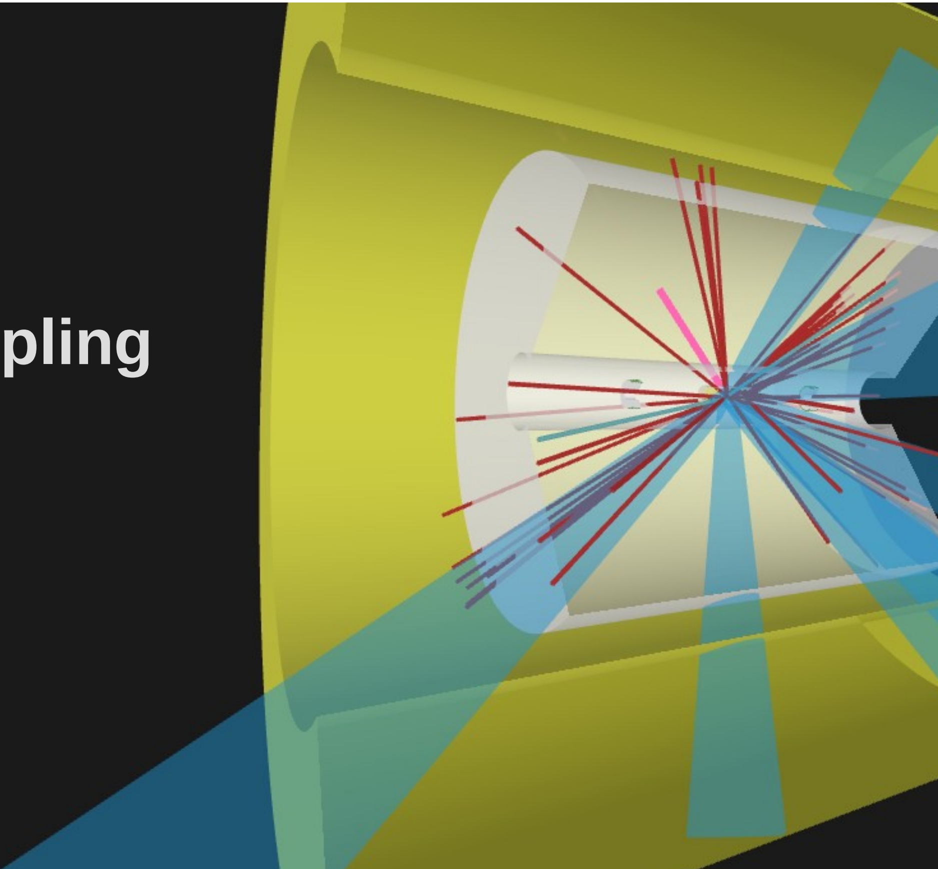


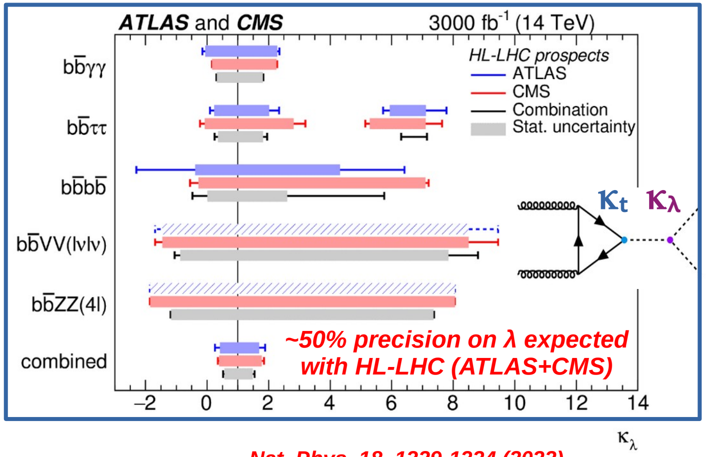
Higgs Mass, cross-section & self-coupling at FCC-ee

Louis Portalès

FCC week 2023, London – 07/06/2023

Higgs properties at (HL-)LHC

CERN-2019-007



~50% precision on λ expected with HL-LHC (ATLAS+CMS)

Extensive Higgs physics program currently ongoing at (HL-)LHC

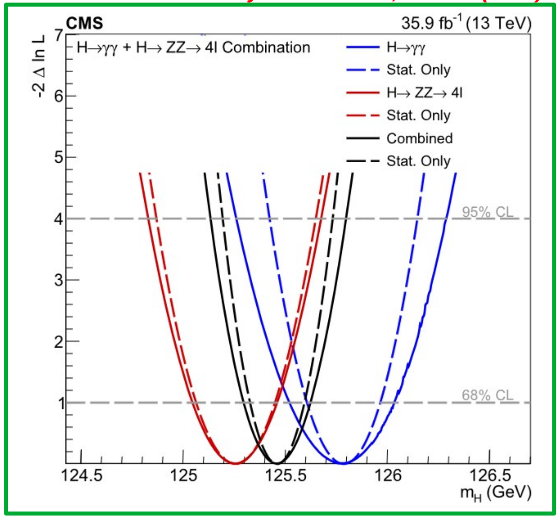
→ With impressive results, despite the harsh conditions of p-p collisions

→ **Higgs mass**, looking at H→ZZ* and H→γγ
- O(‰) uncertainties achieved by ATLAS+CMS
- Can expect ~10-20 MeV precision with HL-LHC

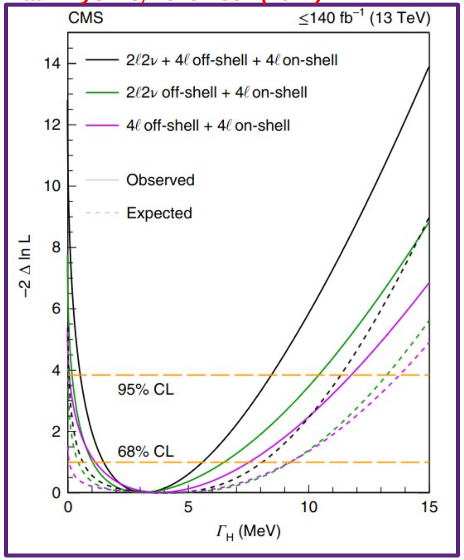
→ **Higgs width**, in H→ZZ* on- & off-shell production
- ~ 50% uncertainties with Run 2
- Great achievement, but far from “precision” realm

→ **Higgs self-coupling**, mainly in HH production
- ~ 50% uncertainty expected with full HL-LHC dataset
- Maybe pessimistic as not accounting for latest (+ future) tool developments, esp. object (b, taus, ...) tagging

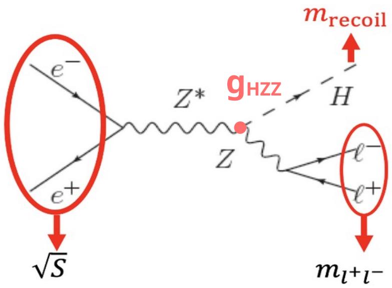
Phys. Lett. B 805, 135425 (2020)



Nat. Phys. 18, 1329-1334 (2022)



FCC-ee – Looking differently



At FCC-ee, things will look much different

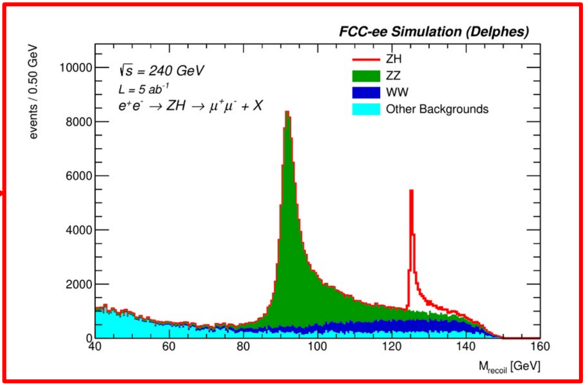
→ Two datasets enriched in ZH (@ 240 GeV) and VBF-H (@365 GeV) will be gathered

- "ZH" run @ 240 GeV: ~ 2 million ZH events, ~ 50.000 VBF-H events w/ 4IP
- "ttbar" run @ 365 GeV: ~ 400.000 ZH events, ~ 100.000 VBF-H events w/ 4 IP

→ ZH events will allow to **study the Higgs boson inclusively**, looking the associated Z boson

- Evaluating the Higgs "recoil" mass: $M^2_{\mathrm{rec.}} = s - 2E_Z\sqrt{s} + M^2_Z$
- **Clean Higgs peak to measure ZH cross-section and m_H**

  → And **unbiased access to g_{HZZ}** from production



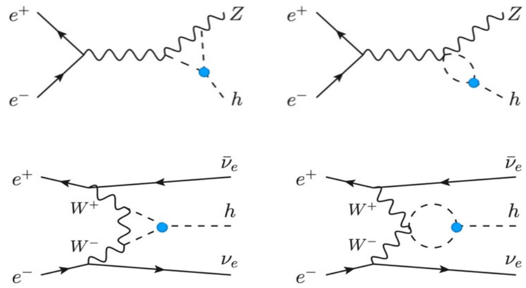
→ With g_{HZZ} precisely determined, can then **constrain Higgs total width in H→ZZ**

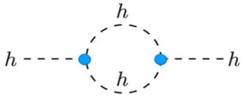
- Through simple parametrisation of cross-section measurement:

$$\sigma_{ZH} BR(H \to ZZ^*) \propto \frac{g^4_{HZZ}}{\Gamma_H}$$

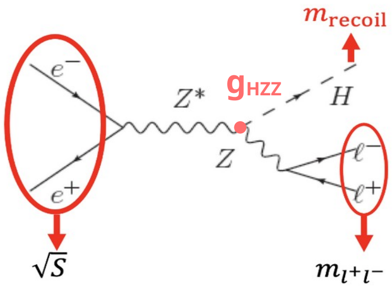
→ **Higgs self coupling** will also be accessible, through loop effects

- And probed (mostly) inclusively





FCC-ee – Looking differently



At FCC-ee, things will look much different

→ Two datasets (enriched in ZH (@ 240 GeV) and VBF-H (@365 GeV)) will be gathered

- "ZH" run @ 240 GeV: ~ 1 million ZH events, ~ 25.000 VBF-H events per IP
- "ttbar" run @ 365 GeV: ~ 200.000 ZH events, ~ 50.000 VBF-H events per IP

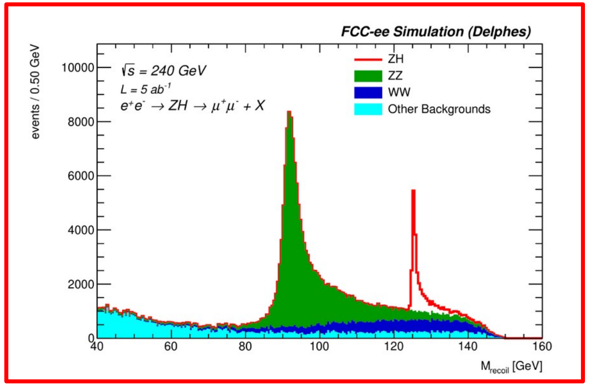
Covered by the ongoing prospect studies (and in the following slides)

Ang Li, Jan Eysermans, Gregorio Bernardi

→ ZH events will allow to **study the Higgs boson inclusively**, looking the associated Z boson

- Evaluating the Higgs "recoil" mass: $M^2_{\text{rec.}} = s - 2E_Z\sqrt{s} + M^2_Z$
- **Clean Higgs peak to measure ZH cross-section and m_H**

→ And **unbiased access to g_{HZZ}** from production



→ With g_{HZZ} precisely determined, can then **constrain Higgs total width in H→ZZ**

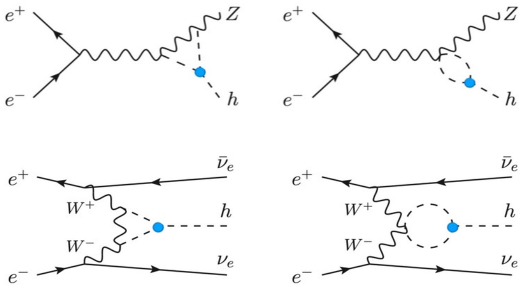
- Through simple parametrisation of cross-section measurement:

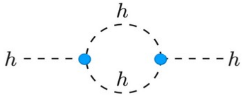
$$\sigma_{ZH} \times BR(H \to ZZ^*) \propto \frac{g^6_{HZZ}}{\Gamma_H}$$

N. Harringer, R. Salerno, L. Portales, R. Lemmon, S. Sasikumar, A.Tishelman-Charny, E. Brost

→ **Higgs self coupling** will also be accessible, through loop effects:

- And probed (mostly) inclusively





Higgs mass and ZH cross-section

→ ***Analysis focusing on Z(→ee/μμ)H***

- Small fraction of Z decays, but better resolution by far
- Allows for clean and narrow M_{rec} peak

→ ***Using “standard” FCC-PED simulations***:

- ***Simulated events from IDEA detector***

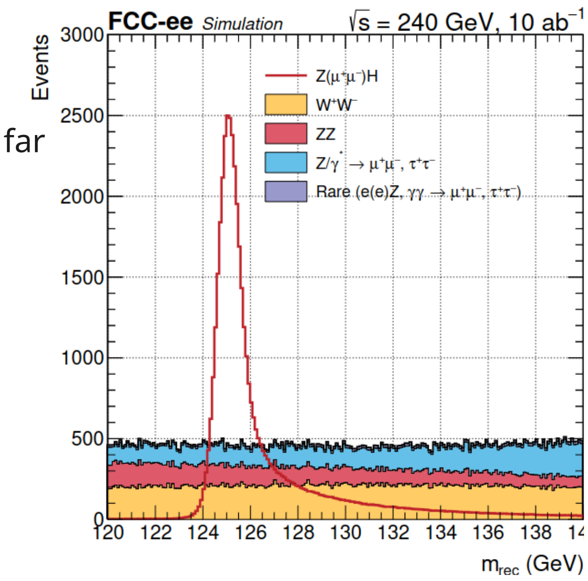
  →Excellent tracking capability w/ drift chambers
- ***Assuming 10 ab^{-1} of data***

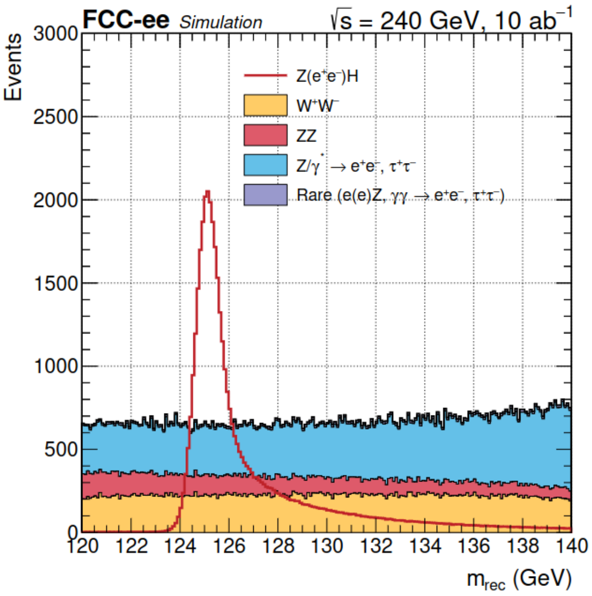
→ ***Analysis selection (in short):***

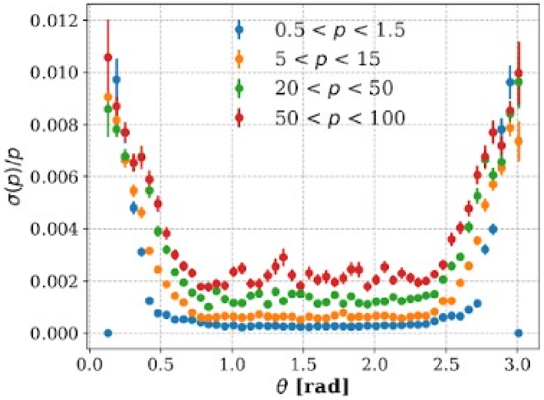
- At least 2 SFOS leptons (pT > 20 GeV)

  → at least one **isolated** lepton
- Selecting lepton pair from Z decay minimizing

  $$\chi^2 = 0.6 \times (\mathrm{m}_{\ell\ell} - \mathrm{m_Z})^2 + 0.4 \times (\mathrm{m}_{\mathrm{rec}} - \mathrm{m_h})^2$$
- $86 < m_{ll} < 96$ GeV
- $20 < p_{ll} < 70$ GeV
- $120 < M_{rec} < 140$ GeV
- ***$|\cos(\theta_{miss})| < 0.98$ (mass measurement only)***







→ ***≤0.2% momentum resolution with IDEA drift chambers***

→ ***Reduced for electrons due to bremstrahlung (despite partial recovery)***

Higgs mass and ZH cross-section

→ ***6 categories defined***

- As a function of leptons flavor & θ (CC, CF & FF)
  → ~ classified according to expected peak resolution

→ ***Using parametric model for signal & backgrounds***

- Signal: 2CBG (beyond double-sided crystal-ball):
  → combination of 2 single-sided crystal-ball and a gaussian:

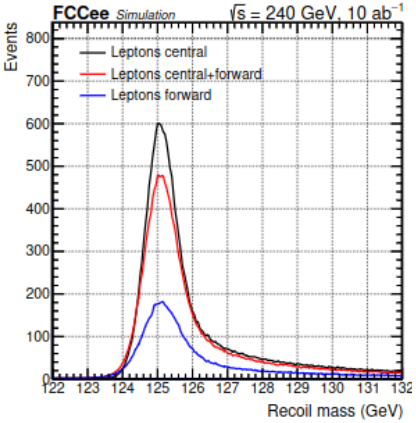
$$\mathrm{pdf}_{\mathrm{rec}} = cb_1\mathrm{CB}(\mu,\sigma,\alpha_1,n_1) + cb_2\mathrm{CB}(\mu,\sigma,\alpha_2,n_2) + \mathrm{Gauss}(\mu_{gt},\sigma_{gt})$$

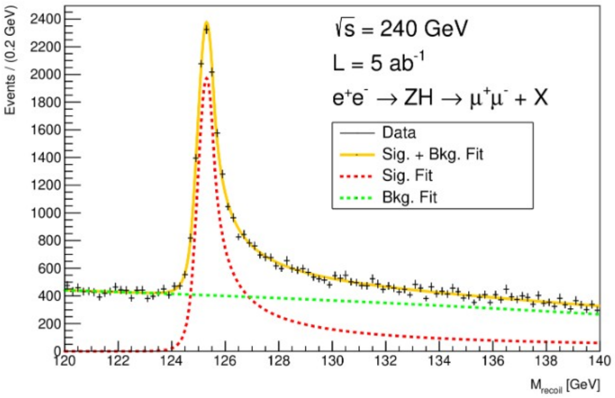
- Background: 3rd order polynomial
  → Sufficient to model smooth sum of main background in SR

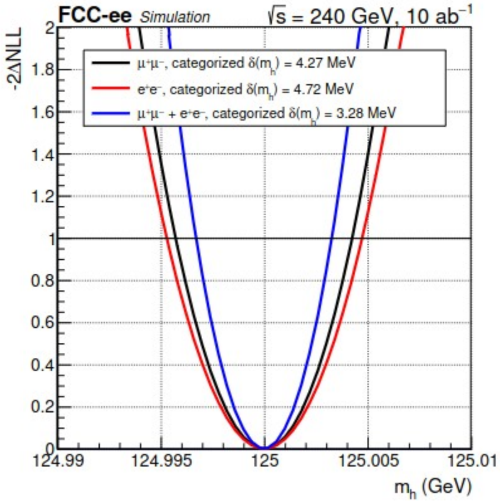
→ ***Signal extraction through likelihood fit:***

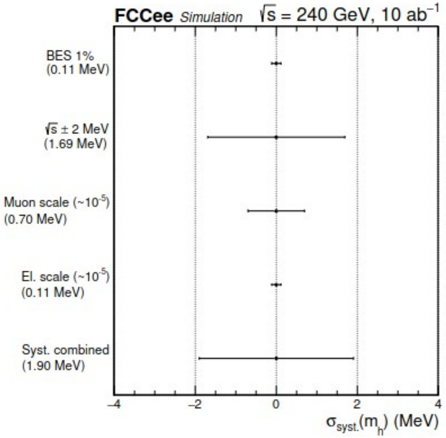
- using CMS’ combine tool
- Signal PDF parametrised as a function of mH
  → Including set of syst. uncertainties (BES, e/μ scales, √s)

Expecting δmH ~ 3.3 MeV (~ 2.67 stat. only)









Detector & machine considerations

→ ***Some extended studies performed regarding detector effects***

- Looking at impact on mH resolution

  → to be compared to **stat-only (syst.) nominal estimates**

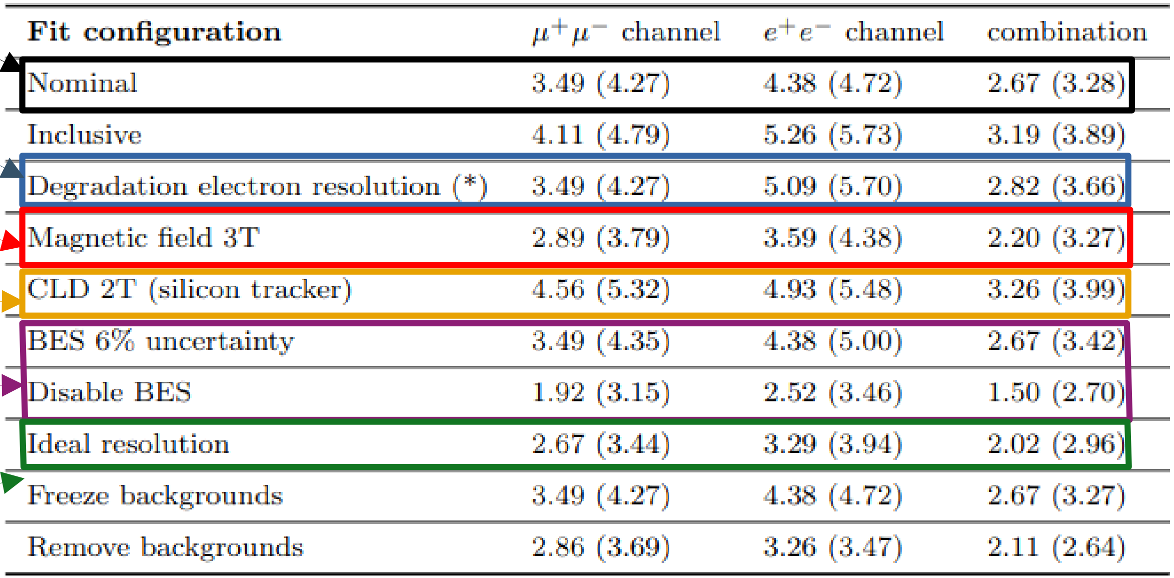
~ Going from crystal calorimeter to Dual readout (tight artificial smearing applied to electrons)

Nominal 2 T field → 3 T
(stronger field → better tracking)

IDEA drift chamber → CLD silicon tracker

Important impact of BES uncertainties AND nominal value

Assuming "perfect" (== gen-level) momentum resolution → Not so far off in some of the cases above :)



Fit configuration	$\mu^+\mu^-$ channel	e^+e^- channel	combination
Nominal	3.49 (4.27)	4.38 (4.72)	2.67 (3.28)
Inclusive	4.11 (4.79)	5.26 (5.73)	3.19 (3.89)
Degradation electron resolution (*)	3.49 (4.27)	5.09 (5.70)	2.82 (3.66)
Magnetic field 3T	2.89 (3.79)	3.59 (4.38)	2.20 (3.27)
CLD 2T (silicon tracker)	4.56 (5.32)	4.93 (5.48)	3.26 (3.99)
BES 6% uncertainty	3.49 (4.35)	4.38 (5.00)	2.67 (3.42)
Disable BES	1.92 (3.15)	2.52 (3.46)	1.50 (2.70)
Ideal resolution	2.67 (3.44)	3.29 (3.94)	2.02 (2.96)
Freeze backgrounds	3.49 (4.27)	4.38 (4.72)	2.67 (3.27)
Remove backgrounds	2.86 (3.69)	3.26 (3.47)	2.11 (2.64)

Higgs mass and ZH cross-section

→ ***Similar selection as mass measurement***

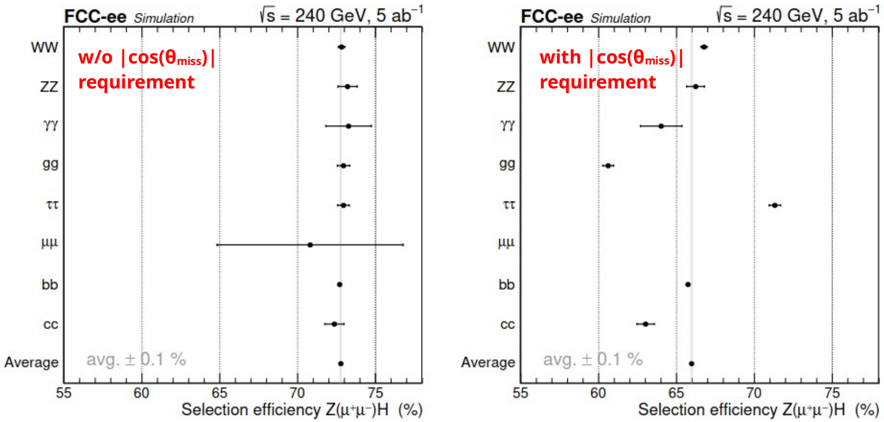
- Dropping $|\cos(\theta_{miss})|$ requirement
  → avoiding selection bias towards H decays w/ neutrinos
  → But lowers sensitivity to signal
- Instead, trained a BDT using (Z) leptons kinematics
  → To help recover lost sensitivity

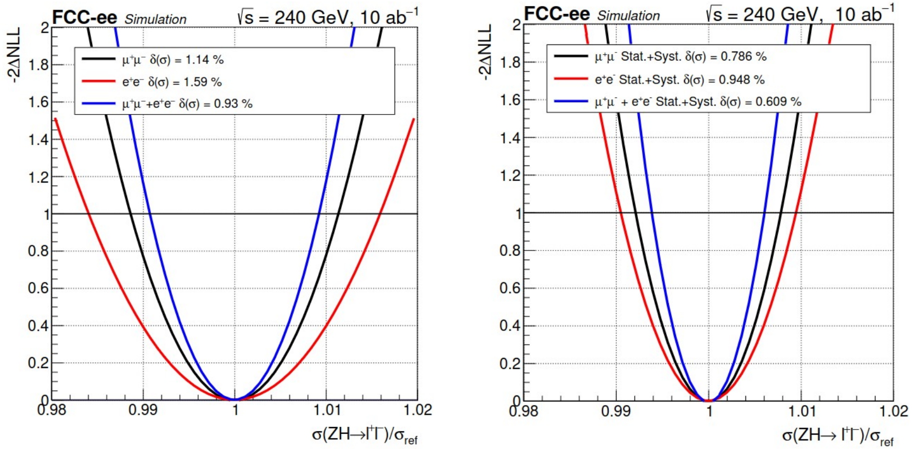
→ ***Comparing fitted cross-section with Mrec & BDT score***

- Binned likelihood fit of distributions
  → With cut on BDT for M_{rec} fit

Expecting $\delta\sigma$ ~ 0.61% (~ 0.60% stat. only) fitting BDT score

$\Delta\sigma$ ~ 0.93% (~ 0.55 stat. Only) with M_{rec}





Higgs self-coupling

Involved in single-higgs processes at NLO

$$\sigma_{i,\mathrm{NLO}} = \underbrace{Z_{\mathrm{H}}}\underbrace{\sigma_{i,\mathrm{LO}}}\left(1+\kappa_\lambda \underbrace{C_{1,i}}\right)$$

Universal wave function renormalization

LO cross-section

Process & energy dependent coeff. From loop-tree interference

→ Can be probed **exclusively**

- Combined fit of all decay modes
- Under consideration (@ BNL: A.Tishelman, E.Brost)

→ Or (partially) **inclusively**

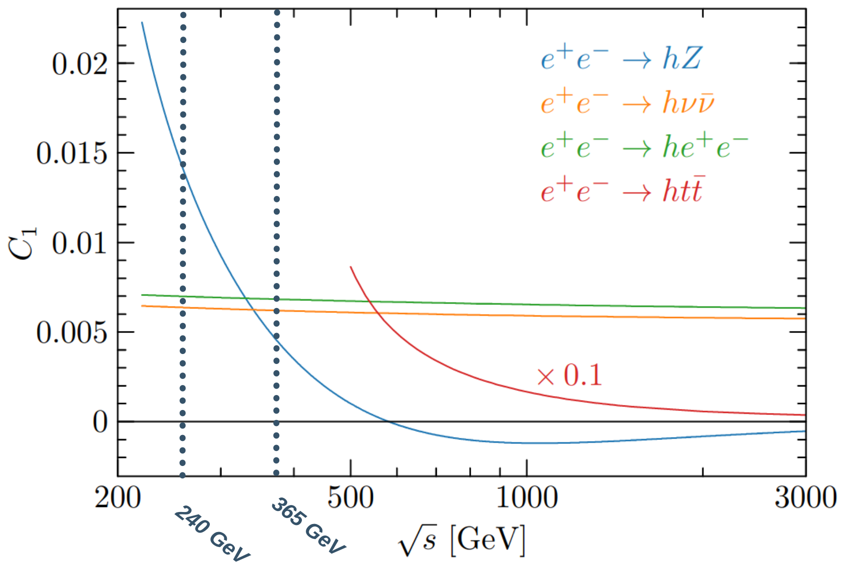
- With combined analysis @ 240 GeV & 365 GeV

  → Discussed in the following slides

Decay Modes

$C_1^\Gamma[\%]$	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66

$$C_1^{\Gamma_{\mathrm{tot}}} \equiv \sum_j \mathrm{BR}^{\mathrm{SM}}(j) C_1^\Gamma(j) \sim 2.3\mathrm{x}10^{-3}$$



Phys. Rev. D 92, 039903 (2015)
J. High Energ. Phys. 2016, 80 (2016)
J. High Energ. Phys. 2018, 178 (2018)

Higgs self-coupling – Analysis

→ ***Analysis setup***:

- **Spring 2021 samples** (older baseline w/ IDEA detector)

  → to be updated!

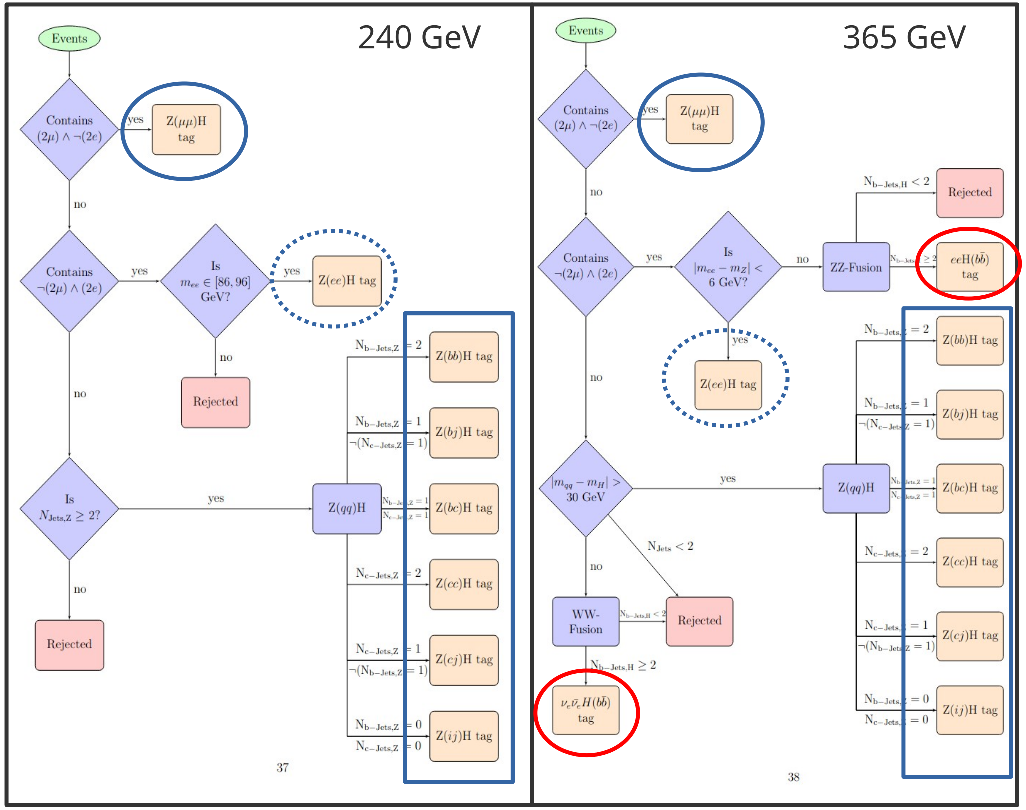
→ ***Categorization tuned for the two energy points (240, 365 GeV)***

- 18 orthogonal categories

  → 2x2 Z(ee/μμ)H categories – similar to mass & xsec analysis

  → 2x6 Z(qq)H categories – per qq flavor

  → Additional eeH(→bb) & ννH(bb) categories @ 365 GeV



Inclusive λ measurement – ZH selection

	b jet	c jet	l jet	g jet
b tag	0.80	0.08	0.01	0.01
c tag	0.10	0.60	0.01	0.03
l tag	-	-	0.80	-

→ ***Similar selection as mH/cross-section analysis for Z→ee/μμ***

- (looking for the same process)

→ ***Tuned selection for Z→qq***

- ***6 flavor categories (bb,cc,ll,bc,bl,cl)***

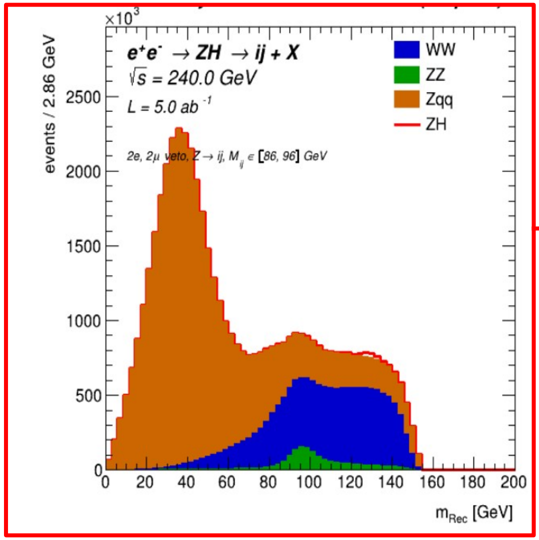
  → Assuming ad-hoc tagging efficiencies

  → Dedicated Z→cc optimisation ongoing (@BNL)
- $86 < m_{qq} < 96$ GeV
- $120 < M_{rec} < 140$ GeV
- $|\cos(\theta_{miss})| < 0.90$

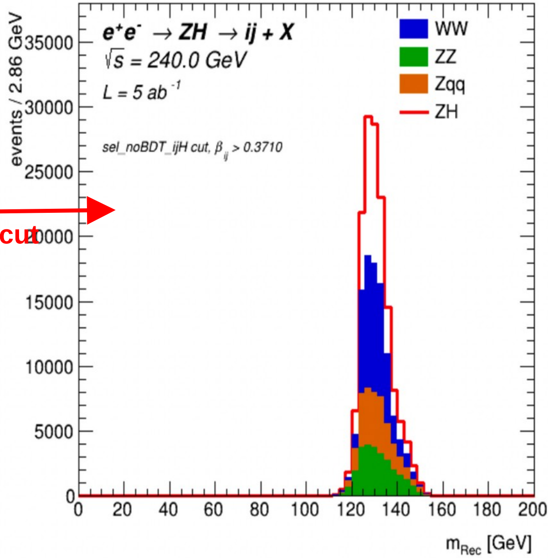
→ ***BDT used for selection***

- One per flavor category

  → Using only Z→qq kinematics



BDT cut



Inclusive λ measurement– VBF selection

→ ***Recoil mass not sufficient to properly isolate a Higgs peak in VBF***

- Instead, looked at VBF H→bb

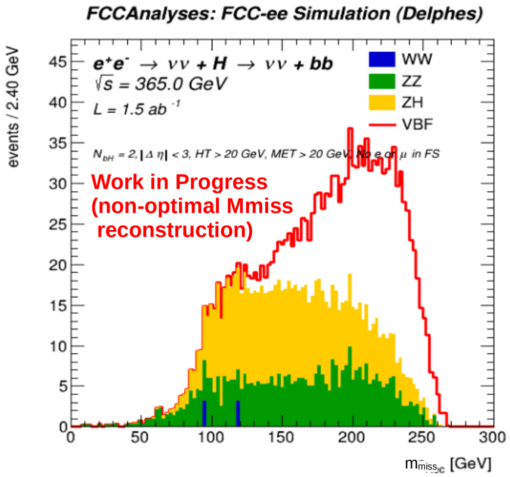
  → Exclusive measurement, some model-dependance introduced

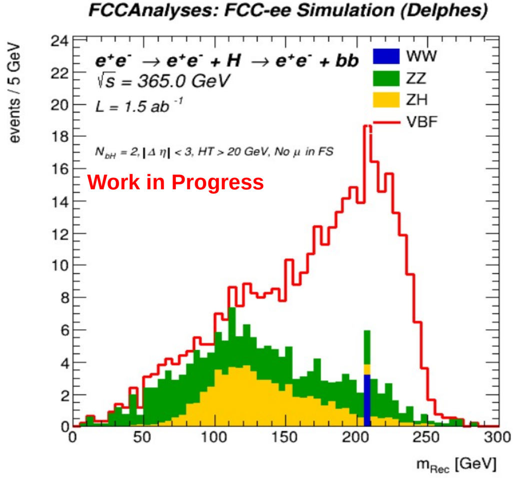
→ ***Defining selection adapted to VBF***

- No μμ pair reconstructed (ννH: no ee pair either)
- 2 b-tagged jets
- H_T > 20 GeV, $|\Delta\eta_{bb}|$<3 (ννH: + MET>20 GeV)
- $|M_{ee} – M_Z|$>=6 GeV (eeH)
- $|M_{qq} – M_H|$<= 30 GeV (ννH)

→ ***Still using Mrec as template variable for the fit***

- Cutting on BDT discriminants, using (b-)jet kinematics and multiplicity as inputs





Inclusive λ measurement – combined fit

→ ***Measuring cross-section & coupling modifier***

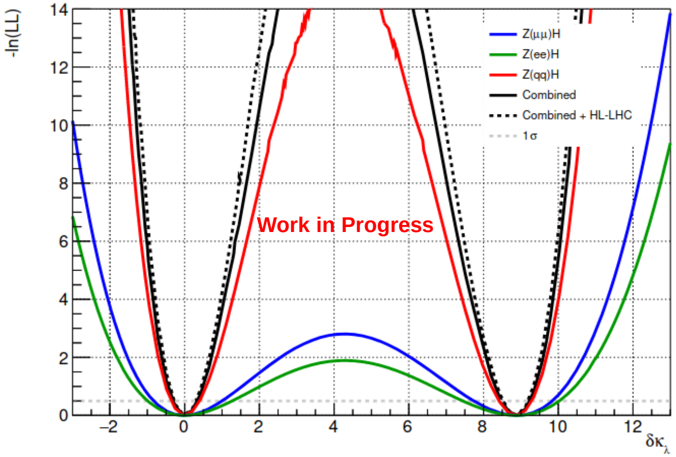
- Parametrised cross-section as a function of κ_λ
- Fitting all categories (ZH + VBF) together

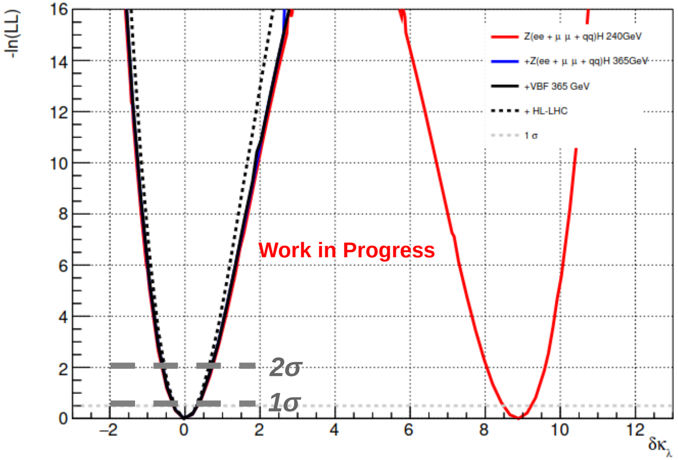
→ ***Assuming:***

- 0.1% luminosity uncertainty
- 1% selection efficiency uncertainty
- 2.8 MeV uncertainty on CoM energy
- m_h = 125.38 +/- 0.14 GeV (latest CMS result)
- Higgs decay BRs (H→bb) fixed to SM values

→ **Reaching $\delta\kappa_\lambda$ ~ 30% (~20% with 10 ab^{-1})**

- Combining with HL-LHC expected constraints
- Sensivity driven by Z(qq)H categories
- Adding ZH@365GeV resolves degerated minima
- Negligible impact from VBF-H





Conclusion & take-away

Prospective study of Higgs parameters (mass, cross-section, self-coupling) @ FCCee

- → **Mainly targeting inclusive ZH production @ 240 GeV** (+ exclusive VBF-H @ 365 GeV for λ)

  → Reaching excellent precisions assuming baseline scenario (IDEA detector & 10 ab^{-1})

Excellent playground to understand detector requirement

→ **Detector/beam performance impact probed in mH measurement:**

- Clear gains from higher field (better lepton momentum resolution) & better control of BES
- Ecal design would impact Z→ee category, but sensitivity driven by Z→μμ

→ **Jet performance would significantly influence sensitivity to λ (driven by Z→qq categories)**

- Good physics usecase to compare calorimeter designs

Room for fine-tuning and to get to a better understanding/more educated design choices

→ ***Include more (and more realistic) systematics in the studies (esp. mH measurement)***

→ ***Refresh analyses with state-of-the-art tools (e.g. ParticleNet), latest samples & detector performance estimates (esp.*** **λ measurement)**

Back up