Update on Higgs Self-Coupling Measurement

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ILD Software and Analysis Meeting, 29.01.2014

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Introduction

- $\sqrt{s} = 500$ GeV, $\mathcal{L} = 2$ ab^{-1}, $m_{\mathrm{H}} = 125$ GeV and $P(e^+e^-) = (0.3, -0.8)$
- consider $\gamma\gamma$ beam background
- **last meeting**: preliminary results of lepton channel
  first insight into neutrino channel

$\nu\nu$HH cuts optimised "without overlay" and "with overlay" respectively

	background	signal ($\nu\nu$bbbb)
expected	$1.67 \cdot 10^6$	80.14
preselection	138200	28.53 (22.67)
	142742	28.39 (22.38)
final	4.52	5.26 (5.19)
	3.96	3.26 (3.23)

- **update**: investigating inconsistency

	$\nu\nu$bb	eνbbqq	$\mu\nu$bbqq	$\tau\nu$bbqq	bbqqqq	bbbb	$\nu\nu$bbbb	$\nu\nu$qqh	bgrd	signal ($\nu\nu$bbbb)
expected	272802	248454	245936	245708	624060	40234.3	97.08	447.01	$1.67 \cdot 10^6$	80.14
preselection	545.42	1787.73	1480.96	37410.7	65529	31292.4	81.98	72.27	138200	28.53 (22.67)
	992.78	1996.63	**318.61**	38659.3	69697.7	30921.9	80.89	74.63	142742	28.39 (22.38)

Preliminary optimised “without overlay” (new)

- **cut1**: $E_{vis} < 364$ GeV $+ 0.83 \cdot P_t^{miss}$, $M_Z < 60$ GeV
- **cut2**: $Npfos_{min} > 6$, $M(HH) > 200$ GeV, 100 GeV $< M(H1) <$ 139 GeV, 91 GeV $< M(H2) <$ 135 GeV
- **cut3**: MVAbbbb > 0.83
- **cut4**: MVAlvbbqq > 0.61
- **cut5**: MVAννbbbb > 0.57
- **cut6**: bmax3 + bmax4 > 1.08

	ννbb	eνbbqq	μνbbqq	τνbbqq	bbqqqq	bbbb	ννbbbb	ννqqh	bgrd	signal (ννbbbb)
expected	272802	248454	245936	245708	624060	40234.3	97.08	447.01	$1.67 \cdot 10^6$	80.14
preselection	545.42	1787.73	1480.96	37410.7	65529	31292.4	81.98	72.27	138200	28.53 (22.67)
cut1 (evis,mpt,mz)	481.01	894.06	867.41	25002.4	1443.64	3943.25	80.5	70.09	32782.4	27.72 (22.00)
cut2 (npfo,mh1,mh2)	7.34	211.92	229.78	5259.57	260.39	390.75	9.88	19.76	6389.41	16.93 (14.9)
cut3 (mvabbbb)	4.88	184.62	200.52	4405.85	126.46	13.48	6.52	16.05	4958.4	15.04 (13.19)
cut4 (mvalvbbqq)	4.28	42.91	57.06	761.5	50.05	8.71	4.54	9.68	938.75	12.53 (11.25)
cut5 (mvavvbbbb)	3.05	31.13	42.3	571.16	49.19	7.34	1.57	4.95	710.72	10.49 (9.42)
cut6 (bmax34)	0	0	0	2.19	0.12	3.09	0.75	1.86	**8.02**	**5.61 (5.54)**

Result consistent with DBD full sim. for $m_H = 120$ GeV (LC-REP-2013-003)

	signal	background	significance
$m_H = 120$ GeV	8.5	7.9	2.1σ
$m_H = 125$ GeV	5.6	8.0	1.4σ

Preliminary optimised “without overlay” (new)

Use optimised cuts for “without overlay” in analysis “with overlay”

	$\nu\nu bb$	$e\nu bbqq$	$\mu\nu bbqq$	$\tau\nu bbqq$	bbqqqq	bbbb	$\nu\nu bbbb$	$\nu\nu qqh$	bgrd	signal ($\nu\nu bbbb$)
expected	272802	248454	245936	245708	624060	40234.3	97.08	447.01	$1.67 \cdot 10^6$	80.14
preselection	545.42	1787.73	1480.96	37410.7	65529	31292.4	81.98	72.27	138200	28.53 (22.67)
	992.78	1996.63	**1661.69**	38659.3	69697.7	30921.9	80.89	74.63	144086	28.39 (22.38)
cut1 (evis,mpt,mz)	481.01	894.06	867.41	25002.4	1443.64	3943.25	80.5	70.09	32782.4	27.72 (22.00)
	859.31	940.37	890.05	23270.3	887.79	3115.73	77.3	68.36	30109.2	26.14 (20.54)
cut2 (npfo,mh1,mh2)	7.34	211.92	229.78	5259.57	260.39	390.75	9.88	19.76	6389.41	16.93 (14.9)
	11.71	238.48	238.83	5061.16	259.73	324.07	9.41	18.67	6162.07	14.63 (12.88)
cut3 (mvabbbb)	4.88	184.62	200.52	4405.85	126.46	13.48	6.52	16.05	4958.4	15.04 (13.19)
	8.03	200.63	207.54	4169.06	136.88	11.23	6.05	15.02	4754.46	12.79 (11.23)
cut4 (mvalvbbqq)	4.28	42.91	57.06	761.5	50.05	8.71	4.54	9.68	938.75	12.53 (11.25)
	6.2	113.53	104.23	1717.91	101.75	9.95	5.19	11.93	2070.71	11.83 (10.54)
cut5 (mva$\nu\nu$bbbb)	3.05	31.13	42.3	571.16	49.19	7.34	1.57	4.95	710.72	10.49 (9.42)
	4.38	57.97	50.14	973.01	80.07	7.35	0.98	3.91	1177.82	8.26 (7.39)
cut6 (bmax34)	0	0	0	2.19	0.12	3.09	0.75	1.86	**8.02**	**5.61 (5.54)**
	0	0	0	7.29	0.44	3.34	0.42	1.46	**12.98**	**4.49 (4.44)**

More background $\rightarrow$ need to optimise cuts for “with overlay” selection

Preliminary optimised "with overlay" (new)

- **cut1**: $E_{vis} < 372$ GeV $+ 0.83 \cdot P_t^{miss}$, $M_Z < 60$ GeV
- **cut2**:
  $Npfos_{min} > 10$, $M(HH) > 200$ GeV, 103 GeV $< M(H1) <$ 141 GeV, 103 GeV $< M(H2) <$ 136 GeV
- **cut3**: MVAbbbb > 0.93
- **cut4**: MVAlvbbqq > 0.73
- **cut5**: MVAvvbbbb > 0.3
- **cut6**: bmax3 + bmax4 > 1.1

	ννbb	eνbbqq	μνbbqq	τνbbqq	bbqqqq	bbbb	ννbbbb	ννqqh	bgrd	signal (ννbbbb)
expected	272802	248454	245936	245708	624060	40234.3	97.08	447.01	$1.67 \cdot 10^6$	80.14
preselection	992.78	1996.63	**1661.69**	38659.3	69697.7	30921.9	80.89	74.63	144086	28.39 (22.38)
cut1	862.421	989.73	929.3	24532	1247.81	3552.61	77.83	69.21	32260.9	26.58 (20.89)
cut2	5.57	163.74	154.34	2951.74	270.47	211.5	4.75	8.64	3770.76	11.64 (10.38)
cut3	2.45	110.95	112.07	1938.31	61.67	4.08	2.41	6.41	2238.37	8.64 (7.69)
cut4	2.45	44.11	45.75	624.46	38.02	3.27	1.91	4.69	764.7	7.52 (6.78)
cut5	2.45	37.35	39.77	568.33	36.88	3.13	1.29	4.09	693.32	7.14 (6.44)
cut6	0	0	0	0.56	0.12	1.27	0.63	1.46	**4.05**	**3.82 (3.78)**

new cut optimisation helps to reduce backgrounds

Summary and Outlook

- last meeting: preliminary results of lepton channel

  first results of neutrino channel

- now: updated results of neutrino channel → correct event numbers

  → analysis without overlay consistent with DBD full simulation for $m_{\mathrm{H}} = 120$ GeV

- preliminary status for $m_H = 125$ GeV without overlay and with overlay

modes	signal	background	sign.
$l^- l^+ HH$	2.79 (2.38)	4.03	0.87σ
	3.09 (2.54)	4.89	0.91σ
$\nu\bar{\nu}HH$	**5.61 (5.54)**	**8.02**	1.44σ

modes	signal	background	sign.
$l^- l^+ HH$	2.35 (2.03)	4.01	0.72σ
	3.01 (2.38)	5.98	0.82σ
$\nu\bar{\nu}HH$	**3.82 (3.78)**	**4.05**	1.22σ

- hadronic channel in progress

BACKUP SLIDES

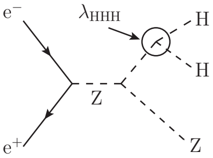
Introduction

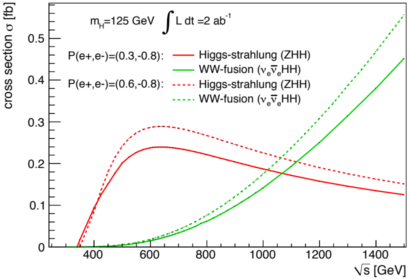
- Higgs properties can be measured precisely at ILC (m_H, Γ_H^{tot}, etc.)

  missing: **Higgs potential**, which represents test of EWSB and mass generation

- to measure Higgs self-coupling one must observe double Higgs production at lepton or hadron colliders

- **Higgs-strahlung**: dominant around $\sqrt{s} = 500$ GeV





DBD Status for m_H=120 GeV

- Measurement at $\sqrt{s} = 500$ GeV, $\mathcal{L} = 2\ \text{ab}^{-1}$ and $P(e^+e^-) = (0.3, -0.8)$
- here: investigated Higgs mass $m_H = 120$ GeV

modes	signal	background (tt, ZZ, ZZH, ZZZ)	significance excess	significance measurement
$ZHH \to l^-l^+HH$	3.7	4.3	1.5σ	1.1σ
	4.5	6.0	1.5σ	1.2σ
$ZHH \to \nu\bar{\nu}HH$	8.5	7.9	2.5σ	2.1σ
$ZHH \to q\bar{q}HH$	13.6	30.7	2.2σ	2.0σ
	18.8	90.6	1.9σ	1.8σ

- cross-section: $\frac{\delta\sigma_{ZHH}}{\sigma_{ZHH}} = 27\%\ (> 3.5\sigma)$ Higgs self-coupling: $\frac{\delta\lambda}{\lambda} = 44\%$

Next steps

- perform analysis with new $m_H = 125$ GeV samples
- consider low-p_T $\gamma\gamma \to$ hadrons beam induced background
- different starting points for improvement

Summary: lepton channel llHH (preliminary)

1. isolated lepton selection
   - new isolation requirement based on neural nets
   - IsolatedLeptonTaggingProcessor/ZHHll4JLeptonSelectionProcessor → J. Tian
   - new lepton selection strategy increases signal efficiency
2. $\gamma\gamma$-overlay removal ($< N_{\gamma\gamma} = 1.7 >$)
   - FastJetClustering: k_TExclusiveNJets4
   - R-value$=$ 1.3 shows best recovery of bare events
3. force pfos into 4 jets and combine them to two Higgs bosons (smallest χ^2)
4. train separate neural nets for dominant backgrounds after preselection
5. preliminary results: optimised "without overlay" and "with overlay", respectfully

	eeHH (eebbbb)	background
expected	40.50	$1.74 \cdot 10^6$
preselection	23.14 (7.59)	4887.79
	22.86 (7.53)	4933.19
ltype=11	11.38 (3.75)	3323.14
	11.24 (3.72)	3273.43
final	2.79 (2.38)	4.03
	2.35 (2.03)	4.01

	$\mu\mu$HH ($\mu\mu$bbbb)	background
expected	40.50	$1.74 \cdot 10^6$
preselection	23.14 (7.59)	4887.79
	22.86 (7.53)	4933.19
ltype=13	11.77 (3.84)	1564.65
	11.62 (3.81)	1659.76
final	3.09 (2.54)	4.89
	3.01 (2.38)	5.98

Selection strategy for neutrino channel

1. reject events with isolated leptons
2. remove low-p_T $\gamma\gamma \to$ hadrons background
3. force the other reconstructed particles into four jets
4. combine the four jets by choosing combination with smallest χ^2

$$\chi^2 = \frac{(M(j_i j_j) - M(H))^2}{\sigma_H^2} + \frac{(M(j_k j_l) - M(H))^2}{\sigma_H^2}$$

   require: $|M_{\mathrm{H}} - 125\ \mathrm{GeV}| < 80\ \mathrm{GeV}$

5. loose cut on $bmax3 > 0.2$
6. neural net analysis performed separately for signal and each background, output classifiers are used to suppress background

divide background into four different categories:

jets-poor background (vvqq)
semileptonic ttbar background (lvbbqq)
full-hadronic background (6-jets and 4-jets)
backgrounds with same final states (ZZH/ZZZ)

Summary: preliminary preselection for $\nu\nu$-channel

Preselection for samples with overlaid low-p_T $\gamma\gamma \to$ hadrons background

	$\nu\bar{\nu}$HH	$\nu\bar{\nu}$qqH	$\nu\bar{\nu}$bbbb	$\nu\bar{\nu}$bb	lνbbqq	bbqqqq	bbbb
expected no. of events	80.14	447.01	97.08	272802	740098	624060	40234.3
reject evts with iso leptons	62.95	393.14	95.65	270348.35	240016.16	617460.12	39725.04
k_T 1.3 ExclusiveNJets4	62.53	393.09	95.65	270348.36	240016.13	617460.12	39725.04
$\lvert M_{\mathrm{H}} - 125\ \mathrm{GeV}\rvert < 80$ GeV	60.76	384.39	92.12	11063.92	237807.36	559498.11	37327.76
$bmax3 > 0.2$	28.39	74.62	80.89	992.78	40974.54	69697	30921.9

Comparison to samples without $\gamma\gamma$-overlay

	$\nu\bar{\nu}$HH	$\nu\bar{\nu}$qqH	$\nu\bar{\nu}$bbbb	$\nu\bar{\nu}$bb	lνbbqq	bbqqqq	bbbb
expected no. of events	80.14	447.01	97.08	272802	740098	624060	40234.3
reject evts with iso leptons	62.46	392.69	95.58	270371.59	238532.66	617430.18	39714.81
k_T 1.3 ExclusiveNJets4	-	-	-	-	-	-	-
$\lvert M_{\mathrm{H}} - 125\ \mathrm{GeV}\rvert < 80$ GeV	61.07	386.45	93.31	8407.49	236087.28	461720.89	37594.43
$bmax3 > 0.2$	28.53	72.27	81.99	545.42	40679.39	65529	31292.4

Exclusive k_T algorithm recovers event without $\gamma\gamma$-overlay very well.

Neutrino channel: NN training after preselection

After preselection:

- train neural nets for: 4jets background (bbbb)
  semileptonic ttbar background (lvbbqq)
  backgrounds similar to signal final state (ZZH/ZZZ)

Input variables: bbbb vs $\nu\nu$HH

- visible energy
- missing pt
- thrust
- M(Z1) when rec. as ZZ
- M(Z2) when rec. as ZZ
- largest 4jet momentum

Input variables: lvbbqq vs $\nu\nu$HH

- missing mass
- Econemax and plmax
- pcmax and coscjmax
- cosbmax
- number of pfos
- mwtt4j
- mh1 and mh2
- mwtt5j, mt1tt5j, mt2tt5j, mjminjets5
- npfosminjets5

Input variables: ZZZ/ZZH vs llHH

- M(Z) when rec. as ZH
- M(H) when rec. as ZH
- M(Z1) when rec. as ZZ
- M(Z2) when rec. as ZZ
- cosine (ZZH)
- cosine (ZZZ)
- largest mom. (ZZH)
- largest mom. (ZZZ)

Comparison of NN outputs and input variables from analysis w and w/o overlay in backup

Preliminary optimised "without overlay" (15.01.14)

- **cut1**: $E_{vis} < 360$ GeV $+ 0.83 \cdot P_t^{miss}$, $M_Z < 60$ GeV
- **cut2**: $NPFO_{min} > 8$, $M(HH) > 200$ GeV, 92 GeV $< M(H1) <$ 137 GeV, 94 GeV $< M(H2) <$ 135 GeV
- **cut3**: MVAbbbb > 0.89
- **cut4**: MVAlvbbqq > 0.55
- **cut5**: MVAννbbbb > 0.56
- **cut6**: bmax3 + bmax4 > 1.14

Cuts optimised for "without overlay"
and applied to "with overlay"

	ννbb	eνbbqq	μνbbqq	τνbbqq	bbqqqq	bbbb	ννbbbb	ννqqh	bgrd	signal (ννbbbb)
expected	272802	248454	245936	245708	624060	40234.3	97.08	447.01	$1.67 \cdot 10^6$	80.14
preselection	545.42	1787.73	1480.96	37410.7	65529	31292.4	81.98	72.27	138200	28.53 (22.67)
	992.78	1996.63	**318.61**	38659.3	69697.7	30921.9	80.89	74.63	142742	28.39 (22.38)
cut1 (evis,mpt,mz)	481.01	874.99	855.19	24453.2	1239.64	3699.86	80.36	69.74	31754	27.58 (21.89)
	856.82	914.52	159.96	22609	741.45	2921.47	76.96	67.85	28348	25.89 (20.33)
cut2 (npfo,mh1,mh2)	9.80	196.17	222.99	4616.09	214.25	384.15	10.55	20.62	5674.62	16.61 (14.68)
	10.55	214.91	49.26	4299.18	207.01	316.64	10.02	19.96	5127.53	14.29 (12.65)
cut3 (mvabbbb)	5.51	150.47	174.77	3401.85	56.35	7.51	5.95	15.05	3817.46	14.45 (12.72)
	5.57	171.71	38.39	3330.89	85.41	8.17	5.94	15.03	3661.11	11.86 (10.45)
cut4 (mvalvbbqq)	4.29	34.28	50.38	618.86	23.91	5.06	4.01	8.71	749.47	12.78 (11.43)
	3.75	102.22	19.07	1660.07	65.45	7.43	5.14	12.43	1875.56	11.07 (9.88)
cut5 (mvavvbbbb)	2.46	22.82	35.14	415.19	23.58	4.25	0.67	4.12	508.24	11.01 (9.84)
	3.15	54.55	8.62	910.39	52.08	5.45	0.95	4.14	1039.34	7.79 (6.99)
cut6 (bmax34)	0	0	0.16	0.99	0	1.65	0.27	1.43	**4.52**	**5.26 (5.19)**
	0	0	0	5.75	0.24	1.91	0.37	1.43	**9.69**	**3.86 (3.82)**

Preliminary optimised “with overlay” (15.01.14)

- **cut1**: $E_{vis} < 373$ GeV $+ 0.83 \cdot P_t^{miss}$, $M_Z < 60$ GeV
- **cut2**: $Npfos_{min} > 7$, $M(HH) > 200$ GeV, 95 GeV $< M(H1) <$ 140 GeV, 94 GeV $< M(H2) <$ 135 GeV
- **cut3**: MVAbbbb > 0.92
- **cut4**: MVAlvbbqq > 0.67
- **cut5**: MVAννbbbb > 0.56
- **cut6**: bmax3 + bmax4 > 1.2

	ννbb	eνbbqq	μνbbqq	τνbbqq	bbqqqq	bbbb	ννbbbb	ννqqh	bgrd	signal (ννbbbb)
expected	272802	248454	245936	245708	624060	40234.3	97.08	447.01	$1.67 \cdot 10^6$	80.14
preselection	992.78	1996.63	**318.61**	38659.3	69697.7	40921.9	80.89	74.63	142742	28.39 (22.38)
cut1	862.421	995.118	171.55	24672.2	1301.68	3607.56	77.89	69.33	31757.8	26.63 (20.93)
cut2	12.41	250.19	49.81	5156.49	379.23	371.17	9.59	19.39	6248.29	15.11 (13.33)
cut3	5.57	181.48	36.65	3502.48	90.98	6.51	5.23	13.86	3842.77	11.51 (10.12)
cut4	4.35	67.72	11.47	1220.41	57.45	5.14	4.07	9.66	1380.26	9.96 (8.92)
cut5	3.75	37.49	4.5	697.34	45.1	4.15	0.82	3.42	796.58	7.12 (6.39)
cut6	0	0	0	1.07	0.12	1.41	0.28	1.08	**3.96**	**3.26 (3.23)**

Neural nets less effective in analysis with overlay
has to be investigated and improved (NN outputs in backup)
tau background needs better handling

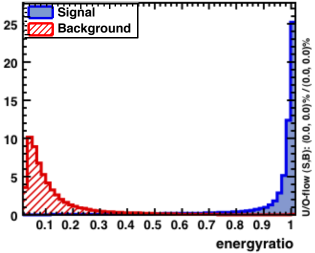
New DiLeptonSelection - Isolation Requirement

old lepton selection - **isolation requirement**:

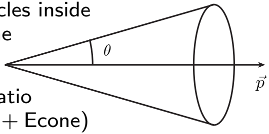
- cut based on energy distributions in calorimeter

new lepton selection - **isolation requirement**:

- neural net based (MVA)
- train neural net with samples for **signal**: eeHH and $\mu\mu$HH
  background: bbbb and lνbbqq
- MVA output is written to lepton collection, can be optimised in final selection
- **Example of input variable: energyratio**



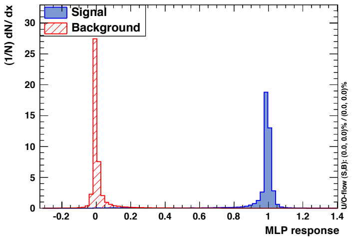
- define cone around direction of rec. particle and sum up energy of particles inside this cone



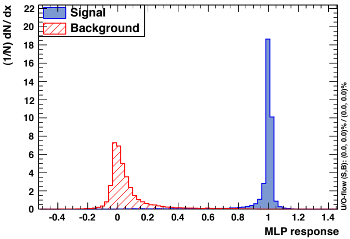
- energyratio is E/(E + Econe)
- isolated lepton has small Econe, so energyratio close to one

New DiLeptonSelection - Isolation Requirement

neural net output for electrons



neural net output for muons



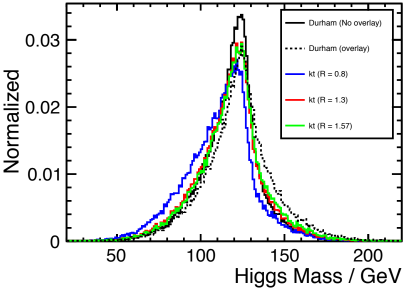
➤ IsolatedLeptonTaggingProcessor/ZHHll4JLeptonSelectionProcessor → J. Tian

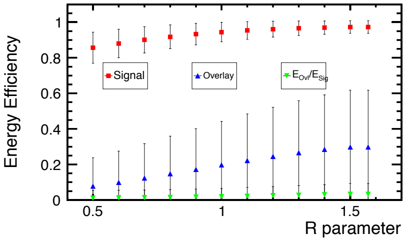
Current Improvement

efficiency (%)	eehh	μμhh	bbbb	eνbbqq	μνbbqq
new selection	86.99	89.11	0.00168	0.315	0.0196
old selection	85.7	88.4	0.028	1.44	0.10

New lepton selection strategy increases signal efficiency.
Suppression of hadronic and one-lepton backgrounds is significantly improved.

Removal of beam induced $\gamma\gamma$ background





- low-p_T $\gamma\gamma \rightarrow$ hadrons overlaid events per interaction:

  $$< N_{\gamma\gamma} >= 1.7$$

  (ILD/SiD standard, but overestimated)
- apply **FastJetClustering:**

  k_TExclusiveNJets4

  which R-value?
- for R $\geq$ 1.2 almost no increase in signal efficiency but in overlay
- best recovery of bare evts **R = 1.3**
- use only reconstructed particles in these 4 jets for analysis