Measurement of the $ZH, H(ZZ^*)$ Cross Section in the Four Lepton Channel at FCC-ee

(FCC-ee Simulations)

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Plan

- FCC Project and Higgs Production at FCC-ee
- Signal and Background Processes
- Analysis
- Encountered Difficulties
- Conclusion

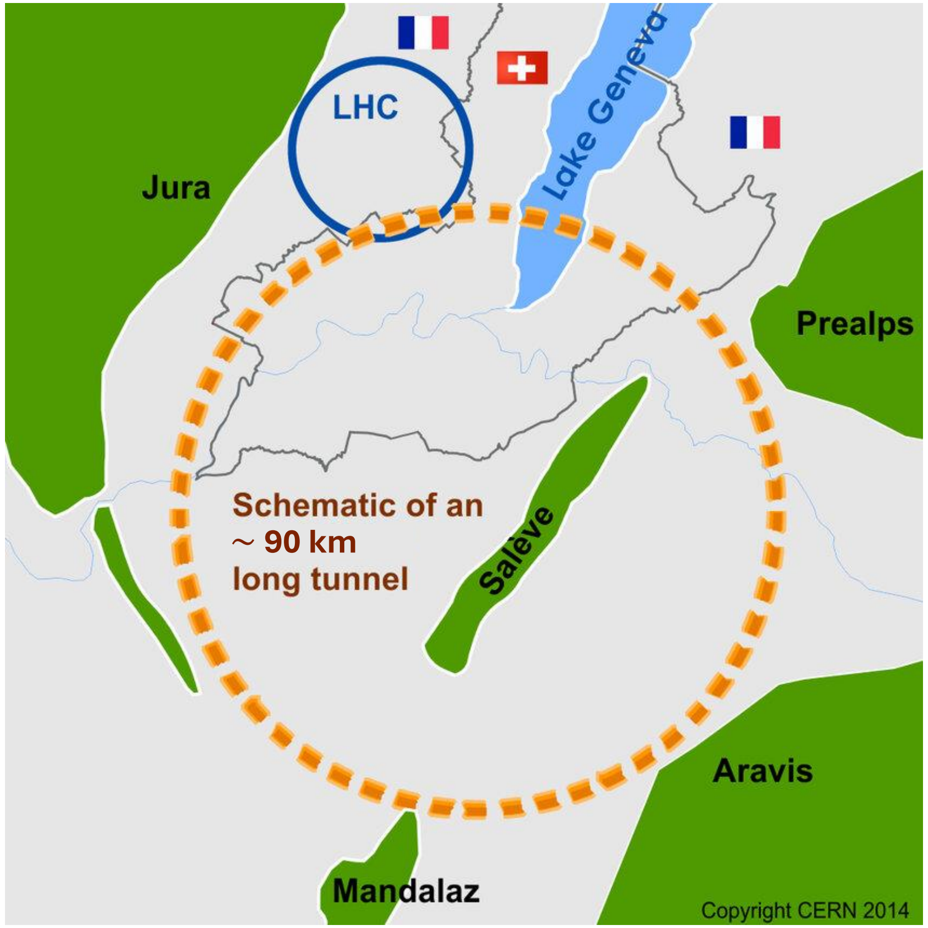
FCC Project

First stage: FCC-ee
- Electron-positron collider
- Higgs physics at $\sqrt{s} = 240$ GeV then $\sqrt{s} = 365$ GeV
- Production of $\sim 10^6$ Higgs bosons

→ Precision measurements of the Higgs properties, complementary to HL-LHC

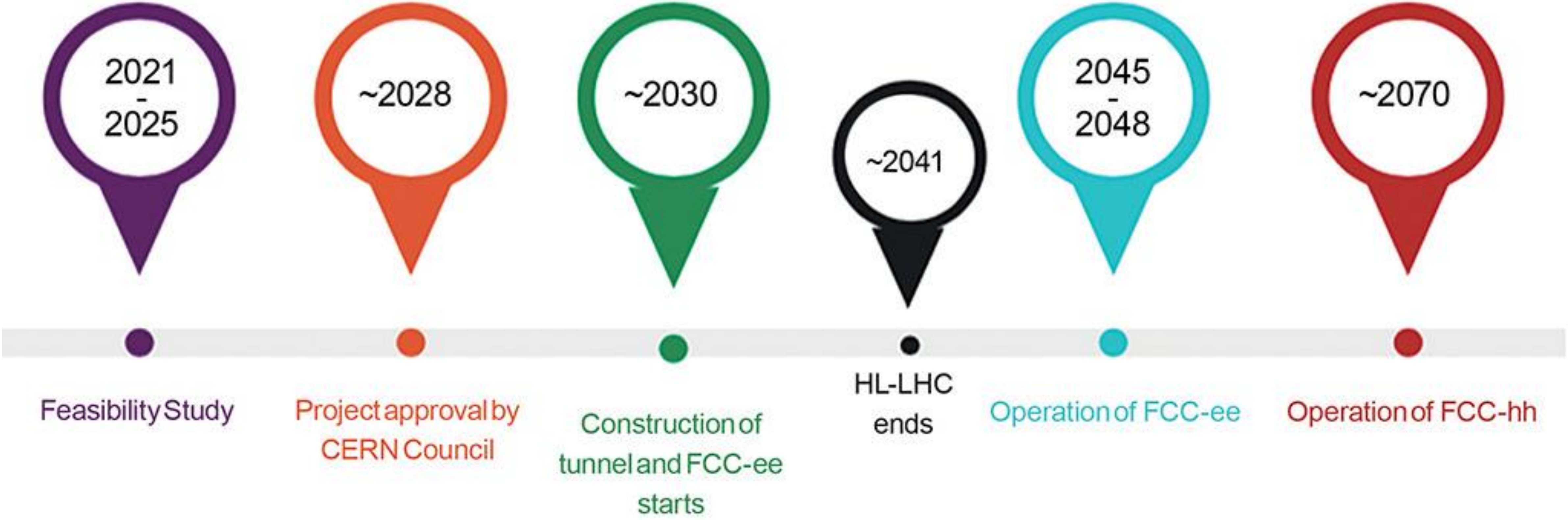
Second stage: FCC-hh
- Hadron collider
- $\sqrt{s} = 100$ TeV
- Exploration of high energy physics

→ Search for physics beyond the Standard Model



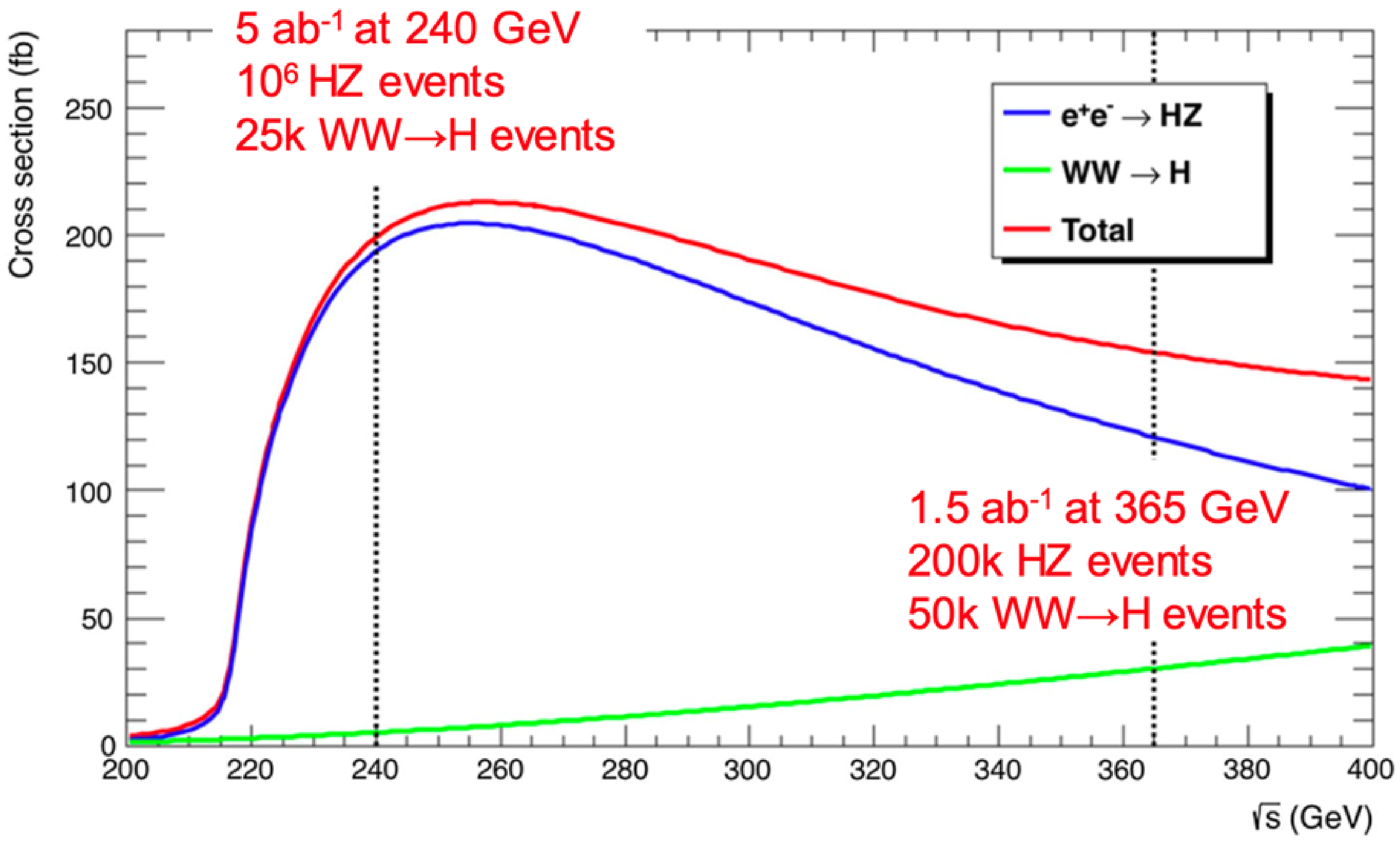
Scheme of a Possible Location for the FCC

FCC Project



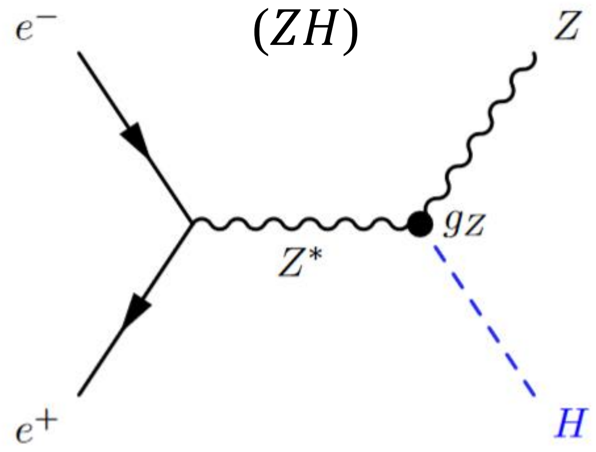
FCC Timeline

Higgs Production at FCC-ee

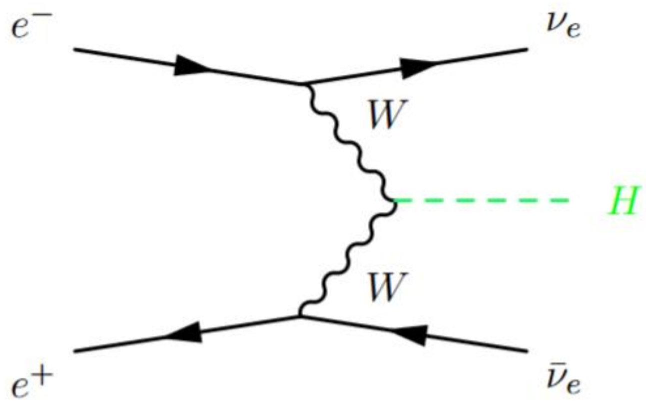


VBF and ZH Cross Section as Functions of $\sqrt{s}$

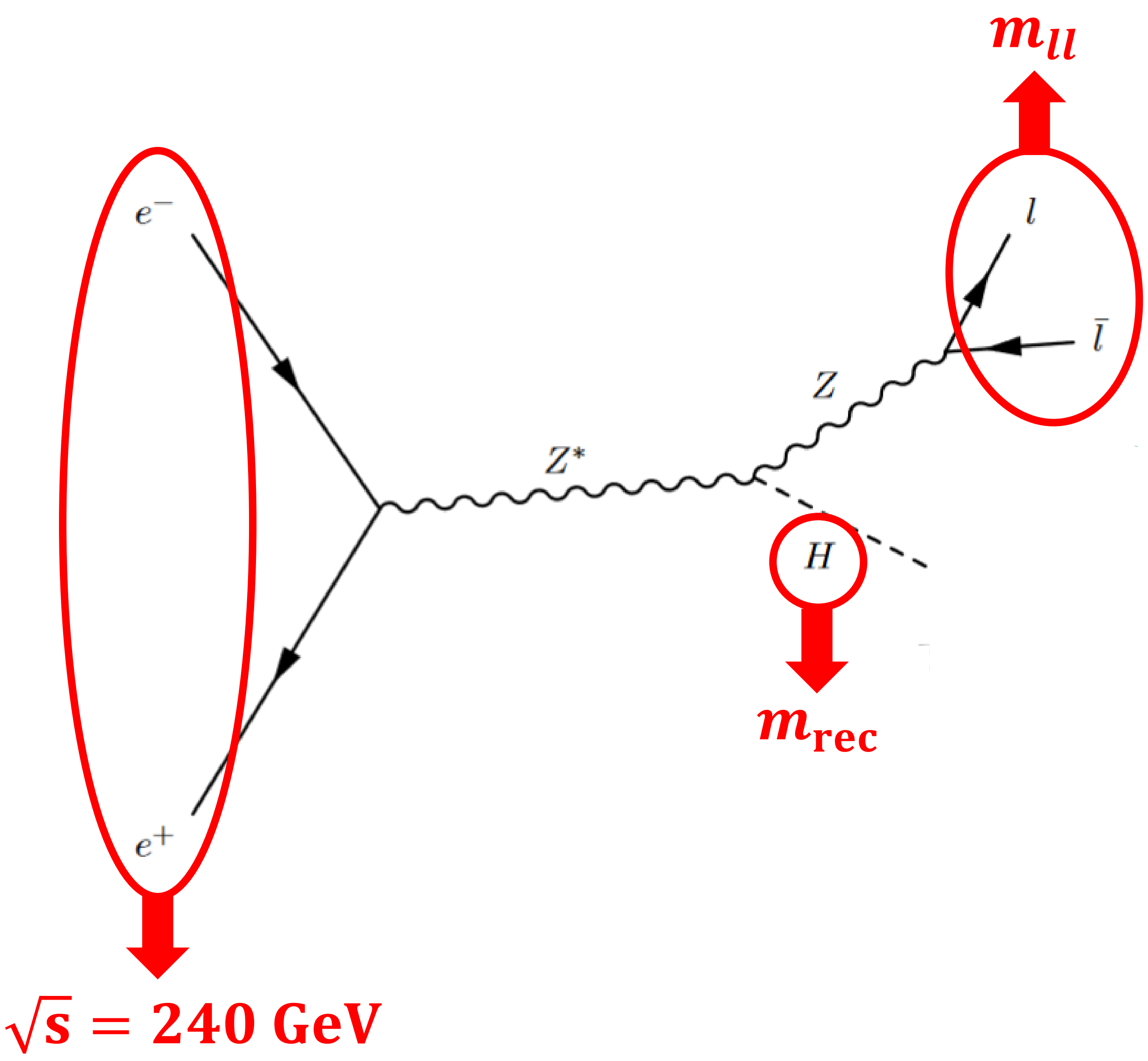
Higgs Strahlung
(ZH)



Vector Boson Fusion



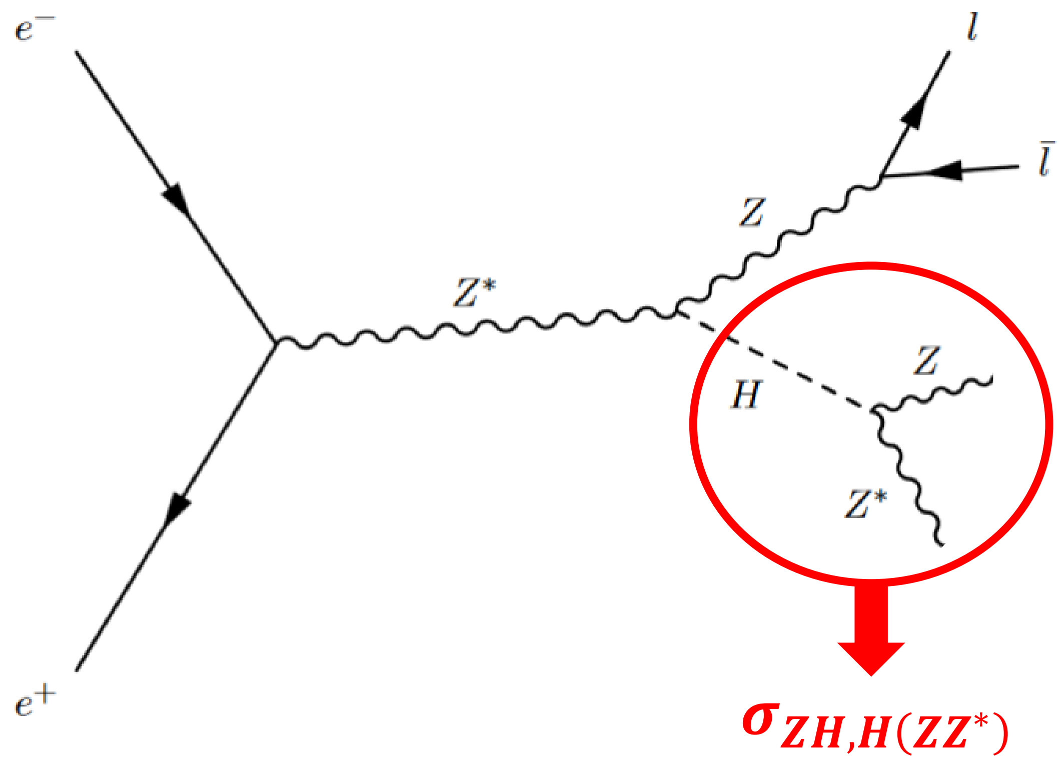
Signal: $ZH, H(ZZ^*)$



Recoil mass method to measure the ***ZH* cross section** without any assumption on the Higgs branching ratios

$$m_{\text{rec}}^2 = (\sqrt{s} - E_{ll})^2 - p_{ll}^2 \Longrightarrow \sigma_{ZH}$$

Signal: $ZH, H(ZZ^*)$



Recoil mass method to measure the ZH cross section without any assumption on the Higgs branching ratios

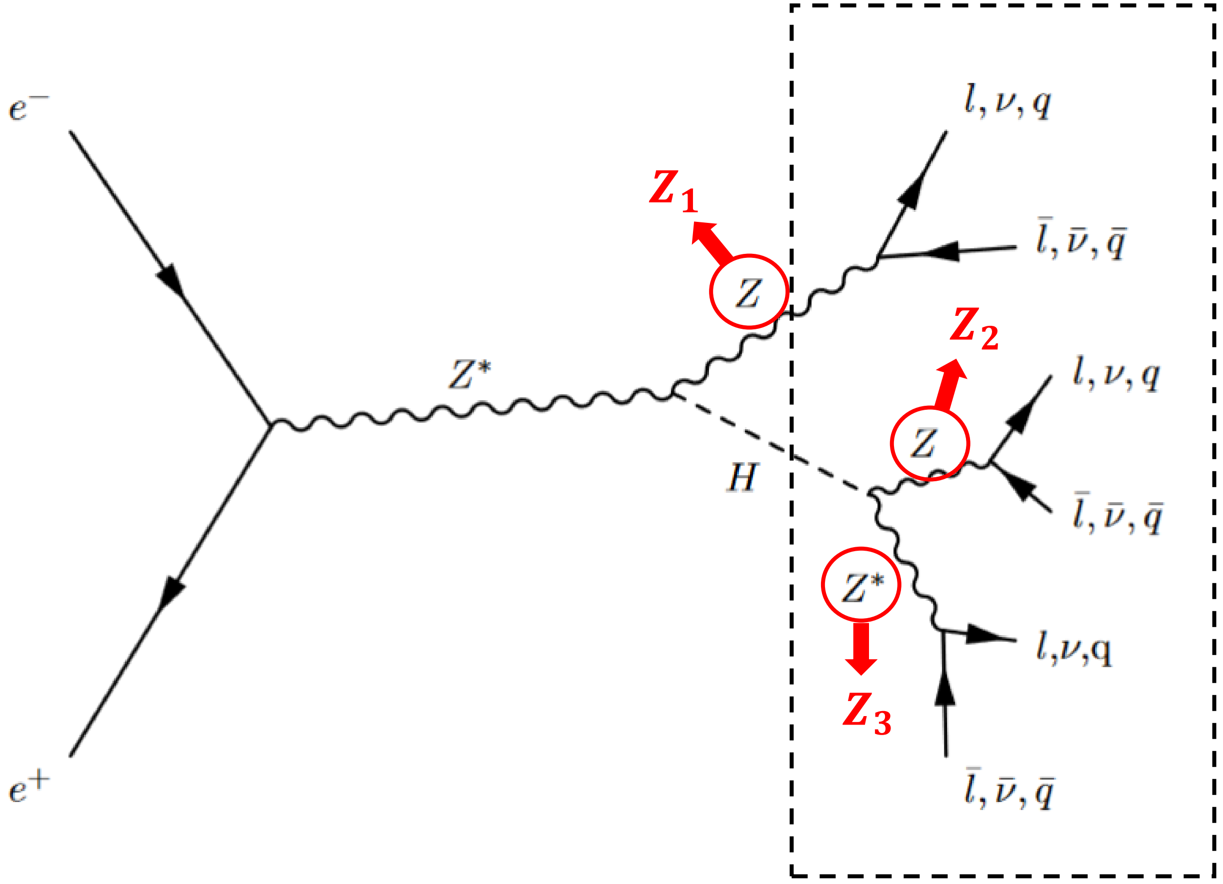
$$m_{\text{rec}}^2 = (\sqrt{s} - E_{ll})^2 - p_{ll}^2 \longrightarrow \sigma_{ZH}$$

Combine with measurements of the **exclusive Higgs decay cross section** to extract total width Γ_H

$$\Gamma_H = \frac{\sigma_{ZH}}{\boldsymbol{\sigma_{ZH,H(ZZ^*)}}} \Gamma_{H\to ZZ^*}$$

Only theoretical input: $\Gamma_{H\to ZZ^*}$

Signal: $ZH, H(ZZ^*)$



$ZH, H(ZZ^*)$ Feynman diagram with possible decays of the Z bosons

Decay	Fraction
$l\bar{l}$ $(e^+e^-, \mu^+\mu^-, \tau^+\tau^-)$	~10 %
$\nu\bar{\nu}$ $(\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau)$	~20 %
$q\bar{q}$ $(u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}, b\bar{b})$	~70 %

Main decays of the Z boson

$ZH, H(ZZ^*)$ Four Lepton Final States

The decays we are interested in: $\boldsymbol{ZH, H(ZZ^*) \rightarrow 4l + xx}$

$$\left\{\begin{matrix} Z_1(ll)Z_2(ll)Z_3(jj) \\ Z_1(ll)Z_2(ll)Z_3(\nu\nu) \end{matrix}\right\}$$

2 on-shell leptonic *Z*

$$\left\{\begin{matrix} Z_1(ll)Z_2(jj)Z_3(ll) \\ Z_1(jj)Z_2(ll)Z_3(ll) \\ Z_1(ll)Z_2(\nu\nu)Z_3(ll) \\ Z_1(\nu\nu)Z_2(ll)Z_3(ll) \end{matrix}\right\}$$

1 on-shell leptonic *Z* and
1 off-shell leptonic *Z*

Mixed final states (different combinations of ll jj $\nu\nu$) and 4 jets final states (ll jj jj) have already been studied studied by Ines Combes

$ZH, H(ZZ^*)$ Four Lepton Final States

2 On-Shell Leptonic Z Bosons

$Z_1(ll)Z_2(ll)Z_3(jj)$ Signature

- 2 on-shell leptonic Z

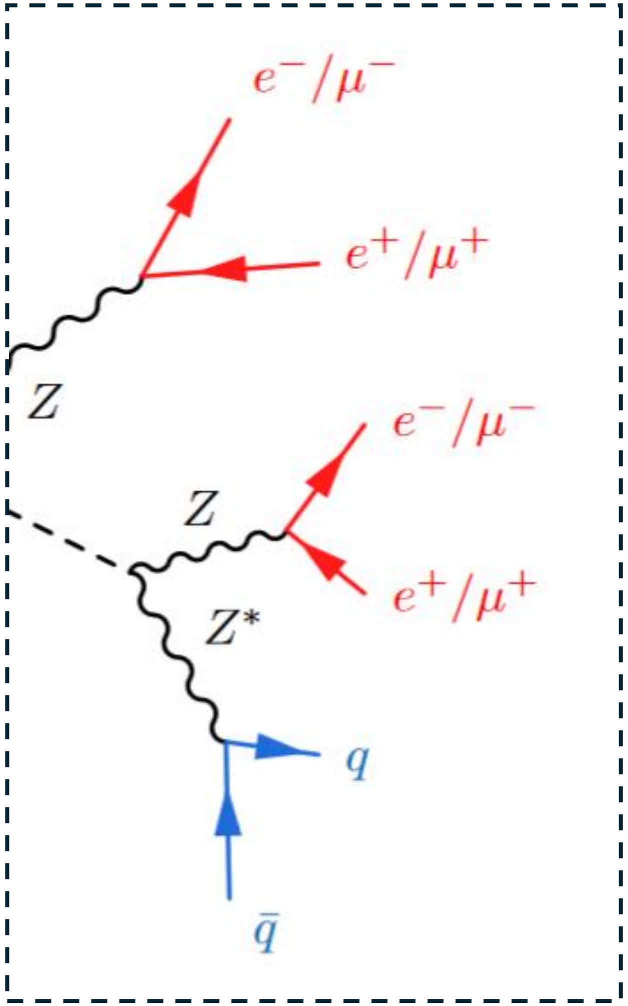
  ➡ 2 pairs of high-momentum leptons of same flavour and opposite sign

  ➡ $\boldsymbol{m_{ll_1}}$ and $\boldsymbol{m_{ll_2}} \sim 91$ GeV

- $Z^*(q\bar{q})$ ➡ $\boldsymbol{m_{jj}} \sim 30$ GeV

- $\boldsymbol{m_{ll_1}^{\mathrm{rec}}}$ and $\boldsymbol{m_{ll_2+jj}} \sim 125$ GeV;

- No neutrinos ➡ Low missing energy



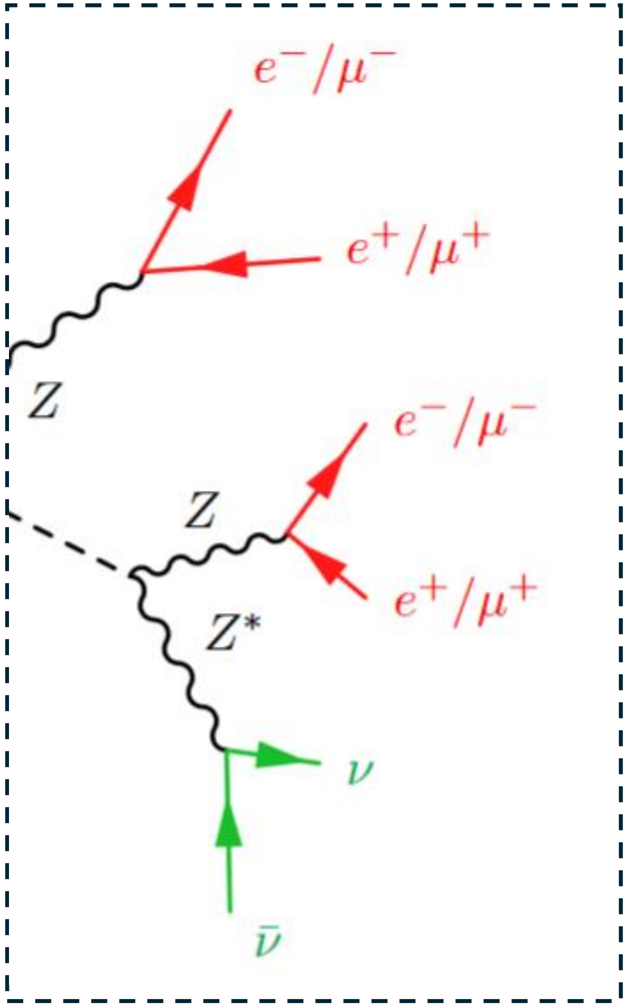
$llll jj$ Decay

$ZH, H(ZZ^*)$ Four Lepton Final States

2 On-Shell Leptonic Z Bosons

$Z_1(ll)Z_2(ll)Z_3(\nu\nu)$ Signature

- 2 on-shell leptonic Z
  - ➡ 2 pairs of high-momentum leptons of same flavour and opposite sign
  - ➡ $\boldsymbol{m_{ll_1}}$ and $\boldsymbol{m_{ll_2}} \sim 91$ GeV
- $\boldsymbol{m_{ll_1}^{\mathrm{rec}}} \sim 125$ GeV;
- 2 neutrinos ➡ High missing energy



$llll\nu\nu$ Decay

1 On-Shell and 1 Off-Shell Leptonic Z Bosons

$Z_1(ll)Z_2(jj)Z_3(ll)$ and $Z_1(jj)Z_2(ll)Z_3(ll)$ Signature

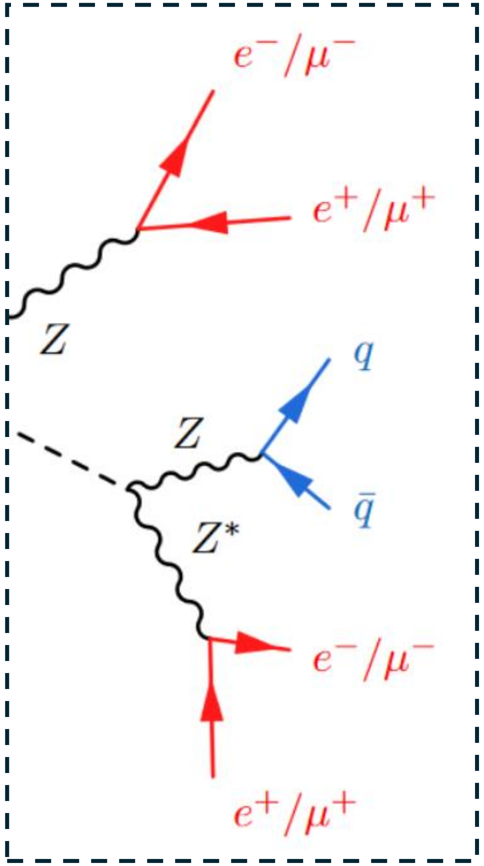
- 1 on-shell leptonic Z

  ➡ 1 pair of high-momentum leptons of same flavour and opposite sign with $\boldsymbol{m_{ll}} \sim$ 91 GeV

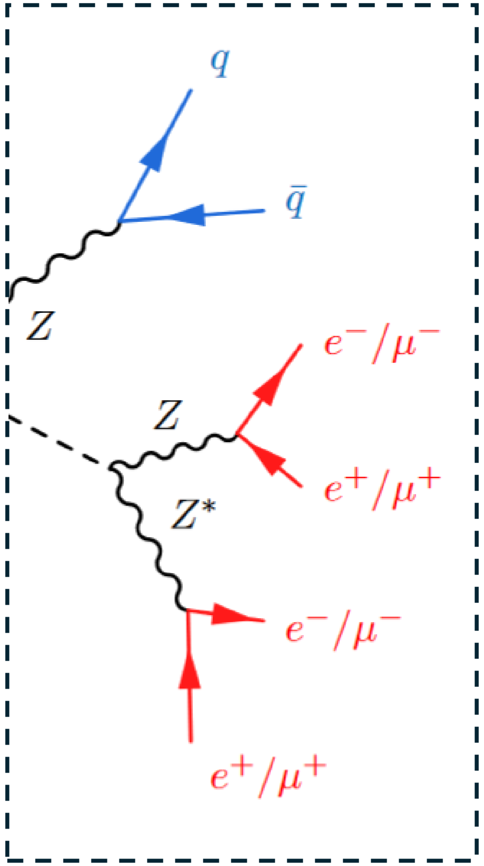
- 1 off-shell leptonic Z

  ➡ 1 pair of low-momentum leptons of same flavour and opposite sign with $\boldsymbol{m_{ll_3}} \sim$ 30 GeV

- $Z(q\bar{q})$ ➡ $\boldsymbol{m_{jj}} \sim$ 91 GeV
- No neutrinos ➡ Low missing energy



$lljjll$ Decay



$jjllll$ Decay

$ZH, H(ZZ^*)$ Four Lepton Final States

1 On-Shell and 1 Off-Shell Leptonic Z Bosons

$Z_1(ll)Z_2(\nu\nu)Z_3(ll)$ and $Z_1(\nu\nu)Z_2(ll)Z_3(ll)$ Signature

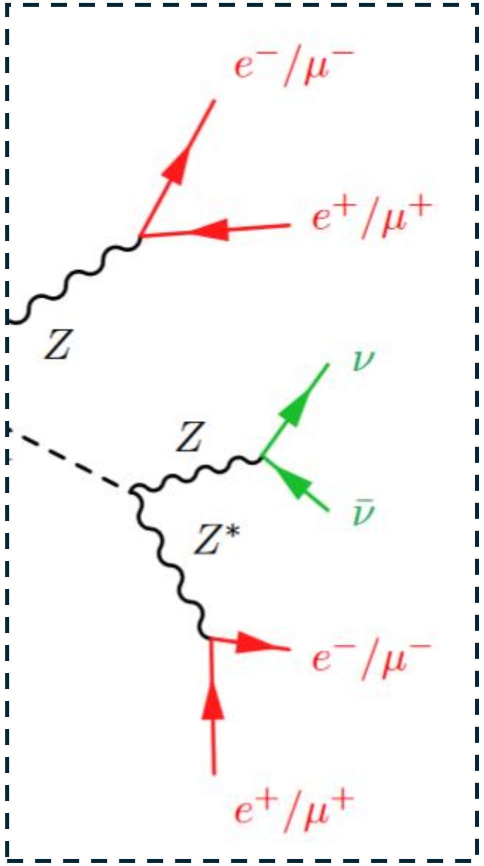
- 1 on-shell leptonic Z

  ➡ 1 pair of high-momentum leptons of same flavour and opposite sign with $\boldsymbol{m_{ll}} \sim 91$ GeV

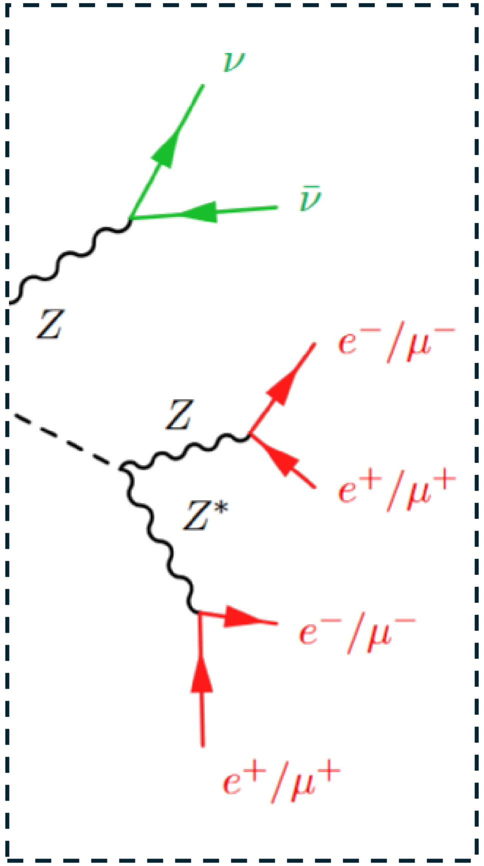
- 1 off-shell leptonic Z

  ➡ 1 pair of low-momentum leptons of same flavour and opposite sign with $\boldsymbol{m_{ll_3}} \sim 30$ GeV

- 2 neutrinos ➡ High missing energy



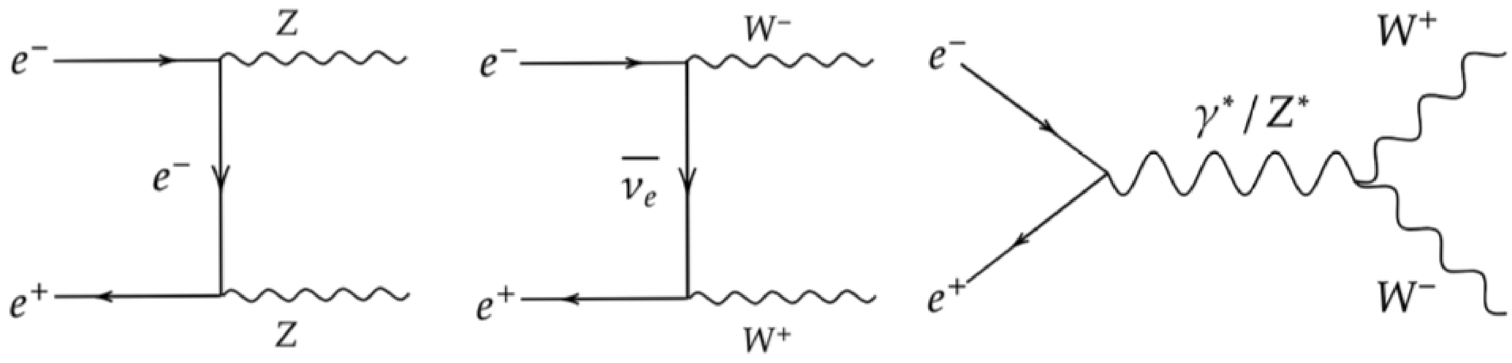
$llvvll$ Decay



$\nu\nu llll$ Decay

Background Processes

- $ee \to \boldsymbol{ZZ}$
- $ee \to \boldsymbol{WW}$

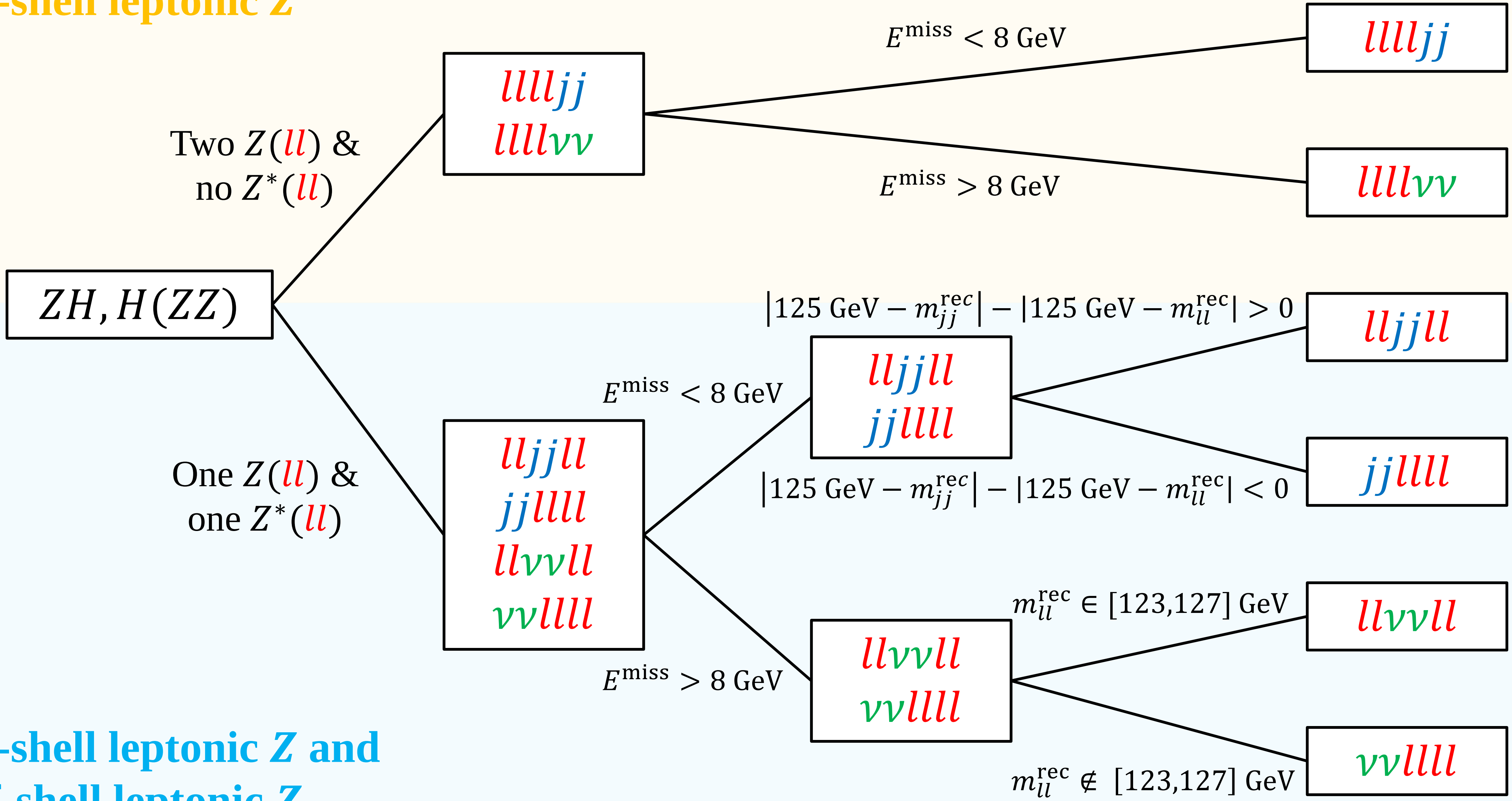


- $ee \to ZH, Z(ee,\mu\mu)$ with **other Higgs decays** $\begin{cases} \boldsymbol{H \to WW} \\ \boldsymbol{H \to \tau\tau} \\ \boldsymbol{H \to \mu\mu} \\ \boldsymbol{H \to qq\ (cc, ss, bb)} \\ \boldsymbol{H \to gg} \\ \boldsymbol{H \to Z\gamma} \end{cases}$

Process	**Signal**	**Background**							
	$\boldsymbol{ZH(ZZ^*)}$	$\boldsymbol{ZH(WW)}$	$\boldsymbol{ZH(\tau\tau)}$	$\boldsymbol{ZH(\mu\mu)}$	$\boldsymbol{ZH(qq)}$	$\boldsymbol{ZH(gg)}$	$\boldsymbol{ZH(Z\gamma)}$	$\boldsymbol{ZZ}$	$\boldsymbol{WW}$
Number of Events	~26000	~15000	~4400	~15	~42600	~5700	~100	~68 10^5	~82 10^6

Analysis

2 on-shell leptonic Z



1 on-shell leptonic Z and 1 off-shell leptonic Z

Analysis

$\boxed{ZH, H(ZZ)}$

We reconstruct up to three leptonic Z bosons: two on-shell Z from electrons and muons with $p \in [20, 80]$ GeV ($\boldsymbol{Z}(\boldsymbol{ll})$) and one off-shell Z from electrons and muons with $p > 5$ GeV ($\boldsymbol{Z}^*(\boldsymbol{ll})$).

All the particles, except the leptons that reconstructed the Z bosons, are used to reconstruct **jets**.

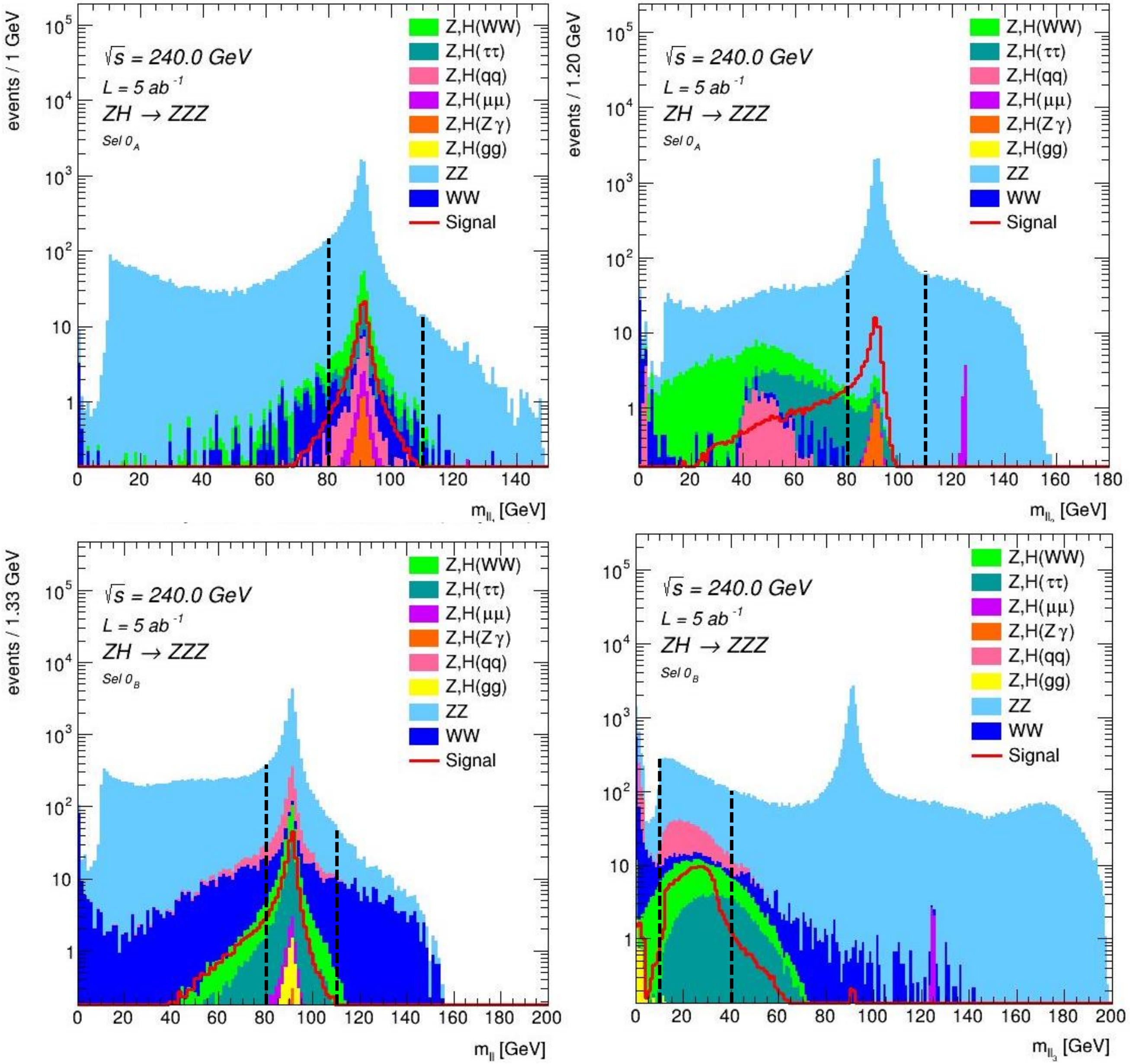
Two $Z(ll)$: Z_1 & Z_2
No $Z^*(ll)$
$m_{ll_1}, m_{ll_2} \in [80, 110]$ GeV

$llll jj$
$llll\nu\nu$

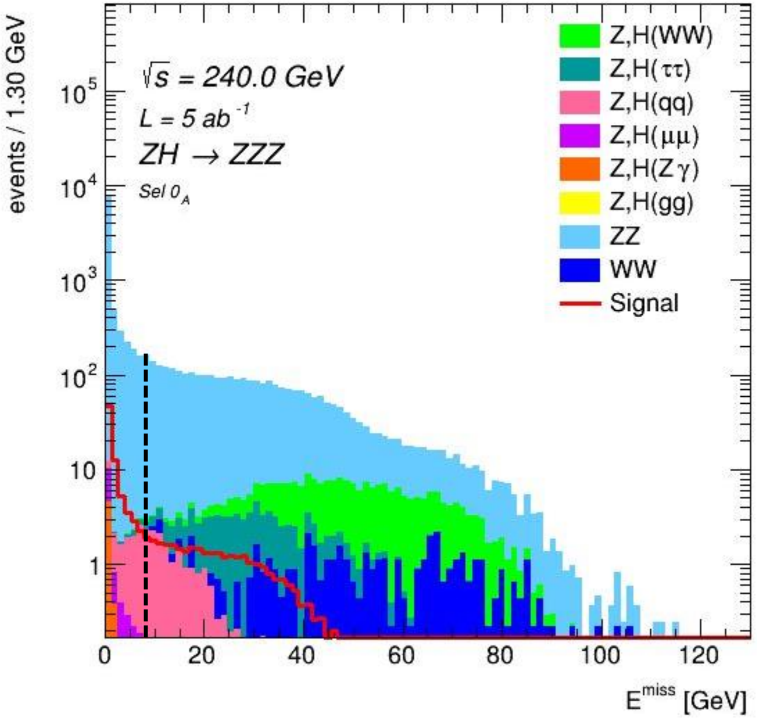
$ZH, H(ZZ)$

$lljjll$
$jjllll$
$ll\nu\nu ll$
$\nu\nu llll$

One $Z(ll)$: Z_1 or Z_2
One $Z^*(ll)$: Z_3
$m_{ll} \in [80, 110]$ GeV
$m_{ll^*} \in [10, 40]$ GeV



Analysis



$llll jj$
$llll\nu\nu$

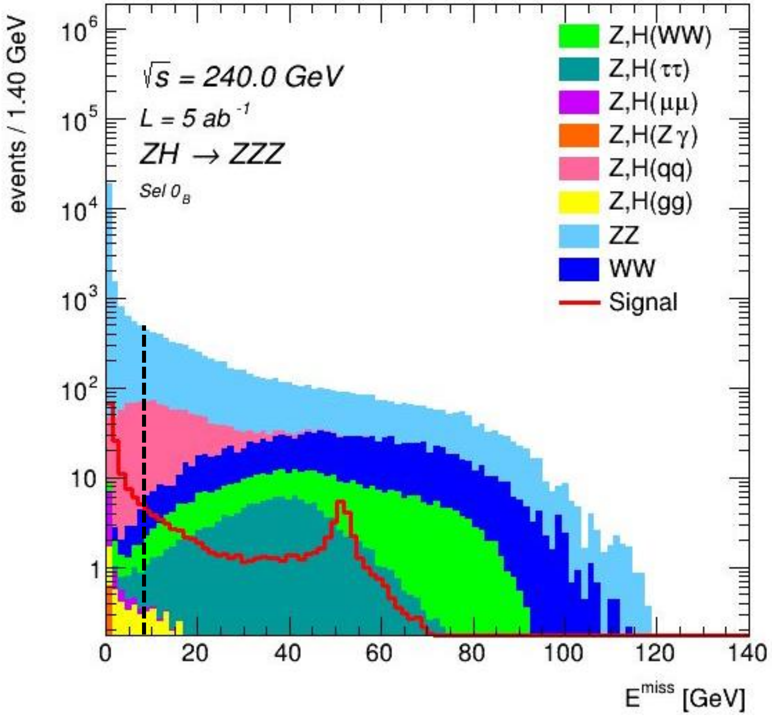
$E^{\text{miss}} < 8$ GeV → $llll jj$

$E^{\text{miss}} > 8$ GeV → $llll\nu\nu$

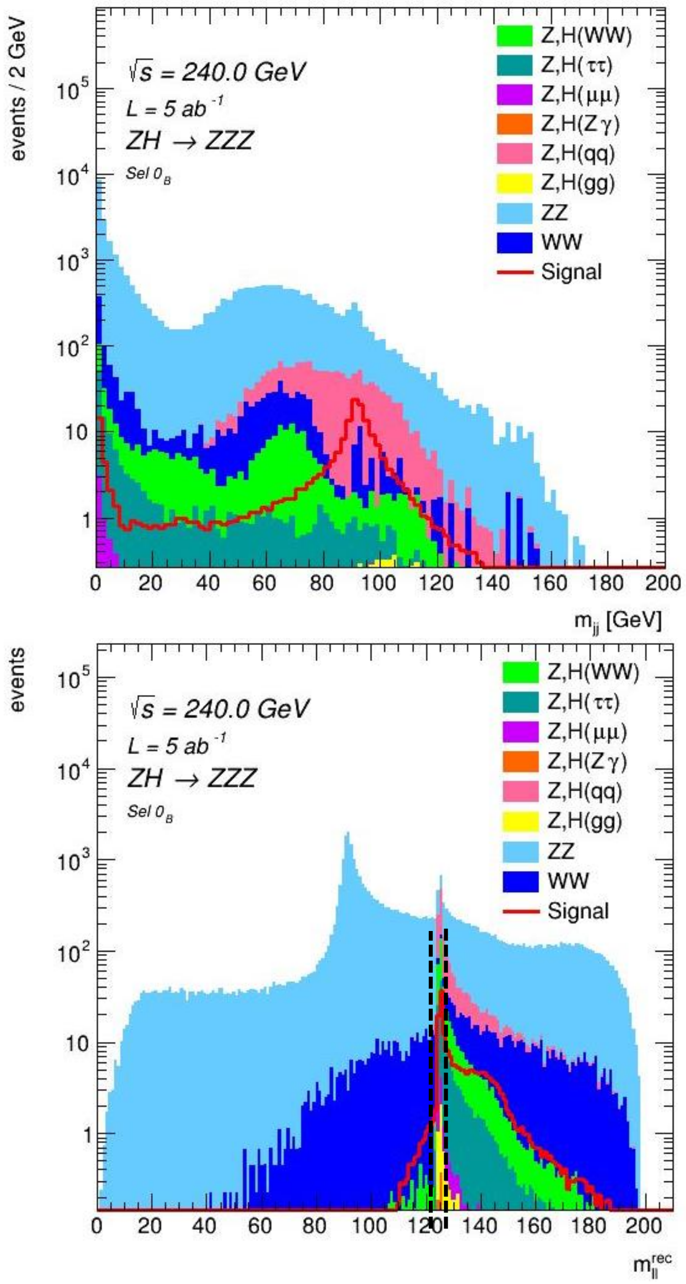
$lljjll$
$jjllll$
$ll\nu\nu ll$
$\nu\nu llll$

$E^{\text{miss}} < 8$ GeV → $lljjll$, $jjllll$

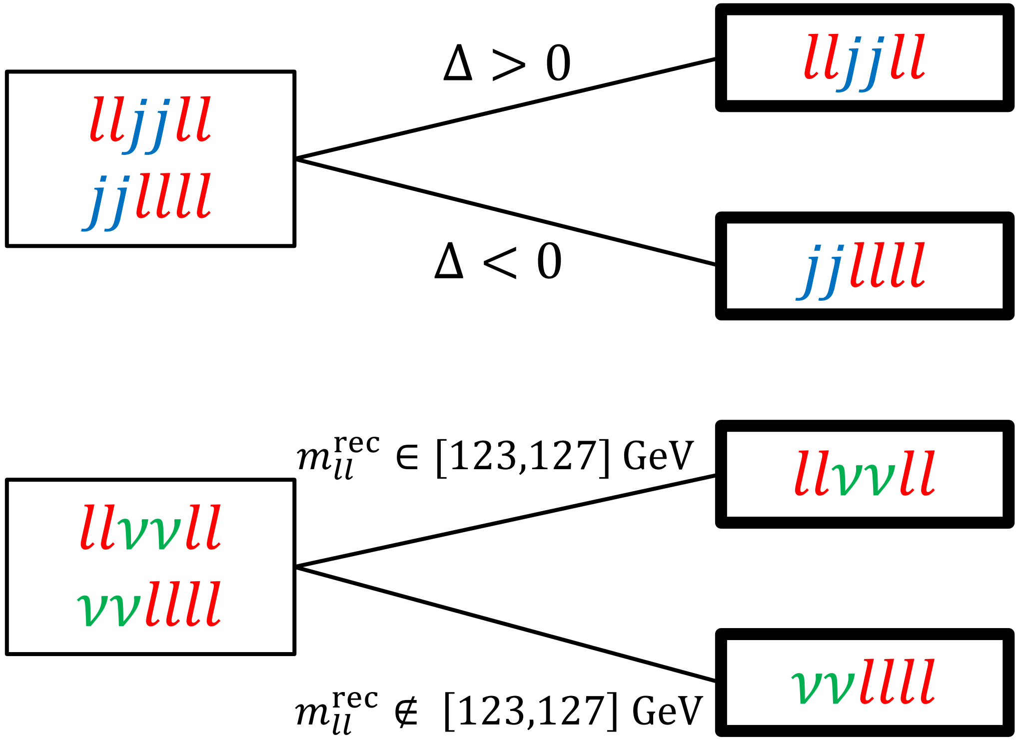
$E^{\text{miss}} > 8$ GeV → $ll\nu\nu ll$, $\nu\nu llll$



Analysis

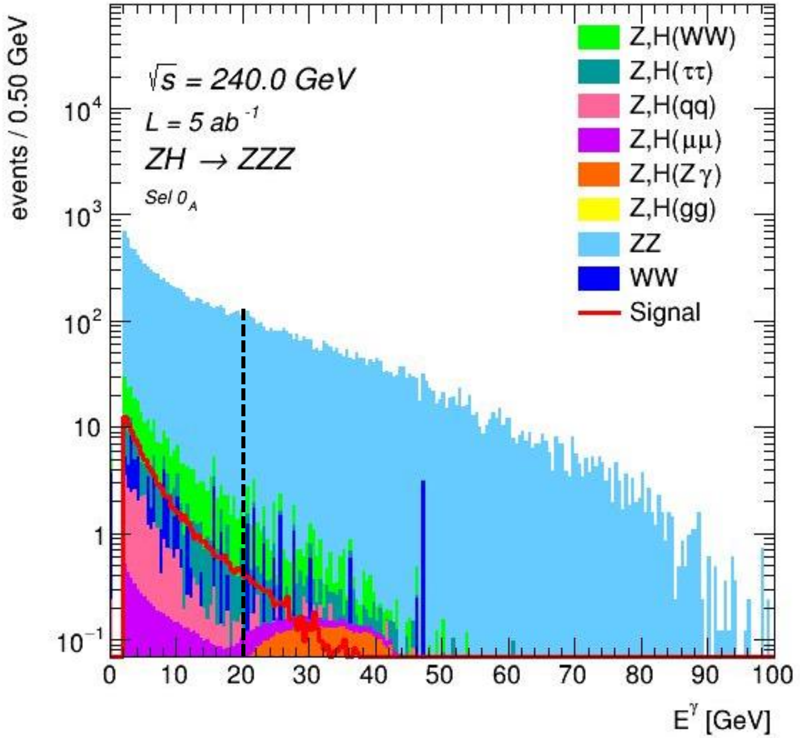


$$\Delta = \left|125\ \mathrm{GeV} - m_{jj}^{\mathrm{rec}}\right| - \left|125\ \mathrm{GeV} - m_{ll}^{\mathrm{rec}}\right|$$

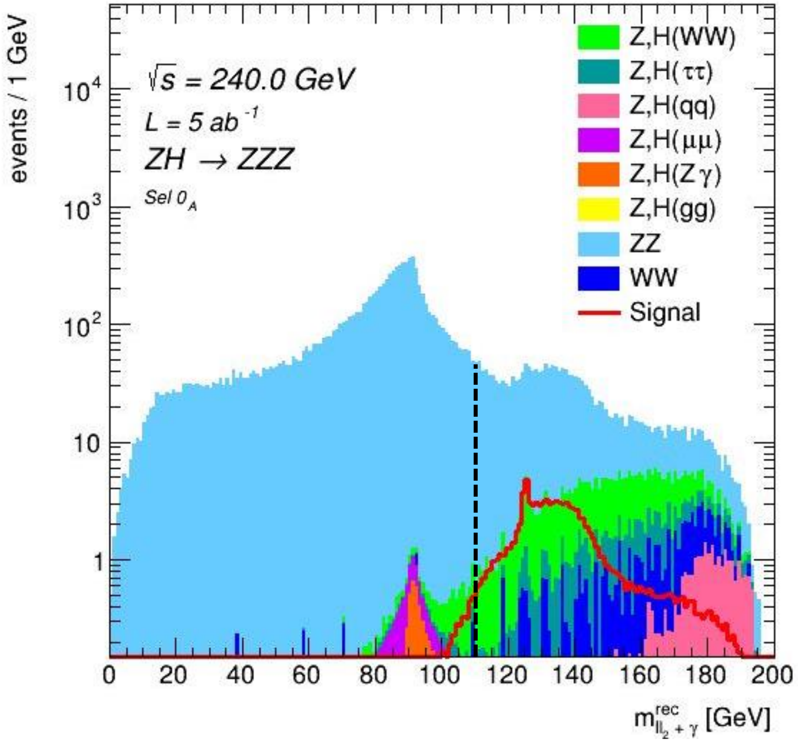


Analysis

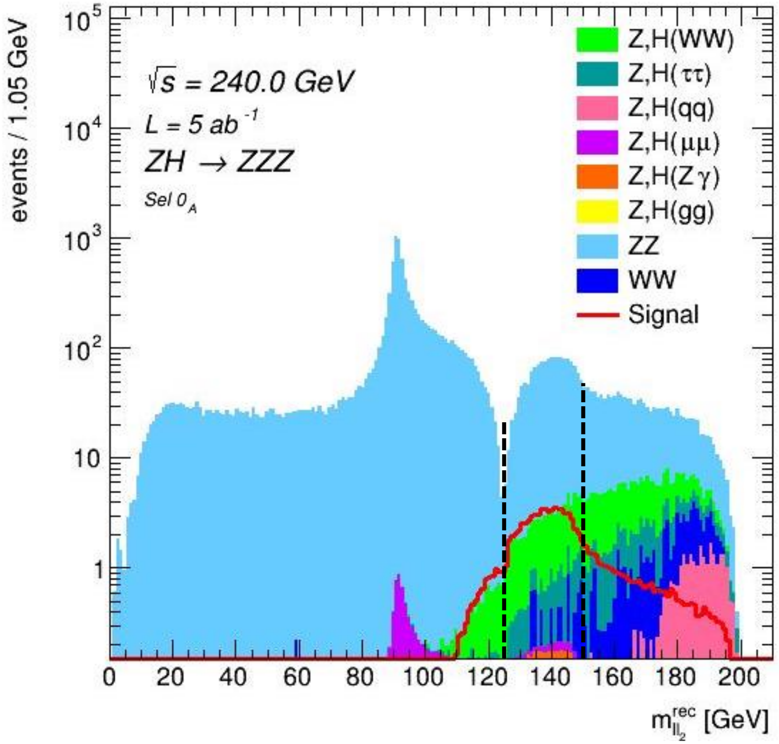
For $Z_1(ll)Z_2(ll)Z_3(jj)$ For $Z_1(ll)Z_2(ll)Z_3(\nu\nu)$



$E^{\gamma} < 20$ GeV



$m^{\text{rec}}_{Z_2+\gamma} > 115$ GeV



$m^{\text{rec}}_{Z_2} \in [125, 150]$ GeV

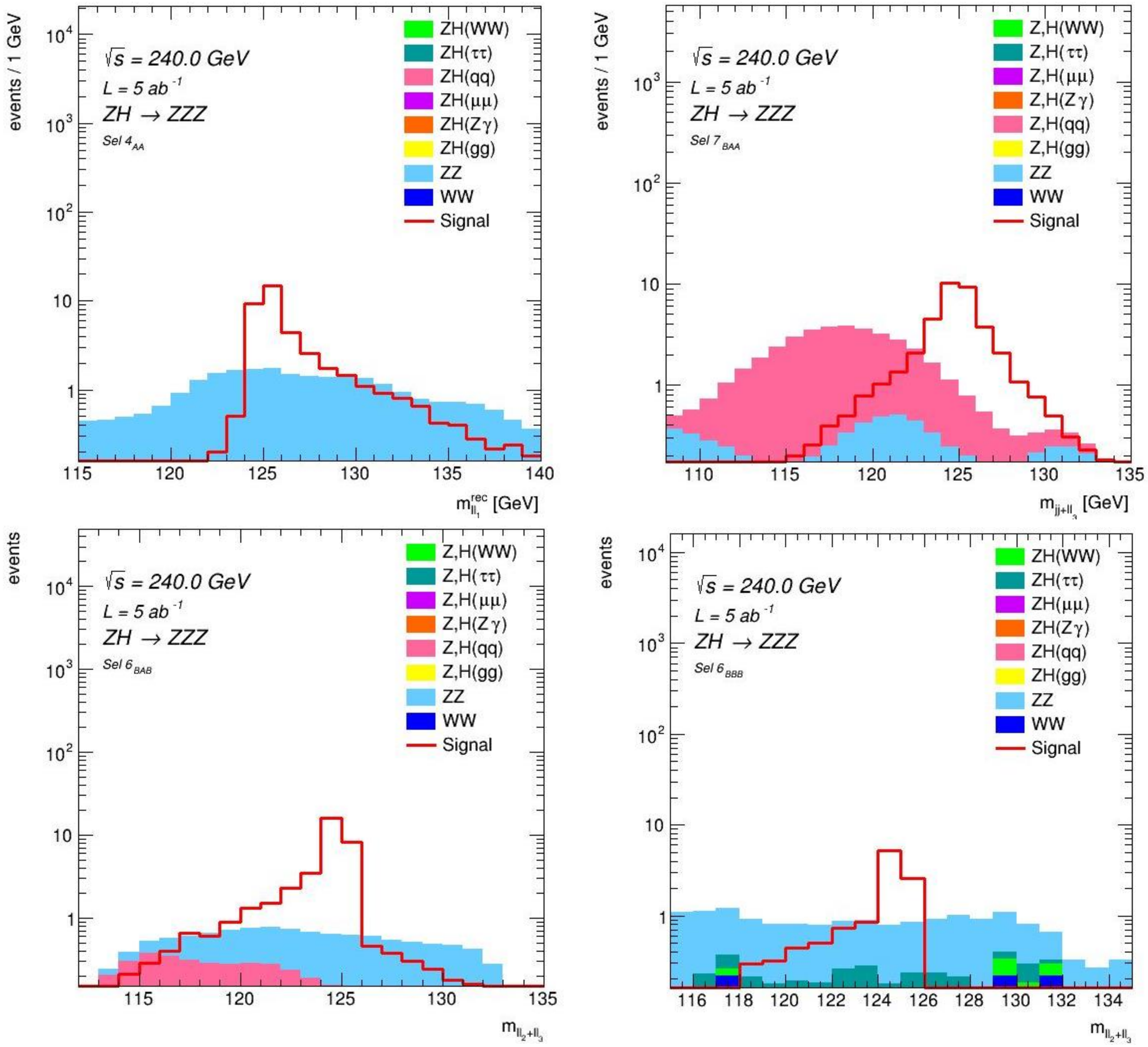
Results

The rectangular cuts bring out **four clean channels**:

$$\begin{cases} Z_1(ll)Z_2(ll)Z_3(jj) \\ Z_1(ll)Z_2(jj)Z_3(ll) \\ Z_1(jj)Z_2(ll)Z_3(ll) \\ Z_1(\nu\nu)Z_2(ll)Z_3(ll) \end{cases}$$

With the respective discriminating variables:

$\boldsymbol{m_{Z_1}^{\mathrm{rec}}}$, $\boldsymbol{m_{jj+Z_3}}$, $\boldsymbol{m_{Z_2+Z_3}}$ and $\boldsymbol{m_{Z_2+Z_3}}$



Results

Channel	S/B	$S/\sqrt{B}$	Discriminating Variable	$\frac{\sigma_{ZH,H(ZZ^*)}}{\sigma^{\mathrm{SM}}_{ZH,H(ZZ^*)}}$
$Z_1(ll)Z_2(ll)Z_3(jj)$	~ 1.5	~ 7.9	$m_{Z_1}^{\mathrm{rec}}$ (recoil mass of Z_1)	$1^{+0.193}_{-0.176}$
$Z_1(ll)Z_2(jj)Z_3(ll)$	~ 0.95	~ 6.2	m_{jj+Z_3} (mass of dijet+Z_3)	$1^{+0.193}_{-0.174}$
$Z_1(jj)Z_2(ll)Z_3(ll)$	~ 3.1	~ 10.9	$m_{Z_2+Z_3}$ (mass of Z_2+Z_3)	$1^{+0.187}_{-0.168}$
$Z_1(\nu\nu)Z_2(ll)Z_3(ll)$	~ 0.75	~ 2.9	$m_{Z_2+Z_3}$ (mass of Z_2+Z_3)	$1^{+0.394}_{-0.329}$

S: number of **signal** events

B: number of **background** events

Results

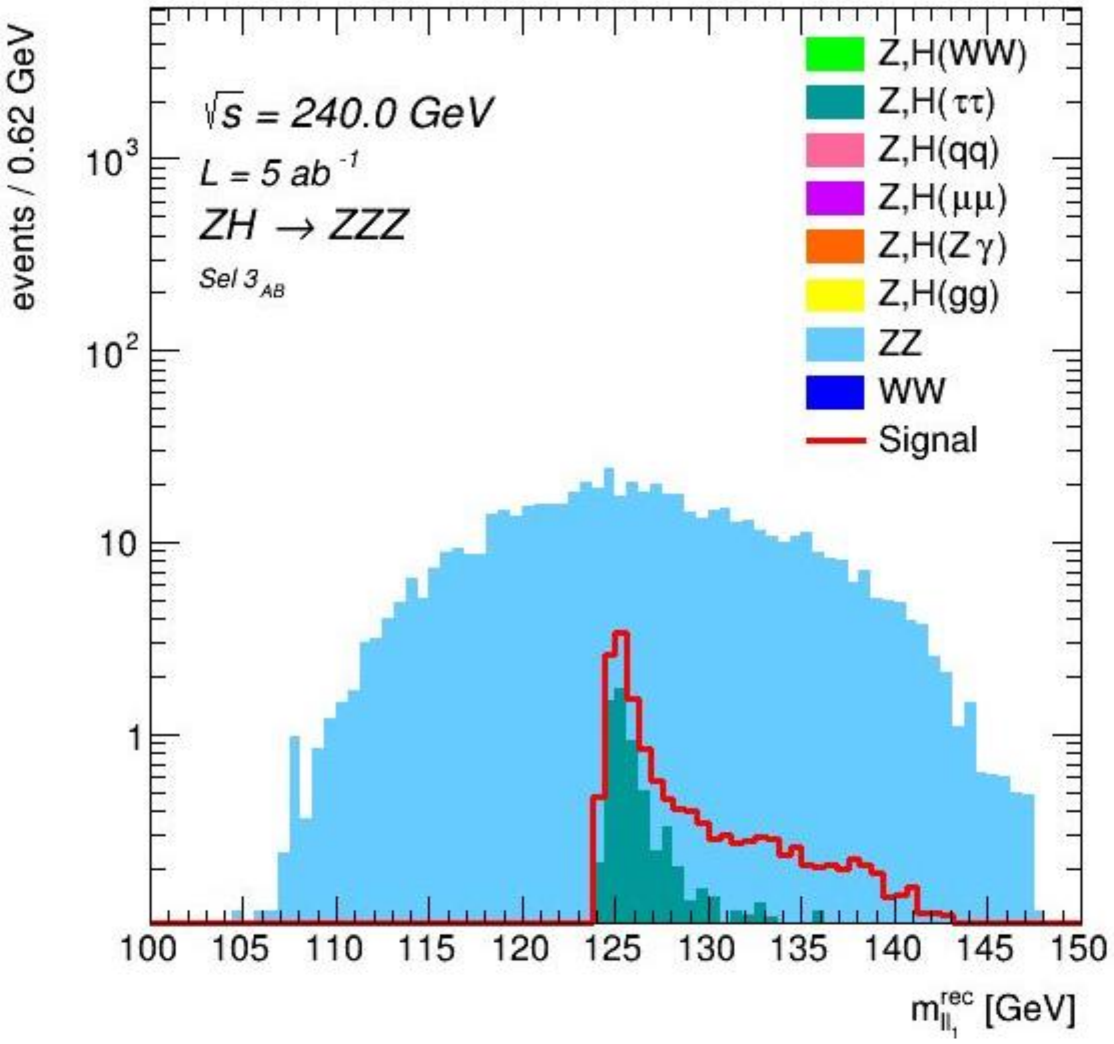
Result of the fit performed on the four channels combined with **10 %** systematic uncertainty on most abundant backgrounds:

$$\boxed{\boldsymbol{\mu = 1^{+0.104}_{-0.098}}}$$

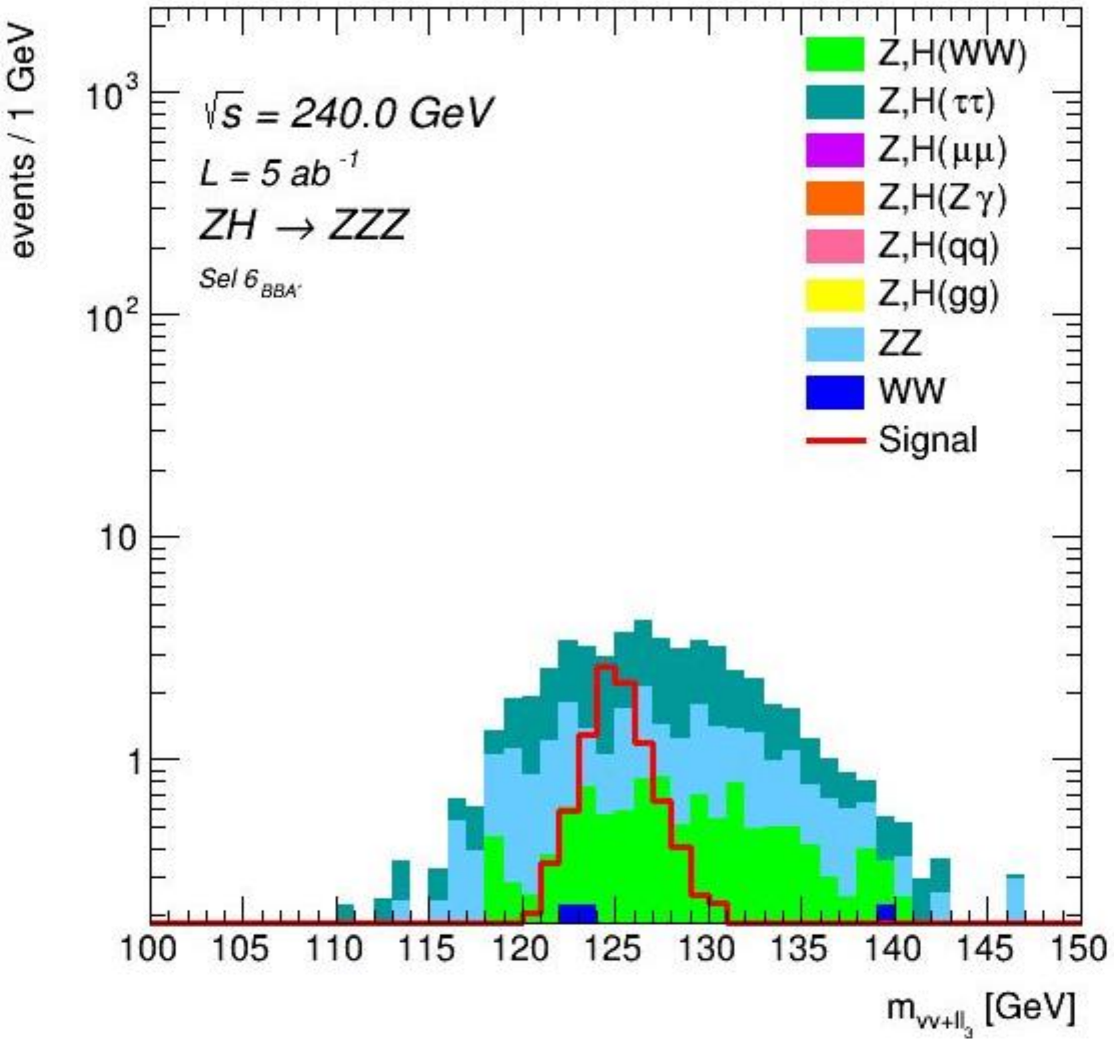
➡ Uncertainty **dominated by statistical uncertainties**

➡ Closely comparable to Ines' results

Encountered Difficulties



$m^{\mathrm{rec}}_{Z_1}$ for the $Z_1(ll)Z_2(ll)Z_3(\nu\nu)$
enhanced signature



$m_{\nu\nu+Z_3}$ for for the $Z_1(ll)Z_2(\nu\nu)Z_3(ll)$
enhanced signature

Conclusion

Results

Four channels used for the statistical treatment: $\boldsymbol{llljj}$, $\boldsymbol{lljjll}$, $\boldsymbol{jjllll}$ and $\boldsymbol{\nu\nu llll}$.

Two unused channels: $\boldsymbol{llll\nu\nu}$ and $\boldsymbol{ll\nu\nu ll}$.

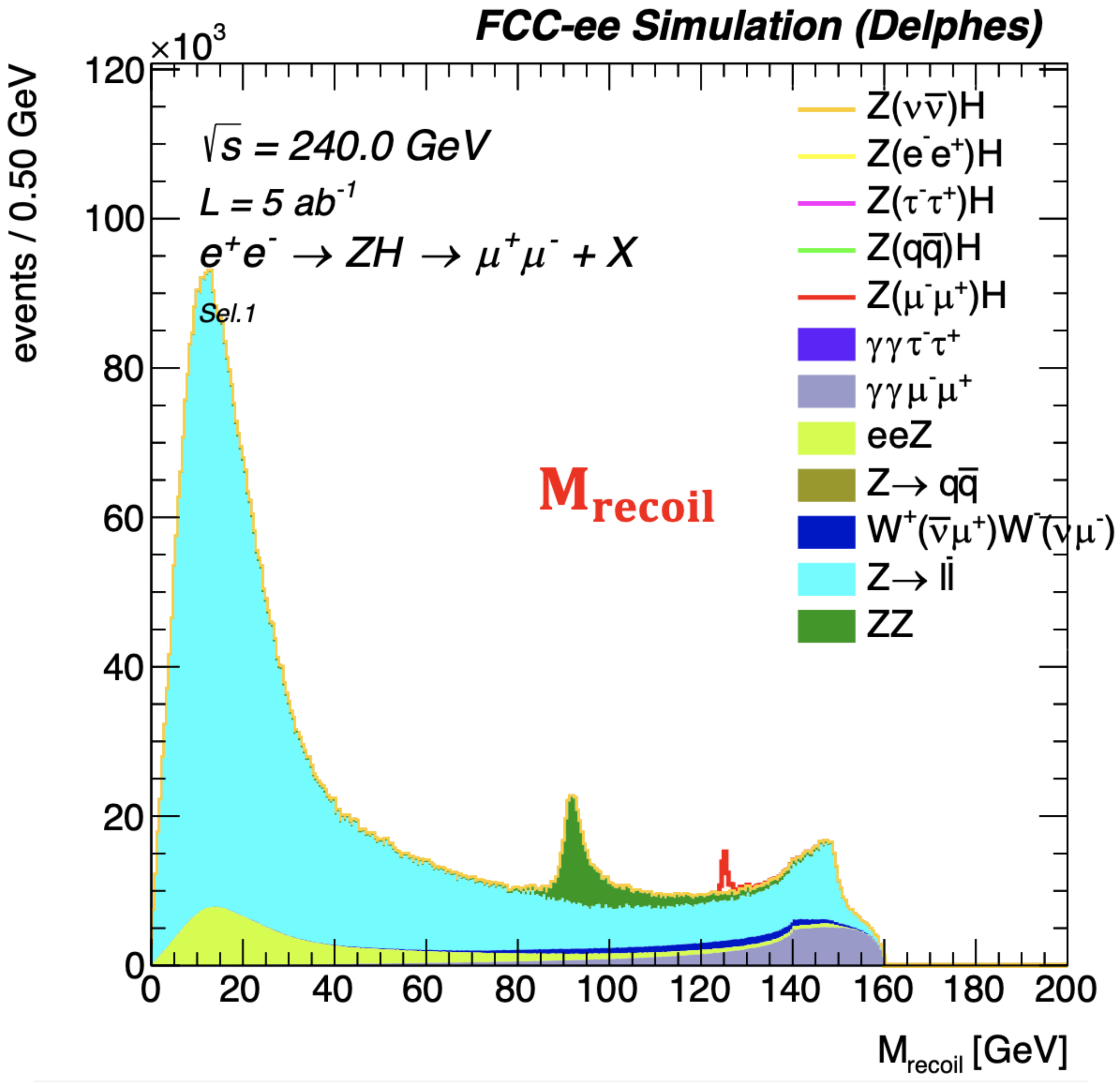
Statistical uncertainty of $\begin{cases} \sim\mathbf{20\ \%} \text{ for } \boldsymbol{llljj}, \boldsymbol{lljjll} \text{ and } \boldsymbol{jjllll} \\ \sim\mathbf{40\ \%} \text{ for } \boldsymbol{\nu\nu llll} \\ \sim\mathbf{10\ \%} \text{ for the combination} \end{cases}$

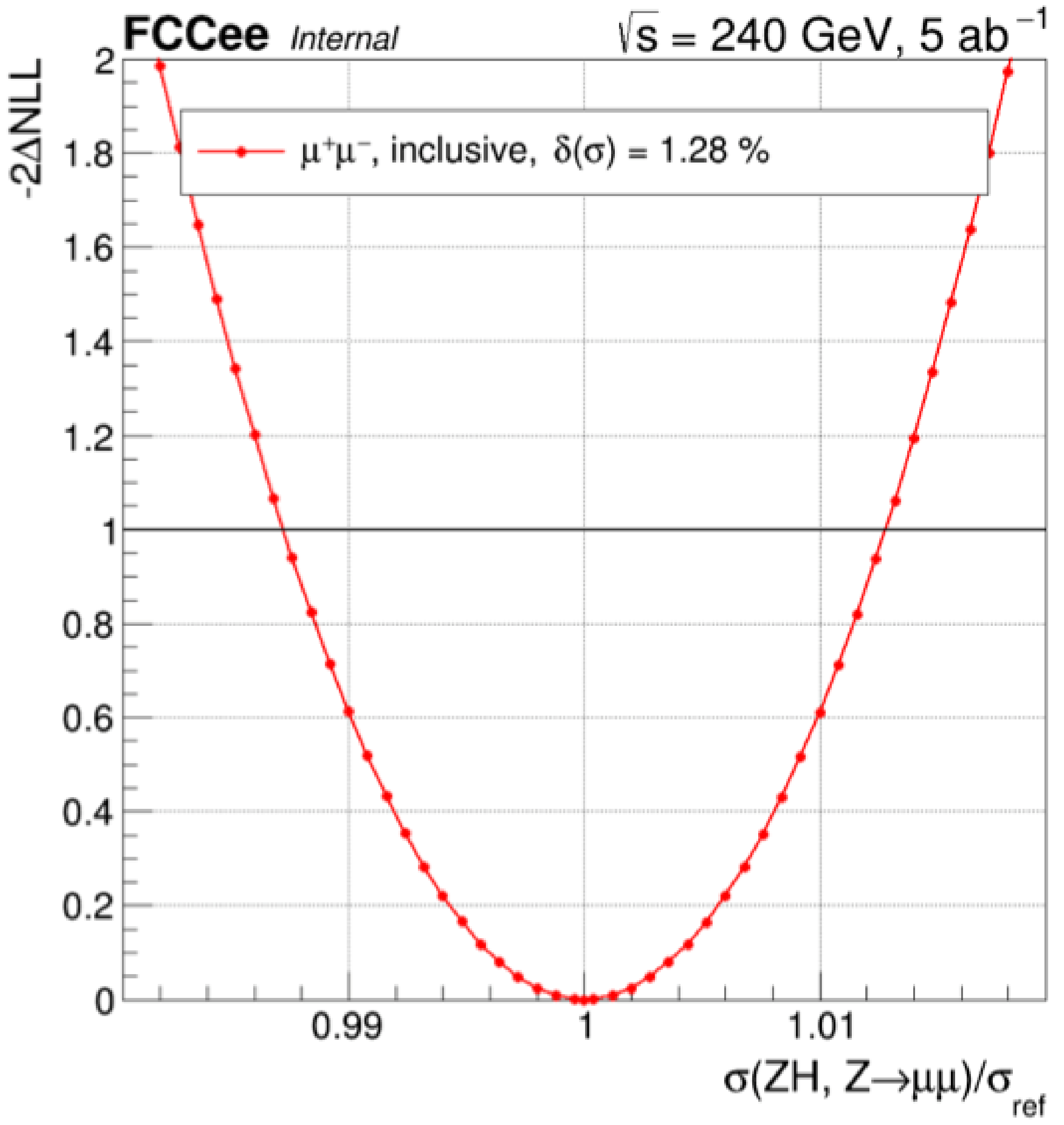
Lookout

Implement **flavour tagging** to reduce the $ZH(qq)$ background

Determine how much the **kinematic reconstruction efficiency** impacts the final result

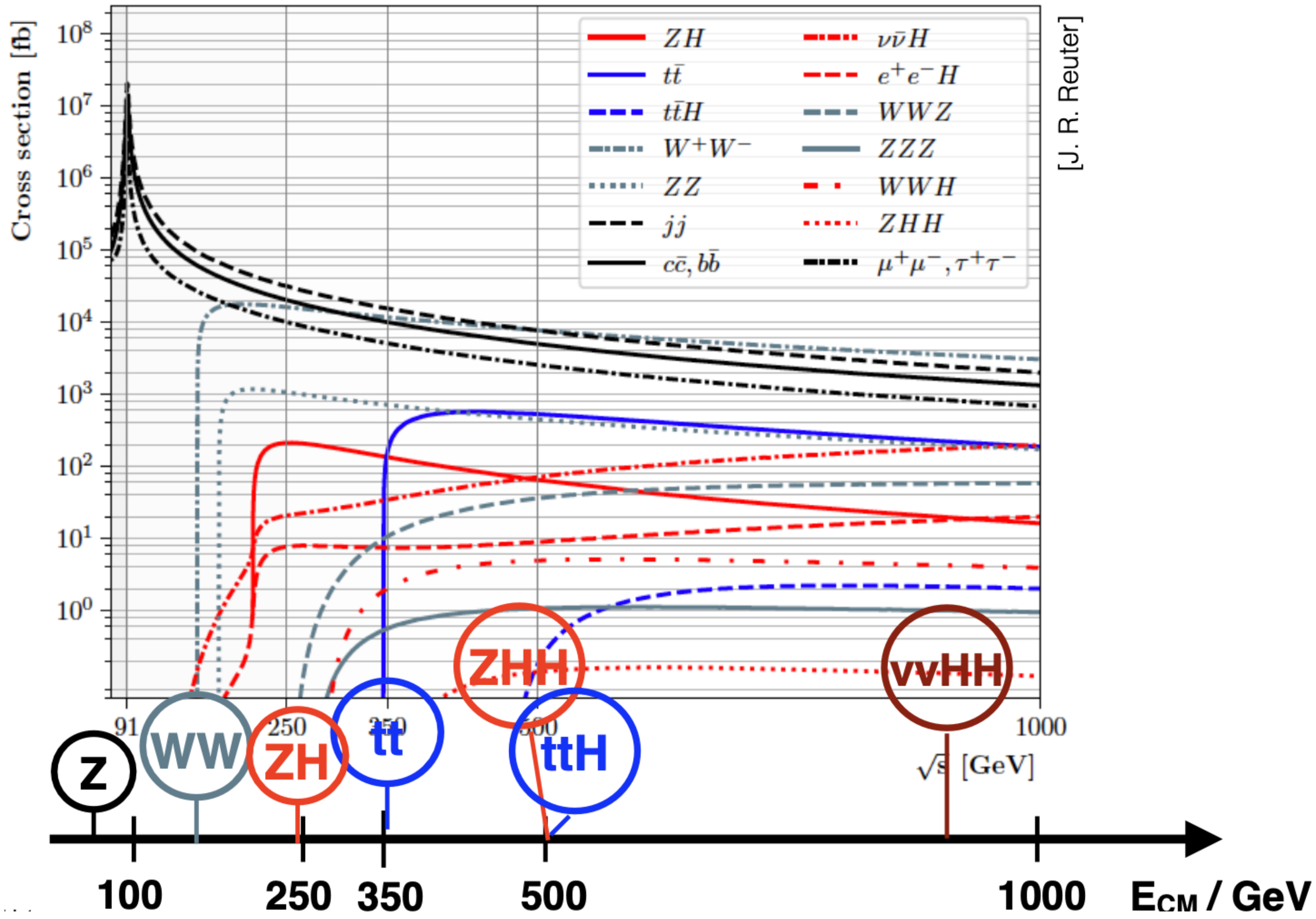
Backup: Measurement of the Inclusive Cross Section σ_{ZH}





Backup: Processes Cross Sections

ee Cross Sections



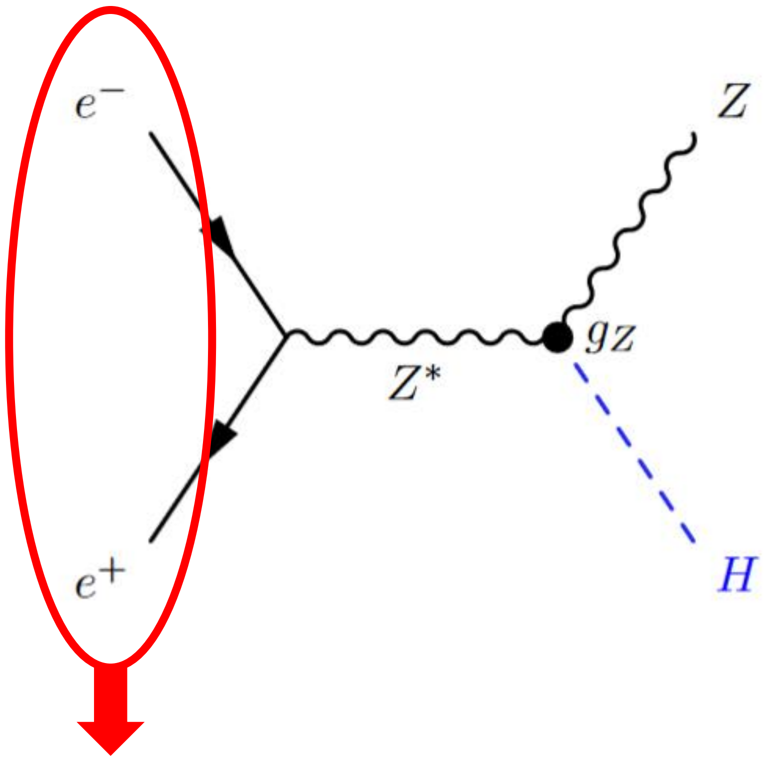
- 91.2 GeV: Z pole
- 160 GeV: WW threshold
- 250 GeV: ZH maximum
- 350 GeV: top threshold, VBF Higgs production
- 500 GeV: ttH, ZHH
- >1 TeV: VBF double Higgs

Backup: Expected $\delta\Gamma_H$

Higgs Width Expected Precision at ee Colliders

Collider	$\delta\Gamma_H$ [%] from Ref.
ILC_{250}	2.3
ILC_{500}	1.6
ILC_{1000}	1.4
CLIC_{380}	4.7
CLIC_{1500}	2.6
CLIC_{3000}	2.5
CEPC	2.8
FCC-ee_{240}	2.7
FCC-ee_{365}	1.3

Backup: Recoil Mass



$\sqrt{s} = 240$ **GeV**

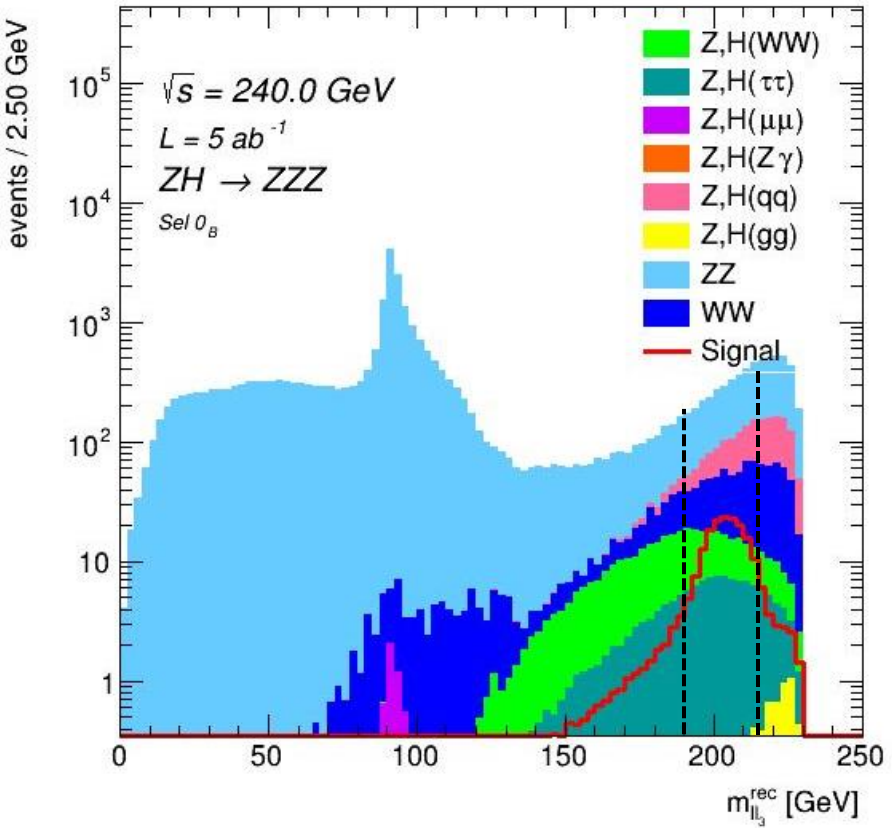
$$\underline{P_{CM}} = \underline{P_Z} + \underline{P_H} \Leftrightarrow \underline{P_H} = \underline{P_{CM}} - \underline{P_Z}$$

$$\begin{cases} \underline{P_{CM}} = (\sqrt{s}, \vec{0}) \\ \underline{P_H} = (E_H, \vec{p}_H) \\ \underline{P_Z} = (E_Z, \vec{p}_Z) \end{cases}$$

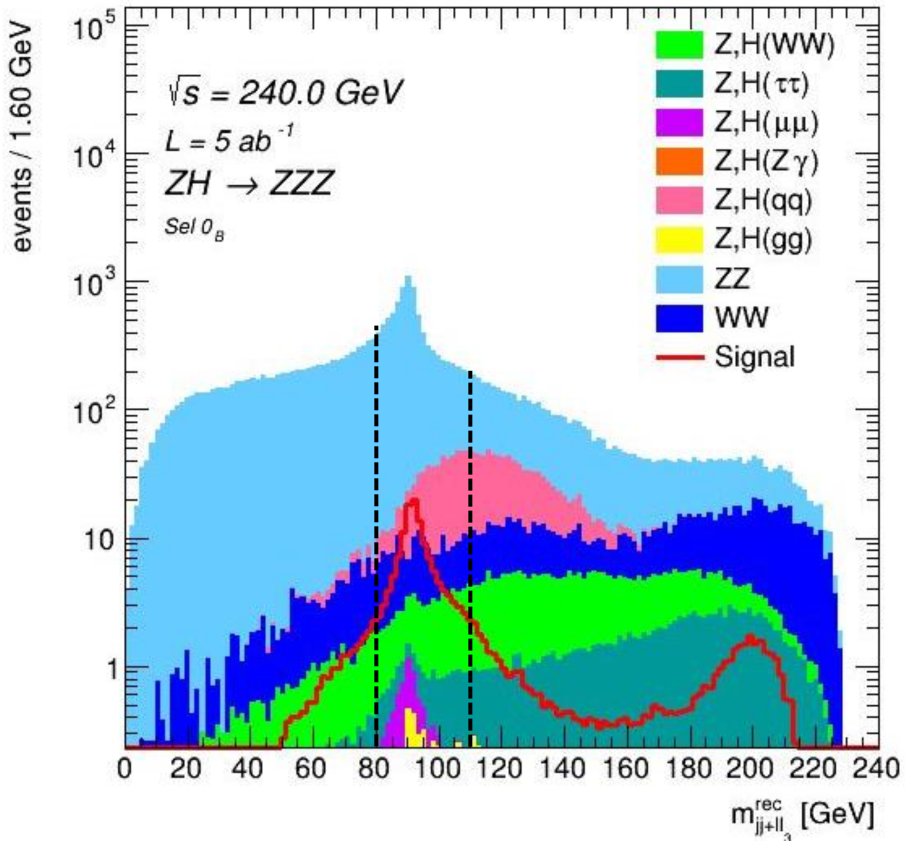
$$\left|\underline{P_H}\right| = \left|\underline{P_{CM}} - \underline{P_Z}\right| \Leftrightarrow m_H = \sqrt{(\sqrt{s} - E_Z)^2 - {p_Z}^2}$$

Backup: Rectangular Cuts

For $Z_1(ll)Z_2(jj)Z_3(ll)$



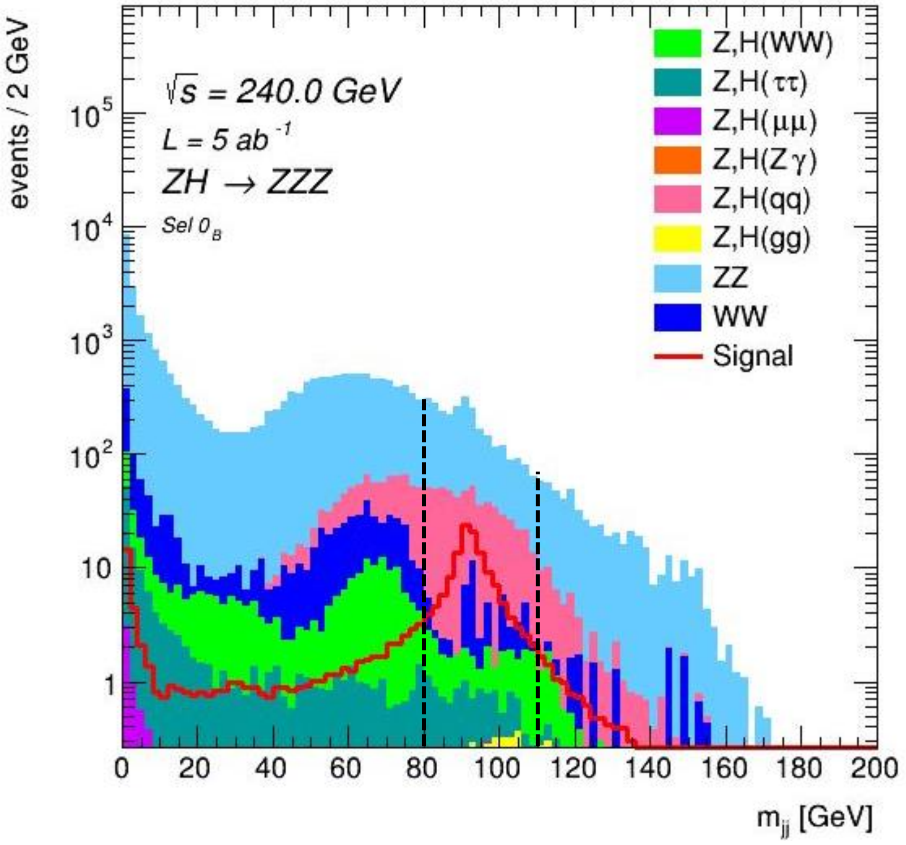
$m^{\text{rec}}_{Z_3} \in [190, 215]$ GeV



$m^{\text{rec}}_{jj+Z_3} \in [80, 110]$ GeV

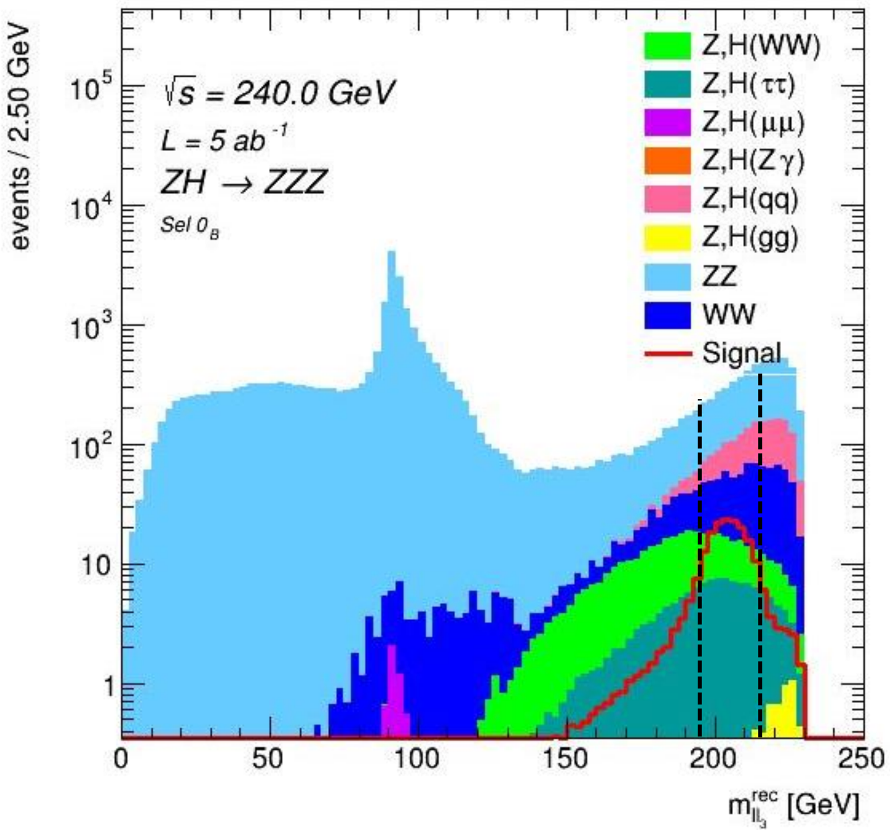
Backup: Rectangular Cuts

For $Z_1(jj)Z_2(ll)Z_3(ll)$ and $Z_1(ll)Z_2(jj)Z_3(ll)$



$m_{jj} \in [80, 110]$ GeV

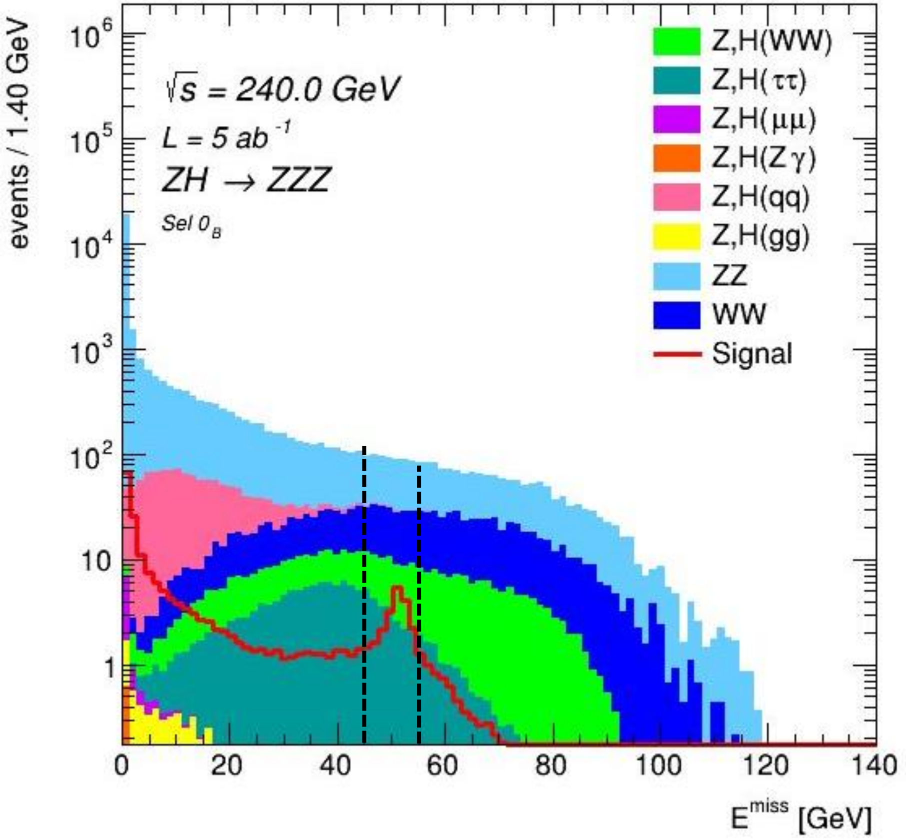
For $Z_1(jj)Z_2(ll)Z_3(ll)$



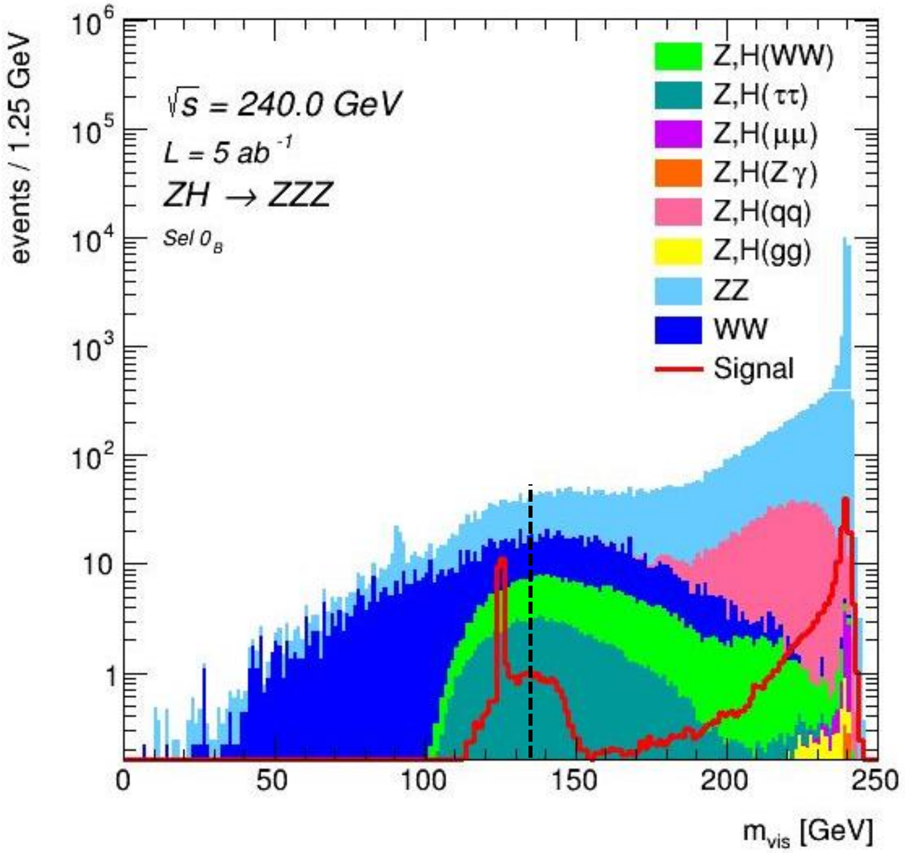
$m^{\text{rec}}_{Z_3} \in [195, 215]$ GeV

Backup: Rectangular Cuts

For $Z_1(\nu\nu)Z_2(ll)Z_3(ll)$



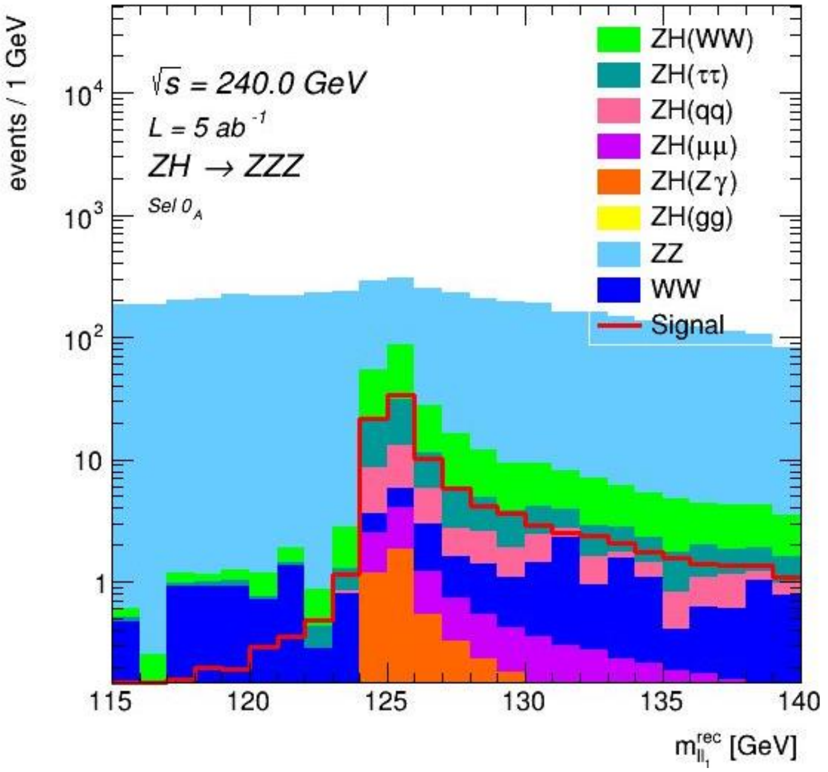
$E^{\text{miss}} \in [45, 55]$ GeV



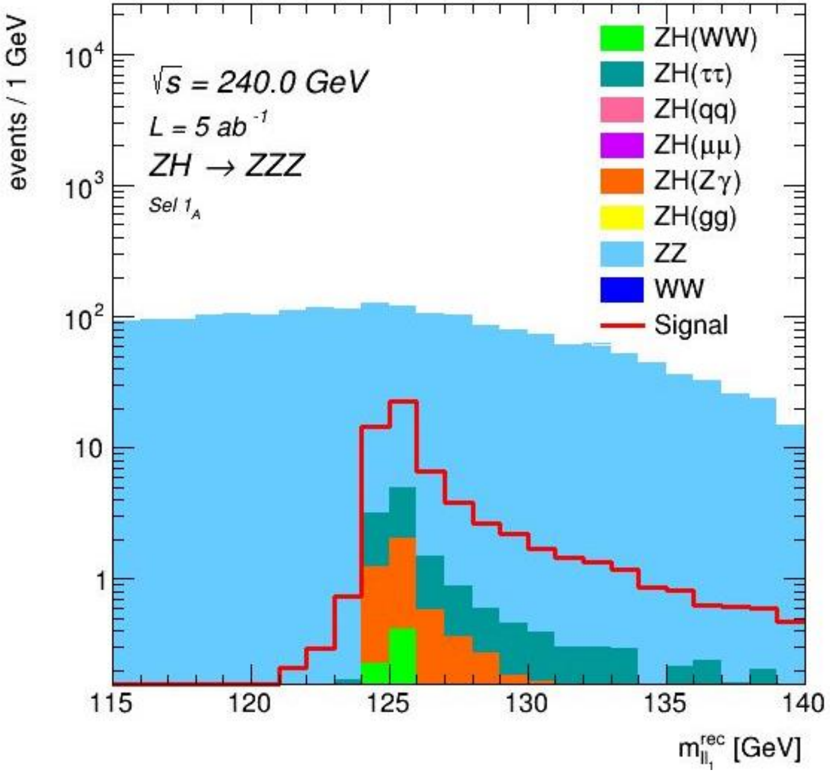
$m^{\text{vis}} < 135$ GeV

Backup: Rectangular Cuts

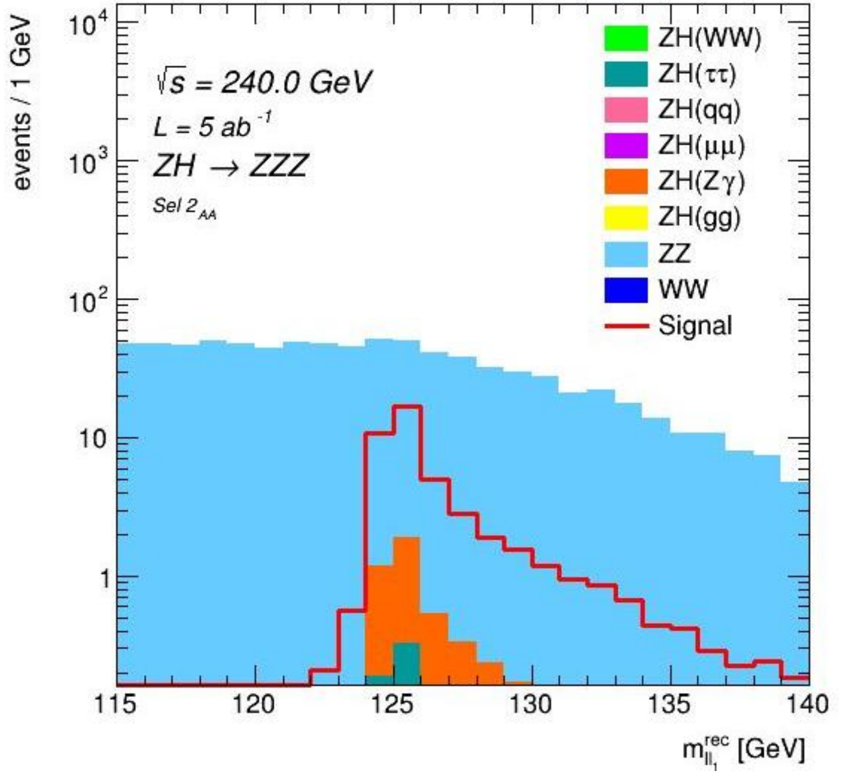
$m_{ll_1}^{\mathrm{rec}}$ Through Successive Cuts



No cut



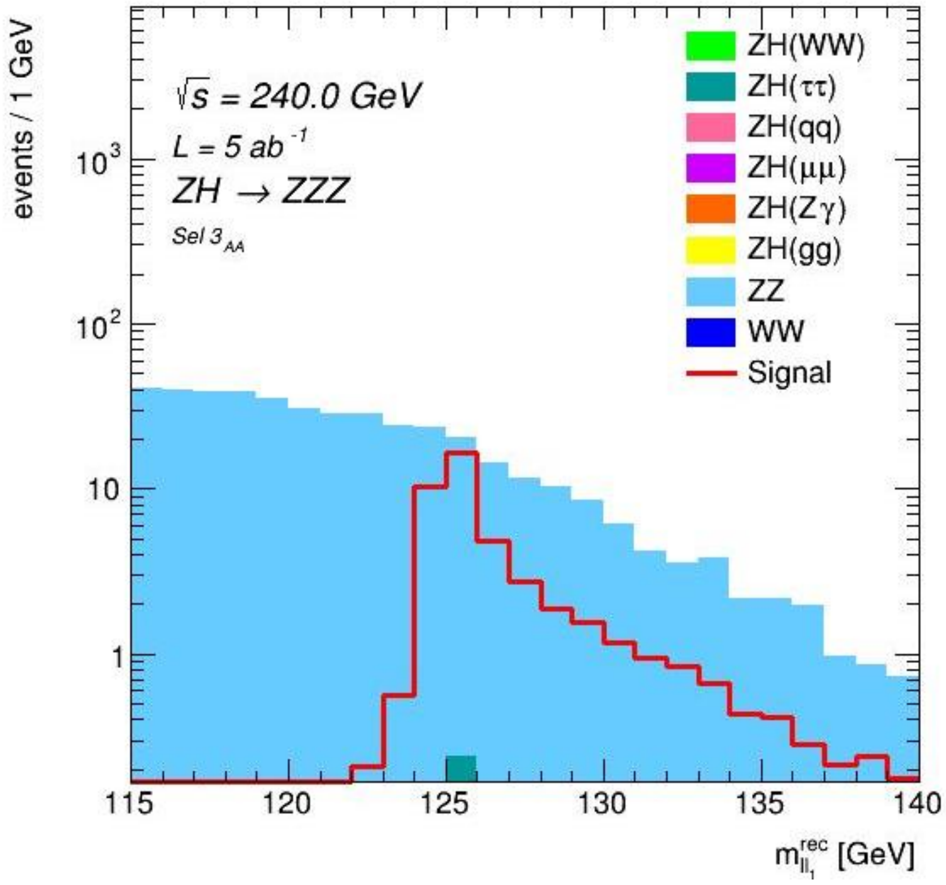
$m_{ll_1}, m_{ll_2} \in [80, 110]$ GeV



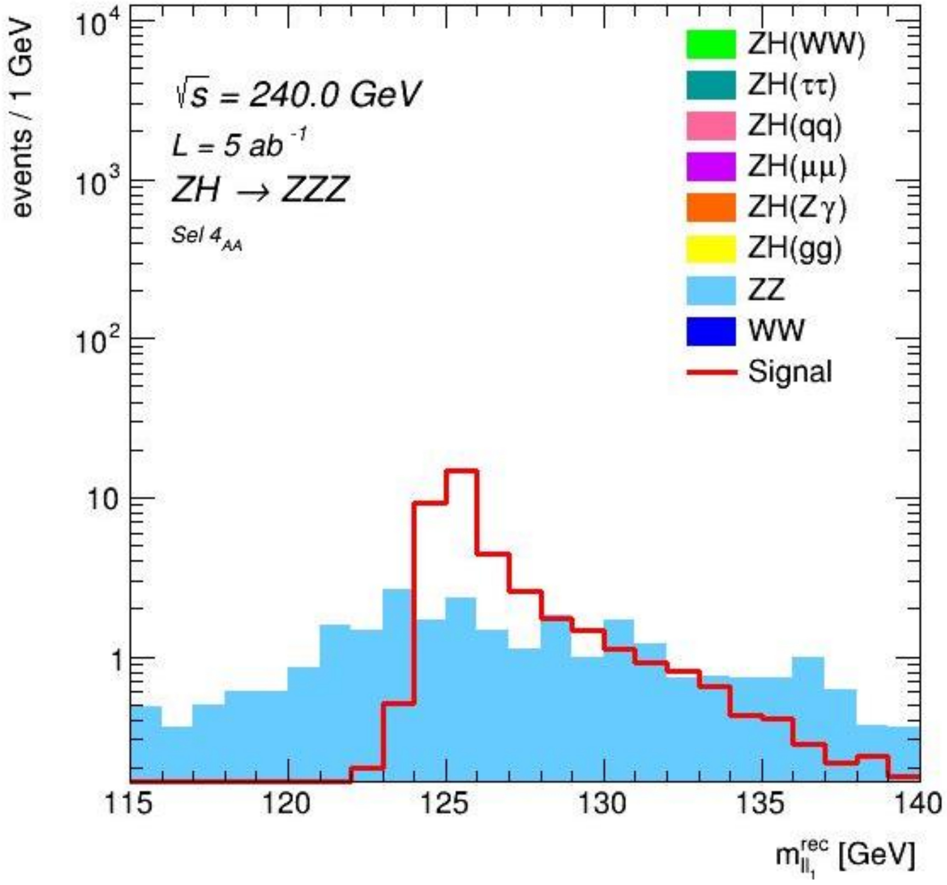
$E^{\mathrm{miss}} < 8$ GeV

Backup: Rectangular Cuts

$m_{ll_1}^{\text{rec}}$ Through Successive Cuts



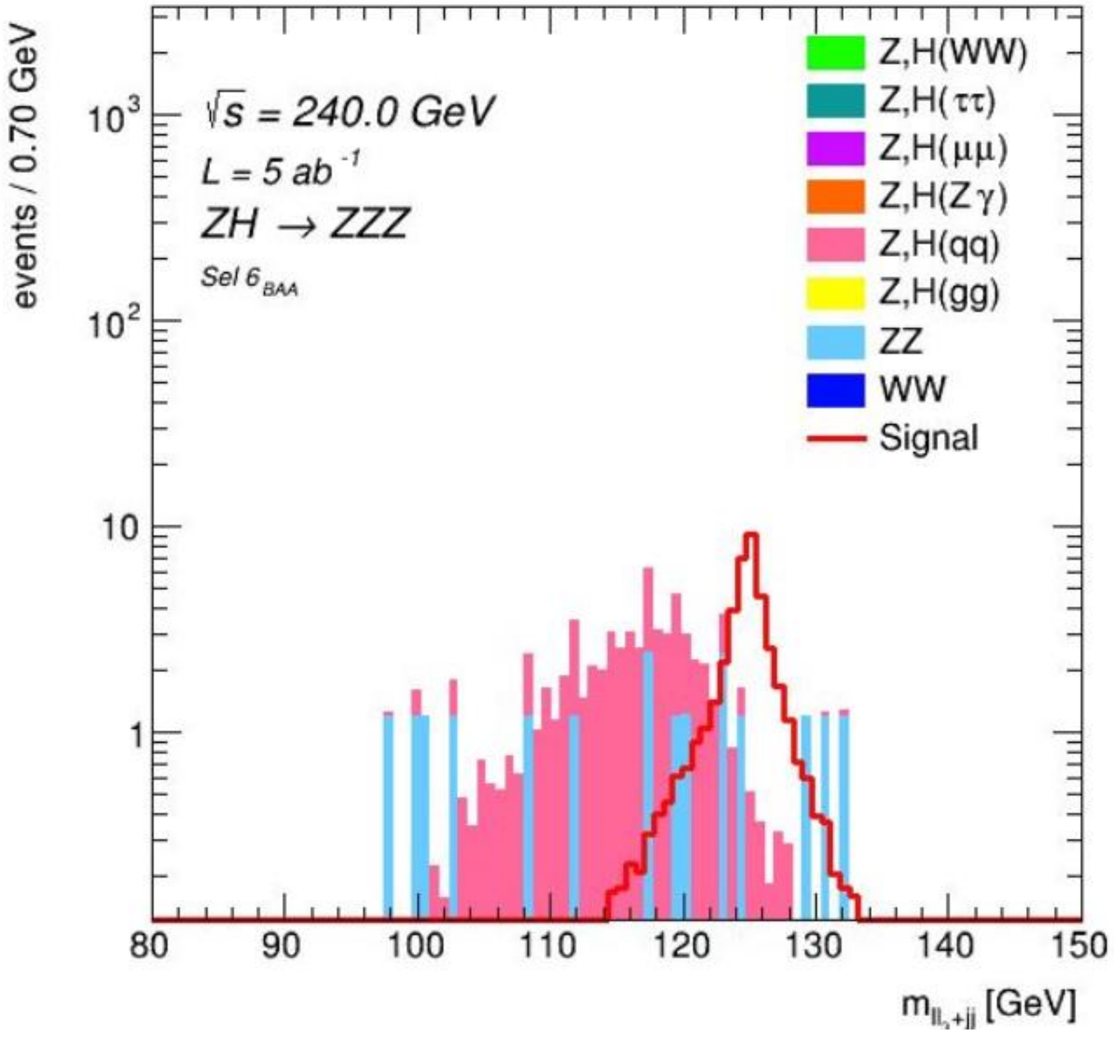
$E^{\gamma} < 20$ GeV



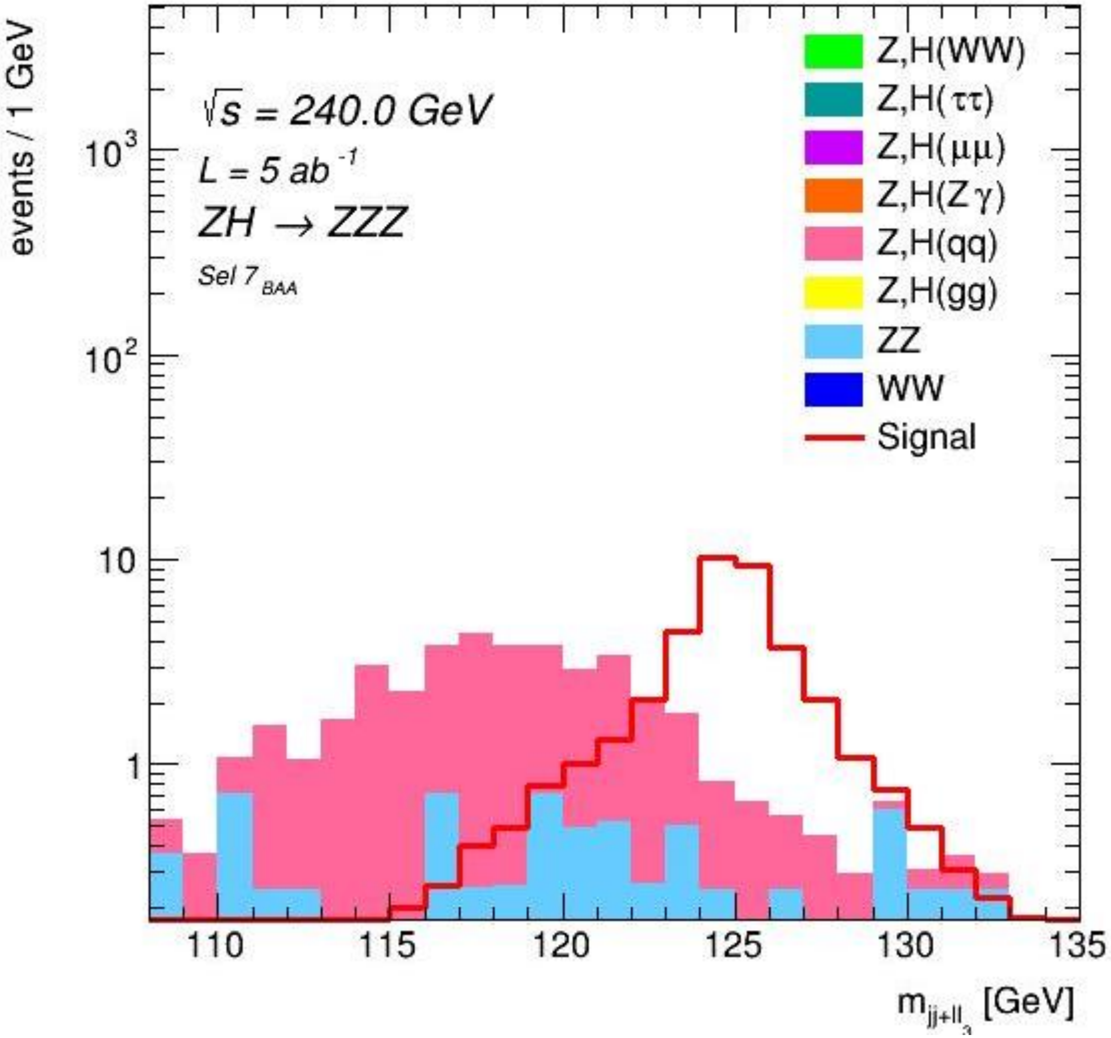
$m_{Z_2+\gamma}^{\text{rec}} > 115$ GeV

Backup: Smoothing Effect

m_{jj+ll_3} using 10 % of the ZZ peudo-data



m_{jj+ll_3} without smoothing



Backup: Statistical and Total Uncertainties

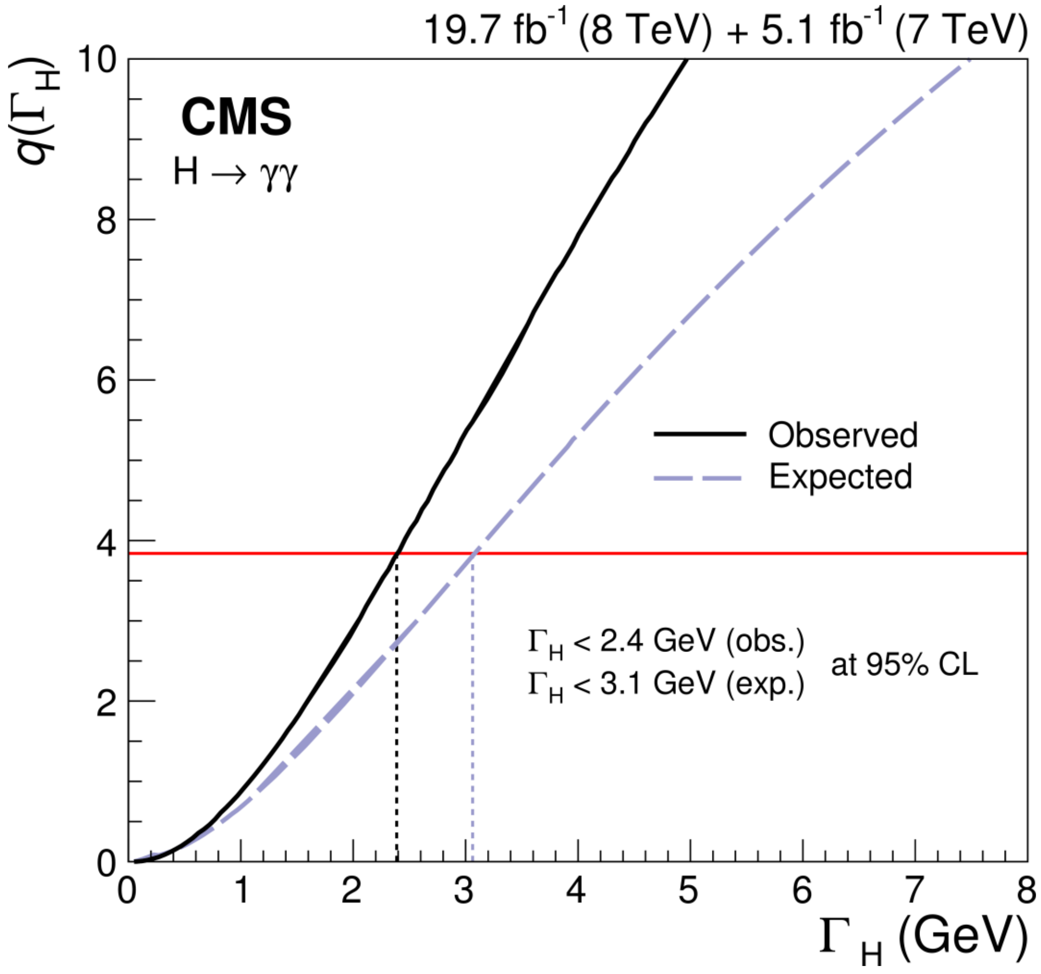
Channel	$\delta_{\mu}^{\text{stat}}$	$\delta_{\mu}^{\text{tot}}$
$Z_1(ll)Z_2(ll)Z_3(jj)$	$+0.191$ -0.173	$+0.193$ -0.176
$Z_1(ll)Z_2(jj)Z_3(ll)$	$+0.191$ -0.173	$+0.193$ -0.174
$Z_1(jj)Z_2(ll)Z_3(ll)$	$+0.186$ -0.168	$+0.187$ -0.168
$Z_1(\nu\nu)Z_2(ll)Z_3(ll)$	$+0.393$ -0.327	$+0.394$ -0.329
Combination	$+0.103$ -0.097	$+0.104$ -0.098

Backup: Higgs Width at the LHC

The total Higgs width is too **small** to be accessed experimentally at the LHC from resonance line-shape in analysis

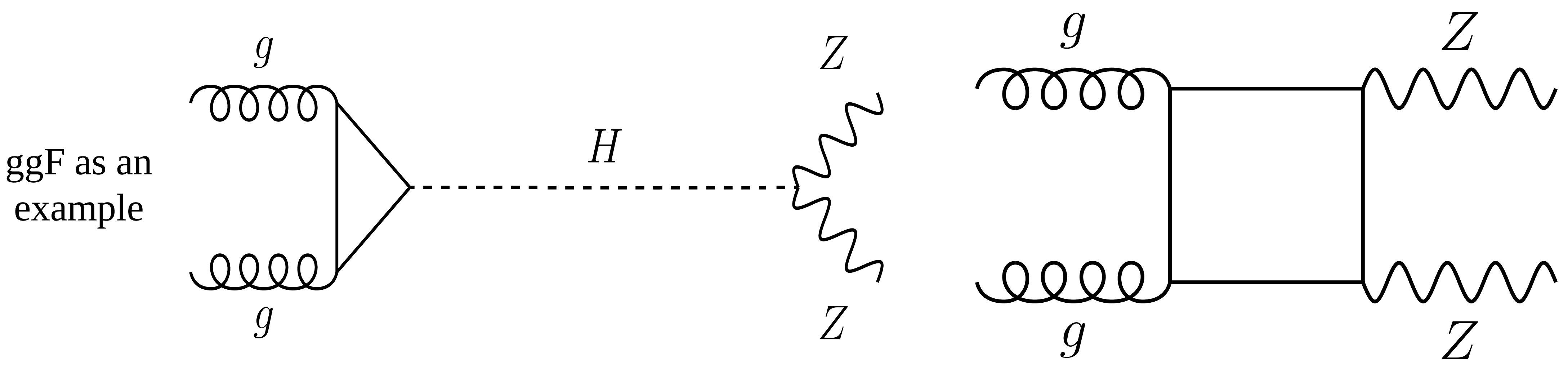
$$\boldsymbol{\Gamma_H^{SM} = 4.07\ \mathrm{MeV}}$$

Direct measurement severely limited by detector resolution



$\Gamma_H <$ **2.4** (3.1) GeV **obs.** (**exp.**)

Backup: Higgs Width at the LHC



Interference impacts both total cross section and $m(VV)$ line-shape

Assuming on-shell and off-shell couplings are equal:

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma}{\Gamma_{\text{SM}}}$$

$vv = gg$

$vv = WW, ZZ, Z\gamma, \gamma\gamma$

$$\sigma^{\text{on-shell}}_{vv\to H\to 4\ell} \propto \frac{g^2_{\text{gluon}} g^2_V}{\Gamma_H} \qquad \sigma^{\text{off-shell}}_{vv\to H\to 4\ell} \propto g^2_{\text{gluon}} g^2_V$$

Backup: Higgs Width at the LHC

Measurements in $4l$ and $2l2\nu$ final states and for different production modes (CMS: ttH, VH, VBF, ggH)

140 fb^{-1} on-shell $4l$
78 fb^{-1}off-shell $4l$
138 fb^{-1} off-shell $2l2\nu$

3.6 σ evidence for off-shell H production

CMS
$\Gamma_H = 3.2^{+2.5}_{-1.7}$ MeV