Measurement of the Higgs boson decays $H \to \gamma\gamma$ and $H \to Z\gamma$ at a CLIC collider operating at 1.4 TeV

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on behalf of the CLIC detector and physics study

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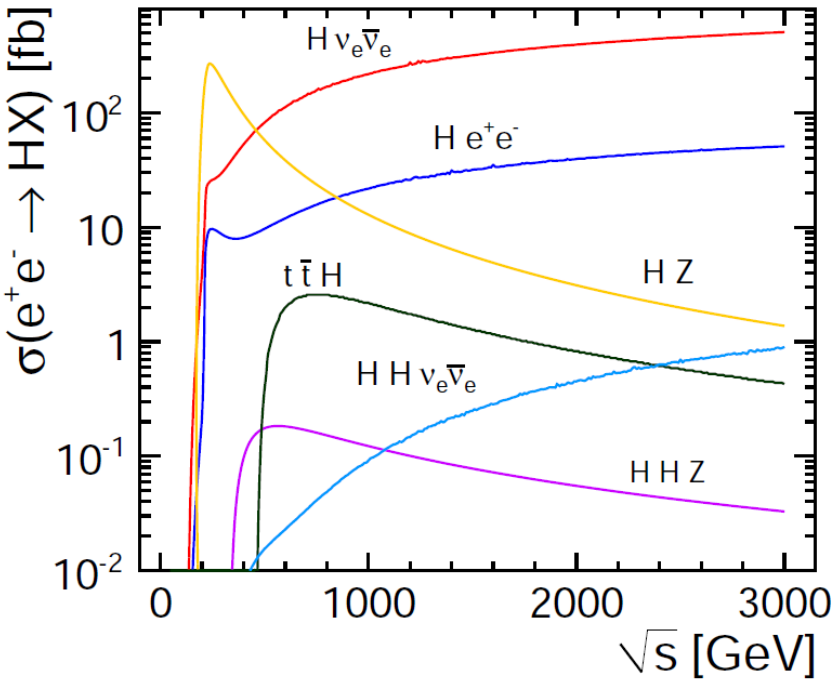
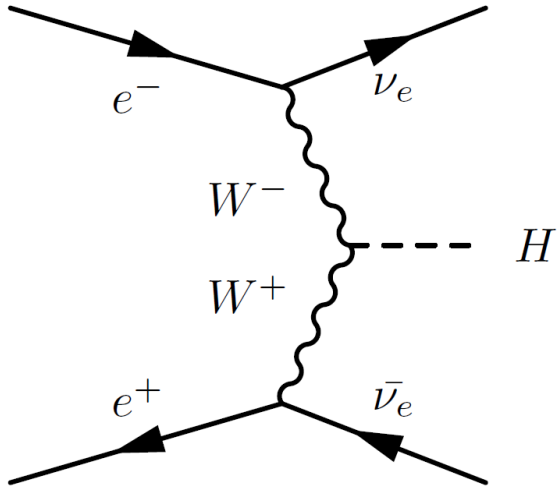
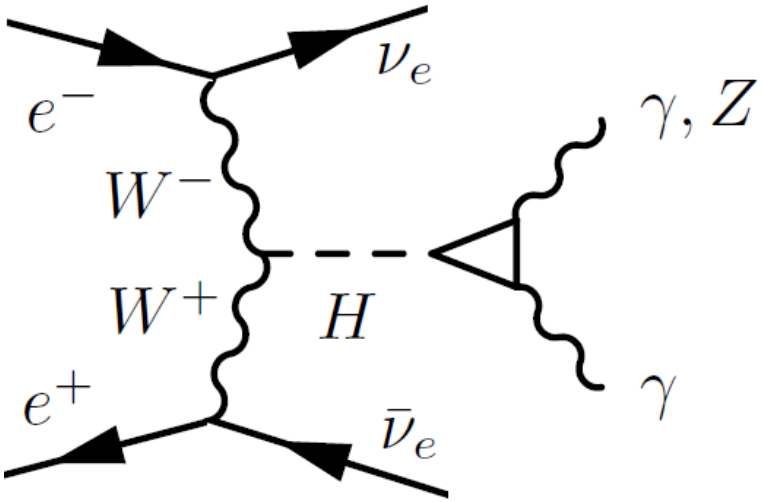
Higgs Production at 1.4 TeV





- At $\sqrt{s} = 1.4\,\text{TeV}$, W^+W^--fusion dominant H production channel $\sigma(e^+e^- \to H\nu\bar{\nu}) \approx 244\,\text{fb}$ (with unpolarised $e^\pm$ beams)
- Possibility to study also rare Higgs decay channels

Rare Higgs Decays $H \to \gamma\gamma$ and $H \to Z\gamma$

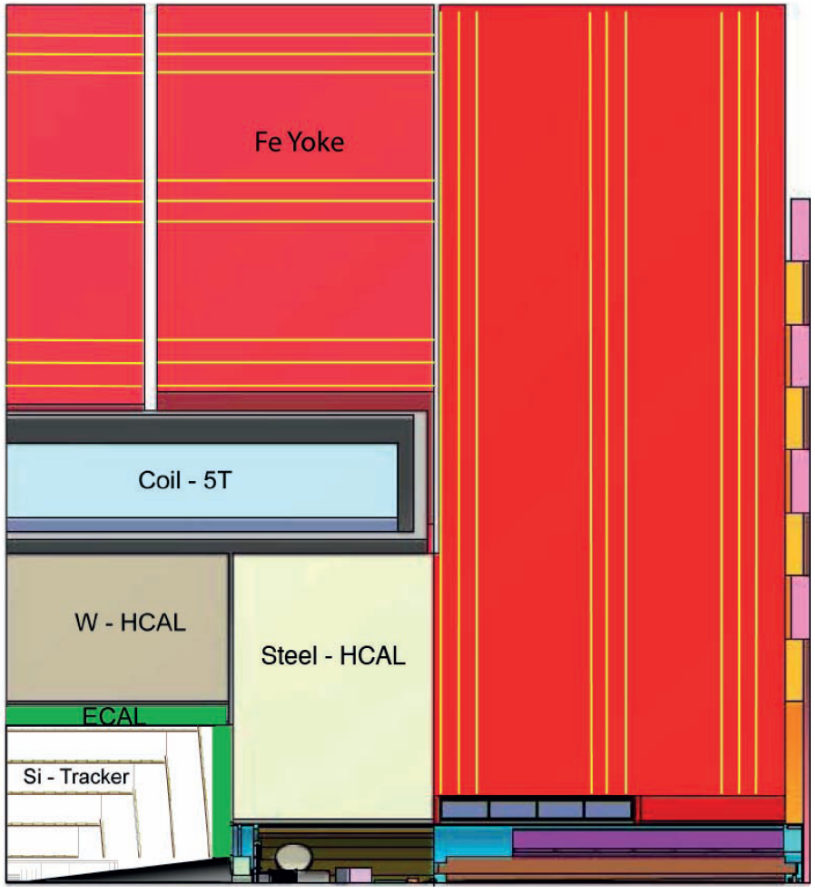


- $H \to \gamma\gamma$ and $H \to Z\gamma$ induced by loops over heavy charged particles
- Sensitive to physics beyond standard model

- Higgs mass of $M_H = 126\,\text{GeV}$
- $\text{BR}_{H\to\gamma\gamma} \approx 0.23\,\% \to \sigma \times \text{BR} \approx 0.56\,\text{fb}$
  - $N_{\text{signal}} \approx 834/1.5\,\text{ab}^{-1}$
- $\text{BR}_{H\to Z\gamma} \approx 0.16\,\% \to \sigma \times \text{BR} \approx 0.39\,\text{fb}$
  - $\text{BR}_{Z\to q\bar{q}} \approx 69.9\,\%$
    $N_{\text{signal}}(Z \to q\bar{q}) \approx 409/1.5\,\text{ab}^{-1}$
  - $\text{BR}_{Z\to e^+e^-} \approx 3.4\,\%$
    $N_{\text{signal}}(Z \to e^+e^-) \approx 21/1.5\,\text{ab}^{-1}$
  - $\text{BR}_{Z\to \mu^+\mu^-} \approx 3.4\,\%$
    $N_{\text{signal}}(Z \to \mu^+\mu^-) \approx 21/1.5\,\text{ab}^{-1}$
  - $Z \to \tau^+\tau^-$ not studied

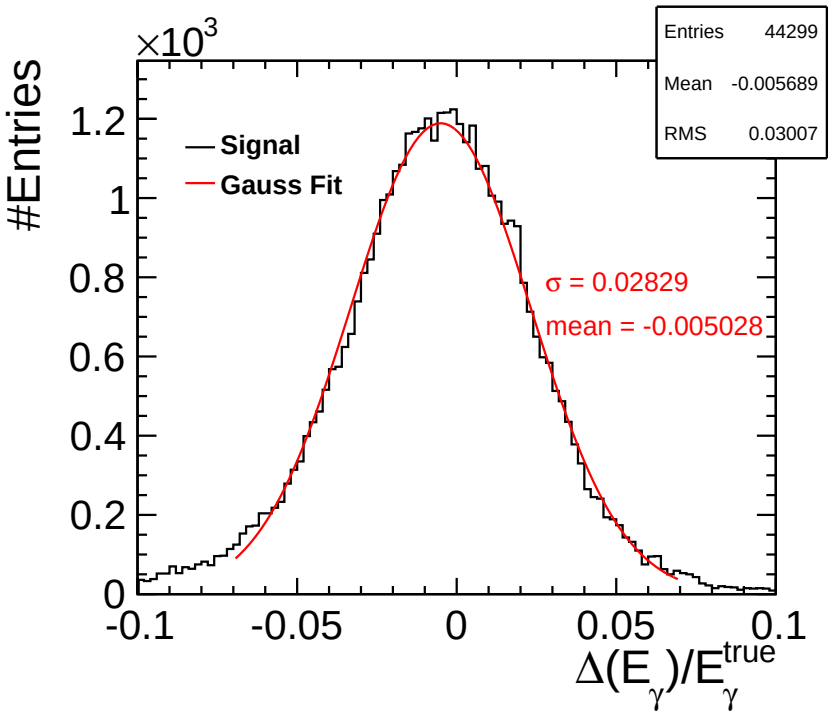
Detector Simulation and Reconstruction

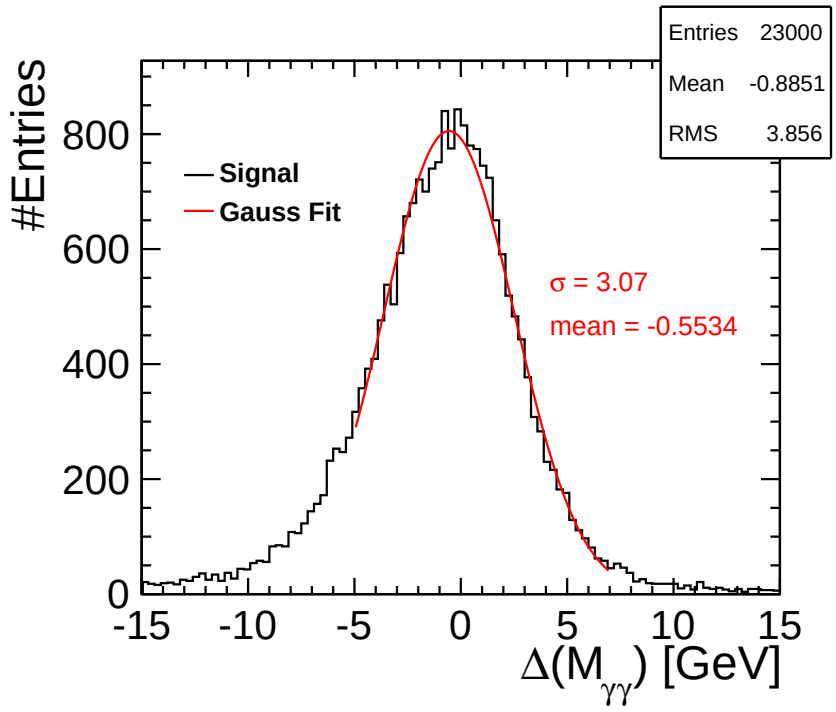
- Full **CLIC_SiD** detector simulation of signal and background events
  - Same software chain as used for the CLIC Conceptional Design Report
  - Full GEANT4 detector simulation
  - Overlay of $\gamma\gamma \rightarrow$ hadrons background
  - Full event reconstruction



Photon Reconstruction

- $H \to \gamma\gamma$ and $H \to Z\gamma$ studies test quality of CLIC_SiD photon reconstruction





- Photon energy resolution and Higgs mass resolution for $H \to \gamma\gamma$ signal sample
- Mean photon energy of signal sample $E_\gamma = 135\,\text{GeV}$

Background Processes $H \to \gamma\gamma$

Generator level cuts

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

Background processes

Process (- ISR)	σ[fb]*	Events in $1.5\,\text{ab}^{-1}$
$e^+e^- \to \nu\bar{\nu}\gamma$	30	44000
$e^+e^- \to \nu\bar{\nu}\gamma\gamma$	17	26000
$e^+e^- \to \gamma\gamma$	27	41000
$e^+e^- \to e^+e^-\gamma$	290	430000
$e^+e^- \to e^+e^-\gamma\gamma$	13	19000
$e^+e^- \to q\bar{q}\gamma$	67	100000
$e^+e^- \to q\bar{q}\gamma\gamma$	17	25000

- $e^\pm\gamma$ and $\gamma\gamma$ initial state processes were found to be negligible for this analysis

*after generator level cuts

Reconstruction and Pre-Selection

Reconstruction

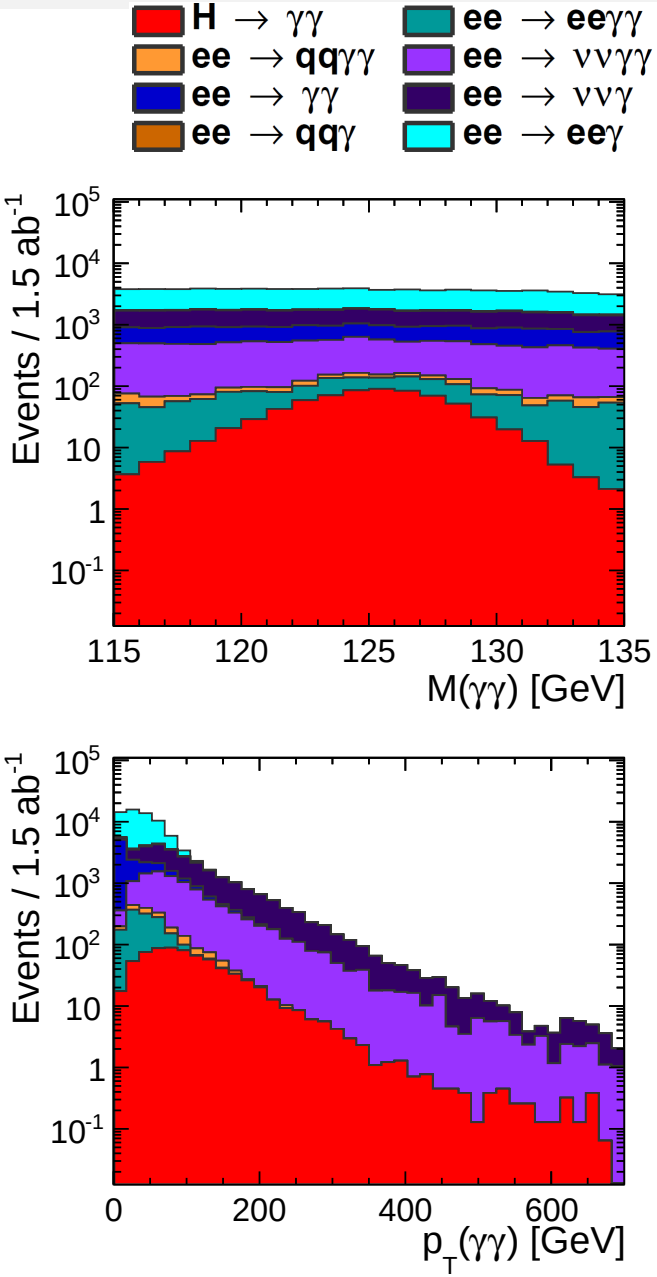
- Use only particles that pass timing cuts
- Search for two photons of highest energy
- Combine two selected photons to Higgs candidate

Pre-selection

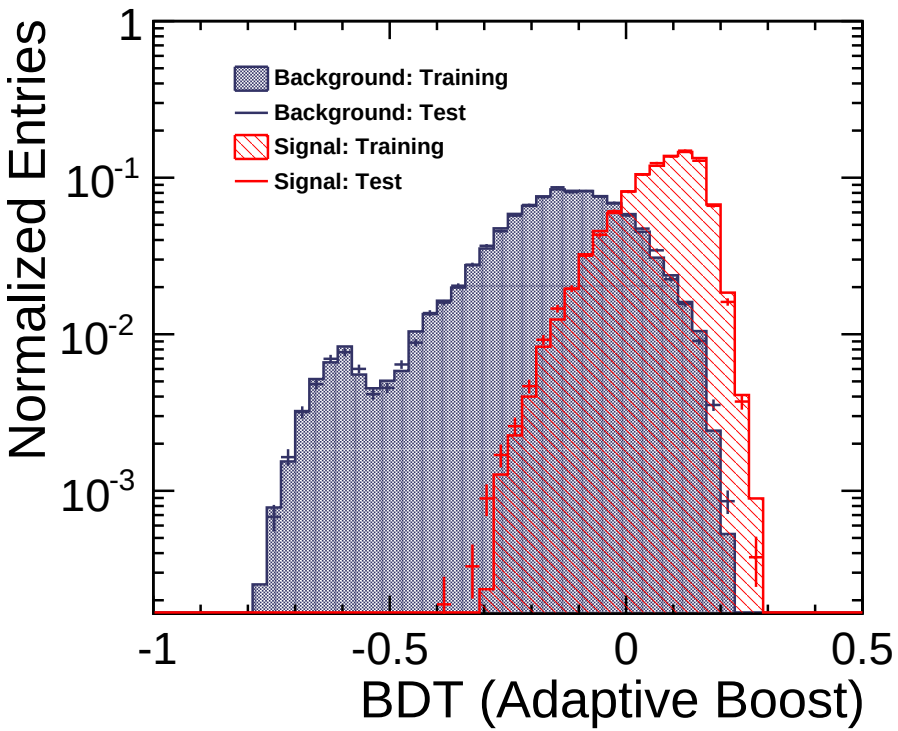
- Use only reconstructed photons with $\mathbf{E > 15\,GeV}$ and $\mathbf{p_T > 10\,GeV}$
- Invariant mass of Higgs candidate daughters $\mathbf{115 < M(\gamma,\gamma) < 135\,GeV}$
- Require both photons to be isolated: no charged PFO with $\mathbf{p_T > 5\,GeV}$ within $\mathbf{30^\circ}$
- Remaining visible energy: $\mathbf{E_{vis} - E(\gamma\gamma) < 250\,GeV}$
- Highest p_T photon: $\mathbf{p_T(\gamma_1) > 40\,GeV}$

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: $\cos\theta^*$

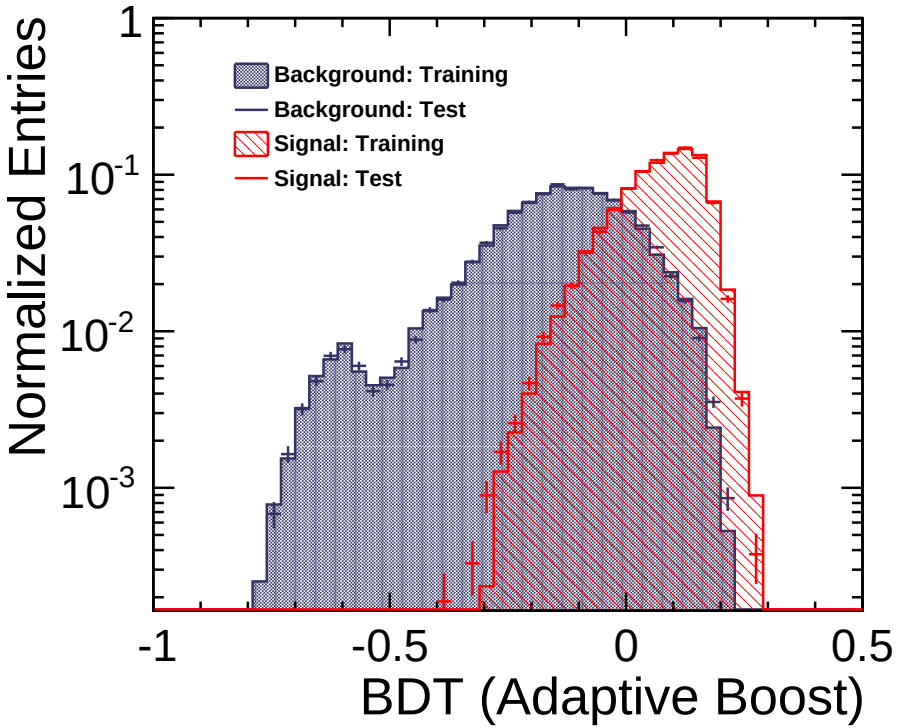


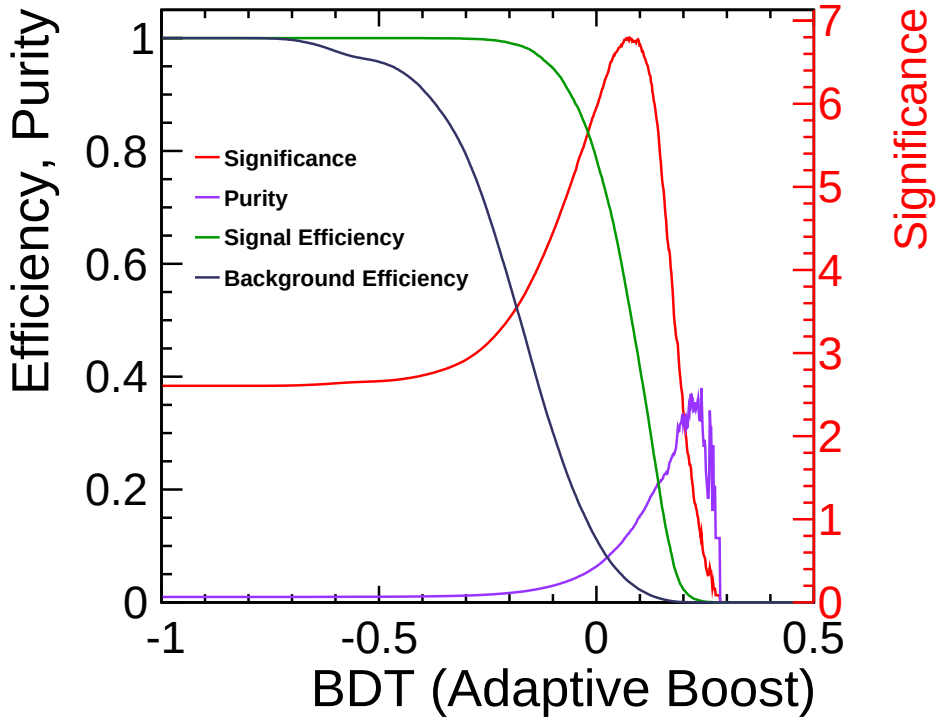
Boosted Decision Tree (BDT)



- Use TMVA for classification
- Adaptive boosting using 400 trees

Boosted Decision Tree (BDT)





- Use TMVA for classification
- Adaptive boosting using 400 trees

- Best significance: 6.8
- $\delta(\sigma \times BR)$: 14.7%
- Signal efficiency: 44%

Selected Events in $H \to \gamma\gamma$ Analysis

Process	σ[fb]*	Events in 1.5 ab^{-1}		
		Generator level cut	Pre-Selection	BDT
$H \to \gamma\gamma$	0.56	834	708 (85%)	367 (44%)
$e^+e^- \to \nu\bar{\nu}\gamma$	30	44250	15130 (34%)	1338 (3%)
$e^+e^- \to \nu\bar{\nu}\gamma\gamma$	17	25988	8066 (31%)	802 (3.1%)
$e^+e^- \to \gamma\gamma$	27	40830	8069 (20%)	73 (0.18%)
$e^+e^- \to e^+e^-\gamma$	290	433465	39717 (9.2%)	341 (0.079%)
$e^+e^- \to e^+e^-\gamma\gamma$	13	18919	993 (5.2%)	4 (0.025%)
$e^+e^- \to q\bar{q}\gamma$	67	100524	825 (0.82%)	1 (0.002%)
$e^+e^- \to q\bar{q}\gamma\gamma$	17	24848	353 (1.4%)	4 (0.017%)

*after generator level cuts, except for signal sample

Background Processes $H \to Z\gamma$: e^+e^-

Generator level cuts

- At least two charged leptons **or** two quarks and one photon of $E > 15\,\text{GeV}$, $p_T > 10\,\text{GeV}$, and $10^\circ < \theta < 170^\circ$.
- At least one Higgs candidate with $100 < M(Z\gamma) < 150\,\text{GeV}$

Background processes

Process (- ISR)	σ[fb]*	Events in $1.5\,\text{ab}^{-1}$
$e^+e^- \to \nu\bar{\nu}q\bar{q}\gamma$	36.9	55k
$e^+e^- \to \nu\bar{\nu}q\bar{q}$	121.8	183k
$e^+e^- \to q\bar{q}$	4009†	6M
$e^+e^- \to q\bar{q}q\bar{q}$	1328†	2M
$e^+e^- \to \nu\bar{\nu}l^+l^-\gamma$	8.7	13k
$e^+e^- \to \nu\bar{\nu}l^+l^-$	23	35k
$e^+e^- \to l^+l^-l^+l^-$	85	128k
$e^+e^- \to q\bar{q}l^+l^-\gamma$	18.2	27k
$e^+e^- \to q\bar{q}l^+l^-$	95	143k
$e^+e^- \to \nu\bar{\nu}H \to \nu\bar{\nu}\gamma\gamma$	0.56	842

*after generator level cuts

†w/o generator level cuts

Background Processes $H \to Z\gamma$: $e^+\gamma/\gamma e^-$

- Photon from beam strahlung (BS) or equivalent photon approximation (EPA)

Process (- ISR)	σ[fb]*	Events in 1.125 ab^{-1}
γ from BS		
$e^\pm\gamma \to e^\pm q\bar{q}\gamma$	72	81k
$e^\pm\gamma \to e^\pm q\bar{q}\nu\bar{\nu}$	2.6	3k
$e^\pm\gamma \to e^\pm l^+l^-\gamma$	66	74k
$e^\pm\gamma \to e^\pm l^+l^- q\bar{q}$	0.94	1k
$e^\pm\gamma \to e^\pm q\bar{q}q\bar{q}$	239	269k
$e^\pm\gamma \to e^\pm l^+l^-$	292†	329k
$e^\pm\gamma \to e^\pm q\bar{q}$	477†	537k
Process (- ISR)	σ[fb]*	Events in 1.5 ab^{-1}
γ from EPA		
$e^\pm\gamma \to e^\pm q\bar{q}\gamma$	43	65k
$e^\pm\gamma \to e^\pm q\bar{q}\nu\bar{\nu}$	0.7	1k
$e^\pm\gamma \to e^\pm l^+l^-\gamma$	51	77k
$e^\pm\gamma \to e^\pm l^+l^- q\bar{q}$	0.5	754
$e^\pm\gamma \to e^\pm q\bar{q}q\bar{q}$	86	128k
$e^\pm\gamma \to e^\pm l^+l^-$	701†	1M
$e^\pm\gamma \to e^\pm q\bar{q}$	551†	827k

*after generator level cuts for $e^+\gamma$, similar for γe^-

†additional cuts during generation $E_{l,q} > 10\,\text{GeV}$, $8^\circ < \theta_{l,q} < 172^\circ$

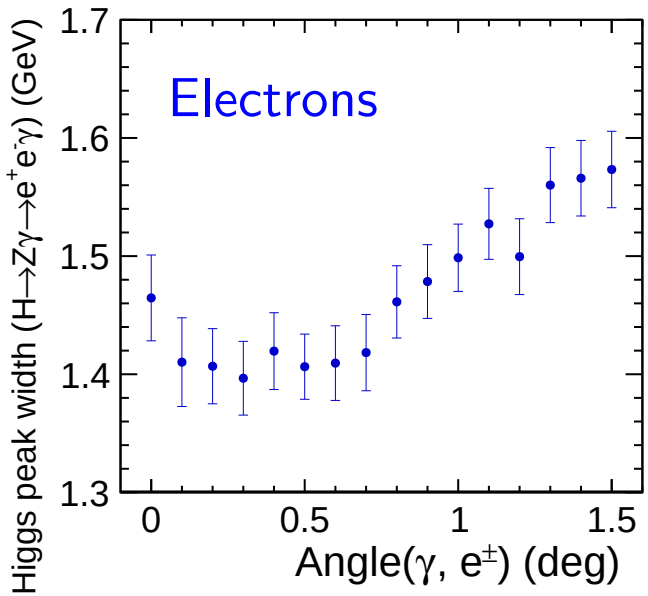
Reconstruction and Preselection

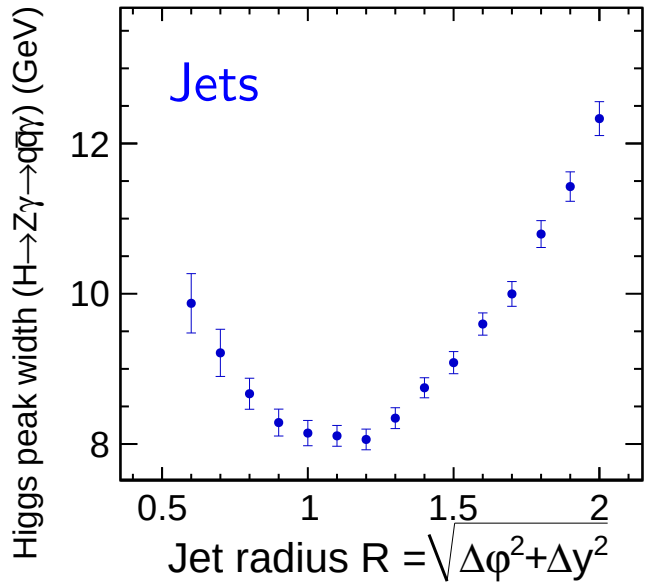
Reconstruction

- Use particles that pass timing cuts
- Search for photon of highest energy
- Search for two e/μ of highest energy
- Combine photons from bremsstrahlung with found leptons: **Angle($l^{\pm}, \gamma$) < 0.3 deg**
- If less than 2 charged leptons are found, use available particles to form two jets:
  k_T-algorithm, jet radius **R < 1.2**
- Combine photon of highest energy and the lepton/jet pair to Higgs candidate

Preselection

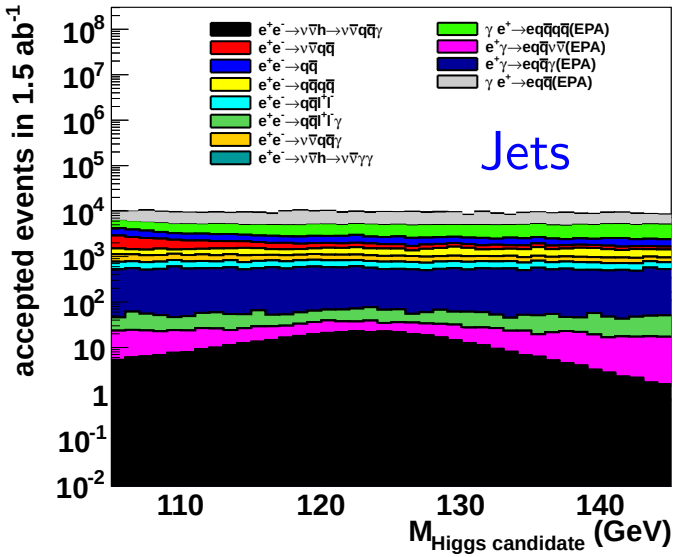
- Use only reconstructed e, μ, jets, and γ of **E > 17.5 GeV** and **p_T > 12.5 GeV**
- Invariant mass of Higgs candidate daughters **105 < M(Z, γ) < 145 GeV**

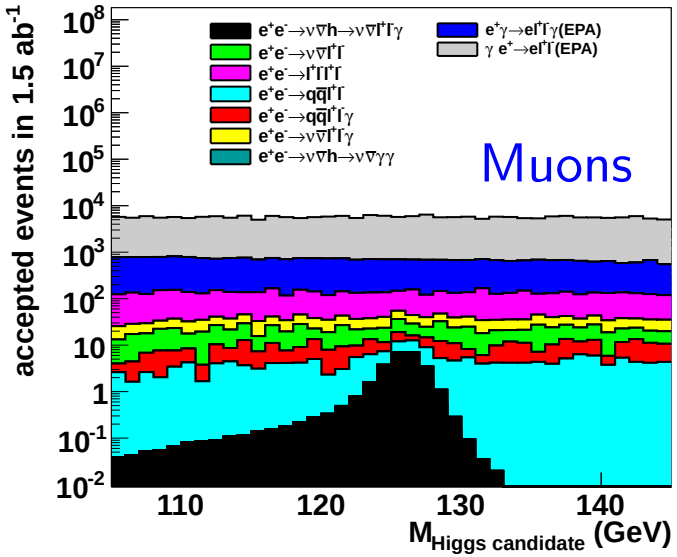




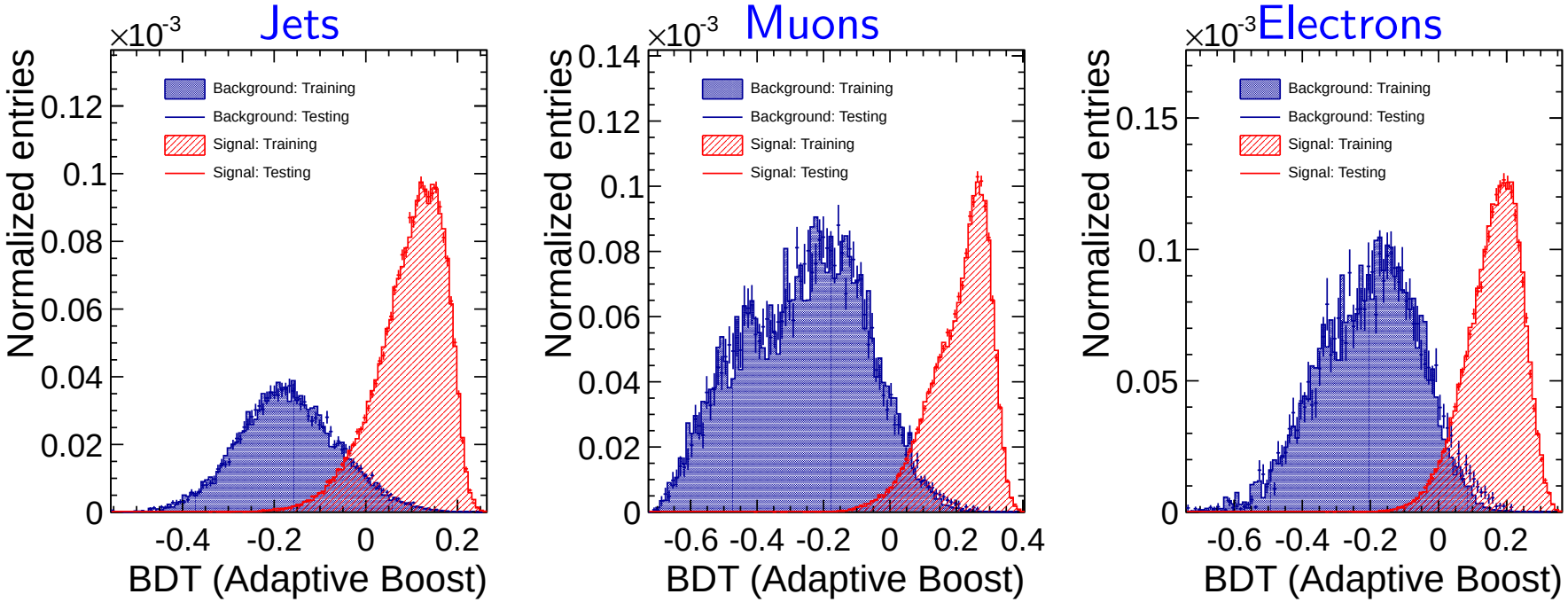
Kinematic Variables

- Mass m, velocity β, polar angle θ, transverse momentum p_T, energy E of H, Z, and γ
- $\sum \overrightarrow{p_T}$ of H candidate daughters
- Thrust, oblateness, sphericity, aplanarity of lepton/jet pair and γ
- Missing (transverse) energy $\not{E}$ ($\not{E}_T$) of lepton/jet pair and γ
- Visible energy excluding the reconstructed H candidate $E_{vis} - E_H$
- Particle multiplicity N
- Angle, $\Delta\theta$ and $\Delta\varphi$ between vectors of Z and γ
- $\cos\theta^*$ in Higgs rest frame
- In $Z \to q\bar{q}$ case
  - Number of particles used to reconstruct Z
  - $y_{n,n+1}$ value associated with merging from n to $n+1$ jets, $n = 1,2,3,4$



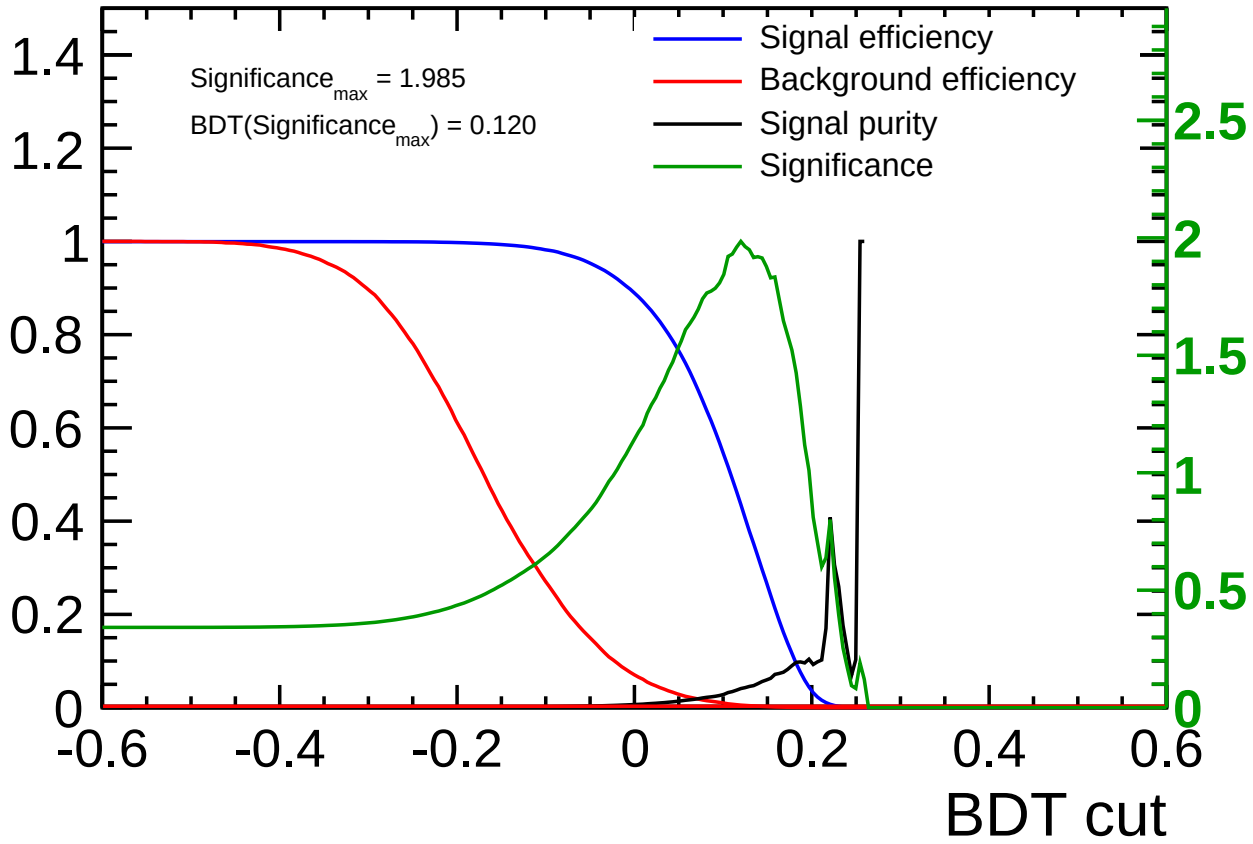


Boosted Decision Tree (BDT) Training



- Use TMVA for classification
- Adaptive boosting using 400 trees gives best results

BDT Classification (Quark Channel)



- Best significance: 1.985
- $\delta(\sigma \times BR) : 50\%$
- Signal efficiency: 23.5 %

Selected Events (Quark Channel)

Process	Events* in 1.5 ab^{-1}	Events after pre-sel.	Events after BDT
$H \to Z\gamma \to q\bar{q}\gamma$	409†	221 (54.0 %)	96 (23.5 %)
$H \to Z\gamma \to l^+l^-\gamma$	21†	2 (9.2 %)	0 (0.6 %)
$H \to \gamma\gamma$	834†	2 (0.2 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}q\bar{q}\gamma$	55k	10k (19.2 %)	986 (1.8 %)
$e^+e^- \to \nu\bar{\nu}q\bar{q}$	183k	20k (10.8 %)	995 (0.5 %)
$e^+e^- \to q\bar{q}$	6M†	34k (0.6 %)	0 (0 %)
$e^+e^- \to q\bar{q}q\bar{q}$	2M†	18k (0.9 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}l^+l^-\gamma$	13k	408 (3.1 %)	3 (∼0 %)
$e^+e^- \to \nu\bar{\nu}l^+l^-$	35k	790 (2.3 %)	2 (∼0 %)
$e^+e^- \to l^+l^-l^+l^-$	127k	3k (2.4 %)	6 (∼ 0 %)
$e^+e^- \to q\bar{q}l^+l^-\gamma$	27k	1k (4.3 %)	3 (∼0 %)
$e^+e^- \to q\bar{q}l^+l^-$	143k	9k (6.6 %)	27 (∼0 %)
$e^{\pm}\gamma \to e^{\pm}q\bar{q}\nu\bar{\nu}$ (BS+EPA)	8k	641 (8.0 %)	28 (0.4 %)
$e^{\pm}\gamma \to e^{\pm}q\bar{q}\gamma$ (BS+EPA)	291k	20k (6.8 %)	38 (∼0 %)
$e^{\pm}\gamma \to e^{\pm}q\bar{q}$ (BS+EPA)	2.7M‡	180k (6.6 %)	153 (∼0 %)
$e^{\pm}\gamma \to e^{\pm}q\bar{q}q\bar{q}$ (BS+EPA)	4.8M	85k (1.8 %)	17 (∼0 %)
$e^{\pm}\gamma \to e^{\pm}l^+l^-$ (BS+EPA)	2.7$M^{\ddagger}$	29K (1.1 %)	0 (0 %)
$e^{\pm}\gamma \to e^{\pm}l^+l^-\gamma$ (BS+EPA)	300k	5k (1.7 %)	0 (0 %)
$e^{\pm}\gamma \to e^{\pm}q\bar{q}l^+l^-$ (BS+EPA)	4k	- (-)	- (-)

*after generator level cuts

†w/o generator level cuts

‡additional cuts during generation $E_{l,q} > 10\,\text{GeV}$, $8^\circ < \theta_{l,q} < 172^\circ$

Summary & Outlook

- **Results at 1.4 TeV using unpolarised beams**
  - $H \to \gamma\gamma$ results
    - Significance 6.8
    - $\delta(\sigma \times \mathrm{B}R) : 14.7\%$
  - $H \to Z\gamma$ (combined) results
    - Significance 2.1
    - $\delta(\sigma \times \mathrm{B}R) : 47.1\%$
    - Update as soon as all backgrounds are available

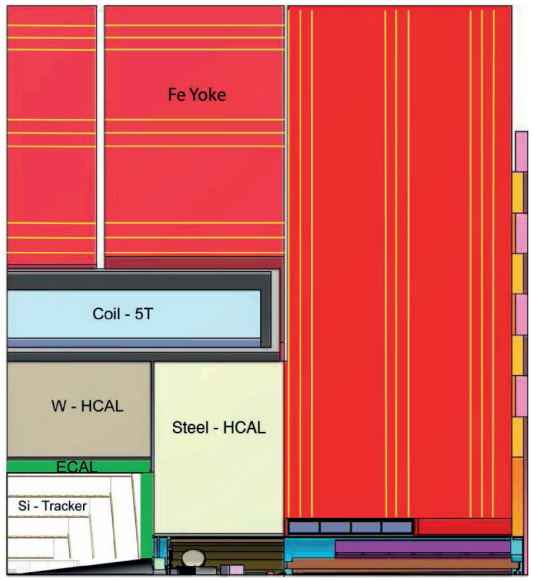
Summary & Outlook

- **Results at 1.4 TeV using unpolarised beams**
  - $H \to \gamma\gamma$ results
    - Significance 6.8
    - $\delta(\sigma \times BR) : 14.7\%$
  - $H \to Z\gamma$ (combined) results
    - Significance 2.1
    - $\delta(\sigma \times BR) : 47.1\%$
    - Update as soon as all backgrounds are available
- **Polarisation**
  - 80 % polarisation of electron beam at 1.4 TeV
  - Signal cross section increases by 80 %
  - Background cross sections increase at most by 80 %
  - Significance increases at least by $\sqrt{1.8}$
    - $\delta(\sigma \times BR_{H\to\gamma\gamma}) \leq 11\%$
    - $\delta(\sigma \times BR_{H\to Z\gamma}) \leq 35\%$
- **Outlook 3 TeV**
  - Cross section of W^+W^--fusion increases by 70 % with respect to 1.4 TeV
  - Expect further decrease of $\delta(\sigma \times BR)$

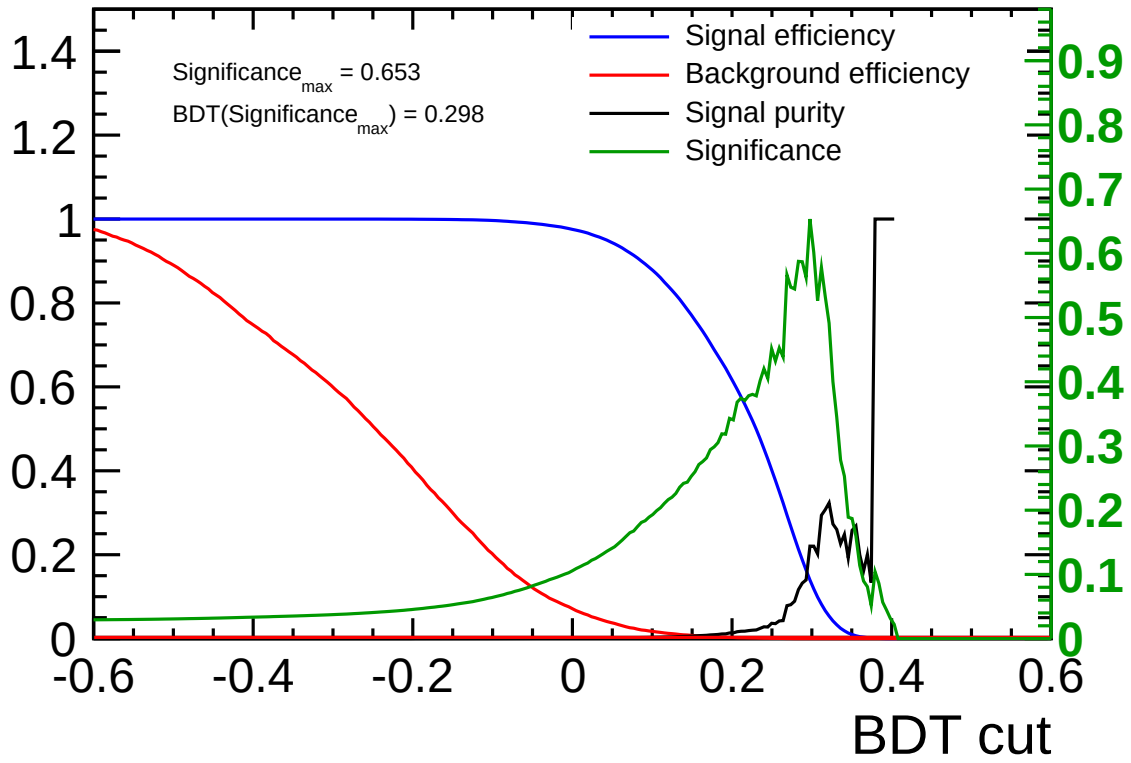
Backup

Detector Simulation and Reconstruction - Details

- Full **CLIC_SiD** detector simulation of signal and background events
  - Assuming $M_H = 126\,\text{GeV}$
  - Event generation with WHIZARD v.1.95, including ISR and CLIC BS
  - Fragmentation using PYTHIA
  - Full simulation with SLIC v.2.9.8 in CLIC_SID_CDR using GEANT4 v.9.3.2
  - Overlay of $\gamma\gamma \to$ hadrons background before digitization
  - Digitization and track reconstruction using `org.lcsim`
  - Particle flow reconstruction and particle identification using PANDORAPFA



BDT Classification (Muon Channel)



- Best significance is 0.653 $\rightarrow$ uncertainty of $\sigma \cdot \mathrm{BR} = 153\,\%$
- BDT signal efficiency: 13 %, 2 events of 14 events after pre-sel.
- BDT bkg. efficiency: 0.003 %, 7 events of 228970 events after pre-sel.

Selected Events (Muon Channel)

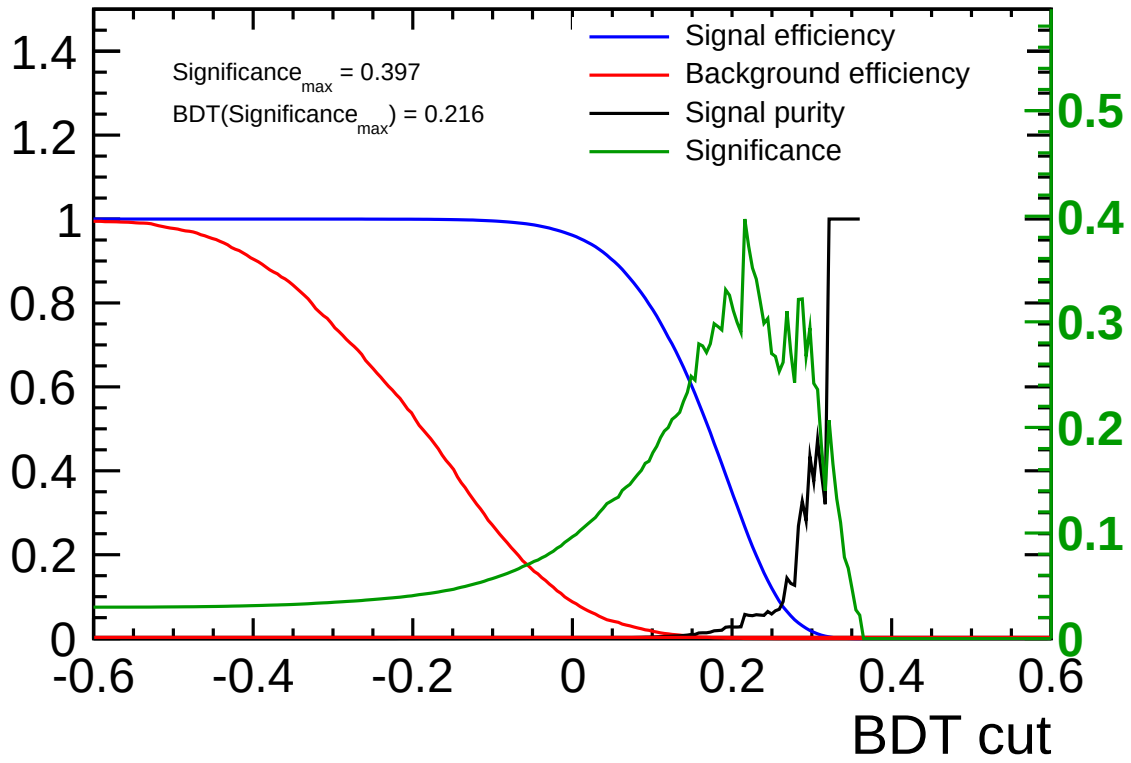
Process	Events* in 1.5 ab^{-1}	Events after pre-sel.	Events after BDT
$H \to l^+l^-\gamma$	21†	14 (66 %)	2 (9.2 %)
$H \to q\bar{q}\gamma$	409†	0 (0 %)	0 (0 %)
$H \to \gamma\gamma$	834†	0 (0 %)	0 (0 %)
$ee \to \nu\bar{\nu}q\bar{q}\gamma$	55k	2 (∼0 %)	0 (0 %)
$ee \to \nu\bar{\nu}q\bar{q}$	183k	7 (∼0 %)	0 (0 %)
$ee \to q\bar{q}$	6M†	531 (∼0 %)	0 (0 %)
$ee \to q\bar{q}q\bar{q}$	2M†	127 (∼0 %)	0 (0 %)
$ee \to \nu\bar{\nu}l^+l^-\gamma$	13k	604 (4.6 %)	5 (∼0 %)
$ee \to \nu\bar{\nu}l^+l^-$	35k	529 (1.5 %)	0 (0 %)
$ee \to l^+l^-l^+l^-$	127k	3981 (3.1 %)	2 (∼0 %)
$ee \to q\bar{q}l^+l^-\gamma$	27k	219 (0.8 %)	0 (0 %)
$ee \to q\bar{q}l^+l^-$	143k	160 (0.1 %)	0 (0 %)
$e^\pm\gamma \to e^\pm q\bar{q}$ (BS+EPA)	2.7M‡	0 (0 %)	0 (0 %)
$e^\pm\gamma \to e^\pm q\bar{q}q\bar{q}$ (BS+EPA)	4.3M	23 (∼0 %)	0 (0 %)
$e^\pm\gamma \to e^\pm l^+l^-$ (BS+EPA)	2.7M‡	200k (7.4 %)	0 (0 %)
$e^\pm\gamma \to e^\pm q\bar{q}\nu\bar{\nu}$ (BS+EPA)	7940	1 (∼0 %)	0 (0 %)
$e^\pm\gamma \to e^\pm l^+l^-\gamma$ (BS+EPA)	302k	23k (7.1 %)	0 (0 %)
$e^\pm\gamma \to e^\pm q\bar{q}\gamma$ (BS+EPA)	292k	23 (∼0 %)	0 (0 %)
$e^\pm\gamma \to eq\bar{q}l^+l^-$ (BS+EPA)	4k	- (-)	- (-)

*after generator level cuts

†w/o generator level cuts

‡additional cuts during generation $E_{l,q} > 10\,\text{GeV}$, $8^\circ < \theta_{l,q} < 172^\circ$

BDT Classification (Electron Channel)



- Best significance is 0.397 $\rightarrow$ uncertainty of $\sigma \cdot \mathrm{BR} = 252\,\%$
- BDT signal efficiency: 26 %, 3 events of 10 events after pre-sel.
- BDT bkg. efficiency: 0.04 %, 45 events of 119287 events after pre-sel.

Selected Events (Electron Channel)

Process	Events* in 1.5 ab^{-1}	Events after pre-sel.	Events after BDT
$H \to l^+l^-\gamma$	21†	10 (48.9 %)	3 (13 %)
$H \to q\bar{q}\gamma$	409†	0 (0 %)	0 (0 %)
$H \to \gamma\gamma$	834†	1 (0.1 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}q\bar{q}\gamma$	55k	11 (∼0 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}q\bar{q}$	183k	16 (∼0 %)	0 (0 %)
$e^+e^- \to q\bar{q}$	6M†	3427 (0.1 %)	0 (0 %)
$e^+e^- \to q\bar{q}q\bar{q}$	2M†	2332 (0.1 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}l^+l^-\gamma$	13k	1279 (9.8 %)	13 (0.1 %)
$e^+e^- \to \nu\bar{\nu}l^+l^-$	35k	2680 (7.7 %)	13 (∼0 %)
$e^+e^- \to l^+l^-l^+l^-$	127k	3664 (2.9 %)	4 (∼0 %)
$e^+e^- \to q\bar{q}l^+l^-\gamma$	27k	209 (0.8 %)	0 (0 %)
$e^+e^- \to q\bar{q}l^+l^-$	143k	743 (0.5 %)	1 (∼0 %)
$e^\pm\gamma \to e^\pm q\bar{q}$ (BS+EPA)	2.7M‡	10k (0.3 %)	0 (0 %)
$e^\pm\gamma \to e^\pm q\bar{q}q\bar{q}$ (BS+EPA)	4.3M	2616 (0.1 %)	0 (0 %)
$e^\pm\gamma \to e^\pm l^+l^-$ (BS+EPA)	2.7M‡	74k (2.7 %)	0 (0 %)
$e^\pm\gamma \to e^\pm q\bar{q}\nu\bar{\nu}$ (BS+EPA)	7940	22 (1.1 %)	0 (0 %)
$e^\pm\gamma \to e^\pm l^+l^-\gamma$ (BS+EPA)	302k	16k (5.3 %)	10 (∼0 %)
$e^\pm\gamma \to e^\pm q\bar{q}\gamma$ (BS+EPA)	292k	1517 (0.5 %)	0 (0 %)
$e^\pm\gamma \to eq\bar{q}l^+l^-$ (BS+EPA)	4k	- (-)	- (-)

*after generator level cuts

†w/o generator level cuts

‡additional cuts during generation $E_{l,q} > 10\,\text{GeV}$, $8^\circ < \theta_{l,q} < 172^\circ$