Higgs mass and ZH cross-section

Gregorio Bernardi[1], Jan Eysermans[2], Ang LI[1]

On behalf of the ZH analysis team

FCC Physics Workshop
Jan. 27th, 2023
Krakow

1,APC-Paris, Université Paris Cité, CNRS/IN2P3
2, MIT

Outline

- ☐ **Motivation and introduction**
- ☐ **Higgs-self coupling**
- ☐ **Basic selection for Higgs mass and Cross-section**
- ☐ **Higgs mass measurement**
  - Signal and background modelling
  - Higgs mass statistical analysis
  - θ categorisation
  - Systematics
- ☐ **Cross-section measurement**
  - BDT-based selection
- ☐ **Conclusion**

Motivation

- **Goal: precise measurements of ZH cross section and Higgs mass**
  - Current best result LHC: $m_H = 125.38 \pm 0.14(\pm 0.12)$ GeV
  - At FCC-ee, m_H and σ_{ZH} accuracy will reach a few MeV and 0.5%, respectively
    - → Measure g_{HZZ}, Higgs width (Γ_H) and other Higgs couplings

See Jorge de Blas's talk for Higgs couplings fit

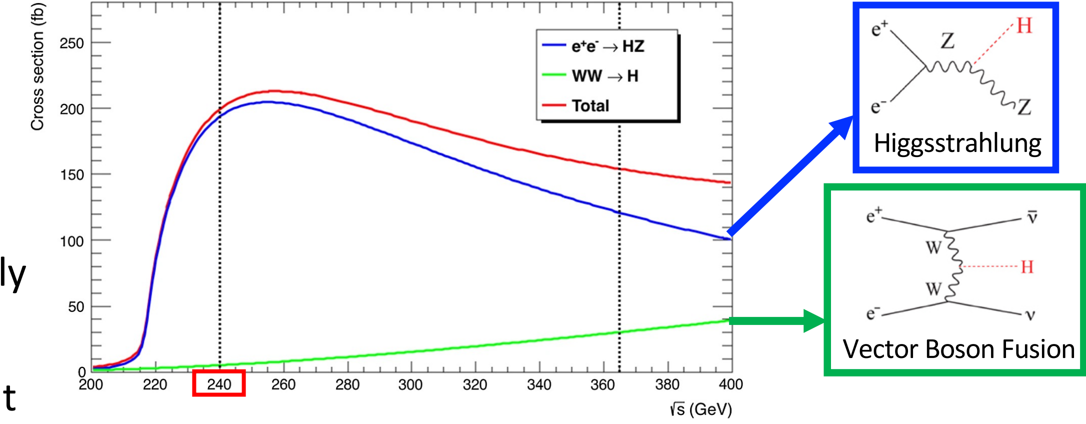
- **Signal: $e^+e^- \rightarrow ZH \rightarrow l\bar{l} + X$**

ZH is the dominant Higgs production process @ 240 GeV e^+e^-machine

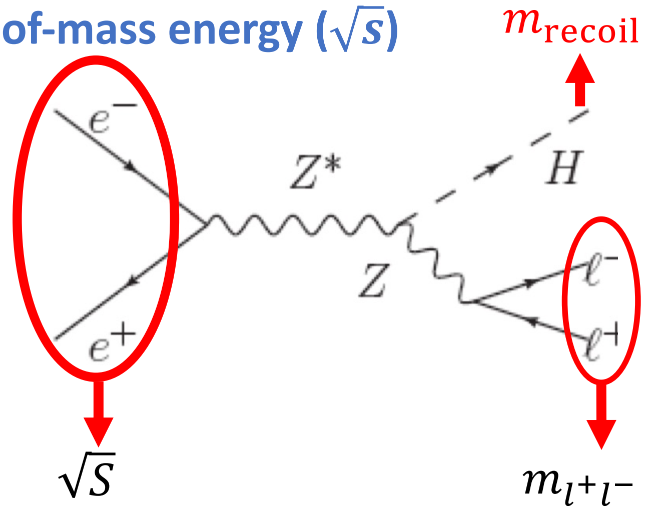
- **Model-independent study**
- **M_{recoil} from the Z production without measuring the Higgs production final state**

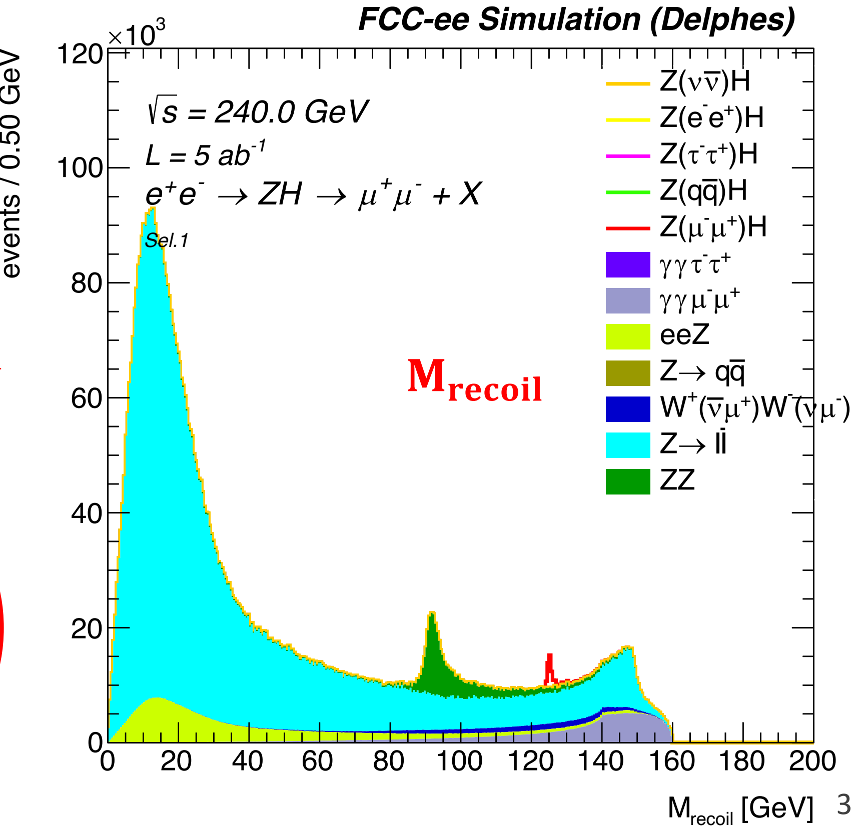
$$\boxed{m_{\text{recoil}}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2}$$

- **Sensitive to the precise knowledge of the centre-of-mass energy ($\sqrt{s}$) and Initial State Radiation (ISR)**
- **WW, ZZ and dilepton backgrounds @ 240 GeV**



1. ZH optimal event rate is at $\sqrt{s}$ ~ 240 GeV : $\sigma \sim 200$ fb ~ 10^6 events (@ $L = 5\ ab^{-1}$)
2. Data at $\sqrt{s} \sim 365$ GeV,1.8×10^5 ZH and 0.45×10^5 WW-fusions (~30%) (@ $L = 1.5\ ab^{-1}$)



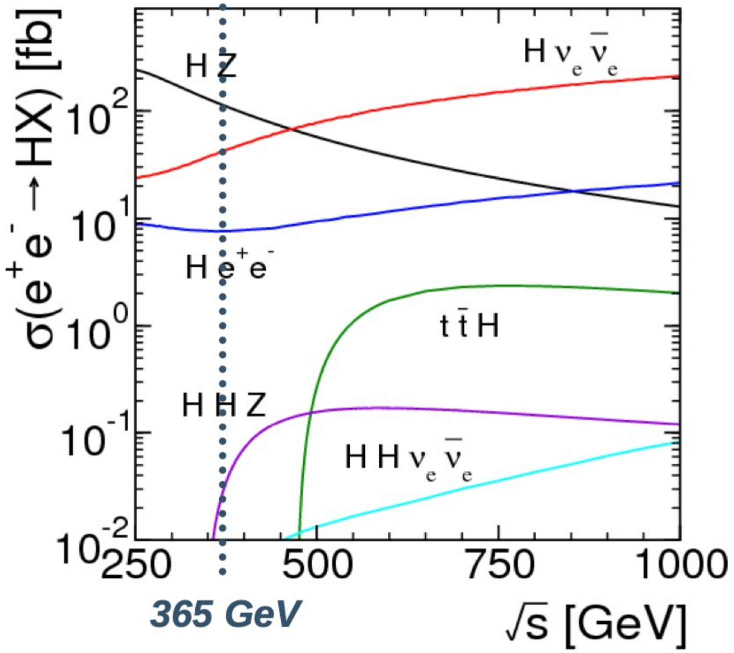


Higgs-self coupling

- **FCC-ee will run below the requirement for HHZ production (above 365 GeV)**
  No direct access to λ

- **Large ZH (@240 GeV) and VBF-H (@365 GeV) cross-section:**
  With intervention of λ at loop-level:
  Sensitive to the cross-section measurement shown above

$$\sigma_{i,\mathrm{NLO}} = \underbrace{Z_{\mathrm{H}}}_{\text{Universal wave function renormalization}} \underbrace{\sigma_{i,\mathrm{LO}}}_{\text{LO cross-section}} \left(1 + \kappa_\lambda \underbrace{C_{1,i}}_{\text{Process \& energy dependent coeff. From loop-tree interference}}\right)$$



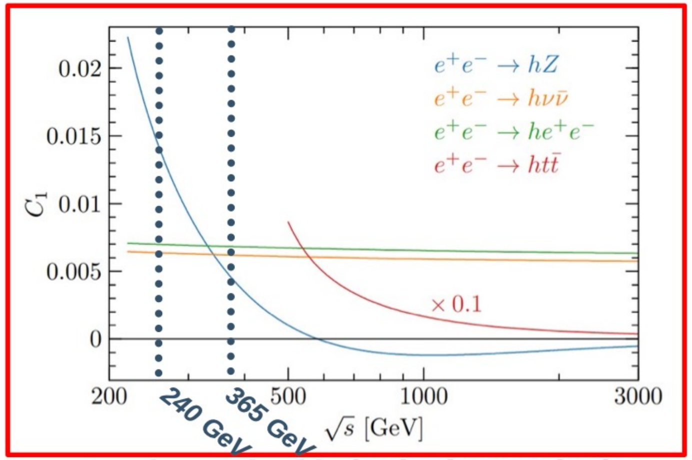
Decay Modes

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

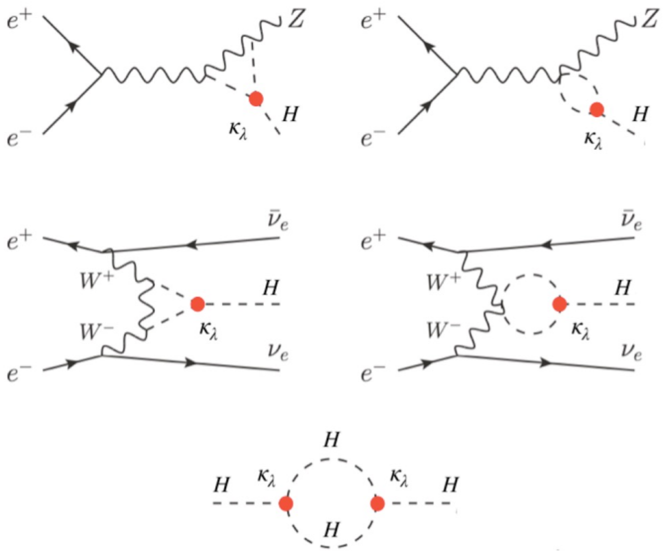
$C_1^{\Gamma_{\rm tot}} \equiv \sum_j \mathrm{BR}^{\mathrm{SM}}(j) C_1^\Gamma(j)$ ~2.3x10-3

Can be probed in exclusive analyses targetting the specific Higgs decays

J. High Energ. Phys. 2016, 80 (2016)
J. High Energ. Phys. 2018, 178 (2018)



Can be probed in inclusive analysis looking at the two relevant energy points



See Jorge de Blas's talk

Talk by Louis Portales on FCC-France-Italy Workshop

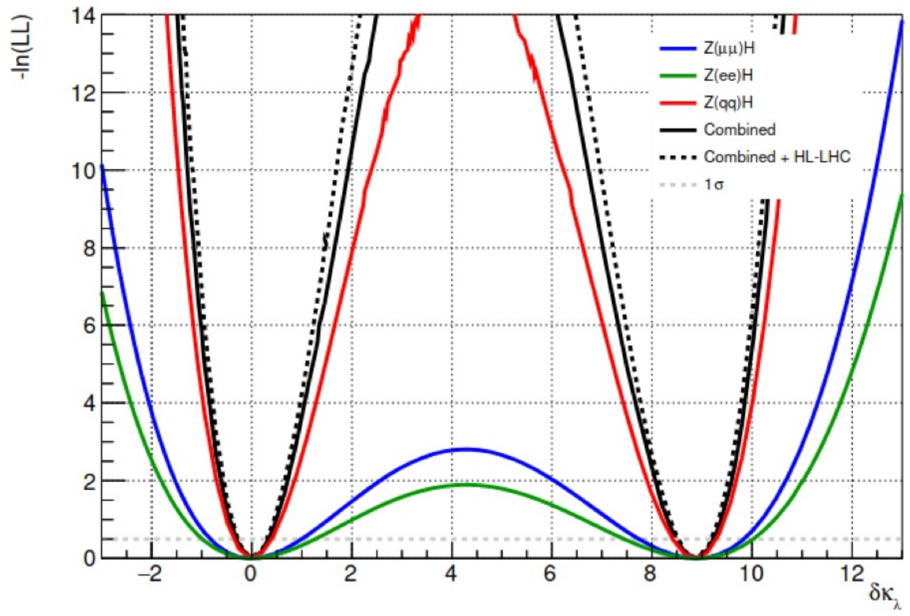
FUTURE CIRCULAR COLLIDER

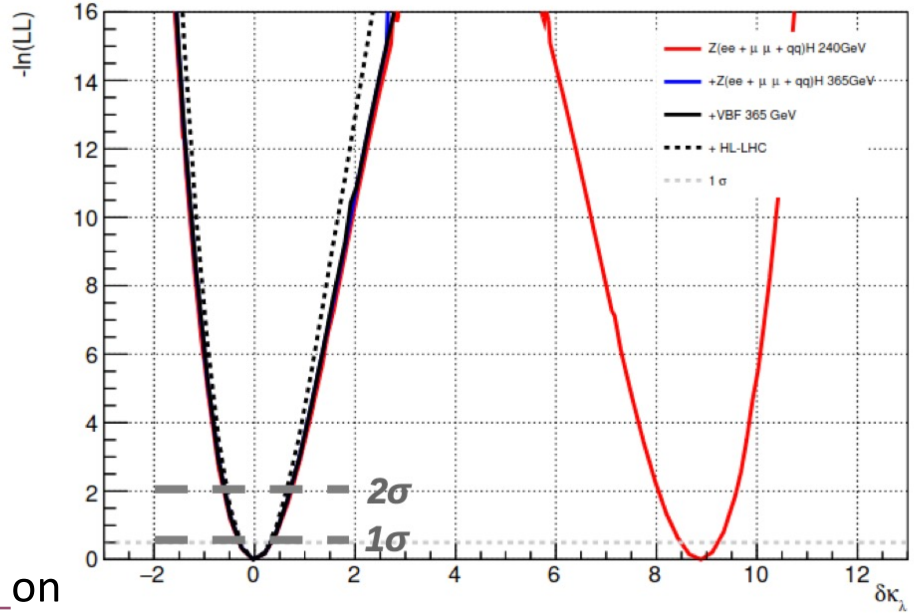
Higgs-self coupling results

- **Recoil technique**
- **Z boson decay channels: $\mu^+\mu^-, e^+e^-, q\bar{q}$**
- **Assuming:**
  - 0.1% luminosity uncertainty
  - 1% selection efficiency uncertainty
  - 2.8 MeV uncertainty on center-of-mass energy
  - $m_H = 125.38 \pm -0.14$ GeV (latest CMS result)
  - Higgs decay BRs ($H \rightarrow b\bar{b}$) fixed to SM values

Reaching $\delta_{\kappa_\lambda} \sim 30\%$

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





Talk by Louis Portales on FCC-France-Italy Workshop

Signal, Background Monte-Carlo simulation, Event Selection

Monte-Carlo simulation:

- $\sqrt{s} = 240$ GeV
- Luminosity: $L = 5\ ab^{-1}$
- Initial State Radiation (ISR) and Final State Radiation (FSR) on
- Beam Energy Spread (BES) set to nominal BES: ± 0.185% = ± 222 MeV (Spring 2021: 0.165%= ± 198MeV)
- IDEA detector; detector response modelled with Delphes
- Winter 2023 for mass determination (Spring 2021 for cross-section studies)

  Since winter2023, we have well defined electrons in the collection, with energy smearing 1.2 w.r.t. muons

Event-Selection (Baseline):

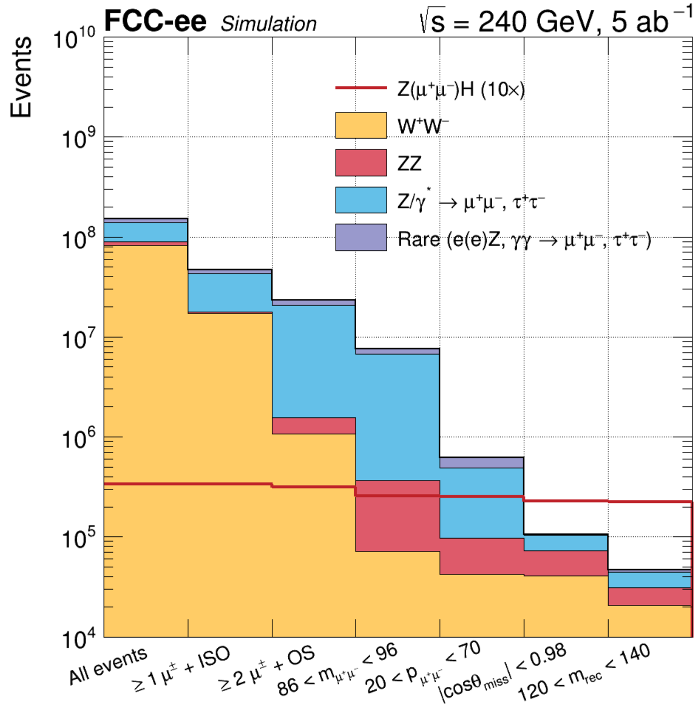
1. Select at least 2 leptons:
   - Momentum $p_l > 20$ GeV
   - Opposite sign
   - One lepton required to be isolated
2. Pair the leptons in case more than 2 leptons found:
   - Take pair that minimizes
     $$\chi^2 = 0.6\times(m_{ll} - m_Z)^2 + 0.4\times(m_{recoil} - m_H)^2$$
   - Pairing efficiency ~ 100 %
3. $m_{l^+l^-} \in [86, 96]$ GeV
4. $p_{l^+l^-} \in [20, 70]$ GeV
5. $|\cos\theta missing| < 0.98$
   - mainly suppresses Z/γ, (only for mass analysis)
6. $m_{recoil} \in [120, 140]$ GeV → used in fit

Signals:

1. $Z(l^+l^-)H$, (Whizard)

Backgrounds:

1. ZZ(inclusive), (Pythia)
2. W^+W^-, (Pythia)
3. $Z \to l^+l^-$, (Whizard)
4. eeZ, (Whizard)
5. $\gamma\gamma \to l^+l^-$ (Whizard)

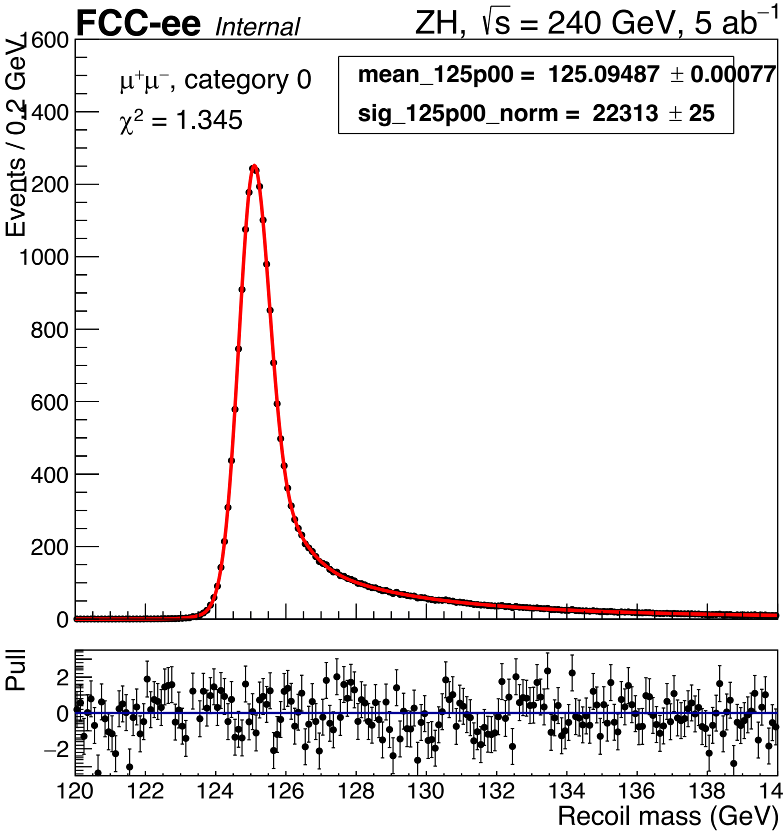


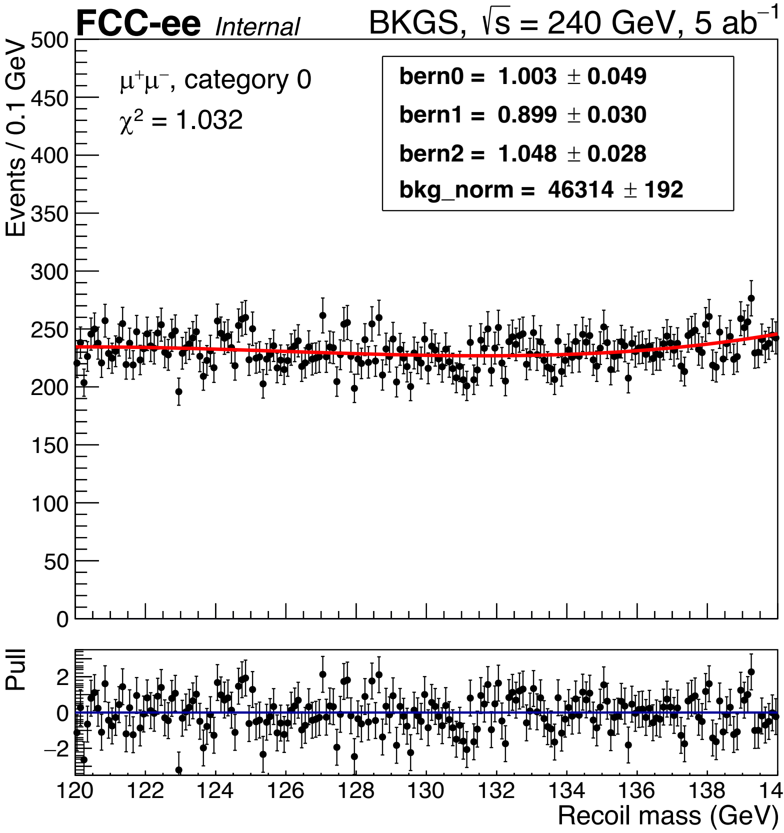
Signal and backgrounds modelling

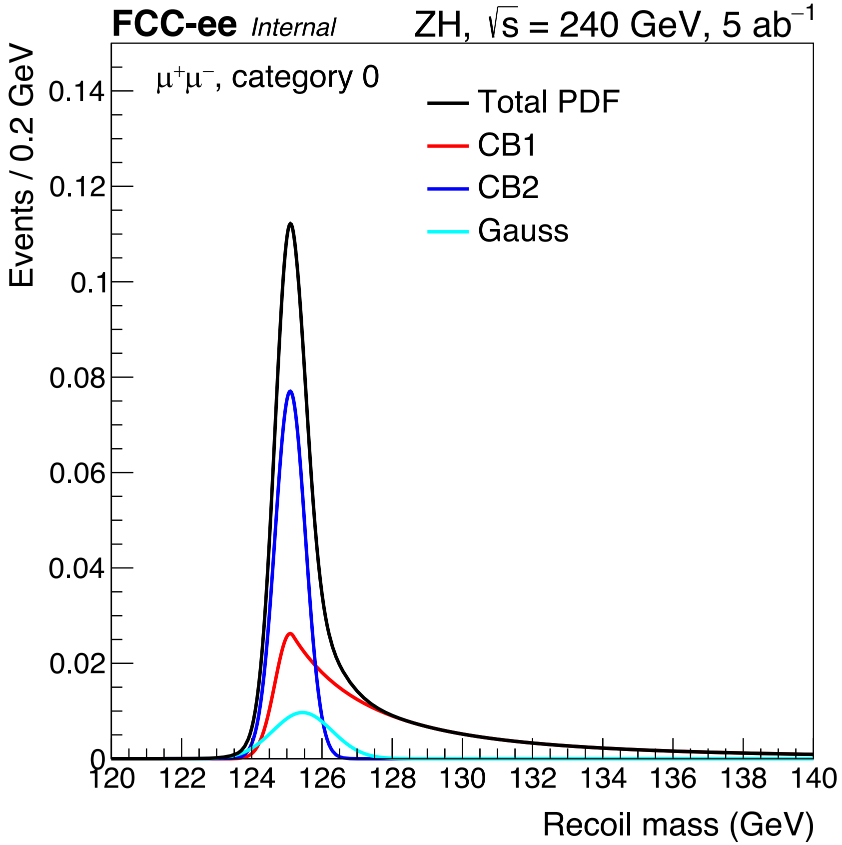
- **Choice of suitable PDF: 2 Crystal-Ball with Gaussian core**

  Fit done for several mass samples (125.00 ± 50 MeV, ± 100 MeV)

  Parameterize mean and other components as function of m_H
- **Backgrounds modelled as polynomial (3th order)**
- **Signal and background model injected in Combine, m_H as POI**





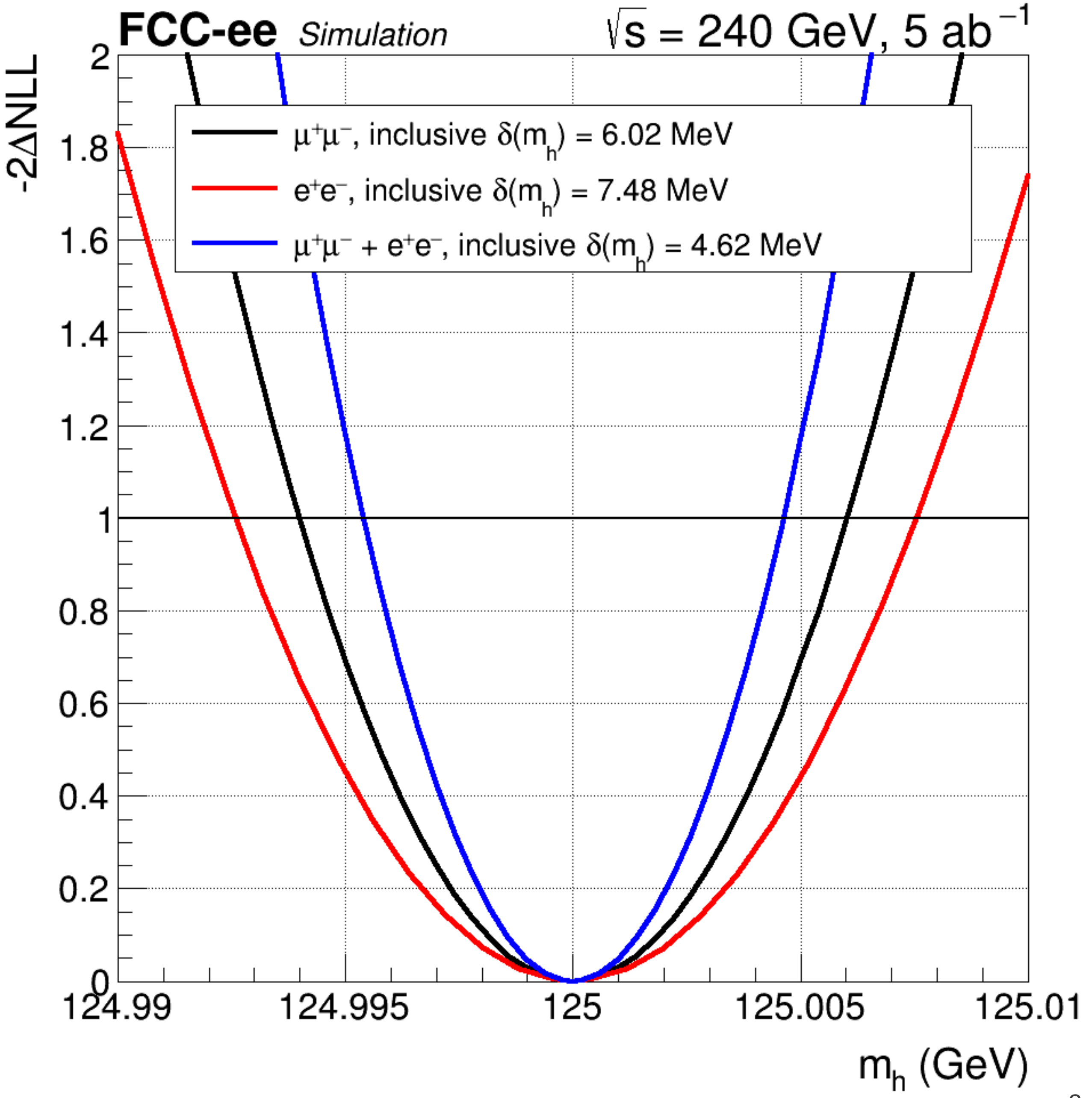


Statistic-Only

- **Likelihood scan to extract mass uncertainty**
  - Muon channel 6.0 MeV
  - Electron channel 7.5 MeV

- **Electron channel worse with factor 1.25 w.r.t. muons, driven by resolution scaling with factor 1.2 (residuals due to background)**

- **Combined uncertainty 4.6 MeV (stat. only)**
  - Sensitivity driven by muon channel, electrons gain ~ 25%



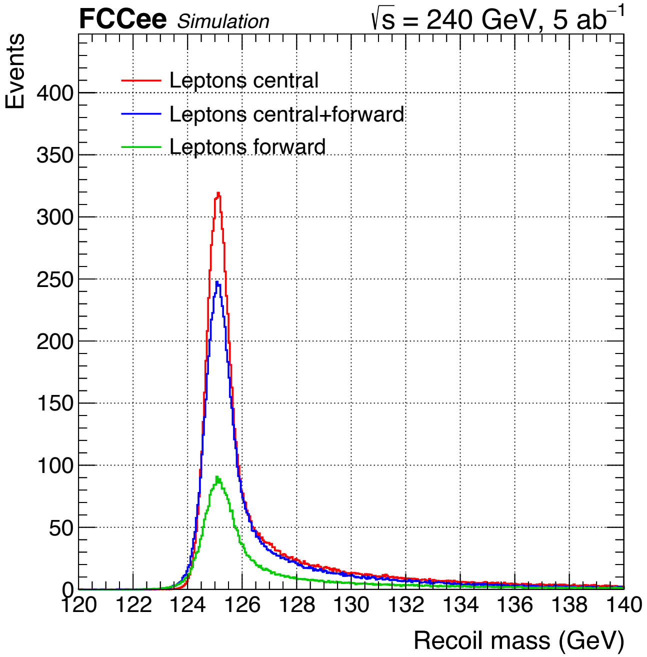
Categorisation

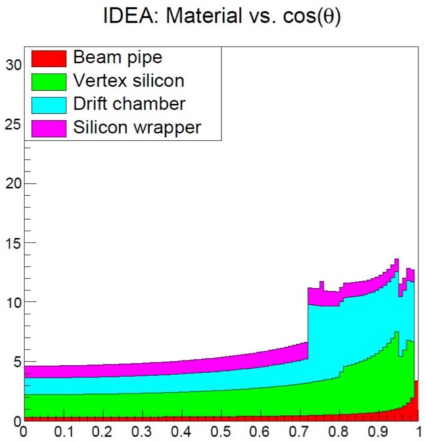
➢ Lepton momentum resolution degraded in forward region due to higher material budget

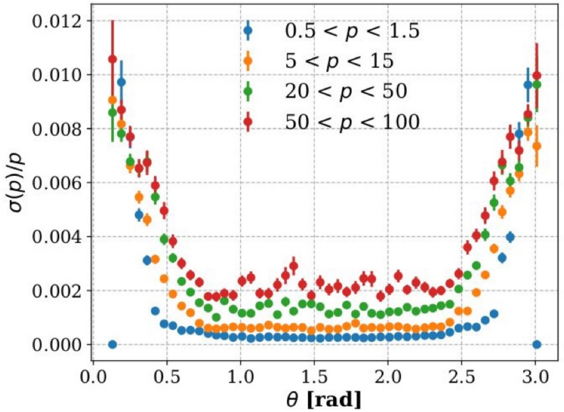
- ○ Split leptons in central and forward regions
  1. Central: $0.8 < \theta < 2.34$,
  2. Forward: the rest
- ○ The combination of two leptons have in total 3 categories:
  1. Two leptons in central region,
  2. Two leptons in forward region,
  3. One lepton in central region + One lepton in forward region
- ○ Perform statistical fit in all categories combined

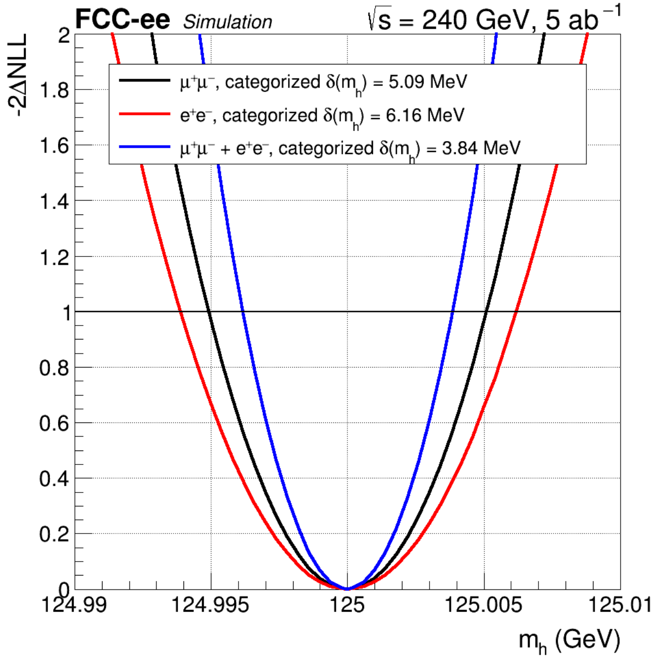
➢ Likelihood scan to extract mass uncertainty

- ○ Total combined uncertainty 3.8 MeV (stat. only)
- ○ Additional gain of ~ 20% due to categorization







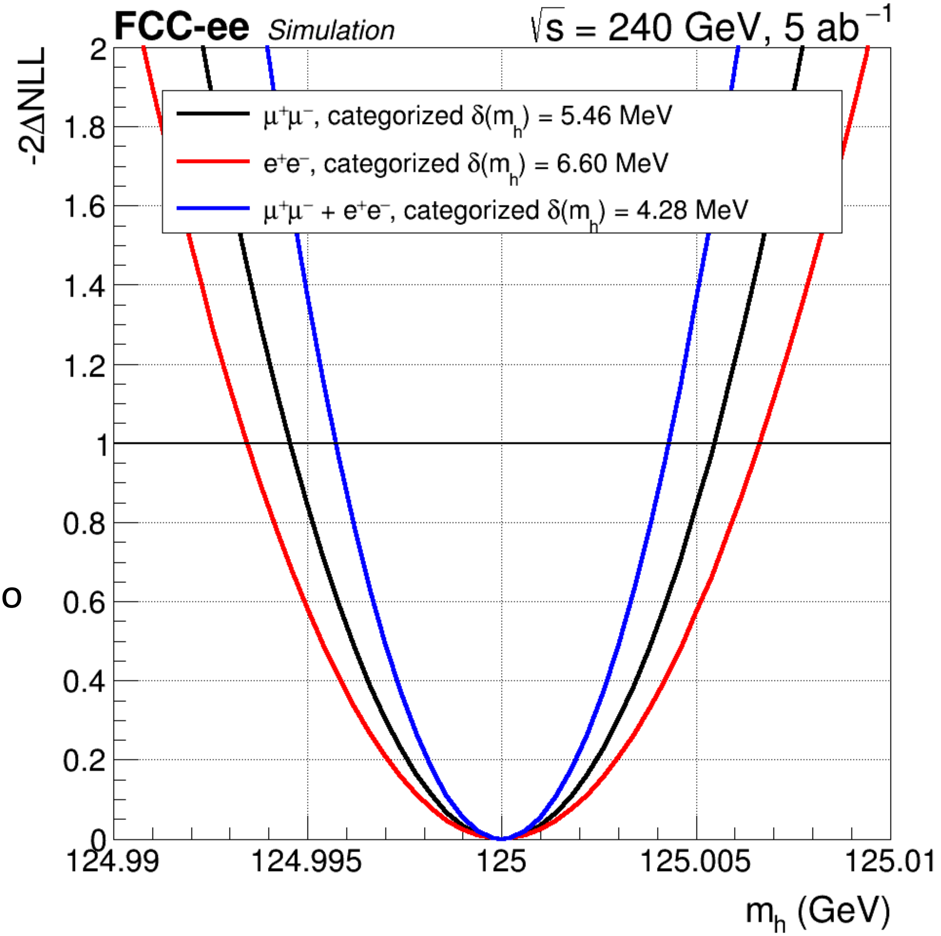


Systematics

- **Beam energy spread uncertainty** (nominal BES: ± 0.185% = ± 222 MeV)
  - Uncertainty driven by accelerator instrumentation:
    bunch length measurement up to 0.3 mm accuracy or better → 6% BES uncertainty
  - Data-driven BES constraining possible → estimated to be 1% BES uncertainty

- **Center-of-mass:** +/- 2 MeV
  - $\sqrt{S}$ parameter in the recoil mass definition →
    uncertainty induces linear shift the recoil distribution
  - Precision ~ 2 MeV at 240 GeV using radiative return events $Z \rightarrow ll$ or $Z \rightarrow qq$

- **Lepton momentum scale:** relative scale uncertainty variation of 1e-5
  - Directly affects m_{ll}, hence shift in recoil mass
  - Statistical potential to measure lepton scale ~ 1e-6, but NMR probes so far limited to yield 1e-5 uncertainty
  - Currently 1e-5 same for muons and electrons, but independent nuisances



Combine likelihood scans to extract the mass uncertainty

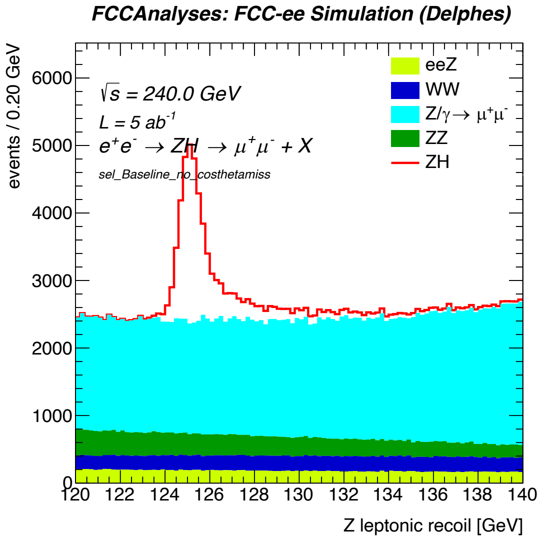
- Total uncertainty of 4.3 MeV (~ 10% worsening w.r.t. stat. only)
- Include ISR systematics via KKMC reweighting technique

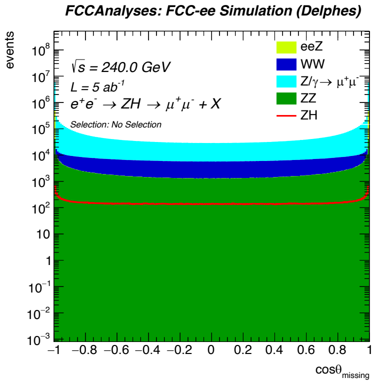
Motivation to use a BDT-based selection

Cross-section study:
without θ categorization
without Electron channels

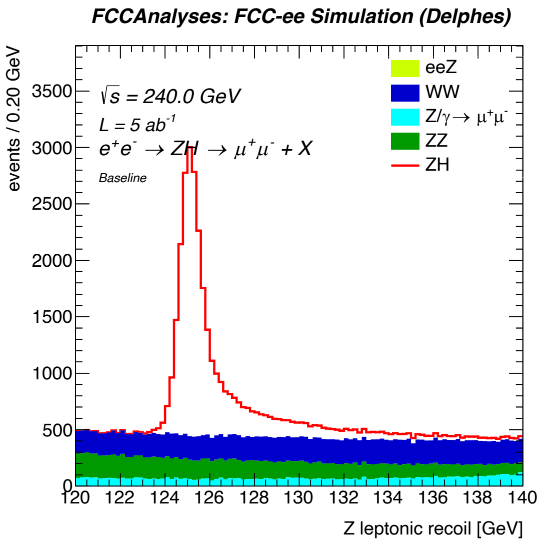
➢ Goal of the BDT-based selection:

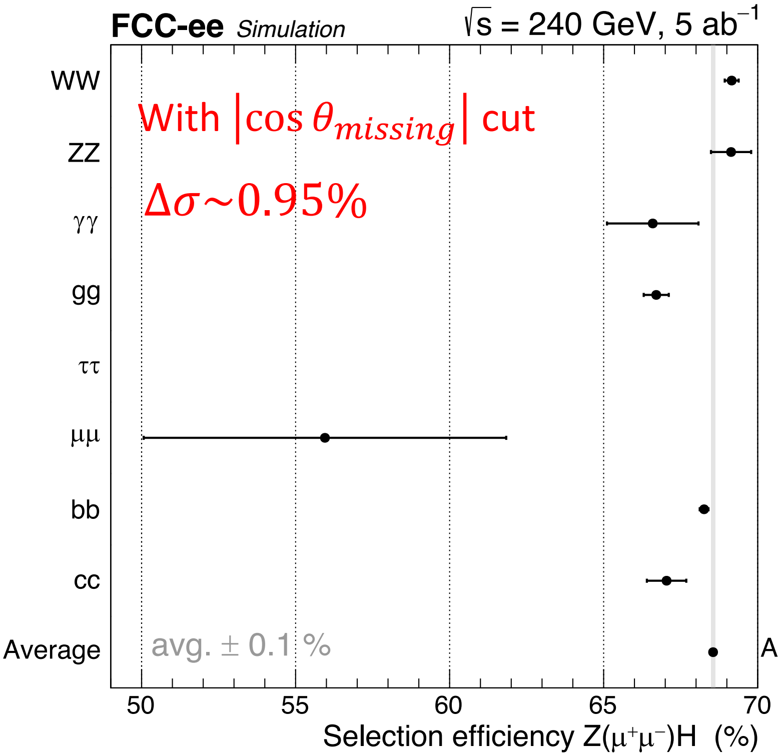
- ☐ Remove the $|\cos\theta_{missing}| < 0.98$ cut
  Will introduce bias on H decays to final states, which can not be measured in the detector
- ☐ Keep the model-independency for the cross-section measurement





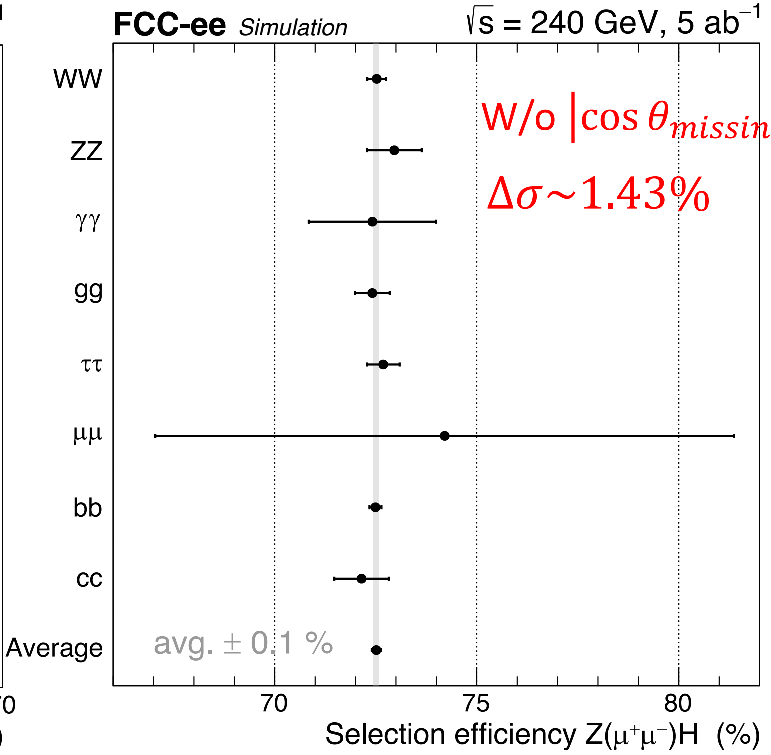
Only including $|\cos\theta_{missing}|$ cut





With $|\cos\theta_{missing}|$ cut

$\Delta\sigma \sim 0.95\%$



W/o $|\cos\theta_{missing}|$ cut

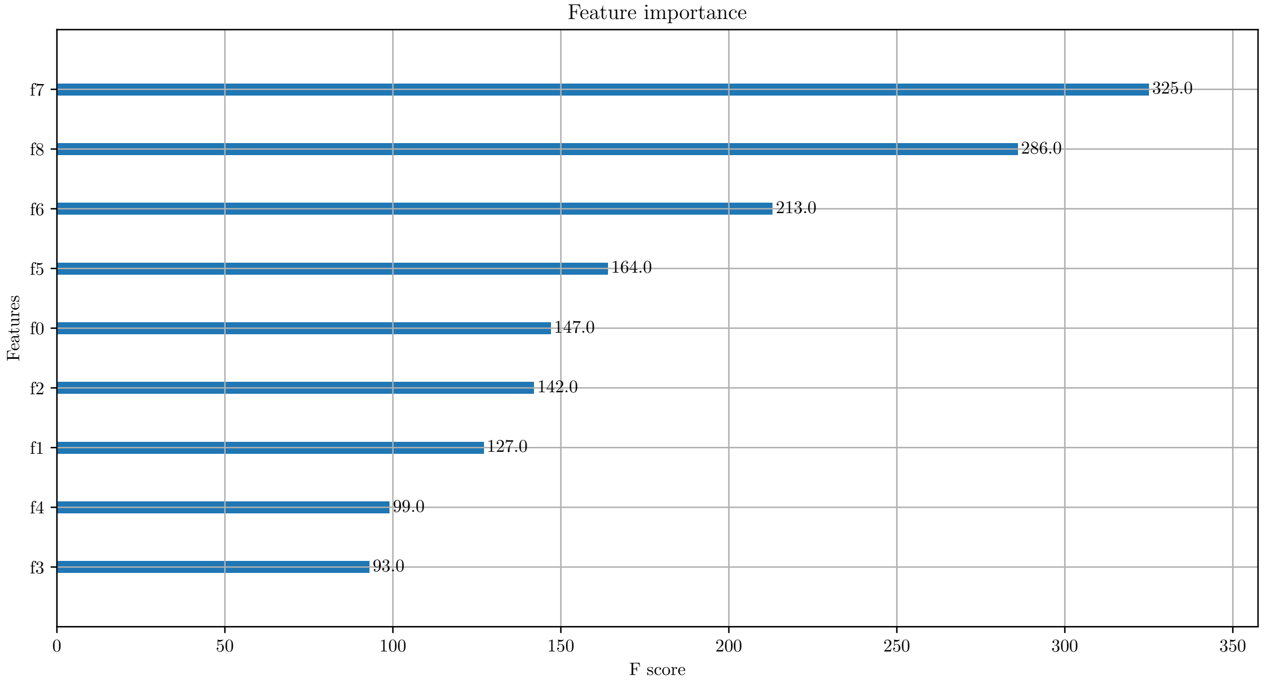
$\Delta\sigma \sim 1.43\%$

$|\cos\theta_{missing}|$ has a large effect on removing eeZ and $Z/\gamma \rightarrow \mu^+\mu^-$

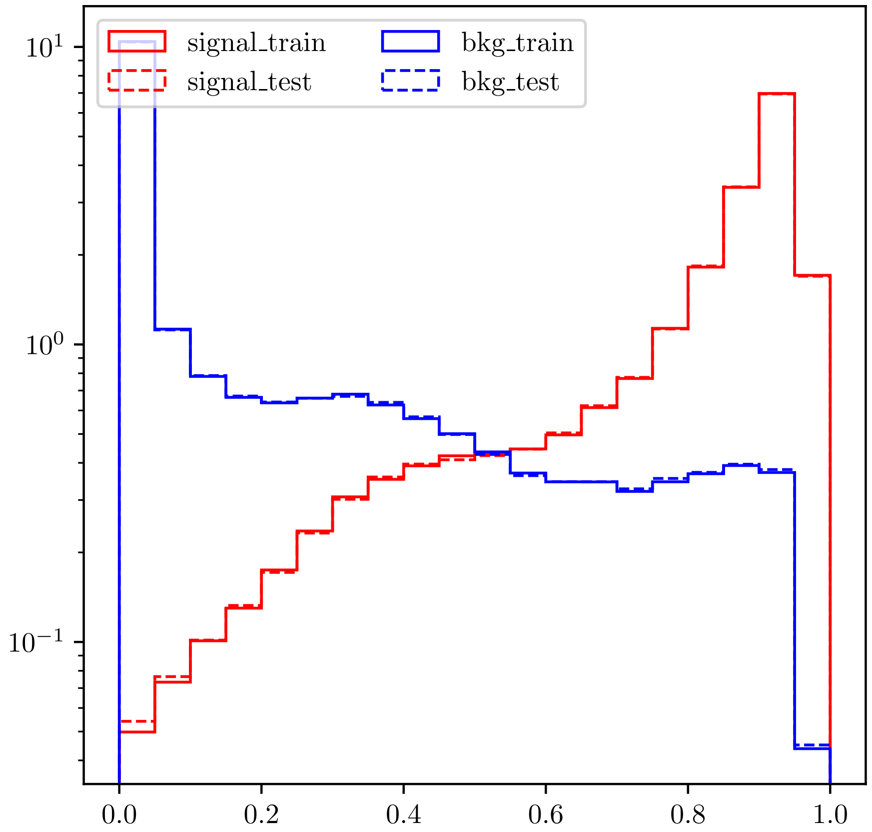
BDT settings

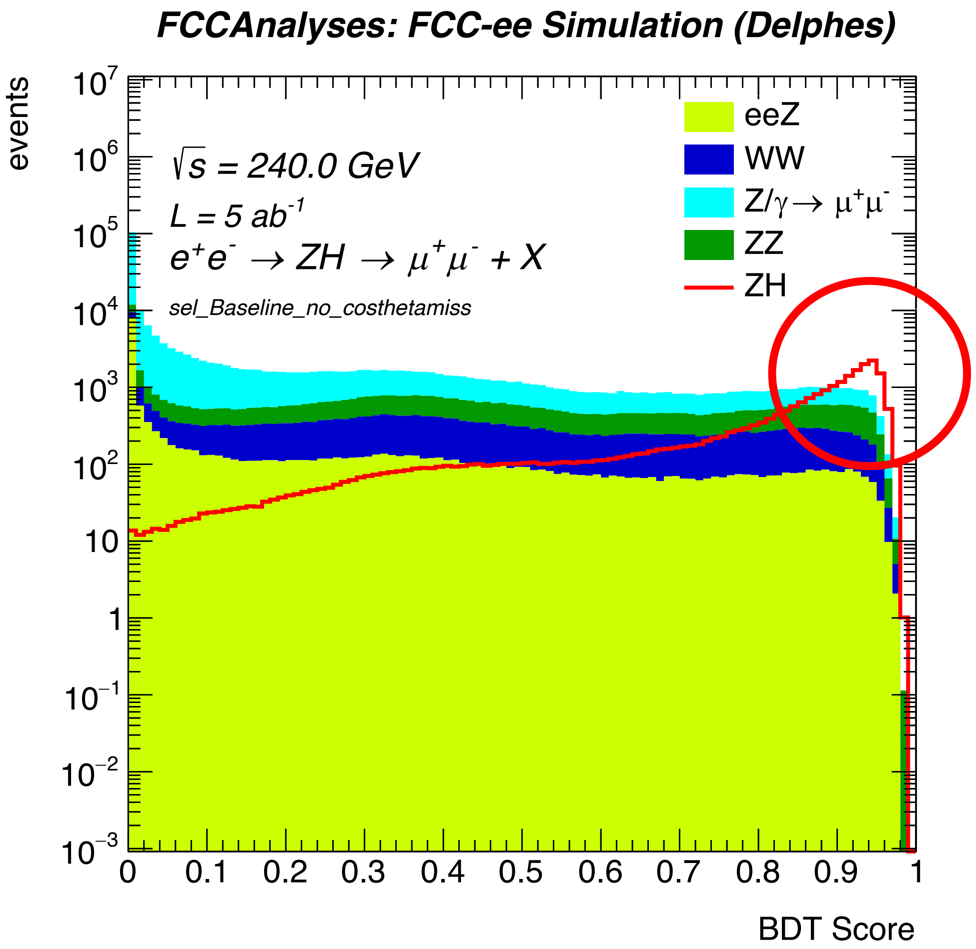
- **XGBoost**
- **Samples**
  - "Spring2021 training" for training and validation of the BDT model (will move to Winter2023 once the training samples are ready)
  - "Spring2021" for final analysis
- **Number of events for BDT training:**
  - All signals passed the baseline_nocosthetamiss selection
  - Total Number of backgrounds = Total Number of Signals
  - Number of events of each process is proportional to their cross-section X cut efficiency (from fcc-event page)
  - 1/2 of events for training
  - 1/2 of events for testing
- **FCC-APC-Input-Variables :**

1. Z_leptonic_p (muon pair transvers momentum)
2. Z_leptonic_theta (muon pair theta)
3. Z_leptonic_m (muon pair invariant mass)
4. Muon_acoplanarity (muon pair acoplanarity)
5. Muon_leading_p
6. Muon_subleading_p
7. Muon_leading_theta
8. Muon_acolinearity (muon pair acolinearity)
9. Muon_subleading_theta



BDT distribution

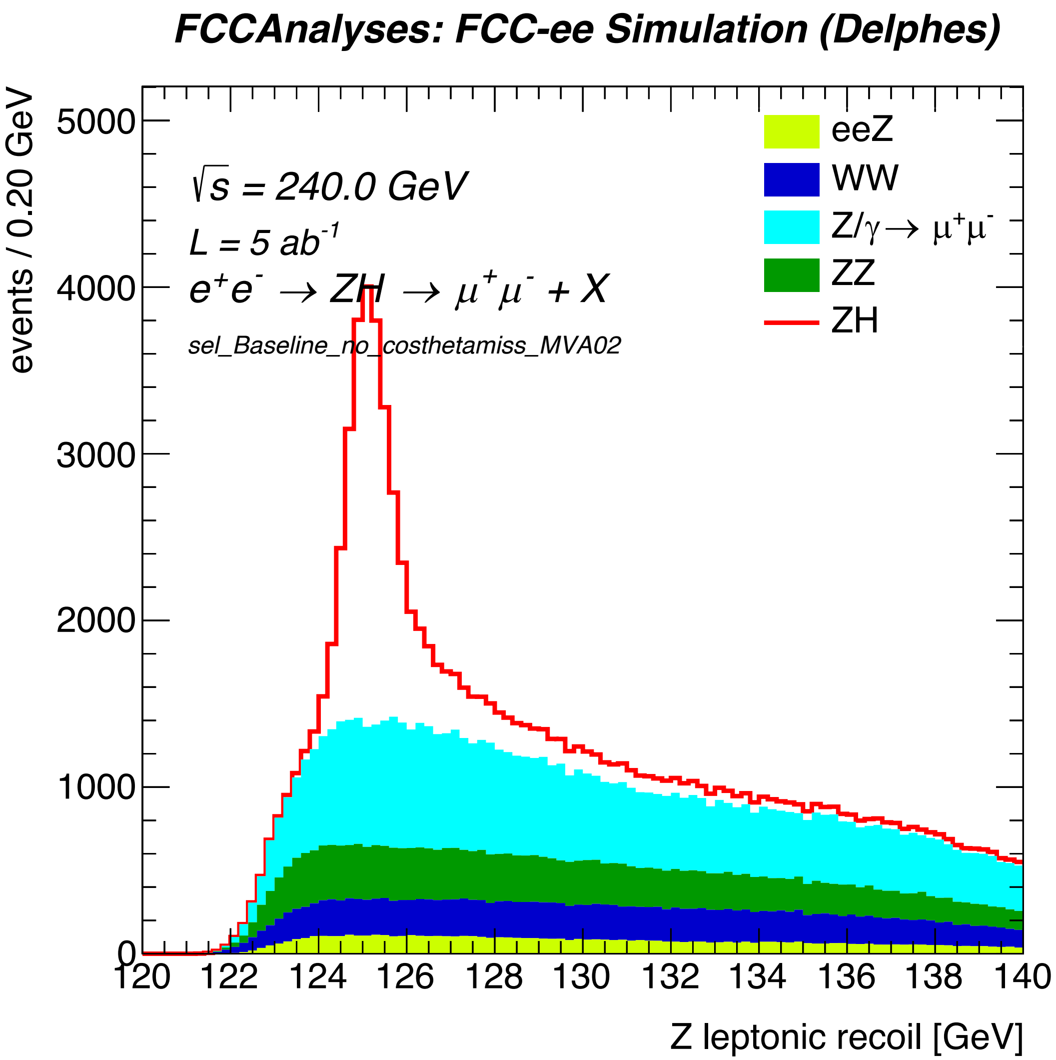


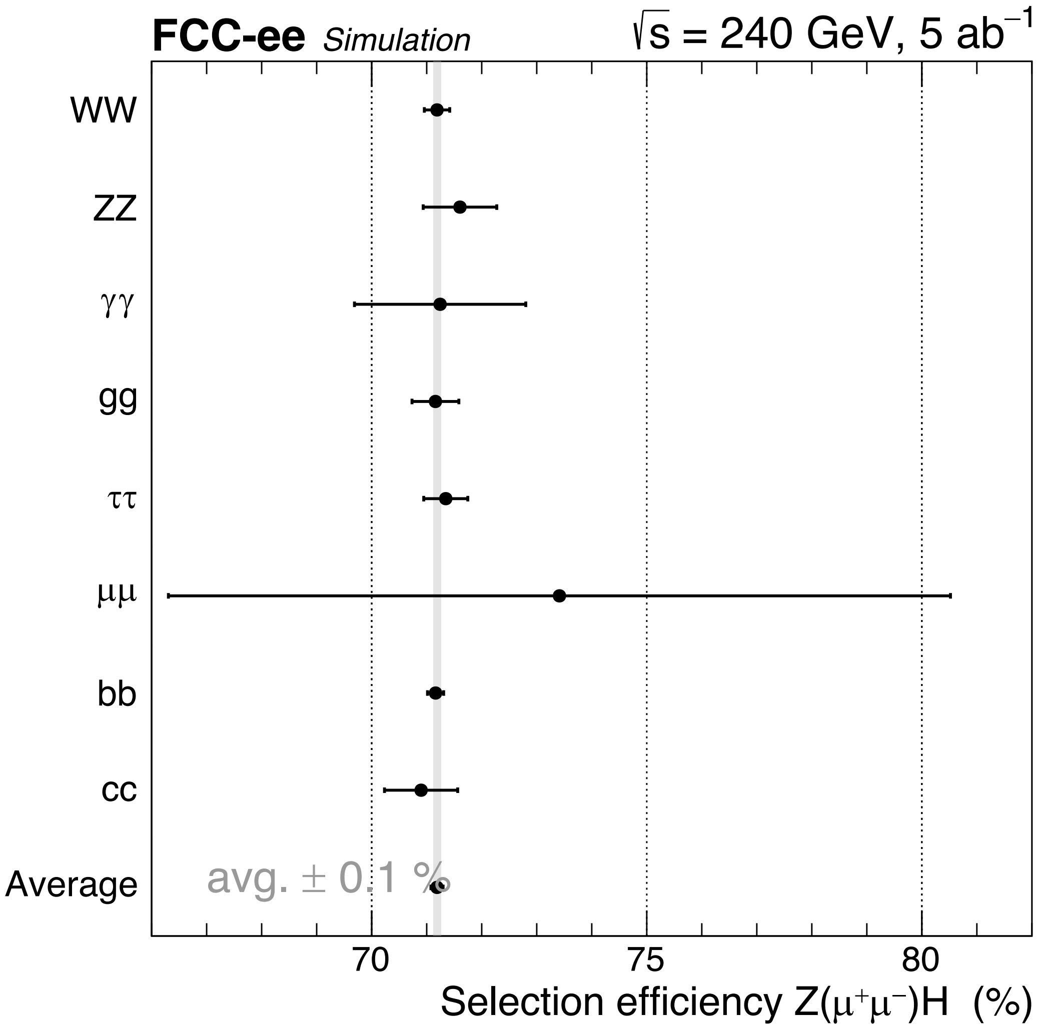


➢ No obvious overtraining:

- ❑ BDT model has similar performance on signal (background) training and validation samples at high (low) BDT score
- ❑ Signal is concentrated at high BDT score,

BDT Cut and Model independency





➢ MVA02: BDT score > 0.2:

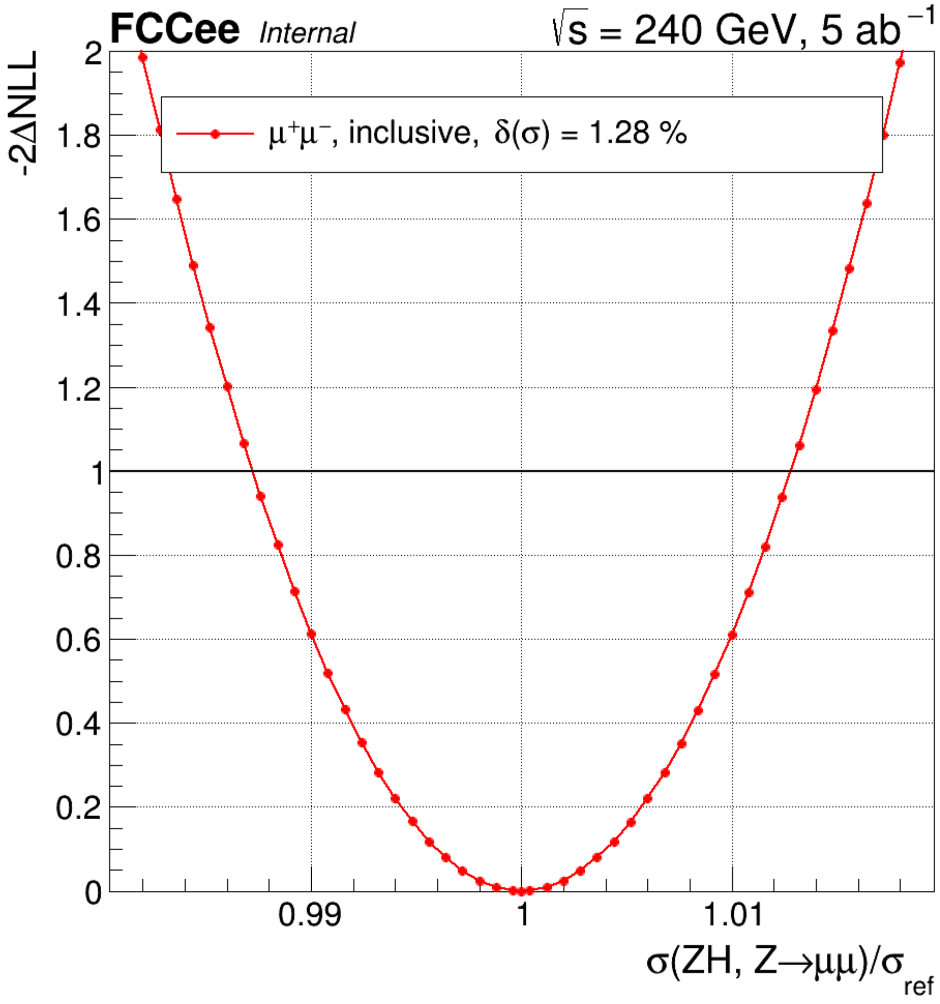
- ❑ Background is shaped by the BDT at low m_{recoil}
- ❑ Model-independency verified within statistical uncertainties

Cross-section fitting results

Statistic-Only
Binned fit

Cuts	μ	$\delta_{\sigma_{ZH}}$(68% CL)
Baseline	1	-0.0095/+0.0095
Baseline, without $\lvert\cos\theta_{missing}\rvert$ cut	1.00001	-0.0143/+0.0143
Baseline, without $\lvert\cos\theta_{missing}\rvert$ cut, with BDT score > 0.2	1	-0.0128/+0.0128

- Removing the $\cos\theta_{missing}$ cut, the uncertainty on cross-section measurement:
  0.95%→1.43% (increased 50%)
- Applying BDT score > 0.2, the uncertainty on cross-section measurement:
  1.43%→1.28% (decreased 10%)
- Including electrons will roughly improve with $\sqrt{2}$, leading to a combined uncertainty of ~ 1%
- This motivates performing the BDT study for electrons as well



Summary and outlook

❖Summary:

- ❑Higgs mass measurement:
  - ○ Moved to Winter2023
  - ○ Included electrons
  - ○ Categorization in θ
- ❑The uncertainty on Higgs mass yields 4.3 MeV (statistic plus systematics)
- ❑Cross section measurement:
  - ○ $\cos\theta_{missing}$ replaced by BDT to reject the larger background
  - ○ Model-independency is conserved
- ❑Cross-section measurement yields 1.28% uncertainty (statistic only)

  10% improvement from the BDT

❖Outlook:

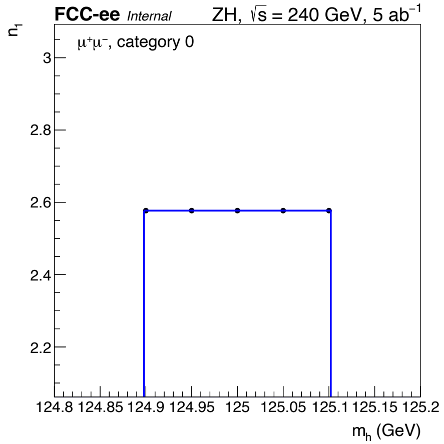
- ❑Cross-section measurement move to Winter2023, include systematics and electrons
- ❑Include ISR systematics via KKMC reweighting technique

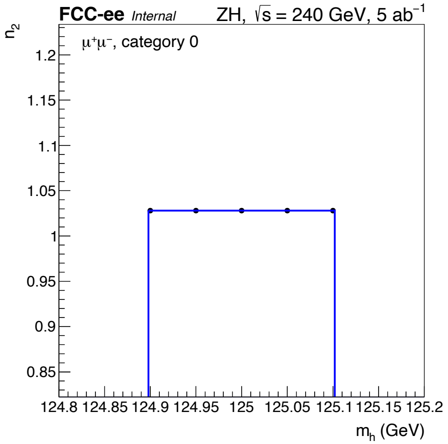
Ang LI email: ang.l@cern.ch

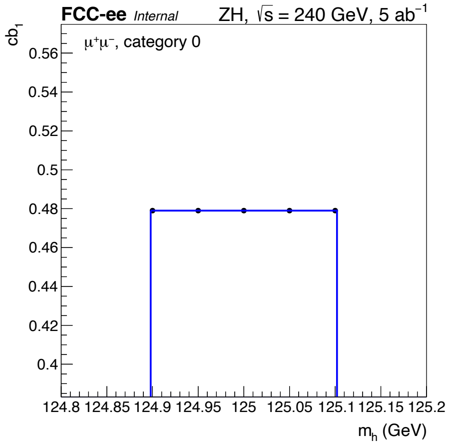
Backup

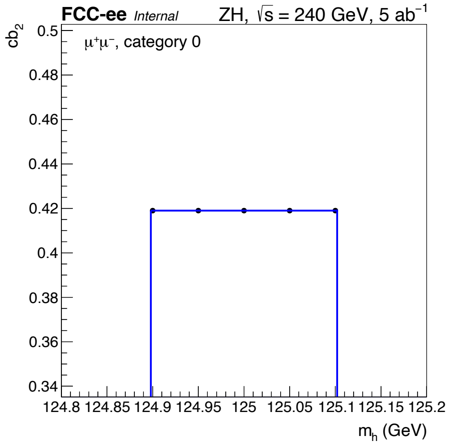
FUTURE CIRCULAR COLLIDER

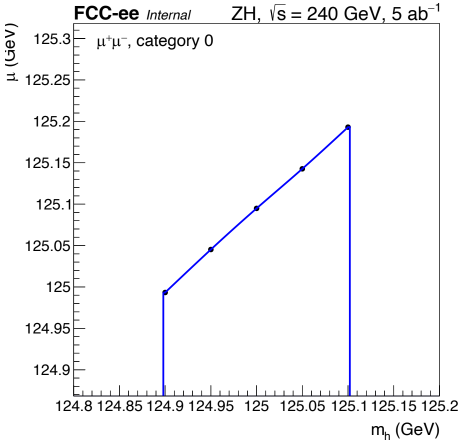
Fit

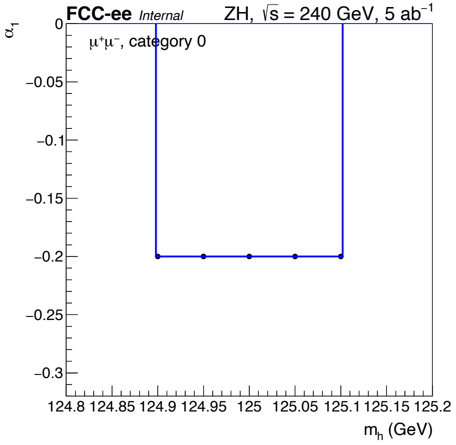


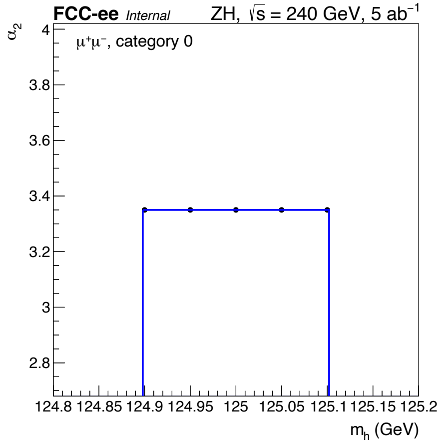


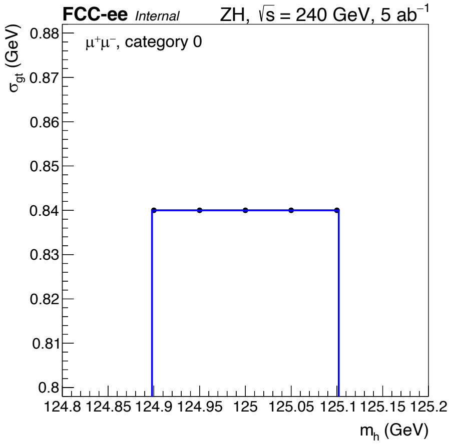


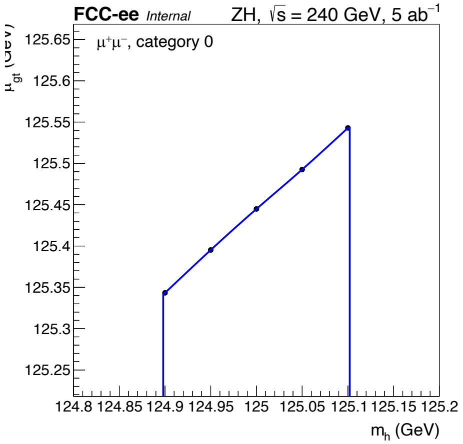


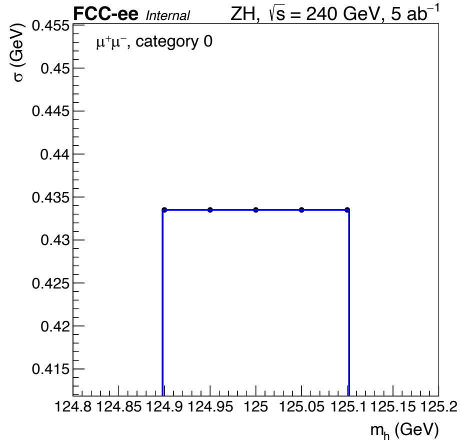


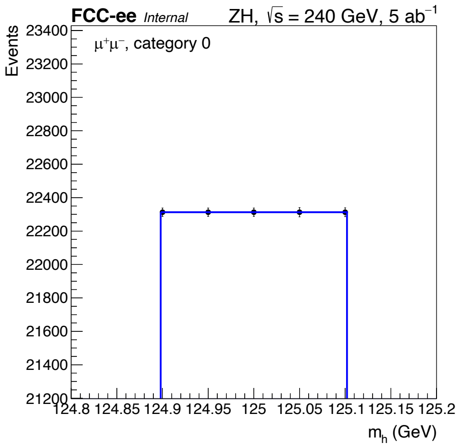












BDT Inputs and Hyperparameters

	mumuH	ZZ	WWmumu	Zll	eeZ
#Events	724264	84259	67204	544613	28186

Hyperparameters	Value
n_estimators	350
learning_rate	0.20
max_depth	3
subsample	0.5
gamma	3
min_child_weight	10
max_delta_step	0
colsample_bytree	0.5

BDT Hyperparameters

Hyperparameters	Value
n_estimators	350
learning_rate	0.20
max_depth	3
subsample	0.5
gamma	3
min_child_weight	10
max_delta_step	0
colsample_bytree	0.5

Cross-section fitting results

Statistic-Only
Binned fit

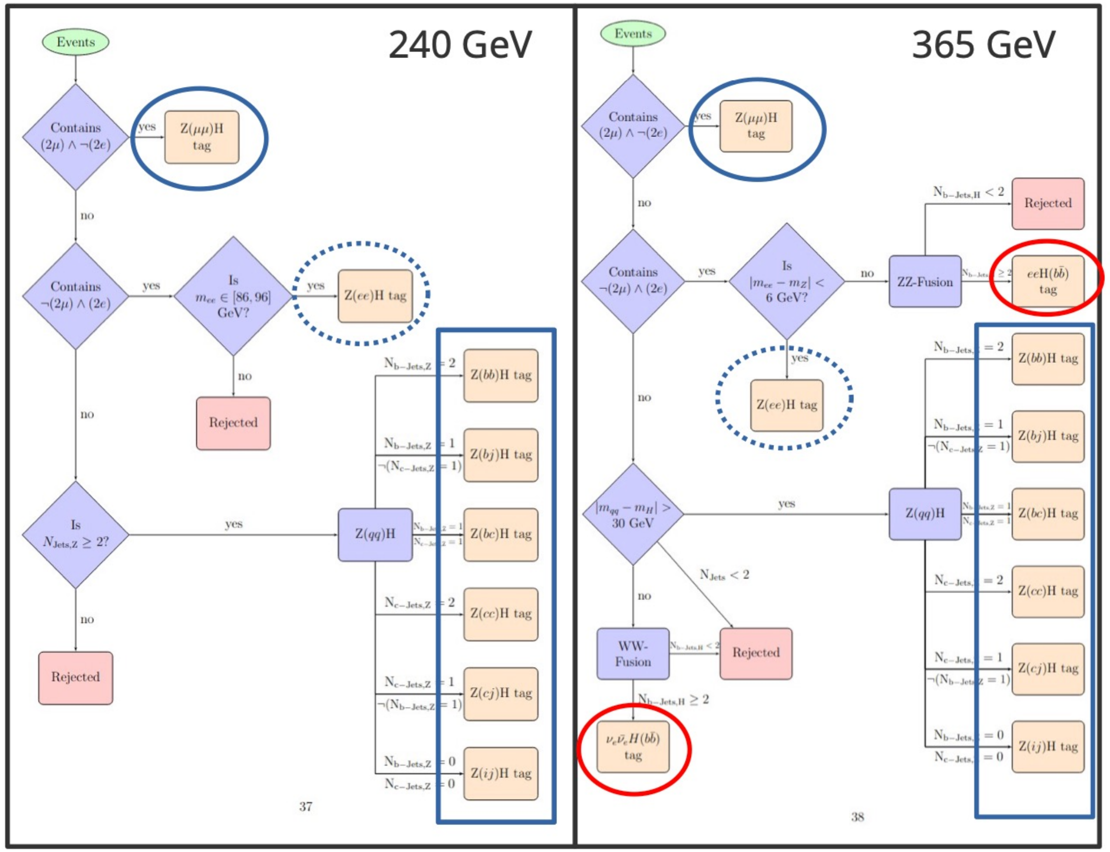
Cuts	mu	(68% CL)
Baseline	1	-0.0095/+0.0095
Baseline_nocosthemiss	1.00001	-0.0143/+0.0143
Baseline_nocosthemiss_MVA01	1.00001	-0.0128/+0.0128
Baseline_nocosthemiss_MVA02	1	-0.0128/+0.0128
Baseline_nocosthemiss_MVA03	1	-0.0129/+0.0130
Baseline_nocosthemiss_MVA04	1	-0.0133/+0.0133

Selections and Categorisations

- **Recoil technique**
- **Z boson decay channels: $\mu^+\mu^-, e^+e^-, q\bar{q}$**
- **Categorization tuned for the two energy points**

  (240 GeV & 365 GeV)
  - Z(qq)H divided into 6 ‘flavor-tag’ categories
  - @240 GeV: only ZH production considered
  - @365 GeV: considering ZH + eeH(bb) + vvH(bb)
  - Using $m_{l^+l^-}$ (m_{miss}) in VBF categories

Talk by Louis Portales on FCC-France-Italy Workshop



- **Selections:**

$Z(l^+l^-)H$

1. Opposite Sign l^+l^- pair
2. $86 < m_{l^+l^-} < 96$ GeV
3. $20 < p_T^{l^+l^-} < 70$ GeV (>70 GeV @365 GeV)
4. $|\cos\theta missing| < 0.98$

$Z(q\bar{q})H$

1. **Anti-kt jets (R=0.5)**
2. 6 Flavor categories (bb,cc,ll,bc,bl,cl) → 86<mqq<96 GeV
3. p_T^{jet} >20 GeV
4. $|\cos\theta missing| < 0.98$
5. BDTs used for selection:
   - one per flavor category
   - 17 input variables characterising the $q\bar{q}$ system