Update on Higgs self-coupling analyses for ILD.

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ALCW15, April 24th 2015

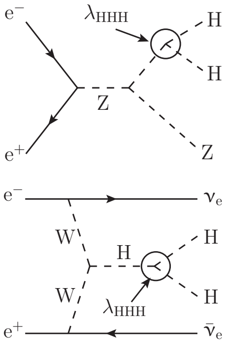
Introduction

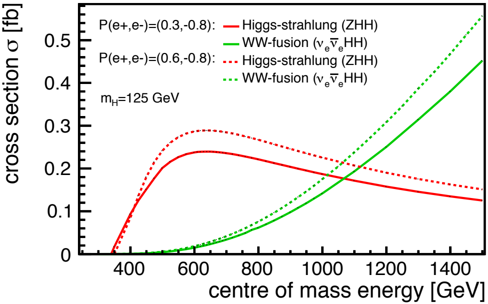
- precise measurement of shape of **SM Higgs potential** via Higgs self-coupling

$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$$

- one must observe double Higgs production

- test mechanism **EWSB** and mass generation
- test of **electroweak baryogenesis**
- test **extended** nature of Higgs (THDM, SUSY)





Higgs Self-Coupling Analyses at ILC

Existing DBD full simulation analyses

studies performed **with** low-p_T $\gamma\gamma \longrightarrow$ hadrons beam background
without low-p_T $\gamma\gamma \longrightarrow$ hadrons beam background

@ 500 GeV

- ZHH→Z(bb)(bb) for $m_H = 125$ GeV
- ZHH→Z(bb)(WW) for $m_H = 125$ GeV

@ 1 TeV

- $\nu\nu$HH →$\nu\nu$(bb)(bb) for $m_H = 125$ GeV
- $\nu\nu$HH →$\nu\nu$(bb)(WW) for $m_H = 125$ GeV

ILC white paper: Higgs self-coupling projections
(full simulation w/ $m_H = 120$ GeV, extrapolated to $m_H = 125$ GeV)

	500 GeV			500 GeV+1 TeV		
Scenario	A	B	C	A	B	C
Baseline	104%	83%	66%	26%	21%	17%
LumiUP	58%	46%	37%	16%	13%	10%

500 GeV: 500 (1600)fb^{-1} $P(e^+e^-)=(0.3,-0.8)$
1 TeV: 1000 (2500)fb^{-1} $P(e^+e^-)=(0.2,-0.8)$

Scenario A: HH → bbbb ✔
Scenario B: adding HH → bbWW ✔, expect 20% relative improvement
Scenario C: analysis improvement (jet-clustering, kinematic fit, flavor tagging, matrix element method, etc.), expect 20% relative improvement (**ongoing**)

Higgs Self-Coupling Analyses Strategy

General event selection strategy:

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

Strategic difficulties:

- very small number of signal events
- irreducible diagrams: significantly degrade self-coupling sensitivity
- 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

there are several key points for potential improvement in analyses
expect 20%* improvement of Higgs self-coupling precision

$\star$ with respect to Snowmass

Application of Kinematic Fits

one possibility is use of kinematic fits:

- find right jet pairing $\rightarrow$ improved jet/boson assignment
- improved mass resolution $\rightarrow$ clearer signal/background separation
- testing of fit hypothesis $\rightarrow$ use fit probability for better signal/background separation

- tool to improve jet energy and invariant mass resolution
- precise initial states at ILC are ideal for application of kinematic fits
- number of 4-vectors, representing final state particles, is fitted under constraints

E, p conservation

invariant mass: $M_{ij} = X$ GeV,

$M_{ij} = M_{lk}$,

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

$$\Downarrow$$

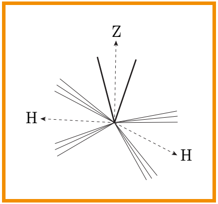
variation of measured quantities under condition that certain imposed constraints are fulfilled

Talk focusses on kinematic fitting $\rightarrow$ results are presented for analyses without overlay

ZHH (HH→bbbb) @ 500 GeV - Kinematic Fitting

Perform analysis for m_H = 125 GeV, assuming $\mathcal{L}$=2 ab^{-1} of data, and P(e^+e^-)=(0.3,-0.8)

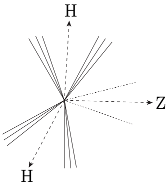
$\rightarrow l^- l^+$HH



$Z \rightarrow l\bar{l}$, HH $\rightarrow b\bar{b}b\bar{b}$

(10% × 60% × 60% ≈ 3.6%)

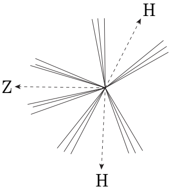
$\rightarrow \nu\nu$HH



$Z \rightarrow \nu\bar{\nu}$, HH $\rightarrow b\bar{b}b\bar{b}$

(20% × 60% × 60% ≈ 7.2%)

$\rightarrow qq$HH



$Z \rightarrow q\bar{q}$, HH $\rightarrow b\bar{b}b\bar{b}$

(70% × 60% × 60% ≈ 25%)

Preliminary results presented at LCWS14 (without overlay)

decay channel	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	5.2	6.9	1.63σ	1.37σ
ZHH $\rightarrow q\bar{q}$HH	9.2	20.9	1.82σ	1.64σ
	7.7	23.5	1.45σ	1.31σ

cross section: $\frac{\Delta\sigma_{ZHH}}{\sigma_{ZHH}} = 32.6\%$

Higgs self-coupling: $\frac{\Delta\lambda}{\lambda} = 53.5\%$

ZHH (HH→bbbb) @ 500 GeV - Kinematic Fitting

- application of kinematic fits to analysis
- for now: investigation of search mode llHH

- **useful in current analysis strategy**

  mass distributions as input parameters for neural net training

  → especially: ZHH vs. ZZH/ZZZ (backgrounds have same final state particles as signal)

- **change analysis strategy**

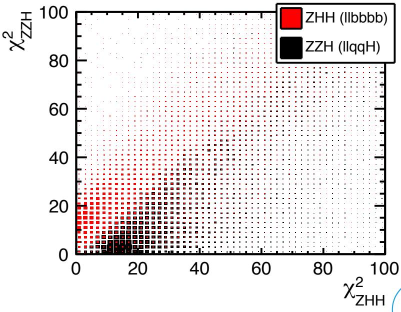
  → **test different fit hypotheses for signal and background**

  → **use information obtained from the fit (χ^2, P(χ^2))**

  → **add to analysis (neural net input or cut)**

test different fit hypothesis

constraint	llHH	ννHH	qqHH
$\sum$ E = 500 GeV	✔	✘	✔
$\sum$ p = 0	✔	✘	✔
$M_Z^{ll/ij}$	✔	✔	✔
M_H^{ij}	✔	✔	✔
$M^{ij} = M_{lk}$	✔	✔	✔



ZHH (HH→bbbb) @ 500 GeV - Kinematic Fitting

preliminary results with kinematic fit applied to llHH search mode (no overlay)

	decay channel	signal	background	significance excess	significance measurement
LCWS14	ZHH $\to l^- l^+$HH	3.0	4.3	1.16σ	0.91σ
		3.3	6.0	1.12σ	0.91σ
ALCW15	**ZHH $\to l^- l^+$HH**	**3.0**	**3.2**	**1.32σ**	**0.99σ**
		4.4	**6.8**	**1.43σ**	**1.18σ**
	ZHH $\to \nu\bar{\nu}$HH	5.2	6.9	1.63σ	1.37σ
	ZHH $\to q\bar{q}$HH	9.2	20.9	1.82σ	1.64σ
		7.7	23.5	1.45σ	1.31σ

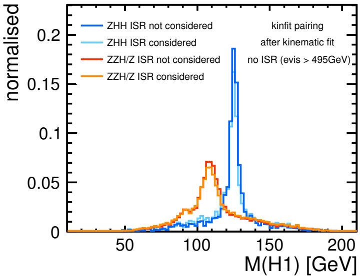
20% improvement in llHH mode due to kinematic fitting!

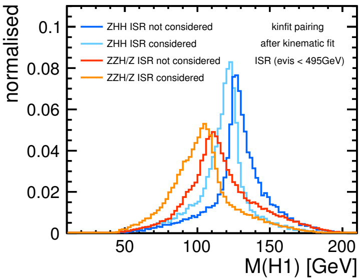
ongoing work:

investigation of kinematic fit in $\nu\nu$HH, qqHH

so far: ISR in samples, but not considered in fit

ISR treatment in fit under investigation → work ongoing





HH→bbWW Search Mode

- HH → (bb)(bb) golden channel (b-tag)
- HH → (bb)(WW) other search mode add to analysis
  improve final result (20% relative improvement expected)

DBD full simulation ZHH→Z(bb)(WW)

- at $\sqrt{s}$ = 500 GeV
- m_H = 125 GeV (w/o overlay)
- $\mathcal{L}$=2 ab^{-1}
- $P(e^+e^-)$=(0.3,-0.8)

DBD full simulation $\nu\nu$HH →$\nu\nu$(bb)(WW)

- at $\sqrt{s}$ = 1 TeV
- m_H = 125 GeV (w/o overlay)
- $\mathcal{L}$=2 ab^{-1}
- $P(e^+e^-)$=(0.2,-0.8)

@ 500 GeV	WW→(qq)(qq)	WW→(qq)(lν)
Z→bb	8 jets	l + 6 jets
Z→cc	8 jets	l + 6 jets
Z→ll	ll+6 jets	3l + 4 jets

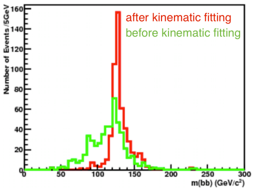
@ 1 TeV	WW→(qq)(qq)	WW→(qq)(lν)
Z→bb	8 jets	l + 6 jets
Z→ll	ll + 8 jets	-
$\nu\nu$HH	6 jets+E_{miss}	-

Masakazus talk on Monday more information on analysis update → kinematic fit

further improvements: lepton-ID for W→ lν based on dE/dx and cluster shape analysis → Masakazus talk on Tuesday (LCTPC)

HH→bbWW @ 500 GeV/ 1 TeV - Kinematic Fit

- at $\sqrt{s} = 500$ GeV investigated channel
  ZHH→Z(bb)(WW)→(bb)(bb)(lνqq)
- test of different fit hypotheses
  → better mass resolution
  → masses as input for MVA classifiers

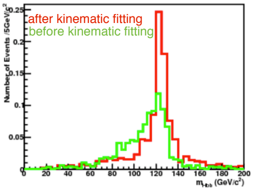


conference	search channel	significance
AWLC14	l + 6 jets	0.41σ
ALCW15	l + 6 jets	0.43σ

5% improvement in search mode due to kinematic fitting

ongoing: further investigation
apply to ZHH all hadronic

- at $\sqrt{s} = 1$ TeV investigated channel
  $\nu\nu$HH→$\nu\nu$(bb)(WW)→($\nu\nu$)(bb)(qqqq)
- apply kinematic fitting for
  → better mass resolution
  → masses as input for MVA classifiers



conference	search channel	significance
LCWS13	$\nu\nu$HH	1.77σ
ALCW15	$\nu\nu$HH	1.96σ

10% improvement in search mode due to kinematic fitting

ongoing: apply to other search mode
$\nu\nu$HH→($\nu\nu$)(bb)(lνqq)

$\nu\nu$HH (HH$\rightarrow$bbbb) @ 1 TeV - Update

measurement assuming $\mathcal{L} = 2$ ab^{-1} and P(e^-, e^+) = (-0.8,+0.2)

- existing DBD full simulation of $\nu\nu$HH $\rightarrow \nu\nu$(bb)(bb) for $m_H = 120$ GeV (LC-REP-2013-003)

Update study for $m_H = 125$ GeV without and with low-p_T $\gamma\gamma \rightarrow$ hadrons beam bgrd

same analysis strategy as in LC-REP-2013-003

- result for $m_H = 120$ GeV without $\gamma\gamma \rightarrow$ hadrons bgrd (extrapolation to $m_H = 125$ GeV)

significance 4.3σ (extrapolated 3.6σ)

expected for $m_H = 125$ GeV:
σ(WWfusion) reduced by 12%
BR(H $\rightarrow b\bar{b}$) reduced by 20%

- new preliminary results for $m_H = 125$ GeV

without overlay: significance 3.6σ
with overlay: significance 2.7σ

at 1 TeV $\gamma\gamma \rightarrow$ hadrons events overlaid per interaction: $< N_{\gamma\gamma} > = 4.1$

Preliminarily achieved significance of 3.6σ w/o overlay consistent with extrapolation!
However, significant impact of overlay $\rightarrow$ significance is 25% worse than extrapolation!

for all DBD benchmark analyses overlay removal exclusive k_T jet-clustering sufficient
more differential strategy needed here

- verify modeling of low-p_T $\gamma\gamma \rightarrow$ hadrons
- develop more sophisticated tools (exploit full power of high granularity detector)

Summary of Updates

@ 500 GeV : ZHH (HH→bbbb) by Claude Dürig (DESY)

investigation of kinematic fitting: applied to leptonic search channel (w/o overlay)

→ **20% improvement in llHH**

ongoing:

- application of kinematic fits to search channels $\nu\nu$HH & qqHH
- investigation of ISR in fit

@ 500 GeV : ZHH (HH→bbWW) by Masakazu Kurata (Tokyo University)
@ 1 TeV : $\nu\nu$HH (HH→bbWW)

investigation of kinematic fitting: applied to one ZHH search mode (w/o overlay)

→ **5% improvement**

applied to one $\nu\nu$HH search mode (w/o overlay)

→ **10% improvement**

ongoing:

- further investigation needed
- apply kinematic fit to other search modes

@ 1 TeV : $\nu\nu$HH (HH→bbbb) by Junping Tian (KEK)

update of analysis for $m_H = 125$ GeV, considering overlay

without overlay: significance of 3.6σ

with overlay: significance of 2.7σ → significant impact of overlay

→ significance 25% worse

Sensitivity of Higgs self-coupling λ in BSM

deviation from λ_{SM} value indicates new physics $\rightarrow$ high precision measurement needed!

	Δ hVV	Δ htt	Δ hbb	Δ hhh
Mixed-in Singlet	6%	6%	6%	18%
composite Higgs	8%	tens of %	tens of %	tens of %
MSSM	$< 1\%$	3%	10%, 100%	2%, 15%

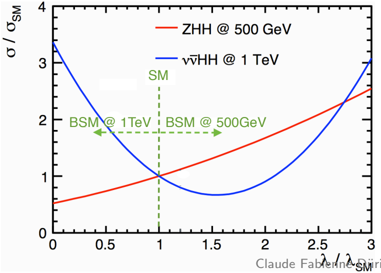
arXiv:1206.3560

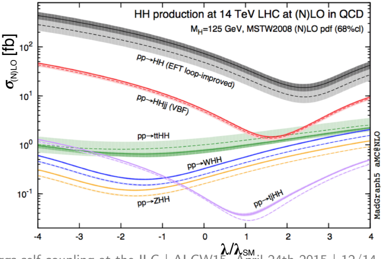
if BSM, then $\lambda_{SM} < \lambda < \lambda_{SM}$

in many BSM models$\rightarrow$ large deviations expected in other Higgs couplings, not only λ

electroweak baryogenesis (THDM) large deviation expected only in λ ($\lambda \geq 1.2 \cdot \lambda_{SM}$)

- ZHH at 500 GeV at ILC
- difficult at LHC





Sensitivity of Higgs self-coupling λ in BSM

BSM scenario: improved accuracy expected
(i.e. electroweak baryogenesis: $\lambda > \lambda_{SM}$)

$\lambda < \lambda_{SM} \rightarrow \nu\nu$HH at 1 TeV

example: $\lambda = 0.5 \cdot \lambda_{SM}$

$\lambda > \lambda_{SM} \rightarrow$ ZHH at 500 GeV

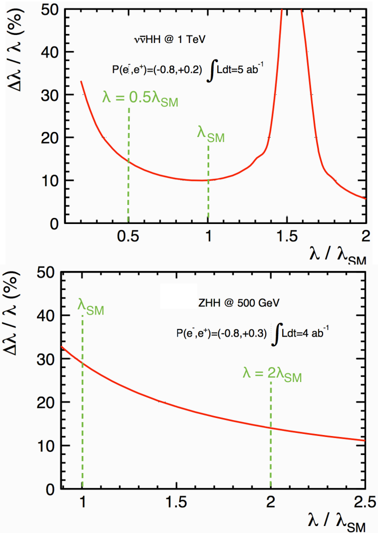
example: $\lambda = 2 \cdot \lambda_{SM}$

- σ_{ZHH} enhanced by 60%
- sensitivity factor reduced ($1.73 \rightarrow 1.08$)
- $\Delta\lambda/\lambda$ improved by factor of 2

both cases:

- λ can be measured to 14% precision
- 7σ discovery
- more than 3σ deviation from SM

extrapolated measurement accuracy of current λ_{SM} measurement (J. Tian)



Summary and Outlook

- measuring Higgs self-coupling is fundamental task for next generation LC
- direct determination of Higgs potential through double Higgs production
- precise measurement important to get insight into new physics
- if BSM $\rightarrow$ expect deviations from λ_{SM} value

  $\rightarrow \lambda_{\text{SM}} < \lambda < \lambda_{\text{SM}} \rightarrow$ better measurement accuracy!

- investigate different starting points for improvement
- 20% relative improvement of accuracy possible by improving analysis methods
- main project presented today kinematic fit

  $\rightarrow$ very promising in all existing Higgs self-coupling analyses

  $\rightarrow$ improvement of 5% up to 20% depending on search modes

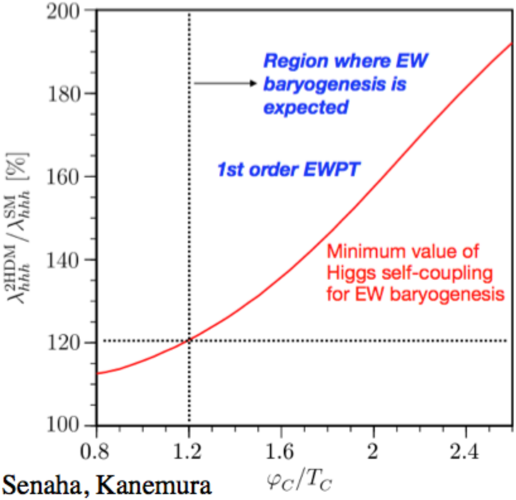
  $\rightarrow$ further investigation ongoing $\rightarrow$ investigate other search channels

  $\rightarrow$ update all analysis results

- more projects ongoing, not presented here (jet clustering algorithm, matrix element method, overlay removal strategy)
- potential improvement of Higgs self-coupling to $\approx$ 40% at $\sqrt{s} = 500$ GeV

BACKUP SLIDES

Electroweak Baryogenesis



Senaha, Kanemura

Application of Kinematic Fits

- tool to improve jet energy and invariant mass resolution
- precise initial states at ILC are ideal for application of kinematic fits
- number of 4-vectors, representing final state particles, is fitted under constraints

E, p conservation

invariant mass: $\mathrm{M_{ij}} = \mathrm{X\ GeV}$,

$\mathrm{M_{ij}} = \mathrm{M_{lk}}$,

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

$\Downarrow$

variation of measured quantities under certain constraints

- variable χ^2 is minimised under condition that imposed constraints are fulfilled
- χ^2 quantifies deviation between measured and fitted parameters

$$\chi^2 = (\eta - a)^T C^{-1} (\eta - a)$$

$a =$ vector of measured quantity

$\eta =$ vector of varied quantity

$C =$ covariance matrix

- χ^2 is converted into a fit probability $P(\chi^2)$

Application of Kinematic Fits in Analysis

useful in current analysis strategy

mass distributions as input parameters for neural net training

$\longrightarrow$ especially: ZHH vs. ZZH/ZZZ

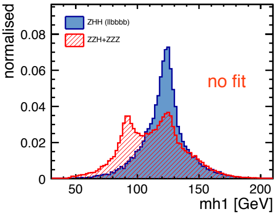
llHH: neural net training

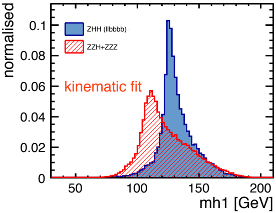
vvHH: cut on mh1, mh2, mhh
neural net training

qqHH: cut on mh1, mh2, mz
neural net training

test different fit hypothesis

constraint	llHH	vvHH	qqHH
$\sum E = 500$ GeV	✔	✘	✔
$\sum p = 0$	✔	✘	✔
$M_Z^{ll/ij}$	✔	✔	✔
M_H^{ij}	✔	✔	✔
$M^{ij} = M_{lk}$	✔	✔	✔

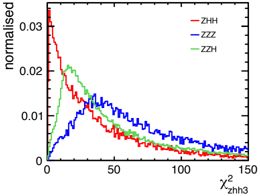




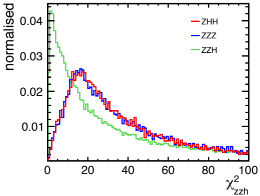
Application of Kinematic Fits in Analysis

change analysis strategy → **test different fit hypothesis for signal and background**
→ use information obtained from fit $(\chi^2, P(\chi^2))$

best hypothesis for ZHH: energy conservation
momentum conservation
m_{Zll}=91 GeV $\pm\ \Gamma_Z$
m_{H1}=125 GeV
m_{H2}=125 GeV

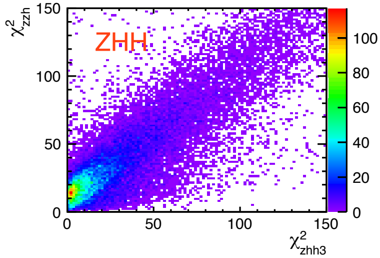


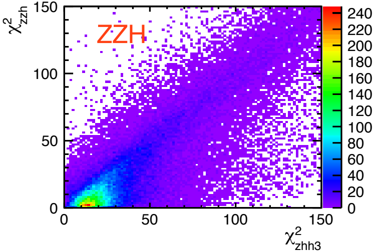
best hypothesis for ZZH: energy conservation
momentum conservation
m_{Zll}=91 GeV $\pm\ \Gamma_Z$
m_{Zqq}=91 GeV $\pm\ \Gamma_Z$
m_H=125 GeV

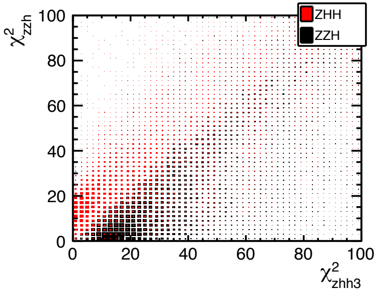


χ^2 could be useful variable for better signal and background separation!
How does correlation between χ^2_{ZHH} and χ^2_{ZZH} look like?

Application of Kinematic Fits in Analysis







use correlation of χ^2 distributions in analysis

for now only llHH $\rightarrow$ investigation of $\nu\nu$HH and qqHH

especially qqHH: performance of fit $\rightarrow$ six jets
dominant search mode
BR(qqHH)$\gg$BR(vvHH) / BR(llHH)

work in progress

Kinematic Fitting: ZHH (llHH channel)

best result when adding χ^2 distributions to analysis!

no overlay results (after adding kinematic fit to llHH)

decay channel	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
	3.0	**3.2**	$\mathbf{1.32\sigma}$	$\mathbf{0.99\sigma}$
	4.4	**6.8**	$\mathbf{1.43\sigma}$	$\mathbf{1.18\sigma}$
ZHH $\rightarrow \nu\bar{\nu}$HH	5.2	6.9	1.63σ	1.37σ
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cross section: $\frac{\Delta\sigma_{\text{ZHH}}}{\sigma_{\text{ZHH}}} = 32.6\%$

Higgs self-coupling: $\frac{\Delta\lambda}{\lambda} = 53.5\%$

cross section: $\frac{\Delta\sigma_{\text{ZHH}}}{\sigma_{\text{ZHH}}} = 31.4\%$

Higgs self-coupling: $\frac{\Delta\lambda}{\lambda} = 51.5\%$

$\rightarrow l^- l^+$HH

Z $\rightarrow l\bar{l}$, HH $\rightarrow$ b$\bar{\text{b}}$b$\bar{\text{b}}$

(10% $\times$ 60% $\times$ 60% $\approx$ 3.6%)

$\rightarrow \nu\nu$HH

Z $\rightarrow \nu\bar{\nu}$, HH $\rightarrow$ b$\bar{\text{b}}$b$\bar{\text{b}}$

(20% $\times$ 60% $\times$ 60% $\approx$ 7.2%)

$\rightarrow qq$HH

Z $\rightarrow q\bar{q}$, HH $\rightarrow$ b$\bar{\text{b}}$b$\bar{\text{b}}$

(70% $\times$ 60% $\times$ 60% $\approx$ 25%)

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):

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

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

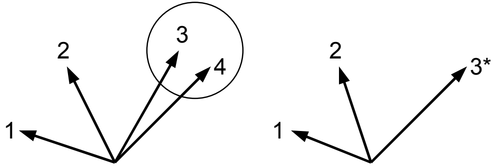
  - the energies E_i, E_j of the particles
  - and their mutual angle θ_{ij}

  by:

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

- 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 $3^\star$.

Kinematic fit Jet/Quark assignment

MarlinKinFit package

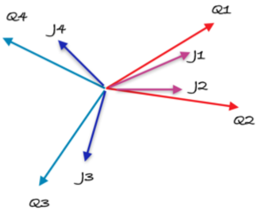
E, p conservation

invariant mass constraints

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

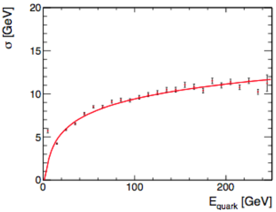
ongoing: implementation in Higgs self-coupling analysis

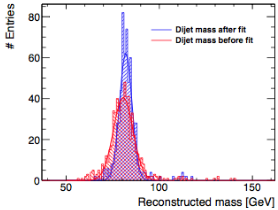
need: jet-quark comparison, association via angle differences



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

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





Prospects for other beam polarisations

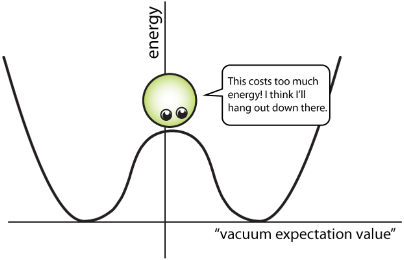
- standard polarisation used in analysis $P(e^-, e^+)$=(-0.8, 0.3) with $\mathcal{L} = 2$ ab^{-1}
- rough estimation of Higgs self-coupling accuracy for other polarisations

Polarisation	no overlay		overlay	
$P(e^-, e^+)$	cross section	self-coupling	cross section	self-coupling
(-0.8, 0.0)	36.7%	60.1%	40.7%	66.7%
(0.8, 0.0)	37.2%	61.1%	41.7%	68.4%
combined	26.2%	42.9%	29.1%	47.8%
(-0.8, 0.3)	**32.6%**	**53.5%**	**35.5%**	**58.1%**
(0.8, -0.3)	33.5%	54.9%	37.1%	60.8%
combined	23.4%	38.3%	25.6%	42.0%
(-0.8, 0.6)	29.9%	49.2%	33.6%	55.1%
(0.8, -0.6)	30.6%	50.2%	33.8%	55.4%
combined	21.4%	35.1%	23.8%	39.1%

combined: $P(+) \cdot 2$ ab^{-1} + $P(-) \cdot 2$ ab^{-1}

- for $P(e^-)$= -0.8: increase $P(e^+) \rightarrow$ 10% improvement
  decrease $P(e^+) \rightarrow$ 10% worsening
- similar results for opposite polarisations

Trilinear Higgs self-coupling



http://www.quantumdiaries.org

Higgs potential after spontaneous symmetry breaking for a physical Higgs field:

$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$$

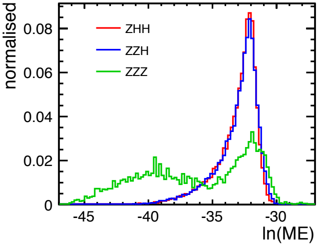
η_H: physical Higgs field

v: vacuum expectation value

- verify the shape of Higgs potential $\longrightarrow$ measure three terms
- to measure λ one must observe double Higgs production at lepton or hadron colliders

Matrixelementmethod (MEM)

- irreducible diagrams significantly degrade self-coupling sensitivity
- **long term goal**: optimise analysis strategy for Higgs self-coupling diagram
- implement MEM in analysis $\longrightarrow$ weighting of reconstructed particles as if they come from a certain process
- **first:** use different MEs for better signal/background separation (ZHH, ZZZ, etc.)



Matrixelement as from ZHH

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