$H \to \gamma\gamma$ and $H \to Z\gamma$ at CLIC with $\sqrt{s} = 1.4$ TeV

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Outline

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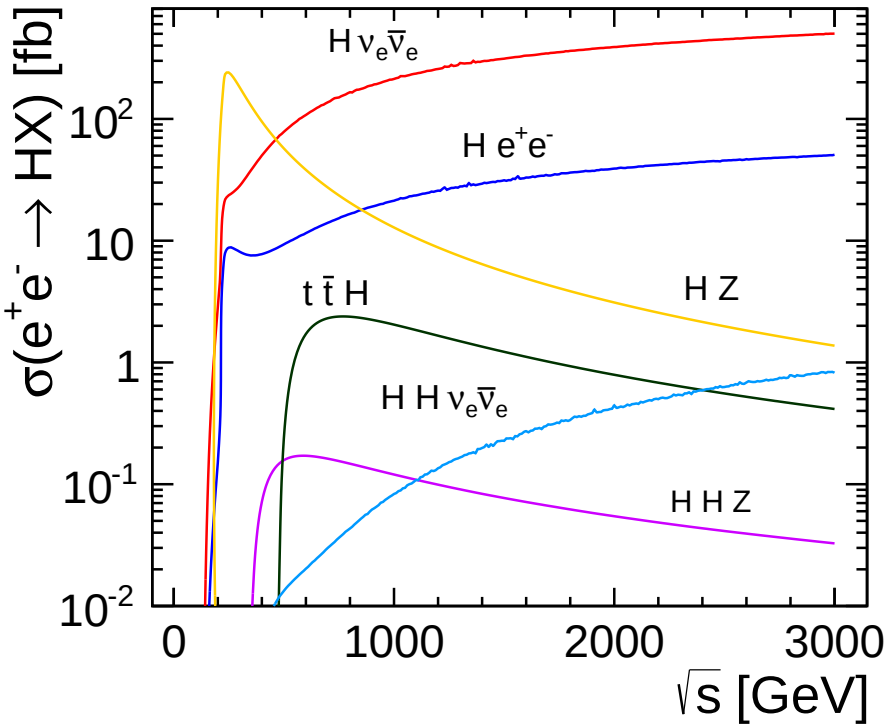
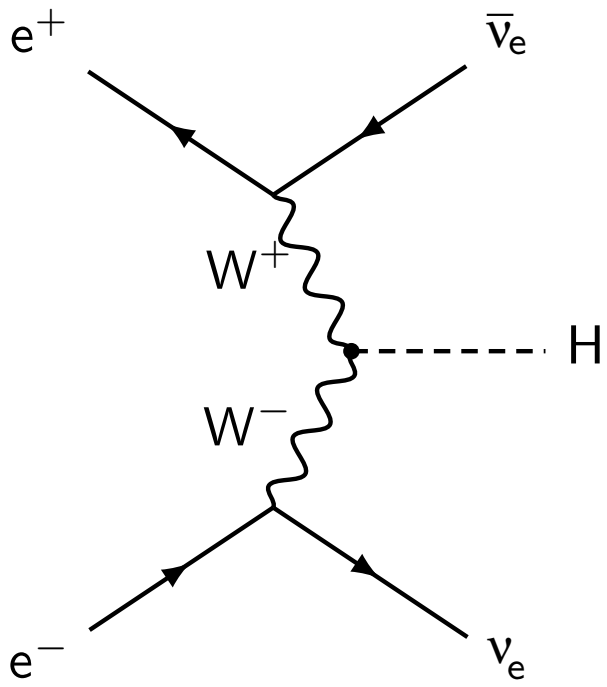
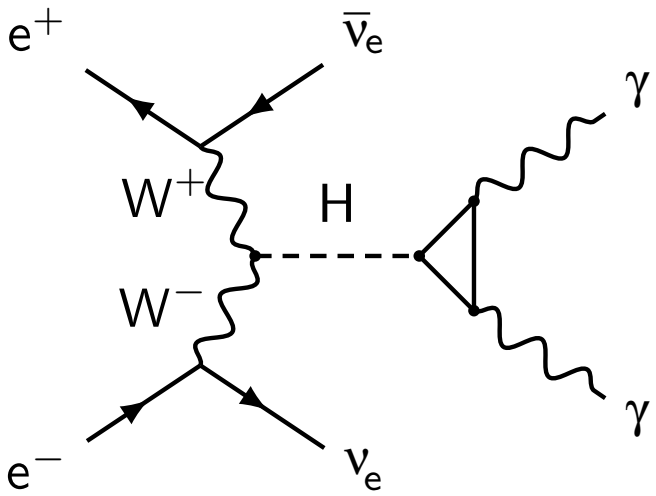
Higgs Production at $\sqrt{s} = 1.4\,\text{TeV}$



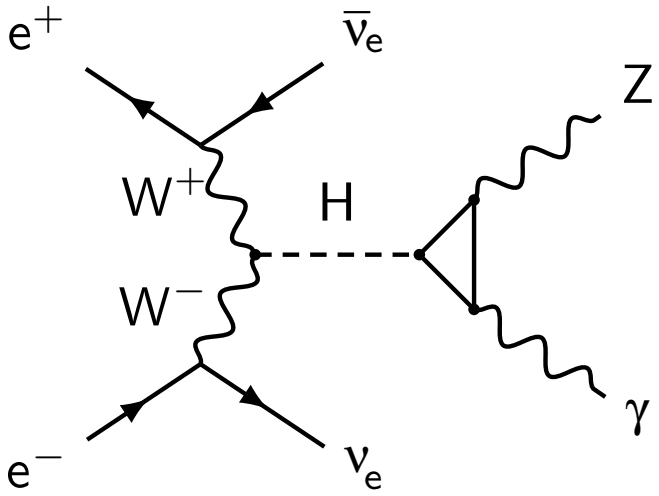


- Assuming $m_{\text{H}} = 126\,\text{GeV}$
- Using WHIZARD v.1.95, including ISR and CLIC BS
- WW fusion dominant H production process
- $\sigma(\text{e}^+\text{e}^- \to \text{H}\nu\bar{\nu}) \approx 244\,\text{fb}$ for $\sqrt{s} = 1.4\,\text{TeV}$ (with unpolarised beams)
- Access to rare H decay modes

Signal Processes



- $BR_{H\to\gamma\gamma} \approx 0.00228 \Rightarrow \sigma \times BR \approx 0.56\,\mathrm{fb}$
- $N_{signal} \approx 840/1.5\,\mathrm{ab}^{-1}$



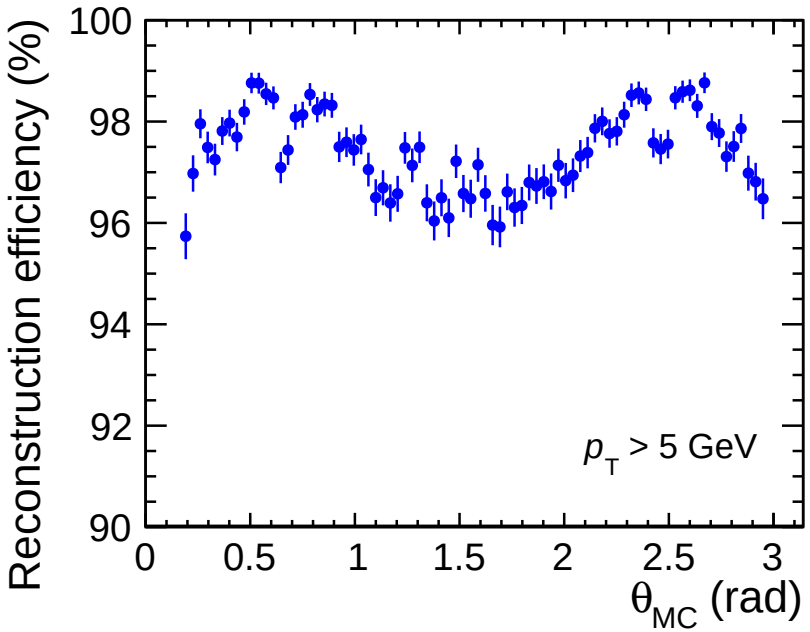
- $BR_{H\to Z\gamma} \approx 0.16\% \Rightarrow \sigma \times BR \approx 0.39\,\mathrm{fb}$
- $BR_{Z\to q\bar{q}} \approx 70\,\% \rightarrow N_{signal}(Z \to q\bar{q}) \approx 409/1.5\,\mathrm{ab}^{-1}$
- $BR_{Z\to e^+e^-} \approx 3.4\,\% \rightarrow N_{signal}(Z^0 \to e^+e^-) \approx 21/1.5\,\mathrm{ab}^{-1}$
- $BR_{Z\to \mu^+\mu^-} \approx 3.4\,\% \rightarrow N_{signal}(Z^0 \to \mu^+\mu^-) \approx 21/1.5\,\mathrm{ab}^{-1}$
- Case $Z \to \tau^+\tau^-$ not studied

Simulation and Reconstruction

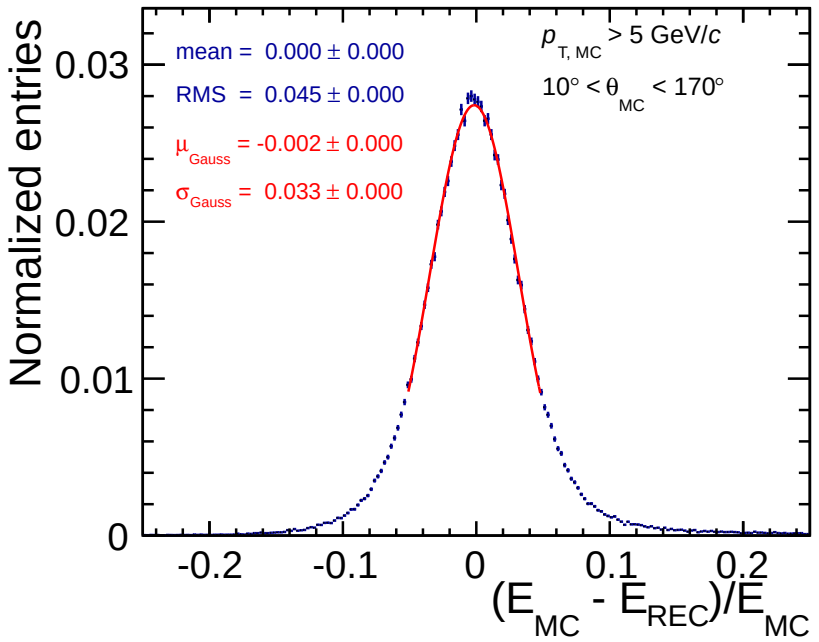
- Event generation with WHIZARD v.1.95, including ISR and CLIC BS
- Full simulation with SLIC v.2.9.8 (GEANT4 v.9.3.2) in CLIC_SiD_CDR model
- Overlay $\gamma\gamma \to$ hadrons background before digitization (assuming readout time windows of 10 ns)
- Digitization and track reconstruction in `org.lcsim`
- Particle flow reconstruction and particle identification in PANDORAPFA

Photon Reconstruction ($H \rightarrow Z\gamma$)

Efficiency: $96 - 98\%$

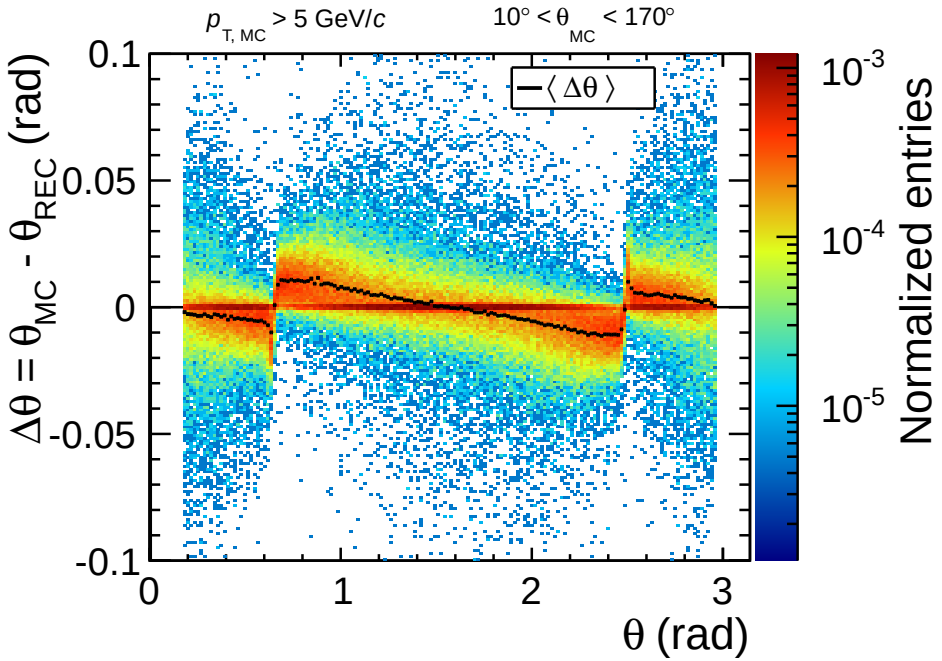


Energy resolution $\approx 3.3\%$



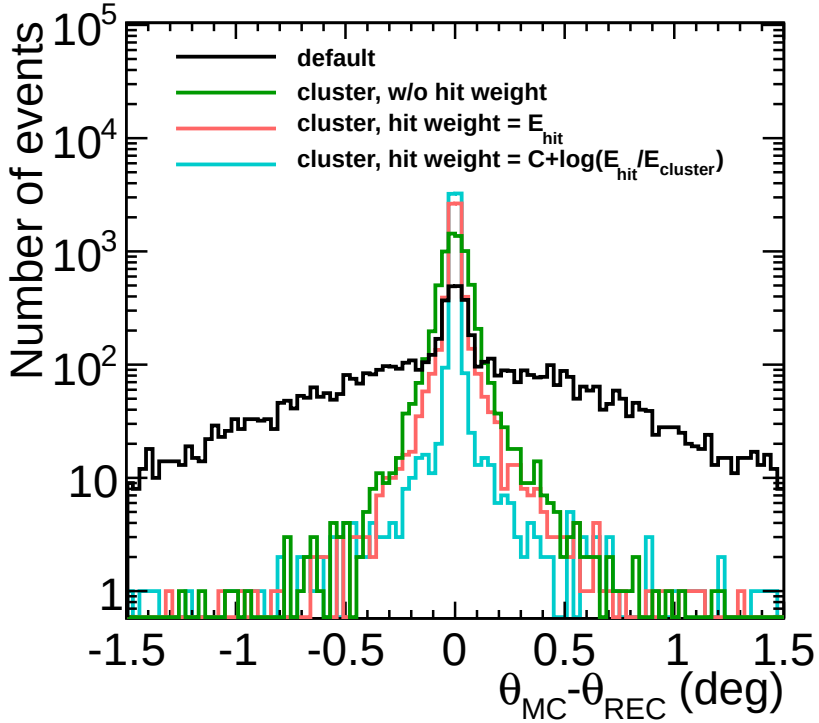
Photon Reconstruction (H → Zγ)

Reconstruction of polar angle



- Bias from calculation of cluster position
- Uses only first layer information and simple arithmetic mean (no weighting by hit energy)

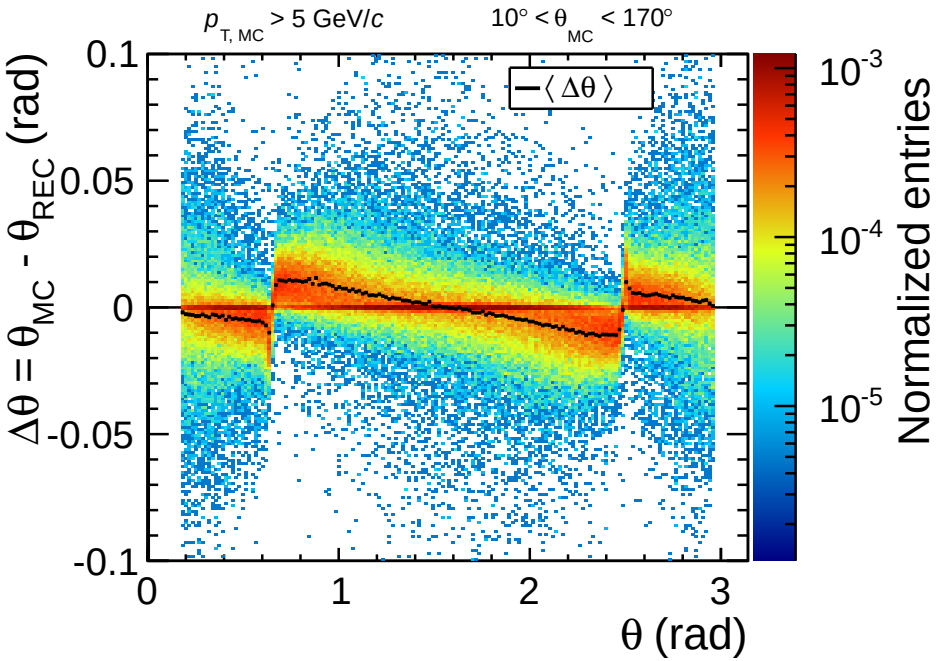
Improved cluster position



- Alternative cluster position calculations improve polar angle reconstruction significantly

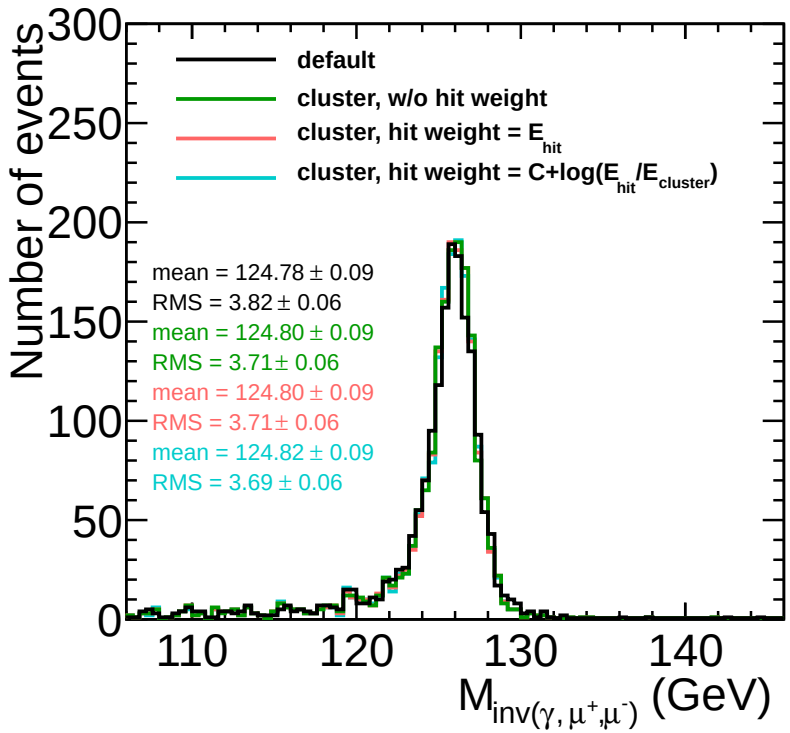
Photon Reconstruction (H → Zγ)

Reconstruction of polar angle



- Bias from calculation of cluster position
- Uses only first layer information and simple arithmetic mean (no weighting by hit energy)

Improved cluster position



- Only marginal impact on M(H) reconstruction
- Use default photon reconstruction throughout analysis

Outline

Generator Level Cuts

- At least two photons with $E > 10\,\mathrm{GeV}$, $p_\mathrm{T} > 5\,\mathrm{GeV}$ and $5° < \theta < 175°$
- At least one Higgs candidate with $110\,\mathrm{GeV} < M(\gamma\gamma) < 140\,\mathrm{GeV}$
- No visible lepton or quark with $10° < \theta < 170°$

Relevant Background Processes

Process	σ[fb][1]	Events in 1.5 ab^{-1}	Events Available[2]	Event Weights
$e^+e^- \to \nu\bar{\nu}\gamma$	30	44000	90000	0.5
$e^+e^- \to \nu\bar{\nu}\gamma\gamma$	17	26000	25000	1.1
$e^+e^- \to \gamma\gamma$	27	41000	42000	1.0
$e^+e^- \to e^+e^-\gamma$	290	430000	280000	1.5
$e^+e^- \to e^+e^-\gamma\gamma$	13	19000	20000	0.9
$e^+e^- \to q\bar{q}\gamma$	67	100000	100000	1.1
$e^+e^- \to q\bar{q}\gamma\gamma$	17	25000	24000	1.1

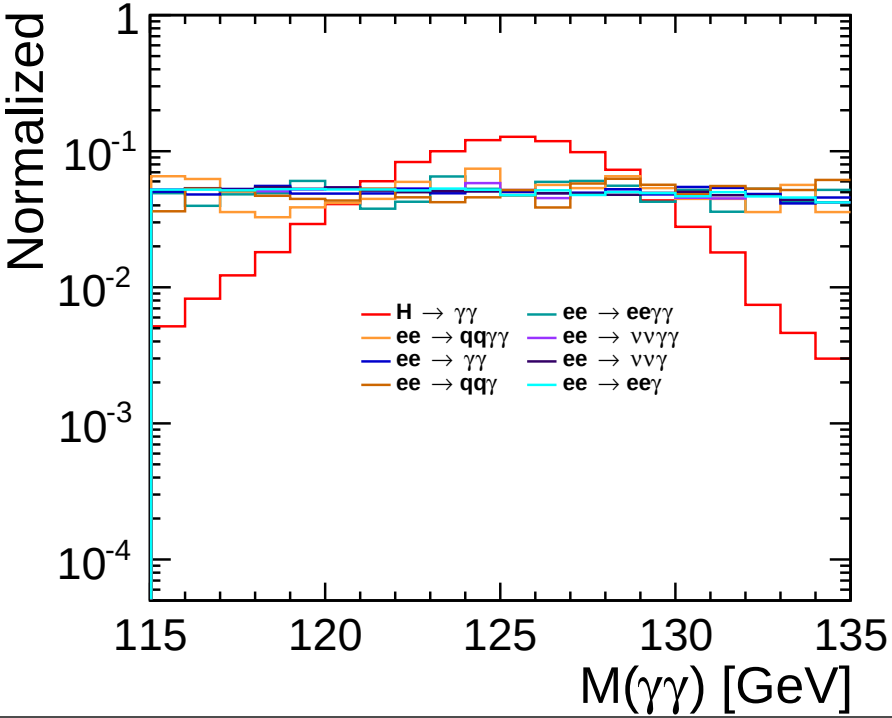
[1] after StdHep cuts
[2] excluding events used for TMVA training

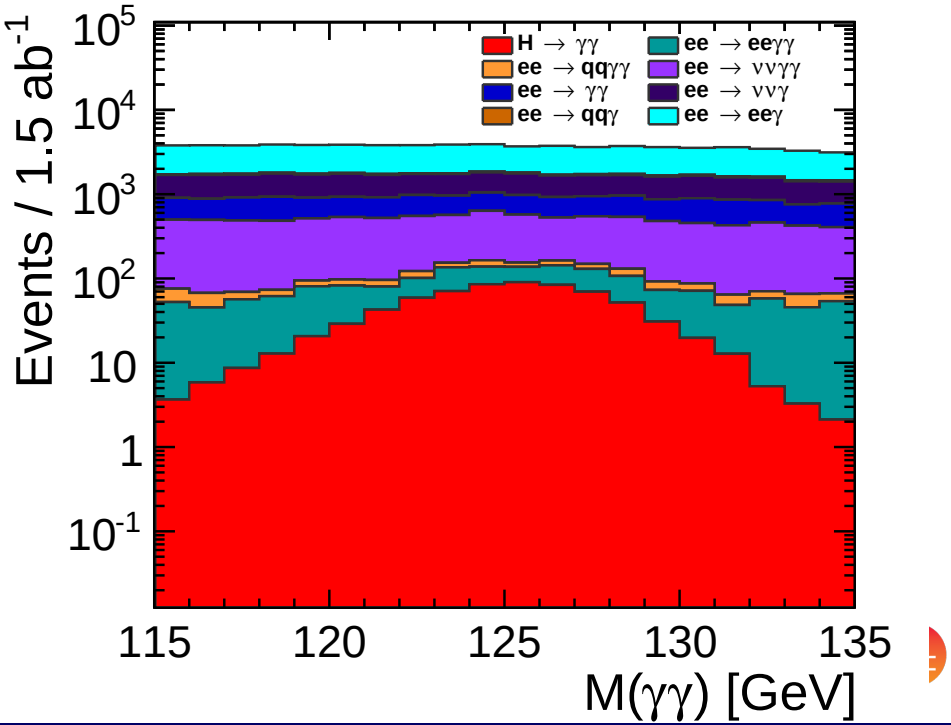
Kinematic Variables

- Higgs candidate mass: $M(\gamma\gamma)$
- Higgs candidate polar angle: $\theta(\gamma\gamma)$
- Higgs candidate azimuthal angle: $\phi(\gamma\gamma)$
- Higgs candidate transverse momentum: $p_{\mathrm{T}}(\gamma\gamma)$
- Higgs candidate energy: $E(\gamma\gamma)$
- Higgs candidate velocity: $\beta(\gamma\gamma)$
- Angle between the photons: $\Delta\theta(\gamma\gamma)$
- Remaining visible energy: $E_{\mathrm{vis}} - E(\gamma\gamma)$
- Photon transverse momenta: $p_{\mathrm{T}}(\gamma_1)$ and $p_{\mathrm{T}}(\gamma_2)$
- Photon polar angles: $\theta(\gamma_1)$ and $\theta(\gamma_2)$
- Helicity angle: $\cos\theta^*$

Pre-Selection

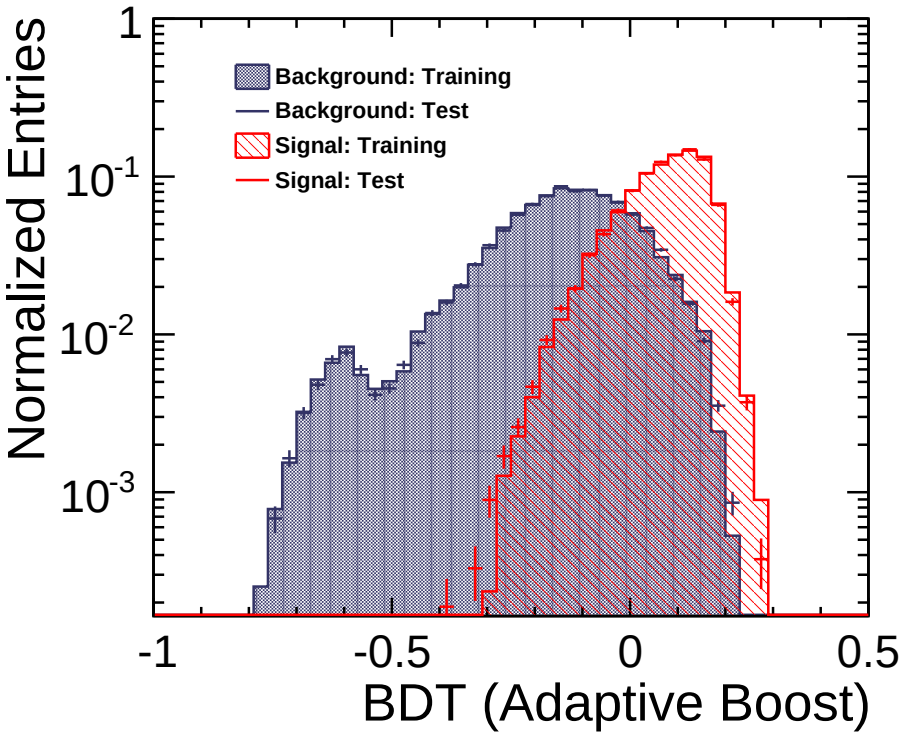
- Use only PFOs that pass the default time selection cuts (reject out-of-time pair backgrounds)
- Use only reconstructed photons with $E > 15\,\mathrm{GeV}$ and $p_\mathrm{T} > 10\,\mathrm{GeV}$
- Select two highest energy photons with $115\,\mathrm{GeV} < M(\gamma\gamma) < 135\,\mathrm{GeV}$ as Higgs candidate
- Require both photons to be isolated: no charged PFO with $p_\mathrm{T} > 5\,\mathrm{GeV}$ within $500\,\mathrm{mrad}$
- Remaining visible energy: $E_\mathrm{vis} - E(\gamma\gamma) < 250\,\mathrm{GeV}$
- Highest p_T Photon: $p_\mathrm{T}(\gamma_1) > 40\,\mathrm{GeV}$

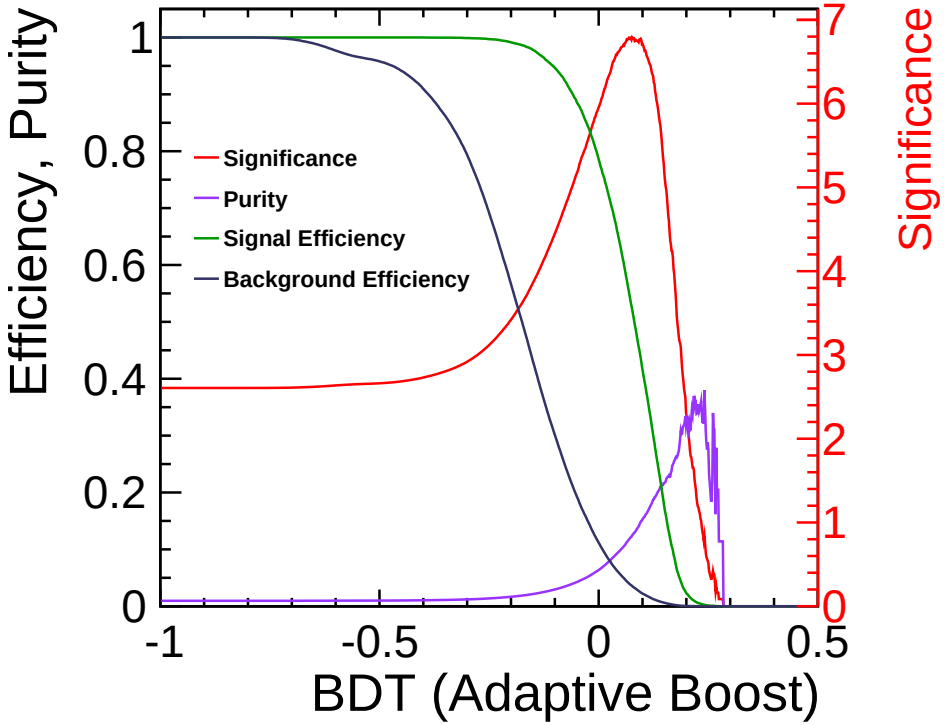




Boosted Decision Tree (BDT)

- Use TMVA for classification
- Adaptive boosting using 400 trees

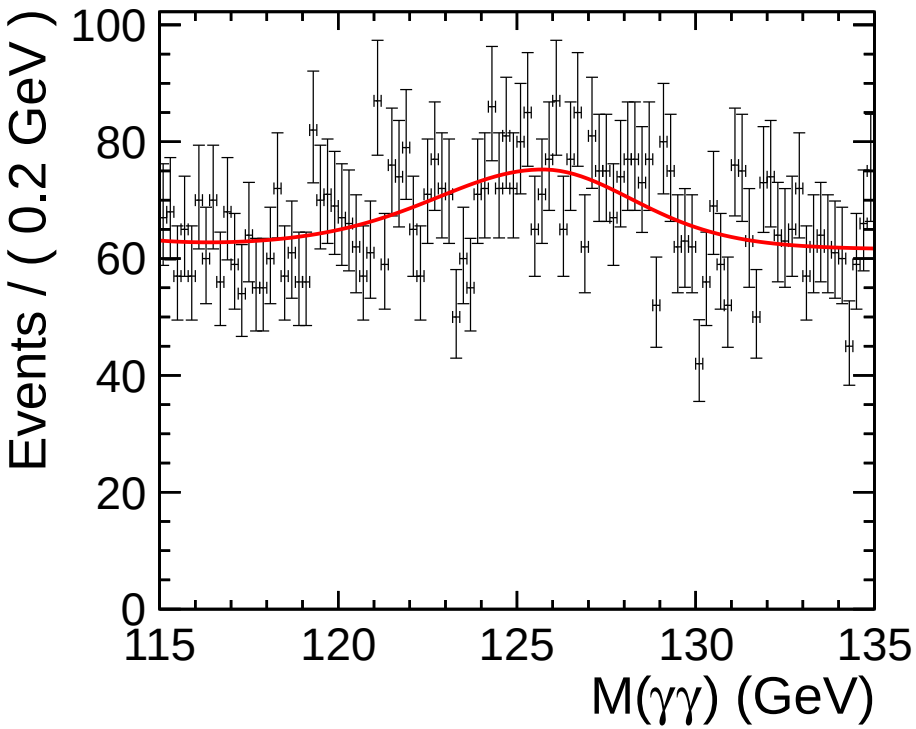




- Best significance: 6.8
- $\delta(\sigma \times \mathrm{BR})$: 14.7%
- Signal efficiency: 44.1%

Invariant Mass Fit

- Re-train BDT with $M(\gamma\gamma)$ excluded
- Select BDT cut with highest significance ($115\,\mathrm{GeV} < M(\gamma\gamma) < 135\,\mathrm{GeV}$)
- Fix PDFs for signal (Gaussian with asymmetric tails) and background (exponential + flat) using full statistics
- Toy MC with signal from "data" and backgrounds from PDF



Results (50 ToyMC)

- Signal efficiency: 53.3%
- $N_{\mathrm{sig}} = 445 \pm 94$
- $\sigma \times \mathrm{BR} = (0.55 \pm 0.11)\,\mathrm{fb}$
- $\delta(\sigma \times \mathrm{BR}) : (23 \pm 6)\%$
- Mean significance: 4.3

Outline

Generator Level Cuts

- Event must contain at least
  - two charged electrons **or** two quarks,
  - one photon **or** photon from ISR.
  - The fermions (and the photon, if available) should fulfill
    - $E > 15\,\text{GeV}$,
    - $p_\text{T} > 10\,\text{GeV}$, and
    - $10^\circ < \theta < 170^\circ$.
  - At least one Higgs candidate with $100 < M(Z\gamma) < 150\,\text{GeV}$

Relevant Background Processes (e^+e^-)

Process (- ISR)	σ(fb)	Events in 1.5 ab^{-1}	Simulated events	Event weights
	- - - - - - - - - - after generator level cuts - - - - - - - - -			
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}\gamma$	37.30	55944	194964	0.29
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}$	121.81	182709	162616	1.1
$e^+e^- \to q\bar{q}$ †	4009.50	6014250	701961	8.6
$e^+e^- \to q\bar{q}q\bar{q}$ †	1328.10	1992150	251138	7.9
$e^+e^- \to \nu_e\bar{\nu}_e l^+l^-\gamma$	8.69	13038	200598	0.065
$e^+e^- \to \nu_e\bar{\nu}_e l^+l^-$	23.32	34981	37989	0.92
$e^+e^- \to l^+l^-l^+l^-$	85.20	127795	133916	0.95
$e^+e^- \to q\bar{q}l^+l^-\gamma$	18.22	27336	38922	0.70
$e^+e^- \to q\bar{q}l^+l^-$	95.63	143447	722725	0.20
$e^+e^- \to \nu_e\bar{\nu}_e H \xrightarrow{H\to\gamma\gamma} \nu_e\bar{\nu}_e\gamma\gamma$ †	0.56	842	53500	0.016
$e^+e^- \to H\nu_e\bar{\nu}_e \xrightarrow{H\to Z\gamma} \nu_e\bar{\nu}_e\tau^+\tau^-\gamma$ †	0.014	21	170263	0.00012

- $\gamma\gamma$ initial state processes are not relevant for this analysis

† No generator level cuts

Relevant Background Processes ($e\gamma$)

Process (γ from BS) (- ISR)	σ(fb)	Events in $1.125\,\mathrm{ab}^{-1}$	Simulated events	Event weights
	- - - - - - - - - after generator level cuts - - - - - - - -			
$e^{\pm}\gamma \to e^{\pm}q\bar{q}\gamma$	103.07	115948	156812	0.74
$e^{\pm}\gamma \to e^{\pm}q\bar{q}$	864.14	972160	38009	25.57
$e^{\pm}\gamma \to e^{\pm}q\bar{q}q\bar{q}$ †	477.36	537028	759592	0.71
$e^{\pm}\gamma \to e^{\pm}q\bar{q}\nu_e\bar{\nu}_e$	4.77	5366	5366	0.14
$e^{\pm}\gamma \to e^{\pm}l^{+}l^{-}\gamma$	83.10	93487	147658	0.63
$e^{\pm}\gamma \to e^{\pm}l^{+}l^{-}$	572.83	644436	84821	7.60
$e^{\pm}\gamma \to e^{\pm}l^{+}l^{-}q\bar{q}$	1.89	2124	n.a.	n.a.
Process (γ from EPA) (- ISR)	σ(fb)	Events in $1.5\,\mathrm{ab}^{-1}$	Simulated events	Event weights
	- - - - - - - - - after generator level cuts - - - - - - - -			
$e^{\pm}\gamma \to e^{\pm}q\bar{q}\gamma$	60.85	91270	108699	0.84
$e^{\pm}\gamma \to e^{\pm}q\bar{q}$	1113.71	1670568	36431	45.86
$e^{\pm}\gamma \to e^{\pm}q\bar{q}q\bar{q}$ †	171.05	256578	798367	0.32
$e^{\pm}\gamma \to e^{\pm}q\bar{q}\nu_e\bar{\nu}_e$	1.33	1995	29426	0.07
$e^{\pm}\gamma \to e^{\pm}l^{+}l^{-}\gamma$	86.04	129057	150612	0.86
$e^{\pm}\gamma \to e^{\pm}l^{+}l^{-}$	1369.23	2053841	91729	22.39
$e^{\pm}\gamma \to e^{\pm}l^{+}l^{-}q\bar{q}$	1.01	1509	n.a.	n.a.

† No generator level cuts

Pre-Selection and Reconstruction

Pre-selection

- Use only reconstructed particles that pass the tight time selection cuts
- Use only reconstructed photons, muons, electrons, and jets of
  - $E > 17.5\,\text{GeV}$ and
  - $p_\text{T} > 12.5\,\text{GeV}$
- Quark case: Number of particles in jet > 5

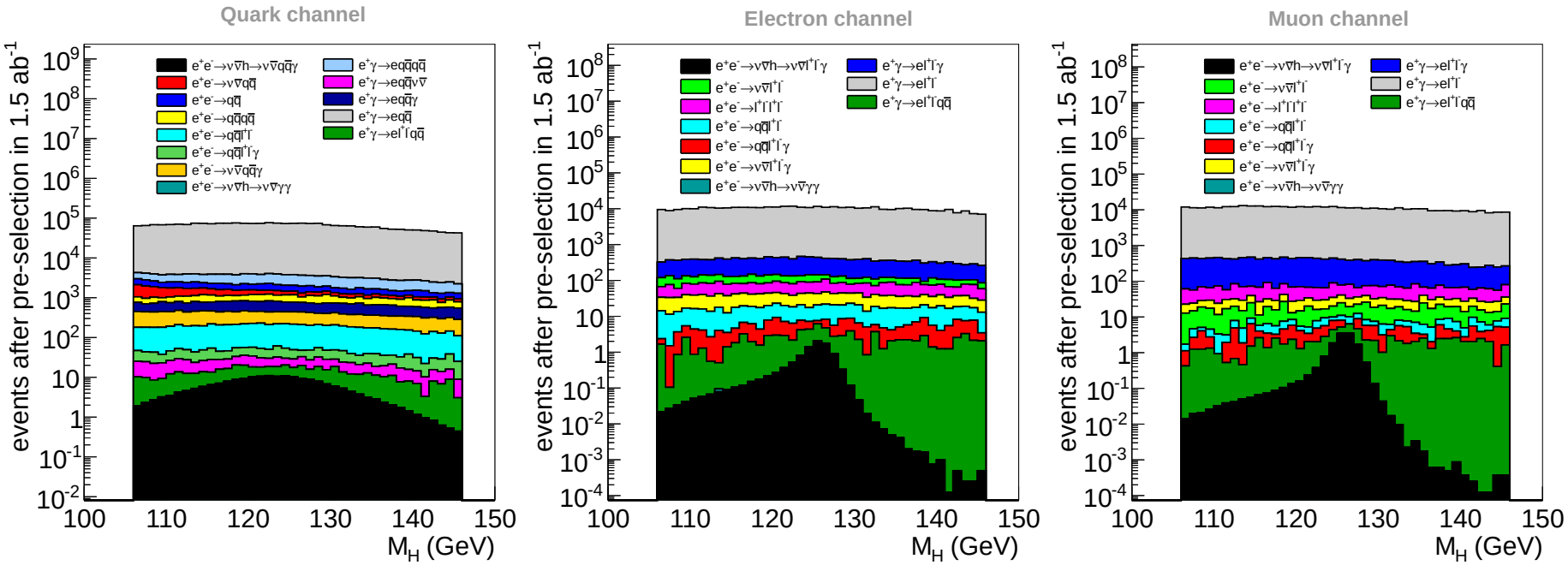
Reconstruction

- First search for two muons, then for two electrons
- Bremsstrahlung recovery with a cone of $0.3°$ around leptons
- If there is no charged lepton pair, use available particles to form two jets (k_T algorithm, jet radius $R = 1.2$)
- Combine photon of highest energy and the charged lepton pair or the jet pair to Higgs candidate
- Select events in which the Higgs candidate has an invariant mass of $105 < M(\text{Z}\gamma) < 145\,\text{GeV}$

Discriminating Variables

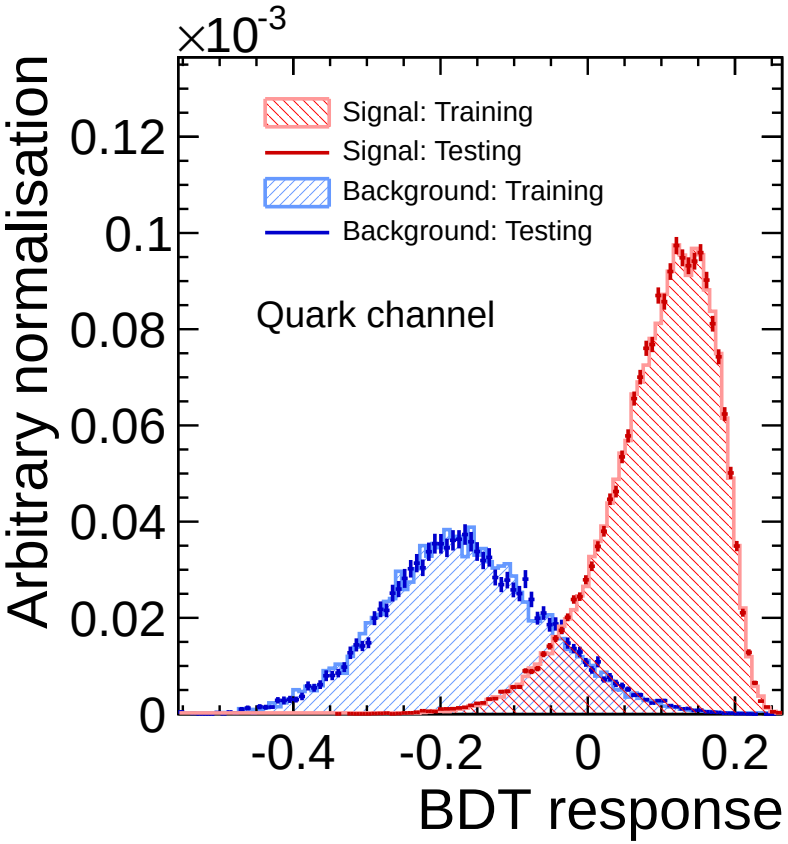
- Properties of H, Z and γ
  - Mass m, velocity β, polar angle θ, transverse momentum p_{T}, energy E
  - $\sum \overrightarrow{p_{\mathrm{T}}}$ of H candidate daughters
- Event properties:
  - thrust, oblateness, sphericity, aplanarity of l^+l^- ($q\bar{q}$) and γ
  - Missing energy $\not{E}$ of l^+l^- ($q\bar{q}$) and γ
  - Missing transverse energy $\not{E}_{\mathrm{T}}$ of l^+l^- ($q\bar{q}$) and γ
  - Visible energy excluding the reconstructed H candidate $E_{\mathrm{vis}} - E_{\mathrm{H}}$
  - Particle multiplicity N
- Angle between Z and γ
  - Angle between vectors of Z and γ
  - $\Delta\theta$ between Z and γ
  - $\Delta\varphi$ between Z and γ
  - $\cos\theta^*$ in Z rest frame
- In quark case
  - Number of particles used to reconstruct Z
  - $y_{n,n+1}$ value associated with merging from n to $n+1$ jets, $n = 1, 2, 3, 4$

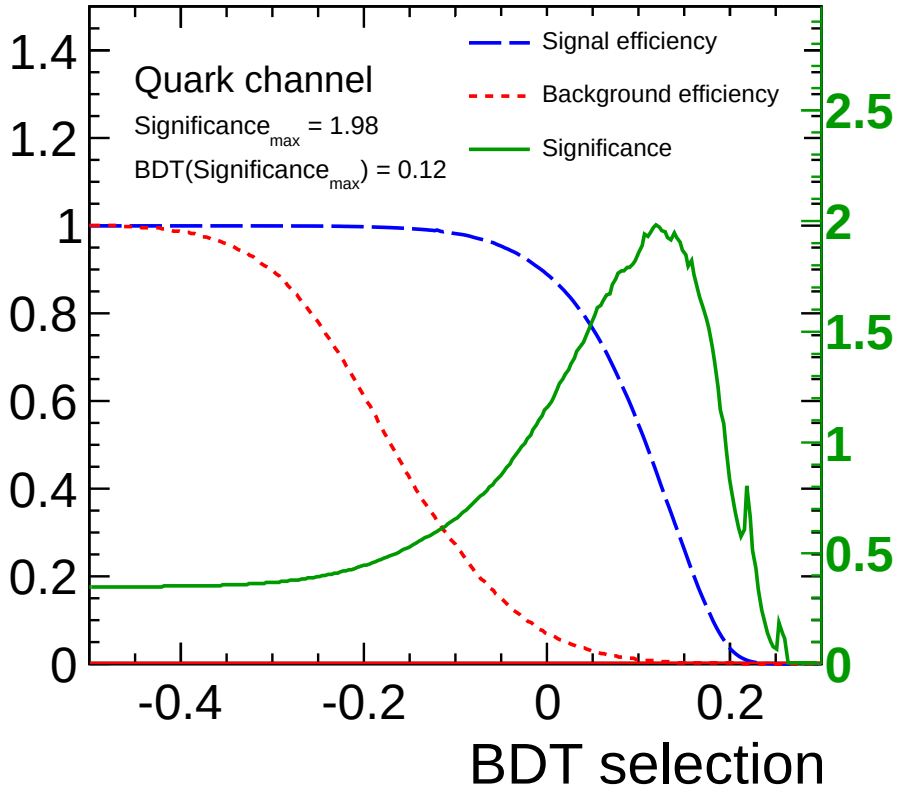
Invariant Mass Distribution (after Pre-Selection)



- Stacked histograms
- Entries are scaled to number of events (after pre-selection) in 1.5(1.125) ab^{-1}
- Signal channels show H mass peak, background channels are flat
- Background channels dominate

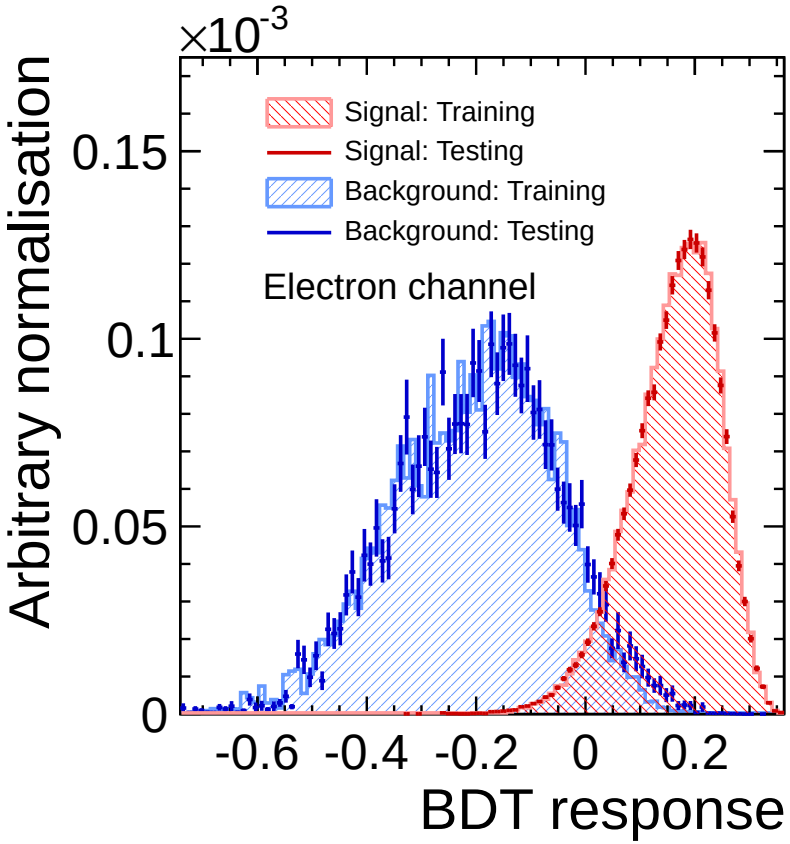
BDT Classification (Quark Channel)

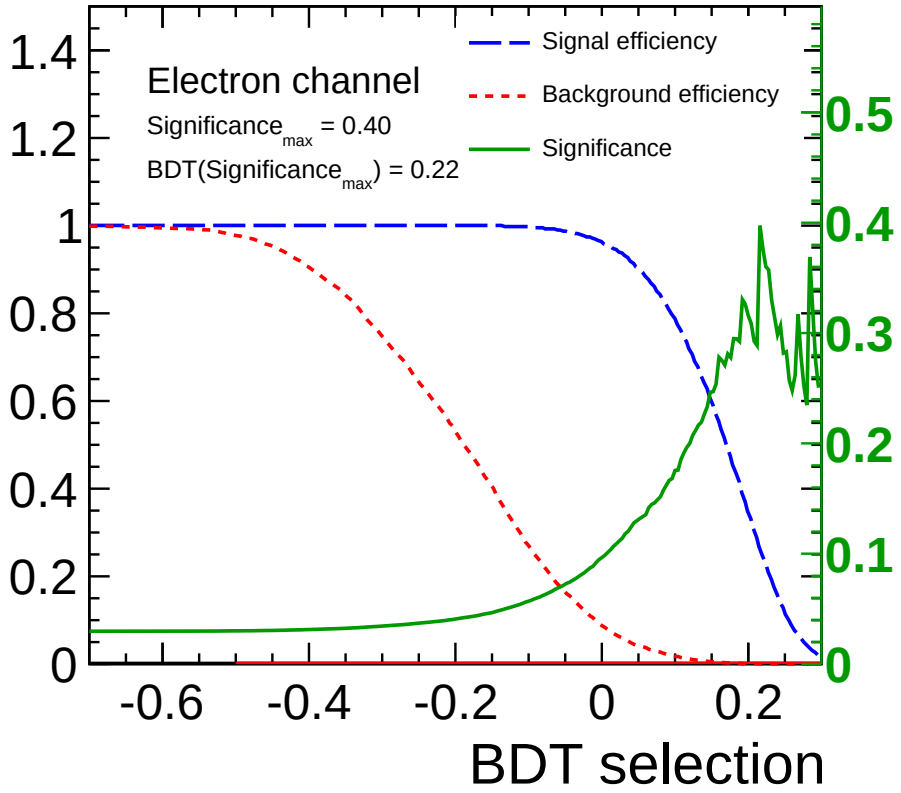




- Use half of the events for training and half for testing
- Best significance is 1.98

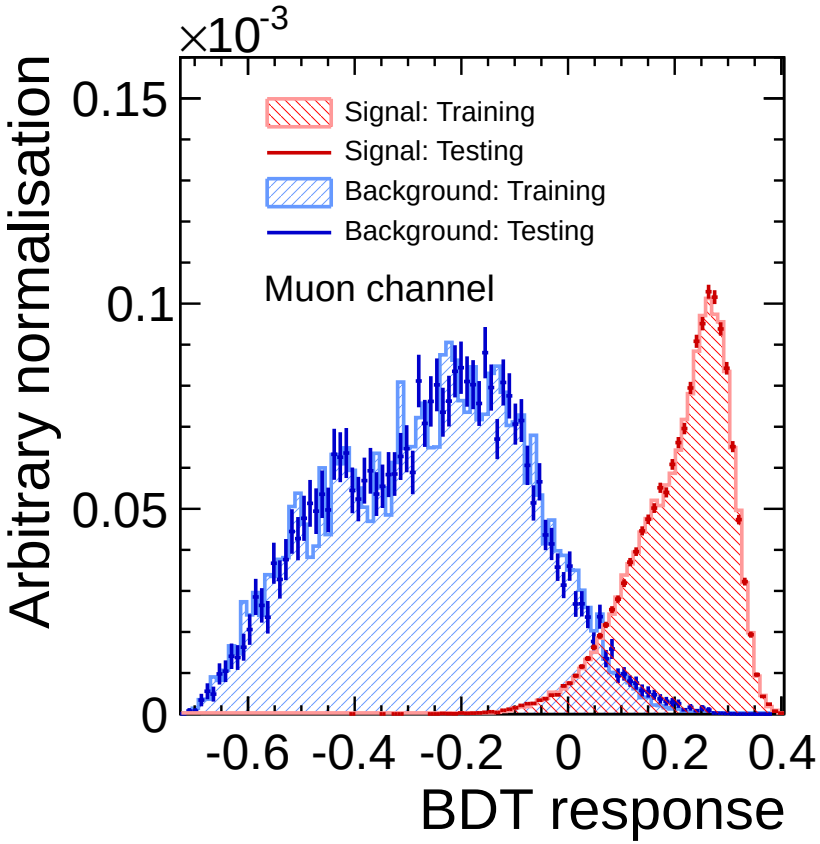
BDT Classification (Electron Channel)

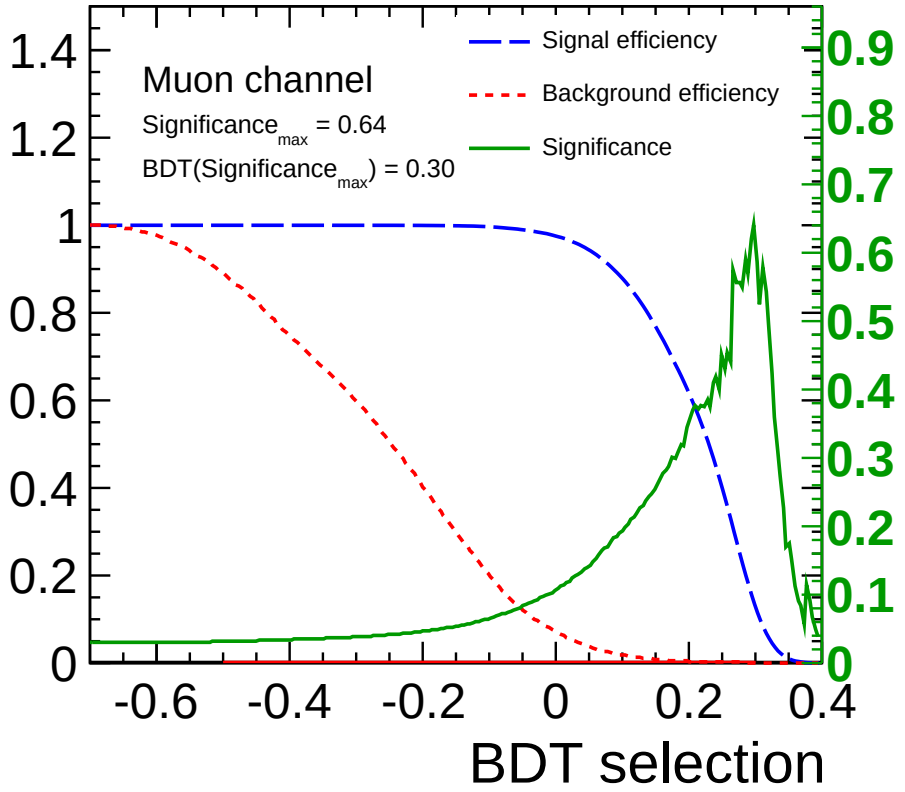




- Use half of the events for training and half for testing
- Best significance is 0.4

BDT Classification (Muon Channel)





- Use half of the events for training and half for testing
- Best significance is 0.64

Outline

Summary ($H \to \gamma\gamma$)

- Significance: 6.79
- $\delta(\sigma \times \mathrm{BR})$: 14.7%
- Overall signal efficiency: 44.1% (367/834)

- Measurement by reconstructing the H mass peak is possible (significance: 4.3)

- 80% electron polarization (and 30% positron polarization) would improve the significance by at least $\sqrt{1.8}$ ($\sqrt{2.3}$)
- Increased WW fusion cross section at $\sqrt{s} = 3\,\mathrm{TeV}$ allows better measurement

Summary (H → Zγ)

- $H \to q\bar{q}\gamma$ results
  - Significance: 1.98
  - Overall signal efficiency: 23.5% (96/409)
- $H \to e^+e^-\gamma$ results
  - Significance: 0.4
  - Overall signal efficiency: 13% (3/21)
- $H \to \mu^+\mu^-\gamma$ results
  - Significance: 0.64
  - Overall signal efficiency: 9.2 % (2/21)

- Combined significance: 2.12
- $\delta(\sigma \times \text{BR})$: 47%

- Polarisation allows to improve $\delta(\sigma \times \text{BR})$ to 35% (30%) or better