

- $\sqrt{s}$ = 240 GeV, L = 5 ab^{-1}
- IDEA detector; detector response modelled with Delphes

Analysis workflow based on recoil method using Z(μμ) final state

- Baseline selection, at least 2 muons in the event
  - in case of more than 2 muons in event, select pair closest to Z mass
  - tight selection of Z mass between [86, 96] GeV
- Background reduction by cut on Z p_T [20, 70] GeV and $|\cos(\theta_{miss})|$ < 0.98
  - the former to suppress Z/γ*, tthe later for $\gamma\gamma \rightarrow \mu\mu/\tau\tau$ events → to be replaced by MVA

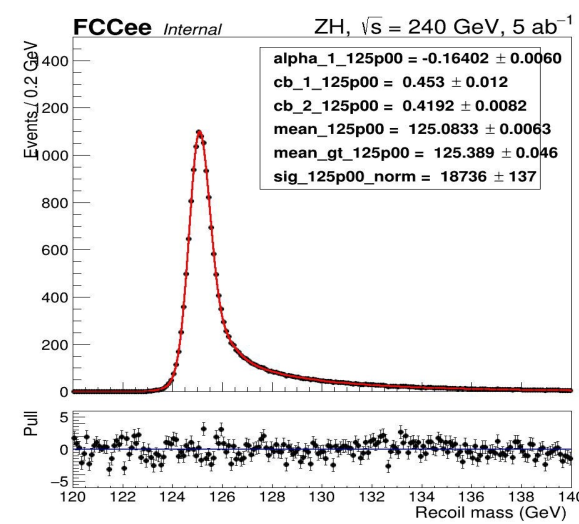


Potential improvements:

- Inclusion of Z(ee), but larger eeZ backgrounds; Z(qq) worse resolution
- Optimize selection for background rejection

Parametric fit based on recoil mass distribution

- Fit function: double-sided Crystal-ball + Gaussian core
- Free parameter: Higgs mass, signal normalization and background norm



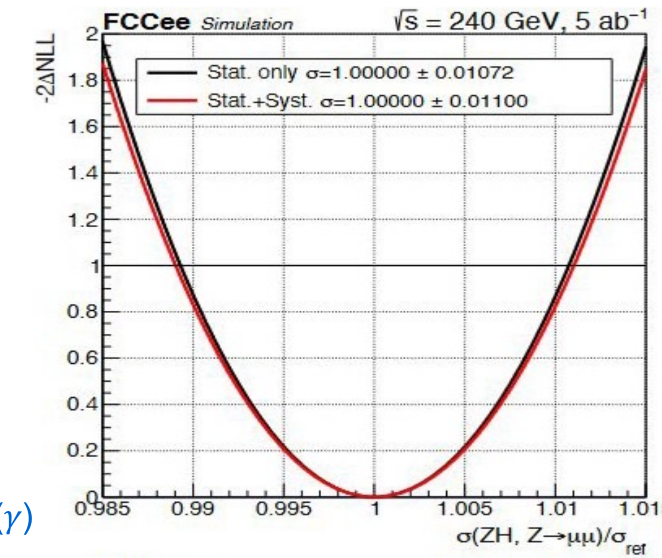
HZ cross section and mass measurement (2)

Likelihood scans to extract uncertainties on cross section and mass

Stat-only uncertainties:

- **Cross-section: 1.07 %**
- **Higgs mass: 6.7 MeV**

Muon channel only



Potential systematic uncertainties studied and propagated to the fit

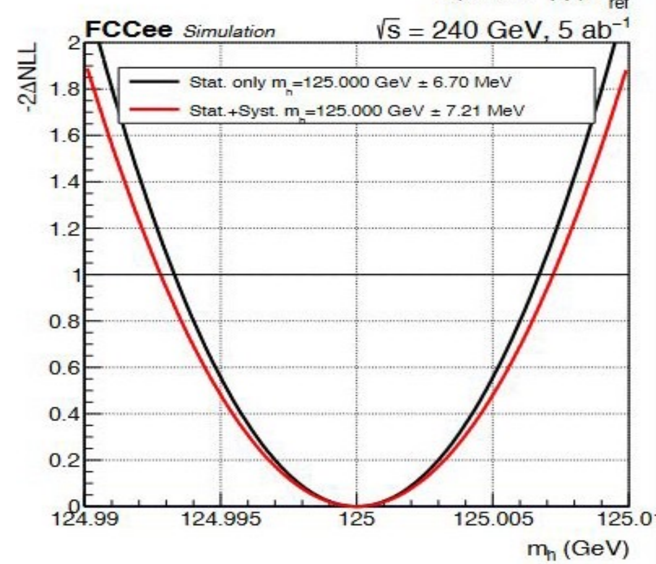
- Beam Energy Spread (BES) ~ 1% at 240 GeV, constrained using $ee \rightarrow ff(\gamma)$
- Initial State Radiation (ISR) estimated using KKMC
- Muon momentum scale relative scale uncertainty ~ 1e-5
- Center-of-mass ~ 2 MeV
- FSR uncertainty to be evalutated

Stat + syst uncertainties:

- **Cross-section: 1.11 %**
- **Higgs mass: 7.1 MeV**

Minor impact, stat. driven

This uncertainty would be reduced with the 240 GeV data by adding the electron channel, possibly increasing the magnetic field from 2T to 3T, and by reconstructing explicitly the Higgs mass in exclusive decays.



H→hadrons and progress on jet flavour tagging

High precision Higgs BRs to hadron measurements:

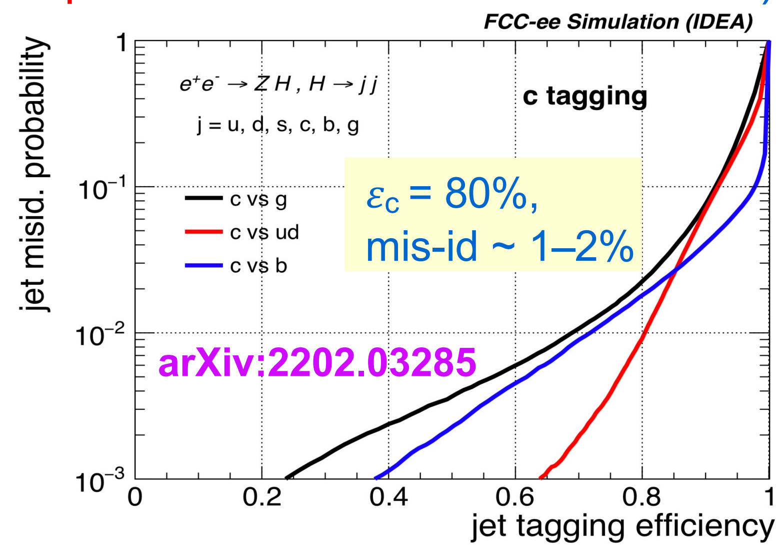
- Bottom and charm, gluons, probe strange coupling?

- Z(ll)H(qq)
- Z(inv)H(qq)
- Z(qq)H(qq)

- Key ingredients:
  - tagging of b, c and g jets
  - detector requirements (tracking, vertexing, timing)
  - tagging performance from old-ish algorithms
    - large room for improvement for σ x BR(cc)
- State-of-the-art flavour-tagging algorithm developed recently in the context of FCC-ee. Exploits experience gained at the LHC.
  - Advanced machine learning (Dynamic Graph Convolutional Neural Network)

Very promising performance

- Mis-id efficiency lower by O(10) compared to traditional approaches

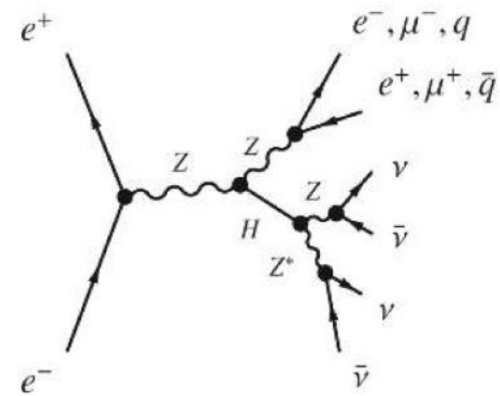


Higgs to invisible particles analysis

Details at link

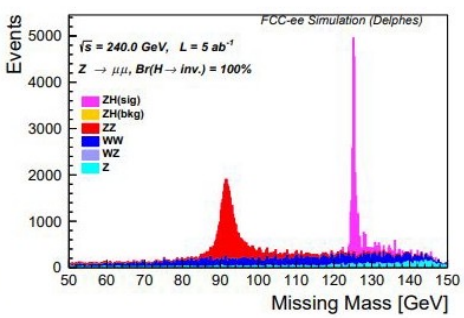
Strategy:

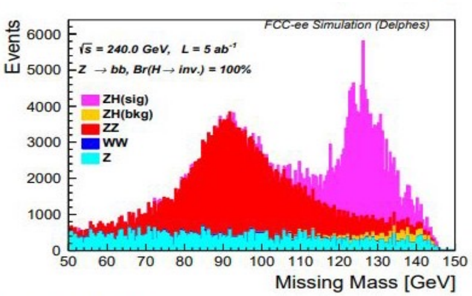
- Tag the Z using muon, electron and hadron final states (qq and bb)
- Tight cut on Z peak [87, 96] GeV, based on leptonic system or sum of all visible particles for hadronic
- Calculate missing mass m_{miss} as 240 GeV minus visible mass m_{vis}
- Additional requirements for Z→bb channel, to cope with worse resolution of bb system
  - relax Z peak constraint by [60, 100]
  - scale visible 4–vector by $91/m_{vis}$ and recalculate m_{miss} to optimize resolution

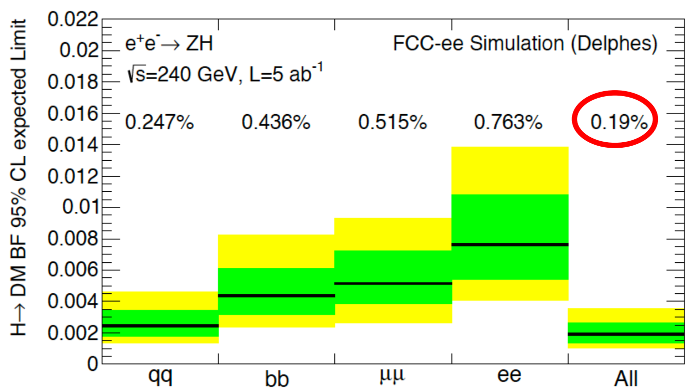


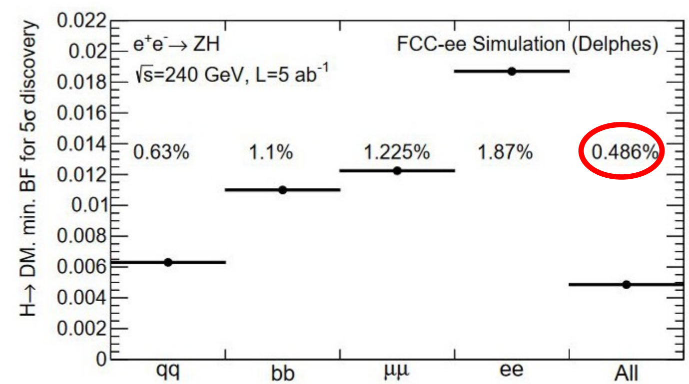
BR(H → inv) @ 95%CL ~ 0.19 %

Discovery potential H → X above SM background with BR ~ 0.5 %









Higgs self coupling at √s < 500 GeV – i.e. ZH & tt thresholds

Details at link

Probe *indirectly* trilinear Higgs self coupling λ_3 through higher-order corrections to single-Higgs processes

NLO correction to SM observable (i.e the cross section) parameterized according to:

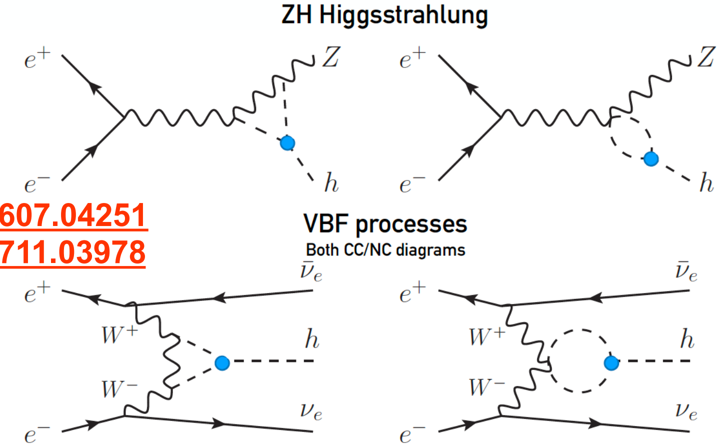
$$\Sigma_{\rm NLO} = \boxed{Z_H}\Sigma_{\rm LO}(1+\kappa_\lambda \boxed{C_1}) \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$

Universal coefficient from wave function

Process and kinematic dependent coefficient

arxiv:1607.04251
arxiv:1711.03978

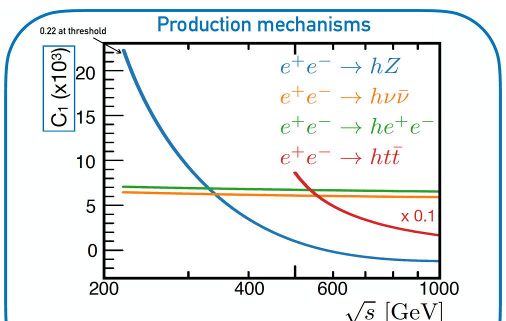
Vertex corrections (linear in k_λ)



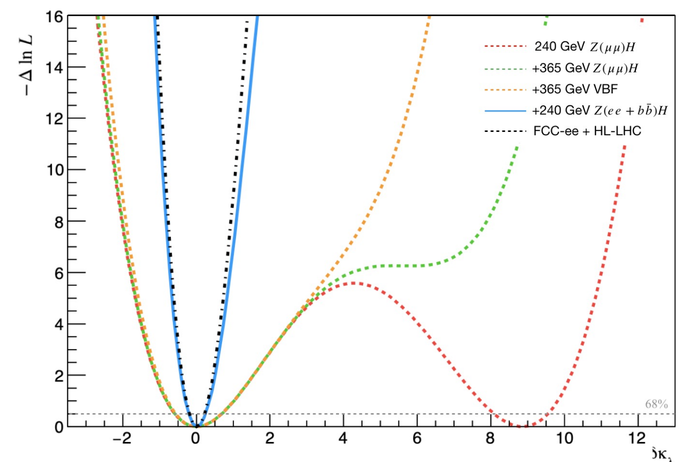
C_1 process-dependent coefficient that encodes the interference between the NLO amplitudes and the LO ones

The total (NLO) cross section can be measured O(1%):

- possible probing NLO deviations from SM: $\delta\kappa_\lambda = \kappa_\lambda - 1$
- parameter C_1 sensitive to √s: exploit different sensitivities at 240 GeV and 365 GeV:
  - ZH @ 240 GeV
  - VBF @ 365 GeV



Negligible impact of a modified λ_{HHH} on the angular asymmetries. At 1-loop C_1 for HZ, WW-boson fusion and ZZ-boson fusion are independent of the beam polarization.

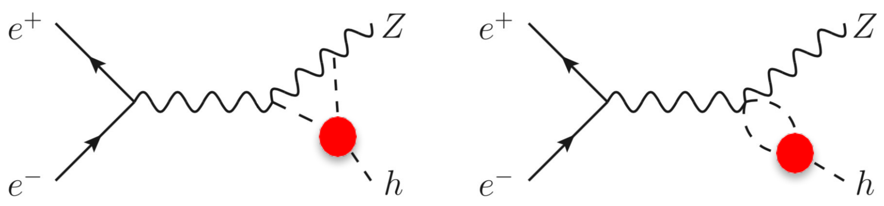


The secondary minimum easily excluded adding a 2nd energy point

Higgs self coupling at √s < 500 GeV – i.e. ZH & tt thresholds

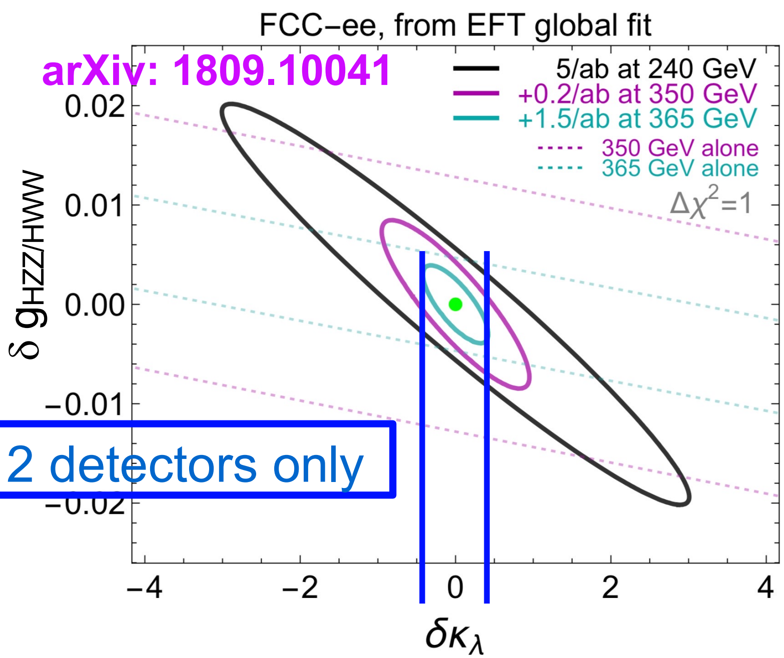
NB: 365 GeV > ZHH threshold, but too low ZHH x-section

λ_3 affects single-Higgs prod at NLO



e.g. 100% variation on λ_3 modifies σ(ZH) by ~ 2% at 240 GeV and ~ 0.5% at 365 GeV. Larger than / comparable with the exp. precision on σ(ZH)

Precise measurement of σ(ZH) constrains a combination of λ_3 and g_{HZZ}.
Measurements at two values of √s needed to determine separately λ_3 and g_{HZZ}.



- FCC-ee baseline (2 IPs): $\delta\kappa_\lambda$ ~ 40% (33% when combined with HL-LHC).
- Recent: 4 IPs possible. More than x2 stat: need less time to complete the EW programme, hence can spend more time at 240 and 365 GeV → $\delta\kappa_\lambda$ ~ 24% (combined with HL-LHC)

JHEP01(2020)139

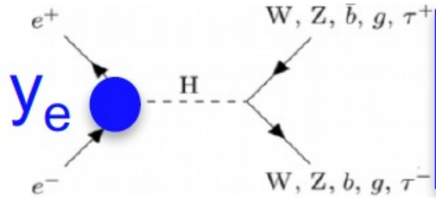
With 4 IPs: 5σ observation of λ_3 within reach with 15 years of operation at FCC-ee.

Higgs Yukawa coupling to electron

arXiv:2107.02686

FCC-ee: unique opportunity to study the Higgs Yukawa coupling to electron, $\mathbf{y_e}$, via resonant s-channel production $\mathbf{e^+e^- \to H}$ in a dedicated run at the Higgs pole, $\sqrt{s} = m_H$.

- **Stat. limited**

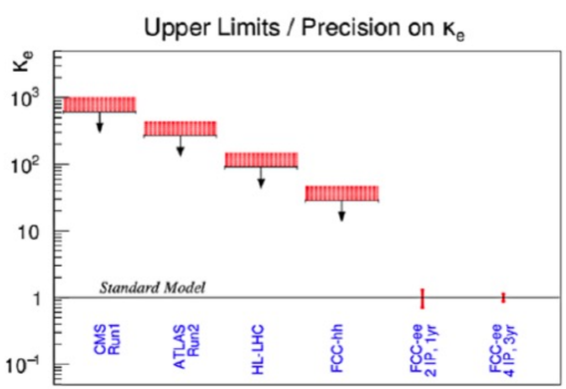


$\sigma(e^+e^- \to H)_{B\text{-}W} = 1.64$ fb

$\sigma(e^+e^- \to H)_{spread} = 280$ ab (ISR + $\sqrt{s}_{spread} = \Gamma_H = 4.2$ MeV)

- Beams must be monochromatized such that the spread of their center-of-mass energy is commensurate with the narrow width of the SM Higgs boson
- Prerequisite: Higgs mass extraction δm_H = **O (3 MeV)** via HZ@ 240,217 GeV
- Generator-level study for signal+background for 10 decay channels:
  - most significant channels: H→gg (for light mistag ~ 1%), H→WW* →lν +jets

For 10 ab^{-1} & $\sqrt{s}_{spread} = \Gamma_H$: Signif ≈ 1.3σ



upper limit @ 95CL on the electron Yukawa coupling at 1.6 times the SM value → **x 100 better than for HL-LHC**

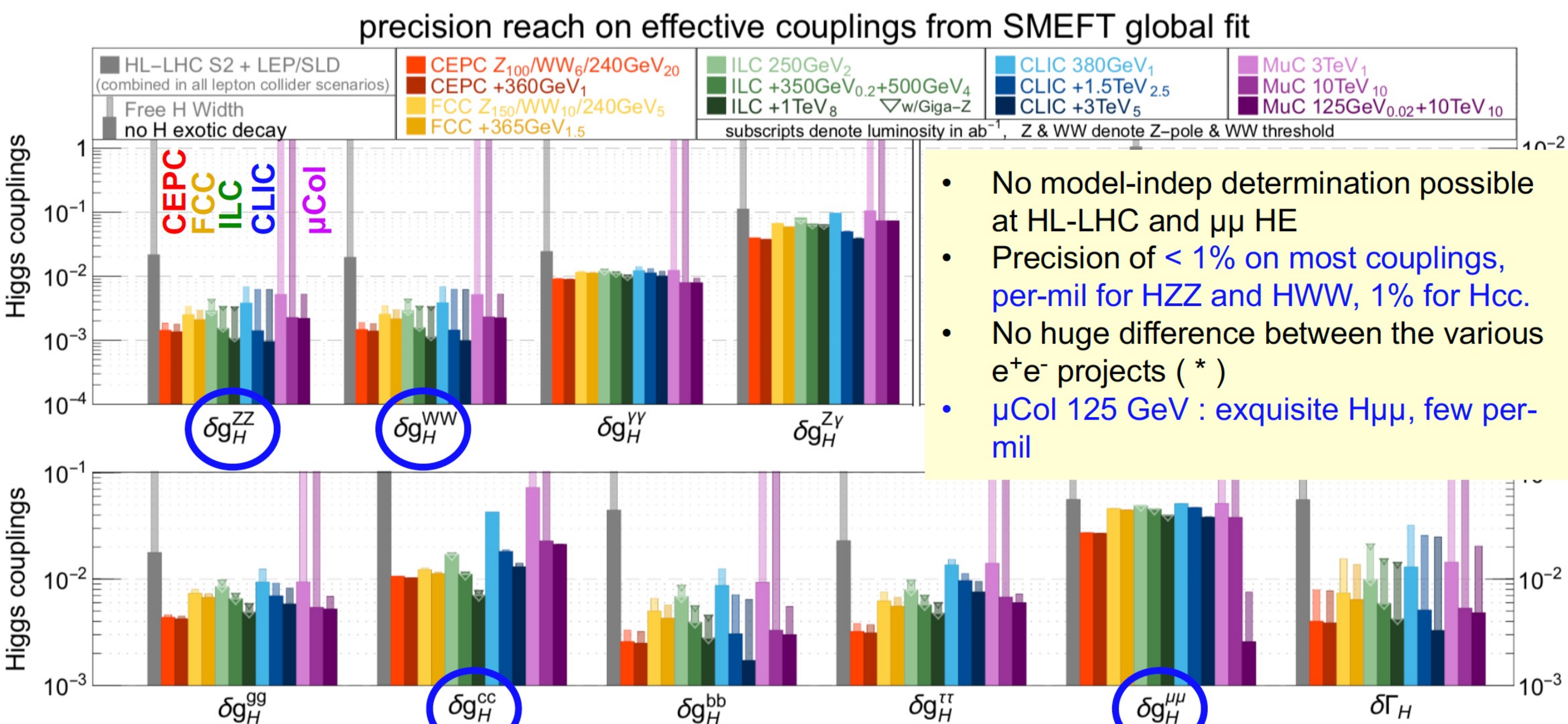
Higgs couplings from global fits (1)

Recent example of a global fit in the SMEFT framework from arXiv:2206.08326

Future colliders combined with HL-LHC

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_j \frac{C_j^{(6)}}{\Lambda^2}\mathcal{O}_j^{(6)}$$

Input Higgs measurements: main difference w.r.t. ESU is the updated CEPC running scenario (20 ab^{-1} vs 5 ab^{-1})



- No model-indep determination possible at HL-LHC and μμ HE
- Precision of < 1% on most couplings, per-mil for HZZ and HWW, 1% for Hcc.
- No huge difference between the various e^+e^- projects (*)
- μCol 125 GeV : exquisite Hμμ, few per-mil

Conclusions

- FCC is a unique project, offering an extremely complete and compelling programme, with synergies and complementarities between the various machines and running scenarios (FCC-ee, FCC-hh, FCC-eh and heavy ions) → prospects for 100 years of great physics at energy and intensity frontiers!

- FCC-ee provides ultimate precision in Higgs sector, aimed at starting at CERN in e^+e^- mode, shortly after the end of the HL-LHC.

- FCC-ee will produce 1-2 millions Higgs in a clean environment (low systematics):
  - allows for model independent measurement of Higgs properties
  - high precision in abundant Higgs decay channels

- New experimental developments coming in: progress on detector R&D, reconstruction algorithms, ML revolution, allow to contemplate more ambitious goals
  - an exciting future for HEP ahead…join the team!

Credits: E. Perez, D. d'Enterria, M. Selvaggi, C. Grojean, P. Azzi et al.

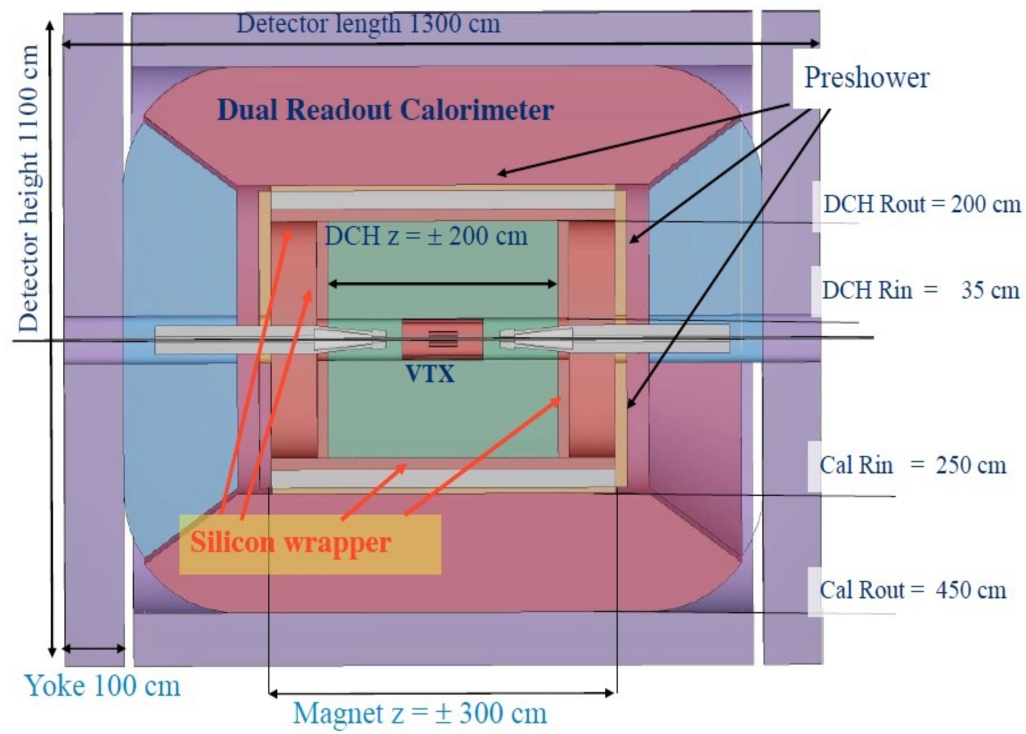
Backup

Higgs physics requirements for an experiment at FCC-ee

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5}$
$H \to \mu^+\mu^-$	$\text{BR}(H \to \mu^+\mu^-)$		$\oplus 1 \times 10^{-3}/(p_T \sin\theta)$
$H \to b\bar{b},\ c\bar{c},\ gg$	$\text{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\text{m}$
$H \to q\bar{q},\ VV$	$\text{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{\text{jet}}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\text{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%\ (\text{GeV})$

As an example: **IDEA** proposal

- a silicon pixel vertex detector
- a large-volume extremely-light drift wire chamber
- surrounded by a layer of silicon micro-strip detectors
- a thin low-mass superconducting solenoid coil
- a preshower detector
- a dual read-out calorimeter
- muon chambers inside the magnet return yoke



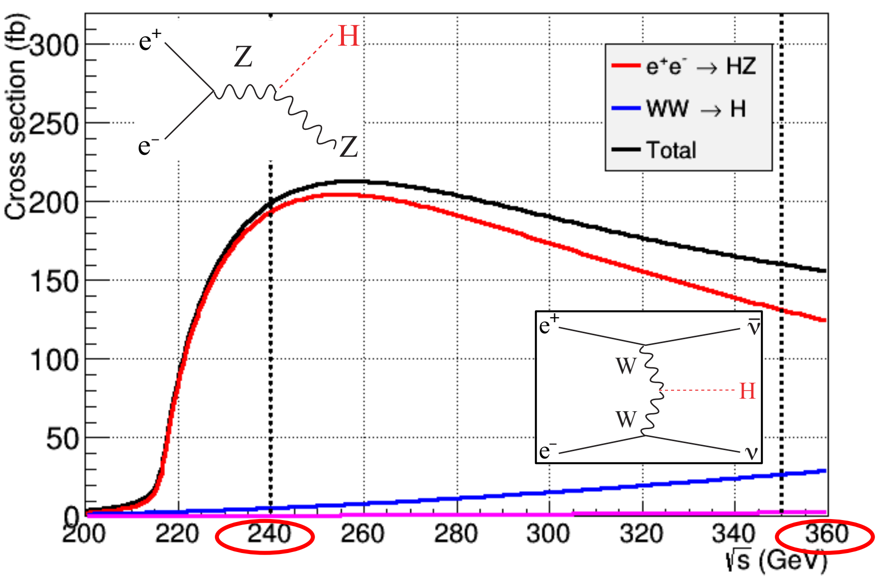
FCC-ee Higgs motivation and contacts

FCC-ee offers broad potential for precision Higgs measurements:

- 5 ab^{-1} integrated luminosity to two detectors over 10 years → 10^6 clean Higgs events
- clean environment
- relative small backgrounds, high S/B

→ FCC-ee can measure the Higgs boson production cross sections and most of its properties with precisions far beyond achievable at the LHC

◆ **Higgs-strahlung (m_H = 125 GeV)**



Max. σ at √s = 250 GeV : σ ≈ 200 fb

FCC-ee Higgs conveners
Performance
Michele Selvaggi, Jan Eysermans

Programme
Gauthier Durieux, Christophe Grojean, Jorge De Blas Mateo

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Model-independent Higgs couplings measurements

Known g_{HZZ} it is possible to measure σ x BR for specific Higgs decays

$$\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \mathrm{X\overline{X}}) \propto \frac{g^2_{\mathrm{HZZ}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$

- H → ZZ* provides Γ_H
- H → XX provides g_{HXX}

H → ZZ* provides Γ_H :
$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

→ **$\delta\Gamma_H / \Gamma_H$ ~ several %**

Select events with H → bb, cc, gg, WW, tt, γγ, μμ, Zγ, …

Deduce g_{Hbb} , g_{Hcc} , g_{Hgg} , g_{HWW} , g_{Htt} , $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, $g_{HZ\gamma}$, …

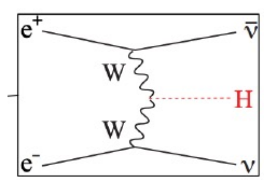
Select events with H → "nothing" → deduce Γ(H→invisible)

→ **$\delta g_{xx}/g_{xx}$ ~ 1 %**

a model-indep determination of Higgs couplings.

Data at higher energy bring important additional observables:

$$\sigma_{\mathrm{H}\nu_e\bar{\nu}_e} \times \mathcal{B}(\mathrm{H} \to \mathrm{X\overline{X}}) \propto \frac{g^2_{\mathrm{HWW}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$



In practice: Higgs couplings and Γ_H extracted from a global fit to all σ x BR measts

- Kappa framework
- SMEFT framework

Higgs measurements: a broad analysis programme

- Mass
- Decay-mode independent cross section
- Width
- Invisible
-
- Self coupling

Global fits in κ-3 framework (arXiv:1905.03764)

Expected relative uncertainties (%) on Higgs couplings

Ch.	HL-LHC	+ 240 GeV	+ 240+365 GeV	+ FCC-hh
κ_W	0.99	**0.88**	**0.41**	0.19
κ_Z	0.99	**0.20**	**0.17**	0.16
κ_g	2.00	**1.20**	**0.90**	0.5
κ_γ	1.60	1.3	1.3	0.31
$\kappa_{Z\gamma}$	10.0	10.0	10.0	0.7
κ_c	–	**1.50**	**1.30**	0.96
κ_t	3.20	3.10	3.10	0.96
κ_b	2.50	**1.00**	**0.64**	0.48
κ_μ	4.40	4.00	3.90	0.43
κ_τ	1.60	**0.94**	**0.66**	0.46
Inv.	1.9	**0.22**	**0.19**	0.024

Analysis ongoing **Analysis not covered**

Higgs couplings

- Vector boson couplings, WW, ZZ
- Fermions
- Electron Yukawa coupling

Exotics

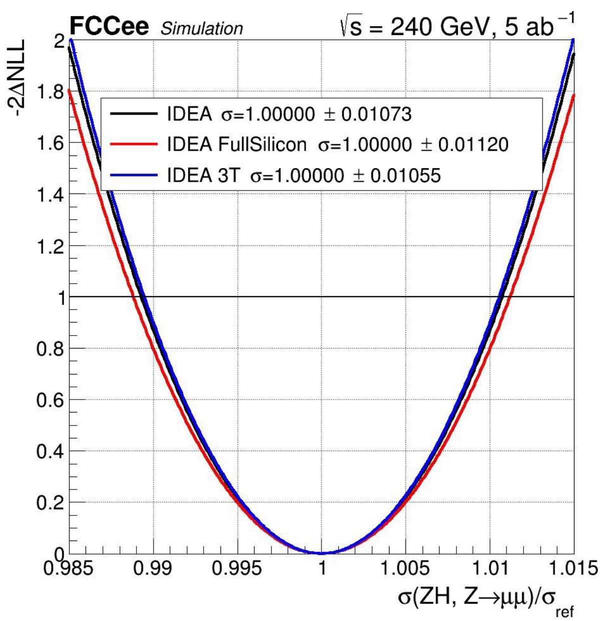
- Exotic/rare Higgs decays (γγ, μμ, γZ), flavor
- Light scalar Higgs searches (@ Z pole)

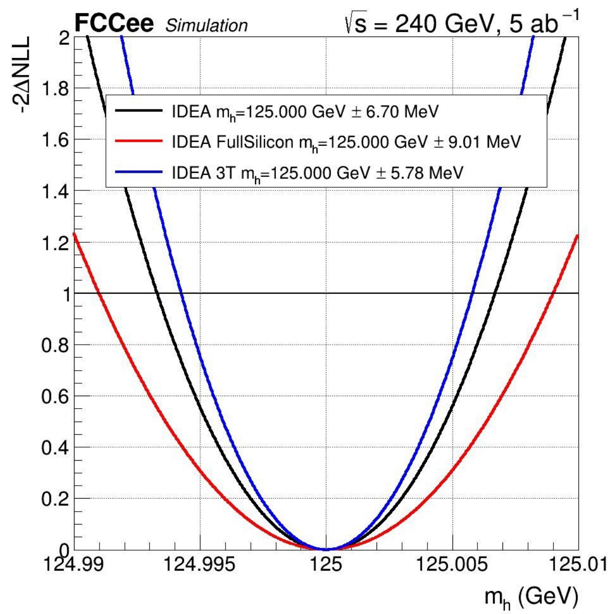
Cross section and mass: detector

Different IDEA detector configurations studied:

- **Magnetic field increased from 2T to 3T → expected better momentum resolution**
- **FullSilicon tracker instead of drift chamber → degraded resolution due to enhanced multiple scattering, especially at low p_T and in the range relevant for this analysis**

Effect on mass scales with resolution, impact on cross-section uncertainty limited





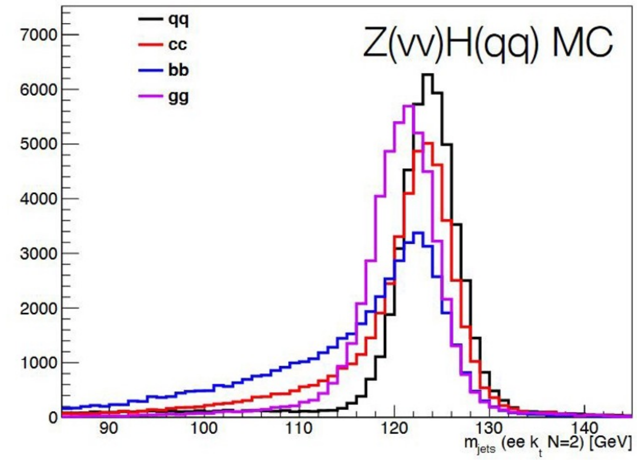
Stat-only result

IDEA	Δm_H (MeV)	$\Delta\sigma$ (%)
Nominal	**6.70**	**1.07**
FullSilicon	**9.01**	**1.12**
3T	**5.78**	**1.06**

Higgs to hadron couplings: Z(ll)H(qq)

Hadronic couplings extracted from Z(ll)H(hadrons) final states

- Using recoil method, for Z muon or electron decays
- Categorization based on tagged b and c jets + gluon jets
- Processes split in bb, cc, gg, and non-hadronic (remainings)



Strategy:

- Jet algorithm: ee anti-kT with E recombination scheme – require max 2 jets
- Jet flavor labelling based on matching to highest energy true parton in cone of DR < 0.5
- Jet flavor tagging: apply tagger WPs for the labelled jets
    - Flavor tagger arXiv:2202.03285, discriminating b,c and gluons – **baseline 80% efficiency**

Strategy	b-tag ε_b, ε_c, ε_l, ε_g	c-tag ε_b, ε_c, ε_l, ε_g	g-tag ε_b, ε_c, ε_l, ε_g
Nominal	**80 / 0.4 / 0.05 / 0.7**	**2.0 / 80 / 0.9 / 2.5**	**2.0 / 5.0 / 15 / 80**
Fake rates x2	80 / **0.8 / 0.1 / 1.4**	**4.0** / 80 / **1.8 / 5.0**	**4.0 / 10 / 30** / 80
Fake rates x5	80 / **2.0 / 0.25 / 3.5**	**10** / 80 / **4.5 / 12.5**	**10 / 25 / 75** / 80
Eff -10%	**70** / 0.4 / 0.05 / 0.7	2.0 / **70** / 0.9 / 2.5	2.0 / 5.0 / 15 / **70**
Eff -20%	**60** / 0.4 / 0.05 / 0.7	2.0 / **60** / 0.9 / 2.5	2.0 / 5.0 / 15 / **60**
WPc 90%	80 / 0.4 / 0.05 / 0.7	**4.0 / 90 / 7.0 / 7.0**	2.0 / 5.0 / 15 / 80
WPc 70%	80 / 0.4 / 0.05 / 0.7	**0.9 / 70 / 0.2 / 1.0**	2.0 / 5.0 / 15 / 80

Effect on tagging WP

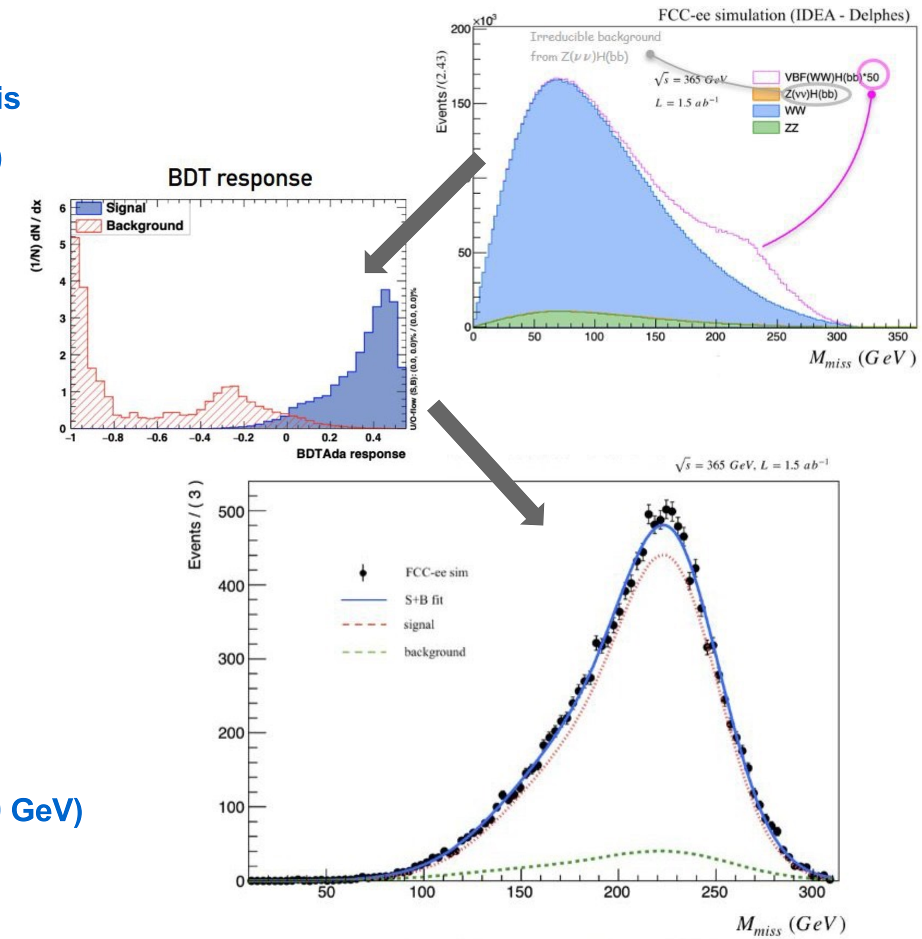
Higgs self coupling: selection

240 GeV: ZH recoil method using Z(mumu), Z(ee), Z(bb)

- Muon final state ~ identical to mass/cross section analysis
- Electron final state suffers from larger backgrounds (eeZ)
- Added Z(bb)H final state to profit from large statistics
  - Adaptive BDT for efficient background rejection
- Fit on recoil mass distribution

365 GeV: VBF analysis:

- WW fusion (vvH) ~ 50k H
  - 2 b-jets, H_T > 10 GeV, MET > 10 GeV
- ZZ fusion (eeH) ~ 4k H
  - 2 electrons + 2 jets, mee > 80 GeV
- Use BDT for background rejection
- Fit on missing mass variable (peaks around 365–125=240 GeV)

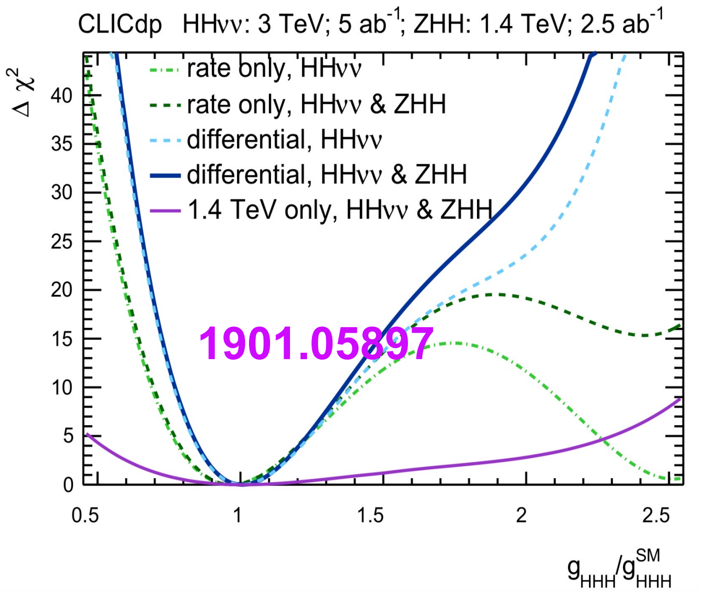


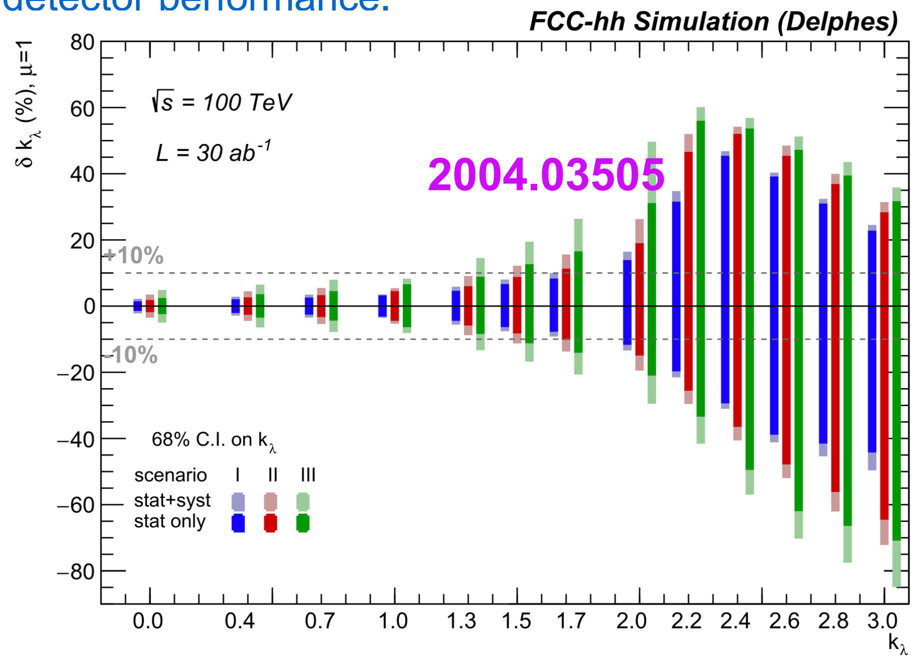
Higgs self coupling at higher energies: HH production

- e^+e^-: σ(ZHH) and σ($\nu\nu$HH), from 0.1 fb (250 GeV) to O(1 fb) at 3 TeV.
  Best sensitivity: HH → 4b.
- μCol: VBF, ννHH
- pp 100 TeV : σ = LHC x40

Best channel is bb$\gamma\gamma$. Sensitivity studied for several assumptions on detector performance.

From σ to g_{HHH}: Some diagrams do not involve HHH. ambiguities, can be resolved by combining measurements or by meas. differential in M(HH).





Going below the 10% level requires highest energies. Not for the "first stages".

	ILC 500 GeV 4 ab-1	27% (oldish ..)
	ILC + 1 TeV 8 ab-1	10%
	CLIC 3 TeV, 5 ab-1	-8% / +11%
μCol	3 TeV 0.9 ab-1	~ 25%
μCol	10 TeV 10 ab-1	4 %
pp	100 TeV 30 ab-1	3 – 8%

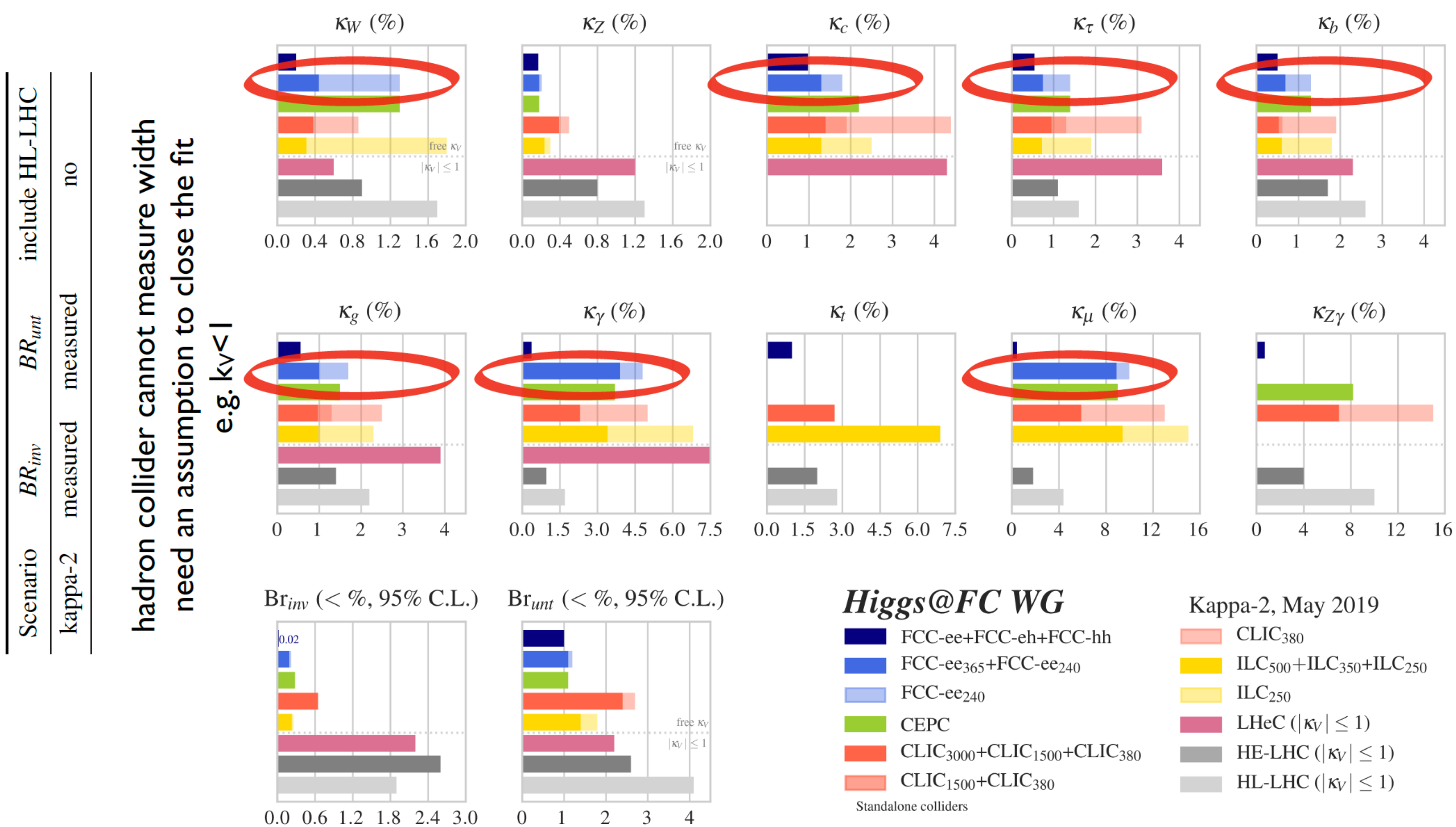
Higgs couplings from global fits (2)

Recent example of a global fit in the Kappa framework from arXiv:1905.03764

Future colliders combined with HL-LHC

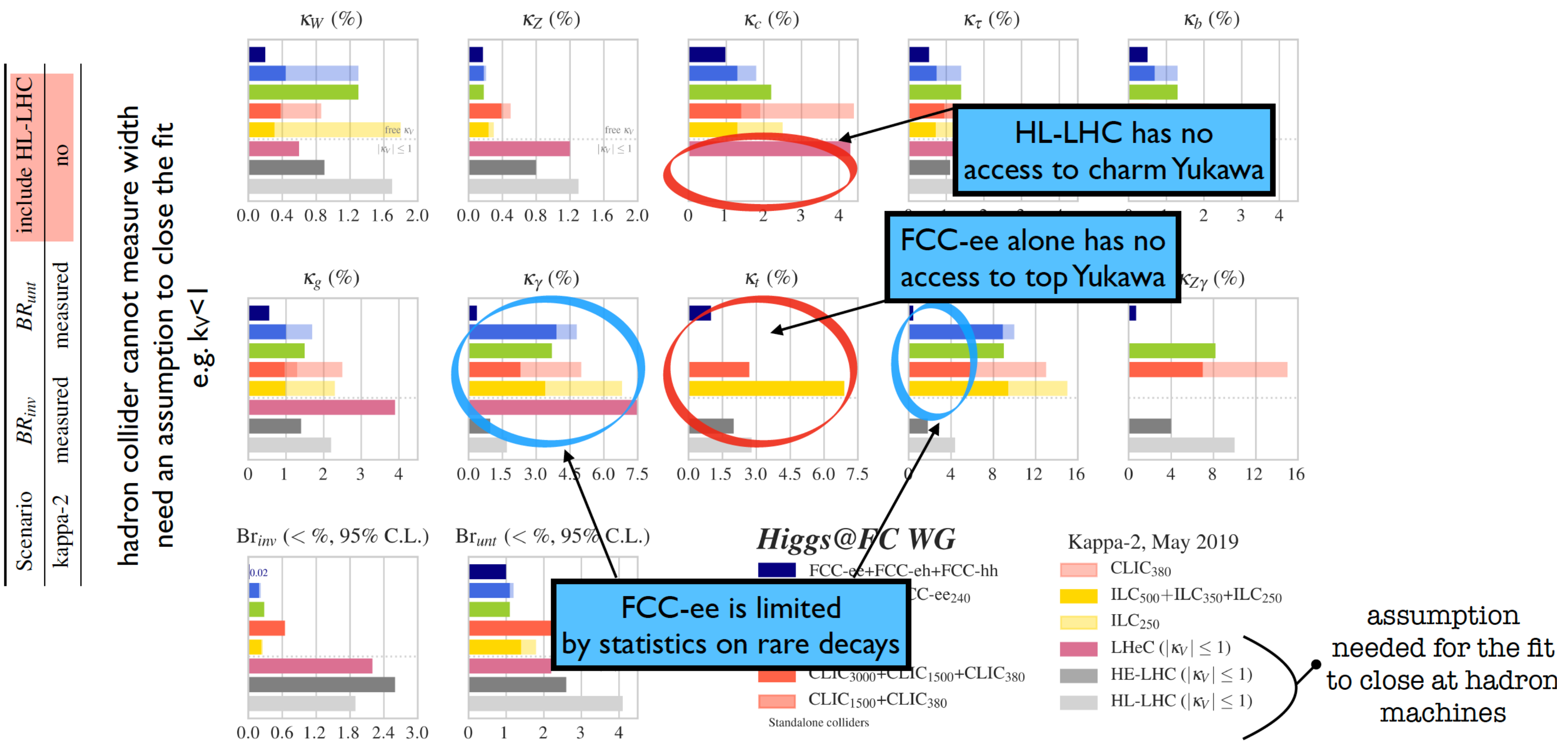
complementarity of 240/365 GeV

ECFA Higgs study group '19



Higgs@FCC-ee: complementarity with HL-LHC

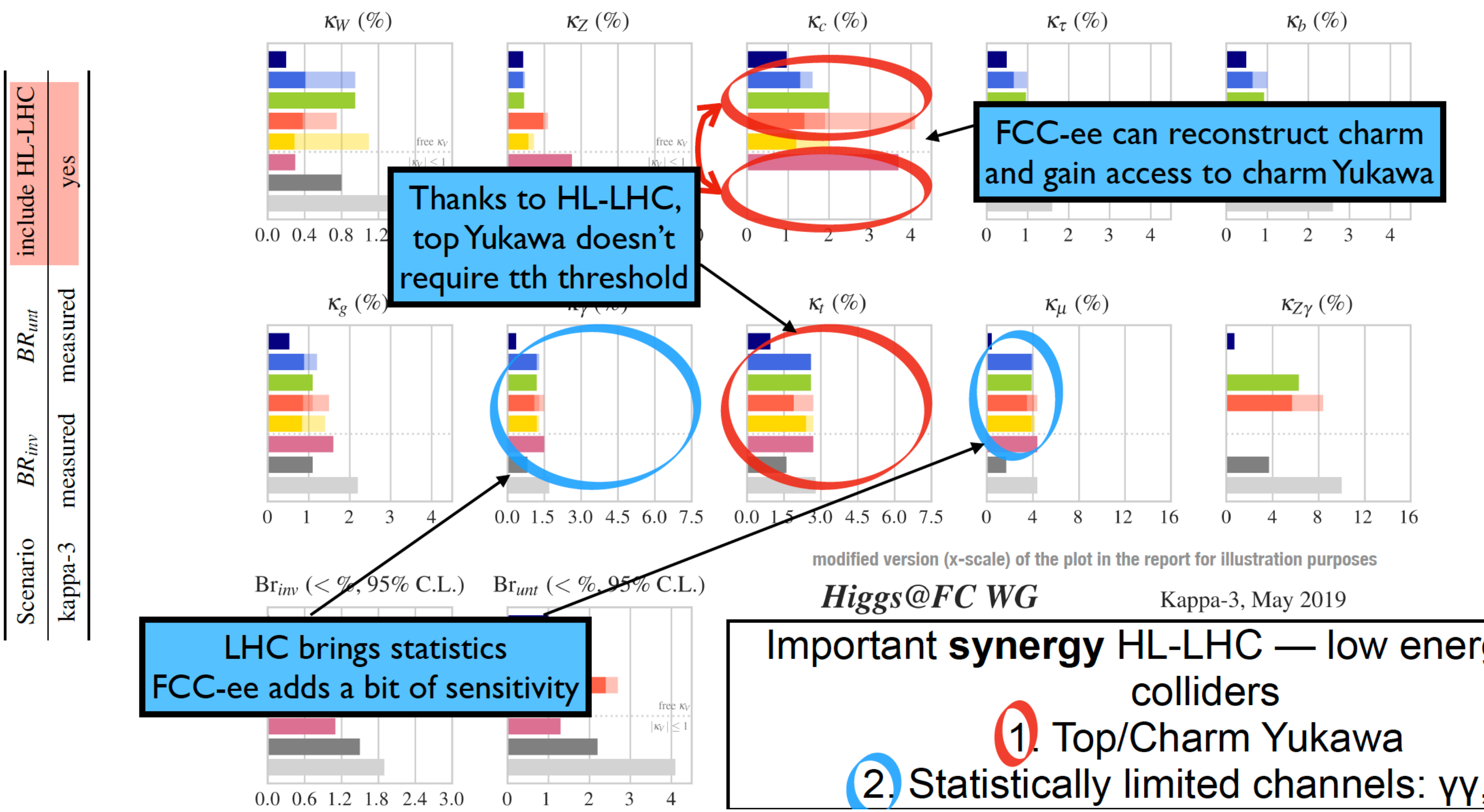
ECFA Higgs study group '19



Higgs couplings from global fits (3)

complementarity with HL-LHC

ECFA Higgs study group '19



Important **synergy** HL-LHC — low energy lepton colliders

1. Top/Charm Yukawa
2. Statistically limited channels: γγ, μμ

Summary direct measurements

	HL-LHC	FCC-ee
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**