Study of the Higgs Self-coupling at the ILC

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JSPS Kickoff Meeting

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outline

- introduction
- current ZHH analysis based on full simulation
- prospects for the Higgs self-coupling measurement with different Higgs masses
- plans for the future improvement towards DBD

motivation of Higgs self-coupling measurement

Higgs Potential: $V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda \upsilon \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$

physical Higgs field — mass term — trilinear coupling — quartic Higgs coupling, which is difficult to measure at both LHC and ILC, even SLHC!

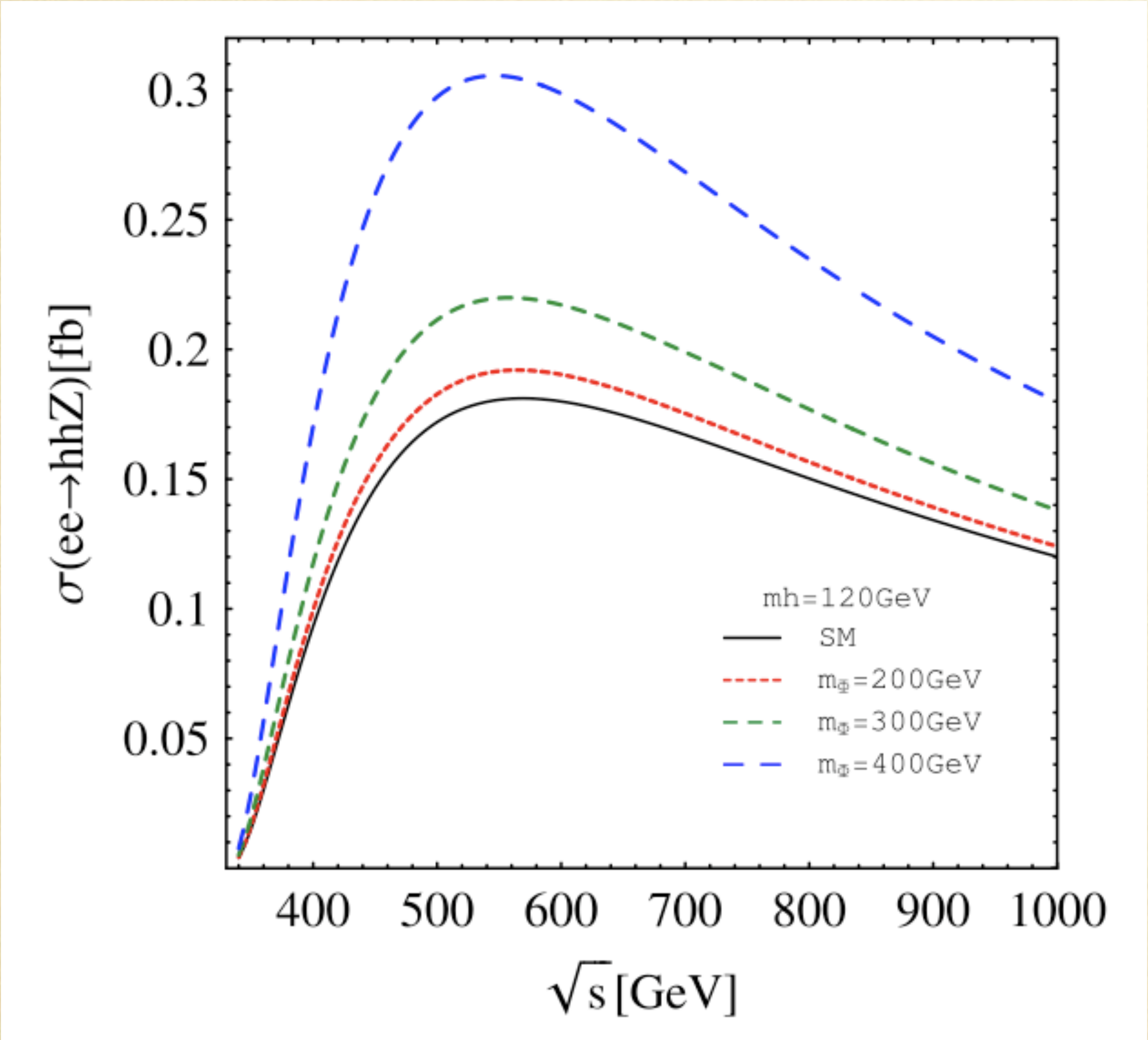
SM: $\lambda = \lambda_{SM} = \frac{m_H^2}{2v^2}$ υ ~ 246 GeV

- just the force that makes the Higgs boson condense in the vacuum (a new force, non-gauge interaction).
- direct determination of the Higgs potential.
- accurate test of this coupling may reveal the extended nature of Higgs sector, like THDM and SUSY.
- difficult to measure at LHC for a light Higgs.

Higgs self-coupling as a probe of new physics

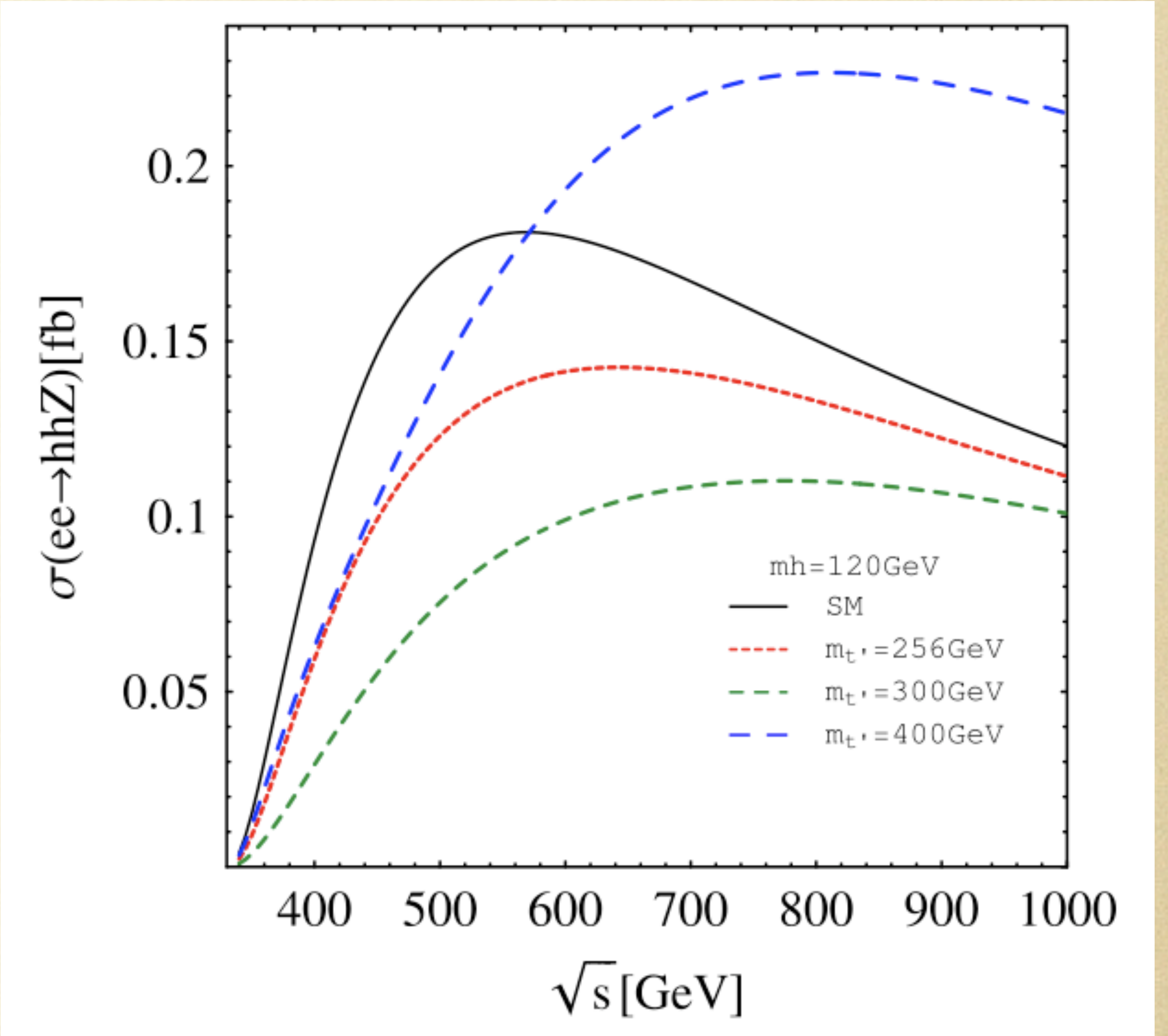
Two Higgs Doublet Model (THDM)

$M_h = 120\text{GeV} \quad M_H = M_A = M_{H^\pm} = M_\Phi$



Chiral Fourth Generation (Ch4)

$M_h = 120\text{GeV}$ t' is the fourth up-type quark



effects on the cross section of Zhh could be O(100%) deviation from the SM value

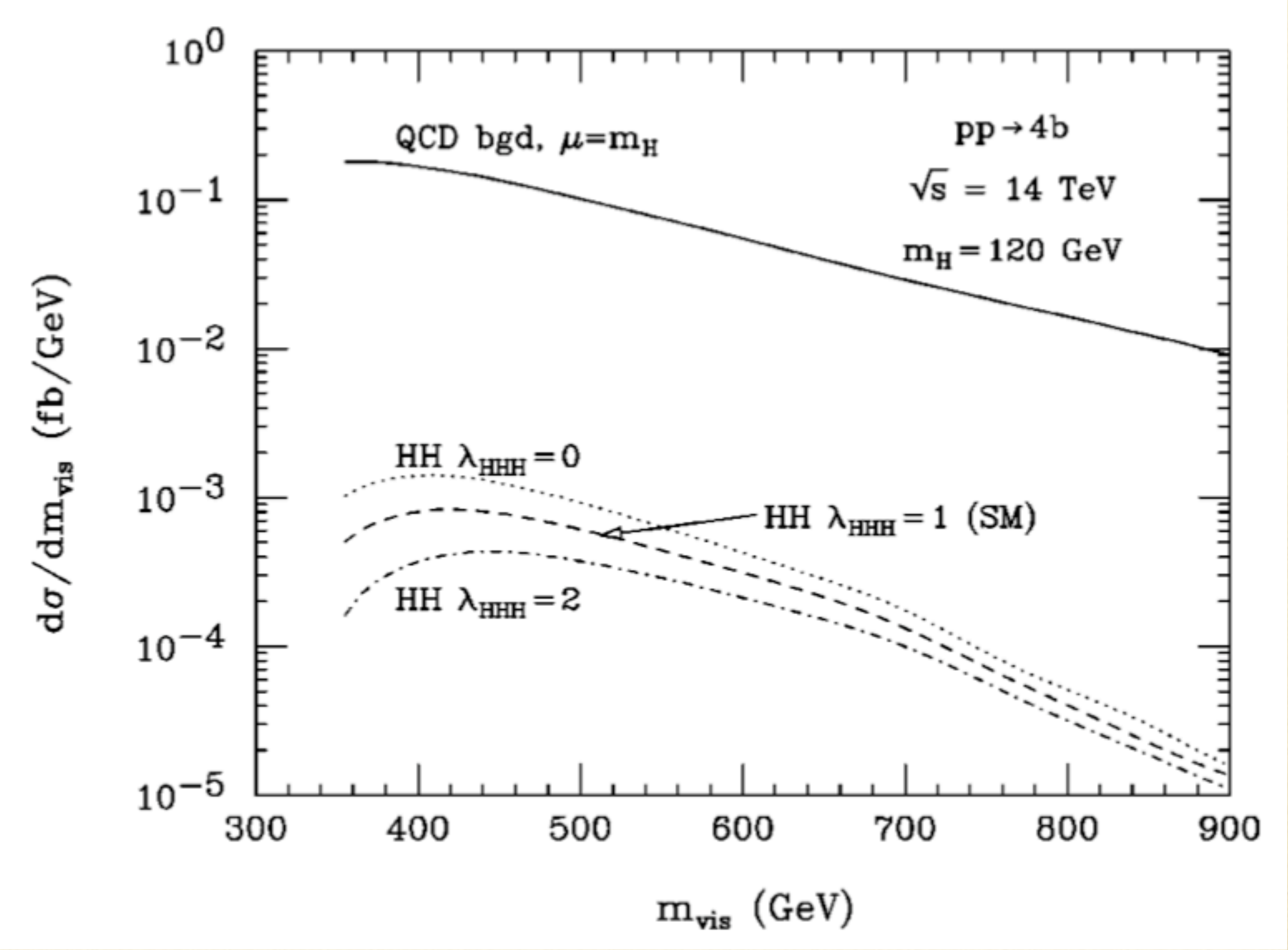
Phys.Rev. D82 (2010) 115002

Higgs self-coupling measurement at LHC

for a low mass Higgs: M(H) < 140 GeV

$$p + p \to HH \to b\bar{b}b\bar{b}$$ (dominant)

cross-section



Invariant mass of visible particles

solid: QCD 4b background
dashed: SM signal
dotted and dotted-dashed: signal with different Higgs self-coupling

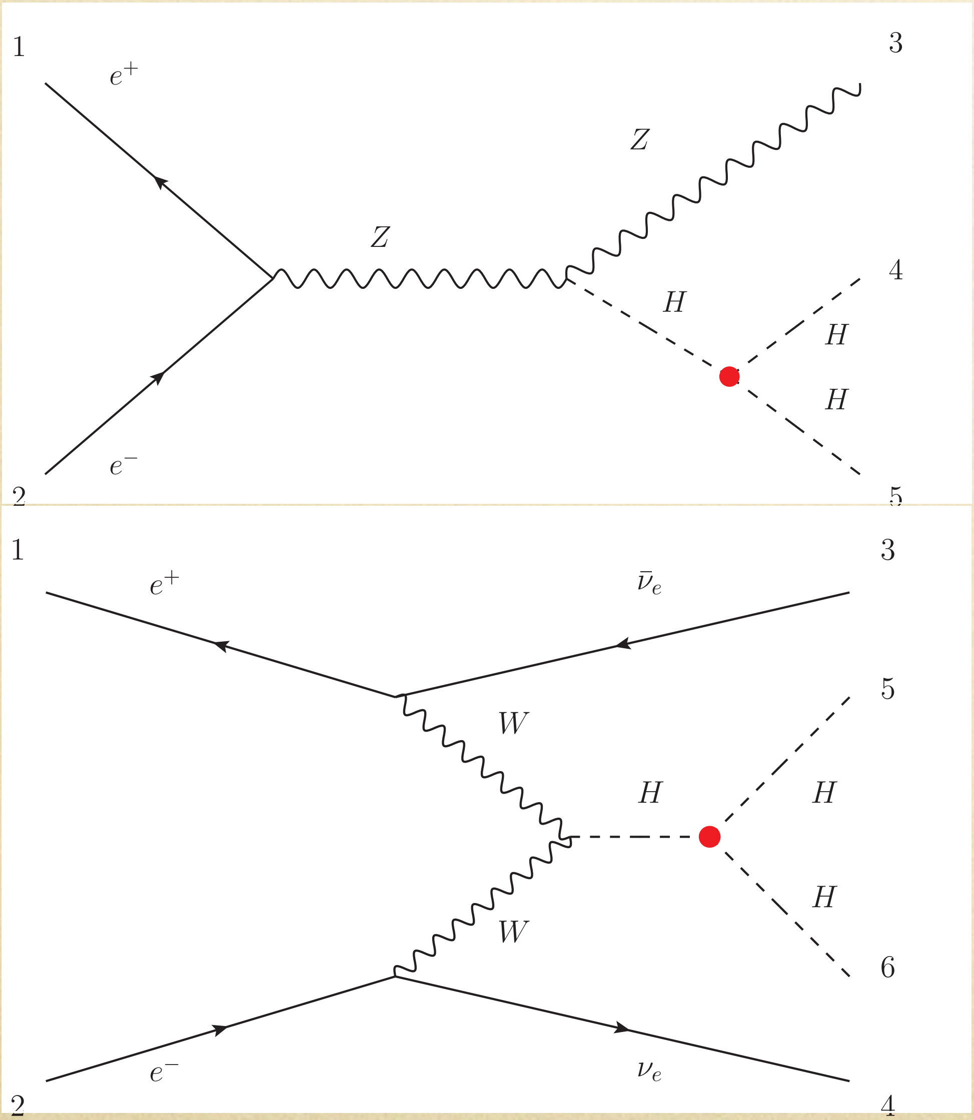
two orders overwhelmed by QCD 4b background!

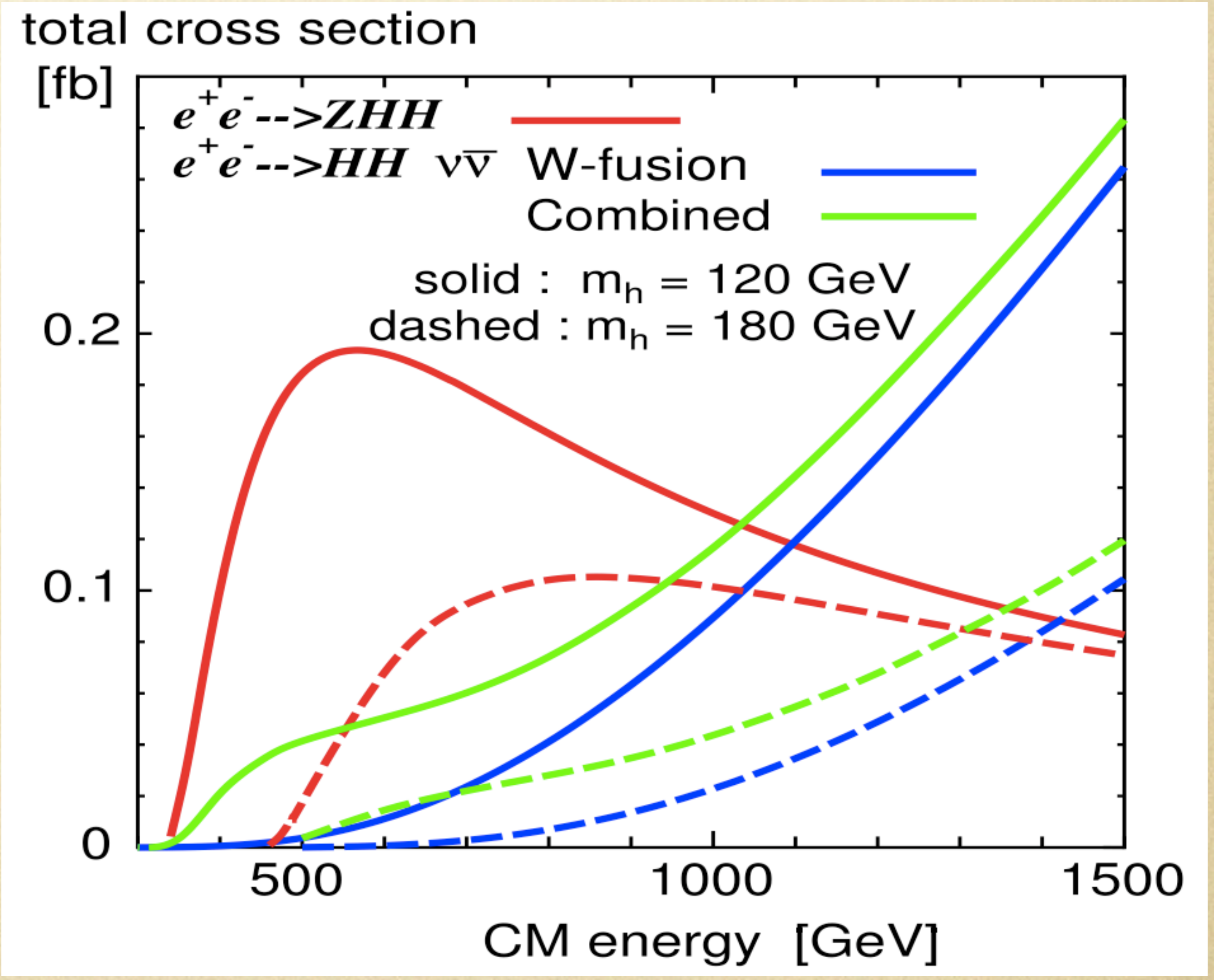
$$-6.8 < \Delta\lambda_{HHH} < 10.1 \qquad (\Delta\lambda_{HHH} = \frac{\lambda}{\lambda_{SM}} - 1)$$

Phys.Rev. D68 (2003) 033001

Measurement of the trilinear Higgs self-coupling @ ILC

- double Higgs-strahlung (dominate at lower energy)
- WW fusion (become important at higher energy)



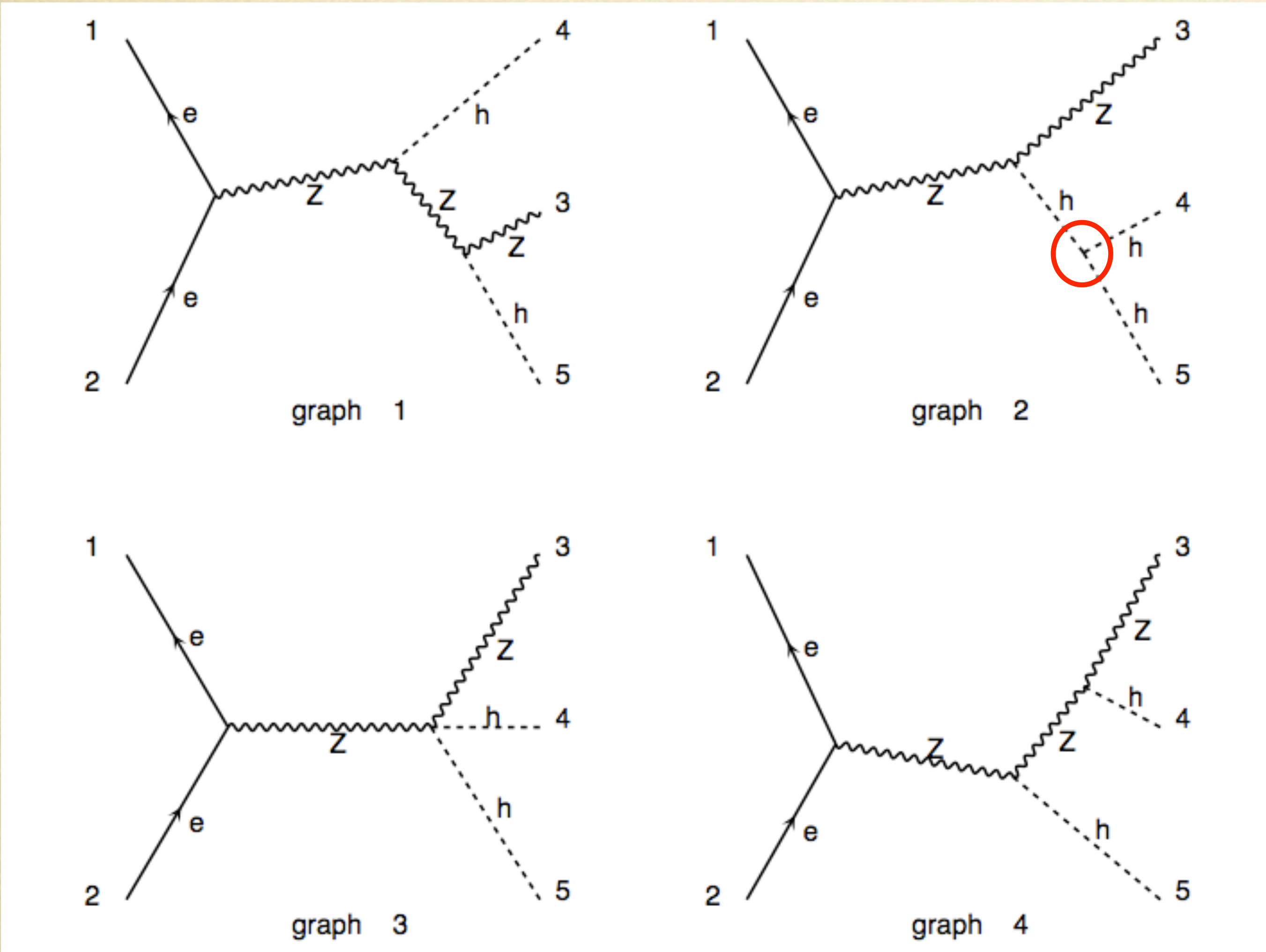


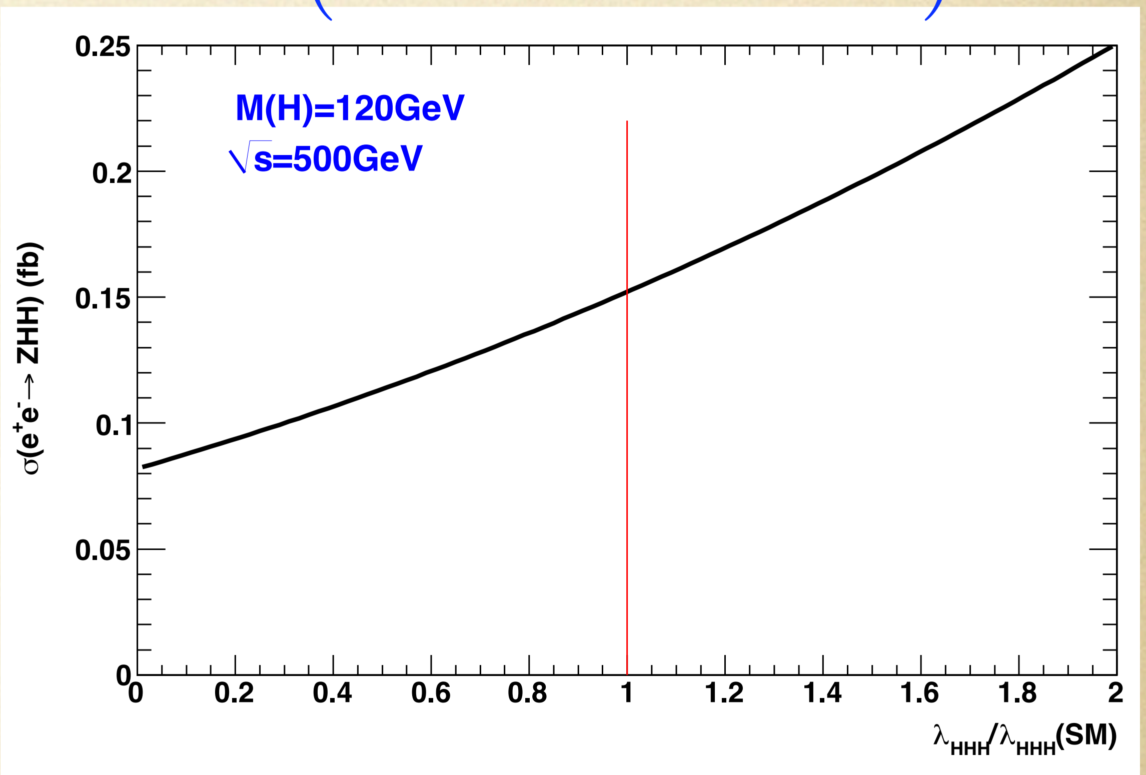
extraction of Higgs self-coupling from the cross section of ZHH

effect of irreducible diagram

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

$\sigma(e^+e^- \to ZHH)$





$$\frac{\Delta\lambda}{\lambda} = 1.8\frac{\Delta\sigma}{\sigma}$$

precision of self-coupling

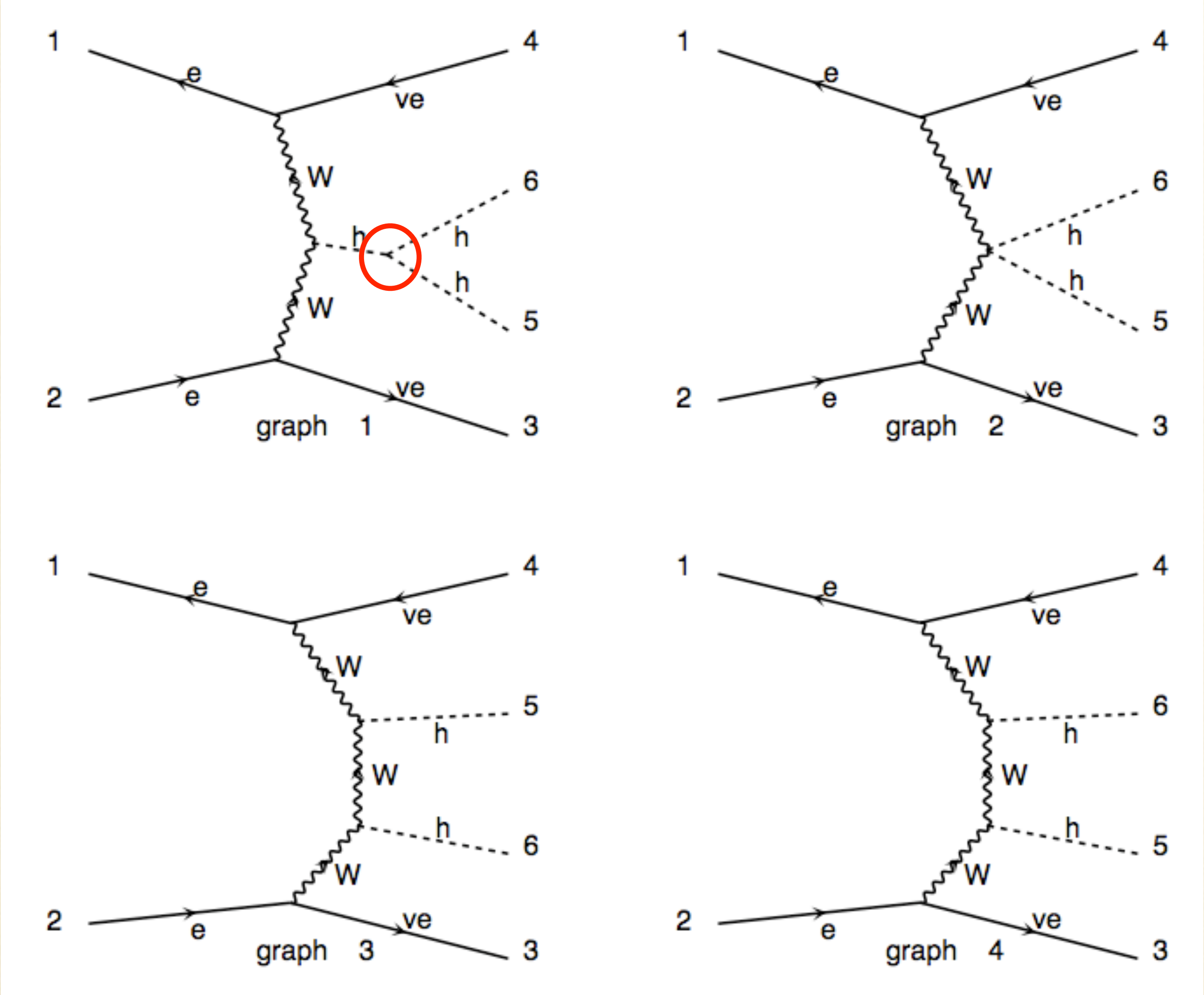
precision of cross-section

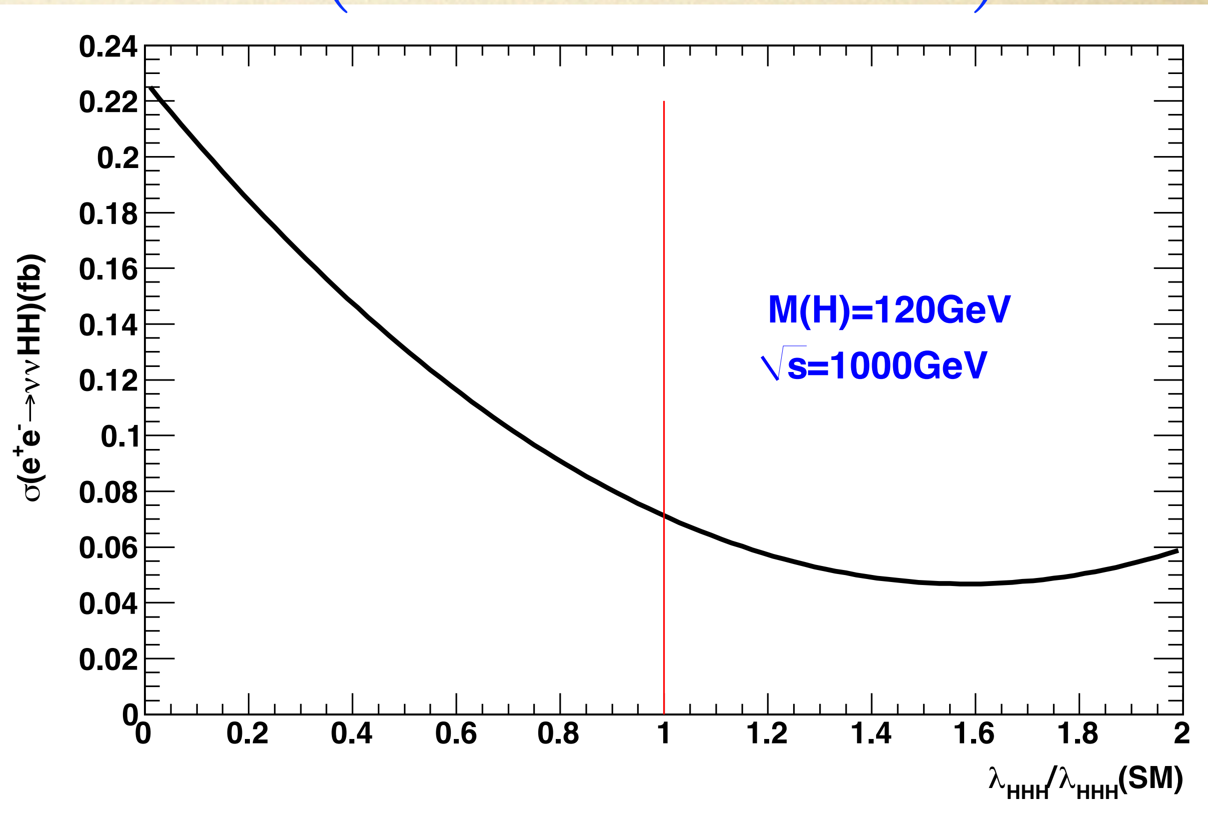
extraction of Higgs self-coupling from the cross section of υυHH

effect of irreducible diagram

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

$\sigma(e^+e^- \to \nu\bar{\nu}\mathrm{HH})$





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

precision of self-coupling

precision of cross-section

Previous studies of Higgs self-coupling at a linear collider

- most of the studies are based on fast simulation.

- ZHH@500GeV based on fast simulation suggests precision of 18% on the Higgs self-coupling with 2 ab^{-1} (**arXiv:hep-ex/0101028v1**)

- ZHH@500GeV based on full simulation, which only included one search mode, gives precision of 160% with 2 ab^{-1} (**arXiv:hep-ex/0901.4895v1**)

- vvHH@1TeV based on fast simulation suggests precision of about 10% with 1 ab^{-1} (Yamashita@**LCWS04**)

No complete investigation of all search mode based on full simulation, and no real demonstration of the feasibility of Higgs self-coupling measurement!

status of current analysis

@ALCPG11

- focus on the ZHH @ 500 GeV, M(H) = 120 GeV.
- three decay modes of ZHH (Z-->ll, vv, qq, H-->bb) are investigated, based on full simulation.
- neural-net methods are used to improve the background suppression.
- effects of different beam polarizations are checked.
- precisions of cross section and self-coupling are given by combining all decay modes.

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	significance	
				excess (I)	measurement (II)
500	$ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$	6.4	6.7	2.1σ	1.7σ
500	$ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	5.2	7.0	1.7σ	1.4σ
500	$ZHH \to (q\bar{q})(b\bar{b})(b\bar{b})$	8.5	11.7	2.2σ	1.9σ
		16.6	129	1.4σ	1.3σ

remained signal and background events

full simulation @ 500GeV

Polarization: (e-,e+)=(-0.8,0.3) $\int L dt = 2\text{ab}^{-1}$ M(H) = 120 GeV

	llHH	vvHH	qqHH (i)	qqHH (ii)
Signal	6.4	5.2	8.5	16.6
BG	6.7	7.0	11.7	129
ZZZ	1.2	0.6	2.1	6.7
ZZH	4.3	1.5	2.7	7.6
tt, ttqq	-	3.3	5.2	105
llbb, bbbb	1.2	1.6	1.3	9.1

hypothesis test (combined significance)

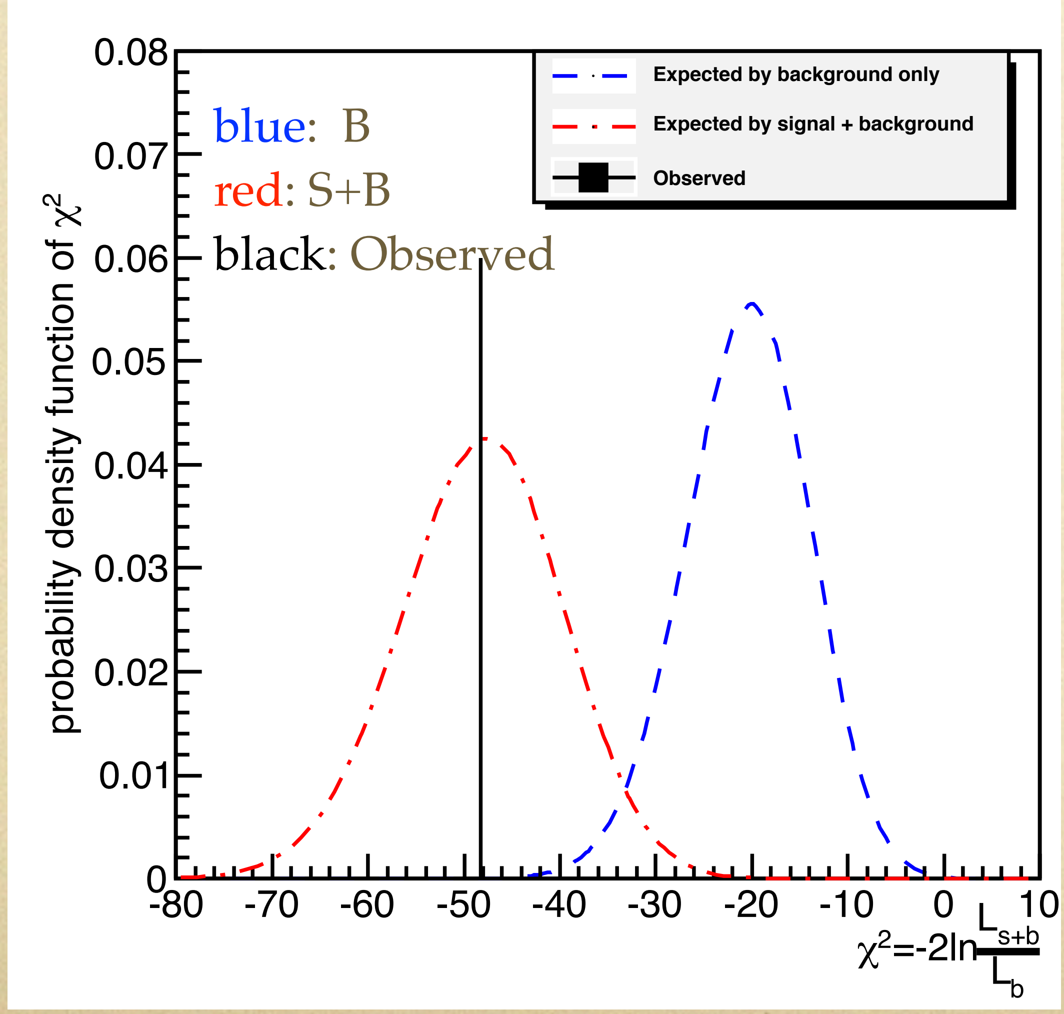
H0: background only H1: ZHH events exist

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

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

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

Distributions of the test



$$p = \int_{-\infty}^{\chi^2_{obv}} f(\chi^2)d\chi^2$$

$$= 4.6 \times 10^{-5}$$

combined significance of ZHH excess: **3.9σ**

extracting the cross section of ZHH

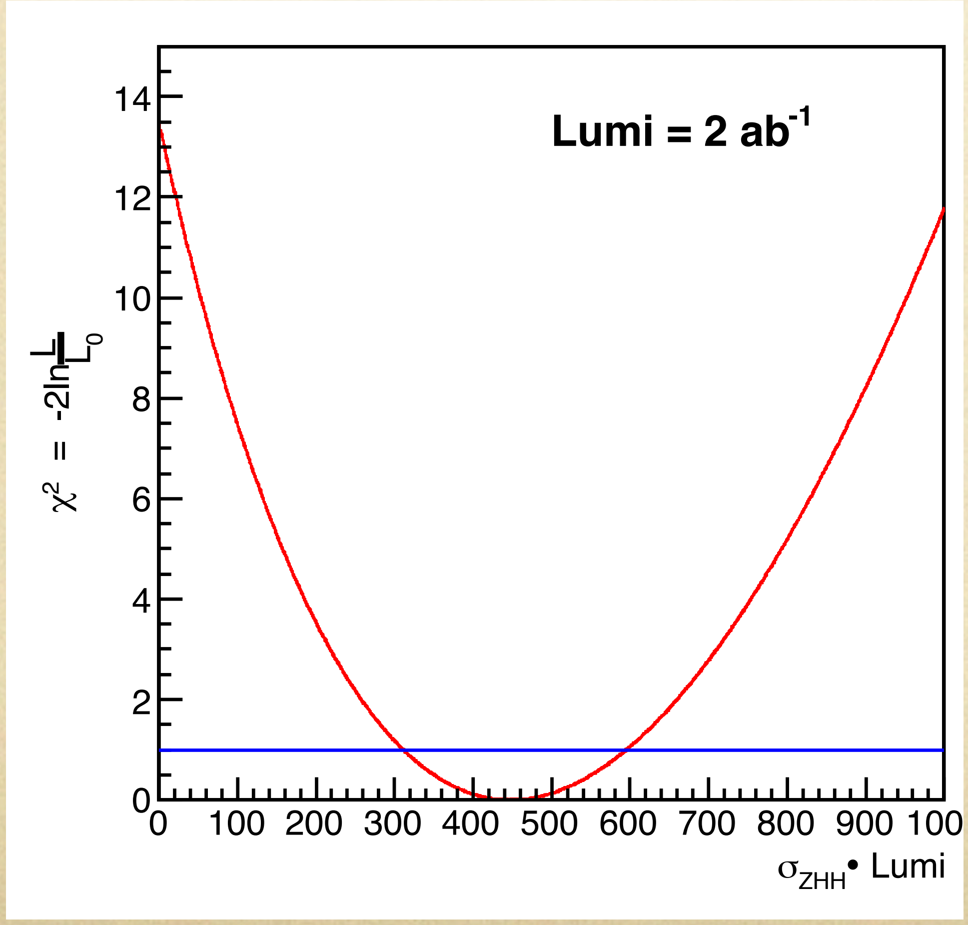
$$L_{s+b} = \Pi_i \frac{e^{-(s_i+b_i)}(s_i+b_i)^{n_i}}{n_i!}$$

b_i: expected background number (known from MC)
n_i: number of observed events (known from Experiment)
s_i: parameter related with the cross section

$$s_i = (\sigma_{ZHH} + \sigma_i) \cdot \text{Lumi} \cdot \text{Br}_i \cdot \text{Eff}_i$$

σi: fusion contribution (negligible at 500 GeV)

$$\chi^2 = -2ln\frac{L}{L_{max}}$$



$$\sigma_{ZHH} \cdot \text{Lumi} = 448^{+145}_{-137}$$

$$\sigma_{ZHH} = 0.22 \pm 0.07 \ \text{ fb}$$

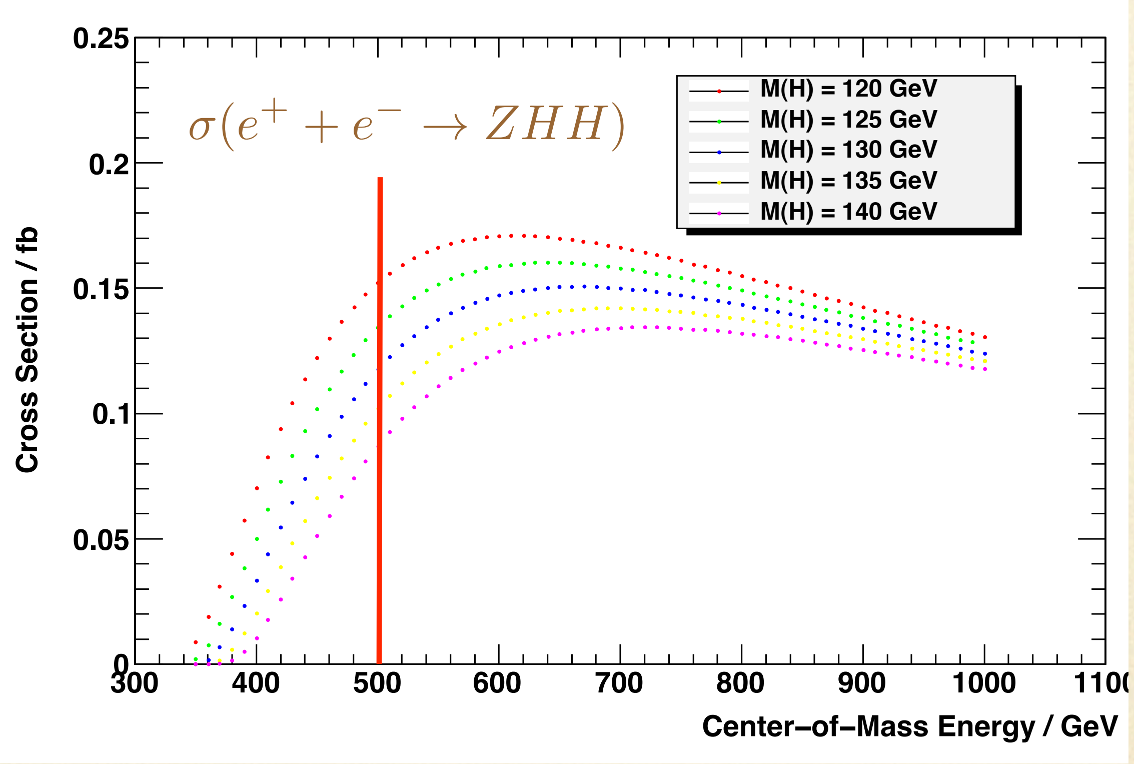
precision of cross section: **32%**
precision of Higgs self-coupling: **57%**

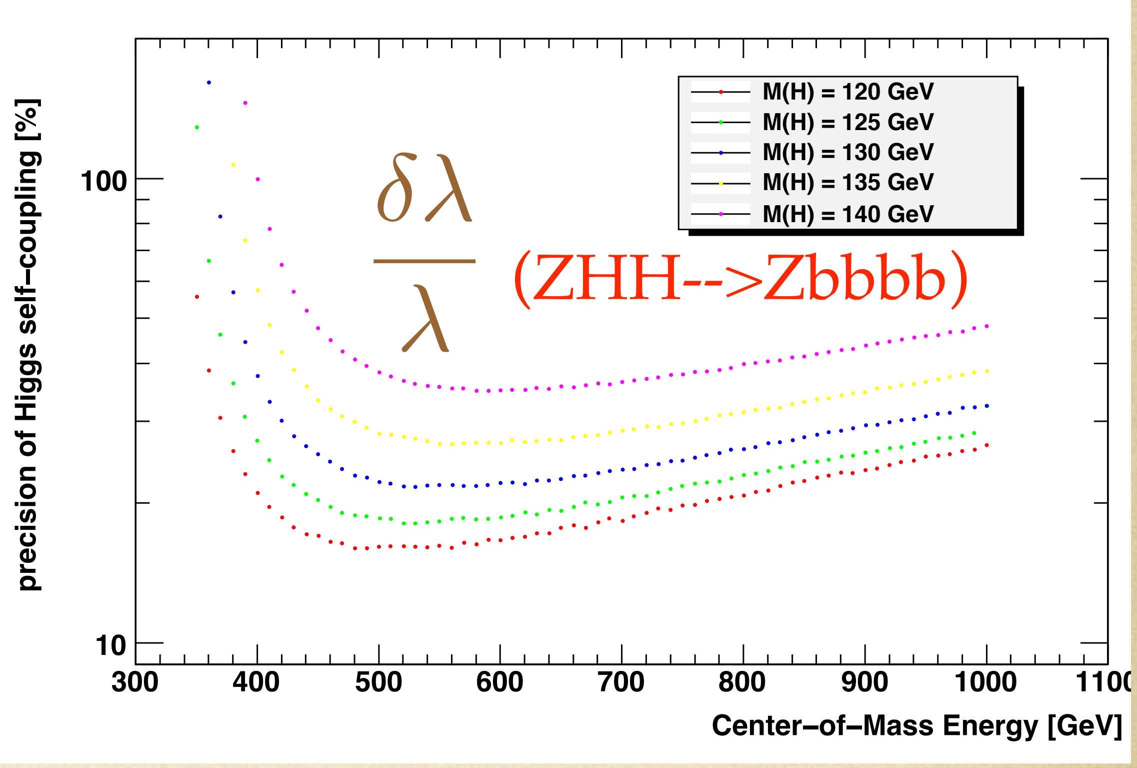
recalling $\frac{\Delta\lambda}{\lambda} = 1.8\frac{\Delta\sigma}{\sigma}$

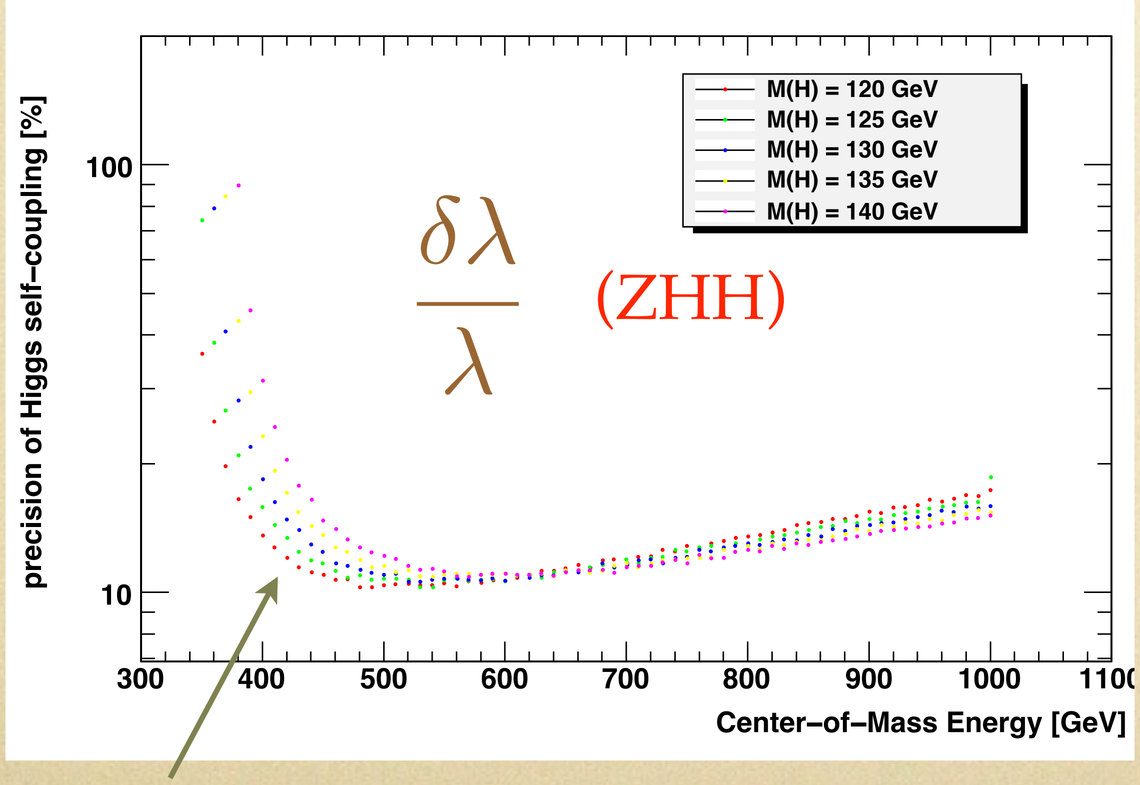
prospects for different Higgs masses

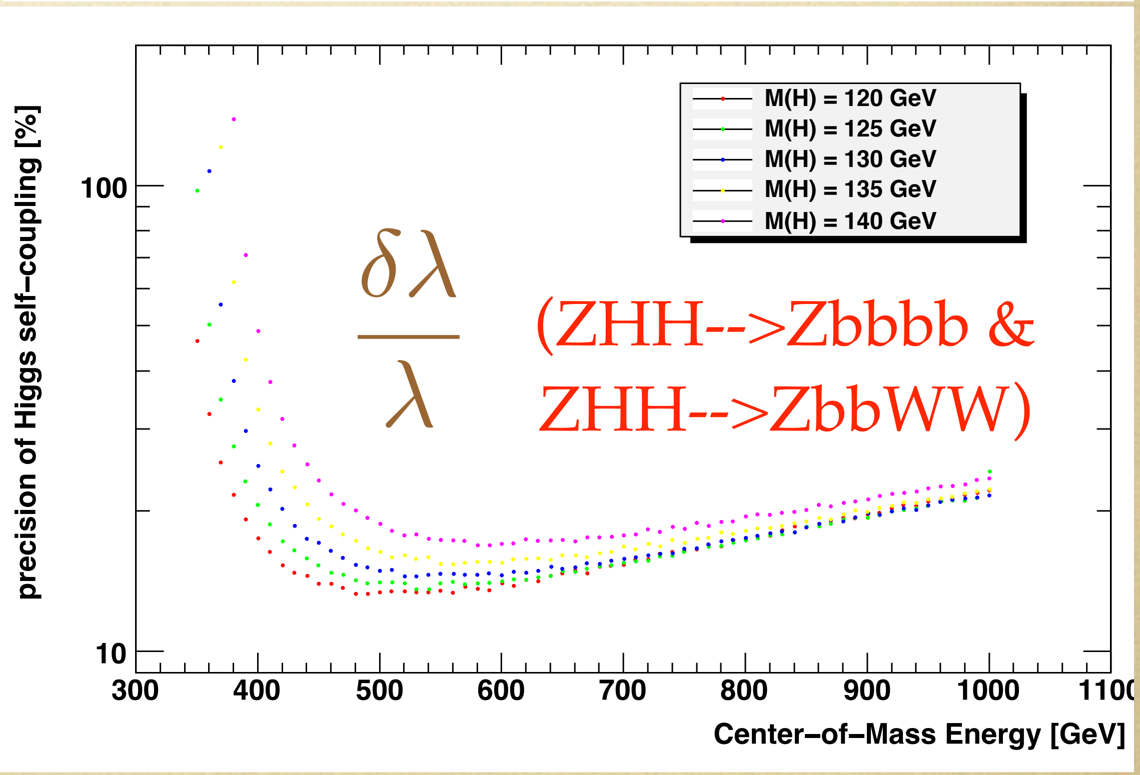
sensitivity of Higgs self-coupling (generator level and without backgound)

- Higgs masses of 120, 125, 130, 135 and 140 GeV are investigated.





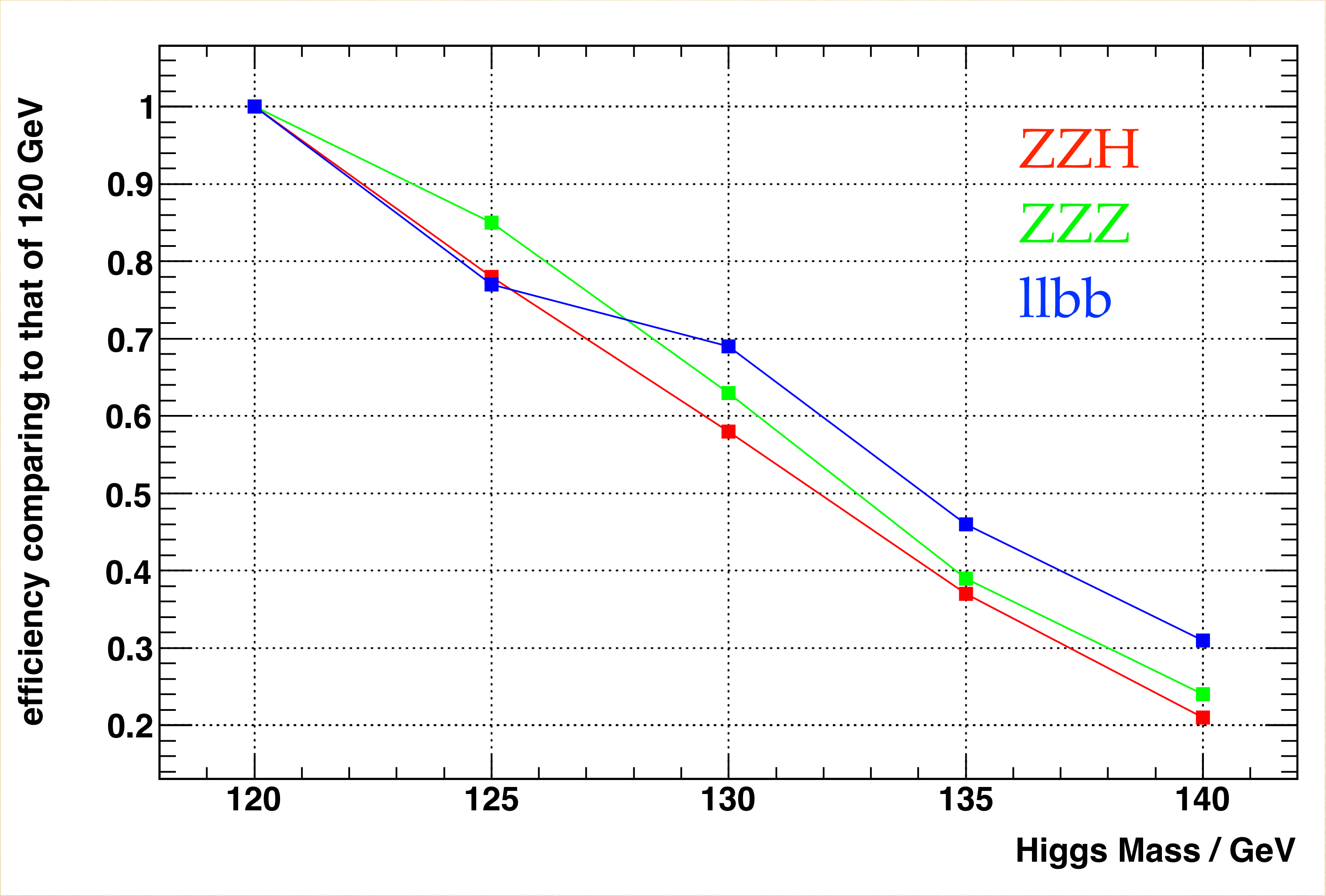




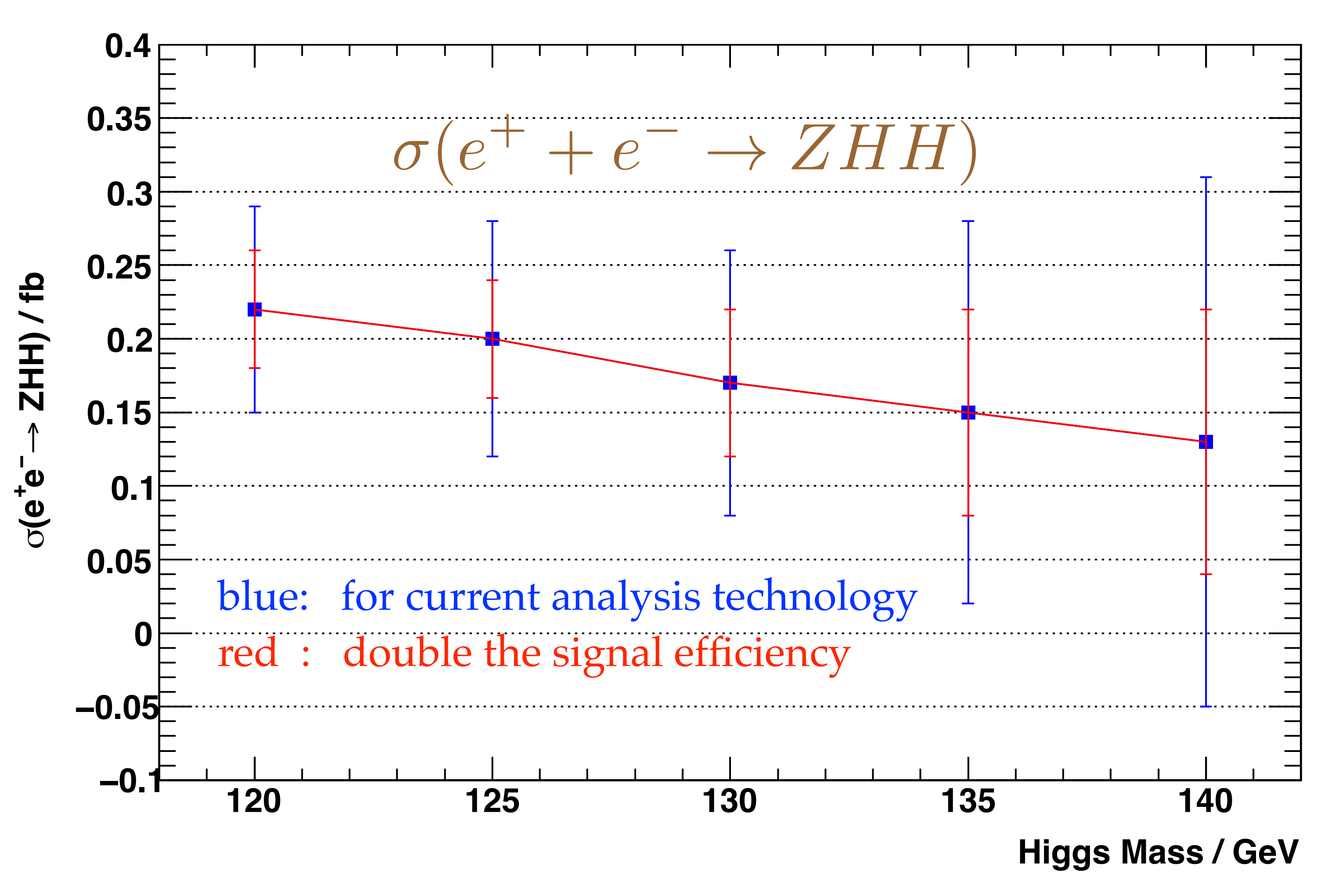
consistent with previous theoretical result

extrapolate results for higher Higgs mass

- assume the signal efficiency unchanged.
- shift the cuts for two Higgs invariant masses to estimate the efficiency drop of the Higgs mass sensitive backgrounds, such as ZZZ, ZZH, llbb.
- keep the t-tbar efficiency unchanged.



extrapolate: precision of the cross section



only H-->bb mode considered!

M(H) (GeV)	120	125	130	135	140
precision	32%	40%	53%	87%	138%
	18%	20%	29%	47%	69%

H-->WW* should be included!

plans for the future improvement towards DBD

future improvements

- jet clustering
    - vertex-based, optimized for b-tagging
- b-tagging
    - based on new jet-clustering
    - neural-net tuning
- jet pairing
    - kinematical, kinematic fitting
    - dynamical? charge?
- lepton ID

tt-bar suppression

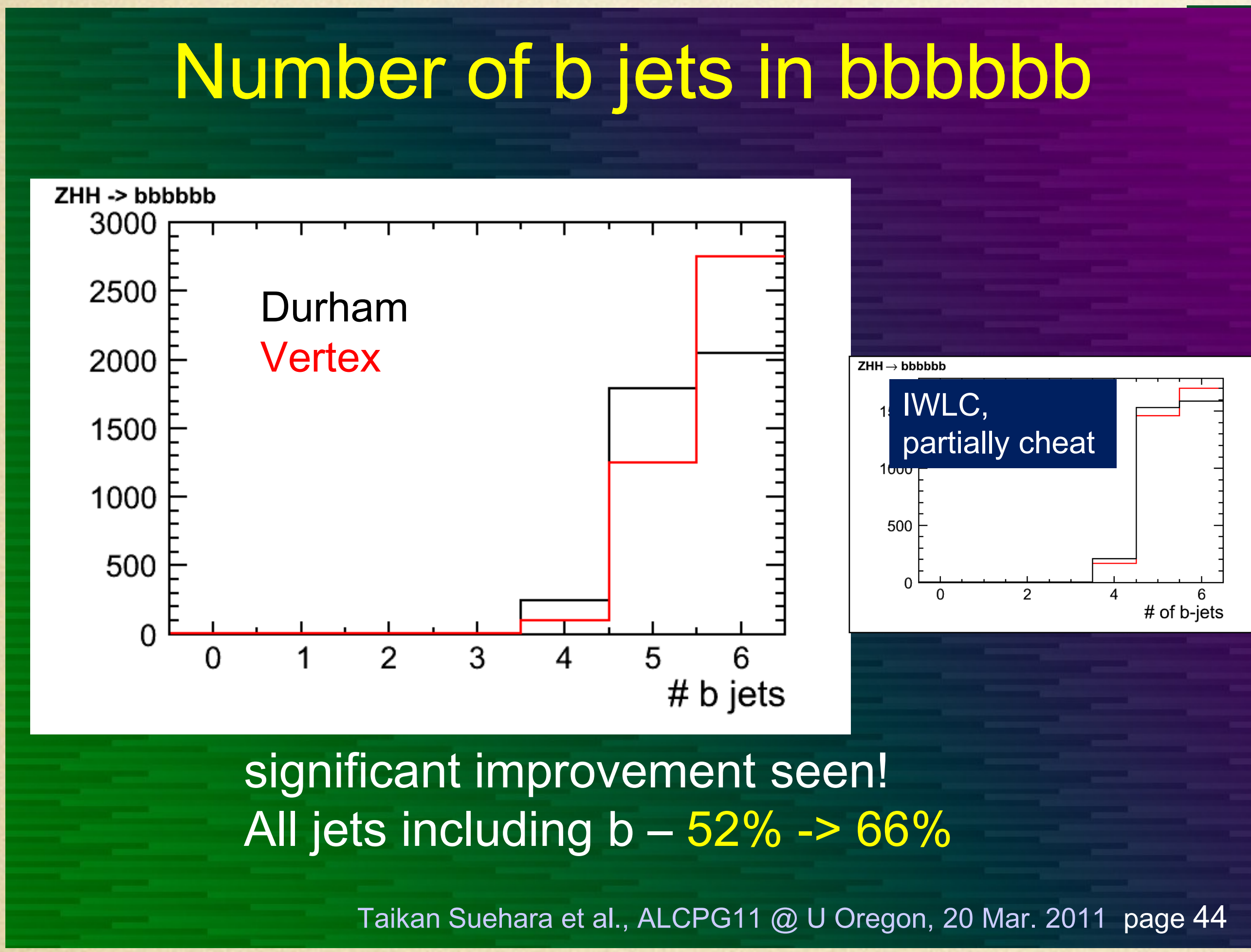
ZZZ, ZZH suppression

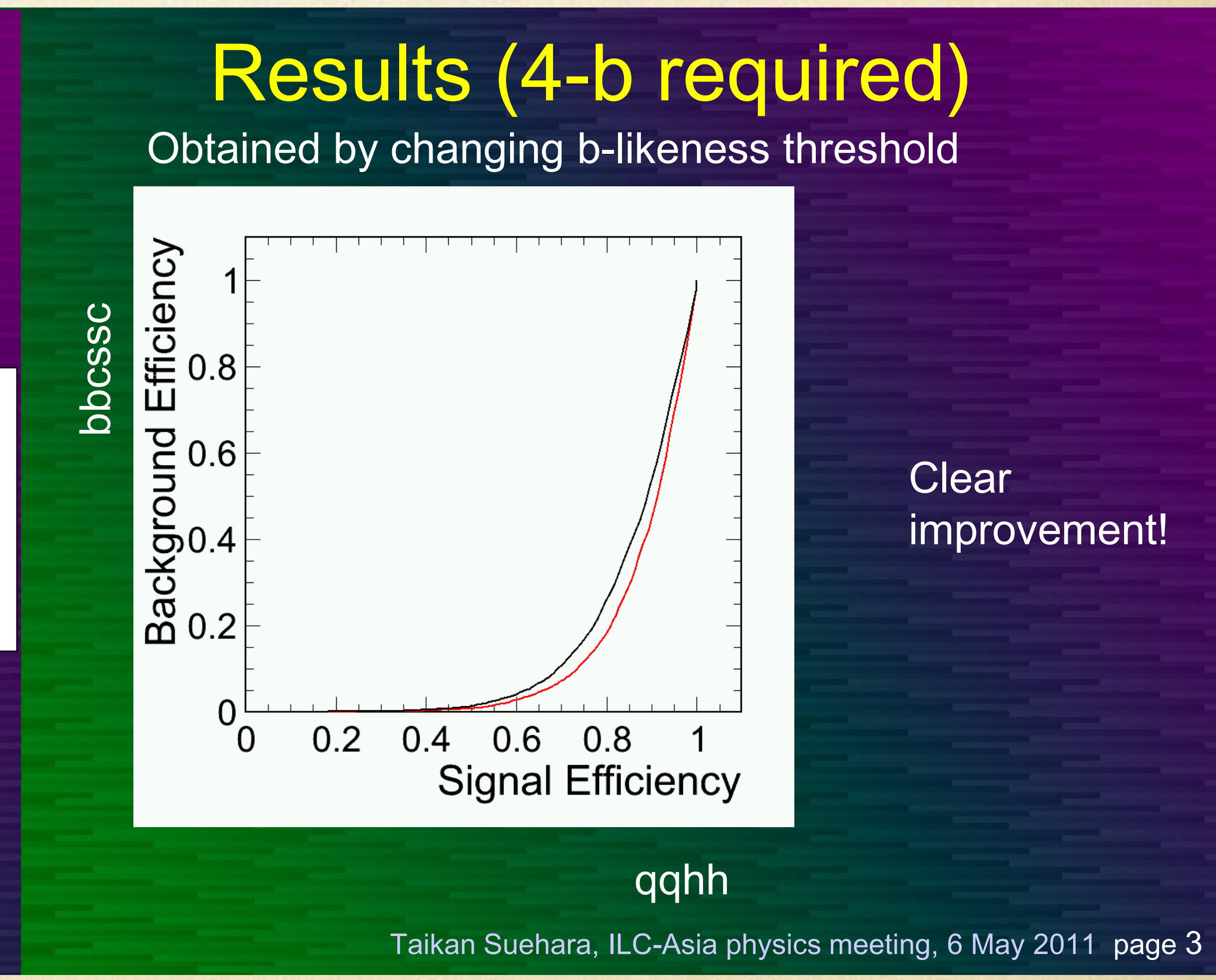
llbb, bbbb suppression

jet clustering

(T. Suehara)

- Vertex Finder --> Jet Cluster --> Flavor Tagger.
- tracks from one B-hadron will not be clustered to different jets





applied to tt-bar suppression

ongoing

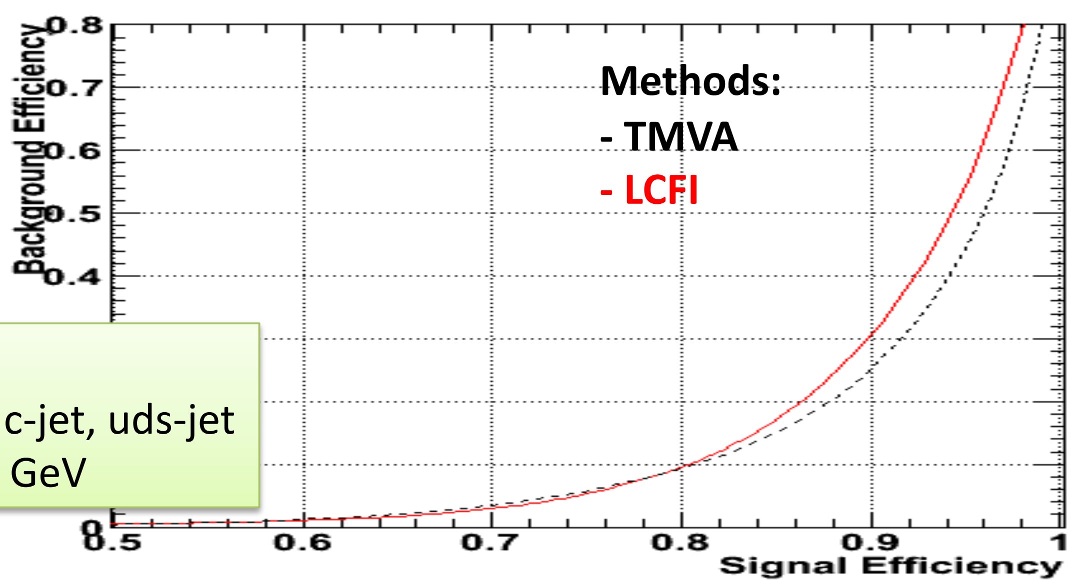
flavor tagging (LCFIVetex)

(T. Tanabe)

- new framework with TMVA, easier to modify
- optimization of input variables.

improvements

- improvements attempts have already begun by incorporating new variables
  - currently incorporate the vertex ordering information (vertex distance and vertex momentum direction)
  - already see improvement in the high signal efficiency region
- will incorporate other variables & optimize at higher energies



signal = b-jet
background = c-jet, uds-jet
Z-> qq @ 91.2 GeV

ongoing

jet pairing

(J. Tian & K. Fujii)

- likelihood pairing algorithm.
- kernel function can well estimate the shape of the invariant mass spectrum

jet pairing using Kernel Function

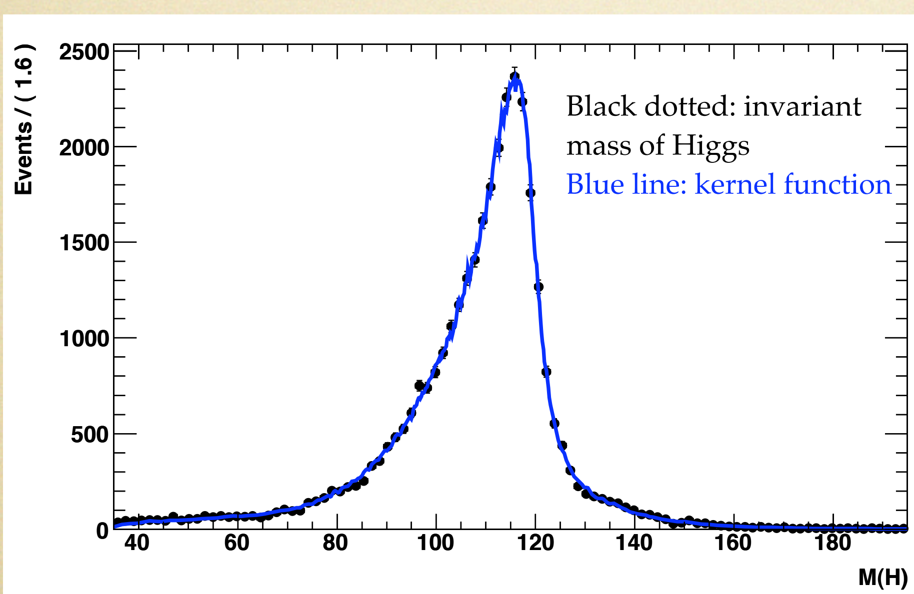
not gaussian!

traditionally: $$\chi^2 = \frac{(M(b,\bar{b}) - M_H)^2}{\sigma^2_{H_1}} + \frac{(M(b,\bar{b}) - M_H)^2}{\sigma^2_{H_2}} + \frac{(M(l,\bar{l}) - M_Z)^2}{\sigma^2_Z}$$

define: $L = f(M_{12})f(M_{34}) \qquad \chi^2 = -\ln L = -\ln f(M_{12}) - \ln f(M_{34})$

f: the real probability density function (from MC)

distribution of invariant mass and estimated kernel function



Non-parametric Kernel Estimation

$$F(x) = \frac{1}{N}\sum_{j=1}^{m} n_j G(x; t_j, h_j)$$

$$h_j = \left(\frac{4}{3}\right)^{1/5} N^{-1/5} \triangle x \sqrt{\frac{N}{n_j}}$$

efficiency of correct pairing improved: 80% ----> 85%

65

kinematic fitting?
charge information?
color singlet information?

ongoing

lepton identification

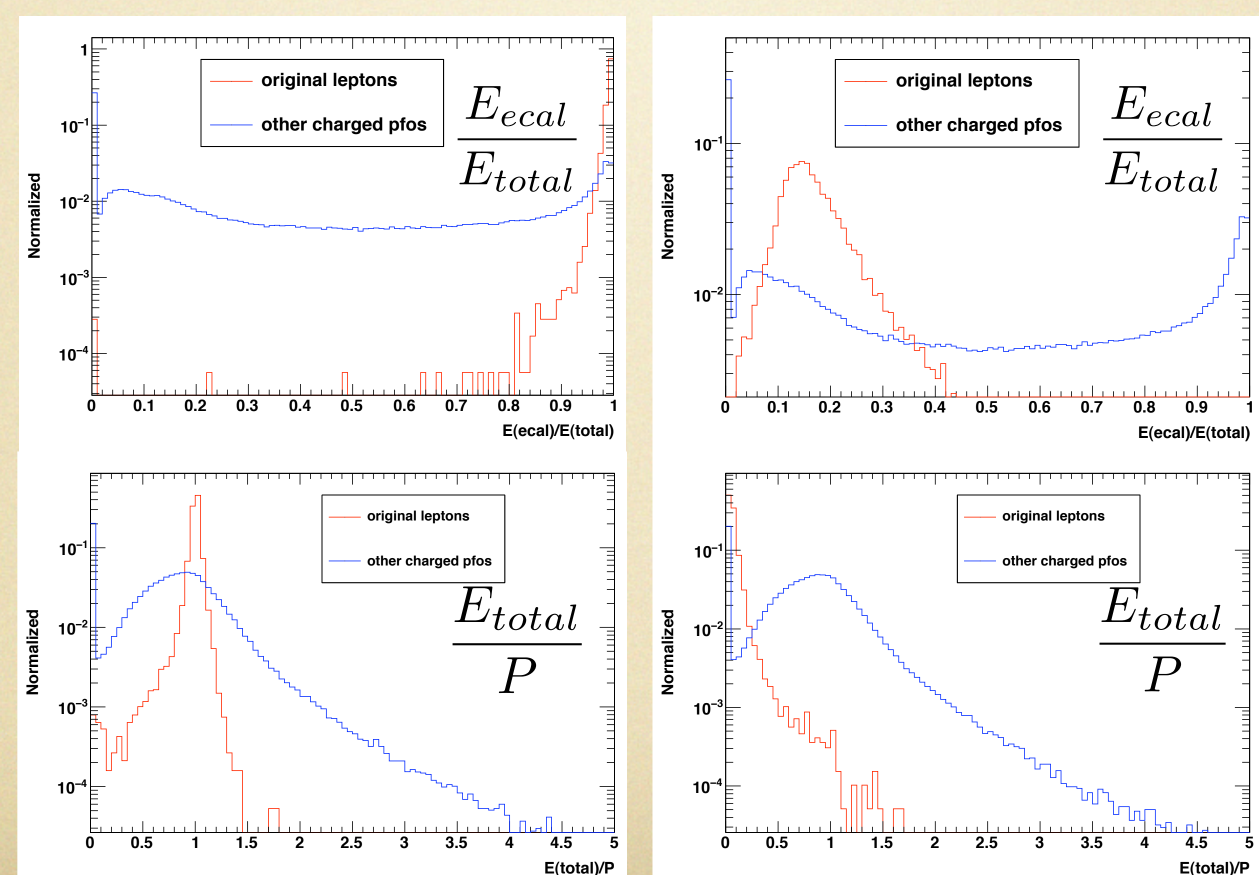
(J. Tian & K. Fujii)

- previously only P, E(Ecal), E(Hcal) and E(cone) used. more information (dE/dx? shower profile?)
- Fisher Classification used for isolation requirement.

lepton identification

- electron almost deposits all the energy in the ECAL.
- muon deposits small part of the energy in both ECAL and HCAL, but more in the HCAL than ECAL.

$$e : \begin{cases} \frac{E_{ecal}}{E_{total}} > 0.9 \\ 0.8 < \frac{E_{total}}{P} < 1.2 \end{cases} \qquad \mu : \begin{cases} \frac{E_{ecal}}{E_{total}} < 0.5 \\ \frac{E_{total}}{P} < 0.3 \end{cases}$$



samples:
eeHH & μμHH

red:
prompt leptons

blue:
other charged pfos

25

leptons in a jet:

- used for flavor tagging
- calibrate the missing neutrino pt

not started yet

further analyses

- 1 TeV full simulation
- alternative Higgs mass (real analysis)

task force for Higgs self-coupling analysis

- currently 4 members: T. Suehara, T. Tanabe, J. Tian and K. Fujii
- chaired by T. Suehara, supervised by K. Fujii
- biweekly meeting
- anyone interested is invited

summary

- an analysis of ZHH @ 500 GeV based on current technology is completed: the first full simulation study with three decay modes.
- effects of higher Higgs masses are investigated: challenge for analysis tools and other decay modes of Higgs should be considered.
- a task force for Higgs self-coupling analysis is formed to work on the improvements.

backup

remained S & B for different Higgs masses

(with cross section drop and branching ratio drop)

M(H)=125 GeV

	llHH	vvHH	qqHH (i)	qqHH (ii)
Signal	4.5	3.6	6.0	11.6
BG	4.7	6.0	9.7	123

M(H)=130 GeV

Signal	2.9	2.3	3.8	7.4
BG	3.2	5.4	8.4	119

M(H)=135 GeV

Signal	2.9	2.3	3.8	7.4
BG	5.6	4.5	7.1	113

M(H)=140 GeV

Signal	0.9	0.7	1.1	2.2
BG	1.0	4.0	6.3	110

combined significance of ZHH excess

Polarization: (e-,e+)=(-0.8,0.3) $\int L dt = 2\mathrm{ab}^{-1}$

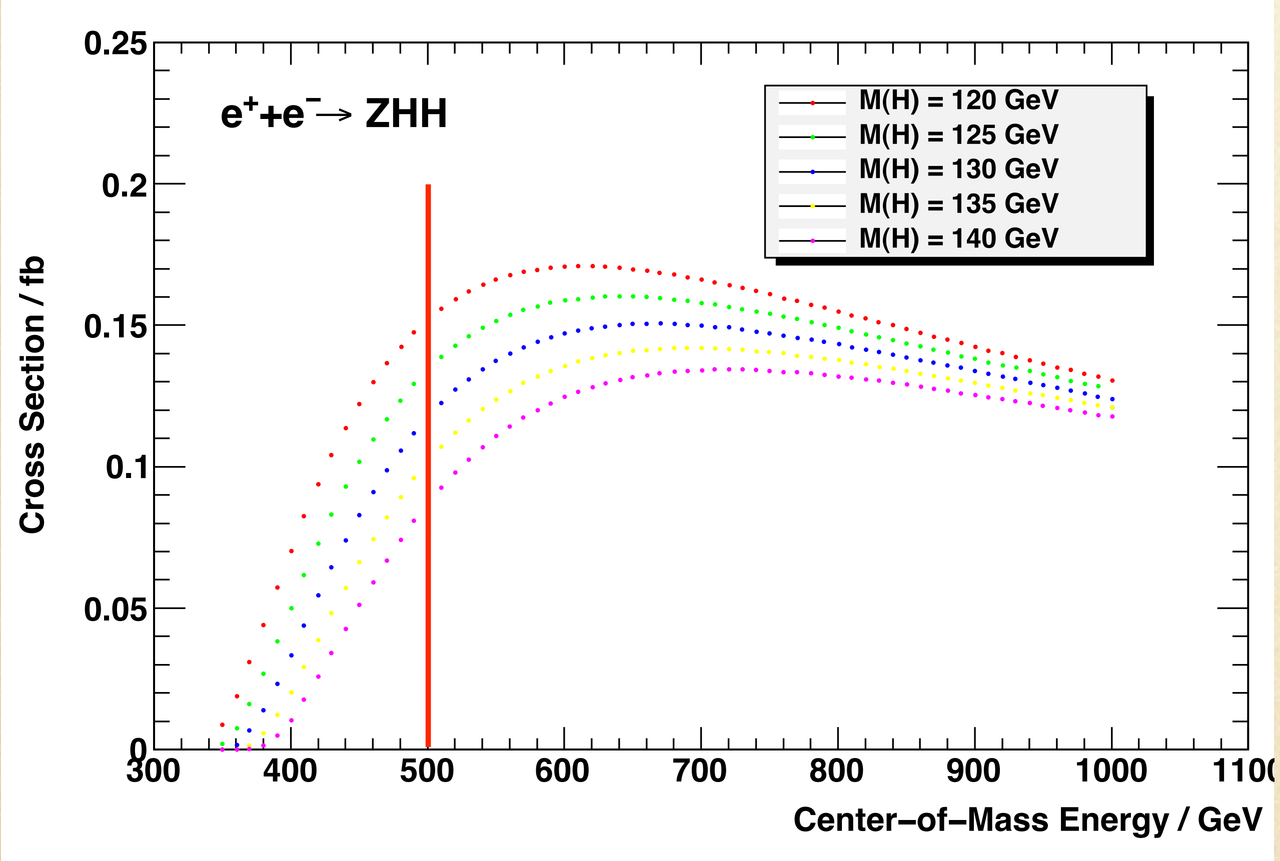
M(H) GeV	120	125	130	135	140
significance	3.9σ	3.4σ	2.2σ	1.4σ	1.0σ
	8.4σ	7.5σ	4.7σ	2.6σ	1.9σ

results for the case we can double the signal efficiency with the future improvement

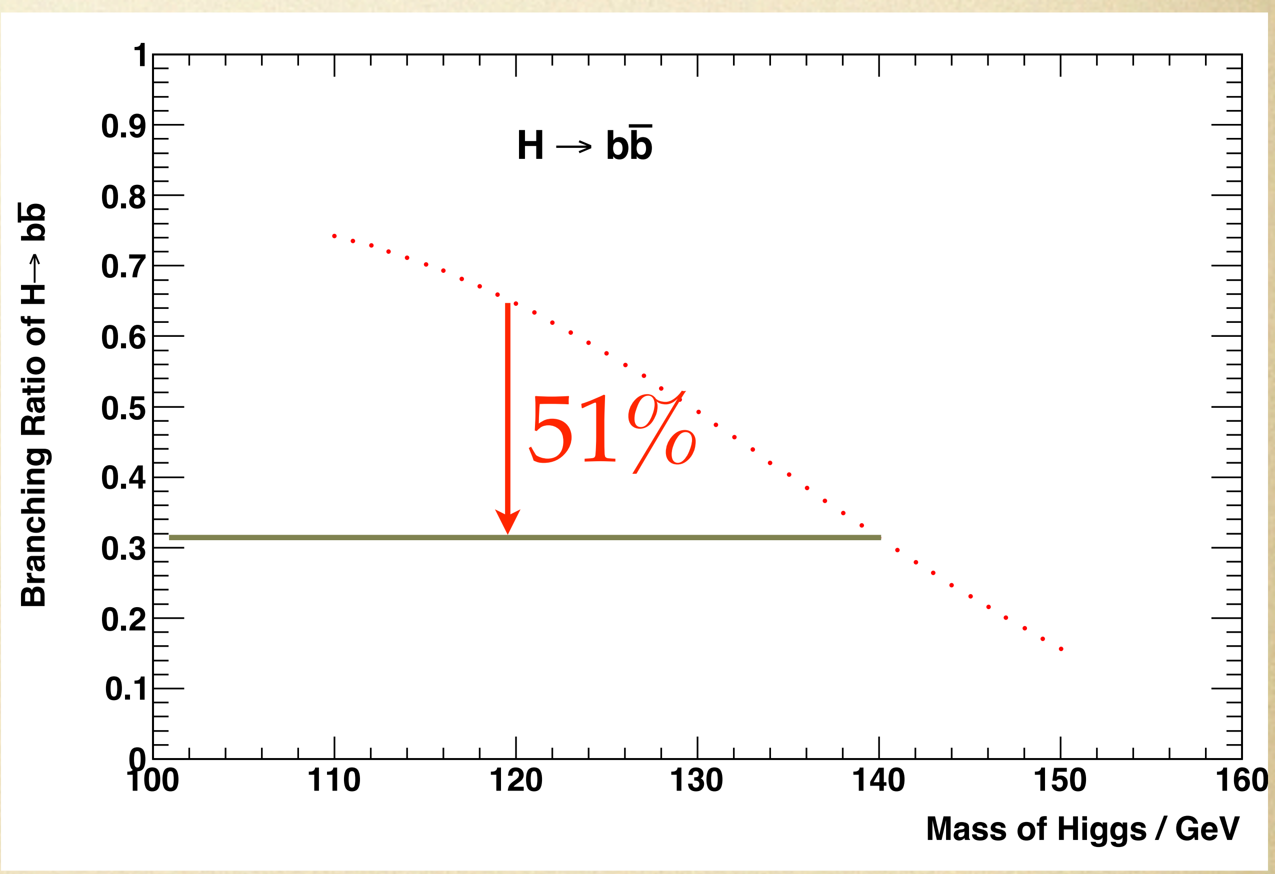
effects on the cross section of ZHH and branching ration of H-->bb

- Higgs masses of 125, 130, 135 and 140 GeV are investigated.

cross section drops quickly

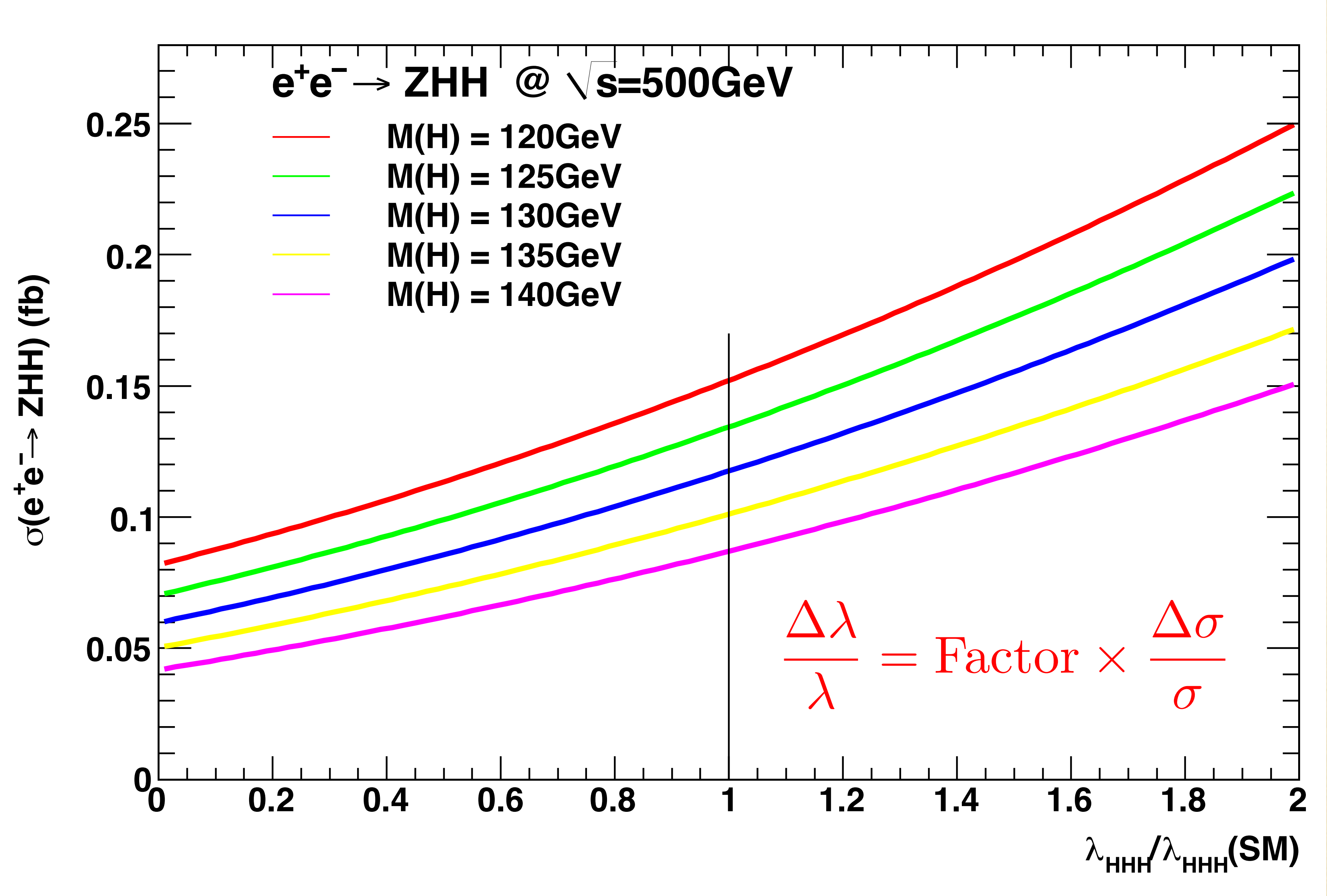


Br(H-->bb) drops quickly



For 140 GeV Higgs, σ(ZHH-->Zbbbb) will be only 13% of that for 120 GeV

precision of the self-coupling



effects of irreducible Feynman diagrams

M(H) (GeV)	120	125	130	135	140
Factor	1.80	1.74	1.68	1.63	1.59
precision	57%	70%	89%	142%	219%
	32%	35%	49%	77%	110%