Higgs Self-Coupling Measurement at the ILC.

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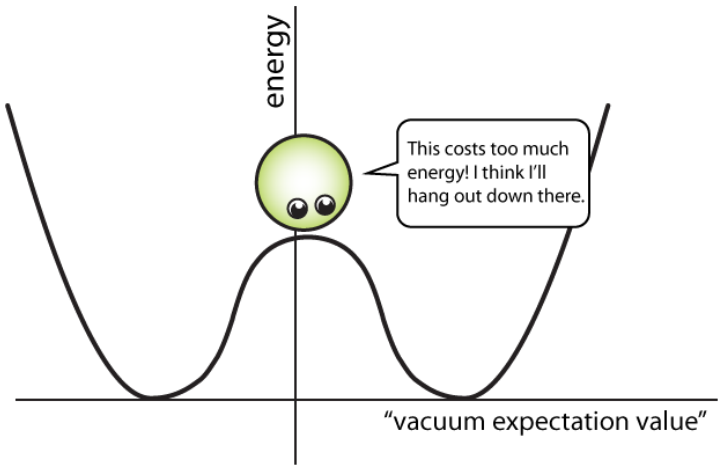
Introduction

- 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

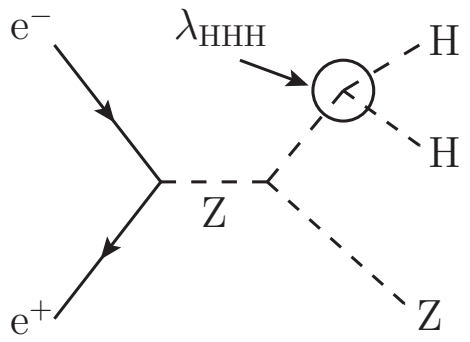
- to probe shape of Higgs potential we need to determine the **Higgs self-coupling**



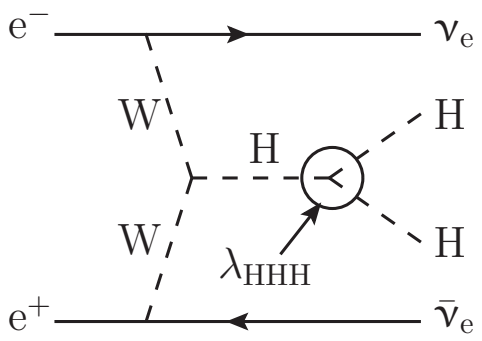
http://www.quantumdiaries.org

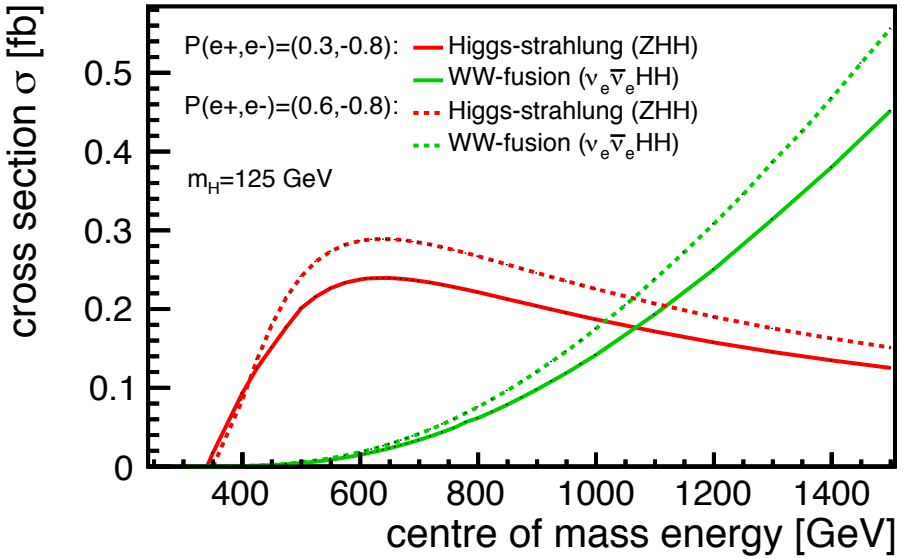
Double Higgs production processes

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



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





Fundamental difficullties of the analysis

fundamental difficulties:

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

Irreducible diagrams and sensitivity of self-coupling

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

example for ZHH:

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

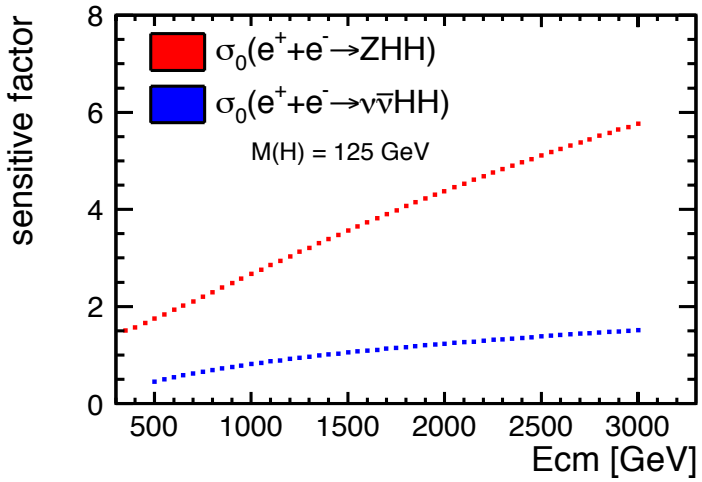
$$\sigma(\lambda) = a\lambda^2 + b\lambda + c$$

a: Higgs self-coupling diagram

b: interference between diagrams

c: irreducible diagrams

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



Higgs-strahlung:

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

WW-fusion:

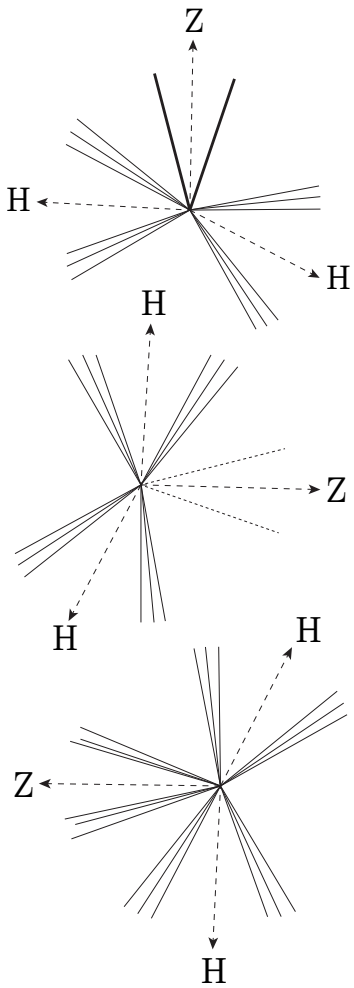
$$\frac{\Delta\lambda}{\lambda} = 0.85 \cdot \frac{\Delta\sigma}{\sigma}$$

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% × 60% × 60% ≈ 3.6%)

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

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

2neutrino 4jet mode (20% × 60% × 60% ≈ 7.2%)

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

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

6jets mode (70% × 60% × 60% ≈ 25%)

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

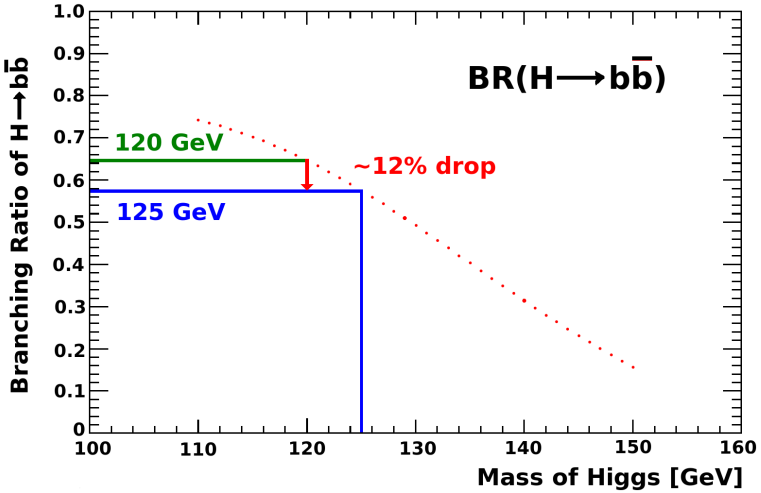
From $m_H = 120$ GeV to $m_H = 125$ GeV

- 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$(e^+e^-) = (0.3,-0.8)$
investigated Higgs mass $m_H = 120$ GeV (finished) and $m_H = 125$ GeV (ongoing)

- 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%

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

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

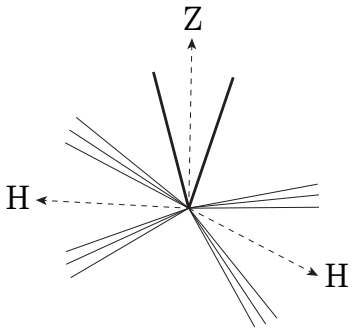
Analysis strategy $e^+e^- \to ZHH$ at $\sqrt{s} = 500$ GeV

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

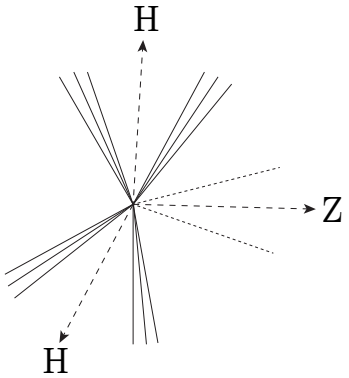
NEW low p_T $\gamma\gamma \to$ hadrons background

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

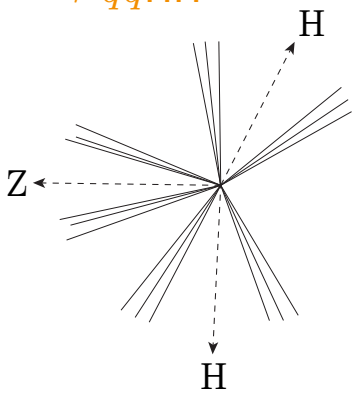
$\to l^- l^+ HH$



$\to \nu\nu HH$



$\to qq HH$



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

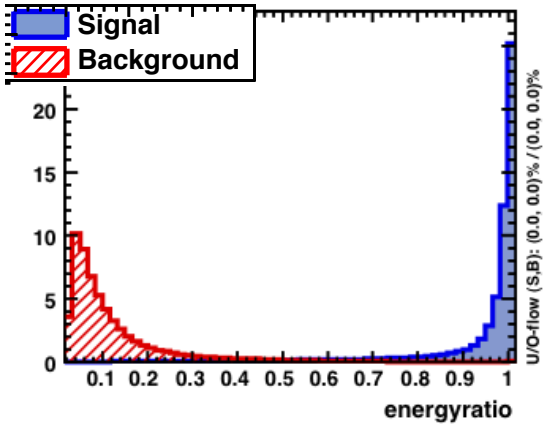
strategic difficulties:

- 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

Isolated lepton selection

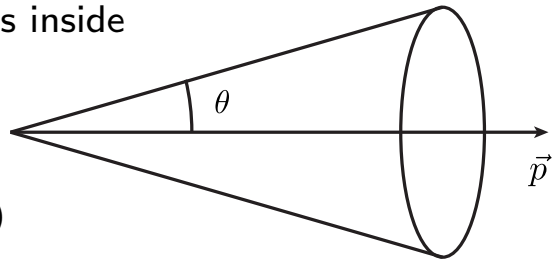
old lepton selection - isolation requirement: cut based on energy distributions in calorimeter

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

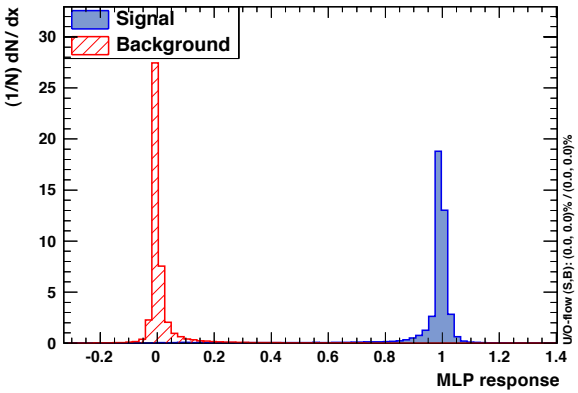


Example of input variable: energyratio

- 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



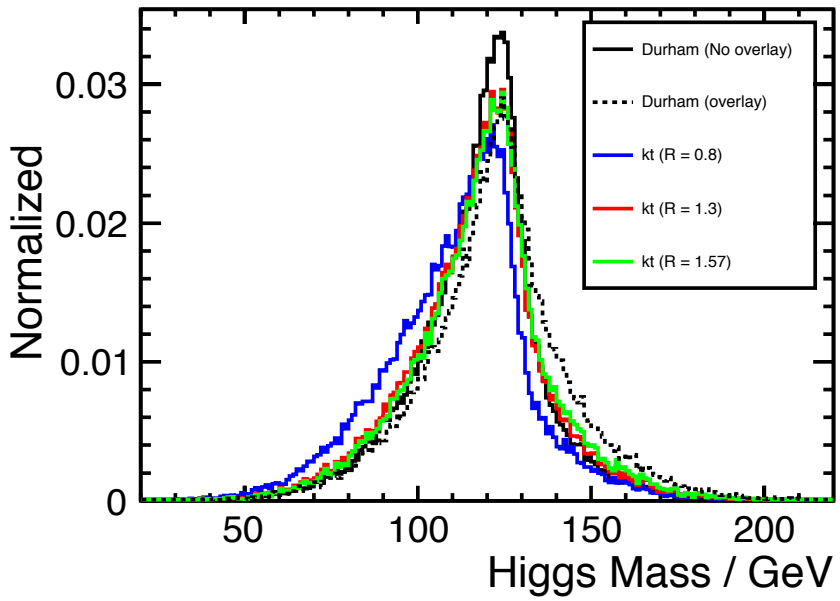
neural net output for electrons

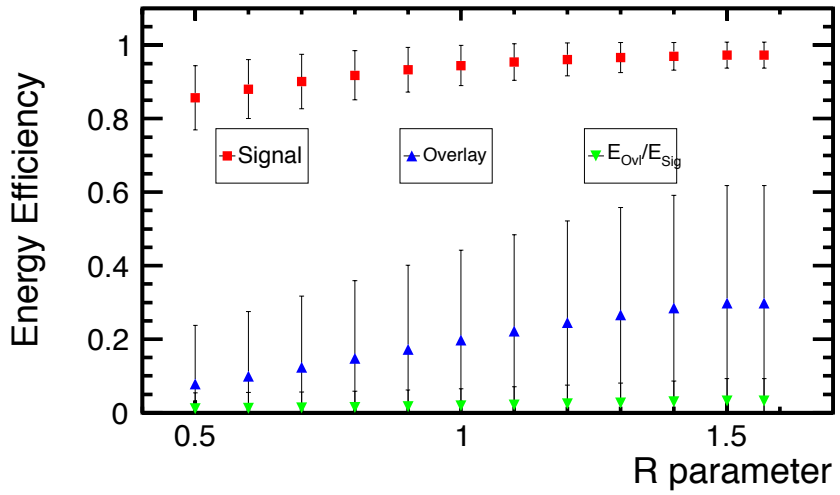


efficiency (%)	eehh	μμhh	bbbb	eνbbqq	μνbbqq
new selection	87.0	89.1	0.0017	0.315	0.020
old selection	85.7	88.4	0.028	1.44	0.10

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_T**ExclusiveNJets**

  which R-value?

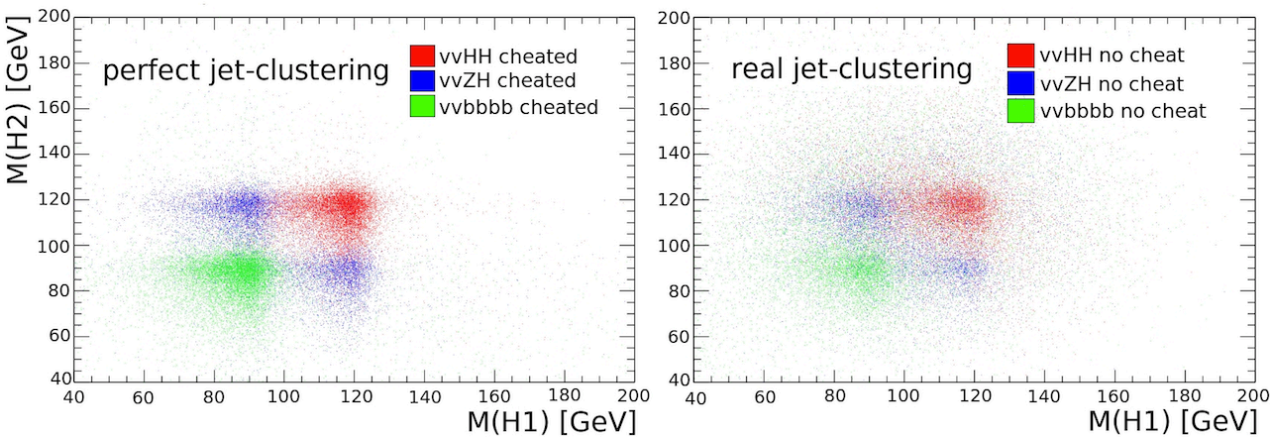
- for R ≥ 1.2 almost no increase in signal efficiency but in overlay

- 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

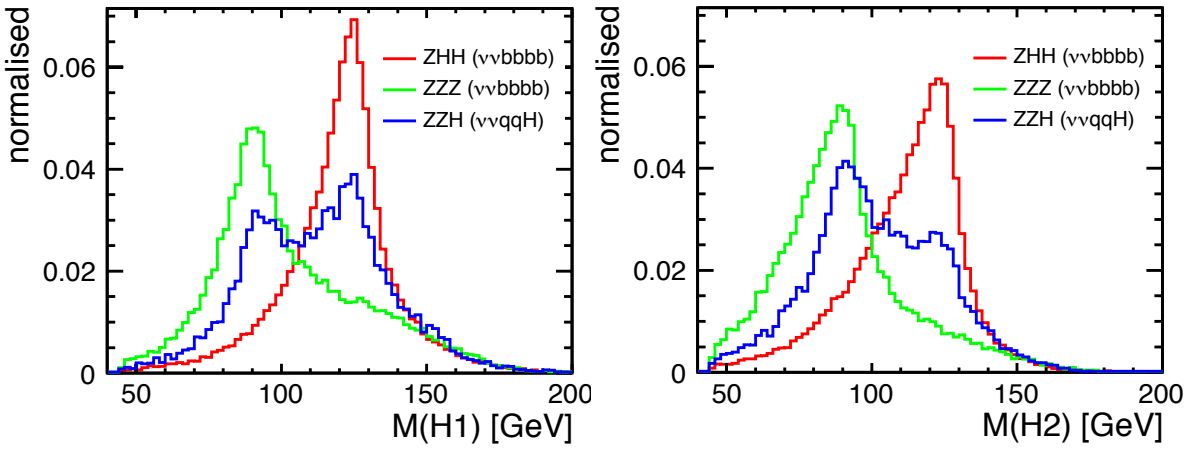


- mis-clustering of particles degrades Higgs mass resolution
- ongoing work: new jet-clustering algorithm
- perfect jet-clustering can improve coupling precision by $\approx 10\%$ or more

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

Preliminary results for 125 GeV without overlay

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

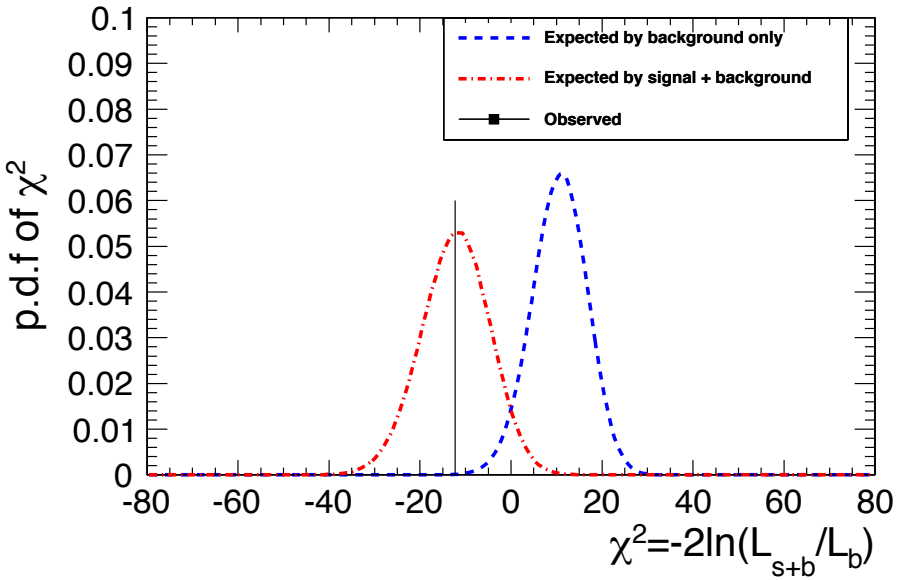
null hypothesis H_0 (B only)
alternative hypothesis H_1 (S+B)

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

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

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

s_i: expected number of signal events
b_i: expected number of background events
n_i: total number of observed events



We achieve a combined signal significance of $s\sigma = 3.8\sigma$

Preliminary results of analysis for 125 GeV

- results extrapolated to m_H= 125 GeV give a precision of 53% on the Higgs self-coupling
- preliminary results for m_H= 125 GeV

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 $\rightarrow$ bbbb
Scenario B: adding HH $\rightarrow$ bbWW*, expect 20% improvement
Scenario C: analysis improvement (jet-clustering, kinematic fit, 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 m_H= 125 GeV with overlay

preliminary results for m_H= 125 GeV 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

We achieve a combined signal significance of $s\sigma = 3.8\sigma$

preliminary results for m_H= 125 GeV with overlay:

modes	signal	background	significance	
			excess	measurement
$ZHH \to l^- l^+ HH$	2.4	4.0	0.94σ	0.72σ
	3.2	7.0	1.01σ	0.83σ
$ZHH \to \nu\bar{\nu}HH$	3.8	4.0	1.53σ	1.22σ
$ZHH \to q\bar{q}HH$	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 $s\sigma = 2.9\sigma$

Preliminary results of analysis for 125 GeV

- results without overlay for $m_H = 125$ GeV give a precision of 52% on the Higgs self-coupling
- preliminary results for $m_H = 125$ GeV with overlay

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
without overlay	52%	41%	33%
with overlay	59%	48%	38%

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

results w/o overlay for $125\ \mathrm{GeV}$
arXiv:1310.0763v3[hep-ph]

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

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

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
- analysis with $H \rightarrow WW^{\star}$ mode
- optimise analysis strategy (current selections are optimised for ZHH, not for the self-coupling diagram)

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

Staged running programme (Higgs part)

250 fb^{-1} (ILC$_{250}$)/1150 fb^{-1}(ILC$_{\mathrm{LumUp}}$) at 250 GeV

- Higgs mass, spin, CP
- absolute HZZ coupling
- total width (initial)
- BR(H$\rightarrow$bb,cc,$\gamma\gamma$,$\tau\tau$,WW*,ZZ*,$\gamma\gamma$,γZ)

500 fb^{-1} (ILC$_{500}$)/1600 fb^{-1}(ILC$_{\mathrm{LumUp}}$) at 500 GeV

- WW-fusion fully activated, absolute HWW coupling
- total Higgs width $\rightarrow$ absolute normalisation of other couplings
- Top-Yukawa coupling through ttγ
- Higgs self-coupling through ZHH
- BRs with high statistics

1000 fb^{-1}(ILC$_{1000}$)/2500 fb^{-1}(ILC$_{\mathrm{LumUp}}$) at 1 TeV

- accumulate much more Higgs events
- H$\rightarrow$ $\mu\mu$ accessible
- improve Top-Yukawa coupling
- Higgs self-coupling through $\nu\nu$HH

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

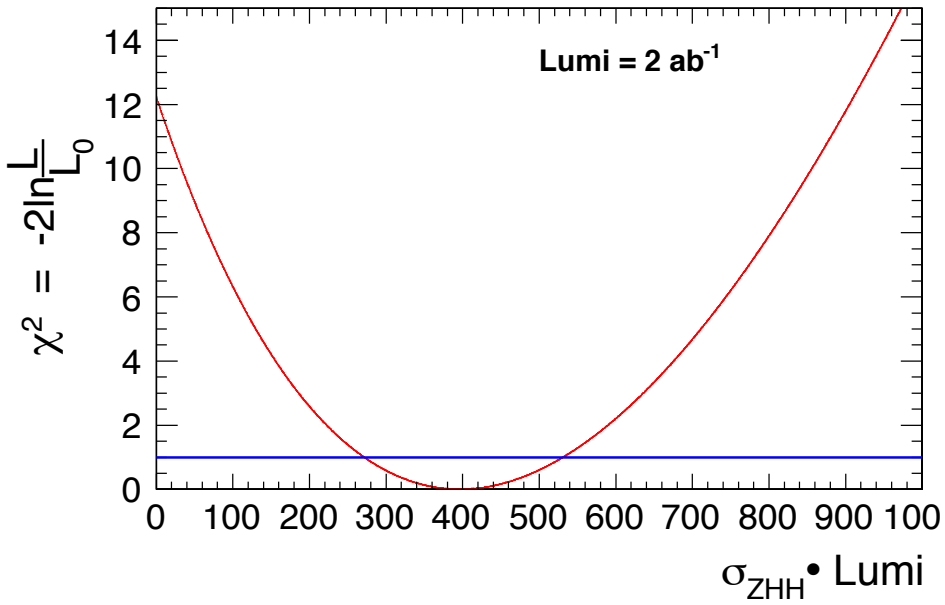
$$\chi^2 = -2\ln(\frac{L_b}{L_{s+b}})$$

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):

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

Higgs self-coupling programme at ILC

full simulation finished with $m_H = 120$ GeV, extrapolated to $m_H = 125$ GeV

ILC

500 GeV: 500 fb^{-1}
1000 GeV: 1000 fb^{-1}

LumiUp

500 GeV: 1600 fb^{-1}
1000 GeV: 2500 fb^{-1}

	500 GeV			500 GeV and 1 TeV		
scenario	A	B	C	A	B	C
ILC	104%	83%	66%	26%	21%	17%
ILC_{LumUp}	58%	46%	37%	16%	13%	10%

Scenario A: $HH \to bbbb$

Scenario B: by adding $HH \to bbWW^\star$ (full simulation ongoing) expect 20% relative improvement

Scenario C: future improvement (jet-clustering), expect 20% relative improvement (conservative)

LHC results on the self-coupling measurement

arXiv:1308.6302v2[hep-ph] by Weiming Yao

- process used: HH $\rightarrow$ 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 $\sqrt{s} = 33$ TeV, expect to observe signal with statistical significance of 6.2σ with $\mathcal{L} = 3$ ab^{-1}
- at $\sqrt{s} = 100$ 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

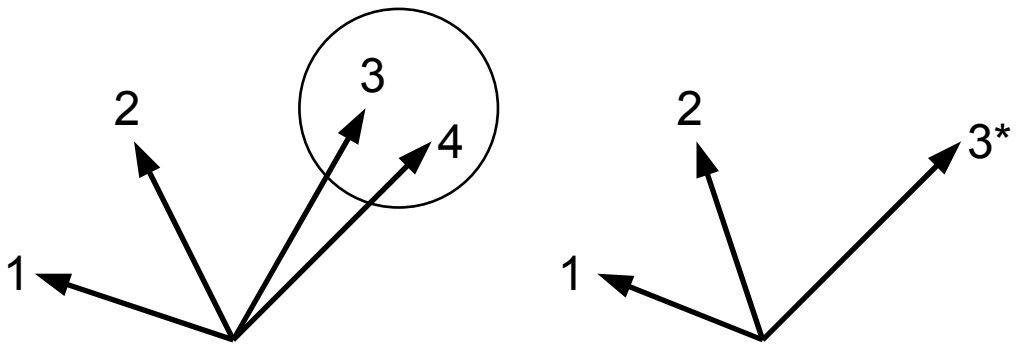
  - the energies E_i, E_j of the particles
  - and their mutual angle θ_{ij}

  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 $3^\star$.

The International Linear Collider

- energy range: $\sqrt{s} = 250$ GeV $-$ 1 TeV
- about 31 km site length for $\sqrt{s} = 500$ GeV
- two movable detectors ("push-pull")
- polarised beams ($\approx 80\%$ for e^- and $\approx 30\% - 60\%$ for e^+)
- analysis for International Large Detector (ILD)