Higgs physics at CLIC

Overview of physics analysis ongoing in Belgrade

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Overview

- Higgs physics at CLIC
- Analyses carried on in Belgrade
- Concept and motivation
- Status of the analyses
- Does forward region play a role?
- Summary

Higgs physics at CLIC

CLIC will be a Higgs factory –

Already at 350 GeV the number of Higgs bosons will be by far surpassing the number of W bosons at LEP

	350 GeV	1.4 TeV	3 TeV
L_{int}	500 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	68 000	20 000	11 000
# $H\nu_e\nu_e$ events	26 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

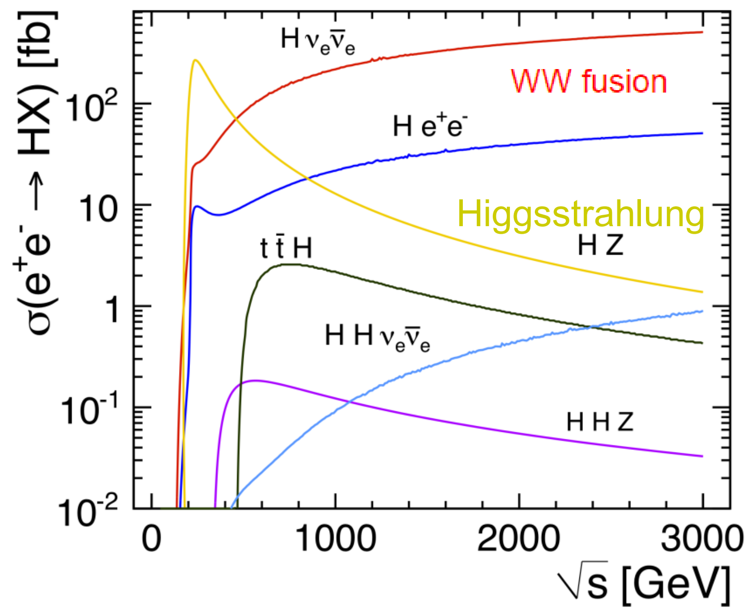
Unpolarised beams

350 GeV, Higgsstrahlung

- Absolute determination of the production x-section O(2%), sensibility to invisible decay modes to BR_{inv}~1%
- $Z\rightarrow ee,\mu\mu$, qq absolute determination g_{HZZ} O(1%) (comparable sensitivity at 350 GeV CLIC and 250 GeV ILC)

1.4 TeV, 3 TeV, W fusion

- Highest precision for rare decays and self-coupling
- Relative couplings to g_{HWW} / g_{HZZ} can be determined at O(1%) – SM test
- Other relative BR measurements i.e. g_{Hcc} /g_{Hbb} O(1.5%)



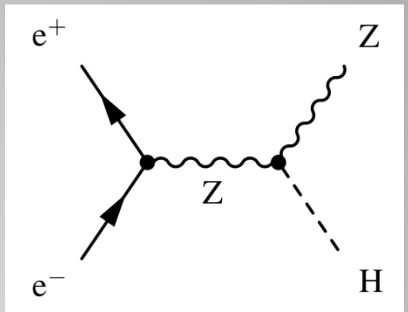
Analyses carried on in Belgrade

350 GeV, Higgsstrahlung

- $H \rightarrow WW$, fully hadronic decays

  Observable: $\frac{g^2_{HWW} \cdot g^2_{HZZ}}{\Gamma_H}$

  Challenge: Multy-jet topology (4/6 jets), flavour-tagging



Higgsstrahlung

1.4 TeV

- $H \rightarrow \mu\mu$, rare decays BR~$2 \cdot 10^{-4}$

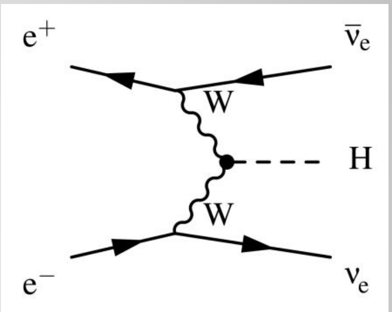
  Observable: $\frac{g^2_{HWW} \cdot g^2_{H\mu\mu}}{\Gamma_H}$

  Challenge: Rare process-small signal yield, μ p_T resolution, *forward e-tagging*

- $H \rightarrow ZZ$, fully hadronic decays

  Observable: $\frac{g^2_{HWW} \cdot g^2_{HZZ}}{\Gamma_H}$

  Challenge: Jet reconstruction (W, Z separation), b-tagging



WW fusion

Concept and motivation

- $\sigma_{prod}\cdot BR$ is a measurable quantity whose uncertainty translates into the corresponding uncertainty of coupling(s)

$$\frac{g^2_{HWW}\cdot g^2_{H\mu\mu}}{\Gamma_H} \qquad \frac{g^2_{HWW}\cdot g^2_{HZZ}}{\Gamma_H}$$

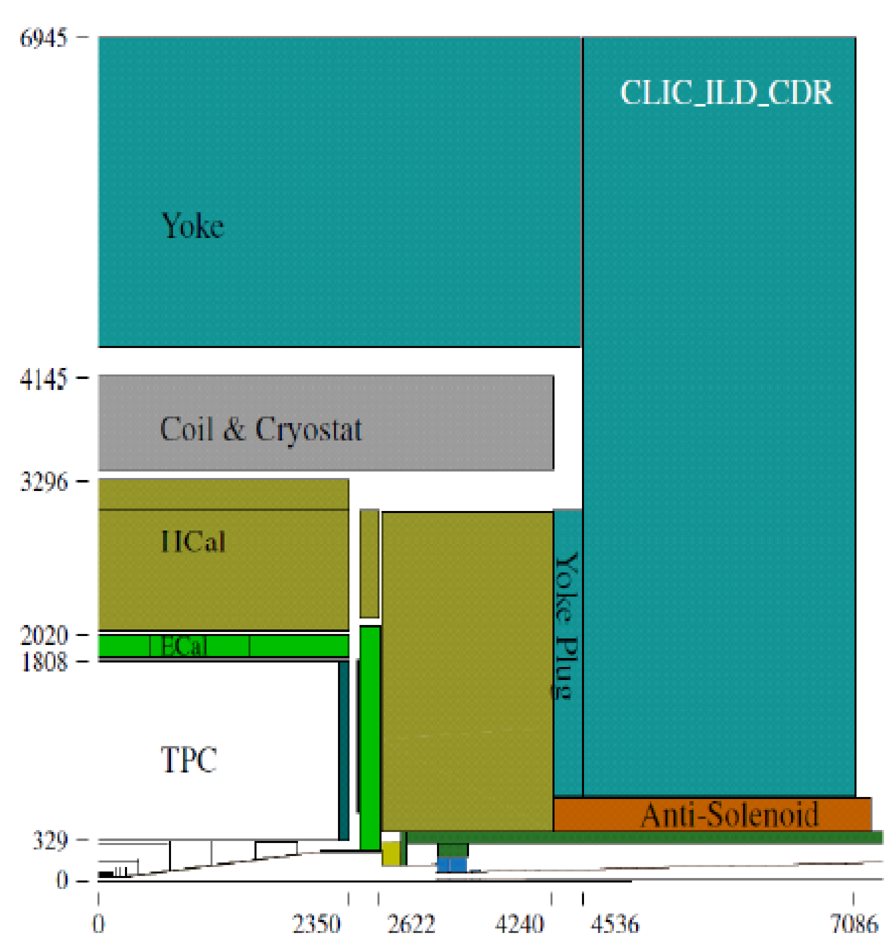
- $\sigma_{prod}\cdot BR$ is determined by finding/fitting the number of signal events
- Statistical uncertainty of the measurement comes from the signal statistics and/or irreducible backgrounds

- Higgs BRs measurements are potential probe for the New Physics (i.e. models that could possibly extend SM Higgs sector impact Higgs couplings to EW bosons and/or Higgs Yukawa couplings)
- They also serve to test the SM predictions (mass-coupling linearity, relative couplings)

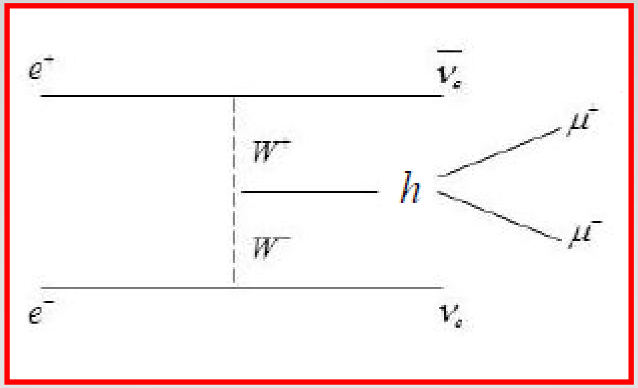
General features

All analyses include:
- Full detector simulation
- Full physics and machine background ($\gamma\gamma$ background has been overlaid before the digitization phase)
- EPA approximation for low Q^2 region
… as realistic as possible

Simulation details:
- Event generation with WHIZARD v.1.95 including ISR and BS
- Beam-spectrum generated with GUINEAPIG
- Hadronization with PYTHIA
- Assuming m_H=126 GeV
- CLIC_ILD detector
- Particle reconstruction and identification using PandoraPFA



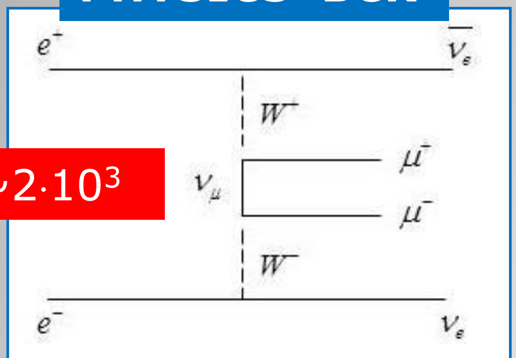
$H \to \mu\mu$ at 1.4 TeV



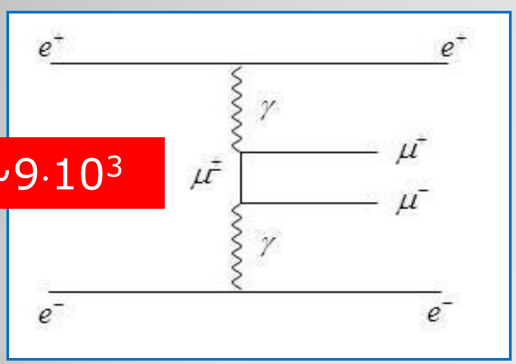
Background processes

PHYSICS BCK

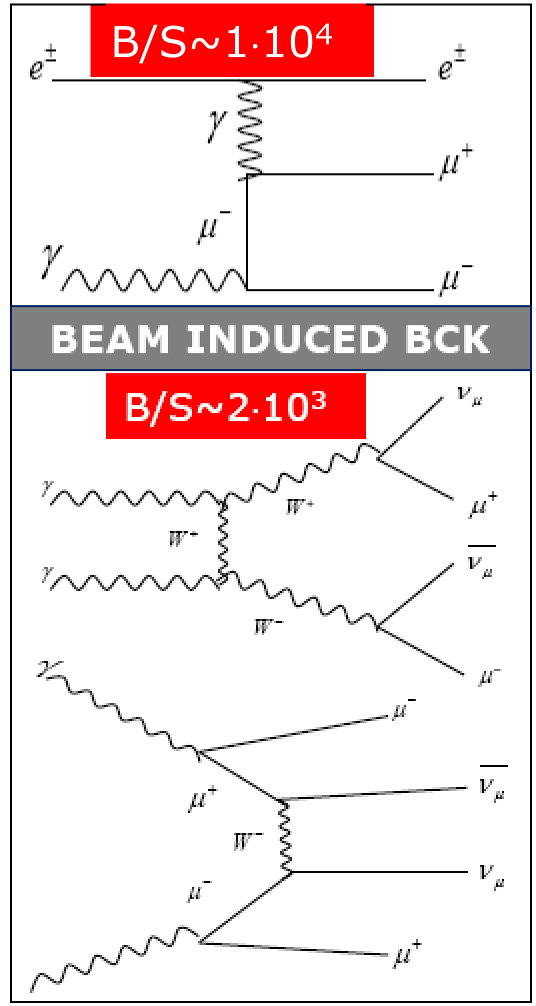
B/S~2·10³



B/S~9·10³



B/S~1·10⁴



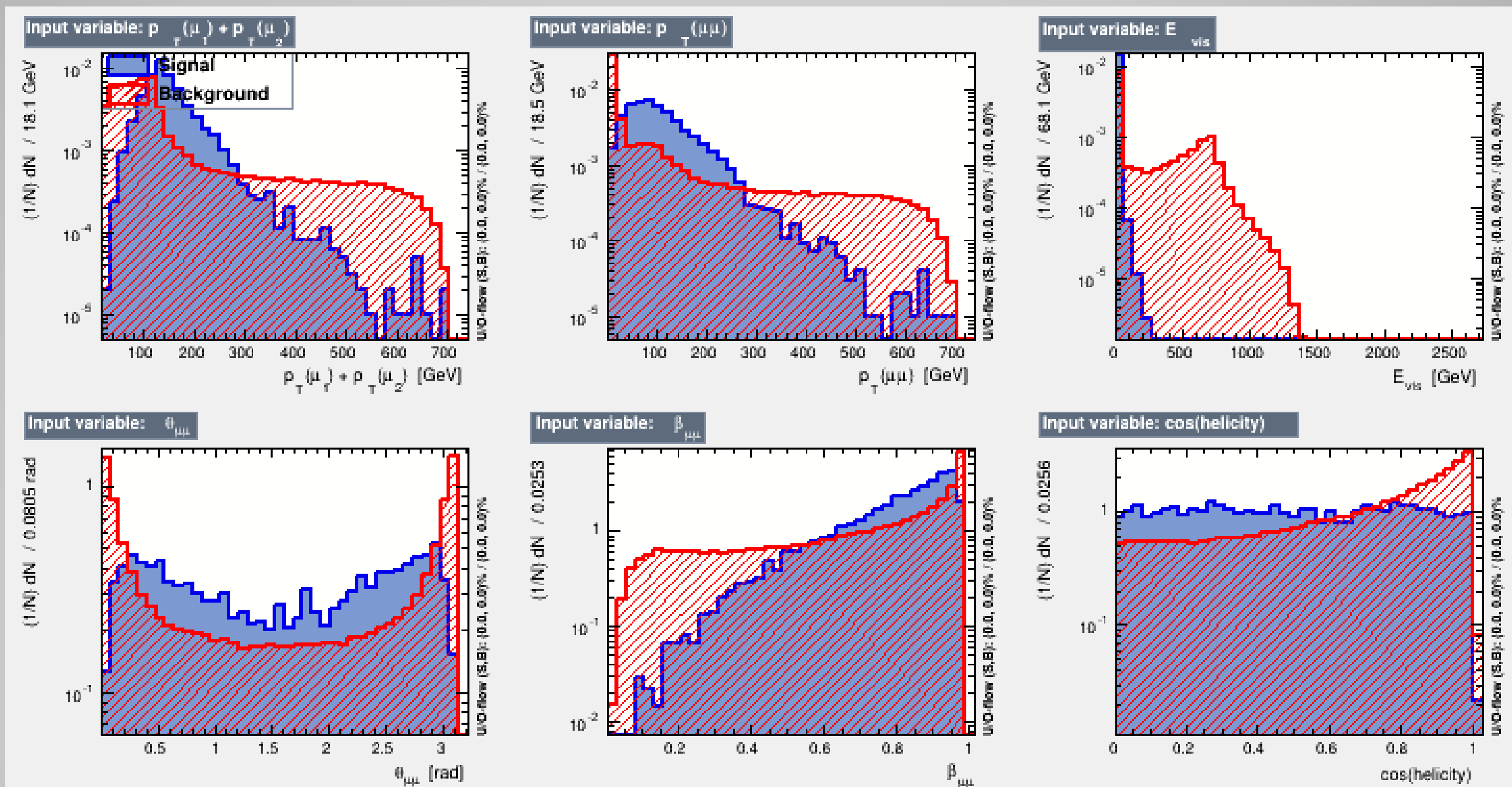
Processes

$e^+e^- \to e^+e^-\mu^+\mu^-$ and

$e^{\pm}\gamma \to e^{\pm}\mu^+\mu^-$

are treated in EPA for low momentum transferred by the exchanged photon (<4 GeV). In that kinematical region electron is substituted by a quasi-real photon.

- The most important kinematical property of the signal is missing energy.
- Process with the same signature like $\gamma\gamma \to \nu_\mu \overline{\nu_\mu} \mu^+ \mu^-$ and $e^+e^- \to \mu^+\mu^-\nu_e\overline{\nu_e}$ give irreducible background (even after MVA)
- Processes like $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^\pm\gamma \to e^\pm\mu^+\mu^-$ with low-angle electron in the final state can be dealt with in MVA + electron tagging



BDT is trained on all background samples, except $e^+e^- \to \mu^+\mu^-\nu_e\overline{\nu_e}$

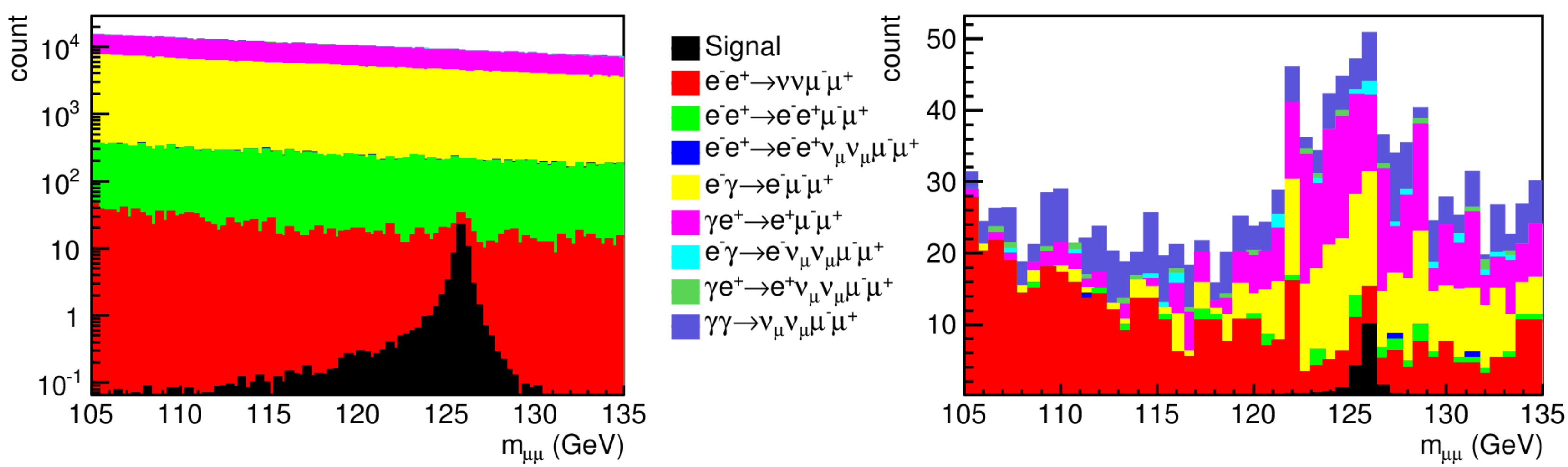
Preselection and MVA analysis

Common integral luminosity of 1.5 ab^{-1} is assumed, without beam polarization $\rightarrow$ 78 signal events.

PRESELECTION:

- Two reconstructed muons
- Di-muon invariant mass window (105-145) GeV
- *Forward electron-tagging*

PRESELECTION +MVA

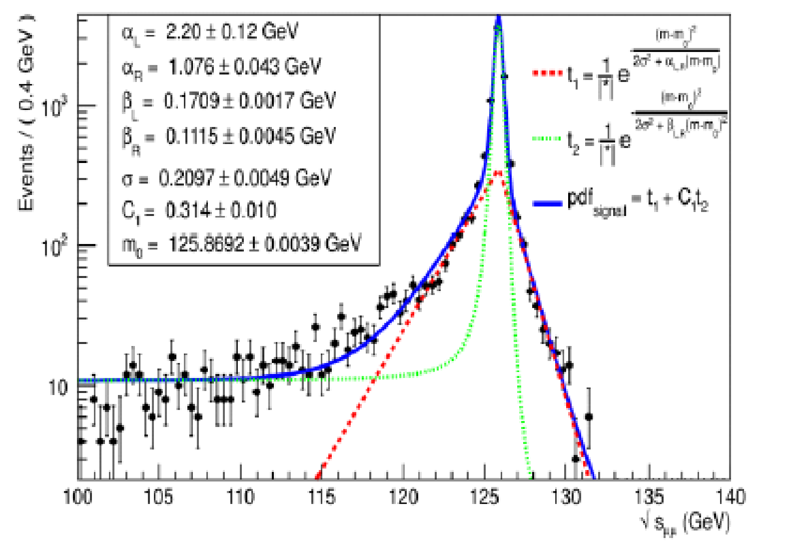


Preselection efficiency 89% BDT>0.098 Overall signal efficiency 27%

Signal and background PDFs

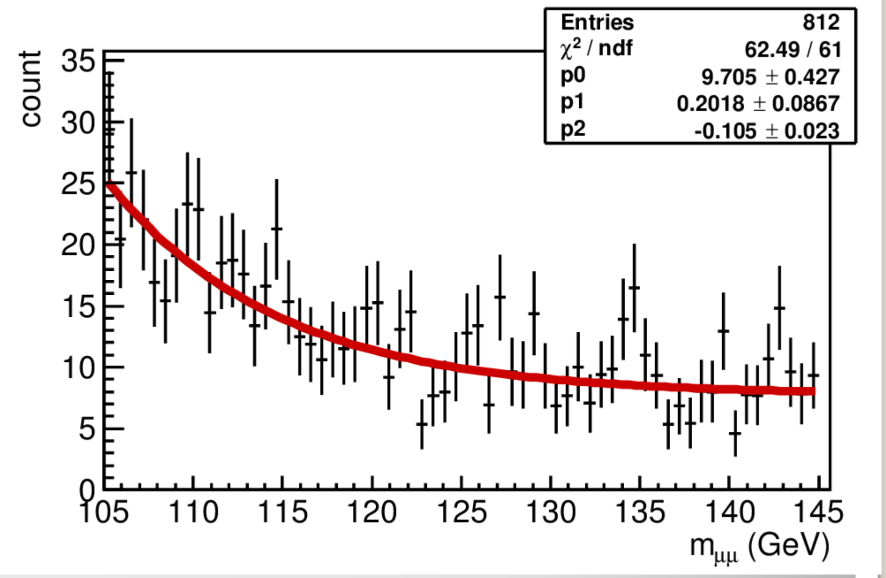
Fully simulated, as large as possible, samples of signal and background to extract PDFs

SIGNAL



$$f_S = t_1 + C \cdot t_2$$

TOTAL BACKGROUND

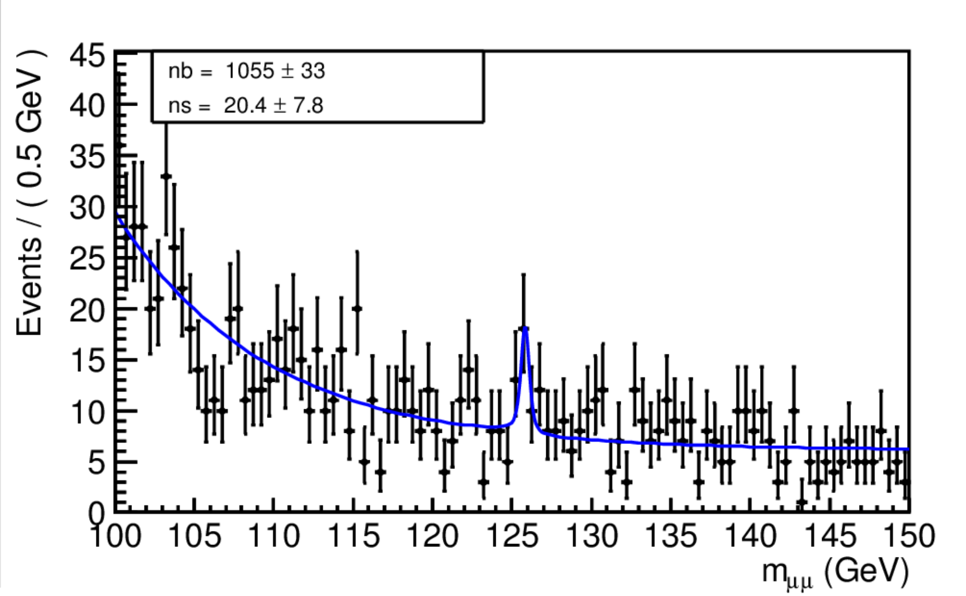


$$f_{BCK} = p_0 (p_1 e^{p_2 (x - m_H)} + (1 - p_1))$$

Toy MC experiments

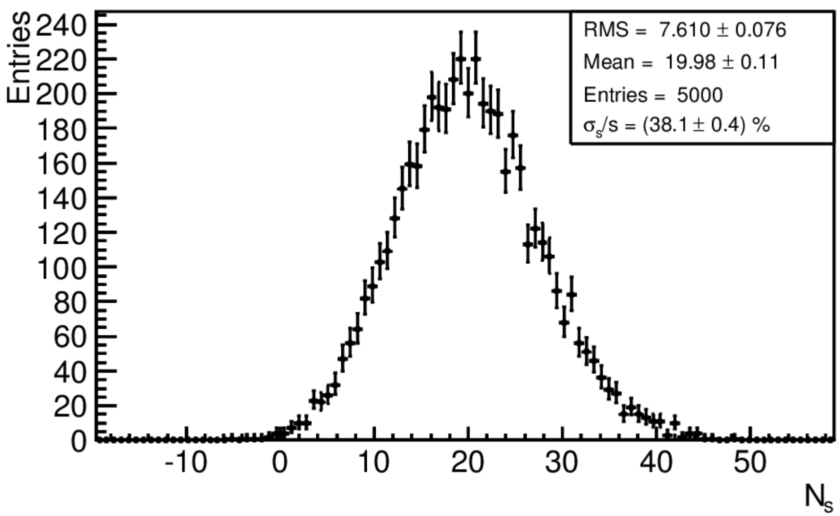
- Pseudo-experiments based on randomly sampled fully simulated signal events + backgrounds generated with PDFs
- Expected shape of data (signal + background) for each Toy MC is fitted with f to extract number of signal N_s

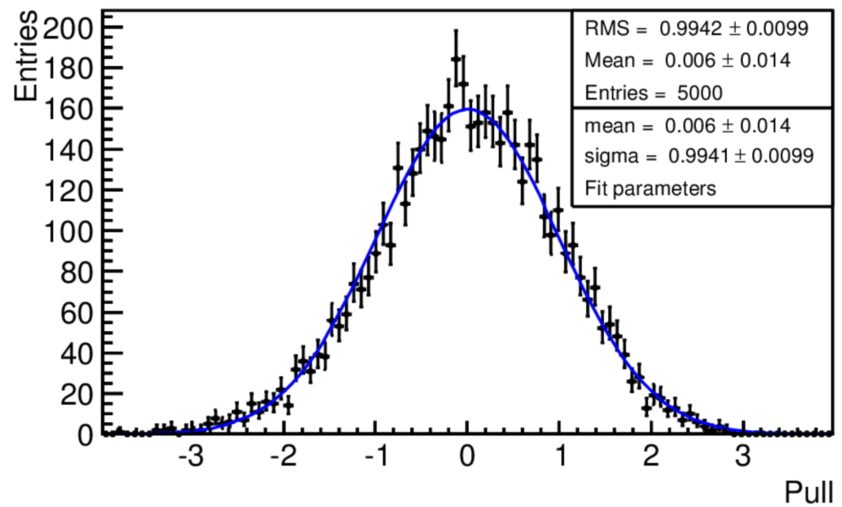
$$f = k \cdot f_S + (1-k) \cdot f_{BCK} \Rightarrow N_S = k \cdot \int f_S dm$$



Statistical uncertainty

5000 Toy MC experiments is performed to extract statistical uncertainty and check the pull distribution





- RMS of the signal distribution give statistical uncertainty of the measurement $\delta(\sigma_{prod}\cdot BR)$=38.1%
- Pull distribution confirms adequate description of signal and background with PDFs

Result of H to $\mu\mu$ analysis

N_s	20±8
ε_s	27%
$\sigma_{prod}\times BR$	0.05 fb
$\delta(\sigma_{WWH}\times BR)$	38%
$\delta(g_{H\mu\mu})$	16%

- Uncertainty of the measurement is dominated by the small statistics of signal and by backgrounds with the true missing energy
- Uncertainty of $g_{H\mu\mu}$ coupling is estimated assuming uncertainties of g_{HWW} and Γ_H in the model independent approach using -80% polarization
- One should note that inclusion of beam polarization will boost production cross-section by a factor 2.34

Publication status: CLICdp Note ready for reviewing, publication in preparation
Also, I. Bozovic-Jelisavcic, S. Lukic, G. Milutinovic-Dumbelovic, M. Pandurovic, SM-like Higgs decay into two muons at 1.4 TeV CLIC, CLICdp-Conf-2014-001, Proceedings of LCWS13, 11-15 November 2013, Tokyo, Japan, http://arxiv.org/abs/1403.6695
Poster accepted at ICHEP 2014

Does forward region play a role?

YES

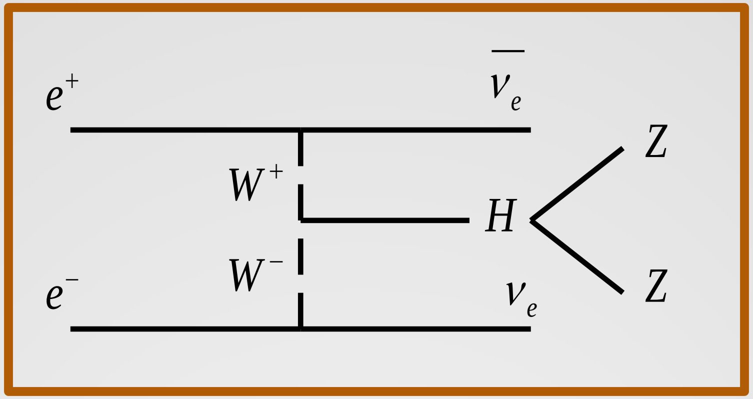
- Forward region calorimetry plays an important role to veto electron spectators from *4-f* and $e\gamma_{BS}$ processes.
- Energy dependent tagging is introduced in LumiCal and BeamCal:

  - Take 5 mrad cone particles (e, gamma) to construct electron,

  - Require 4σ deviation from the background (converted pairs) energy in the layer with the maximal deposition. Energy resolution is taken into account, as well as fluctuations of background deposition over the θ range. *See more in Goran's talk*

Process	Rejection
$e^+e^- \rightarrow e^+e^-\mu^+\mu^-$	44^{EPA}% /25%/17%
$e^\pm\gamma_{BS} \rightarrow e^\pm\mu^+\mu^-$	38^{EPA}%/18%/11%
$H \rightarrow \mu^+\mu^-$	7% /7%/0.2%

$H \rightarrow ZZ$ at 1.4 TeV



Signal and background

Process	$\sigma[fb]$
$e^+e^- \to H\nu_e\overline{\nu_e}, H \to ZZ -> qqqq$	3.45
$e^+e^- \to qq\nu_e\overline{\nu_e}$	788
$e^+e^- \to qqqq\nu_e\overline{\nu_e}$	24.7
$e^+e^- \to H\nu_e\overline{\nu_e}, H \to WW -> qqqq$	27.6
$e^+e^- \to qq$	4009.5
$e^+e^- \to qqqq$	1328.1
$e^+e^- \to qqqqll$	71.7
$e^+e^- \to qqqql\nu$	115.3
$e^+e^- \to H\nu_e\overline{\nu_e}, H \to bb$	136.94
$e^+e^- \to H\nu_e\overline{\nu_e}, H \to ZZ -> qqll / llll$	0.177

- Numerous background
- W decays gives same topology (W-Z separation)
- Selection optimized by MVA

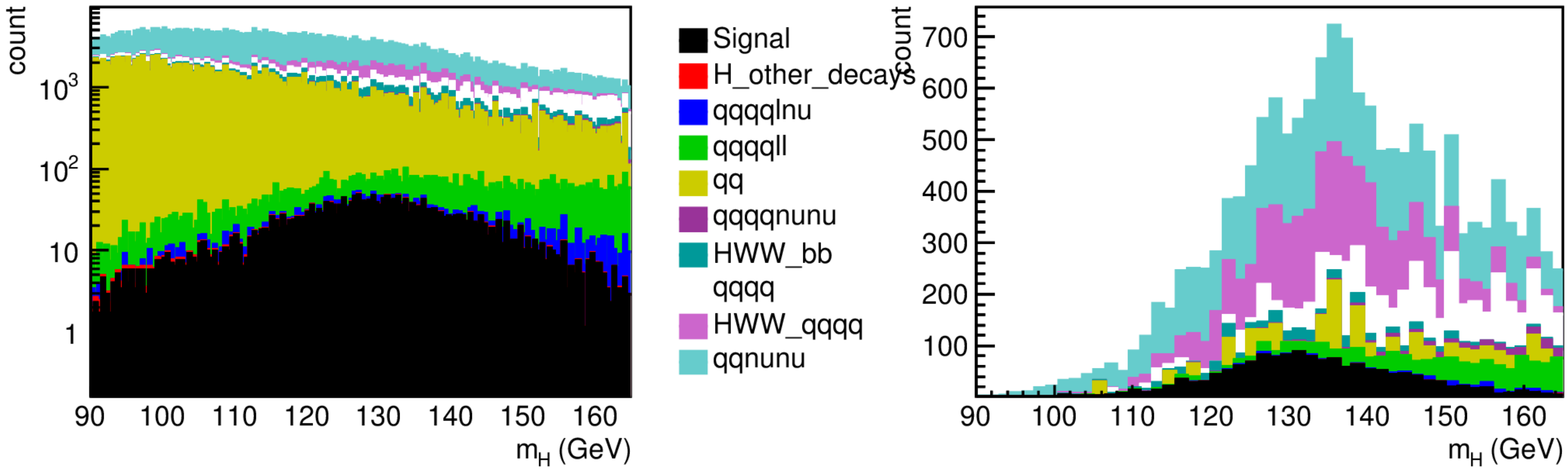
Three possible ZZ decay topologies:

- qqqq~48%
- qqll~42%
- llll~10%
- Only fully-hadronic final state considered

Analysis strategy

- FASTJET: Force events into 4 jets, k_T exclusive, selected PFOs within R=1.0
- b-TAGGING (helps to reduce $e^+e^- \rightarrow H\nu_e\overline{\nu_e}, H \rightarrow bb$)
- PRESELECTION:
  - 45 GeV<m_{Z1}<110 GeV, m_{Z2}<65 GeV
  - 90 GeV<m_{Higgs}<165 GeV
  - -log (y_{34})<3.5
  - -log(y_{23})<3.0
  - 100 GeV<E_{vis}<600 GeV
  - E_{lepton}<30 GeV
  - P_t^{jet}>20 GeV
  - $P(b)^{jet1}$<0.95, $P(b)^{jet2}$<0.95
- MVA selection
- FIT m_H to extract number of signal events *(to be done)*

Preselection and MVA analysis

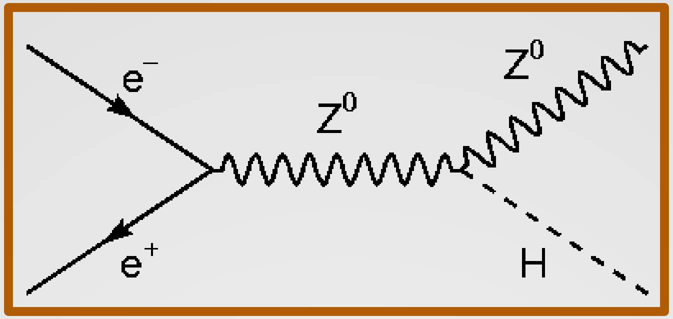


Preselection efficiency 53% BDT>-0.052 Overall signal efficiency 40%

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \sim 9\%$$ (115 GeV< m_H <150 GeV)

- TMVA trained with 8 variables (m_{Z1}, m_{Z2}, -log (y_{34}), -log(y_{23}), $P(b)^{jet1}$, $P(b)^{jet2}$, $P(c)^{jet1}$, $P(c)^{jet2}$) on total background
- Irreducible background from hadronic W decays $e^+e^- \to H\nu_e\overline{\nu}_e, H \to WW -> qqqq$

$H \to WW$ at 350 GeV



Signal and background

HZ @350GeV $\sigma(e^+e^- \rightarrow HZ) \sim 134$ fb $\Rightarrow$68000 events in 4-years detector operation with 50% data-taking efficiency

$H \rightarrow WW \rightarrow qqqq$, $Z \rightarrow ff$, $f = e, \mu, q$

- Numerous background
- Multi-jet topology 4/6 jets depending on Z final state
- Selection optimized by MVA

BF($H \rightarrow WW$)~23%
BF($WW \rightarrow qqqq$)~45%
BF($Z \rightarrow$visible)~80%
Leaves 8% of all Higgs bosons Produced in HZ

Signal HZ, $H \rightarrow WW \rightarrow qqqq$	**σ [fb]**
$Z \rightarrow ee$	0.48
$Z \rightarrow \mu\mu$	0.48
$Z \rightarrow qq$	9.7
Background	
HZ, other H decays, Z vis. d.	92.02
$e^+e^- \rightarrow qqqq$	5847
$e^+e^- \rightarrow qqll$	1704
$e^+e^- \rightarrow qql\nu$	5914
$e^+e^- \rightarrow qq\nu\nu$	324.6

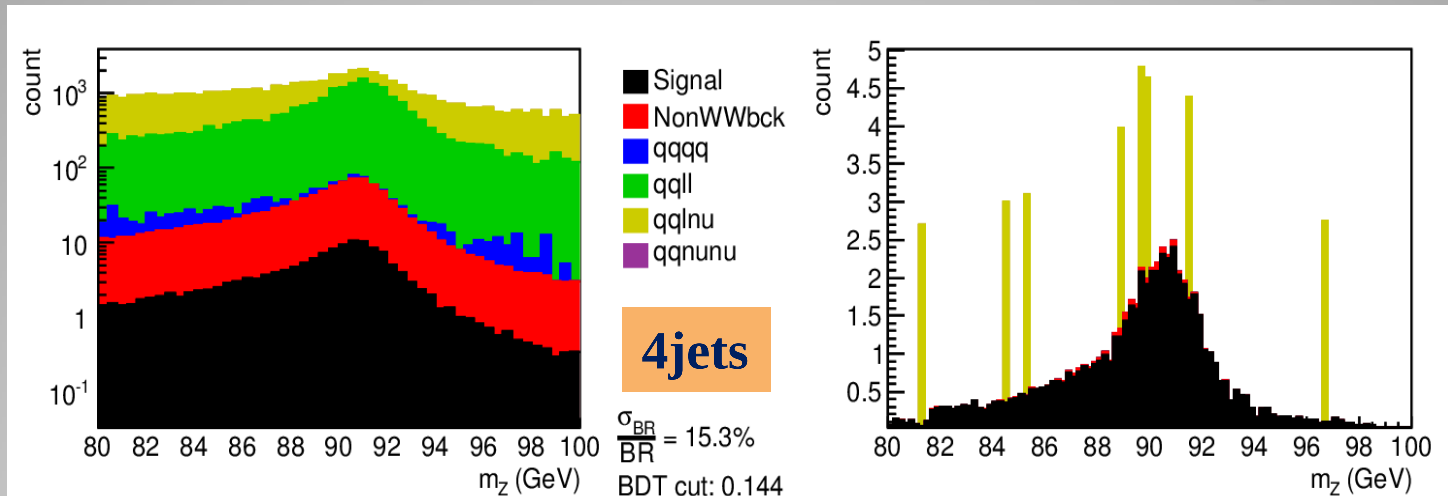
Analysis strategy 4 jets

- FASTJET: Force events into 4 jets,kT exclusive, selected PFO's R=1.2
- b-TAGGING (helps reduce $ee \rightarrow HZ$, $H \rightarrow bb$ background)
- PRESELECTION
- $m_Z > 40$ GeV
- 45 GeV $< m_w < 95$ GeV
- $m_H > 65$ GeV
- $20^o < \theta_{el} < 160^o$
- 100 GeV < Evis <300 GeV
- $P_t^{jet} > 20$ GeV
- -log(y34) < 4.0
- MVA selection (training: 10 variables NPFO, $-\log(y_{23})$, $-\log(y_{34})$, m_w, m_H, θ_{el}, E_{vis}, P_t^{jet}, P(b) ,P(c); samples: HZ, $Z \rightarrow ll$, nonWW-qqqq decays, $ee \rightarrow qqll$, $ee \rightarrow qqll\ qql\nu$)
- FIT m_Z to extract number of signal events *(to be done)*

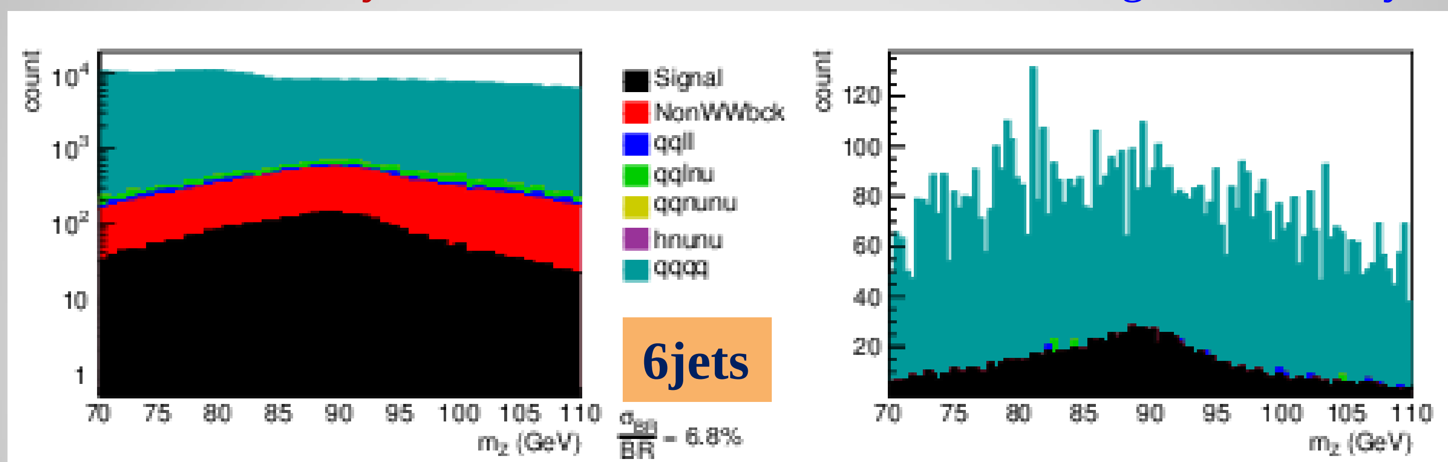
Analysis strategy 6 jets

- FASTJET: Force events into 6 jets, kT exclusive, selected PFO's within R=1.2
- b-TAGGING (helps reduce ee→HZ, H→bb background)
- PRESELECTION
- m_Z >70 GeV
- m_w>10 GeV
- y12 <2.0
- y23<2.6
- y34<3.0
- y45<3.2
- MVA selection (training on 11 variables: NPFO, $-\log(y_{12})$, $-\log(y_{23})$, $-\log(y_{45})$, $-\log(y_{56})$, $-\log(y_{67})$, m_{w}, m_{H}, m_{w^*}, E_{vis}, $P_t^{HiggsJets}$; samples: HZ, Z-qq, nonWW-qqqq decays, ee→qqqq)
- FIT M_Z to extract number of signal events *(to be done)*

Preselection and MVA analysis



Preselection efficiency 83% BDT>0.144 Overall signal efficiency 30%



Preselection efficiency 77% BDT>-0.026 Overall signal efficiency 50%

Summary

- Several Higss analyses have been carried on in Belgrade in order to complement CLIC Physics Program at various energy stages (one PhD thesis ongoing).
- For all processes under study ($H \to \mu\mu$, $H \to ZZ$, $H \to WW$) reduction of background is challenging.
- For measurements like BR($H \to \mu\mu$) specific background can be suppressed by e-tagging – forward region is important.
- While e-tagging, coincidental signal rejection due to Bhabha tagging has to be considered.

$e^+e^- \to H\nu_e\overline{\nu_e}, H \to \mu^+\mu^-$

Process	xs (fb)
$ee \to \nu\nu\mu\mu$	129
$ee \to ee\mu\mu$ (*)	24.5
$ee \to ee\nu_\mu\nu_\mu\mu\mu$	1.59
$e^-\gamma_{EPA} \to e^-\mu\mu$ (*)	217.3
$e^-\gamma_{BS} \to e^-\mu\mu$ (*,**)	248
$\gamma_{EPA}e^+ \to e^+\mu\mu$ (*)	216.9
$\gamma_{BS}e^+ \to e^+\mu\mu$ (*,**)	250
$e^-\gamma_{EPA} \to e^-\nu_\mu\nu_\mu\mu\mu$	3.52
$e^-\gamma_{BS} \to e^-\nu_\mu\nu_\mu\mu\mu$ (**)	11.5
$\gamma_{EPA}e^+ \to e^+\nu_\mu\nu_\mu\mu\mu$	3.50
$\gamma_{BS}e^+ \to e^+\nu_\mu\nu_\mu\mu\mu$ (**)	11.4
$\gamma_{EPA}\gamma_{EPA} \to \nu_\mu\nu_\mu\mu\mu$	5.61
$\gamma_{EPA}\gamma_{BS} \to \nu_\mu\nu_\mu\mu\mu$ (**)	22.9
$\gamma_{BS}\gamma_{EPA} \to \nu_\mu\nu_\mu\mu\mu$ (**)	22.8
$\gamma_{BS}\gamma_{BS} \to \nu_\mu\nu_\mu\mu\mu$ (**)	110

[A] *Including a cut of 100 GeV <m(μμ)<140 GeV and requiring a minimal polar angle of 8° for each muon.*

[B] *Beamstrahlung is included in luminosity used for x-section generation*

BACKUP