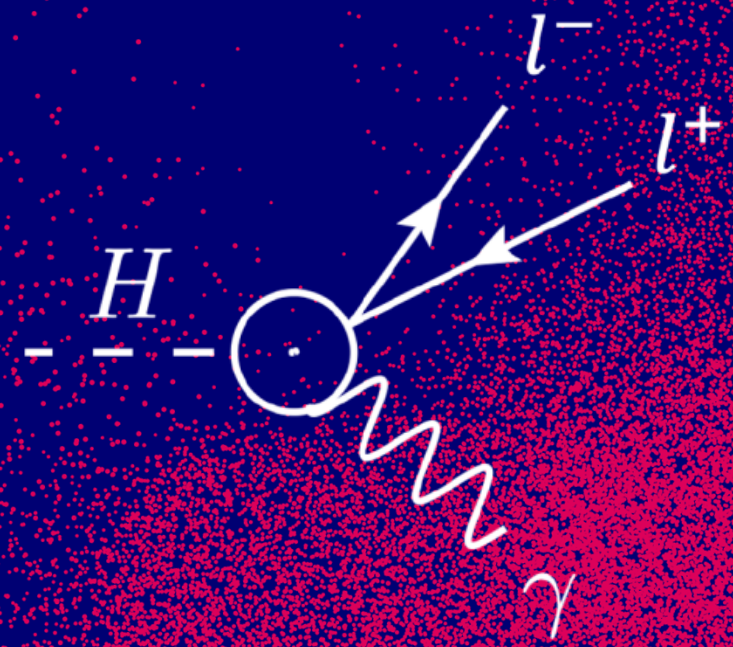
PSI Center for Neutron and Muon Sciences

Universität Zürich[UZH]

Dalitz Decay of Higgs

@ 240 GeV FCC-ee:

1. 4lγ channel: $ZH \rightarrow (l^+l^-)(l^+l^-\gamma)$
2. 2j2lγ channel: $ZH \rightarrow (q\bar{q})(l^+l^-\gamma)$



Shreyas Bakare [1,2], Lea Caminada [1,2], Clemens Lange [2], Aliya Nigamova [2]

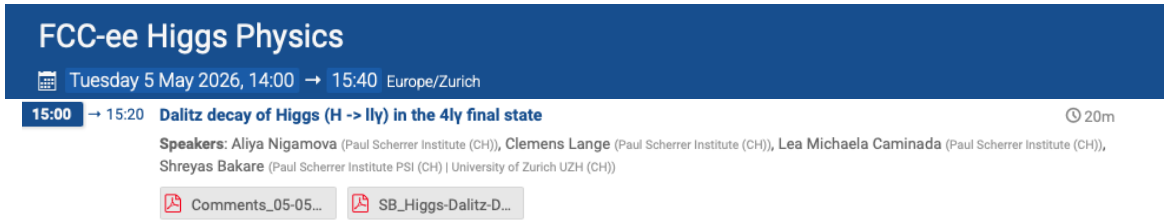
[1]UZH : Universität Zürich, Zürich CH
[2]PSI : Paul Scherrer Institute, Villigen CH

FUTURE CIRCULAR COLLIDER

FCC-ee Higgs Physics Meeting, 6th October 2026

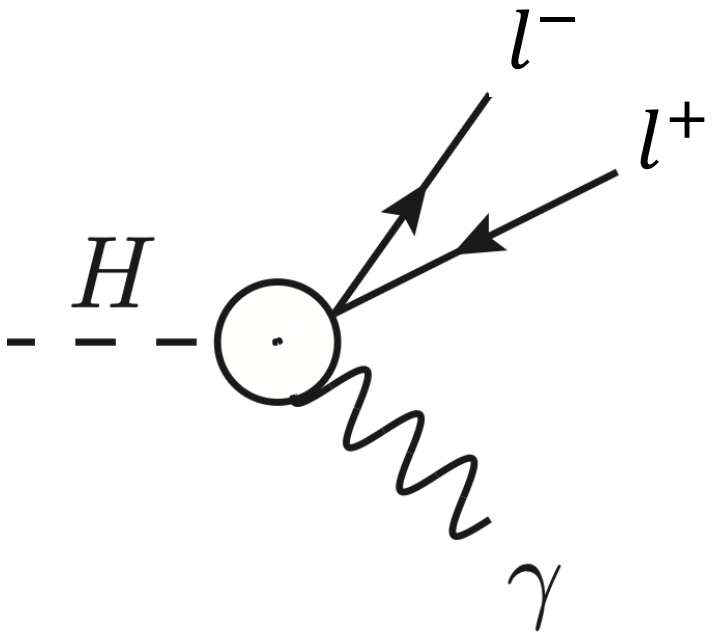
Previous Presentation

Indico Agenda+minutes



Talked about:

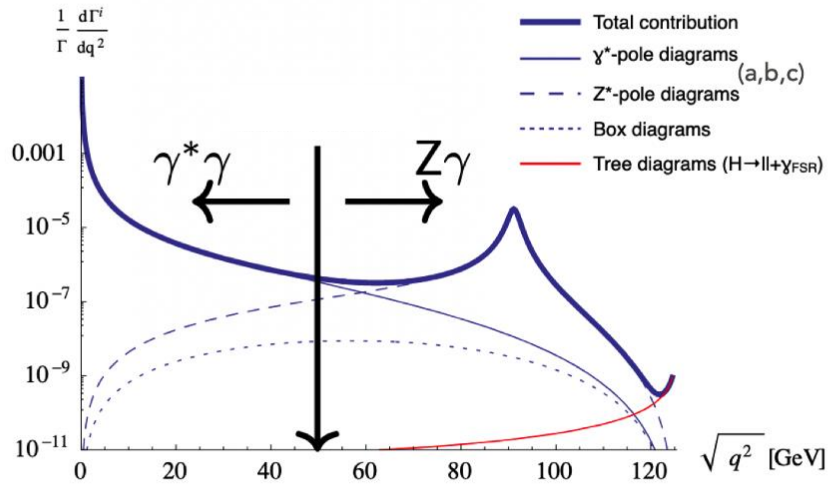
1. Dalitz Decay & LHC Status
2. MC Generation
3. 4lγ Final State



$$H \rightarrow l^+ l^- \gamma \quad , \; l \in \{e,\mu\}$$

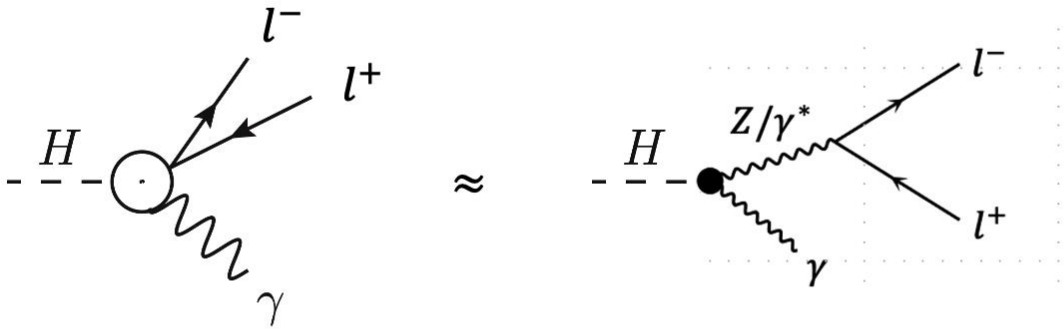
Previous Presentation

$H \to l^+l^-\gamma$ Decays:

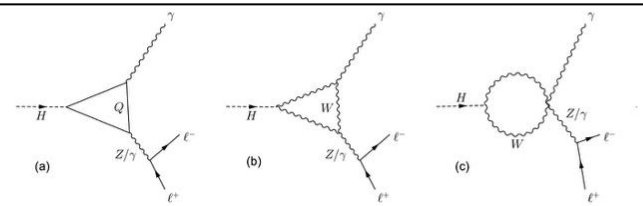


Differential branching ratio ($H \to l^+l^-\gamma$) as a function of m_{ll}

Sun Et al.,2013



1. γ^* Pole
   $H \to \gamma^*\gamma \to l^+l^-\gamma$
2. Z Pole
   $H \to Z\gamma \to l^+l^-\gamma$



…more on contributions in backup

$H \to l^+l^-\gamma$, $l \in$ {e,μ}

Previous Presentation

Indico Agenda+minutes

FCC-ee Higgs Physics

Tuesday 5 May 2026, 14:00 → 15:40 Europe/Zurich

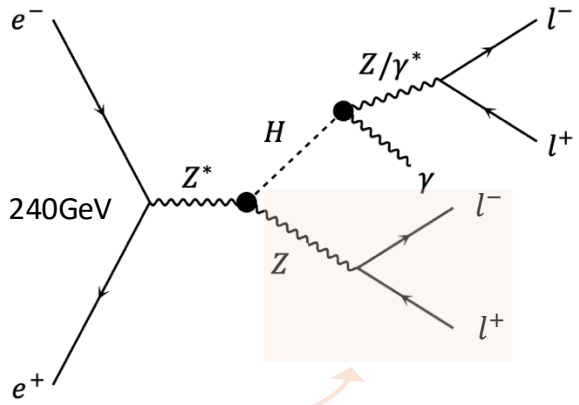
15:00 → 15:20 **Dalitz decay of Higgs (H -> llγ) in the 4lγ final state** 20m

Speakers: Aliya Nigamova (Paul Scherrer Institute (CH)), Clemens Lange (Paul Scherrer Institute (CH)), Lea Michaela Caminada (Paul Scherrer Institute (CH)), Shreyas Bakare (Paul Scherrer Institute PSI (CH) | University of Zurich UZH (CH))

Comments_05-05... SB_Higgs-Dalitz-D...

Talked about:

1. Dalitz Decay & LHC Status
2. MC Generation
3. 4lγ Final State



Previous Presentation

Indico Agenda+minutes

FCC-ee Higgs Physics

Tuesday 5 May 2026, 14:00 → 15:40 Europe/Zurich

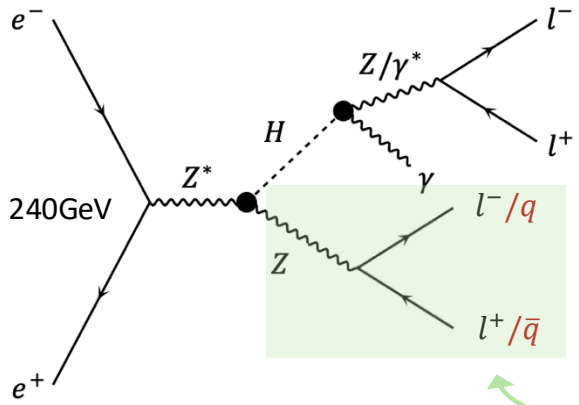
15:00 → 15:20 **Dalitz decay of Higgs (H -> llγ) in the 4lγ final state** 20m

Speakers: Aliya Nigamova (Paul Scherrer Institute (CH)), Clemens Lange (Paul Scherrer Institute (CH)), Lea Michaela Caminada (Paul Scherrer Institute (CH)), Shreyas Bakare (Paul Scherrer Institute PSI (CH) | University of Zurich UZH (CH))

Comments_05-05... SB_Higgs-Dalitz-D...

Talked about:

1. Dalitz Decay & LHC Status
2. MC Generation
3. 4lγ Final State



Today about:

1. Updated 4lγ Final State
2. 2j-2lγ Final State
3. Combined Results

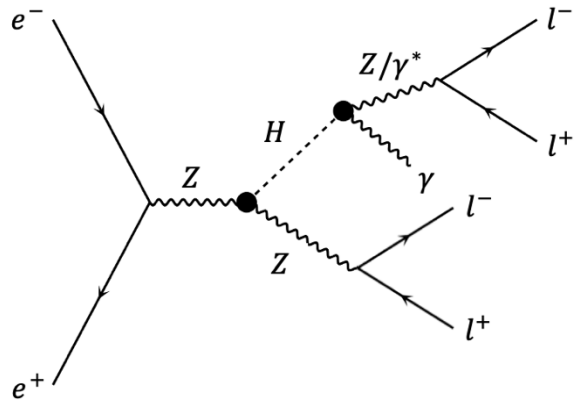
I. Signal & Backgrounds

All leptonic final state (4lγ) @240 GeV FCC-ee:

32.2 signal events for 10.8 ab^{-1}

(σ x BR = 2.98 x 10^{-6} pb)

Local MC Production



Background Processes	4lγ	σ x BR (pb)	Yields for 10.8 ab^{-1}
ZZ	ZZ → (l^+l^-) $(l_\circ^+l_\circ^-)$	6.5×10^{-3}	~70,660
ZH (H→WW)	ZH → (e^+e^-) (WW) → (e^+e^-) $(l^+\upsilon_l\ l^-\bar{\upsilon}_l)$	3.3×10^{-5}	~360
	ZH → $(\mu^+\mu^-)$ (WW) → $(\mu^+\mu^-)$ $(l^+\upsilon_l\ l^-\bar{\upsilon}_l)$	3.3×10^{-5}	~360
ZH (H→ZZ)	ZH → $(q\bar{q})$ (ZZ) → $(q\bar{q})$ $(l^+\ l^-\ l_\circ^+l_\circ^-)$	1.8×10^{-5}	~190
	ZH → $(\upsilon\bar{\upsilon})$ (ZZ) → $(\upsilon\bar{\upsilon})$ $(l^+\ l^-\ l_\circ^+l_\circ^-)$	5×10^{-6}	~54
	ZH → $(l^+\ l^-)$ (ZZ) → $(l^+\ l^-)$ $(q\bar{q}\ l_\circ^+l_\circ^-)$	3.5×10^{-5}	~380
γH	γH → γ (ZZ) → γ $(l^+l^-\ l_\circ^+l_\circ^-)$	$\sim 1.5 \times 10^{-6}$	~16

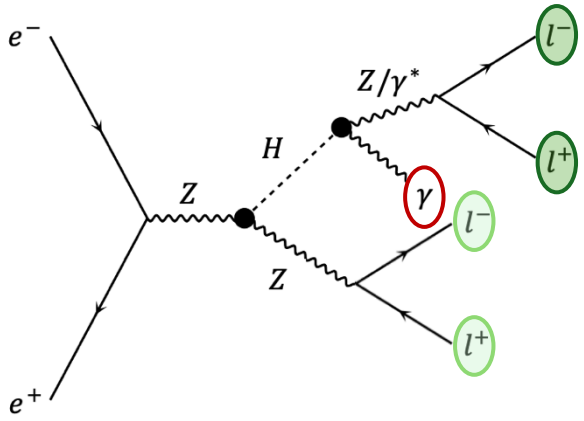
Winter2023 : Central FCC Production

II. Selection & Tagging

Selection: exact 2 OSSF lepton pairs [p($l^{\pm}$) > 2 GeV]

≥ 1 γ [p(γ) > 17 GeV]

Challenge: Identify the correct particles to reconstruct Z & H bosons



- Z decay products:
  - Tag **one pair** such that its mass $(M_{(Z_{l^1},\, Z_{l^2})})$ peaks at Z and recoils against H mass

$$\chi^2 = 0.6 \times (m_{\ell^+\ell^-} - 91.2\ GeV)^2 + 0.4 \times (m_{recoil} - 125\ GeV)^2$$

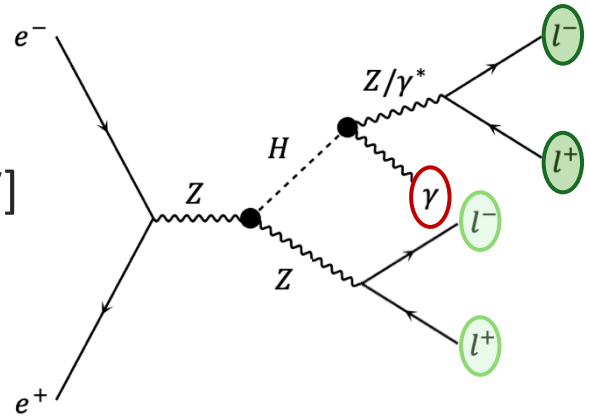
  - p(Z_{l^1}, Z_{l^2}) > 17 GeV

II. Selection & Tagging

Selection: exact 2 OSSF lepton pairs [p($l^{\pm}$) > 2 GeV]

≥ 1 γ [p(γ) > 17 GeV]

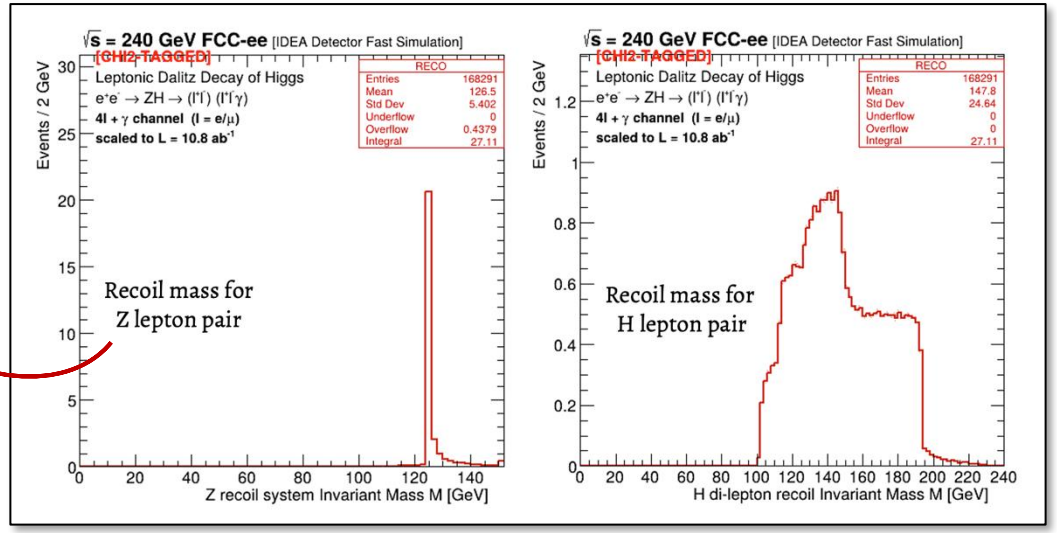
Challenge: Identify the correct particles to reconstruct Z & H bosons



- Z decay products:
  - Tag **one pair** such that its mass $(M_{(Z_{l^1},\, Z_{l^2})})$ peaks at Z and recoils against H mass

$$\chi^2 = 0.6 \times (m_{\ell^+\ell^-} - 91.2\ GeV)^2 + 0.4 \times (m_{recoil} - 125\ GeV)^2$$

  - p(Z_{l^1}, Z_{l^2}) > 17 GeV

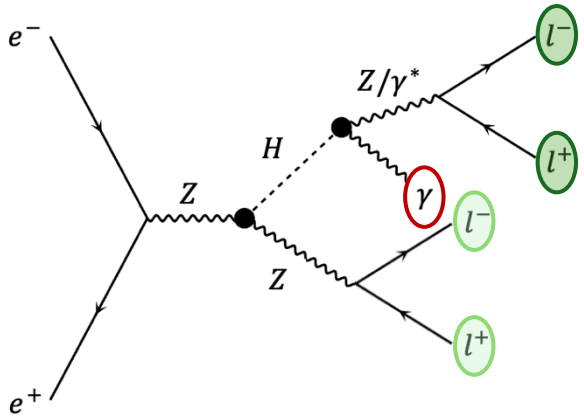


II. Selection & Tagging

Selection: exact 2 OSSF lepton pairs [p($l^{\pm}$) > 2 GeV]

≥ 1 γ [p(γ) > 17 GeV]

Challenge: Identify the correct particles to reconstruct Z & H bosons



- Z decay products:
  - Tag **one pair** such that its mass $(M_{(Z_{l^1},\, Z_{l^2})})$ peaks at Z and recoils against H mass

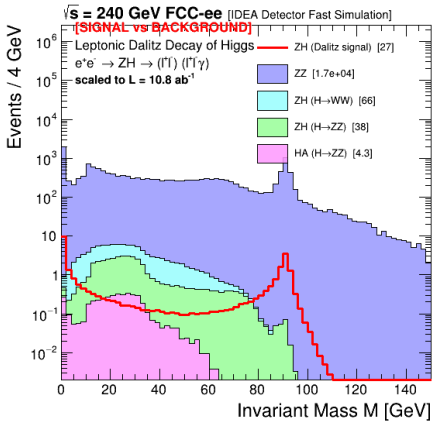
$$\chi^2 = 0.6 \times (m_{\ell^+\ell^-} - 91.2\ GeV)^2 + 0.4 \times (m_{recoil} - 125\ GeV)^2$$

  - p(Z_{l^1}, Z_{l^2}) > 17 GeV
- H decay products:
  - Tag the **other pair** as H_{l^1} and H_{l^2}
  - H_γ such that $\boldsymbol{M}_{(\boldsymbol{H}_{l^1},\, \boldsymbol{H}_{l^2}, \boldsymbol{H}_\gamma)}$ is closest to 125 GeV

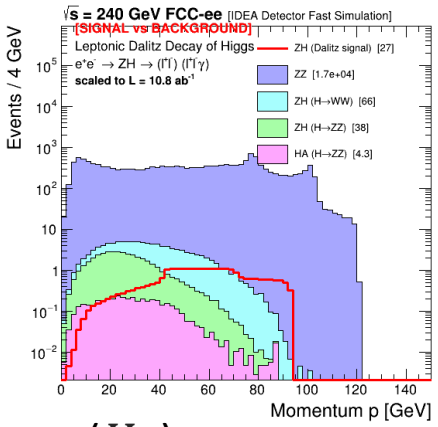
We get 94% & 98% tagging accuracies for leptons & photon respectively.

…more on accuracies in backup

III. Boosted Decision Tree



Mass(H_{ll})



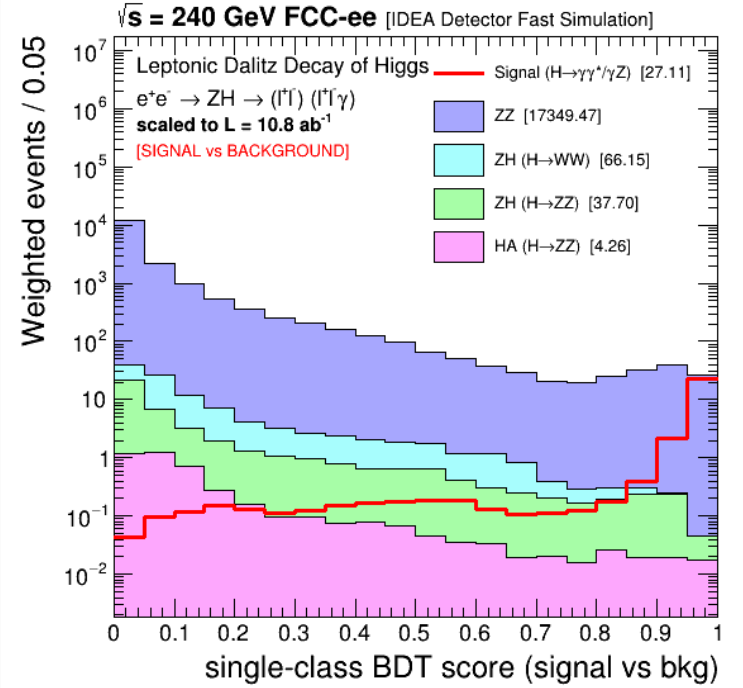
p(H_{ll})

…14 i/p

Mass(Z)
Mass(Z_{recoil})
Mass(H)
Mass(H_{ll})
Mass(H_{γ})
p(Z)
p(Z_{recoil})
p(H)
p(H_{ll})
p(H_{γ})
ΔR(Z,H)
ΔR(Z_{l^1}, Z_{l^2})
ΔR(H_{l^1}, H_{l^2})
ΔR(H_{γ},H_{ll})

→ XGBoost →

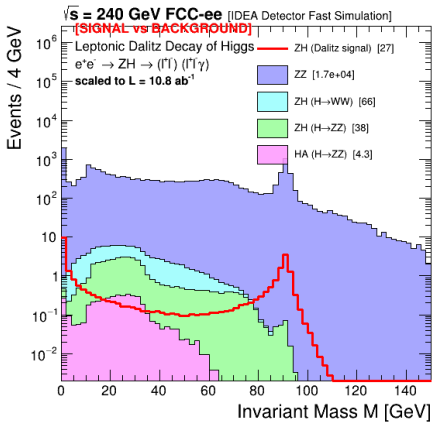
Train a classifier to isolate signal from backgrounds



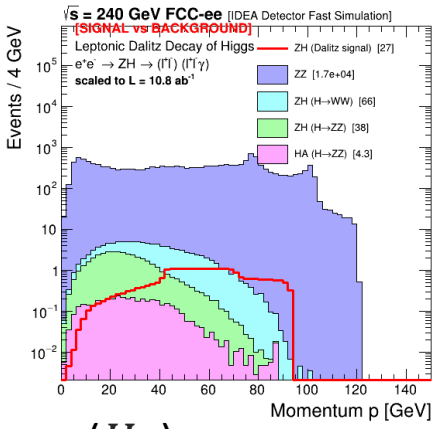
OLD

Did not distinguish between $H \to \gamma^*\gamma$ and $H \to Z\gamma$

III. Boosted Decision Tree: Multiclass



Mass(H_{ll})



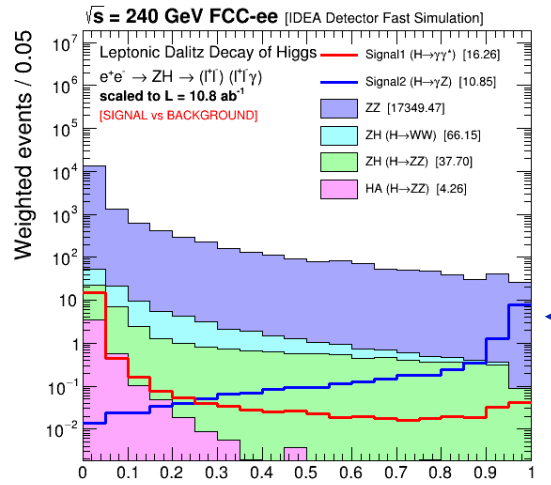
p(H_{ll})

…14 i/p

- Mass(Z)
- Mass(Z_{recoil})
- Mass(H)
- Mass(H_{ll})
- Mass(H_{γ})
- p(Z)
- p(Z_{recoil})
- p(H)
- p(H_{ll})
- p(H_{γ})
- ΔR(Z,H)
- ΔR(Z_{l^1}, Z_{l^2})
- ΔR(H_{l^1}, H_{l^2})
- ΔR(H_{γ},H_{ll})

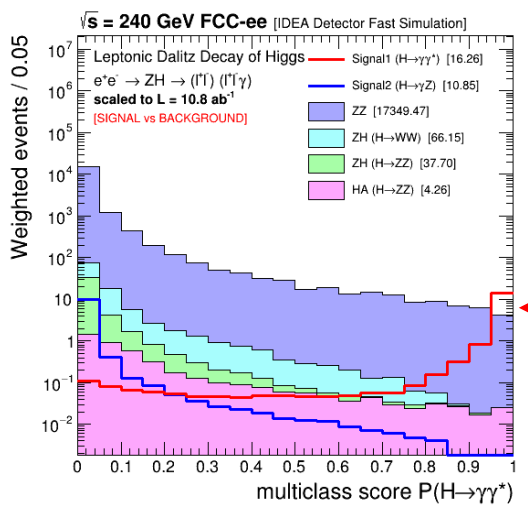
→ XGBoost →

Train a classifier to isolate both signals and backgrounds

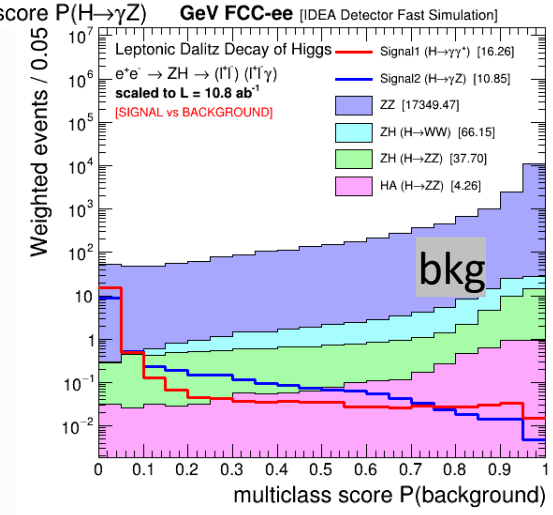


← Zγ

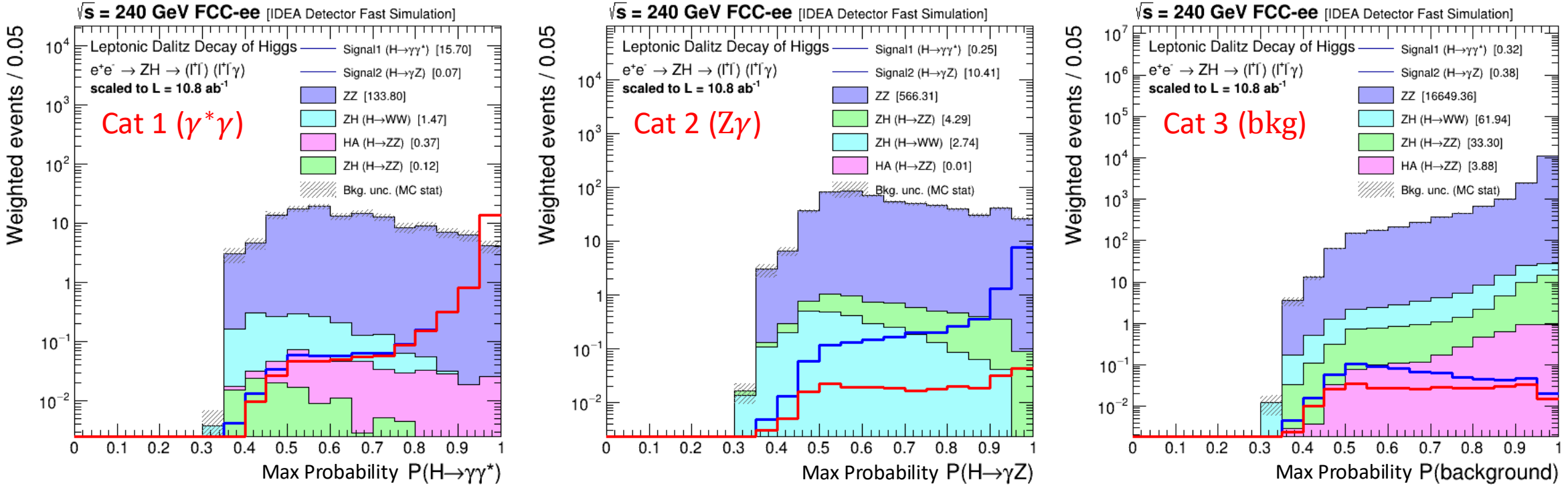
NEW



← $\gamma^*\gamma$



IV. Probability Event Categories



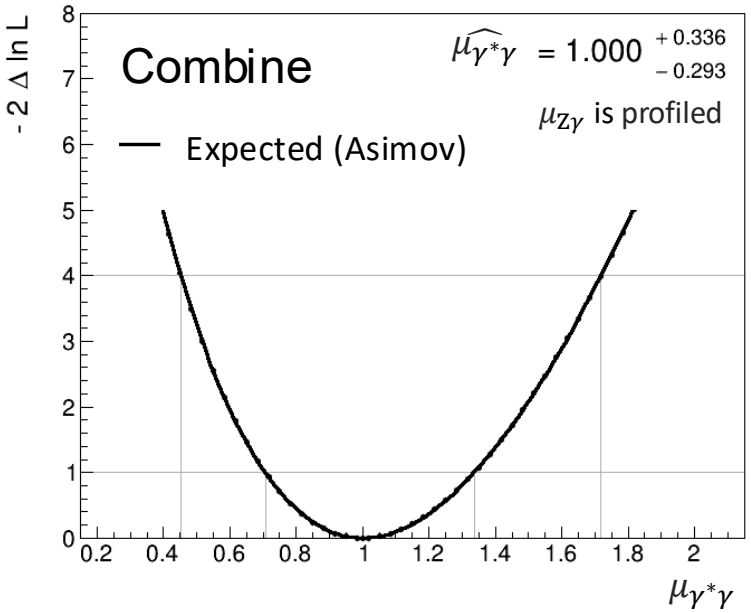
Events are split into 3 categories based on highest BDT score's category

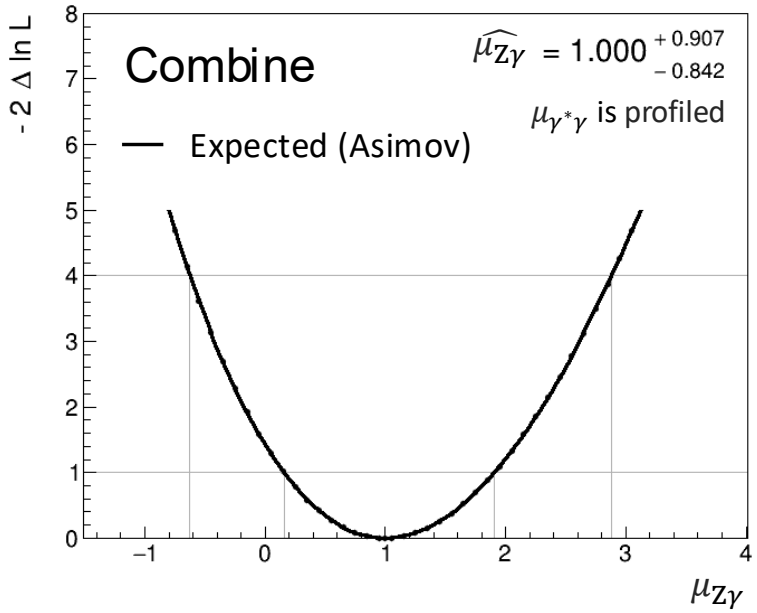
Perform simultaneous maximum likelihood fits on these 3 categories using Asimov data

V. Maximum Likelihood Fit

1. Expected per-mode sensitivity and significance (other mode is free to float)

Higgs Decay Mode	Sensitivity	Significance
$H \to \gamma^*\gamma$	~ 30%	4.2 σ
$H \to \mathrm{Z}\gamma$	~ 85%	1.2 σ





Note:

1. No experimental systematics are considered
2. 1% luminosity & background uncertainties (ZZ: 1% ,HA: 3% & other: 2%) are used

V. Maximum Likelihood Fit

1. Expected per-mode sensitivity and significance (other mode is free to float)

Higgs Decay Mode	Sensitivity	Significance
$H \to \gamma^*\gamma$	~ 30%	4.2 σ
$H \to Z\gamma$	~ 85%	1.2 σ

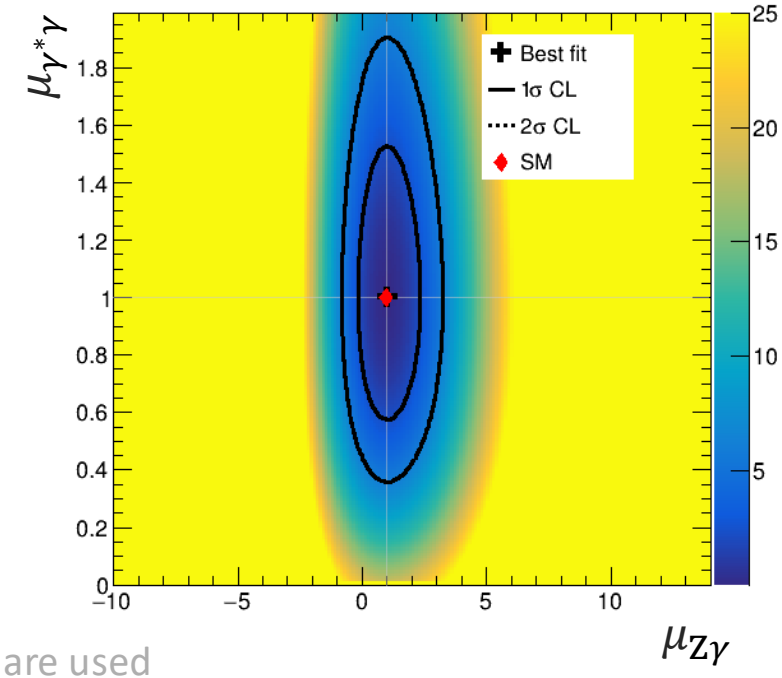
2. 2 POI joint significance:

   Fowlie significance (Z) = 4.1 σ

$$Z = \Phi^{-1}(1-p),$$
$$p = \frac{1}{4}[\,2\,\mathbb{P}(\chi_1^2 \geq \lambda) + \mathbb{P}(\chi_2^2 \geq \lambda)],$$
$$\lambda = 2\,\Delta\mathrm{NLL} = 2\left[ln\,L\left(\widehat{\mu_{\gamma^*\gamma}}, \widehat{\mu_{Z\gamma}}\right) - ln\,L\,(0,0)\right]$$

Fowlie, 2022

Two-dimensional likelihood scan



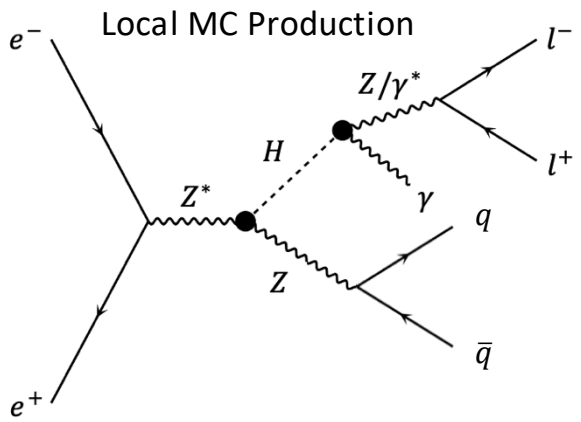
Note:
1. No experimental systematics are considered
2. 1% luminosity & background uncertainties (ZZ: 1% ,HA: 3% & other: 2%) are used

I. Signal & Backgrounds

Semi leptonic final state (2j2lγ) @240 GeV FCC-ee:

~334.74 signal events for 10.8 ab^{-1}
(σ x BR = 30.99 x 10^{-6} pb)

10×4lg



Background Processes	4lγ	σ x BR (pb)	Yields for 10.8 ab^{-1}
ZZ	ZZ → $(q\bar{q})$ (l^+l^-)	63.9 ×10^{-3}	690,500
ZH (H→WW)	ZH → $(q\bar{q})$ (WW)	5.4 ×10^{-4}	5,876
	ZH → (e^+e^-) (WW)	2.2 ×10^{-4}	2,439
	ZH → $(\mu^+\mu^-)$ (WW)	2.1 ×10^{-4}	2,305
	ZH → $(\tau^+\tau^-)$ (WW)	1.3 ×10^{-5}	143
ZH (H→ZZ)	ZH → $(q\bar{q})$ (ZZ)	7.7 ×10^{-6}	84
	ZH →$(\upsilon\bar{\upsilon})$ (ZZ)	5.5 ×10^{-5}	594
	ZZ → (e^+e^-) (ZZ)	3.5 ×10^{-5}	382
	ZH → $(\mu^+\mu^-)$ (ZZ)	3.3 ×10^{-5}	360
	ZH → $(\tau^+\tau^-)$ (ZZ)	2.1 ×10^{-6}	22
ZH (H→ $\tau^+\tau^-$)	ZH → $(q\bar{q})$ $(\tau^+\tau^-)$	9.8 ×10^{-6}	106

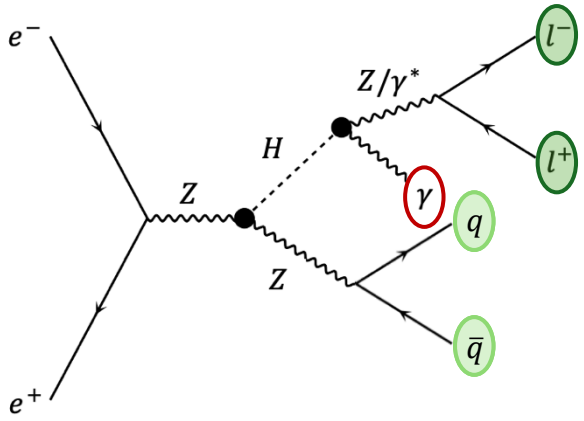
Winter2023 : Central FCC Production

II. Selection & Tagging

Selection: ≥ 2 leptons (≥ 1 OSSF pair) [p($l^{\pm}$) > 2 GeV]

≥ 1 γ [p(γ) > 17 GeV]

Challenge: Identify the correct particles to reconstruct Z & H bosons



- H decay products:
  - Tag **1 OSSF pair & 1 photon** such that its mass $(M_{(\mathrm{H}_{l^1},\ \mathrm{H}_{l^2},\ \mathrm{H}_{\gamma})})$ peaks at H and recoils against Z mass

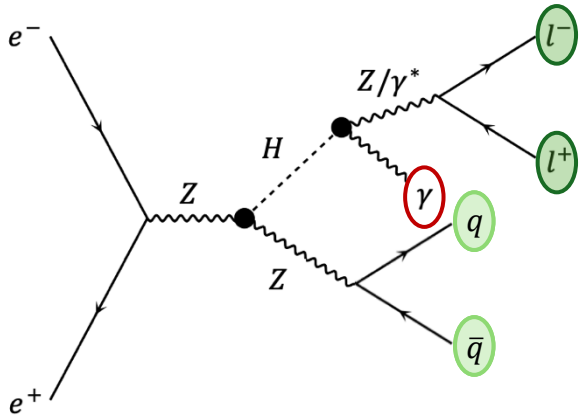
$$\chi^2 = (1-f) \times (m_{l^+l^-\gamma} - 125\ GeV)^2 + f \times (m_{recoil} - 91.2\ GeV)^2$$

II. Selection & Tagging

Selection: ≥ 2 leptons (≥ 1 OSSF pair) [p($l^{\pm}$) > 2 GeV]

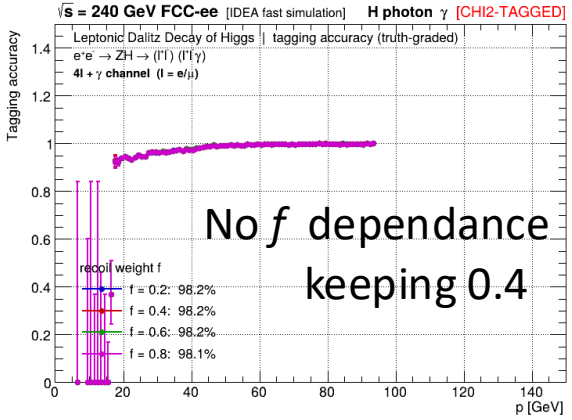
≥ 1 γ [p(γ) > 17 GeV]

Challenge: Identify the correct particles to reconstruct Z & H bosons



- H decay products:
  - Tag **1 OSSF pair & 1 photon** such that its mass $(M_{(H_{l1},\, H_{l2},\, H_{\gamma})})$ peaks at H and recoils against Z mass

$$\chi^2 = (1-f) \times (m_{l^+l^-\gamma} - 125\,GeV)^2 + f \times (m_{recoil} - 91.2\,GeV)^2$$



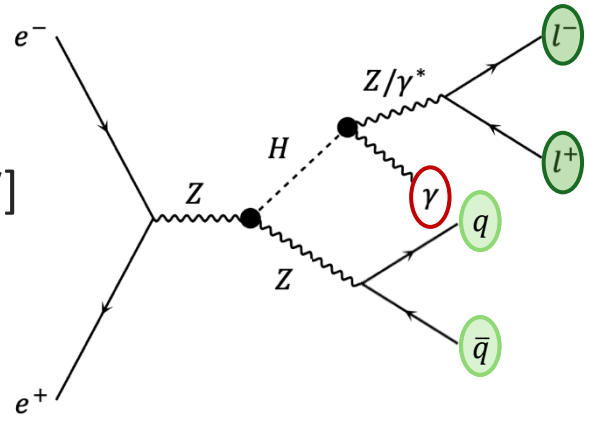
We get 98% tagging accuracy for Higgs boson decay products

II. Selection & Tagging

Selection: ≥ 2 leptons (≥ 1 OSSF pair) [p($l^{\pm}$) > 2 GeV]

≥ 1 γ [p(γ) > 17 GeV]

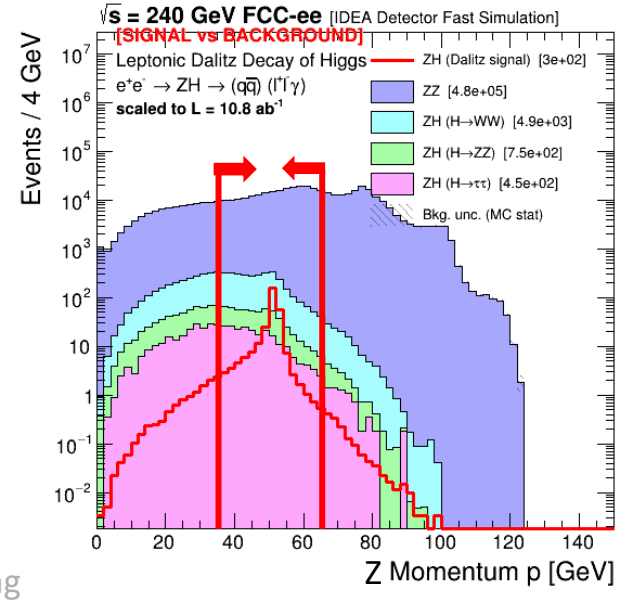
Challenge: Identify the correct particles to reconstruct Z & H bosons



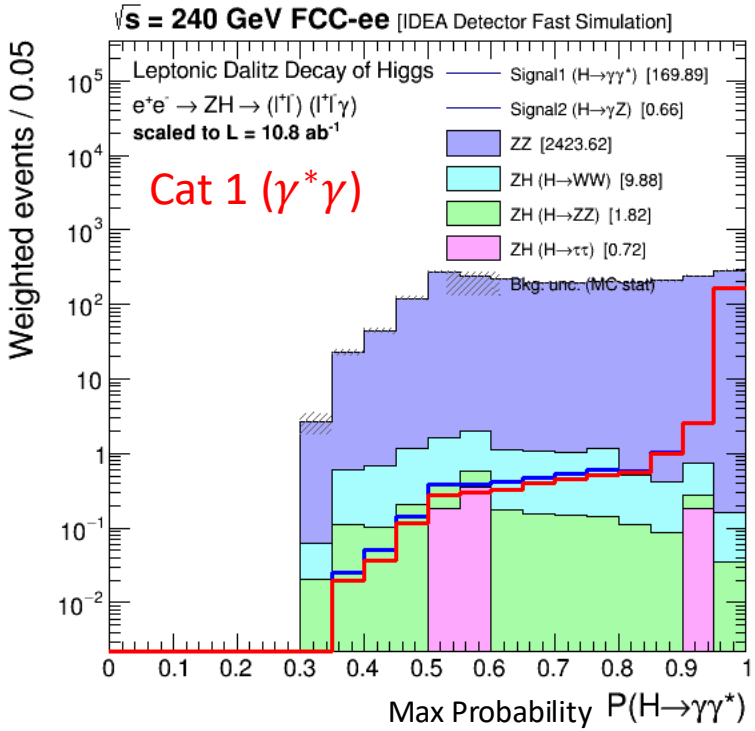
- H decay products:
  - Tag **1 OSSF pair & 1 photon** such that its mass $(M_{(H_{l^1},\, H_{l^2},\, H_\gamma)})$ peaks at H and recoils against Z mass

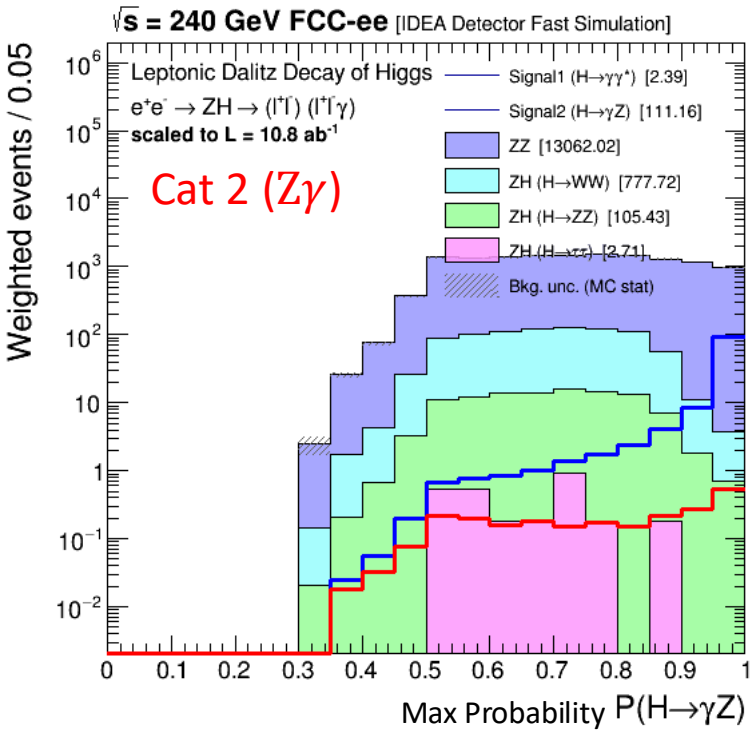
$$\chi^2 = (1-f) \times (m_{l^+l^-\gamma} - 125\ GeV)^2 + f \times (m_{recoil} - 91.2\ GeV)^2$$

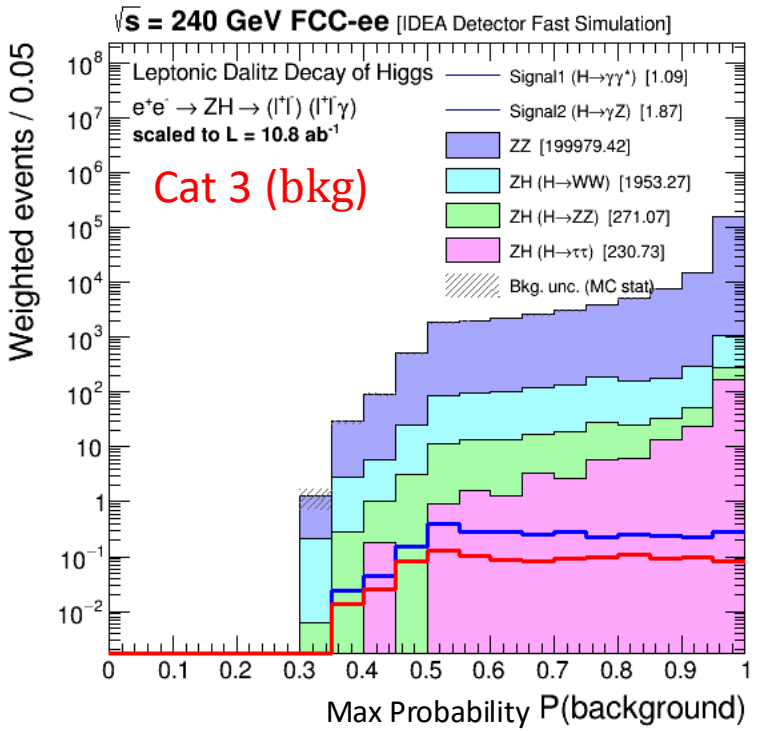
- Z jets:
  - Remove these Higgs particles from reconstructed PF collection and make Durham ee_kt(N=2) jets: Z_{j^1} & Z_{j^2}
  - 35 GeV < p(Z) > 65 GeV



III. Probability Event Categories







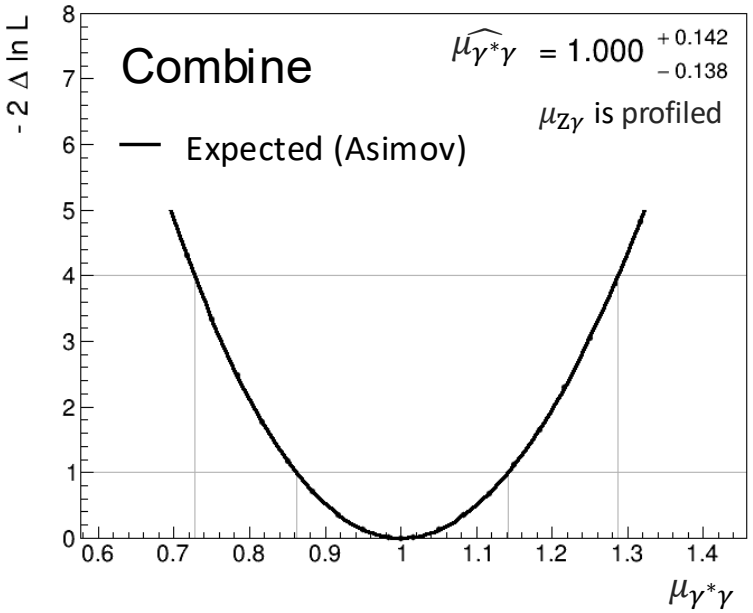
Multiclass BDT, features & event categorization are the same as 4lγ analysis

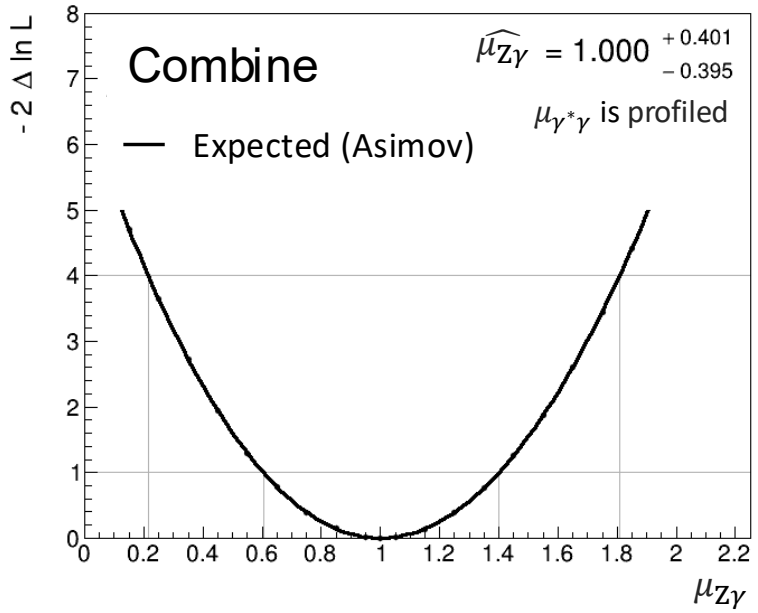
Perform simultaneous maximum likelihood fits on these 3 categories using Asimov data

IV. Maximum Likelihood Fit

1. Expected per-mode sensitivity and significance (other mode is free to float)

Higgs Decay Mode	Sensitivity	Significance
$H \to \gamma^*\gamma$	~ 15%	> 5 σ
$H \to Z\gamma$	~ 40%	2.6 σ





Note:

1. No experimental systematics are considered
2. 1% luminosity & background uncertainties (ZZ: 1% ,H$\tau\tau$: 3% & other: 2%) are used

IV. Maximum Likelihood Fit

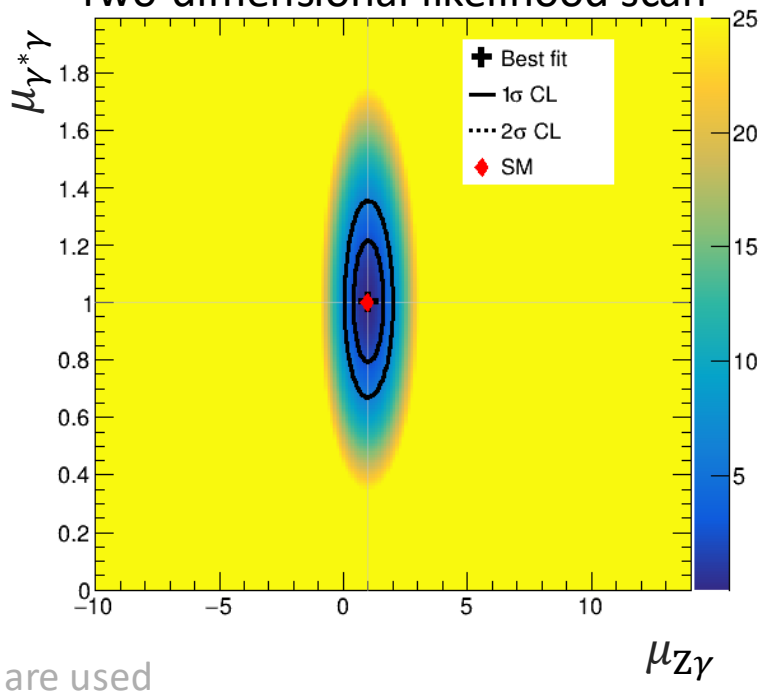
1. Expected per-mode sensitivity and significance (other mode is free to float)

Higgs Decay Mode	Sensitivity	Significance
$H \to \gamma^{*}\gamma$	~ 15%	> 5 σ
$H \to \mathrm{Z}\gamma$	~ 40%	2.6 σ

2. 2 POI joint significance:

   Fowlie significance (Z) > 5 σ

Two-dimensional likelihood scan

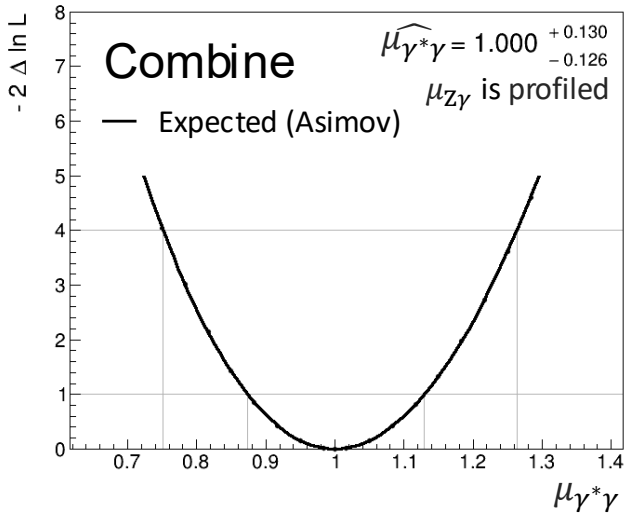


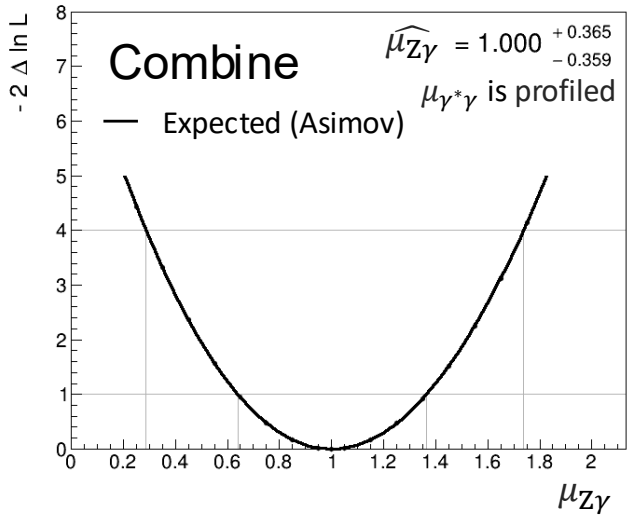
Note:

1. No experimental systematics are considered
2. 1% luminosity & background uncertainties (ZZ: 1% ,H$\tau\tau$: 3% & other: 2%) are used

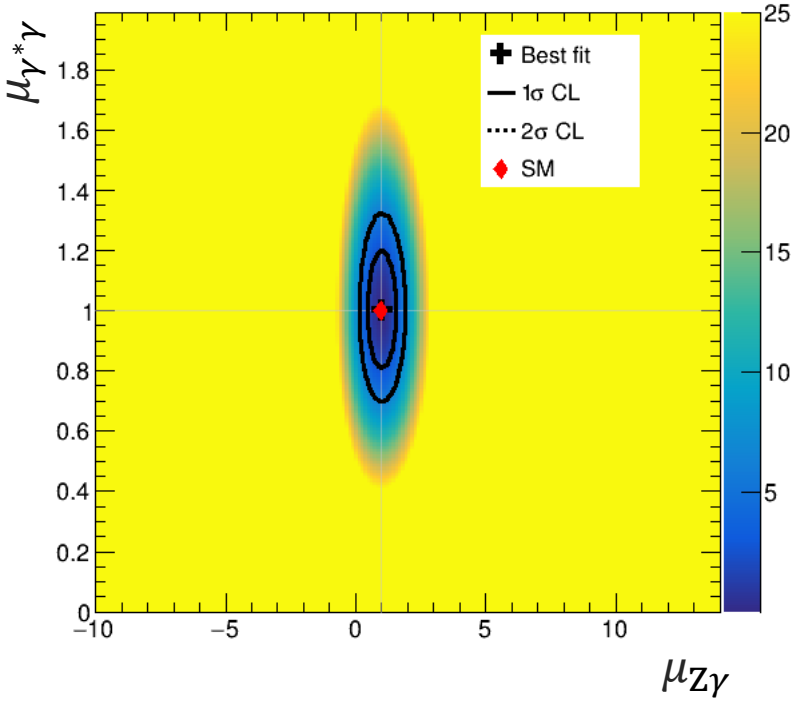
4lγ + 2j2lγ Combined Fit Results

Channel	Higgs Decay Mode	Yields for 10.8 ab^{-1}	Sensitivity	Significance	Fowlie significance
4lγ	$H \to \gamma^*\gamma$	17	~ 30%	4.2 σ	4.1 σ
	$H \to Z\gamma$	15	~ 85%	1.2 σ	
2j2lγ	$H \to \gamma^*\gamma$	178	~ 15%	> 5 σ	> 5 σ
	$H \to Z\gamma$	156	~ 40%	2.6 σ	
Combined	$H \to \gamma^*\gamma$	195	~ 13%	> 5 σ	> 5 σ
	$H \to Z\gamma$	171	~ 36%	2.8 σ	





Two-dimensional likelihood scan



We get combined sensitivity of

~ 13% for $H \to \gamma^*\gamma$ ($\approx \sqrt{N_{H \to \gamma^*\gamma}}$)

~ 36% for $H \to Z\gamma$

Conclusions & Next Steps

1. Addressed the comments from previous meeting
2. Split $H \to l^+l^-\gamma$ signal into $H \to \gamma^*\gamma / \mathrm{Z}\gamma$ decay modes using multiclass BDT
3. Used BDT scores-based probability event categories as analysis observable
4. Added hadronic Z decay channel (2j2lγ) [10 times 4lγ channel]
    1. Gain in sensitivity to: ~ 13% for $H \to \gamma^*\gamma$ & ~ 36% for $H \to \mathrm{Z}\gamma$

Next steps:

Ongoing

1. Add invisible Z decay channel (2υ2lγ)
2. Investigate $\upsilon\bar{\upsilon}$H production channel

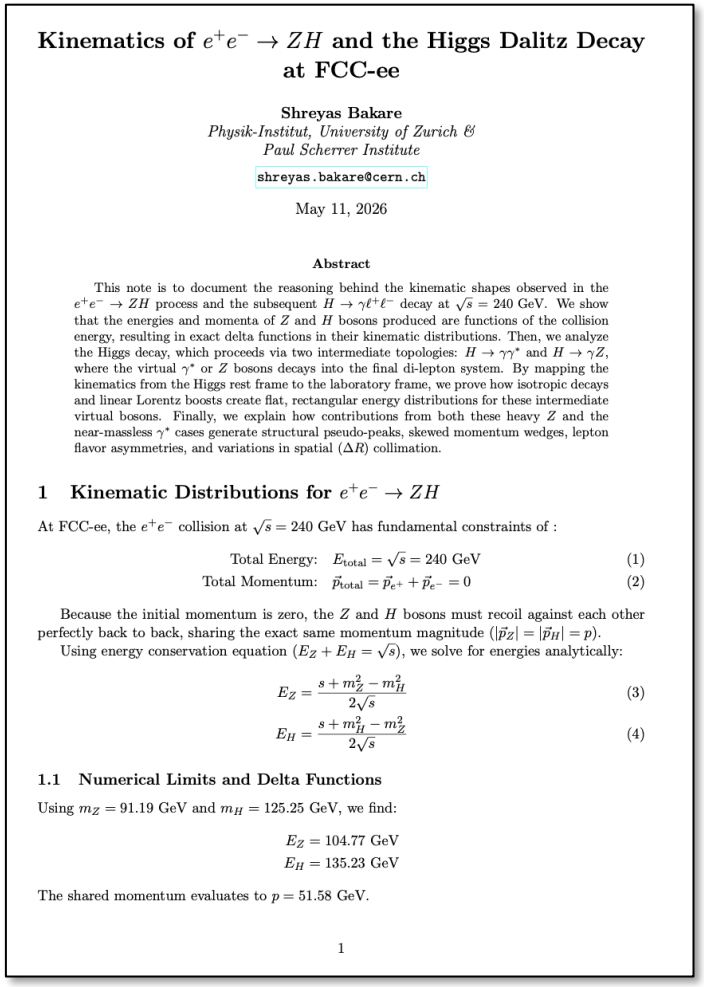
} Conclude $H \to l^+l^-\gamma$ analysis at 240 GeV FCC-ee

3. Move towards full simulation-based analysis

Thank you!

Backup slides …

Comments: Kinematic Shapes



Kinematics of $e^+e^- \to ZH$ and the Higgs Dalitz Decay at FCC-ee

Shreyas Bakare
Physik-Institut, University of Zurich &
Paul Scherrer Institute
shreyas.bakare@cern.ch

May 11, 2026

Abstract

This note is to document the reasoning behind the kinematic shapes observed in the $e^+e^- \to ZH$ process and the subsequent $H \to \gamma\ell^+\ell^-$ decay at $\sqrt{s} = 240$ GeV. We show that the energies and momenta of Z and H bosons produced are functions of the collision energy, resulting in exact delta functions in their kinematic distributions. Then, we analyze the Higgs decay, which proceeds via two intermediate topologies: $H \to \gamma\gamma^*$ and $H \to \gamma Z$, where the virtual γ^* or Z bosons decays into the final di-lepton system. By mapping the kinematics from the Higgs rest frame to the laboratory frame, we prove how isotropic decays and linear Lorentz boosts create flat, rectangular energy distributions for these intermediate virtual bosons. Finally, we explain how contributions from both these heavy Z and the near-massless γ^* cases generate structural pseudo-peaks, skewed momentum wedges, lepton flavor asymmetries, and variations in spatial (ΔR) collimation.

1 Kinematic Distributions for $e^+e^- \to ZH$

At FCC-ee, the e^+e^- collision at $\sqrt{s} = 240$ GeV has fundamental constraints of :

$$\text{Total Energy:} \quad E_{\text{total}} = \sqrt{s} = 240 \text{ GeV} \tag{1}$$
$$\text{Total Momentum:} \quad \vec{p}_{\text{total}} = \vec{p}_{e^+} + \vec{p}_{e^-} = 0 \tag{2}$$

Because the initial momentum is zero, the Z and H bosons must recoil against each other perfectly back to back, sharing the exact same momentum magnitude ($|\vec{p}_Z| = |\vec{p}_H| = p$).

Using energy conservation equation ($E_Z + E_H = \sqrt{s}$), we solve for energies analytically:

$$E_Z = \frac{s + m_Z^2 - m_H^2}{2\sqrt{s}} \tag{3}$$
$$E_H = \frac{s + m_H^2 - m_Z^2}{2\sqrt{s}} \tag{4}$$

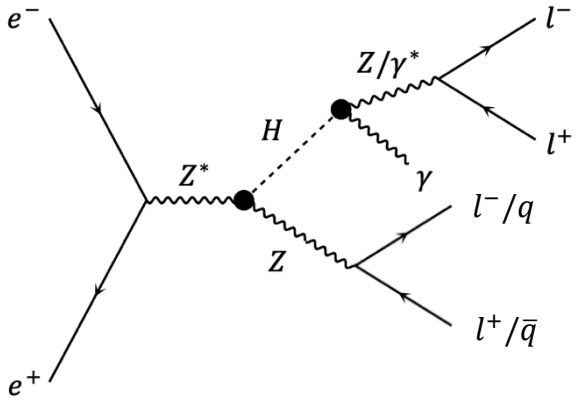
1.1 Numerical Limits and Delta Functions

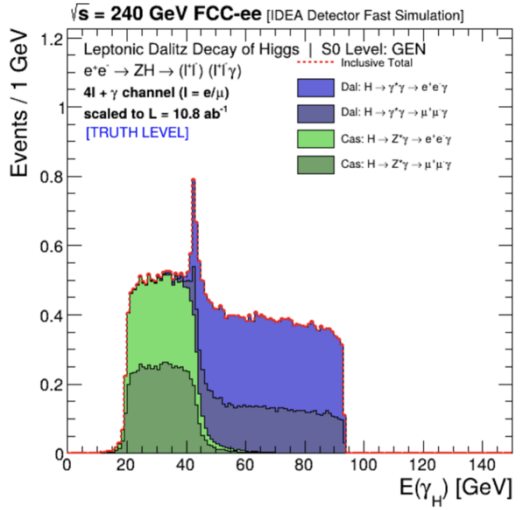
Using $m_Z = 91.19$ GeV and $m_H = 125.25$ GeV, we find:

$$E_Z = 104.77 \text{ GeV}$$
$$E_H = 135.23 \text{ GeV}$$

The shared momentum evaluates to $p = 51.58$ GeV.

1





1. At √s = 240 GeV, $e^+e^- \to$ ZH production, p(H) ≈ 51.6 GeV
2. This creates two overlapping boxes:
   1. $H \to \gamma^*\gamma$: photon energy is bound between [42, 93] GeV
   2. $H \to$ Z γ : photon energy is bound between [20, 44] GeV
3. Full kinematic explanations, including pseudo peaks and other phenomena, are documented in attached PDF note

→ Kinematics_Explanation_ZH_Hllg.pdf