Higgs Self-Coupling Measurement at the ILC.

Claude-Fabienne Dürig[1], Junping Tian[2], Jenny List[1], Keisuke Fujii[2]

[1]DESY Hamburg, Germany
[2]KEK, Japan

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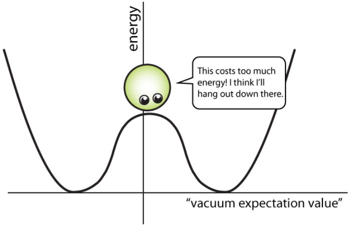
Introduction

- 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

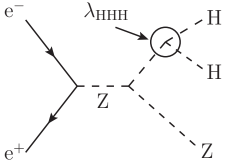
- to probe shape of Higgs potential we need to determine the **Higgs self-coupling**



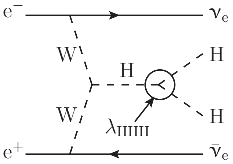
http://www.quantumdiaries.org

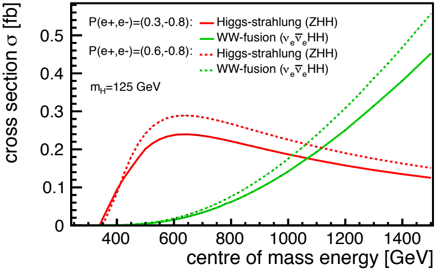
Double Higgs production processes

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



- **WW-fusion**: dominant at high $\sqrt{s}$





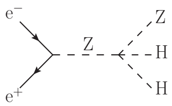
Fundamental difficulties

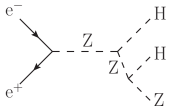
Fundamental difficulties:

- irreducible SM diagrams: significantly degrade the coupling sensitivity
- production cross-sections are small $\longrightarrow$ high luminosities needed
- very large SM background
- low-p_T $\gamma\gamma \rightarrow$ hadrons background (analysis with and without overlay)
- BR($H \rightarrow b\bar{b}$) drop to higher Higgs masses

Irreducible diagrams and sensitivity of self-coupling

- **irreducible diagrams with same final state, but do not concern self-coupling**





- **cross-section σ(ZHH) as a function of λ**

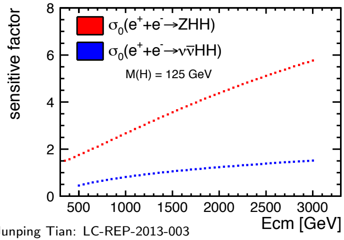
$$\sigma(\lambda) = a\lambda^2 + b\lambda + c$$

a: Higgs self-coupling diagram

b: interference between diagrams

c: irreducible diagrams

- **precision of Higgs self-coupling for $m_H = 125$ GeV**



Junping Tian: LC-REP-2013-003

Higgs-strahlung:

$$\frac{\Delta\lambda}{\lambda} = 1.64 \cdot \frac{\Delta\sigma}{\sigma}$$

WW-fusion:

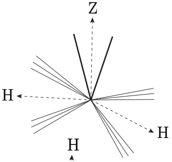
$$\frac{\Delta\lambda}{\lambda} = 0.76 \cdot \frac{\Delta\sigma}{\sigma}$$

w/o interference the factor would be 0.5

Analysis strategy - Decay Channels

$e^+e^- \to$ ZHH	cross-section [fb]	expected no. of events
before discovery (finished analysis): $m_H = 120$ GeV	0.23	460
after discovery (ongoing analysis): $m_H = 125$ GeV	0.20	396

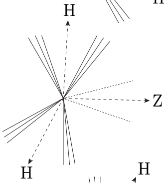
assuming $P(e^+e^-) = (0.3, -0.8)$ at $\mathcal{L} = 2\ ab^{-1}$



$e^+e^- \to ZHH \to l^-l^+HH$

2leptons 4jets mode ($10\% \times 60\% \times 60\% \approx 3.6\%$)

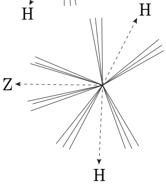
$Z \longrightarrow l\bar{l}$ $H \longrightarrow b\bar{b}$ $H \longrightarrow b\bar{b}$



$e^+e^- \to ZHH \to \nu\bar{\nu}HH$

2neutrino 4jet mode ($20\% \times 60\% \times 60\% \approx 7.2\%$)

$Z \longrightarrow \nu\bar{\nu}$ $H \longrightarrow b\bar{b}$ $H \longrightarrow b\bar{b}$



$e^+e^- \to ZHH \to q\bar{q}HH$

6jets mode ($70\% \times 60\% \times 60\% \approx 25\%$)

$Z \longrightarrow q\bar{q}$ $H \longrightarrow b\bar{b}$ $H \longrightarrow b\bar{b}$

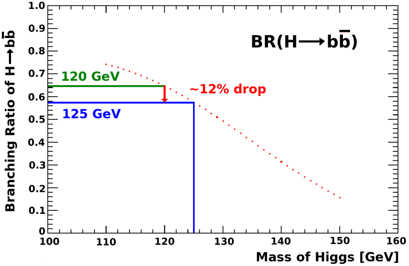
From $m_H = 120$ GeV to $m_H = 125$ GeV

- smaller cross-section σ_{ZHH} to higher Higgs masses

$e^+e^- \to$ ZHH	cross-section [fb]	expected no. of events
$m_H = 120$ GeV	0.23	460
$m_H = 125$ GeV	0.20	396

assuming $P(e^+e^-) = (0.3,-0.8)$ at $\mathcal{L} = 2\ ab^{-1}$

- decreasing branching ratio $BR(H \to b\bar{b})$



Results for 120 GeV, extrapolation to 125 GeV

- measurement at $\sqrt{s} = 500$ GeV, $\mathcal{L} = 2$ ab^{-1} and P$(e^+e^-) = (0.3,-0.8)$
- results for $m_H = 120$ GeV without $\gamma\gamma-$overlay *[Junping Tian, LC-REP-2013-003]*

cross-section: $\frac{\delta\sigma_{ZHH}}{\sigma_{ZHH}} = 27\%$

Higgs self-coupling: $\frac{\delta\lambda}{\lambda} = 44\%$

- result extrapolated to $m_H = 125$ GeV

	500 GeV at $\mathcal{L} = 2$ ab^{-1}		
scenario	A	B	C
$m_H = 120$ GeV	44%	35%	28%
$m_H = 125$ GeV	53%	42%	34%

weighted results

Scenario A: HH $\rightarrow$ bbbb
Scenario B: adding HH $\rightarrow$ bbWW*, expect 20% improvement
Scenario C: analysis improvement (jet-clustering, kinematic fit, etc.), expect 20% improvement

Using ZHH (H $\rightarrow$ b$\bar{\text{b}}$) at $\sqrt{s}$ =500 GeV we would expect a precision of 53% on the Higgs self-coupling for $m_H = 125$ GeV

Analysis strategy $e^+e^- \to ZHH$ at $\sqrt{s} = 500$ GeV

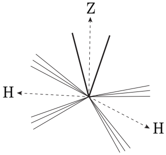
Perform analysis for $m_H = 125$ GeV without and with overlay and investigate the differences

analysis strategy identical to *LC-REP-2013-003*

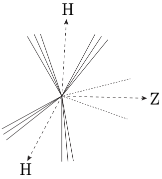
NEW low p_T $\gamma\gamma \to$ hadrons background

- virtual photons which got radiated off the primary beam electrons
- real photons due to bremsstrahlung and synchrotron radiation

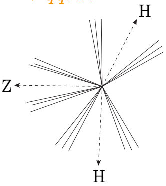
$\to l^- l^+ HH$



$\to \nu\nu HH$



$\to qqHH$



Event selection:

1. isolated lepton selection or rejection
2. $\gamma\gamma$-overlay removal
3. cluster particles into jets and get flavor tag information
4. pair jets to form signal bosons
5. each dominant background is suppressed by training a separate neural net

Strategic difficulties

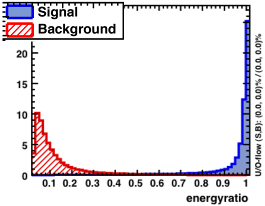
Strategic difficulties:

- flavor tagging and isolated lepton selection: need very high efficiency and purity
- Higgs mass reconstruction: mis-clustering, wrong jet-pairing
- neural net training: train separate neural nets, large statistics needed
- analysis strategy optimised for ZHH, not just self-coupling diagram

Isolated lepton selection

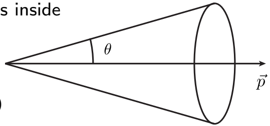
old lepton selection - **isolation requirement**: cut based on energy distributions in calorimeter

new lepton selection - **isolation requirement**: neural net based (MVA)

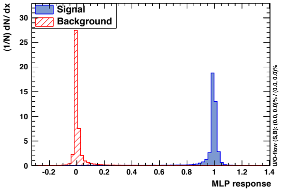


Example of input variable: energyratio

- 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



neural net output for electrons

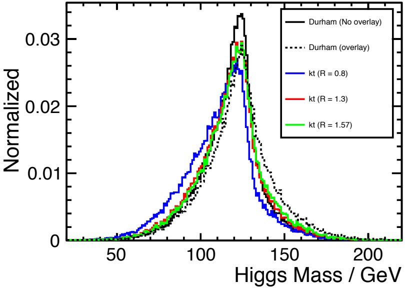


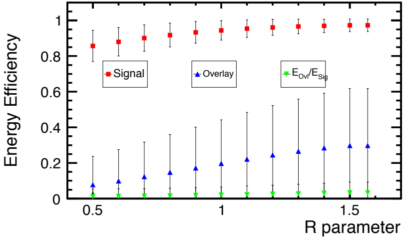
efficiency (%)	eehh	μμhh	bbbb	eνbbqq	μνbbqq
new selection	87.0	89.1	0.0017	0.315	0.020
old selection	85.7	88.4	0.028	1.44	0.10

New lepton selection strategy increases signal efficiency.

Suppression of hadronic and one-lepton backgrounds is significantly improved.

Removal of low-p_T $\gamma\gamma \to$ hadrons background





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

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

  (ILD/SiD standard, but overestimated)

- apply **FastJetClustering:**

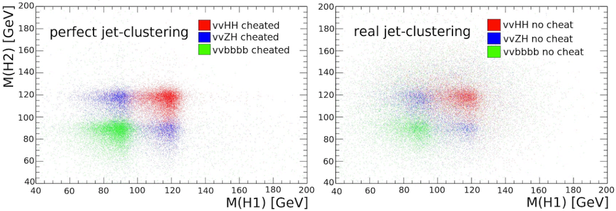
  k_TExclusiveNJets

  which R-value?

- for R ≥ 1.2 almost no increase in signal efficiency but in overlay
- best recovery of bare evts R $= 1.3$
- use only reconstructed particles in the clustered jets for analysis

Jet-clustering

- after isolated lepton selection or rejection cluster remaining particles into jets
- clustering algorithm: Durham algorithm

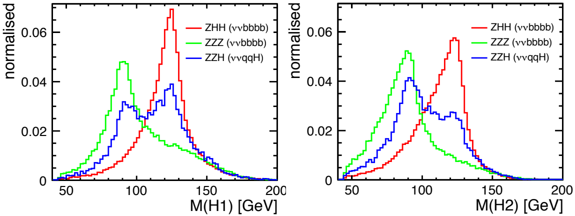


- mis-clustering of particles degrades Higgs mass resolution
- ongoing work: new jet-clustering algorithm
- perfect jet-clustering can improve coupling precision by $\approx 10\%$ or more

Jet-pairing

- combine the jets by choosing combination with smallest χ^2

$$\chi^2 = \underbrace{\underbrace{\frac{(M(j_i j_j) - M(H))^2}{\sigma_H^2} + \frac{(M(j_k j_l) - M(H))^2}{\sigma_H^2}}_{\text{pair 4 jets to H1 and H2}} + \frac{(M(j_m j_n) - M(Z))^2}{\sigma_Z^2}}_{\text{pair 6 jets to H1, H2 and Z}}$$



- Higgs mass resolution important for neural net training (input variables)
- jet-pairing ($\approx$ 70% correct pairing)
- additionally: investigate kinematic fitting

Kinematic Fitting

MarlinKinFit package

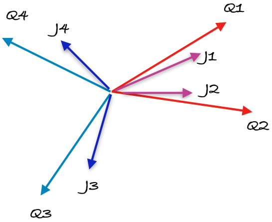
E, p conservation

invariant mass constraints

- $M_{ij} = \mathrm{X\ GeV}$
- $M_{ij} = M_{lk}$
- $M_{ij} = (\mathrm{X} \pm \mathrm{Y})\ \mathrm{GeV}$

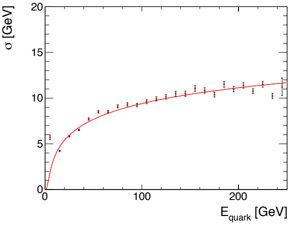
ongoing: implementation in Higgs self-coupling analysis

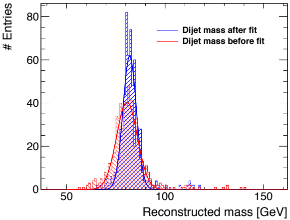
need: jet-quark comparison, association via angle differences



best permutation with smallest sum of angles $\sum \alpha_i$ btw quark & jet

$$\alpha_i = \frac{\vec{p}_{j1} \cdot \vec{p}_{q1}}{|\vec{p}_{j1}| \cdot |\vec{p}_{q1}|}$$





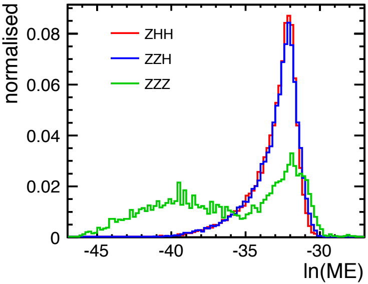
Matrix Element Method

ME tools within Marlin framework, thanks to Junping Tian and Keisuke Fujii

$\longrightarrow$ talk by Junping Tian "Matrix Element Method for ILC physics analysis"

GOAL implement MEM in Higgs self-coupling analysis

1. **next**: use different MEs for better signal/background separation (ZHH, ZZZ, etc.)



Matrix element as from ZHH

2. **future**: optimise selection for self-coupling diagram in ZHH: ME irreducible diagrams,
ME self-coupling diagram

Preliminary results for 125 GeV without overlay

- m_H= 120 GeV results extrapolated to 125 GeV give precision of 53% on Higgs self-coupling
- preliminary results without overlay

modes	signal	background	significance	
			excess	measurement
$ZHH \to l^-l^+HH$	3.0	4.3	1.16σ	0.91σ
	3.3	6.0	1.12σ	0.91σ
$ZHH \to \nu\bar{\nu}HH$	5.4	7.0	1.72σ	1.45σ
$ZHH \to q\bar{q}HH$	9.1	21.3	1.78σ	1.61σ
	9.0	34.7	1.41σ	1.30σ

cross-section: $\frac{\delta\sigma_{ZHH}}{\sigma_{ZHH}} = 32\%$

Higgs self-coupling: $\frac{\delta\lambda}{\lambda} = 52\%$

	500 GeV at $\mathcal{L} = 2\ ab^{-1}$		
scenario	A	B	C
extrapolated	53%	42%	34%
full analysis	52%	41%	33%

Extrapolation works, slightly conservative

Scenario A: $HH \to bbbb$

Scenario B: adding $HH \to bbWW^\star$, expect 20% improvement

Scenario C: analysis improvement (kinematic fit, jet-clustering, etc.) expect 20% improvement

We achieve a precision of 52% on the Higgs self-coupling for $m_H = 125$ GeV!

Effect of $\gamma\gamma$-overlay?

Preliminary results for 125 GeV with overlay

modes	signal	background	significance	
			excess	measurement
ZHH → l^-l^+HH	2.4	4.0	0.94σ	0.72σ
	3.2	7.0	1.01σ	0.83σ
ZHH → $\nu\bar{\nu}$HH	3.8	4.0	1.53σ	1.22σ
ZHH → $q\bar{q}$HH	8.3	22.3	1.59σ	1.44σ
	8.7	39.3	1.29σ	1.19σ

cross-section: $\frac{\delta\sigma_{ZHH}}{\sigma_{ZHH}} = 36.2\%$

Higgs self-coupling: $\frac{\delta\lambda}{\lambda} = 59.4\%$

	500 GeV at $\mathcal{L} = 2$ ab^{-1}		
scenario	A	B	C
w/o overlay	52%	41%	33%
w overlay	59%	48%	38%

Scenario A: HH → bbbb

Scenario B: with HH → bbWW*, ≈ 20% improvement

Scenario C: analysis improvement (kinematic fit, jet-clustering, etc.) expect 20% improvement

Considering $\gamma\gamma$-overlay, we achieve a precision of 59% on the Higgs self-coupling

1 TeV at $\mathcal{L} = 2.5$ ab^{-1}		
A	B	C
16%	13%	10%

arXiv:1310.0763v3[hep-ph]

After 10 years of running ILC we can achieve a precision of 10% on the Higgs self-coupling (w/o overlay)

Summary and Outlook

Ongoing work

- key algorithms: b-tagging, lepton selection, jet-finding, jet-clustering
- **investigate kinematic fitting** (Benjamin Hermberg, DESY)
- **Matrix Element Method** (Junping Tian & Keisuke Fujii, KEK)
- optimise analysis strategy (now optimised for ZHH, not for self-coupling diagram)
- analysis with $H \to WW^\star$ (Masakazu Kurata, University of Tokyo) $\to$ **next talk**

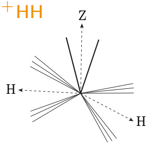
Conclusion

- measuring Higgs self-coupling is fundamental task for next generation LC
- direct determination of Higgs potential through double Higgs production
- measurement of Higgs self-coupling challenging
- considering $\gamma\gamma-$overlay
- preliminary results for $m_H = 125$ GeV gives precision of 59.4% at $\sqrt{s} = 500$ GeV
- starting points for improvement
- **long term perspective**: at 1 TeV achieve precision of $< 10\%$

BACKUP SLIDES

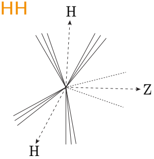
Analysis strategy

$\rightarrow l^- l^+$HH



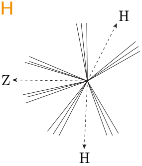
- select two isolated charged leptons consistent with M_Z
- cluster other particles into four jets
- pair four jets to form two Higgs bosons
- neural net analysis performed

$\rightarrow \nu\nu$HH



- reject events with isolated charged leptons
- cluster other particles into four jets
- pair four jets to form two Higgs bosons
- use flavor tagging information
- neural net analysis performed

$\rightarrow qq$HH



- reject events with isolated charged leptons
- cluster other particles into six jets
- pair six jets to form two Higgs bosons and a Z-boson
- use flavor tagging information
- neural net analysis performed

leptonic channel: optimised cuts

ELECTRON TYPE

optimised with overlay

- **cut1**: $|M_Z - 91\text{ GeV}| < 32\text{ GeV}$
- **cut2**: MVAllbb > 0.79
- **cut3**: MVAlvbbqq > 0.81
- **cut4**: bmax3 > 0.22
- **cut5**: MVAllbbbb > 0.3

optimised without overlay

- **cut1**: $|M_Z - 91\text{ GeV}| < 32\text{ GeV}$
- **cut2**: MVAllbb > 0.78
- **cut3**: MVAlvbbqq > 0.62
- **cut4**: bmax3 > 0.18
- **cut5**: MVAllbbbb > 0.25

MUON TYPE

optimised with overlay

- **cut1**: $|M_Z - 91\text{ GeV}| < 32\text{ GeV}$
- **cut2**: MVAllbb > 0.71
- **cut3**: MVAlvbbqq > 0.65
- **cut4**: bmax3 > 0.13
- **cut5**: MVAllbbbb > 0.27

optimised without overlay

- **cut1**: $|M_Z - 91\text{ GeV}| < 32\text{ GeV}$
- **cut2**: MVAllbb > 0.78
- **cut3**: MVAlvbbqq > 0.84
- **cut4**: bmax3 > 0.13
- **cut5**: MVAllbbbb > 0.24

leptonic channel: cutflow - electron type

without overlay

with overlay

	$eebb$	$\mu\mu bb$	$e\nu bbqq$	$\mu\nu bbqq$	$\tau\nu bbqq$	$bbqqqq$	$bbbb$	$llbbbb$	$llqqH$	bgrd	signal ($ll4b$)
expected	284117	49565.7	248454	245936	245708	624060	40234.4	69.5	150.9	$1.7 \cdot 10^6$	40.5
preselection	2697.4	1414.9	520.0	75.0	31.6	4.2	0.4	15.0	129.3	4887.8	23.2 (7.6)
	2660.9	1516.3	509.9	67.9	30.9	4.2	0.4	14.8	128.1	4933.2	22.9 (7.5)
ltype $= 11$	2697.4	0.1	520.0	1.2	29.2	4.2	0.4	7.4	63.3	3323.1	11.4 (3.8)
	2660.9	0.2	509.9	0.5	27.4	4.2	0.4	7.2	62.8	3273.4	11.2 (3.7)
cut1	2383.9	0.1	426.9	0.3	23.4	1.8	0.3	7.1	62.8	2906.6	11.3 (3.7)
	2375.9	0.1	417.6	0.5	19.7	1.8	0.3	7.0	62.2	2885.0	11.1 (3.7)
cut2	38.1	0	245.0	0.2	12.5	1.8	0.1	4.6	43.5	345.8	8.4 (3.5)
	41.7	0	233.3	0	13.0	1.8	0.1	4.3	41.6	335.7	8.3 (3.4)
cut3	34.1	0	24.1	0	2.9	0.6	0	4.3	41.8	107.9	7.9 (3.4)
	37.4	0	24.9	0	2.6	0.6	0	4.0	39.3	108.8	7.5 (3.2)
cut4	3.5	0	0.9	0	0.3	0.3	0	3.9	9.5	18.6	3.9 (3.1)
	3.5	0	1.4	0	0.3	0.3	0	3.5	7.8	16.9	3.4 (2.8)
cut5	0.7	0	0.2	0	0	0.2	0	0.6	2.6	4.3	3.0 (2.5)
	0.8	0	0.5	0	0	0.2	0	0.5	2.0	4.0	2.4 (2.0)

leptonic channel: cutflow - muon type

without overlay

with overlay

	$eebb$	$\mu\mu bb$	$e\nu bbqq$	$\mu\nu bbqq$	$\tau\nu bbqq$	$bbqqqq$	$bbbb$	$llbbbb$	$llqqh$	bgrd	signal ($ll4b$)
expected	284117	49565.7	248454	245936	245708	624060	40234.4	69.5	150.9	$1.7 \cdot 10^6$	40.5
preselection	2697.4	1415.0	520.0	75.0	31.6	4.2	0.4	15.0	129.3	4887.8	23.2 (7.6)
	2660.9	1516.3	509.9	67.9	30.9	4.2	0.4	14.8	128.1	4933.2	22.9 (7.5)
ltype $= 13$	0	1414.9	0	73.8	2.5	0	0	7.6	66.0	1564.7	11.8 (3.8)
	0	1516.1	0	67.4	3.5	0	0	7.5	65.3	1659.8	11.6 (3.8)
cut1	0	1363.4	0	61.7	2.2	0	0	7.4	65.5	1500.2	11.7 (3.8)
	0	1461.8	0	55.3	3.2	0	0	7.3	64.8	1592.4	11.5 (3.8)
cut2	0	35.7	0	30.6	1.6	0	0	4.8	45.1	117.9	8.8 (3.6)
	0	49.3	0	29.6	2.2	0	0	4.9	46.0	132.0	9.1 (3.5)
cut3	0	33.2	0	2.0	0.3	0	0	4.5	42.7	82.6	8.0 (3.4)
	0	48.5	0	5.6	0.3	0	0	4.9	45.1	104.4	8.6 (3.5)
cut4	0	4.4	0	0	0	0	0	4.2	10.9	19.6	4.2 (3.2)
	0	8.4	0	0.59	0	0	0	4.6	12.2	25.8	4.5 (3.3)
cut5	0	1.7	0	0	0	0	0	0.9	3.4	6.0	3.3 (2.6)
	0	2.0	0	0.6	0	0	0	0.8	3.6	7.0	3.2 (2.5)

neutrino channel: optimised cuts

optimised with overlay

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

optimised without overlay

- **cut1**:
  $E_{vis} < 364\ \text{GeV} + 0.83 \cdot P_t^{miss}$,
  $M_Z < 60\ \text{GeV}$
- **cut2**:
  $\text{npfos}_{min} > 6$,
  $\text{M(HH)} < 200\ \text{GeV}$,
  $100\ \text{GeV} < \text{M(H1)} < 139\ \text{GeV}$,
  $91\ \text{GeV} < \text{M(H1)} < 134\ \text{GeV}$
- **cut3**: MVAbbbb > 0.93
- **cut4**: MVAlvqqqq > 0.66
- **cut5**: MVAvvbbbb > 0.56
- **cut6**: bmax3 + bmax4 > 1.08

neutrino channel: cutflow table

without overlay

with overlay

	ννbb	eνbbqq	μνbbqq	τνbbqq	bbqqqq	bbbb	ννbbbb	ννqqh	bgrd	signal (νν4b)
expected	272802	248454	245936	245708	624060	40234.3	97.1	447.0	$1.7 \cdot 10^6$	80.1
preselection	545.4	1787.7	1480.9	37410.7	65529	31292	81.9	72.3	138200	28.5 (22.7)
	992.8	1996.6	1661.7	38659.3	69698	30922	80.9	74.6	144086	28.4 (22.4)
cut1	481.0	894.1	867.4	25002.4	1443.6	3943.2	80.5	70.1	32782.4	27.7 (22.0)
	862.4	989.7	929.3	24532.0	1247.8	3552.6	77.8	69.2	32260.9	26.6 (20.9)
cut2	6.7	208.0	225.3	5161.1	252.8	382.9	9.7	19.6	6266.3	16.8 (14.8)
	5.6	163.7	154.3	2951.7	270.5	211.5	4.8	8.6	3770.8	11.6 (10.4)
cut3	4.3	181.5	196.8	4325.4	121.6	13.3	6.4	15.9	4865.2	14.9 (13.1)
	2.4	110.9	112.1	1938.3	61.7	4.1	2.4	6.4	2238.4	8.6 (7.7)
cut4	4.3	34.5	45.3	602.9	42.8	7.7	4.1	8.5	750.3	11.8 (10.6)
	2.4	44.1	45.8	624.5	38.0	3.3	1.9	4.7	764.7	7.5 (6.8)
cut5	3.1	24.9	35.1	454.7	41.9	6.5	1.4	4.4	527.0	9.9 (8.9)
	2.4	37.3	39.8	568.3	36.9	3.1	1.3	4.1	693.3	7.1 (6.4)
cut6	0	0	0	1.6	0.1	3.0	0.6	1.7	7.0	5.4 (5.3)
	0	0	0	0.6	0.1	1.3	0.6	1.4	4.0	3.8 (3.8)

hadronic channel: opt. cuts - dominant bbHH

optimised with overlay

- **cut1**: prop31 + prob32 > 0.54
- **cut2**:
  $P_t^{\text{miss}} < 77$ GeV,
  npfos > 245,
  37 GeV $<$ M(Z) < 136 GeV,
  83 GeV $<$ M(H1) < 159 GeV,
  62 GeV $<$ M(H1) < 162 GeV
- **cut3**: MVAbbbb > 0.83
- **cut4**: MVAbbqqq > 0.51
- **cut5**: MVAqqbbbb > 0.16
- **cut6**: bmax3 + bmax4 > 1.21

optimised without overlay

- **cut1**: prop31 + prob32 > 0.54
- **cut2**:
  $P_t^{\text{miss}} < 80$ GeV,
  npfos > 246,
  34 GeV $<$ M(Z) < 136 GeV,
  81 GeV $<$ M(H1) < 170 GeV,
  73 GeV $<$ M(H1) < 167 GeV
- **cut3**: MVAbbbb > 0.71
- **cut4**: MVAbbqqq > 0.48
- **cut5**: MVAqqbbbb > 0.14
- **cut6**: bmax3 + bmax4 > 1.22

hadronic channel: cutflow - dominant bbHH

without overlay

with overlay

	bbbb	lνbbqq	bbuddu	bbcsdu	bbcssc	qqbbbb	qqqqh	ttz	ttg	bgrd	signal (6b)
expected	40234.3	740098	156144	312013	155904	140.5	662.6	2197.2	2109.5	$1.4 \cdot 10^6$	273.13
preselection	23233.7	16136.2	570.0	6167.0	12588.5	83.6	114.7	166.4	428.9	59488.9	81.6 (59.7)
	23589.4	18813.7	952.9	8143.2	14255.2	83.5	116.2	175.1	434.6	66563.9	81.8 (59.4)
cut1	2294.9	318.2	11.4	90.4	261.4	14.2	15.4	16.9	45.3	3068.3	19.1 (16.1)
	2681.6	496.0	20.0	165.7	376.6	14.8	16.3	17.9	48.8	3837.9	19.6 (16.4)
cut2	673.8	109.0	11.3	82.2	246.1	12.9	14.5	14.8	31.9	1196.5	18.3 (15.6)
	796.2	185.7	18.2	148.9	341.6	12.9	14.9	15.1	33.0	1566.6	18.3 (15.7)
cut3	11.9	18.7	9.9	67.4	201.5	9.1	12.3	13.3	26.7	371.0	16.2 (14.3)
	11.5	21.2	12.7	109.0	242.8	7.4	10.9	12.7	24.8	453.1	14.9 (13.1)
cut4	10.0	14.8	7.3	48.6	130.9	8.1	11.4	12.7	24.8	268.7	15.6 (13.8)
	10.1	17.3	9.9	77.2	160.5	6.2	9.9	12.1	22.4	325.9	14.1 (12.4)
cut5	9.5	14.0	7.3	47.2	127.5	7.1	11.1	12.5	24.3	260.5	15.4 (13.7)
	9.6	17.0	9.7	74.5	157.1	5.6	9.7	12.2	22.3	317.8	13.9 (12.3)
cut6	3.8	0	0.7	0.7	3.0	3.2	5.0	2.3	2.7	21.3	9.1 (8.5)
	2.7	0	0.3	2.2	4.2	2.3	4.5	2.4	3.0	22.3	8.3 (7.8)

hadronic channel: opt. cuts - dominant light qqHH

optimised with overlay

- **cut1**: prop31 + prob32 < 0.54
- **cut2**:
  $P_t^{\text{miss}} < 77$ GeV,
  npfos > 245,
  65 GeV $<$ M(Z) $<$ 133 GeV,
  100 GeV $<$ M(H1) $<$ 136 GeV,
  96 GeV $<$ M(H1) $<$ 141 GeV
- **cut3**: MVAbbbb > 0.73
- **cut4**: MVAbbqqqq > 0.52
- **cut5**: MVAqqbbbb > 0.11
- **cut6**:
  bmax3 > 0.92,
  bmax3 + bmax4 > 1.37

optimised without overlay

- **cut1**: prop31 + prob32 < 0.54
- **cut2**:
  $P_t^{\text{miss}} < 80$ GeV,
  npfos > 246,
  64 GeV $<$ M(Z) $<$ 129 GeV,
  104 GeV $<$ M(H1) $<$ 134 GeV,
  98 GeV $<$ M(H1) $<$ 140 GeV
- **cut3**: MVAbbbb > 0.59
- **cut4**: MVAbbqqqq > 0.43
- **cut5**: MVAqqbbbb > 0.15
- **cut6**:
  bmax3 > 0.91,
  bmax3 + bmax4 > 1.38

hadronic channel: cutflow - dominant light qqHH

without overlay

with overlay

	bbbb	lνbbqq	bbuddu	bbcsdu	bbcssc	qqbbbb	qqqqh	ttz	ttg	bgrd	signal (6b)
expected	40234.3	740098	156144	312013	155904	140.5	662.6	2197.2	2109.5	$1.41 \cdot 10^6$	273.13
preselection	23233.7	16136.2	570.0	6167.0	12588.5	83.6	114.7	166.4	428.9	59488.9	81.6 (59.7)
	23589.4	18813.7	952.9	8143.2	14255.2	83.5	116.2	175.1	434.6	66563.9	81.8 (59.4)
cut1 (probZ)	20938.8	15818.0	558.6	6076.6	12327.1	69.3	99.2	149.5	383.6	56420.7	62.5 (43.6)
	20907.8	18317.7	932.9	7977.5	13878.5	68.7	99.9	157.2	385.8	62726.0	62.1 (43.0)
cut2 (m,pfos,pt)	158.6	212.7	65.5	800.0	1552.1	5.2	13.3	21.8	41.5	2870.9	20.7 (17.7)
	196.2	338.7	141.1	1263.7	2132.6	6.8	17.2	27.2	49.6	4173.1	21.9 (18.4)
cut3 (mlp1)	12.3	81.8	62.4	741.1	1431.1	4.6	12.4	21.5	40.1	2407.3	19.5 (16.8)
	13.9	134.0	128.8	1116.5	1866.8	5.6	15.1	26.5	47.4	3354.6	19.8 (16.7)
cut4 (mlp2)	11.8	65.5	51.6	549.8	989.3	4.5	12.2	21.1	38.9	1744.8	19.2 (16.6)
	11.9	109.6	82.1	666.7	1034.3	5.1	14.1	25.2	42.7	1991.9	19.0 (16.1)
cut5 (mlp3)	11.3	64.7	50.3	541.7	973.4	4.1	12.1	21.1	38.7	1717.4	19.1 (16.5)
	11.8	109.6	81.2	661.7	1028.9	4.9	14.0	25.2	42.6	1979.9	18.9 (16.0)
cut6 (bmax3)	4.6	0.3	2.9	5.2	4.9	1.7	4.6	4.3	6.0	34.7	9.0 (8.2)
	5.6	0.5	2.4	6.2	5.1	2.0	5.8	5.0	6.6	39.3	8.7 (7.9)

Preliminary results for m_H= 125 GeV with overlay

preliminary results for m_H= 125 GeV without overlay:

modes	signal	background	significance	
			excess	measurement
ZHH → l^-l^+HH	3.0	4.3	1.16σ	0.91σ
	3.3	6.0	1.12σ	0.91σ
ZHH → $\nu\bar{\nu}$HH	5.4	7.0	1.72σ	1.45σ
ZHH → $q\bar{q}$HH	9.1	21.3	1.78σ	1.61σ
	9.0	34.7	1.41σ	1.30σ

We achieve a combined signal significance of $s\sigma = 3.8\sigma$
We achieve a precision on the Higgs self-coupling without weighting of 56.7%

preliminary results for m_H= 125 GeV with overlay:

modes	signal	background	significance	
			excess	measurement
ZHH → l^-l^+HH	2.4	4.0	0.94σ	0.72σ
	3.2	7.0	1.01σ	0.83σ
ZHH → $\nu\bar{\nu}$HH	3.8	4.0	1.53σ	1.22σ
ZHH → $q\bar{q}$HH	8.3	22.3	1.59σ	1.44σ
	8.7	39.3	1.29σ	1.19σ

Considering overlay, we achieve a combined signal significance of $s\sigma = 2.9\sigma$
We achieve a precision on the Higgs self-coupling without weighting of 63%

Cross-section and self-coupling determination

- Cross-section measurement via parameter estimation through **minimum likelihood method**
- Define likelihood:

$$L_{s+b} = \prod_i \frac{e^{-(s_i+b_i)}}{n_i!}(s_i + b_i)^{n_i}$$

$$L_b = \prod_i \frac{1}{n_i!} e^{-b_i} b_i^{n_i}$$

- Only s_i (i = search mode) is related to σ_{ZHH}: $s_i = \sigma_{ZHH} \cdot \mathcal{L} \cdot BR_i \cdot \epsilon_i$

- Minimisation of

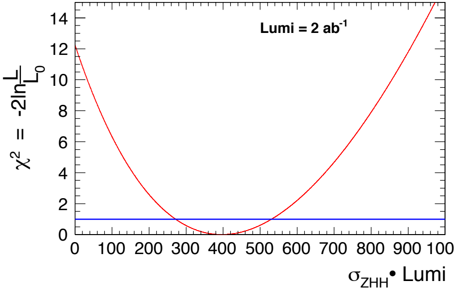
$$\chi^2 = -2\ln(\frac{L_b}{L_{s+b}})$$

gives minimum $\sigma_{ZHH} \cdot \mathcal{L}$

- Precision of Higgs self-coupling:

$$\frac{\Delta\lambda}{\lambda} = 1.64 \cdot \frac{\Delta\sigma}{\sigma}$$

for $m_H = 125$ GeV at $\sqrt{s} = 500$ GeV



Excess and measurement significance

excess significance: assuming there is no signal, the probability of observing events equal or more than the expected number of events $(N_S + N_B)$

$$p = \int_{N_S+N_B}^{\infty} f(x; N_B)dx$$

in case of large statistics: $\frac{N_S}{\sqrt{N_B}}$

measurement significance: assuming signal exists, the probability of observing events equal or less than the expected number of background events (N_B)

$$p = \int_{-\infty}^{N_B} f(x; N_S + N_B)dx$$

in case of large statistics: $\frac{N_S}{\sqrt{N_S+N_B}}$

convert to gaussion significance (s):

$$1 - p = \int_{-\infty}^{s\sigma} N(x; 0, 1)dx$$

LHC results on the self-coupling measurement
arXiv:1308.6302v2[hep-ph] by Weiming Yao

- process used: $HH \to bb\gamma\gamma$
- investigated energies: $\sqrt{s} = 14$ TeV, $\sqrt{s} = 33$ TeV, $\sqrt{s} = 100$ TeV
- integrated luminosity: $\mathcal{L} = 3\ ab^{-1}$

energy	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 33$ TeV	$\sqrt{s} = 100$ TeV
precision	50%	20%	8%

- high luminosity running at $\sqrt{s} = 14$ TeV, possible to observe signal with statistical significance of 2.3σ with $\mathcal{L} = 3\ ab^{-1}$ of data
- at $\sqrt{s} = 33\ \mathrm{TeV}$, expect to observe signal with statistical significance of 6.2σ with $\mathcal{L} = 3\ ab^{-1}$
- at $\sqrt{s} = 100\ \mathrm{TeV}$, expect to observe signal with statistical significance of 15.0σ with $\mathcal{L} = 3\ ab^{-1}$

Durham clustering algorithm

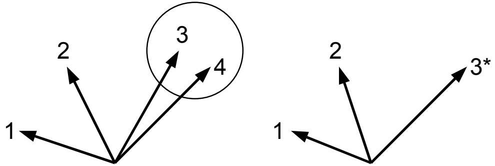
- Durham algorithm clusters the 2 objects i and j with the smallest mutual angle θ_{ij} and energy min(E_i^2, E_j^2).
- **algorithm work iterative**: beginning with a list of jets that are all just particles
- between every particle pair (i,j) the relative distance y_{ij} is determined from
  - the energies E_i, E_j of the particles
  - and their mutual angle θ_{ij}

  by:

$$y_{ij} = \frac{2\text{min}(E_i^2, E_j^2)(1 - cos\theta_{ij})}{E_{vis}^2}$$

- two particles with smallest relative distance value y_{ij} are combined to a new object with four-momentum:

$$p_k^\mu = p_i^\mu + p_j^\mu$$



In figure object 3 and 4 are clustered to a new object $3^\star$.

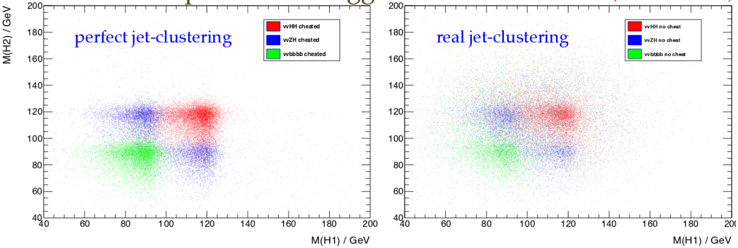
New Jet-clustering (Junping Tian & Keisuke Fujii)

Junping Tian ECFA 2013 talk (DBD full simulation with 120 GeV Higgs boson)

Color-singlet Jet-clustering

(challenging)

scatter plot of two Higgs masses vvHH mode: (ZZH and ZZZ)



- the mis-clustering of particles degrades the mass resolution very much
- it is studied using perfect color-singlet jet-clustering can improve $\delta\lambda \sim 40\%$
- Mini-jet based clustering (Durham works when Np in mini-jet ~ 5, need better algorithm to combine the mini-jets, using such as color-singlet dynamics: rapidity gap, coplanarity, energy pdf)