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

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CLIC Detector and Physics Collaboration Meeting

1. October 2013

Outline

1. Introduction
2. H $\rightarrow \gamma\gamma$
3. H $\rightarrow$ Zγ
4. Summary and Outlook

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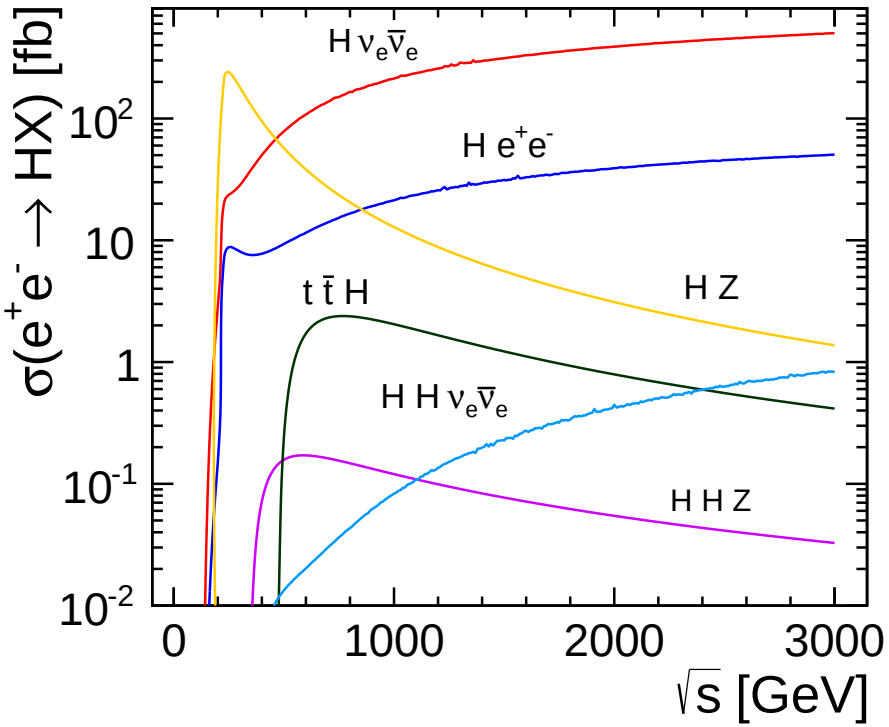
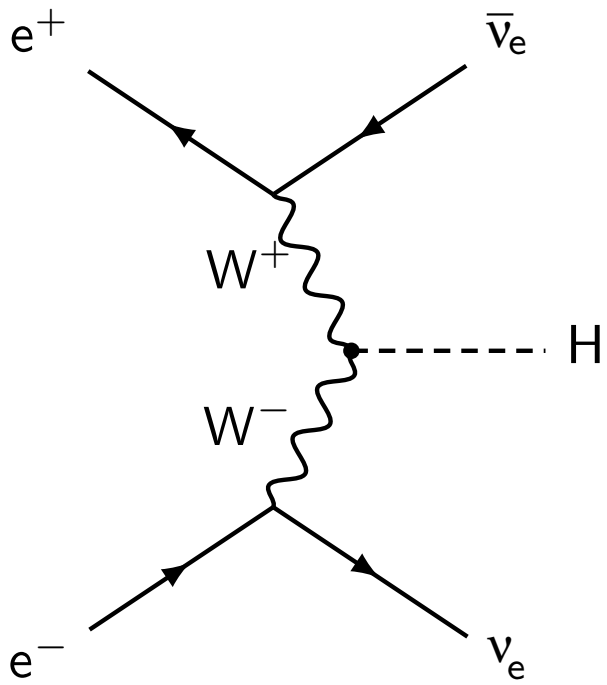
2. H → γγ
3. H → Zγ
4. Summary and Outlook

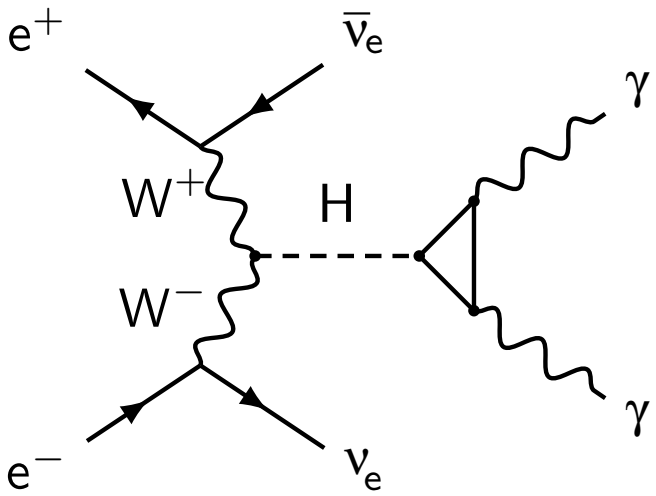
Higgs Production at $\sqrt{s} = 1.4\,\mathrm{TeV}$



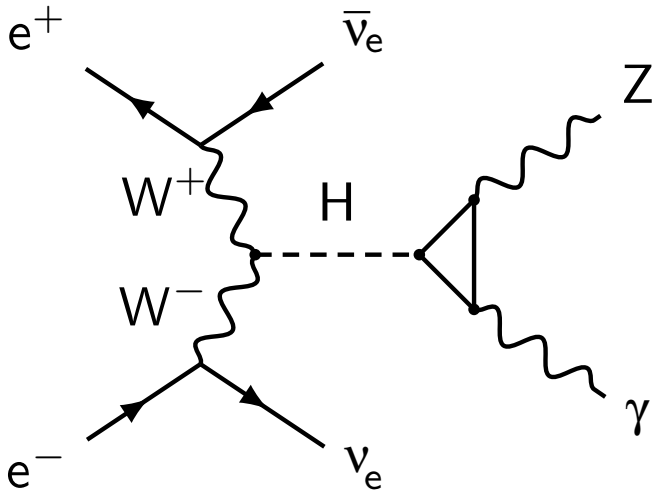


- Assuming $m_{\mathrm{H}} = 126\,\mathrm{GeV}$
- Using WHIZARD v.1.95, including ISR and CLIC BS
- $\sigma(\mathrm{e^+e^-} \to \mathrm{H}\nu\bar{\nu}) \approx 244\,\mathrm{fb}$ for $\sqrt{s} = 1.4\,\mathrm{TeV}$

Signal Processes



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



- $BR_{H\to Z\gamma} \approx 0.16\% \Rightarrow \sigma \times BR \approx 0.39\,\mathrm{fb}$
- $BR_{Z\to q\bar{q}} \approx 70\,\% \to N_{signal}(Z \to q\bar{q}) \approx 409/1.5\,\mathrm{ab}^{-1}$
- $BR_{Z\to e^+e^-} \approx 3.4\,\% \to N_{signal}(Z^0 \to e^+e^-) \approx 21/1.5\,\mathrm{ab}^{-1}$
- $BR_{Z\to \mu^+\mu^-} \approx 3.4\,\% \to N_{signal}(Z^0 \to \mu^+\mu^-) \approx 21/1.5\,\mathrm{ab}^{-1}$
- 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

Outline

1 Introduction

2 H → γγ

3 H → Zγ

4 Summary and Outlook

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

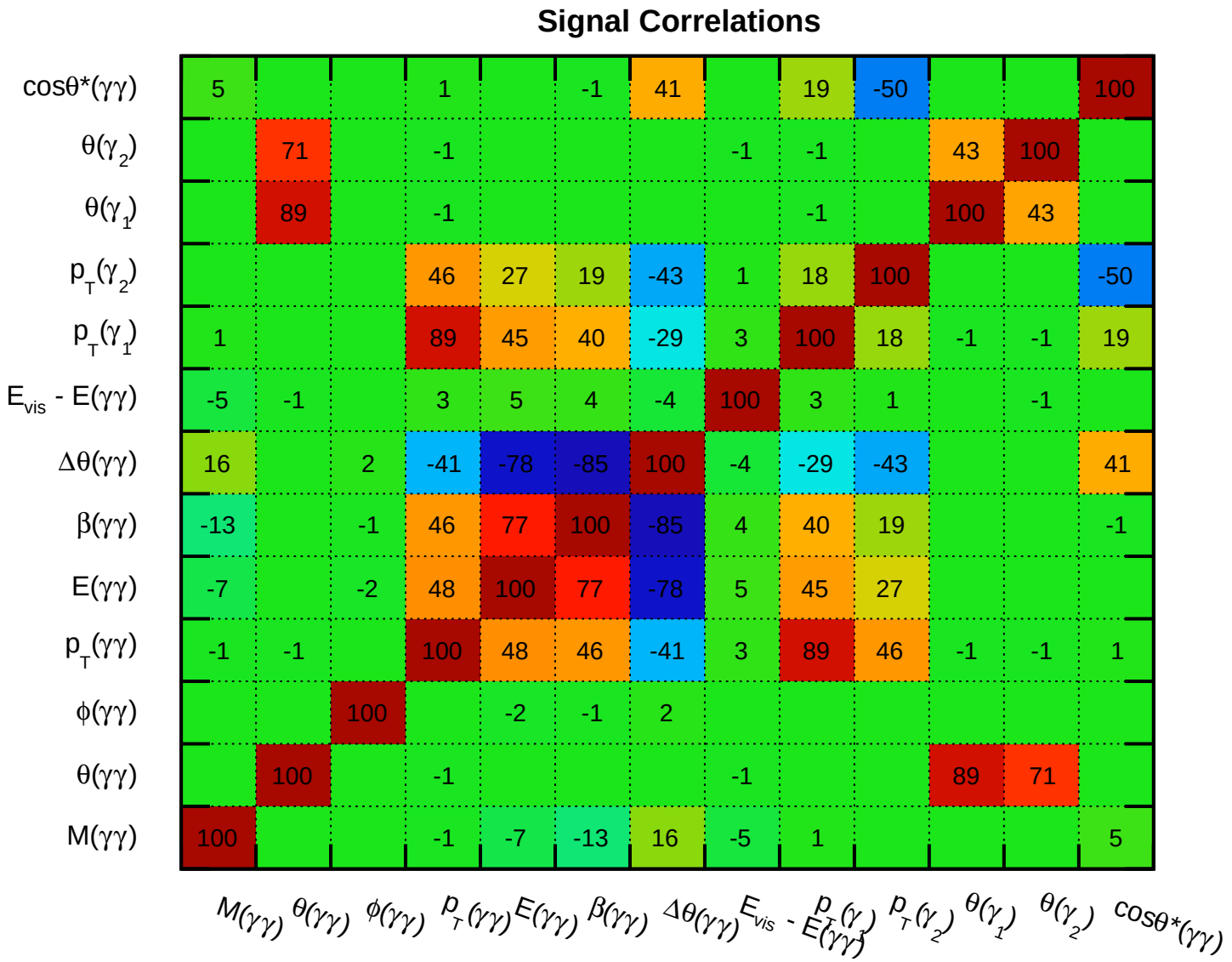
Process	σ[fb][1]	Events in $1.5\,\mathrm{ab}^{-1}$	Events Available[2]	Event Weights
$e^+e^- \to \nu\bar{\nu}\gamma$	30	44000	90000	0.5
$e^+e^- \to \nu\bar{\nu}\gamma\gamma$	17	26000	25000	1.1
$e^+e^- \to \gamma\gamma$	27	41000	42000	1.0
$e^+e^- \to e^+e^-\gamma$	290	430000	280000	1.5
$e^+e^- \to e^+e^-\gamma\gamma$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

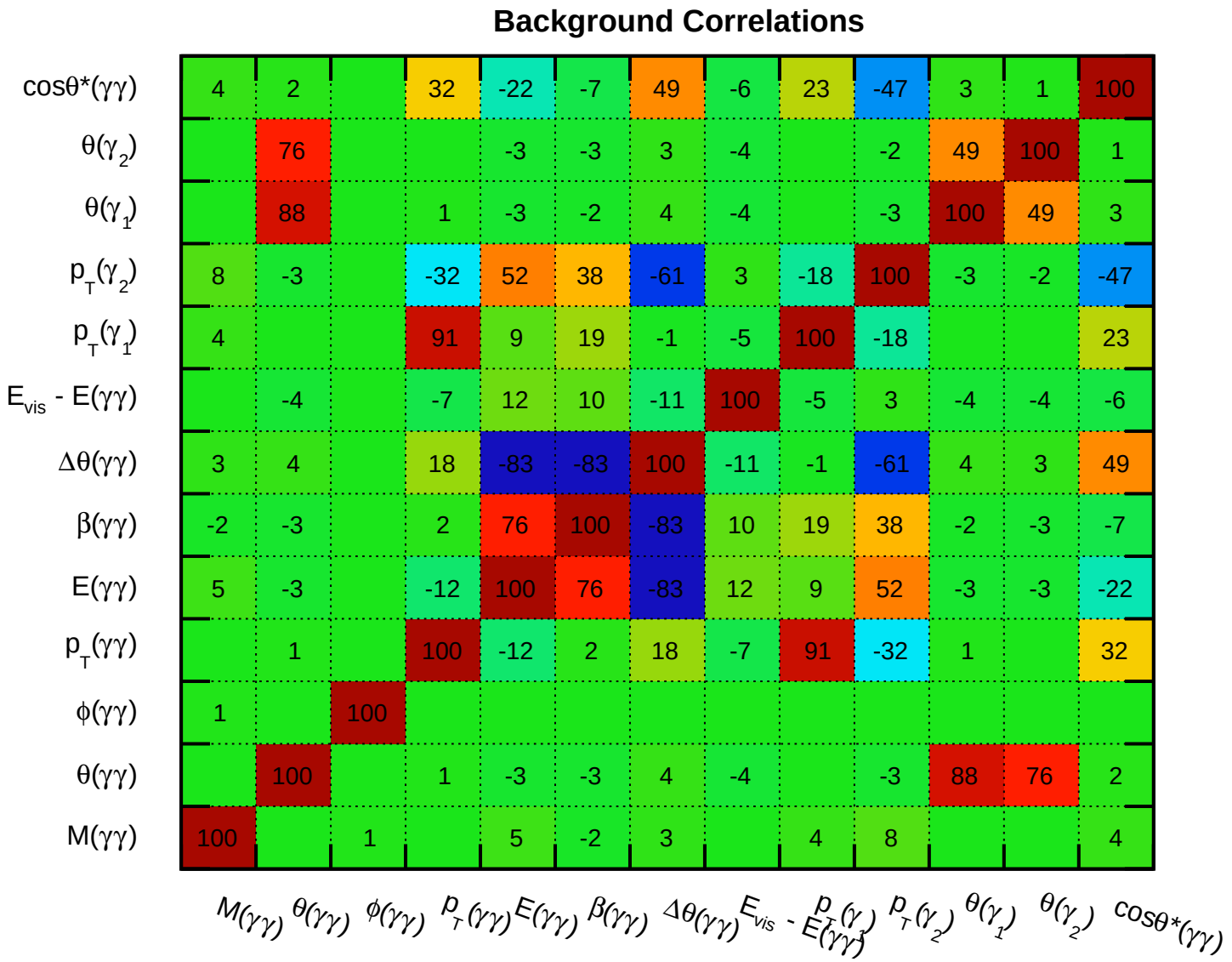
Kinematic Variables

- 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: $\cos\theta^*$

Variable Correlations: Signal

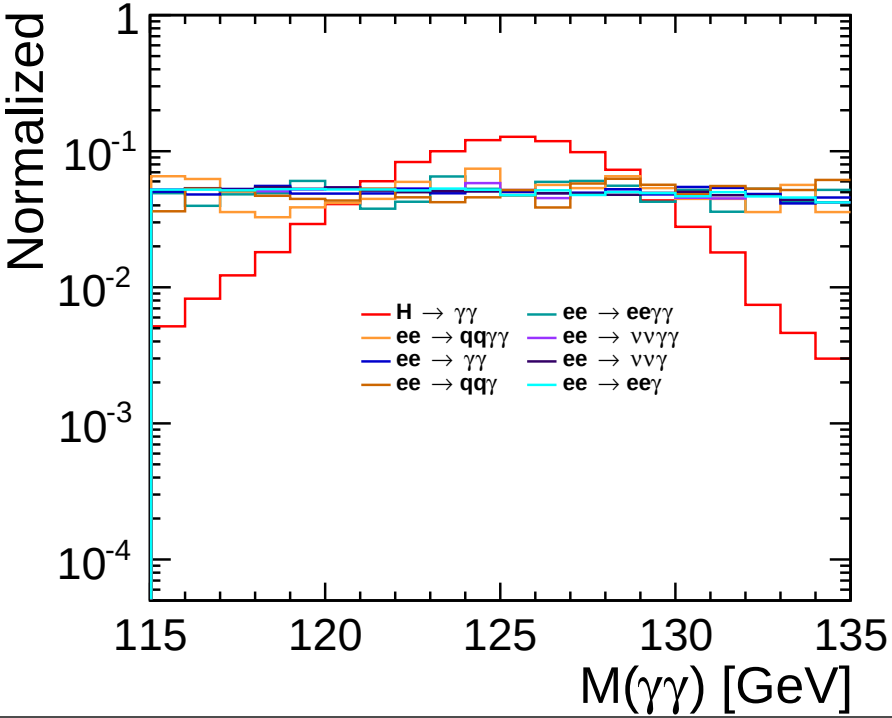


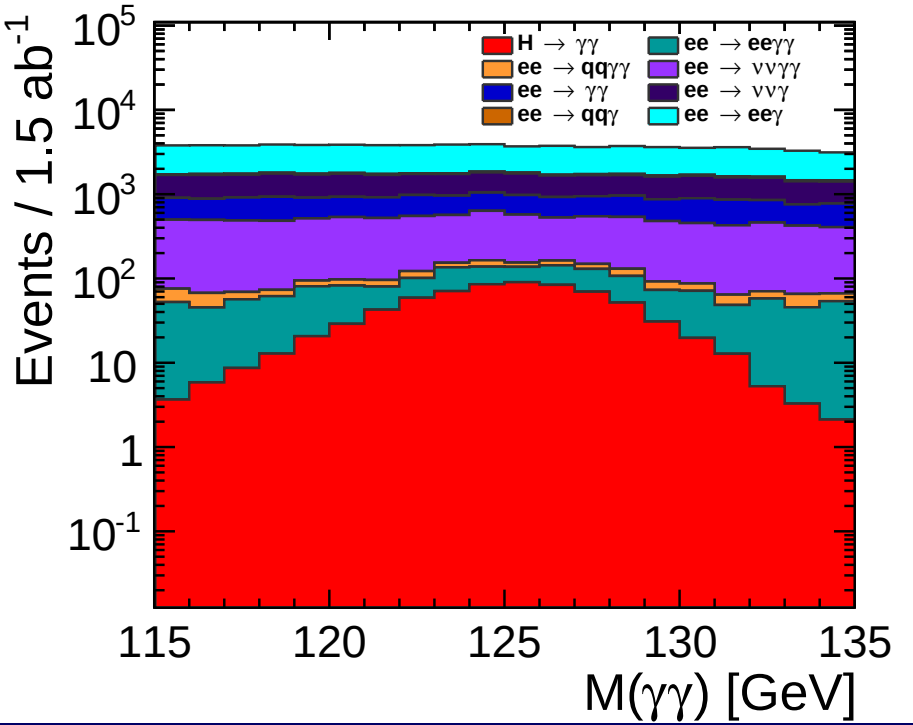
Variable Correlations: Background



Pre-Selection

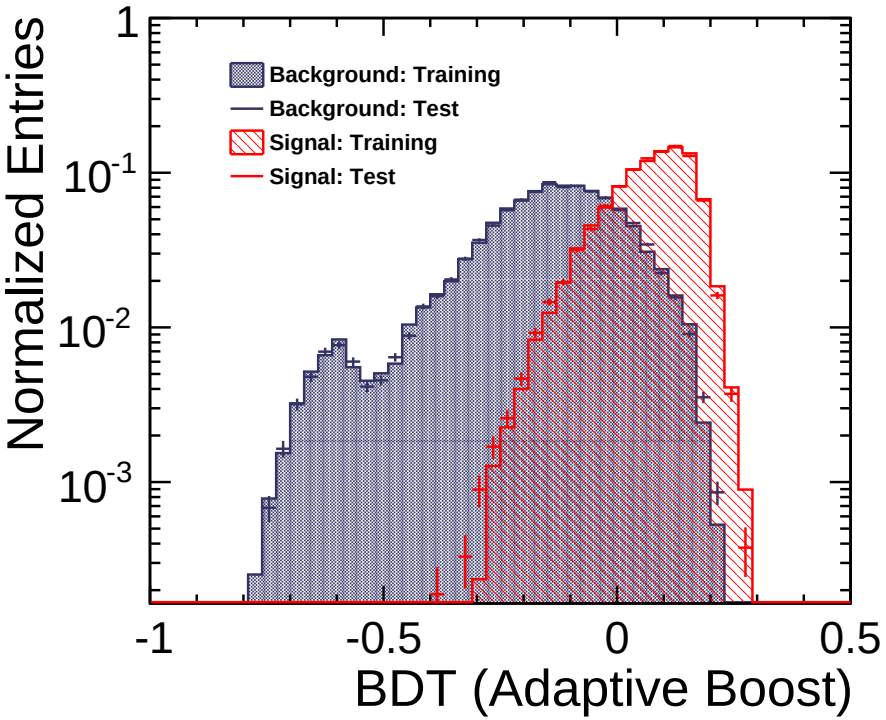
- Use only PFOs that pass the default time selection cuts (reject out-of-time pair backgrounds)
- Use only reconstructed photons with $E > 15\,\mathrm{GeV}$ and $p_\mathrm{T} > 10\,\mathrm{GeV}$
- Select two highest energy photons with $115\,\mathrm{GeV} < M(\gamma\gamma) < 135\,\mathrm{GeV}$ as Higgs 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: $p_\mathrm{T}(\gamma_1) > 40\,\mathrm{GeV}$

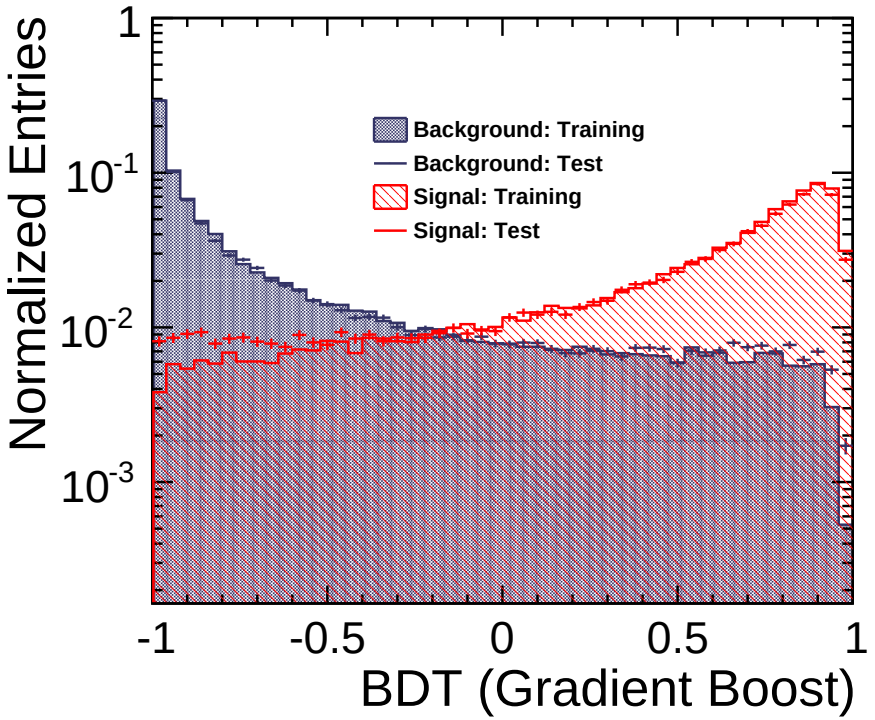




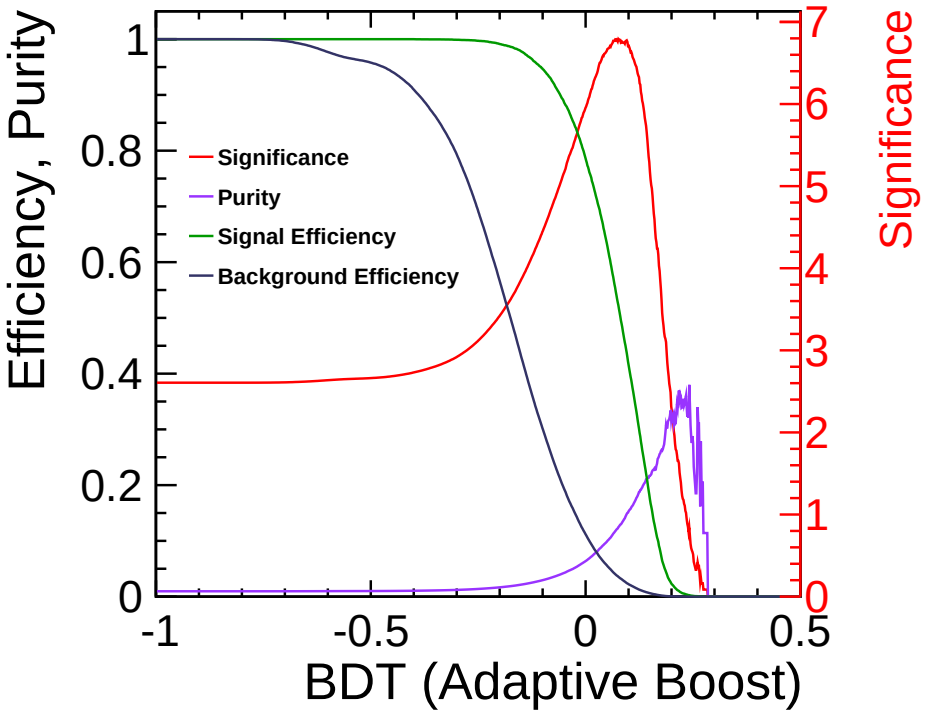
Boosted Decision Tree (BDT) Training

- Use TMVA for classification
- Adaptive boosting using 400 trees
- Gradient boosting using 200 trees (performance degrades for 150 or 300 trees)

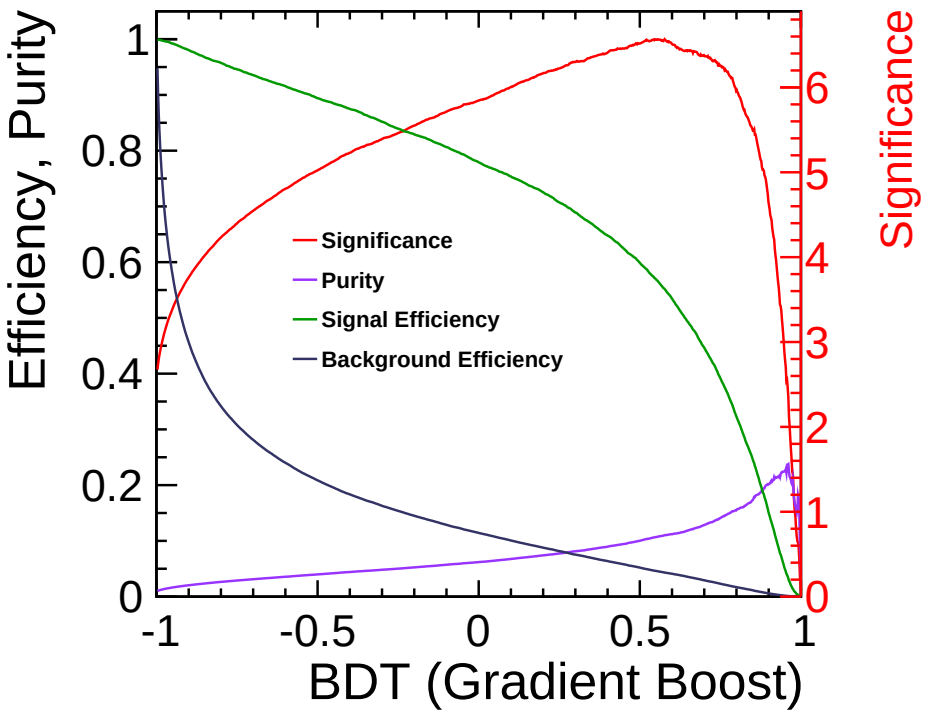




BDT Performance



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



- Best significance: 6.6
- $\delta(\sigma \times BR)$: 15.2%
- Signal efficiency: 46.8%

Selected Events

Process	σ[fb][3]	Events in $1.50\,\mathrm{ab}^{-1}$ StdHep Cuts	Pre-Selection	BDT	BDTG
$H \to \gamma\gamma$	0.56	834	708 (85%)	367 (44%)	390 (47%)
$e^+e^- \to \nu\bar{\nu}\gamma$	30	44250	15130 (34%)	1338 (3%)	1606 (3.6%)
$e^+e^- \to \nu\bar{\nu}\gamma\gamma$	17	25988	8066 (31%)	802 (3.1%)	982 (3.8%)
$e^+e^- \to \gamma\gamma$	27	40830	8069 (20%)	73 (0.18%)	89 (0.22%)
$e^+e^- \to e^+e^-\gamma$	290	433465	39717 (9.2%)	341 (0.079%)	452 (0.1%)
$e^+e^- \to e^+e^-\gamma\gamma$	13	18919	993 (5.2%)	4 (0.025%)	4 (0.025%)
$e^+e^- \to q\bar{q}\gamma$	67	100524	825 (0.82%)	1 (0.002%)	2 (0.003%)
$e^+e^- \to q\bar{q}\gamma\gamma$	17	24848	353 (1.4%)	4 (0.017%)	6 (0.025%)

[3] after StdHp cuts, except for signal sample

Outline

1 Introduction

2 H → γγ

3 H → Zγ

4 Summary and Outlook

Generator Level Cuts

- Event must contain at least
  - two charged leptons **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 $100 < M(Z^0\gamma) < 150\,\text{GeV}$

Relevant Background Processes (e^+e^-)

Process (- ISR)	σ[fb][4]	Events in 1.5 ab^{-1}	Events Available	Event Weights
$e^+e^- \to \nu\bar{\nu}q\bar{q}\gamma$	155.5	185000	17000	10.8
$e^+e^- \to \nu\bar{\nu}q\bar{q}$	121.8	183000	163000	1.1
$e^+e^- \to q\bar{q}$	4009[5]	6013000	702000	8.6
$e^+e^- \to q\bar{q}q\bar{q}$	1328[2]	1992000	251000	7.9
$e^+e^- \to \nu\bar{\nu}l^+l^-\gamma$	35	53000	18000	2.9
$e^+e^- \to \nu\bar{\nu}l^+l^-$	23	35000	38000	0.9
$e^+e^- \to l^+l^-l^+l^-$	85	128000	134000	0.95
$e^+e^- \to q\bar{q}l^+l^-\gamma$	18.2	27000	39000	0.7
$e^+e^- \to q\bar{q}l^+l^-$	95	143000	1800000	0.1
$e^+e^- \to \nu\bar{\nu}H \to \nu\bar{\nu}\gamma\gamma$	0.56	842	53500	0.016

- e^+e^- background processes are complete, but some have large weights
- $\gamma\gamma$ initial state processes are not relevant for this analysis

[4] after generator level cuts
[5] w/o generator level cuts

Relevant Background Processes ($e\gamma$)

Process (- ISR)	σ[fb]	Events in 1.125 ab^{-1}	Events Available	Event Weights
γ from BS				
$e^+\gamma \to e^+q\bar{q}\gamma$	–	–	–	–
$e^+\gamma \to e^+q\bar{q}$	38313	42000000	483000	87
$e^+\gamma \to e^+q\bar{q}q\bar{q}$	1160	1306000	397000	3.3
$e^+\gamma \to e^+q\bar{q}\nu\bar{\nu}$	–	–	–	–
$e^+\gamma \to e^+l^+l^-\gamma$	–	–	–	–
$e^+\gamma \to e^+l^+l^-$	–	–	–	–
$e^+\gamma \to e^+l^+l^-q\bar{q}$	–	–	–	–
Process (- ISR)	σ[fb]	Events in 1.5 ab^{-1}	Events Available	Event Weights
γ from EPA				
$e^+\gamma \to e^+q\bar{q}\gamma$	–	–	–	–
$e^+\gamma \to e^+q\bar{q}$	16154	24200000	490000	49
$e^+\gamma \to e^+q\bar{q}q\bar{q}$	287	430000	404000	1.1
$e^+\gamma \to e^+q\bar{q}\nu\bar{\nu}$	–	–	–	–
$e^+\gamma \to e^+l^+l^-\gamma$	–	–	–	–
$e^+\gamma \to e^+l^+l^-$	–	–	–	–
$e^+\gamma \to e^+l^+l^-q\bar{q}$	–	–	–	–

- Similar processes from $e^-\gamma$ also taken into account

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

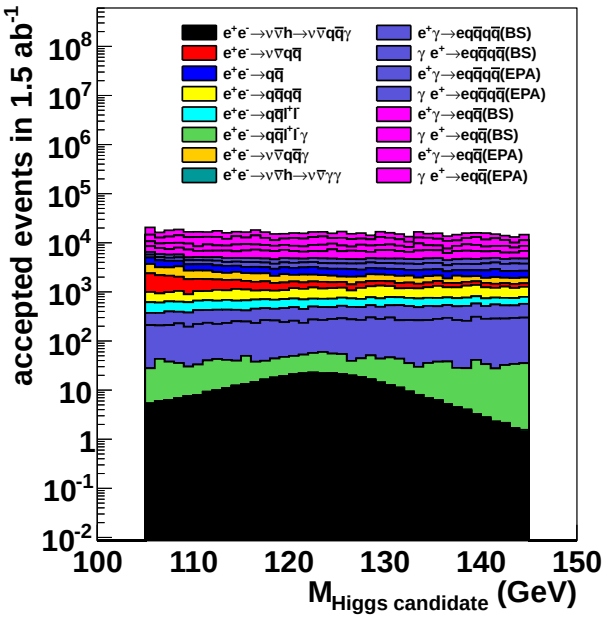
- First search for two muons, then for two electrons
- If there is no charged lepton pair, use available particles to form two jets (k_T algorithm, jet radius $R = 1.2$)
- Combine photon of highest energy and the charged lepton pair or the jet pair to Higgs candidate
- Select events in which the Higgs candidate has an invariant mass of $105 < M(Z^0\gamma) < 145\,\text{GeV}$

Discriminating Variables

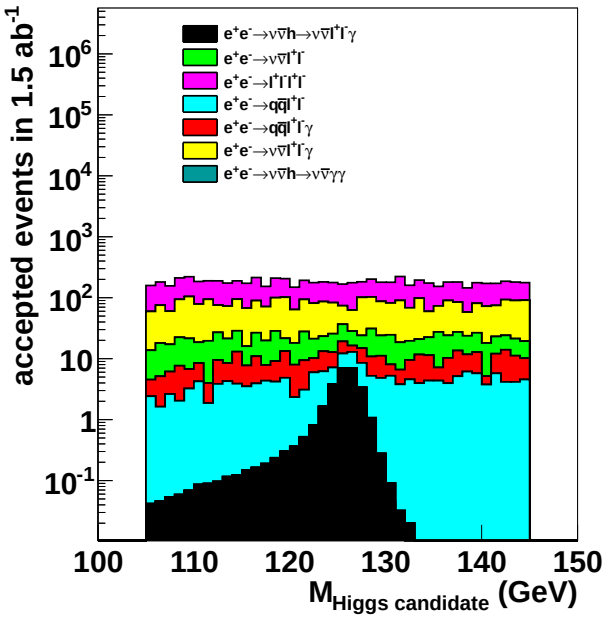
- Properties of H, Z^0 and γ
  - Mass m, velocity β, polar angle θ, transverse momentum p_{T}, energy E
  - $\sum \overrightarrow{p_{\mathrm{T}}}$ of H candidate daughters
- Event properties:
  - thrust, oblateness, sphericity, aplanarity of $\mathrm{l}^+\mathrm{l}^-$ $(\mathrm{q}\overline{\mathrm{q}})$ and γ
  - Missing energy $\not{E}$ of $\mathrm{l}^+\mathrm{l}^-$ $(\mathrm{q}\overline{\mathrm{q}})$ and γ
  - Missing transverse energy $\not{E}_{\mathrm{T}}$ of $\mathrm{l}^+\mathrm{l}^-$ $(\mathrm{q}\overline{\mathrm{q}})$ and γ
  - Visible energy excluding the reconstructed H candidate $E_{\mathrm{vis}} - E_H$
  - Particle multiplicity N
- Angle between Z^0 and γ
  - Angle between vectors of Z^0 and γ
  - $\Delta\theta$ between Z^0 and γ
  - $\Delta\varphi$ between Z^0 and γ
  - $\cos\theta^*$ in Higgs rest frame
- In quark case
  - Number of particles used to reconstruct Z^0
  - $y_{n,n+1}$ value associated with merging from n to $n+1$ jets, $n = 1, 2, 3, 4$

Invariant Mass Distribution (after Pre-Selection)

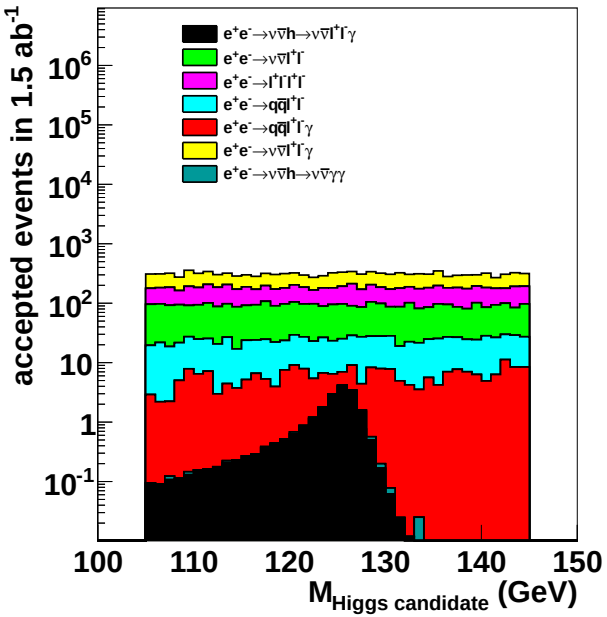
Jets



Muons

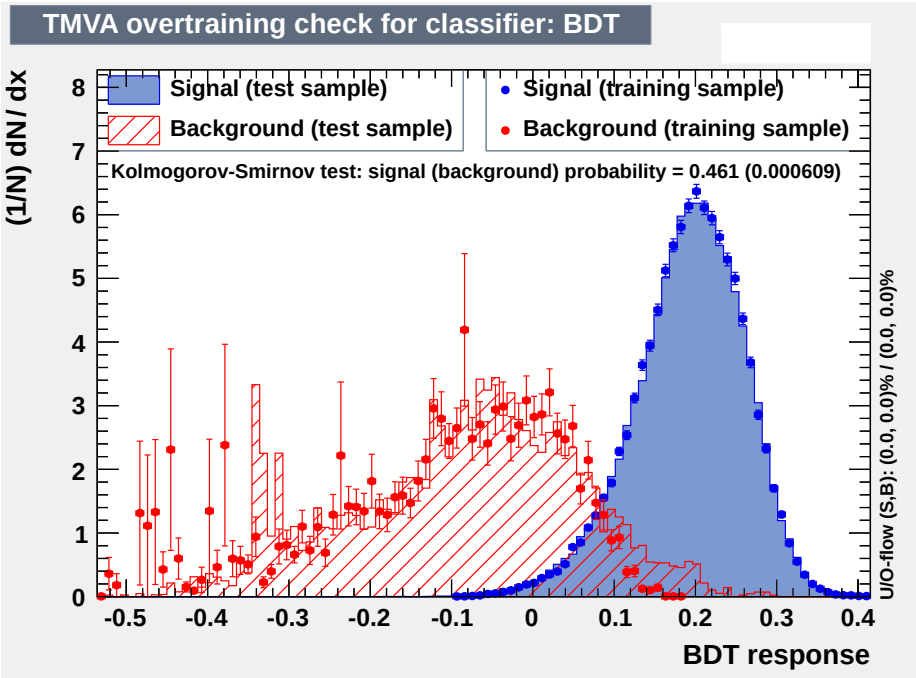


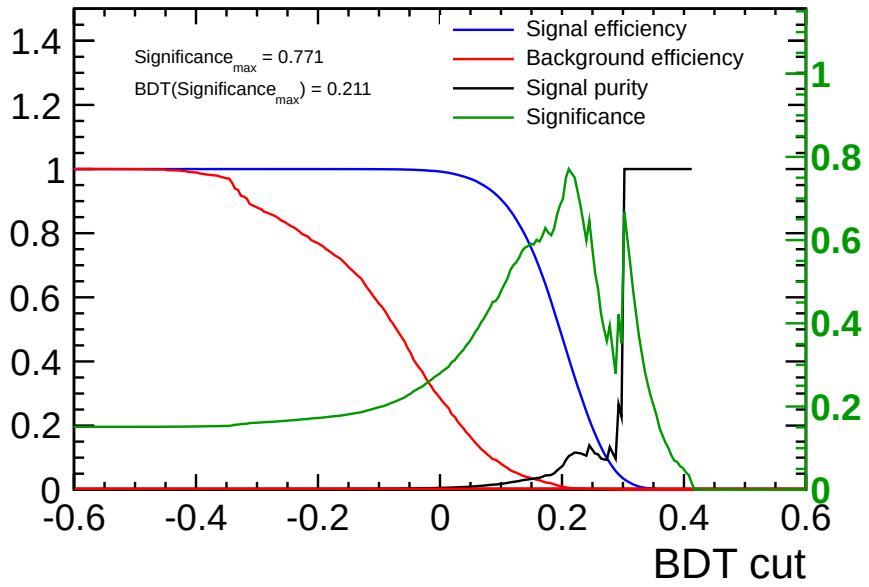
Electrons



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

BDT Classification (Muon Channel)





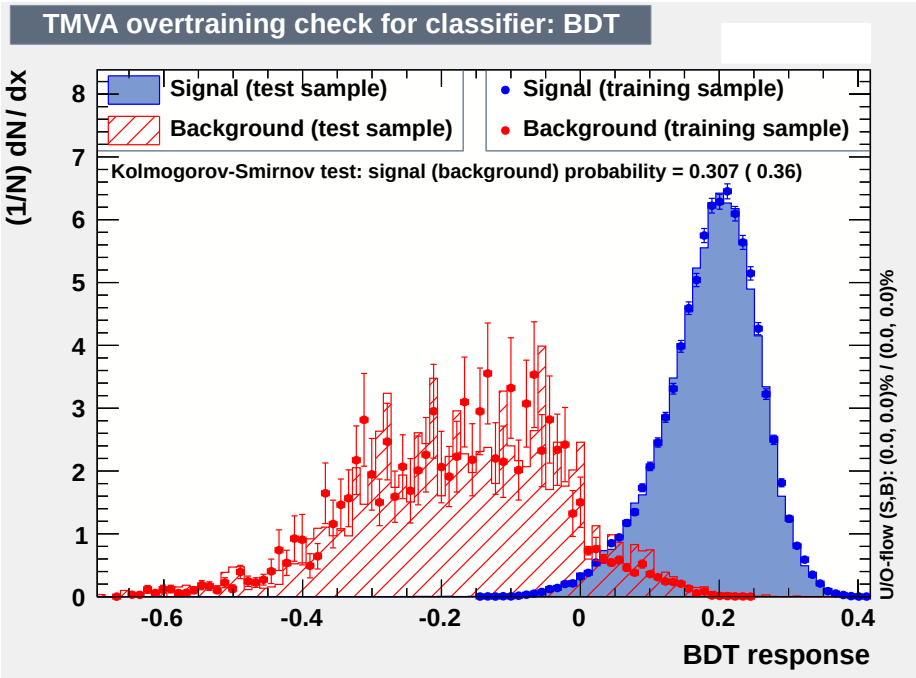
- Use half of the events for training and half for testing
- Best significance is 0.771 $\rightarrow$ uncertainty of $\sigma\cdot$BR = 129 %
- BDT signal efficiency: 43 %, 6 events of 14 events after pre-sel.
- BDT bkg. efficiency: 0.57 %, 48 events of 8370 events after pre-sel.

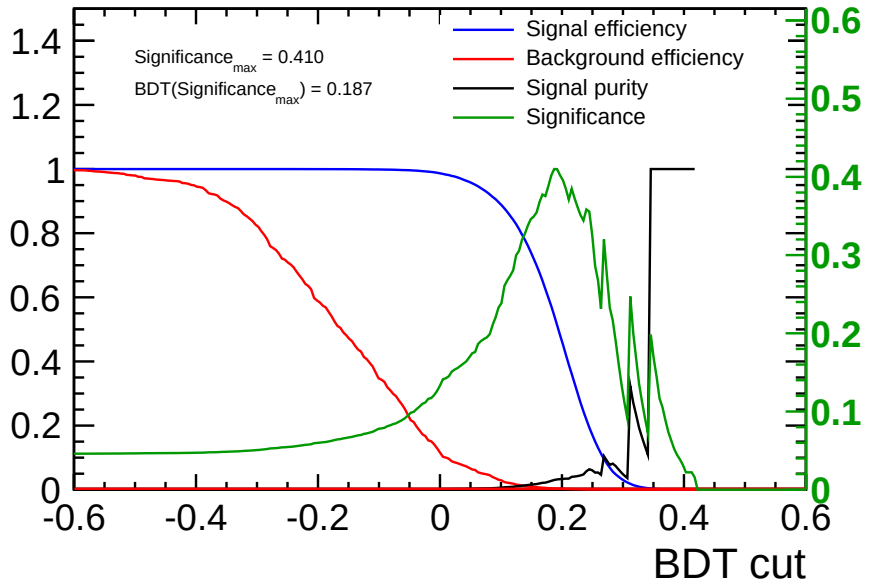
Selected Events (Muon Channel)

Process (- ISR)	Events in 1.5 ab^{-1}	Events after pre-sel.	Events after BDT
$e^+e^- \to H \to \mu\mu\gamma$	21	14 (67 %)	6 (28 %)
$e^+e^- \to H \to q\bar{q}\gamma$	409	0 (0 %)	0 (0 %)
$e^+e^- \to H \to \gamma\gamma$	842	0 (0 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}q\bar{q}\gamma$	185k	21 (0.001 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}q\bar{q}$	183k	7 (0.004 %)	0 (0 %)
$e^+e^- \to q\bar{q}$	6.0M	550 (0.008 %)	0 (0 %)
$e^+e^- \to q\bar{q}q\bar{q}$	1.9M	127 (0.007 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}l^+l^-\gamma$	52k	2.3k (4.5 %)	23 (0.04 %)
$e^+e^- \to \nu\bar{\nu}l^+l^-$	35k	530 (1.5 %)	14 (0.04 %)
$e^+e^- \to l^+l^-l^+l^-$	127k	3.9k (3.1 %)	10 (0.008 %)
$e^+e^- \to q\bar{q}l^+l^-\gamma$	27k	220 (0.8 %)	0 (0 %)
$e^+e^- \to q\bar{q}l^+l^-$	143k	160 (0.1 %)	1 (0.0001 %)
$\gamma e(\gamma e) \to eq\bar{q}$ (BS+EPA)	132M	392 (0 %)	0 (0 %)
$\gamma e(\gamma e) \to eq\bar{q}q\bar{q}$ (BS+EPA)	3.5M	28 (0 %)	0 (0 %)

- Includes only already simulated channels!

BDT Classification (Electron Channel)





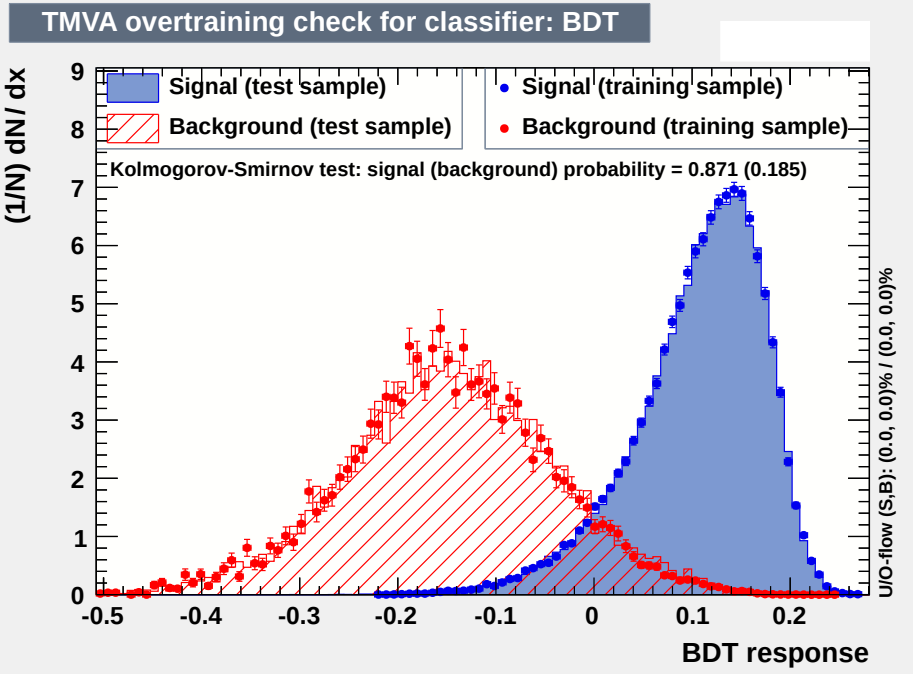
- Use half of the events for training and half for testing
- Best significance is 0.410 $\rightarrow$ uncertainty of $\sigma \cdot \mathrm{BR} = 244\,\%$
- BDT signal efficiency: 60 %, 6 events of 10 events after pre-sel.
- BDT bkg. efficiency: 0.36 %, 177 events of 49180 events after pre-sel.

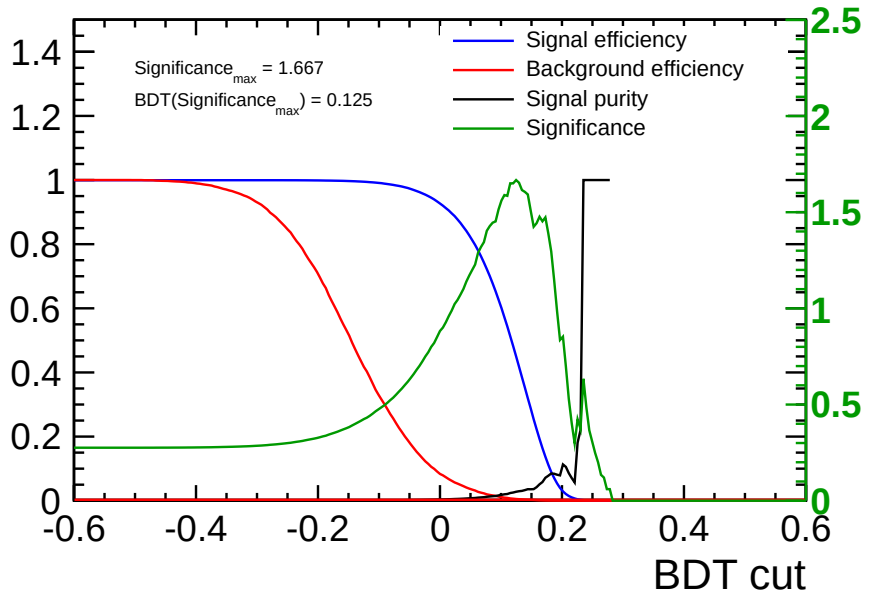
Selected Events (Electron Channel)

Process (- ISR)	Events in $1.5\,\text{ab}^{-1}$	Events after pre-sel.	Events after BDT
$e^+e^- \to H \to e^+e^-\gamma$	21	10 (48 %)	6 (28 %)
$e^+e^- \to H \to q\bar{q}\gamma$	409	0 (0 %)	0 (0 %)
$e^+e^- \to H \to \gamma\gamma$	842	1 (0.1 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}q\bar{q}\gamma$	185k	21 (0.001 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}q\bar{q}$	183k	16 (0.008 %)	0 (0 %)
$e^+e^- \to q\bar{q}$	6.0M	3.5k (0.06 %)	0 (0 %)
$e^+e^- \to q\bar{q}q\bar{q}$	1.9M	2.4k (0.1 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}l^+l^-\gamma$	52k	5.0k (9.5 %)	92 (0.2 %)
$e^+e^- \to \nu\bar{\nu}l^+l^-$	35k	2698 (7.7 %)	52 (0.01 %)
$e^+e^- \to l^+l^-l^+l^-$	127k	3.7k (2.9 %)	23 (0.02 %)
$e^+e^- \to q\bar{q}l^+l^-\gamma$	27k	214 (0.8 %)	7 (0.03 %)
$e^+e^- \to q\bar{q}l^+l^-$	143k	760 (0.5 %)	4 (0.005 %)
$\gamma e(\gamma e) \to eq\bar{q}$ (BS+EPA)	132M	28k (0.02 %)	0 (0 %)
$\gamma e(\gamma e) \to eq\bar{q}q\bar{q}$ (BS+EPA)	3.5M	2.6k (0.07 %)	0 (0 %)

- Includes only already simulated channels!

BDT Classification (Quark Channel)





- Use half of the events for training and half for testing
- Best significance is 1.667 $\rightarrow$ uncertainty of σ·BR = 60 %
- BDT signal efficiency: 45 %, 100 events of 220 events after pre-sel.
- BDT bkg. efficiency: 0.54 %, 3460 events of 641800 events after pre-sel.

Selected Events (Quark Channel)

Process (- ISR)	Events in $1.5\,ab^{-1}$	Events after pre-sel.	Events after BDT
$e^+e^- \to H \to q\bar{q}\gamma$	409	220 (51.2 %)	100 (24.5 %)
$e^+e^- \to H \to l^+l^-\gamma$	63	2 (3.2 %)	0 (0 %)
$e^+e^- \to H \to \gamma\gamma$	842	2 (0.2 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}q\bar{q}\gamma$	185k	26.3k (14.2 %)	1798 (1.0 %)
$e^+e^- \to \nu\bar{\nu}q\bar{q}$	183k	19.8k (10.8 %)	928 (0.5 %)
$e^+e^- \to q\bar{q}$	6.0M	34k (0.6 %)	51 (0.001 %)
$e^+e^- \to q\bar{q}q\bar{q}$	1.9M	18k (0.9 %)	0 (0 %)
$e^+e^- \to \nu\bar{\nu}l^+l^-\gamma$	52k	1.2k (2.3 %)	11 (0.02 %)
$e^+e^- \to \nu\bar{\nu}l^+l^-$	35k	790 (2.3 %)	11 (0.03 %)
$e^+e^- \to l^+l^-l^+l^-$	127k	3095 (2.4 %)	10 (0.008 %)
$e^+e^- \to q\bar{q}l^+l^-\gamma$	27k	1.1k (4.2 %)	6 (0.02 %)
$e^+e^- \to q\bar{q}l^+l^-$	143k	9.5k (6.6 %)	41 (0.02 %)
$\gamma e(\gamma e) \to eq\bar{q}$ (BS+EPA)	132M	441k (0.3 %)	536 (0.0003 %)
$\gamma e(\gamma e) \to eq\bar{q}q\bar{q}$ (BS+EPA)	3.5M	86k (2.5 %)	67 (0.002 %)

- Includes only already simulated channels!

Outline

1 Introduction

2 H → γγ

3 H → Zγ

4 Summary and Outlook

Summary (H $\rightarrow \gamma\gamma$)

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

Summary and Outlook (H → Zγ)

- $H \to q\bar{q}\gamma$ results
  - Significance 1.667
  - Overall signal efficiency 25 % (100/409)
- $H \to \mu\mu\gamma$ results
  - Significance 0.771
  - Overall signal efficiency 28 % (6/21)
- $H \to e^+e^-\gamma$ results
  - Significance 0.410
  - Overall signal efficiency 28 % (6/21)

- Most important background channels $e^+e^- \to \nu\bar{\nu}q\bar{q}\gamma$ and $e^+e^- \to l^+l^-q\bar{q}\gamma$ have high weights → Increase number of events
- Optimize TMVA settings further (cuts, variables, ...)