Higgs Performance at FCC-ee

Jan Eysermans
Massachusetts Institute of Technology

FCC Week – May 31 2022

Higgs Physics potential @ FCC-ee

FUTURE CIRCULAR COLLIDER

FCC-ee offers broad potential for precision Higgs measurements

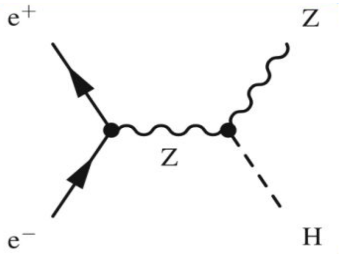
- Higgs factory: production of million Higgs bosons
- Clean environment
- Relative small backgrounds, high S/B

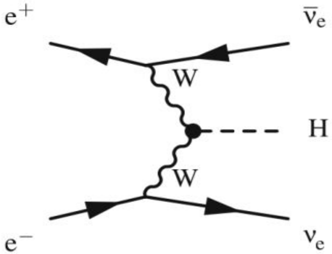
Higgs production @ FCC-ee		
Threshold	ZH production	VBF production
240 GeV / 5 ab^{-1}	1e6	2.5e4
Higgs **365 GeV / 1.5 ab^{-1}**	2e5	5e4

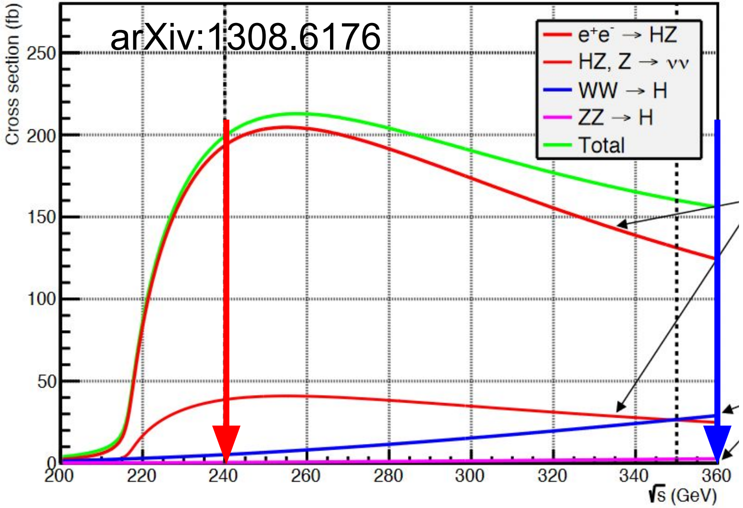
Main production mechanisms

- **ZH production** "Higgs–strahlung" – also used for light scalar at the Z-pole
- **Vector boson fusion** (VBF), WW dominant

FCC-ee Higgs performance: *exploit various production and decay channels and combination to establish the detector requirements that will match the systematic uncertainties with the statistical ones*







Strategy and challenges

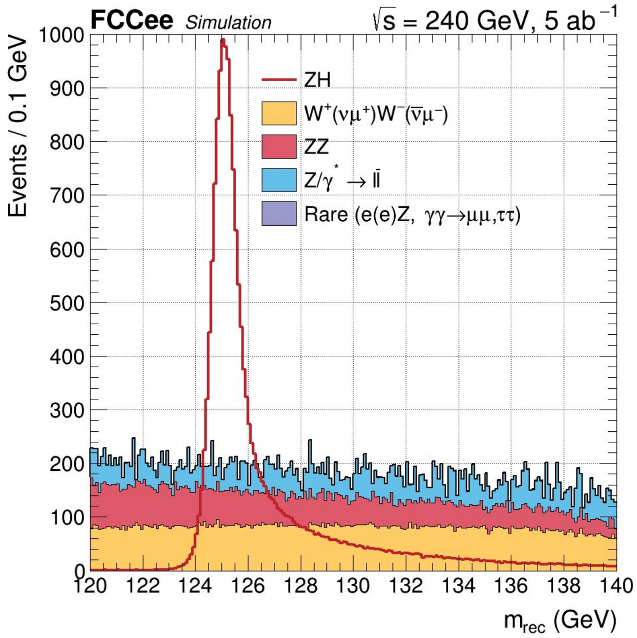
Highest precision obtained from ZH analyses @ 240 GeV

Main strategy of such analyses based on recoil method

- Tag the Z boson (tight invariant mass constraints) using leptons or jets
- Compute recoil, distribution sharp peaked at Higgs mass, width dominated by detector resolution

$$m^2_{recoil} = \left(\sqrt{s} - E_{ff}\right)^2 - p^2_{ff}$$
$$= s + m^2_Z - 2E_{ff}\sqrt{s} \approx m^2_H$$

- Either fit and/or apply cuts on recoil distribution



Backgrounds: dominated by vector boson (pair) production (WW, ZZ) and Z/γ*

Challenges

- Detector performance: resolution, tracking, vertexing, timing, angular
- Flavor tagging for Higgs couplings
- Jet reconstruction algorithms (inclusive vs. exclusive)

Overview of Higgs analyses

Broad Higgs analysis programme envisaged in the FCC-ee Higgs group

e-group: FCC-PED-PhysicsGroup-Higgs@cern.ch

Intrinsic properties

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

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)

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

Cross-section and mass: overview

→ Precise Higgs mass measurement up to ~ O(MeV)

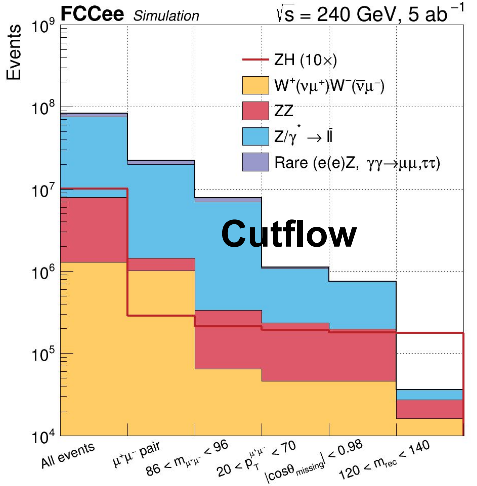
→ Model-independent cross-section, sensitive to H → invisible, new physics

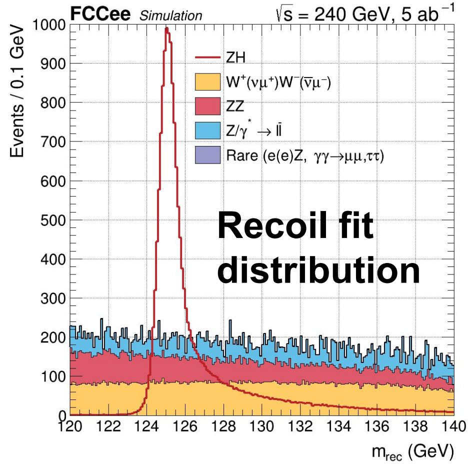
Analysis workflow based on recoil method using Z(μμ) final state

- 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 latter suppress Z/γ*, to be replaced by MVA with inputs on muon kinematics only (to preserve decay independency)
  - Already encouraging results

Potential improvements:

- Inclusion of Z(ee), but larger eeZ backgrounds; Z(qq) worse resolution
- Optimize selection for background rejection of mass measurement by abandoning the model-dependent constraint



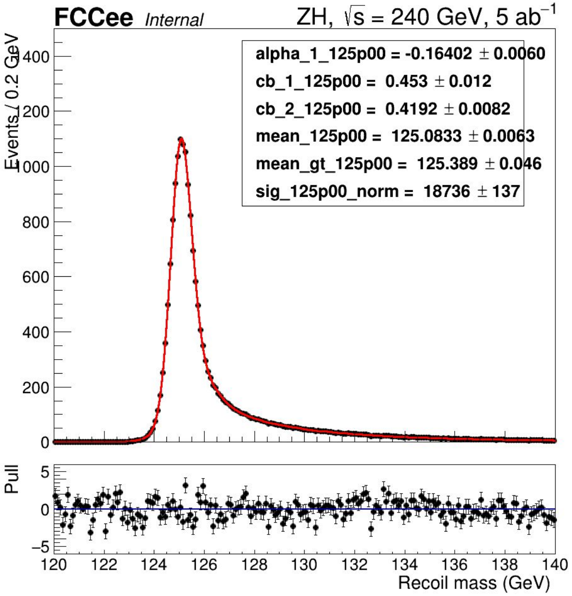


See talk A. Li at Liverpool workshop

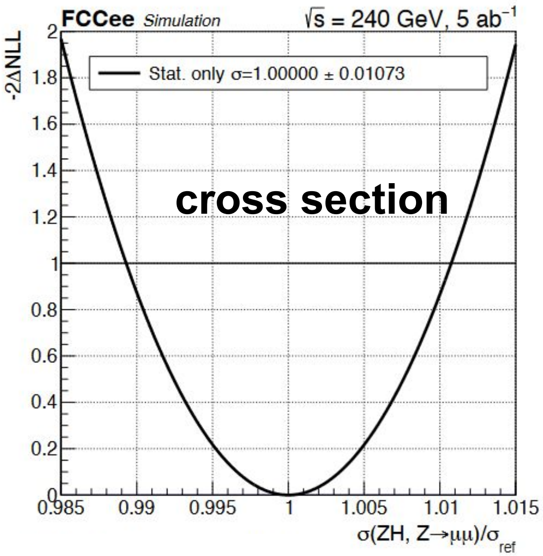
Cross-section and mass: stat.only

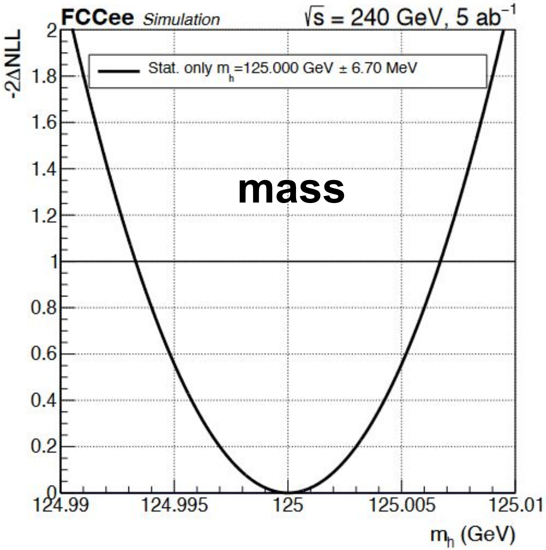
Parametric fit based on recoil mass distribution

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



Likelihood scans to extract uncertainties on cross section and mass





Stat-only uncertainties:

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

See talk A. Li at Liverpool workshop

Cross-section and mass: systematics

Potential systematic uncertainties studied and propagated to the fit

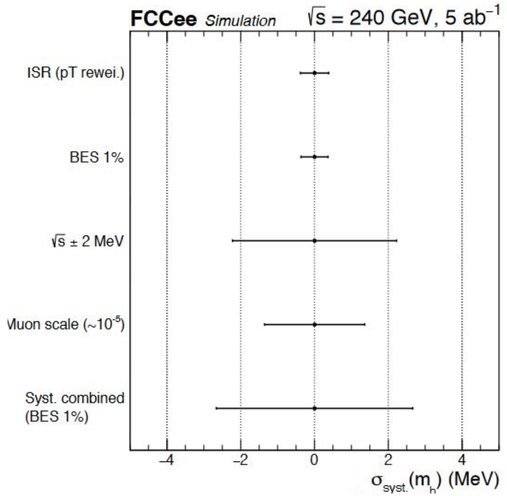
- Beam Energy Spread (BES) ~ 1% at 240 GeV, constrained using $ee \rightarrow ff(\gamma)$
- Initial State Radiation (ISR) estimated using KKMC by reweighting Whizard p_T spectrum
- Muon momentum scale ~ 1e-5
- Center-of-mass ~ 2 MeV

Systematics propagated as shape uncertainties

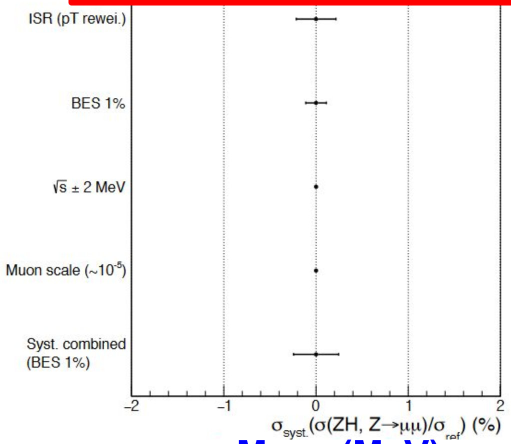
Stat + syst uncertainties:

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

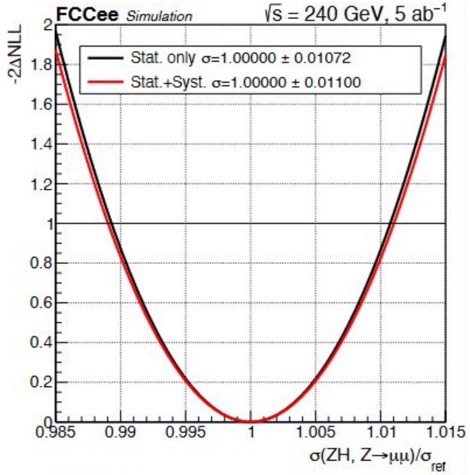
Minor impact, stat. driven

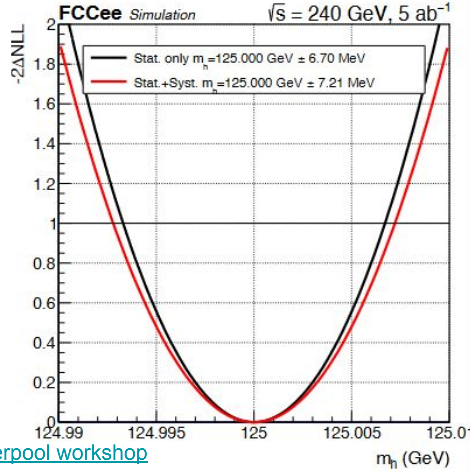


Cross section (%)



Mass (MeV)





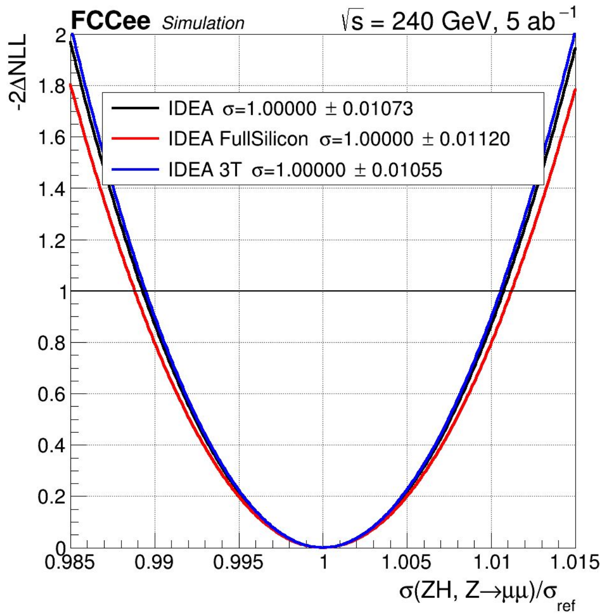
See talk A. Li at Liverpool workshop

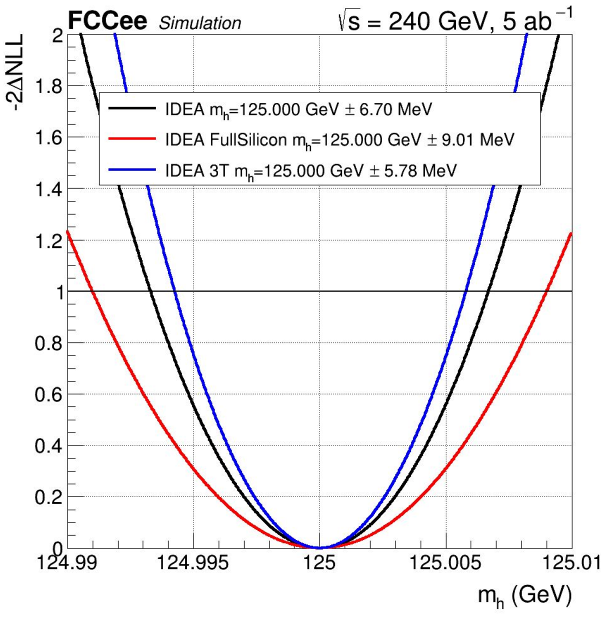
Cross-section and mass: detector configs

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 results

IDEA	Δm_H (MeV)	Δσ (%)
Nominal	**6.70**	**1.07**
FullSilicon	**9.01**	**1.12**
3T	**5.78**	**1.06**

See talk A. Li at Liverpool workshop

Higgs to hadron couplings

High precision Higgs couplings to hadrons at FCC-ee

- Bottom and charm
- Gluons
- Probe strange coupling? ~ O(100 events)

Channel	# events at ZH	Projected unc. (%)
Bottom	40k	~ 1
Charm	2k	~ 5
Gluon	7k	~ 6

(scaled to Z(ll))

Analysis channel strategies:

- Z(ll)H(qq) clean channel by tagging precisely the Z, recoil method (see next slides)
- Z(inv)H(qq) resolution
- Z(qq)H(qq) multi-jet environment, hadronic separation, jet algorithms (analysis not covered yet)

For all mentioned above, flavor tagging and jet algorithm performance important

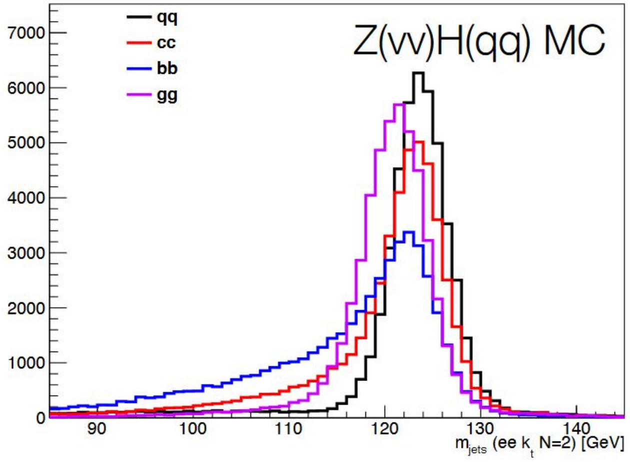
- Detector requirements (tracking, vertexing, timing)
- See dedicated talk "Towards Higgs couplings and H->inv" by M. Selvaggi later today

See talk G. Marchiori at Liverpool workshop

Higgs to hadrons 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, see talk M. Selvaggi

See talk G. Marchiori at Liverpool workshop

Higgs to hadrons Z(ll)H(qq)

FUTURE CIRCULAR COLLIDER

Event categorization based on combinatorics of the tagged jets

Fit recoil mass simultaneously in all categories

- Fit different true processes (bb, cc, gg, non-hadronic);
- Signal model Crystal-Ball
- Background modelling; polynomial
- Extract simultaneously the branching ratios

Fix the non-hadronic BR according to SM

- Assume this will be measured in precisely in other analyses, or combined fit (some constraining power in 0-jet)

S/√S+B	ZH(bb)	ZH(cc)	ZH(gg)	ZH(non hadr.)
2b	100	0	0	0
2c	0	15	0	2
1b1c	13	0	0	1
1b	69	0	0	1
1c	1	6	3	24
2g	0	0	34	1
1g	1	0	11	8
0 jets	5	0	1	16

Stat-only uncertainties:

- **bb ~ 1 %**
- **cc ~ 6.5 %**
- **gg ~ 3.0%**

Improvements possible:

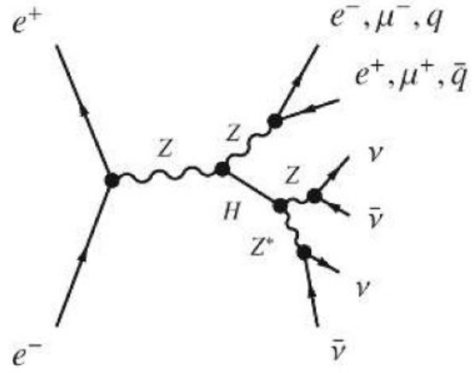
- Selection for background/non-hadr reduction (esp. cc)
- Choice of tagger, mistag, …
- Simplify categorization using MVA

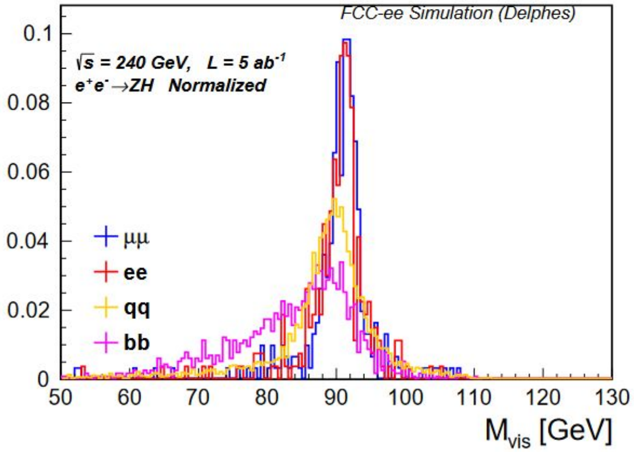
See talk G. Marchiori at Liverpool workshop

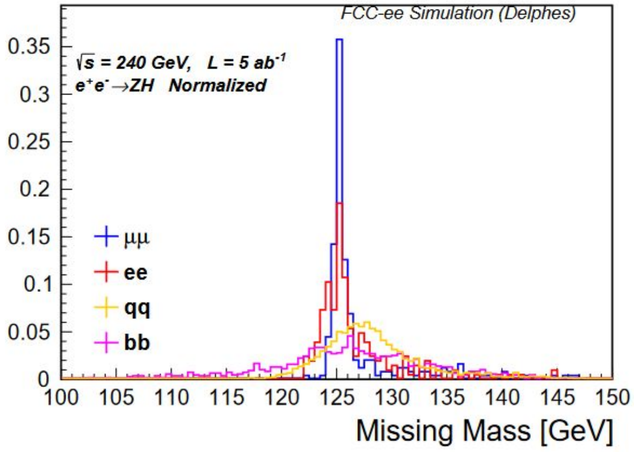
Higgs to Invisible

Exploit various decay modes of the Z to extract the invisible decay mode

- 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 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







Jet algorithm:
- Inclusive valencia
- DR = 0.5
- E ordering/scheme

bb system worse resolution due to semileptonic decays

See talk A. Mehta at Liverpool workshop

Higgs to Invisible

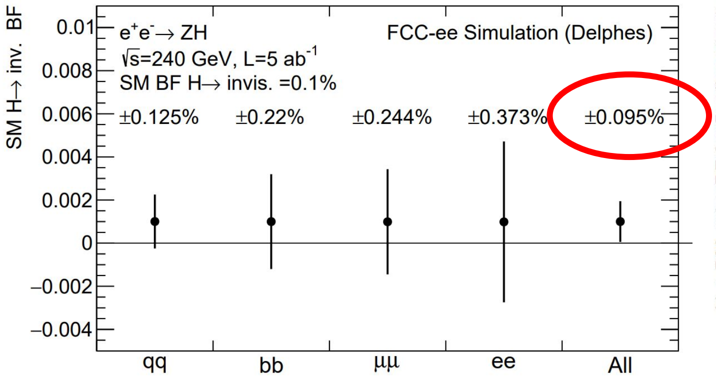
FUTURE CIRCULAR COLLIDER

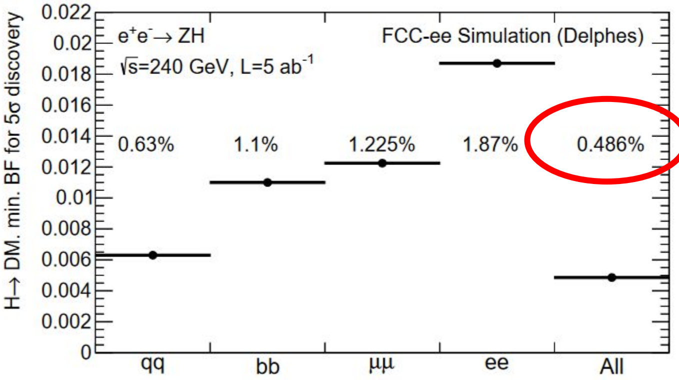
Fitting strategy and categorization

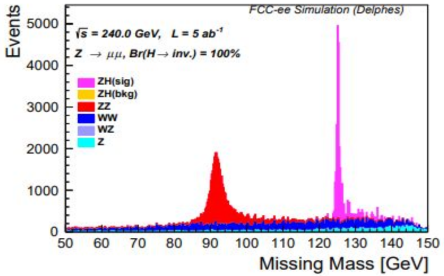
- Categorization based on 2mu, 2el and hadronic
- Hadronic channel split in jet multiplicity: < 3, =3, >3 jets, useful to constrain WW background
- Fit based on missing mass variable m_{miss}

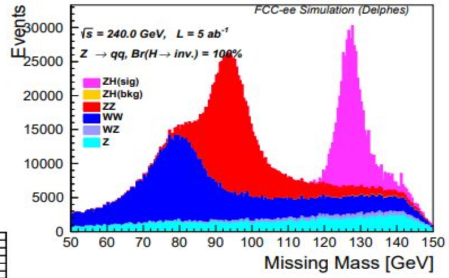
Stat-only uncertainty: H → inv ~ 0.1 %

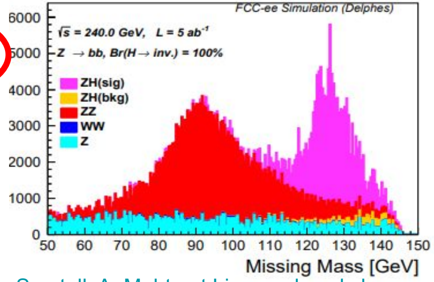
Discovery potential H → X above SM background with BR ~ 0.5 %











See talk A. Mehta at Liverpool workshop

Higgs self coupling

FUTURE CIRCULAR COLLIDER

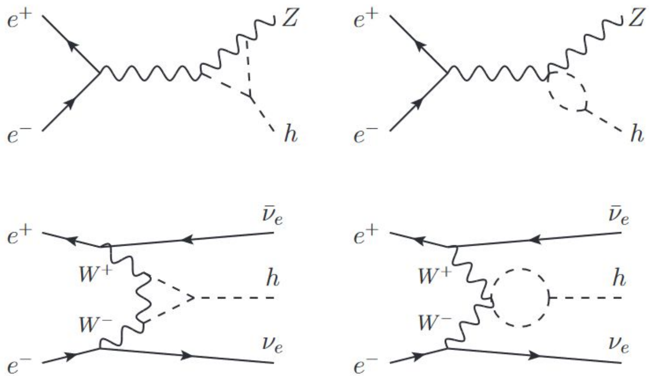
Probe *indirectly* trilinear Higgs self coupling λ_3 through single Higgs boson cross section

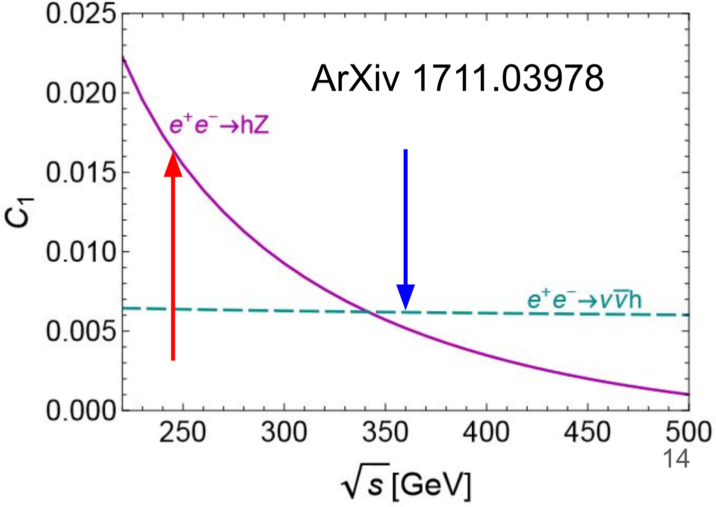
NLO from SM parameterized according to:

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

The total (NLO) cross can be measured O(1 %) at FCCee

- Therefore possible probing NLO deviations from SM: $\delta\kappa_\lambda = \kappa_\lambda - 1$)
- Parameter C_1 sensitive to $\sqrt{s}$: exploit different sensitivities at 240 GeV and 365 GeV, including VBF channels:
  - ZH @ 240 GeV
  - VBF @ 365 GeV



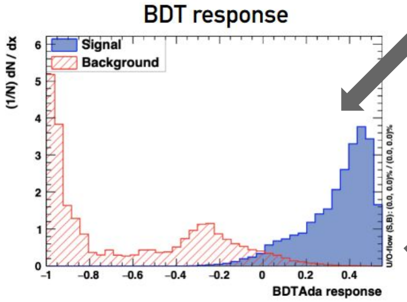


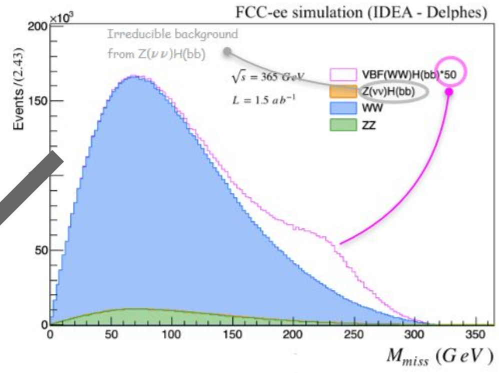
See talk R. Salerno at Liverpool workshop

Higgs self coupling: selection

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

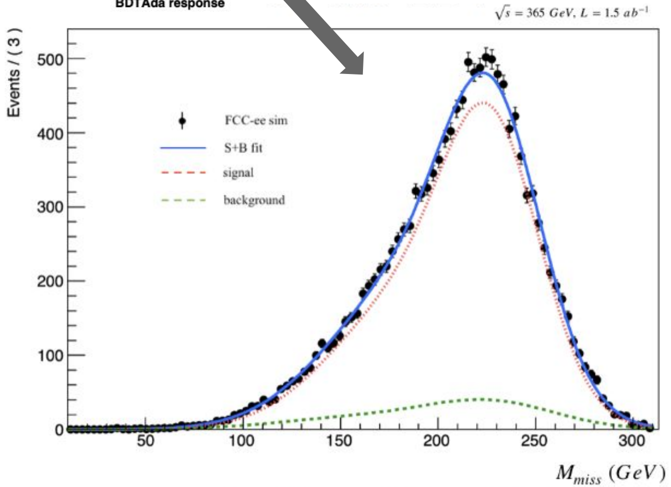
- Muon final state ~ identical to mass/cross section analysis
- Electron final state suffers from larger backgrounds (eeZ)
- Added Z(bb)H final state to profit from large statistics
    - Adaptive BDT for efficient background rejection
- Fit on recoil mass distribution





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)



See talk R. Salerno at Liverpool workshop

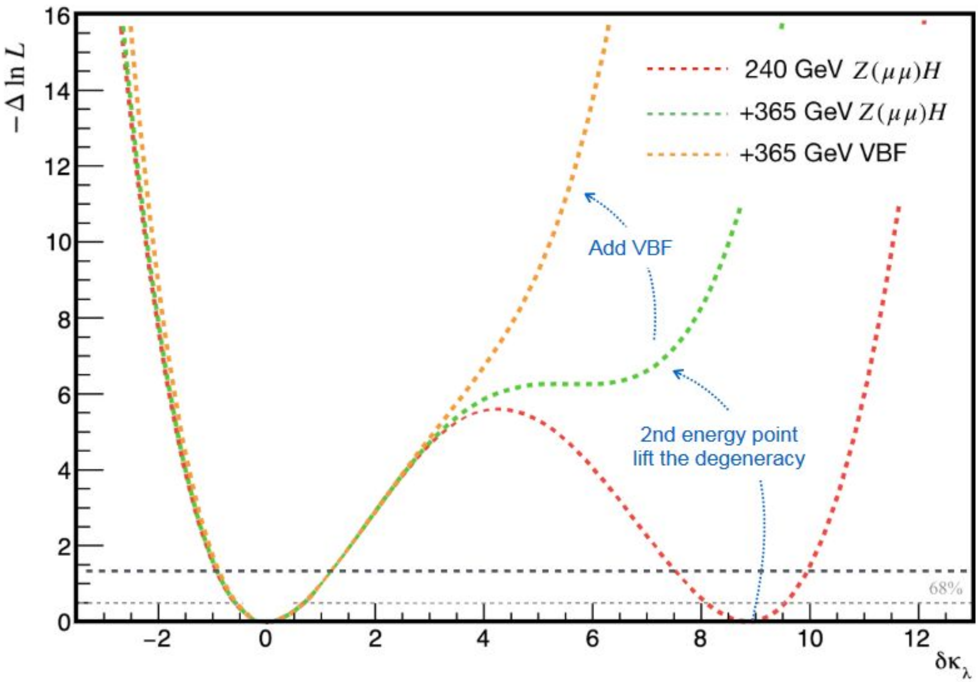
Higgs self coupling

Fit all analyses with $\delta\kappa_\lambda$ as POI

- Clearly adding 365 GeVenergy point resolves degeneracy
- Additional VBF channels yield large improvement

Analysis improvements:

- Improve statistics by adding hadronic Z(qq) channel
- Angular separation of Z(νν)H and VBF ννH interference



See talk R. Salerno at Liverpool workshop

Higgs width and electron-Yukawa

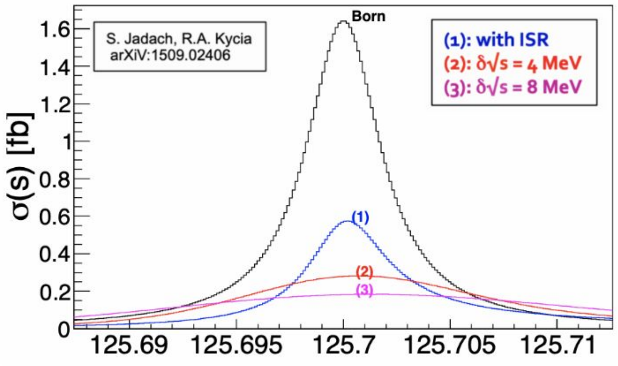
Higgs Width: measuring inclusive ZH and H→ZZ at FCC-ee @ 240 GeV

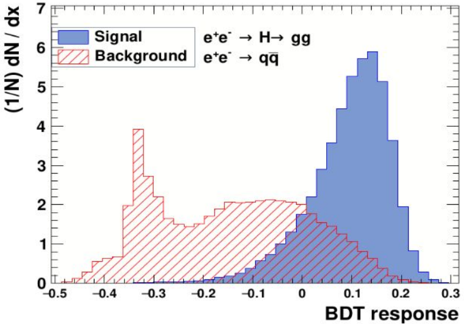
$$\frac{\sigma(e^+e^- \to ZH)}{BR(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{SM} \times \Gamma_H$$

Stat-only uncertainties ~ 1.1 %
Improvement using VBF channels and/or H → WW + e.g. H → bb
Contributions welcome!

Probe electron-Yukawa coupling:

- Direct measurement with coupling too small to be measured
- Using s-channel and beam monochromotization @ √s = 125 GeV
  - ISR+FSR → 40 % reduction δE = 4.2 MeV = Γ_H → 45 % reduction
  - Total convoluted cross section ~ 280 ab^{-1}: large lumi needed
  - With ~ 20 ab^{-1}/y @ √s = 125 GeV → ~ **6k eeH bosons /y**
- Cope with large backgrounds, H→gg most significant
  - Efficient reduction using BDT (bkg reduction 17x, sig 2x)
  - Significance at 10 ab^{-1} = 1.1 → **limit y_e < 2.5 x y_e(SM) (95% CL)**





See talk D. d'Enterria at Liverpool workshop

Summary and outlook

Presented overview of ongoing Higgs analyses at FCC-ee

Assess Higgs precision measurements with actual analysis techniques (generation → analysis → fit)

- Detector performance and optimization
- Studying jet tagging, flavor, jet reconstruction algorithms
- Study of systematic uncertainties

Open analyses still to be covered for experimental assessment

→ Contact the Higgs conveners in case of interest!

Next appointments

- Aim for regular/monthly performance meeting
- Programme + Performance meeting beginning of July (date TBD)
- Mini-workshop planned after ECFA workshop in November (TBD)

FCC-ee Higgs conveners

Performance

Michele Selvaggi, Jan Eysermans

Programme

Gauthier Durieux, Christophe Grojean, Jorge De Blas Mateo

FCC-PED-PhysicsGroup-Higgs@cern.ch