HIGGS SELF COUPLING ANALYSIS AT ILC

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INTRODUCTION

- Measuring the Higgs self coupling is the key point to prove the electroweak symmetry breaking mechanism
  - Higgs potential in SM:

$$V = \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

Mass term

Trilinear coupling

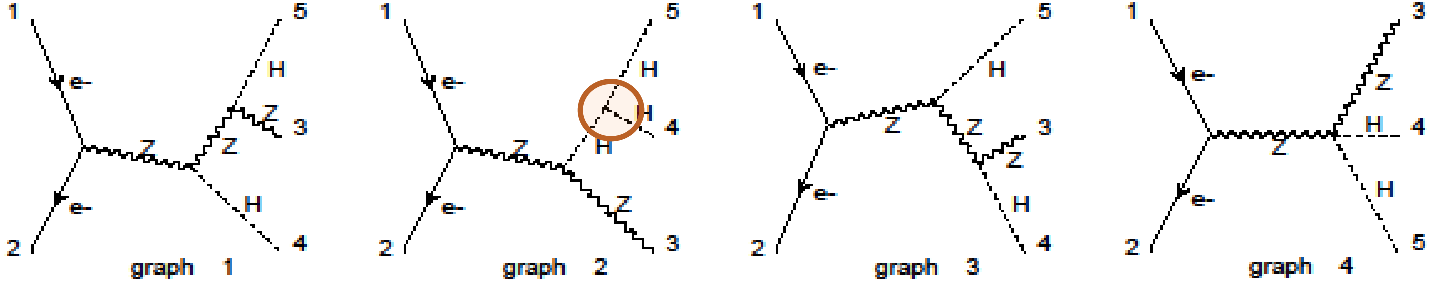
$SM: \quad \lambda = \frac{m_H^2}{2v^2} \quad v \sim 246 GeV$

Quartic coupling
→difficult to measure

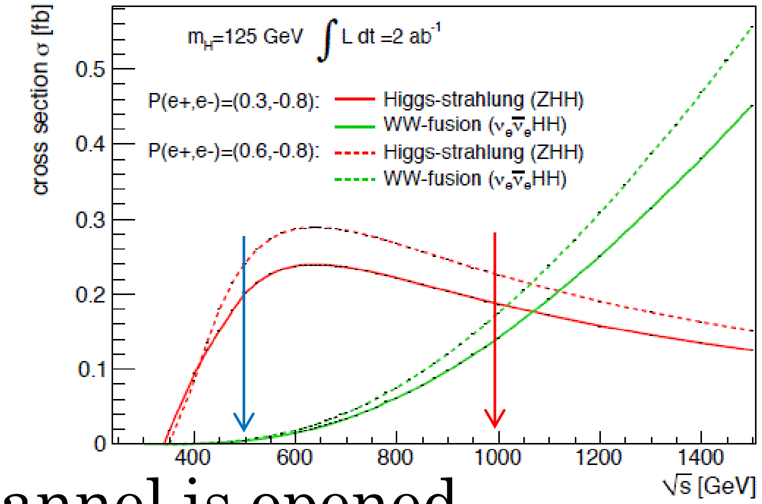
- Observing two Higgs bosons in the event is the only way to measure the self coupling
- Accurate test of the coupling may lead to the extended nature of Higgs sector → may go to new physics
- Our goal is to observe and measure the Higgs self coupling first

SIGNAL EVENTS

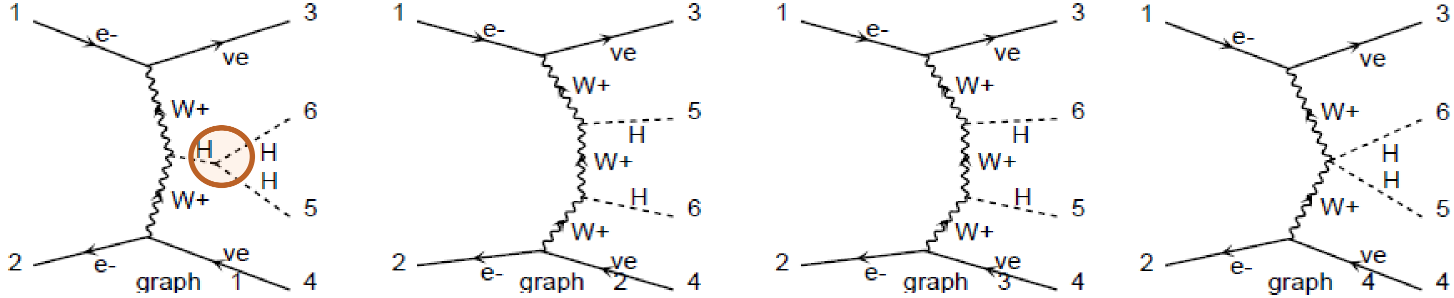
- Signal@500GeV - $e^+e^- \to Z^* \to ZH \to ZHH$ can be used



Signal: 2 Irreducible B.G.: 1, 3,4



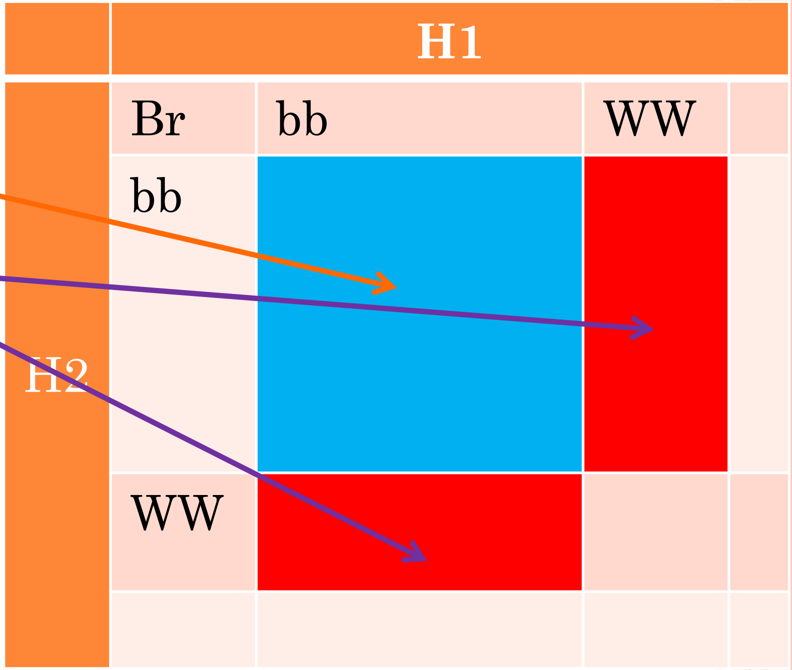
- Signal@1TeV – VBF $e^+e^- \to$vvHH channel is opened
  - Increase the cross section of VBF



Signal:1 Irreducible B.G.: 2, 3,4

STATUS OF THIS ANALYSIS

- Golden channel: Z(bb)(bb)
  - b-tagging can suppress backgrounds
- Requirement of **H→WW*** decay
  - Contribution on the total sensitivity
  - Difficulty of background rejection



		H1	
	Br	bb	WW
H2	bb	🟦	🟥
	WW	🟥	

- Backgrounds
  - ttbar and ZWW: huge events
  - bbbb final states: ZZ, Zγ, bbZ – b-rich backgrounds
  - triboson: ZZH, ZZZ
  - ttbar + X: jet-rich and b-rich
- Difficulty of the analysis
  - S/B~1/3500 @500GeV, ~1/2000 @1TeV

SELF-COUPLING AND CROSS SECTION RELATIONSHIP

- Irreducible backgrounds cause the interference with the signal diagram:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

From background diagrams

Interference between signal and background diagrams

From signal diagram

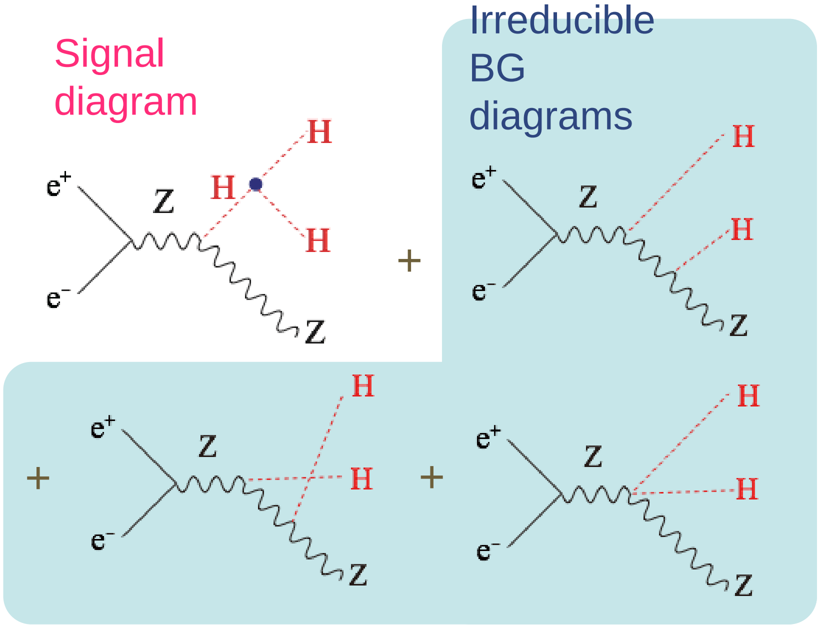
  - →Irreducible backgrounds may degrade the sensitivity of self-coupling

- Precision of self-coupling can be related to the precision of cross section measurement :

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

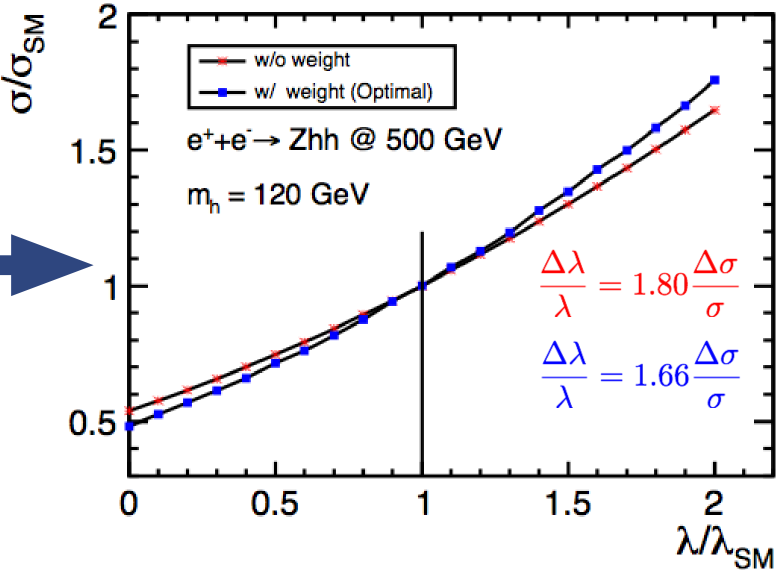
  - F=0.5 if no interference(only λ^2 term)
  - F becomes large due to the interference → difficult to estimate the coupling

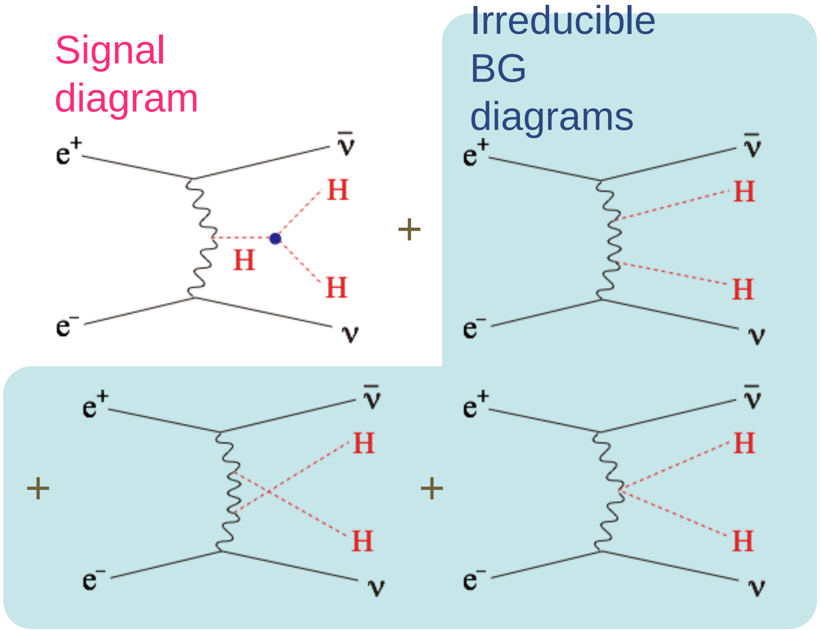
GENERAL ISSUE: SENSITIVITY OF COUPLING TO THE CROSS SECTION



Signal diagram

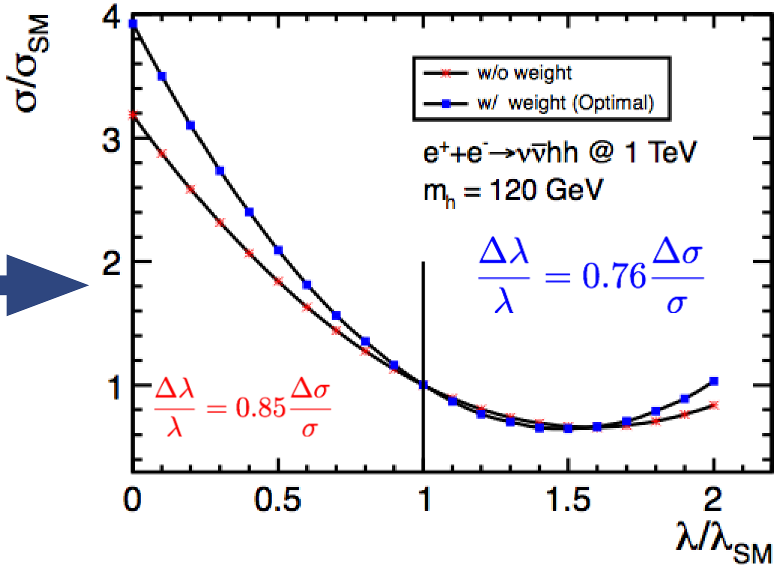
Irreducible BG diagrams





Signal diagram

Irreducible BG diagrams



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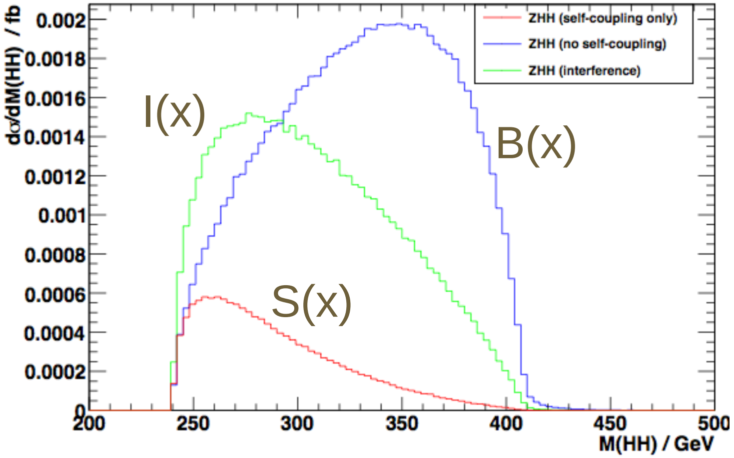
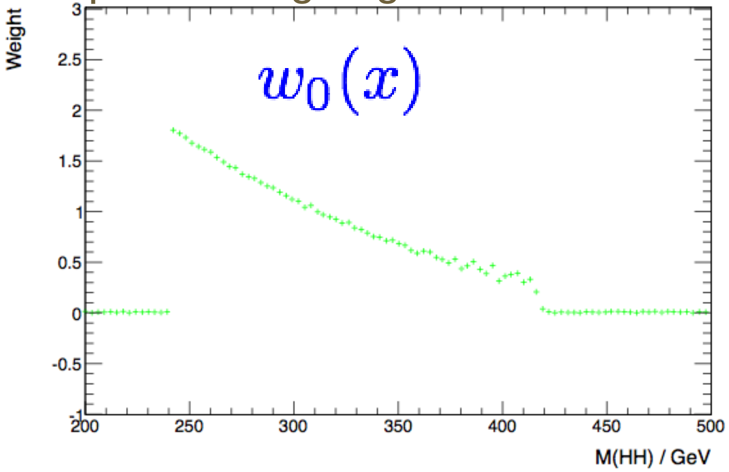
WEIGHTING METHOD TO ENHANCE THE COUPLING SENSITIVITY

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

differential cross-section



optimal weighing function



observable: weighted cross-section

$$\sigma_w = \int \frac{\mathrm{d}\sigma}{\mathrm{d}x} w(x)\mathrm{d}x$$

equation of the optimal w(x) (variance principle):

$$\sigma(x)w_0(x)\int(I(x)+2S(x))w_0(x)\mathrm{d}x = (I(x)+2S(x))\int\sigma(x)w_0^2(x)\mathrm{d}x$$

general solution:

$$w_0(x) = c\cdot\frac{I(x)+2S(x)}{\sigma(x)}$$

c: arbitrary normalization factor

Corrected relationship:

$$\frac{\delta\lambda}{\lambda} = F_w\frac{\delta\sigma_w}{\sigma_w} = F'\frac{\delta\sigma}{\sigma}$$

DIFFICULTIES FOR THE ANALYSIS

General difficulties

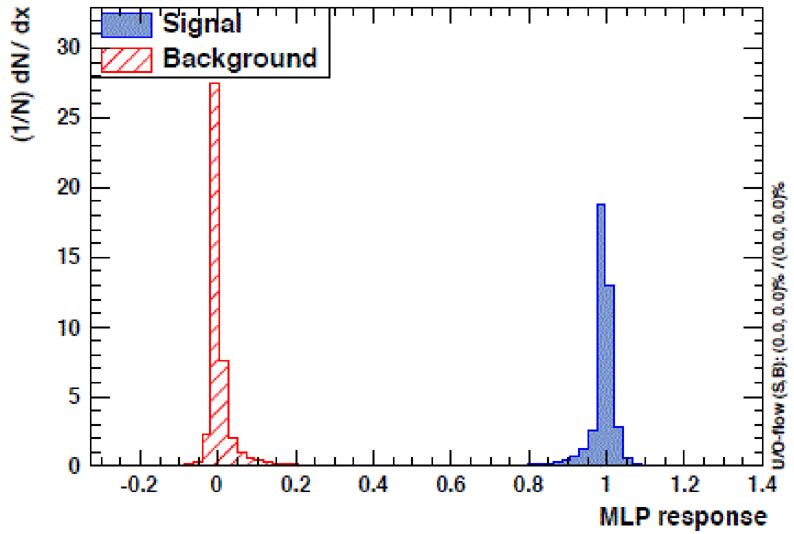
- irreducible SM diagrams: significantly degrade the coupling sensitivity
- production cross-sections are small → high luminosities needed
- very large SM background

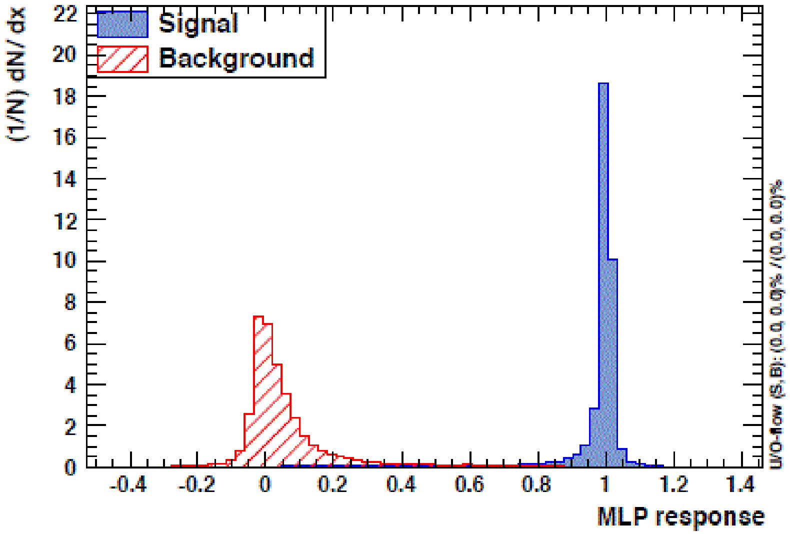
Technical difficulties(& requirement)

- Higgs mass reconstruction: jet clustering, jet pairing
- Flavor tagging and isolated lepton selection: need very high efficiency and purity
- neural net training: separated neural-nets, large statistics needed
- →good flavor tag, good leptonID, good jet finding,
  good jet finding

LEPTON ID IMPROVEMENT

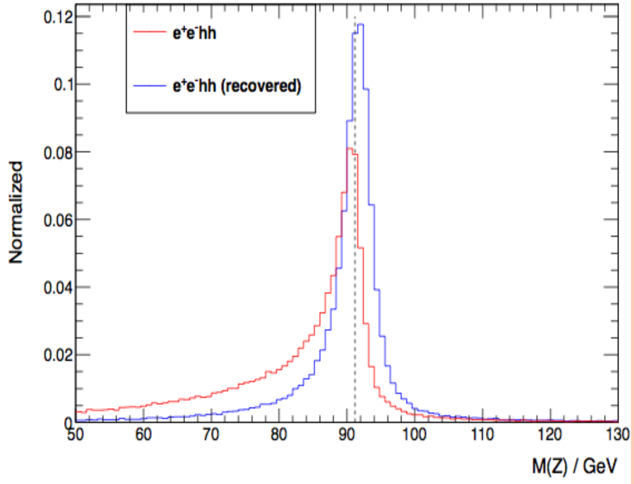
- Old method for lepton ID
  - Cut based selection using calorimeter information
- Lepton ID using MVA
  - MVA training: signal(eeHH & μμHH)vs. (bbbb & lvbbqq)
  - Calorimeter information is used as input variables for the MVA training


neural net output for electrons

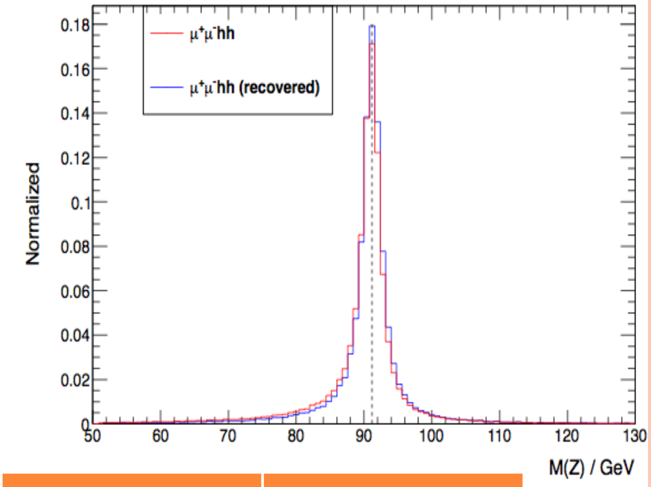

neural net output for muons

LEPTON ID FOR DILEPTON FINDING

- Blemsstrahlung and FSR recovery
  - Adding the photon energy emitted in small angle



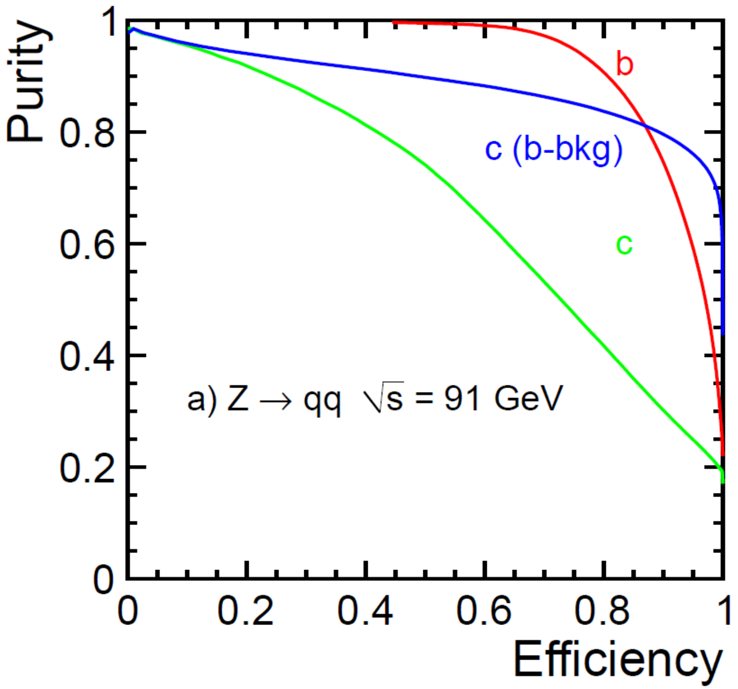
- New lepton ID is applied for lepton pair finding from Z boson
  - New lepton ID can increase signal efficiency
  - Hadronic and lepton+jets background can be suppressed significantly



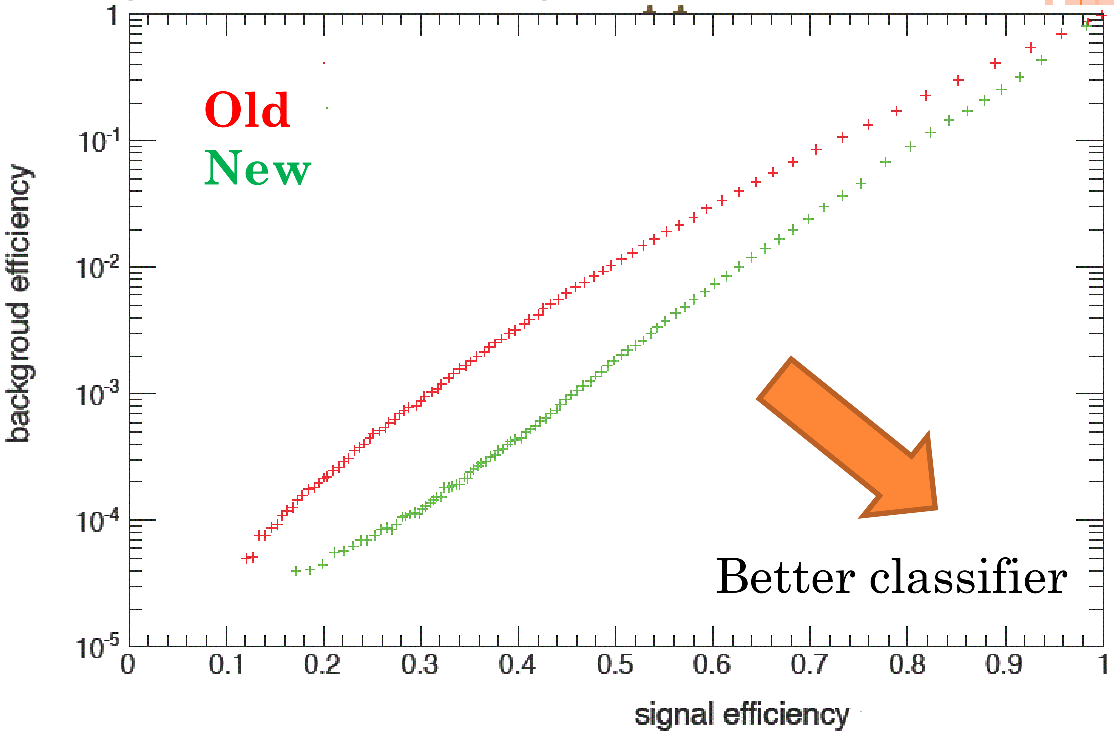
Efficiency(%)	eeHH	μμHH	bbbb	evbbqq	μvbbqq
MVA ID	87.0	89.1	0.0017	0.32	0.020
Cut based	85.7	88.4	0.028	1.44	0.10

FLAVOR TAGGING

- Flavor tagging performance is improved →LCFIPlus
  - Better efficiency on secondary vertex finding
  - Heavy flavor likeliness is parameterized using Multi Variate Analysis
  - Operation points of b-likeliness depend on the analysis

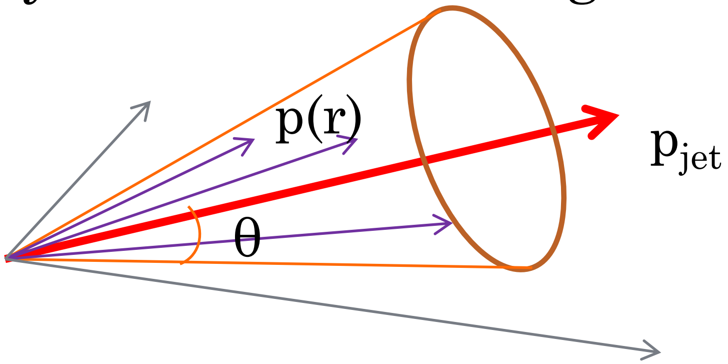


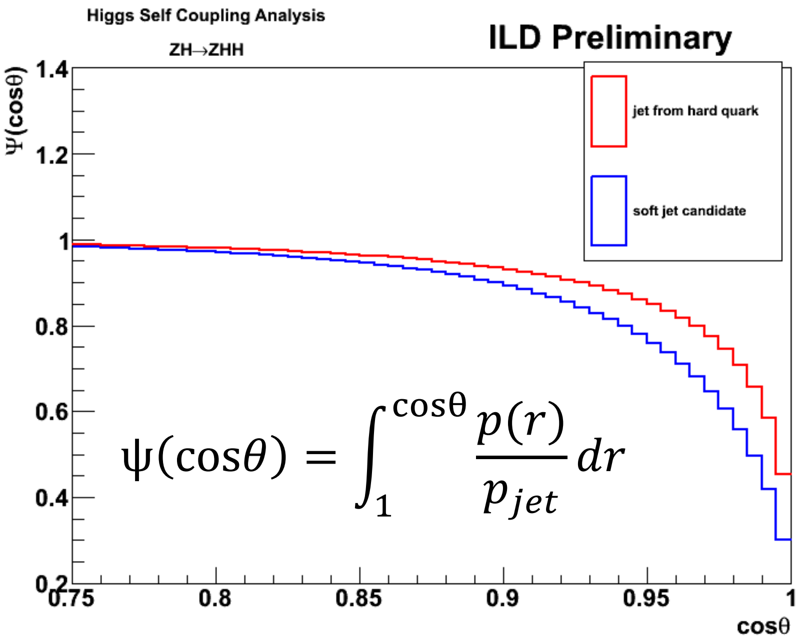
Signal eff. vs. background(ttbar) rejection



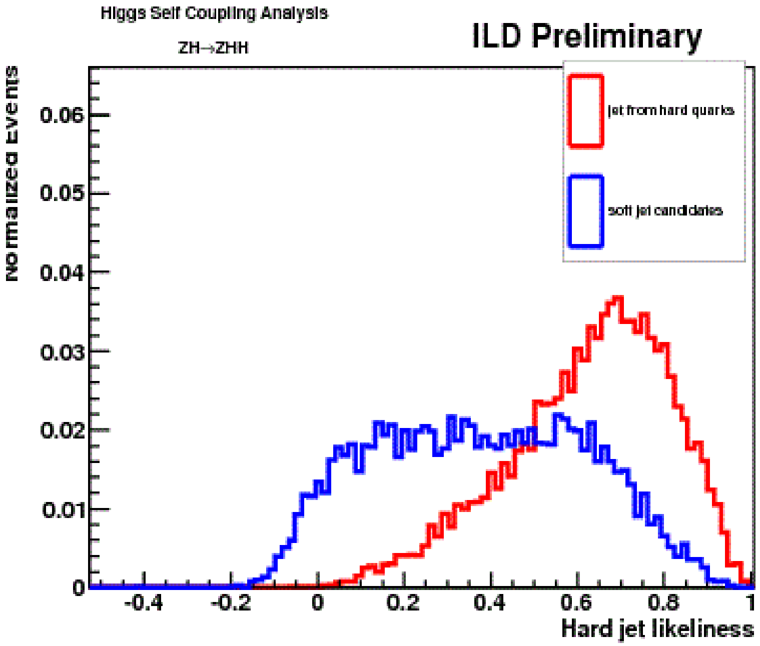
SOFT JET FINDING

- Tracks in the gluon jets spread wider than those in quark jets(e.g. analyses on hadron collider)
  - Traditional jet shape can be a good estimator
- Using Multivariate Analysis and estimating the hard jet likeliness for each jet



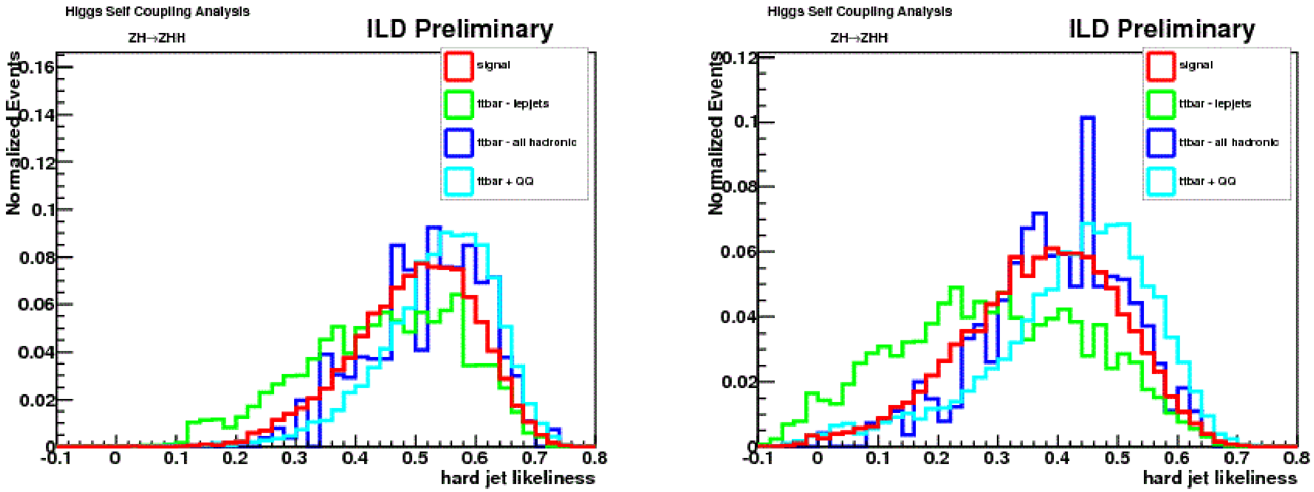


$$\psi(\cos\theta) = \int_1^{\cos\theta} \frac{p(r)}{p_{jet}} dr$$

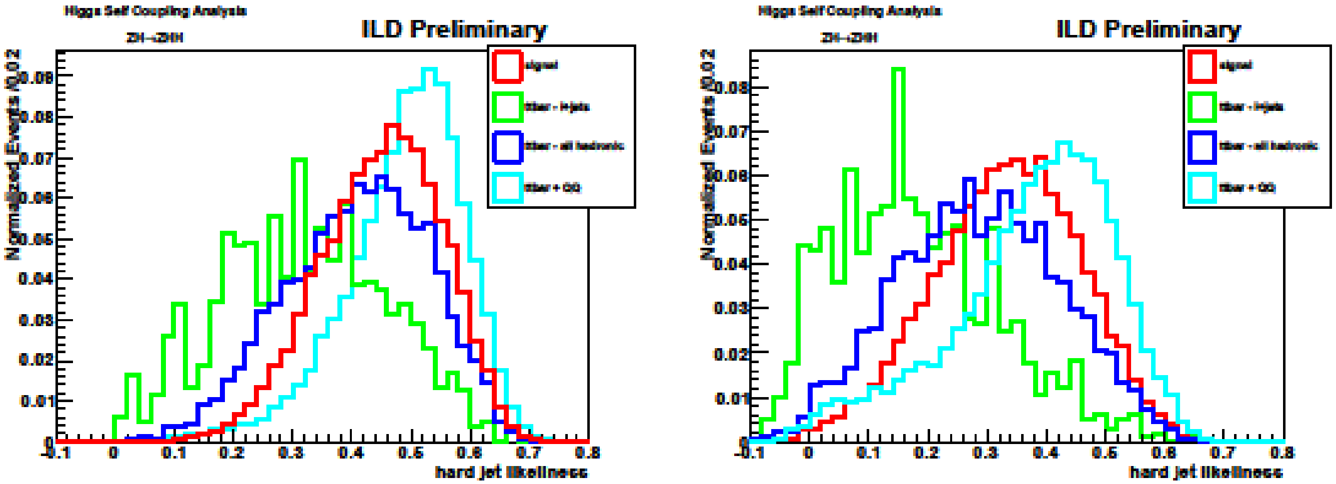


CHECK THE PERFORMANCE

- Check the jets with small hard jet likeliness – signal vs. ttbar
- For 6jets



- For 8jets



ANALYSIS STRATEGY FOR HH→(BB)(BB)

- **$e^+ + e^- \rightarrow ZHH$ @500GeV**
  - Searching mode can be classified with Z decay:
    - llHH: llbb (ZZ, γZ, bbZ), lvbbqq (tt-bar), llbbbb (ZZZ/ZZH)
    - vvHH: bbbb (ZZ, γZ, bbZ), τvbbqq (tt-bar), vvbbbb (ZZZ/ZZH)
    - qqHH: bbbb (ZZ, γZ, bbZ), bbqqqq (tt-bar), qqbbbb (ZZZ/ZZH)
  - Event selection
    - isolated-lepton selection or rejection
    - jet clustering and flavor tagging
    - missing energy or visible energy requirement
    - event reconstructed as from signal and dominant background
    - each dominant background is suppressed by training a neural-net

- **$e^+ + e^- \rightarrow vvHH$ @ 1 TeV**
  - Similar strategy to the case of 500GeV

ANALYSIS STRATEGY FOR HH→(BB)(WW)

- Classify the events with Z and W decays:

@500GeV	WW→(qq)(qq)	WW→(qq)(lv)
Z→bb	8jets	Lepton+6jets
Z→cc	8jets	Lepton+6jets
Z→ll	Dilepton+6jets	Trilepton+4jets

@1TeV	WW→(qq)(qq)	WW→(qq)(lv)
Z→bb	8jets	Lepton+6jets
Z→ll	Dilepton+6jets	N/A
vvHH	6jets (+missing)	N/A

- **Z decays into heavy flavor pair or lepton pair mainly**
  - Need flavor tagger or clean Z mass distribution to reject huge backgrounds
- Number of b jet candidates in the event and number of leptons can form exclusive samples
  - Number of b-tagging available: up to 4
    - Basically, 2 or 4 b-tagged jets events can be used
    - c-tagging is also available
  - Number of leptons: from 0 to 3

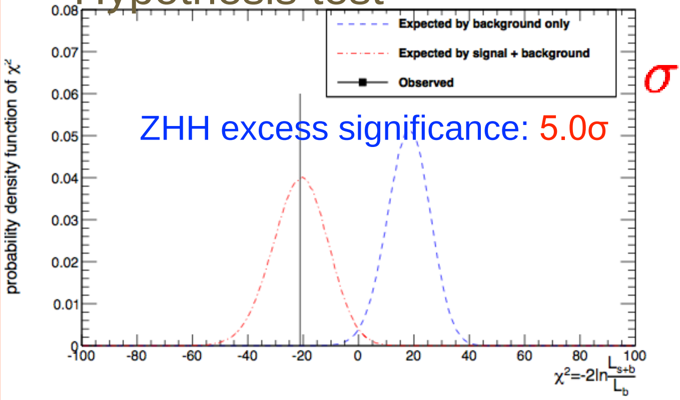
DBD full simulation

HIGGS SELF-COUPLING @ 500 GEV (COMBINED)

P(e-,e+)=(-0.8,+0.3) $e^+ + e^- \to ZHH$ $M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

Energy (GeV)	Modes	signal	background (tt, ZZ, ZZH/ZZZ)	significance	
				excess (I)	measurement (II)
500	$ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$	3.7	4.3	1.5σ	1.1σ
		4.5	6	1.5σ	1.2σ
500	$ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	8.5	7.9	2.5σ	2.1σ
500	$ZHH \to (q\bar{q})(b\bar{b})(b\bar{b})$	13.6	30.7	2.2σ	2.0σ
		18.8	90.6	1.9σ	1.8σ

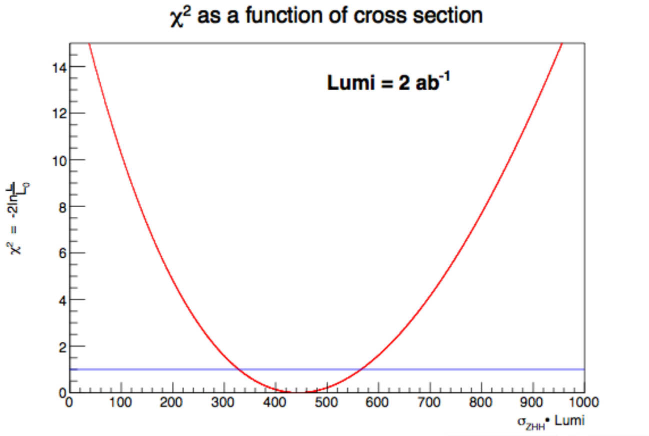
Hypothesis test



ZHH excess significance: 5.0σ

$$\sigma_{ZHH} = 0.22 \pm 0.06 \text{ fb}$$

$$\frac{\delta\sigma}{\sigma} = 27\%$$



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

DBD full simulation

Higgs self-coupling @ 1 TeV

P(e-,e+)=(-0.8,+0.2) $e^+ + e^- \to \nu\bar{\nu}HH$ $M(H) = 120\mathrm{GeV}$ $\int Ldt = 2\mathrm{ab}^{-1}$

	Expected	After Cut
vvhh (WW F)	272	35.7
vvhh (ZHH)	74	3.88
BG (tt/vvZH)	7.86×10^5	33.7
significance	0.3	4.29

- better sensitive factor
- benefit more from beam polarisation
- BG tt x-section smaller
- more boosted b-jets

$$\frac{\Delta\sigma}{\sigma} \approx 23\% \qquad \frac{\Delta\lambda}{\lambda} \approx 18\%$$

Double Higgs excess significance: > 7σ

Higgs self-coupling significance: > 5σ

SENSITIVITY@500GEV

- HH→(bb)(WW)
  - As mentioned, categorized with decay tipes of Z and W boson
    - Z→bb, cc or ll
  - b-tagging strategy – introduce looser b-tag category
    - 4-btag & 3-btag
  - E_{CM}=500GeV, L=2ab-1
  - **Significance ～1.91σ**

Modes	Z decay	b tag	Signal	Background	Significance
All hadronic	Z→bb	4btag	15.20	87.52	1.50σ
		3btag	19.43	3099.49	0.35σ
	Z→cc		11.29	366.13	0.58σ
Lepton + jets	Z→bb		1.65	17.62	0.38σ
	Z→cc		1.50	819.61	0.05σ
Dilepton	Z→ll		2.24	8.44	0.69σ
Trilepton	Z→ll		1.05	2.60	0.55σ
Combined					**1.91σ**

SENSITIVITY@1TEV

- HH→(bb)(WW)
  - As mentioned, categorized with decay types of Z and W boson
    - Z→bb and ll, VBF channel
  - b-tagging strategy – fully used the b-tagging for each category
  - E_{CM}=1TeV, L=2ab-1
  - **Significance ~2.80σ**

Modes	Z decay	Signal	Background	Significance
All hadronic	Z→bb	17.15	48.17	2.12σ
Lepton + jets	Z→bb	1.16	9.24	0.36σ
Dilepton	Z→ll	1.03	14.30	0.26σ
6jets+ Missing	No Z, vvHH	6.90	8.24	1.77σ
Combined				**2.80σ**

- Fast simulation results, need to update

ILC 500 GeV & 1 TeV

Higgs Self-coupling Projections @ ILC

full simulation done w/ mH = 120 GeV, extrapolated to mH = 125 GeV

$\Delta\lambda_{HHH}/\lambda_{HHH}$	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%

Scenario A: HH-->bbbb, full simulation done
Scenario B: by adding HH-->bbWW*, full simulation ongoing,
expect ~20% relative improvement
Scenario C: color-singlet clustering, future improvement,
expected ~20% relative improvement (conservative)

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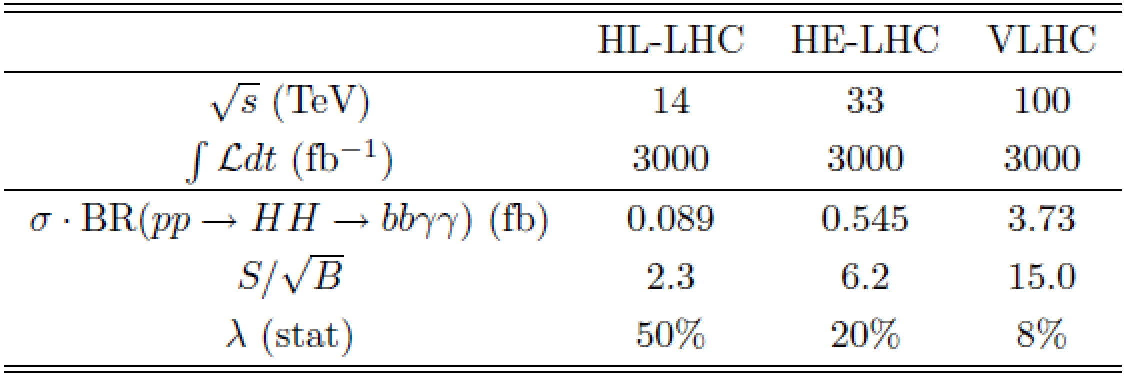
LHC PROSPECTS

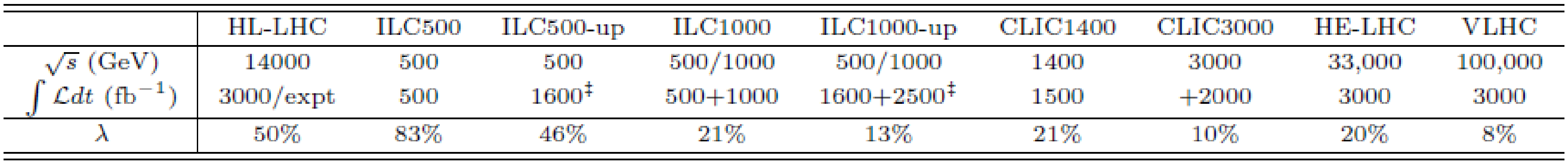
- From snowmass report:



	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

- Combined result of HL-LHC(ATLAS&CMS)

  ~ **30%** precision



	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

SUMMARY AND PLAN

Higgs self coupling analysis is ongoing:

- One of the important task for the next linear collider
- Results of HH→(bb)(bb) – precision of the self coupling @∫L=2ab-1:

energy	500GeV	1TeV
δλ/λ	~44%	~18%
δσ/σ	~27%	~23%

- Results of HH→(bb)(WW*) - signal significance @ ∫L=2ab-1

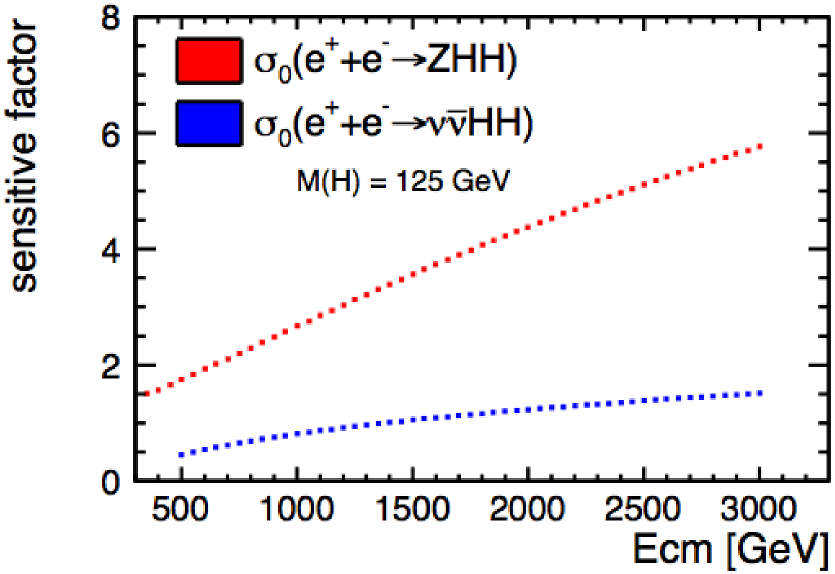
energy	500GeV	1TeV
Signal significance	1.91σ	2.80σ

Plans

- Combine all the channels
- Improvement of basic components for the analysis
  - B-tagging
  - Lepton ID
  - Jet finding, Jet clustering
- Lots of efforts are necessary and ongoing

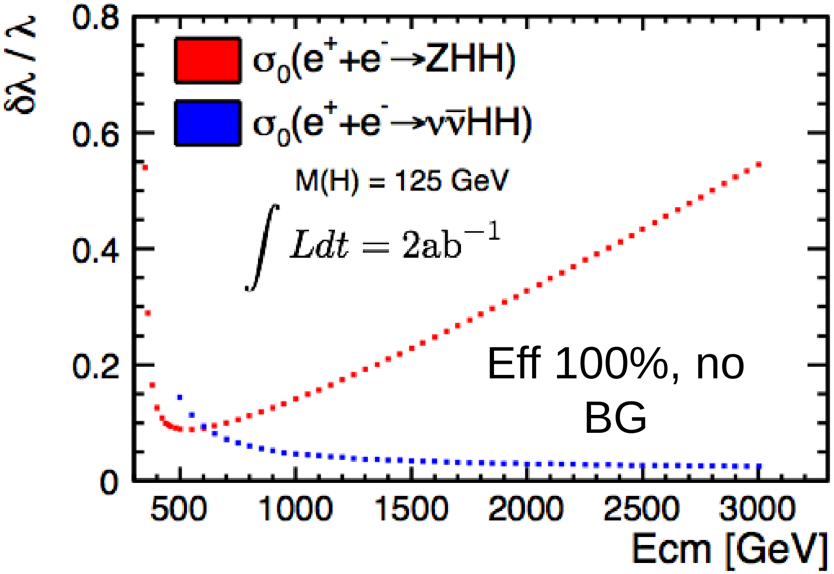
BACKUPS

GENERAL ISSUE: RUNNING OF THE SENSITIVITY FACTOR AND EXPECTED COUPLING PRECISION AT DIFFERENT ECM



$$\frac{\Delta\lambda}{\lambda} = \mathrm{F} \cdot \frac{\Delta\sigma}{\sigma}$$

Factor increases quickly as going to higher energy



Eff 100%, no BG

for ZHH, the expected optimal energy ~ 500 GeV (though cross section is maximum ~ 600 GeV)

for vvHH, expected precision improves slowly as going to higher energy