$H \rightarrow ZZ^*$@3TeV CLIC *revisited*

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Overview

- Motivation
- $H \rightarrow ZZ^{*} \rightarrow q\bar{q}e^{+}e^{-}(\mu^{+}\mu^{-})$
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  - Lepton isolation
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Motivation

- Why to come back to $H \to ZZ^*$ decays?
  - We intend to publish results from 1.4 TeV and 3 TeV CLIC done by our group ($H \to ZZ^* \to q\bar{q}ll$ ($l=e,\mu,\tau$)).
  - However, the person in charge for these analysis has left to industry and in order to publish the paper we had to *reproduce* the results.
  - *In addition, we wanted to consider cleaner $q\bar{q}e^+e^-(\mu^+\mu^-)$ channel*, as a starting point for the CPV measurement in the scalar-pseudoscalar (Higgs) mixing (*see the discussion by Ivanka*)

- Motivation for CPV is clear:
  - Almost all BSM theories with extended Higgs sector predict possible anomalous contribution and/or CP violation in the Higgs sector.

    Example: scalar h_0 and pseudoscalar A_0 in 2HDM.
  - If Higgs potential is not CP symmetric, the lightest mass eigenstate is their (CP even and CP odd) superposition.
  - We should look into it (my PhD topic) proposed by Philipp (Roloff)

Simulation details

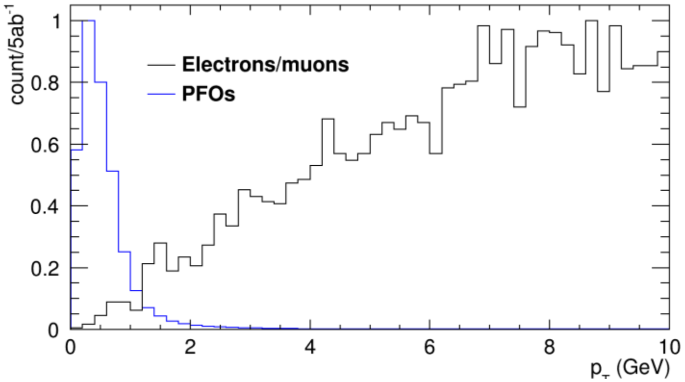
- Assuming m_H = 126 GeV, 5ab^{-1}
- Signal and background simulation: WHIZARD v1.95 (v57), including ISR and BS and realistic luminosity spectrum.
- Particle interaction with the CLIC_ILD detector is fully simulated.
- Hadronic background from BS is overlaid in the digitization phase.
- ILCSoft Version 2017-12-21.

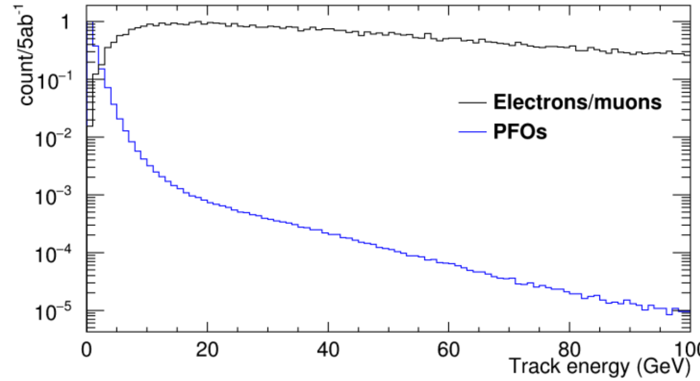
Signal and background processes

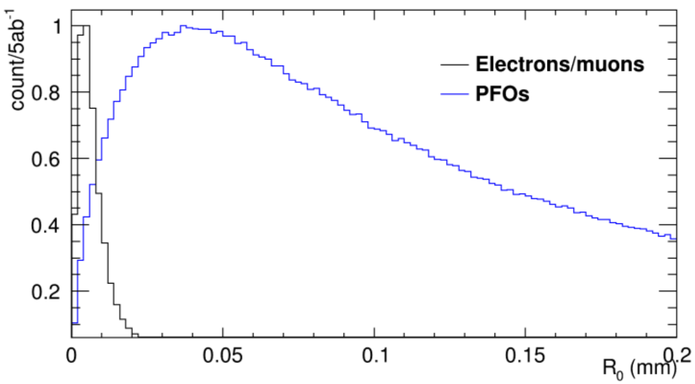
Process	σ(fb)	Expected events at 5 ab^{-1}	Events Simulated
$e^+e^- \rightarrow H\nu_e\bar{\nu}_e, H \rightarrow ZZ^*, ZZ^* \rightarrow q\bar{q}l^+l^-$, $(l = e, \mu)$	1.13	5650	22 618
$e^+e^- \rightarrow H\nu_e\bar{\nu}_e, H \rightarrow WW, WW \rightarrow q\bar{q}q\bar{q}$	43	215 000	219 005
$e^+e^- \rightarrow H\nu_e\bar{\nu}_e, H \rightarrow b\bar{b}$	233	1 165 000	1 065 894
$e^+e^- \rightarrow H\nu_e\bar{\nu}_e, H \rightarrow c\bar{c}$	11.7	58 500	51 798
$e^+e^- \rightarrow H\nu_e\bar{\nu}_e, H \rightarrow gg$	35.2	176 000	128 055
$e^+e^- \rightarrow H\nu_e\bar{\nu}_e, H \rightarrow others$	91	455 000	464 994
$e^+e^- \rightarrow q\bar{q}l^+l^-$	3319.6	16 598 000	423 850
$e^+e^- \rightarrow q\bar{q}l\nu$	5560.9	27 804 500	2 054 725
$e^+e^- \rightarrow q\bar{q}\bar{\nu}_e\nu_e$	1317.5	6 587 500	569 250
$\gamma\gamma \rightarrow q\bar{q}l^+l^-$	20293.4	135 724 500	1 032 075
$\gamma\gamma \rightarrow q\bar{q}$	112038.6	517 430 000	1 044 945
$e^\pm\gamma \rightarrow q\bar{q}e$	20661	60 284 000	462 023
$e^\pm\gamma \rightarrow q\bar{q}\nu$	36832.4	138 261 500	691 812

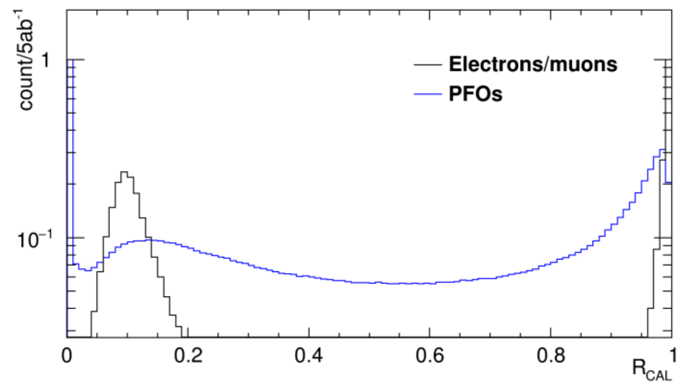
Lepton (e, μ) isolation

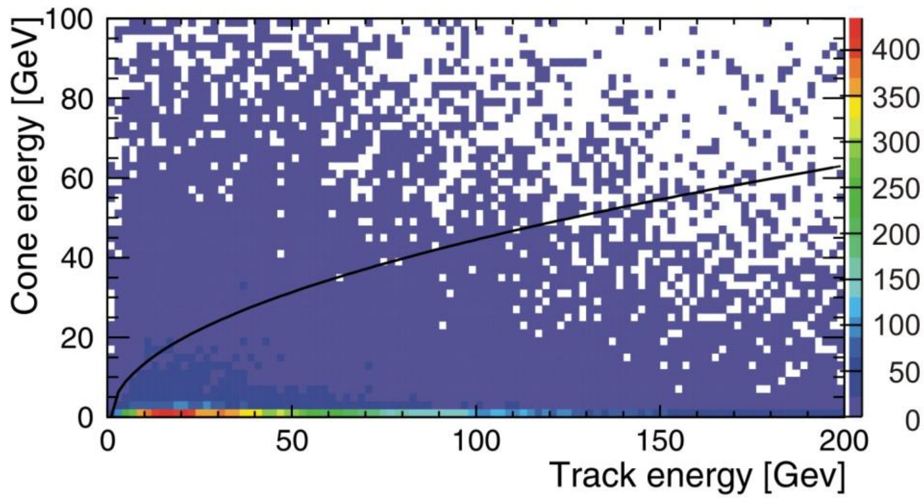
- Criteria for lepton isolation:
  - $E_{track} > 6\ GeV$
  - $p_T > 2\ GeV$ for all PFOs inside isolation cone
  - $d_0 < 0.02\ mm, z_0 < 0.02\ mm$ and $R_0 < 0.03\ mm$
  - $R_{CAL} = 0.02\ - 0.35$ and $R_{CAL} > 0.94$
  - $E_{cone}^2 < 0\ * E_{track}^2 + 20\ GeV * E_{track} - 20\ GeV^2$


count/5ab-1
Electrons/muons
PFOs
0
0.2
0.4
0.6
0.8
1
0
2
4
6
8
10
p_T (GeV)


count/5ab-1
Electrons/muons
PFOs
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
20
40
60
80
100
Track energy (GeV)


count/5ab-1
Electrons/muons
PFOs
0.2
0.4
0.6
0.8
1
0
0.05
0.1
0.15
0.2
R_0 (mm)


count/5ab-1
Electrons/muons
PFOs
1
10^{-1}
0
0.2
0.4
0.6
0.8
1
R_{CAL}


Cone energy [GeV]
0
20
40
60
80
100
0
50
100
150
200
Track energy [Gev]
0
50
100
150
200
250
300
350
400

- Aim of the preselection is to reduce backgrounds with large x-section
- Preselection condition: Find 2 isolated leptons

Process@5 ab^{-1}	$\varepsilon_{preselection}$
Signal	
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to ZZ^*, ZZ^* \to q\bar{q}l^+l^-$, $l = e, \mu$	**52 %**
Background	
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to WW, WW \to q\bar{q}q\bar{q}$	3.8 ‰
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to b\bar{b}$	1.6 ‰
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to c\bar{c}, gg$	3.1 ‰
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to others$	2.3 %
$e^+e^- \to q\bar{q}l^+l^-$	7.4 ‰
$e^+e^- \to q\bar{q}l\nu$	4.8 ‰
$e^+e^- \to q\bar{q}\bar{\nu}_e\nu_e$	1.7 ‰
$\gamma\gamma \to q\bar{q}l^+l^-$	1.3 %
$\gamma\gamma \to q\bar{q}$	2.5 ‰
$e^{\pm}\gamma \to q\bar{q}e$	7 ‰
$e^{\pm}\gamma \to q\bar{q}\nu$	1.6 ‰

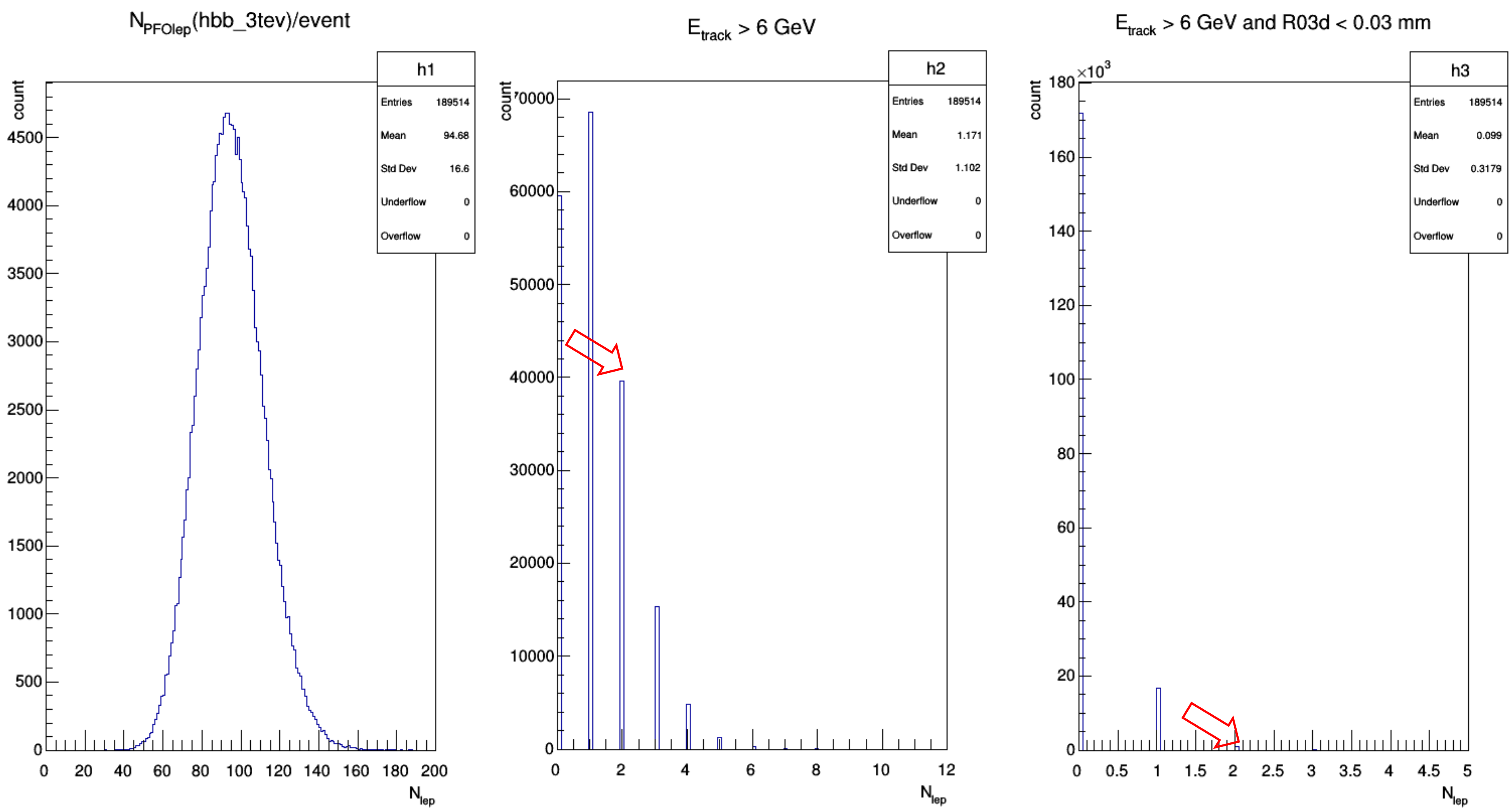
Lepton (e,μ) Isolation

- Signal efficiency is primarily reduced due to the requirement for 2 isolated leptons per event.

- Isolation criteria enable background selection efficiencies at the ‰ level.
- Despite that, S/B after preselection is ~ 10^{-3} (Initial S/B is ~ $6 \cdot 10^{-6}$)
- As illustrated in the $H \rightarrow bb$ case, permile background selection is due to the background suppression either with the track energy or impact parameter cut.
- When τ channel is included residual background (after preselection) is at level of 10s of %. This is due to the fact that TauFinder might consider part of the jet final states as a τ candidate.

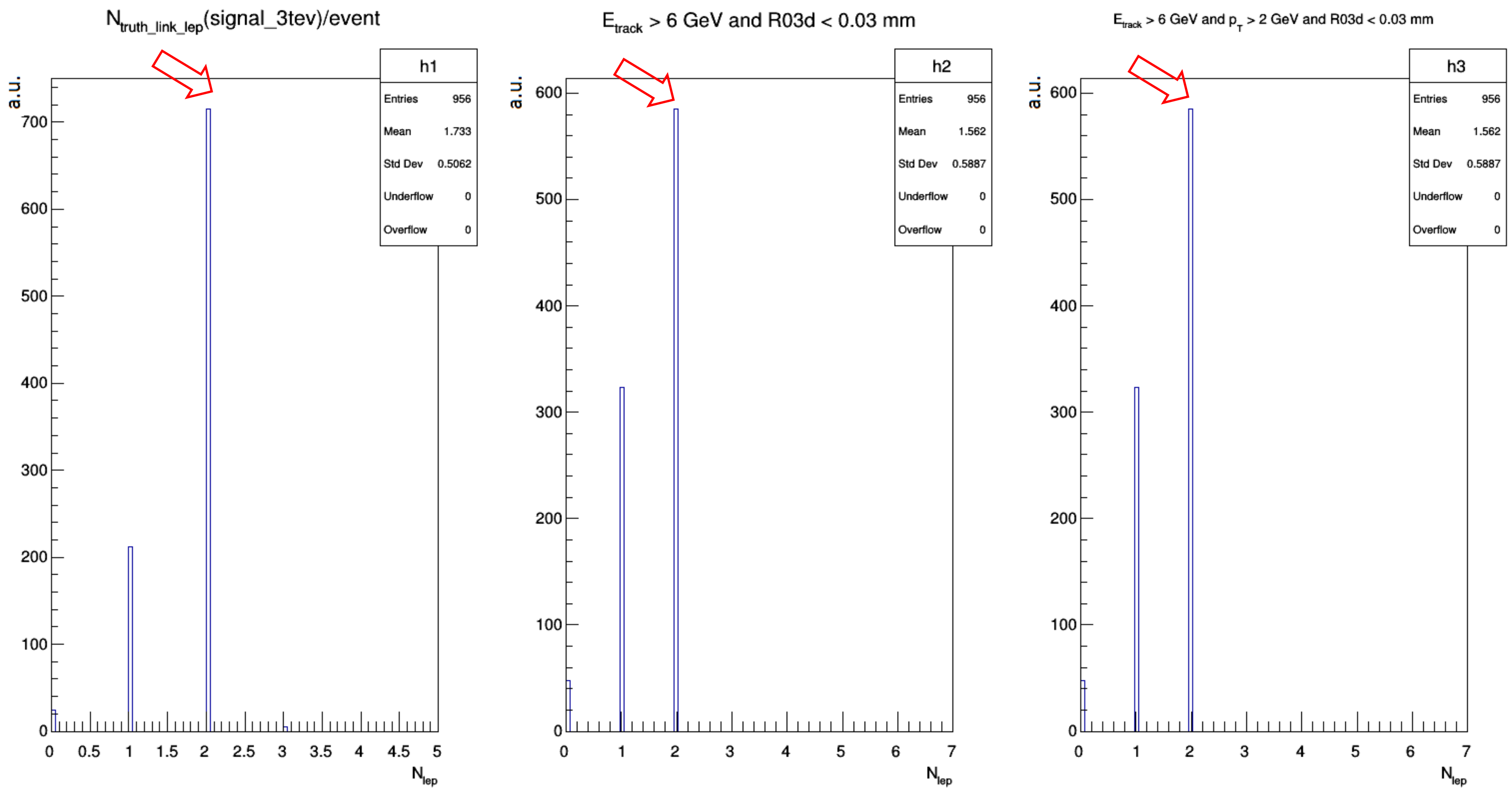
Lepton (e, μ) isolation

- Isolation criteria $E_{track} > 6\ \mathrm{GeV}$ and $R_0 < 0.03\ \mathrm{mm}$ applied to $H \to b\bar{b}$ background.



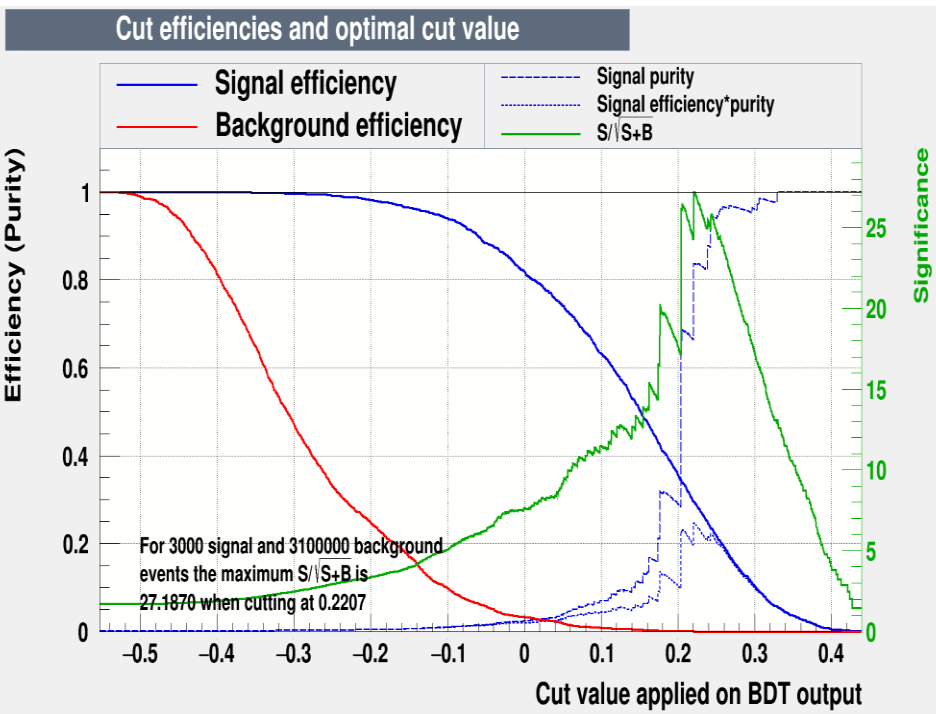
Lepton (e, μ) isolation

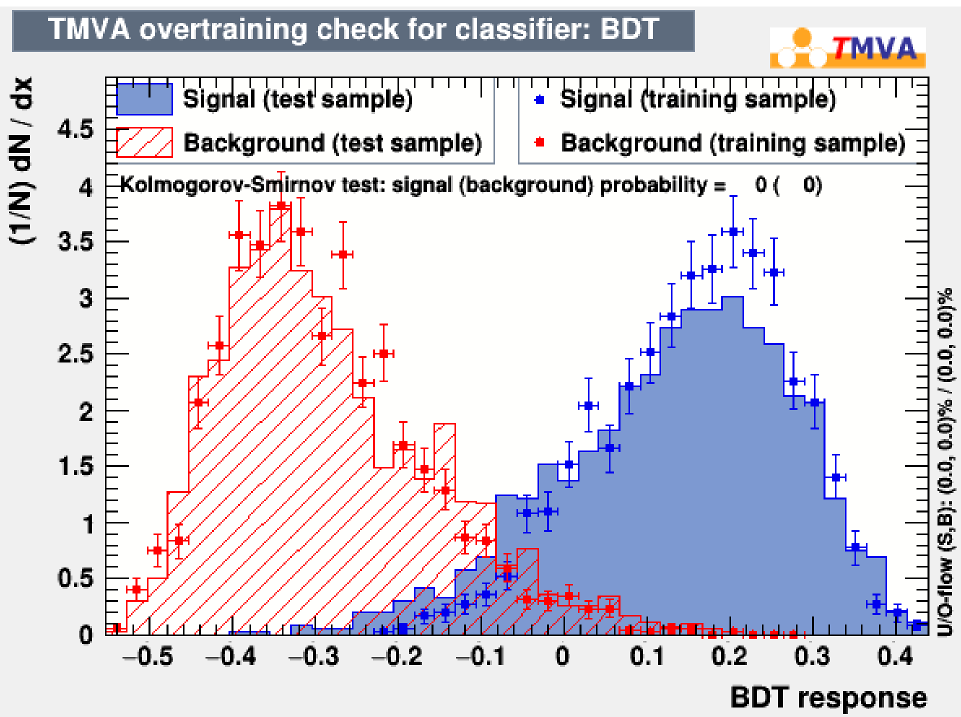
- Preselection impact on signal efficiency:
  - It is evident that about 40% of the signal is lost on 2-lepon requirement and about 8% on other isolation criteria.



MVA results

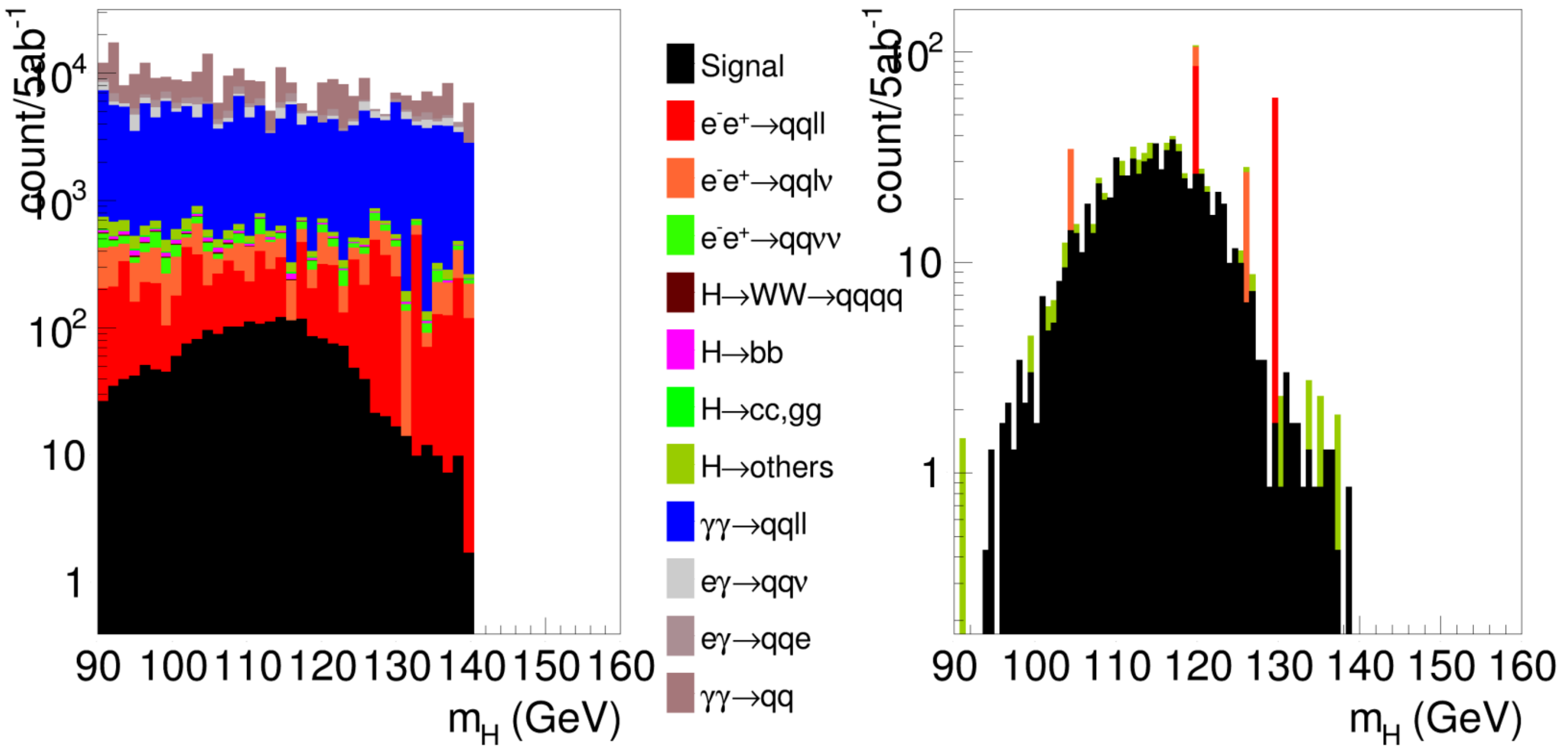
- TMVA is trained with 16 observables: $m_Z, m_{Z^*}, m_{l^+l^-}, m_{q\bar{q}}, m_H,$ $E_{vis}, E_{vis} - E_H, -\log y_{23}, -\log y_{12}, P(b)^{jet_1}, P(b)^{jet_2}, P(c)^{jet_1}, P(c)^{jet_2}, p_T^{miss},$ θ_H, N_{PFO}.
- Training is performed on all background.
- The method (BDT) is stable w.r.t. the number of observables and a choice of the training/application samples.





MVA results

- $\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{N_S+N_B}}{N_S} \sim 4\ \%, \quad S/B \sim 3.4$

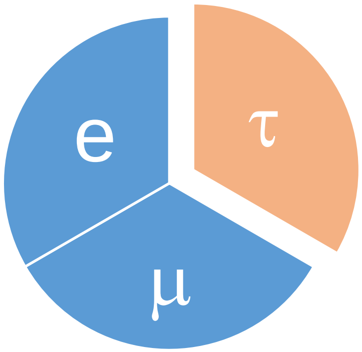


Efficiencies

Process@5 ab^{-1}	ε_{pres}	ε_{BDT}	N_{BDT}@5ab^{-1}
SignaL			
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to ZZ^*, ZZ^* \to q\bar{q}l^+l^-,$ $l = e, \mu$	52 %	32.5 %	807
Background			
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to WW, WW \to q\bar{q}q\bar{q}$	3.8 ‰	0	0
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to b\bar{b}$	1.6 ‰	0	0
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to c\bar{c}, gg$	3.1 ‰	0	0
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to others$	2.3 %	7.2 ‰	61
$e^+e^- \to q\bar{q}l^+l^-$	7.4 ‰	5 ‰	117
$e^+e^- \to q\bar{q}l\nu$	4.8 ‰	3.6 ‰	61
$e^+e^- \to q\bar{q}\bar{\nu}_e\nu_e$	1.7 ‰	0	0
$\gamma\gamma \to q\bar{q}l^+l^-$	1.3 %	0	0
$\gamma\gamma \to q\bar{q}$	2.5 ‰	0	0
$e^\pm\gamma \to q\bar{q}e$	7 ‰	0	0
$e^\pm\gamma \to q\bar{q}\nu$	1.6 ‰	0	0

Discussion

Comparison with previous $q\bar{q}ll$ (l=e, μ,τ) analysis



	1.4TeV CLIC $1.5ab^{-1}/2ab^{-1}$	1.4TeV CLIC $1.5ab^{-1}/2ab^{-1}$	3TeV CLIC $2ab^{-1}/5ab^{-1}$
Signal	$ZZ^* \rightarrow q\bar{q}q\bar{q}$	$ZZ^* \rightarrow q\bar{q}l^+l^-$	$ZZ^* \rightarrow q\bar{q}l^+l^-$
ε_s	18.4%	28.4%	30%
$\delta(\sigma \times BR)_{unpol.}$	17.5%/15.2%	5.6%/4.8%	4.4%/2.8%

- Previous result was obtained with 2ab^{-1}
- Exclusion of taus introduces into statistical uncertainty the effect of: 1/√(2/3)
- Enhanced integrated luminosity to 5 ab^{-1} reduces statistical error for: 1/√(5/2)
- Combined , it's a factor of 0.77 w.r.t. 2 ab^{-1} result with taus
- What leads to ~3.4% expectation in electron(muon) final state with 5 ab^{-1}
- The result of 4% we obtained *can be considered as consistent*, though the overall efficiency for signal is lower in the e, μ case (what is compensated by the more efficient background rejection: S/B ratio is >3, while with taus included S/B is ~ 1)

Summary

- Revised $H \rightarrow ZZ^*$ @ 3 TeV analysis is being presented for the semileptonic (l=e, μ) final state.
- Motivated by:
  - Paper publication on $H \rightarrow ZZ^*$ at all energies
  - Continuation towards CPV measurement
- Statistical uncertainty is found to be 4 %, what is consistent with previous results performed for the full semileptonic state and 2 ab^{-1} of (pseudo)data. There is a slight gain in the statistical significance (22.7 $\rightarrow$ 25) w.r.t. the final state with taus.
- Estimated number of signal events after MVA separation is 807.
- More importantly, signal to background ratio after MVA is 3.4, while in analysis with τs included it is 1.1. Cleaner signal in this case makes e, μ sample more sensitive to study Higgs CPV mixing.
- *The question (to be further discussed by Ivanka) is: Is the estimated number of 807 selected events sufficient to measure Higgs CPV mixing (+ issue of charge determination for quarks).*